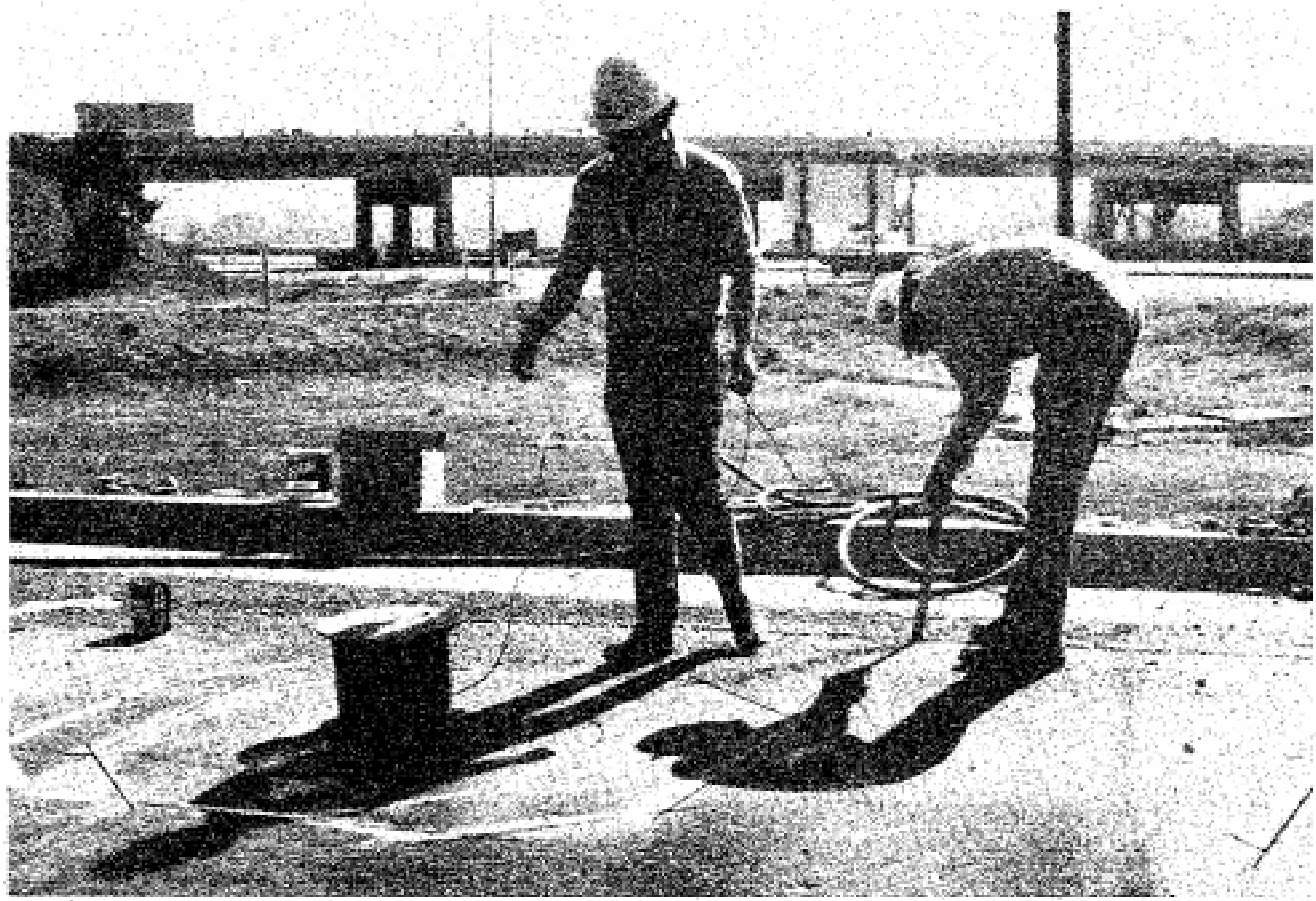
Traffic Detector Handbook

Second Edition

Publication No. FHWA-IP-90-002

July 1990



U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
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Foreword

The Traffic Detector Handbook is a product of the Federal Highway Administration technology transfer program. It is intended for use by traffic engineers and technicians having responsibility for the design, installation and maintenance of traffic detectors.

Judicious application of the concepts and procedures set forth in the Handbook should result in improved installations of traffic detectors and a long-term savings of public funds.

Other resources to assist with selection and installation and maintenance of traffic and vehicle detectors are under development. They include a Traffic Detector Field Manual and a videotape training course. Both will be tied to the Handbook and will focus on practical considerations in installing and maintaining detectors.

Sufficient copies of this Handbook are being distributed to provide a minimum of one copy to each FHWA regional office, division office, and State highway agency. Direct distribution is being made to the division offices.

Richard A. McComb/for
Director, Office of Implementation

Notice

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. This Handbook does not constitute a standard, specification or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturers' names appear herein only because they are considered essential to the objective of the Handbook.

Technical Report Documentation Page

1. Report No.
FHWA-IP-90-002

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

TRAFFIC DETECTOR HANDBOOK

5. Report Date
July 1990

6. Performing Organization Code

8. Performing Organization Report No.

7. Author(s)
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9. Performing Organization Name and Address
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10. Work Unit No. (TRAIS)
3B9a0083

11. Contract or Grant No.
DTFH61-88-C-00020

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Highway Administration
Office of Research and Development

13. Type of Report and Period Covered
Technical Handbook
May 1988 - July 1990

14. Sponsoring Agency Code

15. Supplementary Notes
FHWA Contracting Officer's Technical Representative: Juan Morales (HRT-20)
Roger Dean (HRT-20)

FHWA Contract Administrator: Roger Martin (HCP-42)

16. Abstract
This handbook is a revised, updated version of the Federal Highway Administration's (FHWA) Traffic Detector Handbook, originally published as Implementation Package FHWA-IP-85-1. This upgraded version of the Handbook supersedes and replaces the previous edition. It has been restructured, corrected, and revised to update discussions of concepts and equipment to reflect the current state of the art, particularly as it relates to the microprocessor revolution, advances in control technology, and real-world application experience.

The overall objective of this Handbook is to provide a single resource and basic reference to aid the practicing engineer and technician in planning, designing, installing, and maintaining detectors.

It provides a compendium of existing detector technology to facilitate the understanding of all aspects of detector systems. Best current practices are described with emphasis on proper design, applications, and installation processes and techniques.

17. Key Words
Detectors, Inductive Loops, Magnetometers, Magnetic Detectors, Traffic Signal Control, Traffic Surveillance & Control, Vehicle Detection, System Sensors.

18. Distribution Statement
This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
354

22. Price

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When you know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	25.4	millimeters	mm
in	inches	*2.54	centimeters	cm
ft	feet	0.3	meters	m
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares (10,000 m^2)	ha
	MASS (weight)			
oz	ounces	28.4	grams	g
lb	pounds	0.46	kilograms	kg
	short tons (2000 lb)	0.9	metric tons	
	VOLUME			
fl oz	fluid ounces	29.6	milliliters	ml
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
**F	Fahrenheit temperature	5/9 (after subtracting 32°)	Celsius temperature	**C

* 1 inch equals 2.54 centimeters exactly. For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures.

Approximate Conversions from Metric Measures

Symbol	When you know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	10.8	square feet	ft^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
	metric tons	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35.3	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
**C	Celsius temperature	9/5 (then add 32°)	Fahrenheit temperature	**F

** Exact conversion.

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ACKNOWLEDGMENTS

No project of this type can be carried out without the input and help of dozens of people and organizations. Possibly the one activity that required the most time and energy was the review of the draft Handbook. For this we are especially grateful to: Peter Yauch, Florida Department of Transportation; Tom Potter and Bill Russell of Detector Systems; George Palm of 3M; Jim Gould and James Magerkurth of Indicator Controls Corporation; and D. F. J. Evans of Sarasota Engineering Co., Inc.

We would also like to say "Thank you" to all those listed below who shared their knowledge and experience.

E. D. Arnold, Jr. - Virginia Department of Highways & Transportation
Wendell A. Blikken - Michigan Department of Transportation
Donald L. Burmeister - Illinois Department of Transportation
Leon Dennison - Never Fail Detector Systrems
Ralph Fergerson - Ralph Fergerson & Associates
Panos G. Michalopoulos - University of Minnesota
Donald L. Woods - Texas Transportation Institute, Texas A & M University

I. INTRODUCTION

A vehicle detection system, defined by the National Electrical Manufacturers Association (NEMA) Standards as "…. a system for indicating the presence or passage of vehicles," provides input for traffic-actuated signal control, traffic-responsive system control, freeway surveillance, and data collection systems. As such, the application, design, installation, and maintenance of detectors becomes increasingly important as traffic control and surveillance systems continue to proliferate and become more sophisticated.

Millions of research dollars have been, and are being, applied to controlling traffic and alleviating congestion and delay on the Nation's existing streets and freeways. The success of these control systems depends to a large extent on the proper design, installation, and maintenance of the detector component of the overall system. Consequently, it is incumbent on the jurisdictions or agencies implementing or operating these systems to assure that appropriate attention is directed toward this relatively straightforward but critical system element.

This handbook is a revised, updated version of the Federal Highway Administration's (FHWA) *Traffic Detector Handbook,* originally published as Implementation Package FHWA-IP-85-1. This upgraded version of the Handbook supersedes the previous edition. However, the valuable materials and basic scope of the original document have been retained. It has been restructured and revised to update discussions of concepts and equipment to reflect the current state of the art, particularly as it relates to the microprocessor revolution, advances in control technology, and real-world application experience.

SCOPE AND OBJECTIVES OF THE HANDBOOK

The overall objective of this Handbook is to provide a single resource and basic reference to aid the practicing engineer and technician in planning, designing, installing, and maintaining detectors. Specifically, the Handbook is intended to:

- Provide a compendium of existing detector technology.
- Facilitate the understanding of the basic elements of detector systems.
- Aid in the understanding and application of new technology.
- Identify the best current practices.
- Serve as a training aid for traffic engineers, traffic technicians, and field personnel.

EVOLUTION OF DETECTOR TECHNOLOGY

In the 1920's when manually-operated traffic signals were being replaced by automatic, pretimed traffic control devices, engineers soon pointed to the need for some means of collecting the traffic data previously obtained visually by the police officer on duty. Among those concerned was Charles Adler, Jr. of Baltimore, a railway signal engineer. He developed a detector that was activated when a driver sounded his car horn at a specified location. This device consisted of a microphone mounted in a small box on a nearby utility pole. Adler's device, first installed in 1928 at a Baltimore intersection, constituted the first semi-actuated signal installation to assign right of way by means of a vehicle detector.

At nearly the same time, Henry A. Haugh, an electrical engineer, developed a pressure-sensitive pavement detector using two metal plates acting as electrical contacts brought together by the wheel pressure of passing vehicles. This pressure-sensitive, treadle type, in-road detector proved more popular than the horn-activated detector. In fact, this detector enjoyed widespread use for over 30 years as the primary means of detecting vehicles at actuated signals.

Concomitantly, Adler continued his work with sound detectors and in 1931 introduced another sound detector which employed hollow steel boxes embedded in the intersection approach. These boxes picked up the sound of passing wheels and transmitted this to microphones.

Mechanical problems with the contact-plate detector led to the introduction of the electro-pneumatic detector. Although this device found some application, it was costly to install, it was only capable of passage (motion) detection, and its (axle) counting accuracy was limited by the generation of air pressure waves and capsule contact bounce.

In retrospect, it seems unfortunate that the treadle detector, which utilized the most obvious and most easily detected property of vehicles–their mass (weight)–could not be economically improved further. Snow plows tended to lift the plate from the roadway resulting in costly repairs. There was also the expense of reinstalling the detector after roadway resurfacing. These problems led to the search for detectors based on more subtle properties such as:

- Sound (acoustic detectors).
- Opacity (optical detectors).
- Geomagnetism (magnetic detectors, magnetometers).
- Reflection of radiation (infrared, ultrasonic, radar, and microwave detectors).
- Electromagnetic induction (loop detectors).
- Vibration (tribo-electric, seismic, and inertia-switch detectors).

Not all of these concepts have been commercially exploited. Today, the inductive loop detector is, by far, the most widely used detector in modern traffic control systems. The magnetometer and the magnetic detector are also produced commercially and are used for various applications. The optical detector has found use for the detection of priority vehicles and research is on-going for infrared, ultrasonic, and radar detectors.

Also under development are wide-area detection systems (WADS). One promising system uses video imaging techniques and is known as VIDS.

It is reasonable to assume that as operational needs proliferate, and technical advances keep pace, detector technology will continue to be a dynamic and expanding field.

INTRODUCTION TO MODERN DETECTORS

The following discussion provides a broad overview of the basic types of detectors in use today. While the emphasis in this summary overview is directed toward typical use of detectors for traffic signal control, subsequent chapters cover other applications (i.e., freeway ramp metering, freeway mainline control, etc.) as well as emerging concepts, practices, and products.

The three main types of vehicle detectors used in current practice are inductive loop detectors, magnetic detectors, and magnetometers. Each of these detector systems consists of sensors in or below the roadway, a lead-in cable connecting the sensor at a pull box to the controller cabinet, and an electronic unit housed in the controller cabinet (Figure 1).

By far the most popular method of vehicle detection is the inductive loop detector system. As shown in

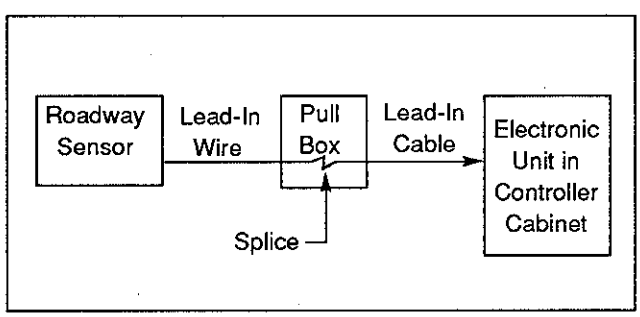


Figure 1. Vehicle detector system.

Figure 2, the total system consists of three parts: a detector oscillator, a lead-in cable, and a loop embedded in the pavement consisting of one or more turns of wire. The detector oscillator (amplifier) transmits its own energy (electrical field) and operates on the principle that a vehicle resting in, or passing over, the loop will unbalance a tuned circuit resulting in a detection. The size, shape, and configuration of the loop varies considerably depending upon the specific application, ranging from the most common size 6- x 6- ft (1.8- x 1.8- m) loops, to long rectangular loops (6- x 40- to 70- ft (1.8- x 12- to 21-m). Because of the flexibility of its design, the loop detector provides for the broadest range of vehicle detection.

Loop detector systems are constructed with electrical characteristics that match an oscillator/amplifier. The oscillator serves as a source of energy for the loop. When a vehicle passes over the loop or is stopped within the loop area, it reduces the loop inductance, causing an increase in the oscillator frequency. The change in inductance or frequency activates a relay or circuit which sends an electrical output to the controller signifying that it has detected the presence of a vehicle.

The loop itself is constructed by cutting a slot in the pavement and placing one or more turns of wire in the slot. The wire is then covered with sealant. An alternate, more durable construction is to place the turns of wire in a plastic conduit just below the pavement surface. Another alternative is to encase the wire in a plastic sleeve before installing in the saw-cut slot in the pavement. A wide variety of loop sizes and shapes may be used to meet specific needs (see Chapter 4). The 6- x 6- ft (1.8- x 1.8- m) square loop is the most commonly used loop for actuated traffic signal control.

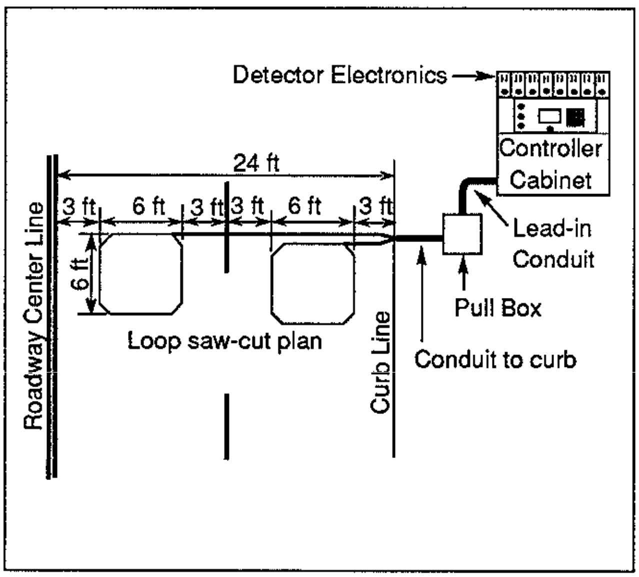


Figure 2. Loop detector system.

Magnetic detector probes (Figure 3) are cylindrical in shape (no larger than 2.25 in (57 mm) in diameter or more than 21 in (53 cm) in length) and are placed below the roadway. They detect vehicles based upon a change in the lines of flux from the Earth's magnetic field. These detectors provide only passage data and not occupancy or presence data. Accordingly, their use is limited to special circumstances and is being phased out of general use.

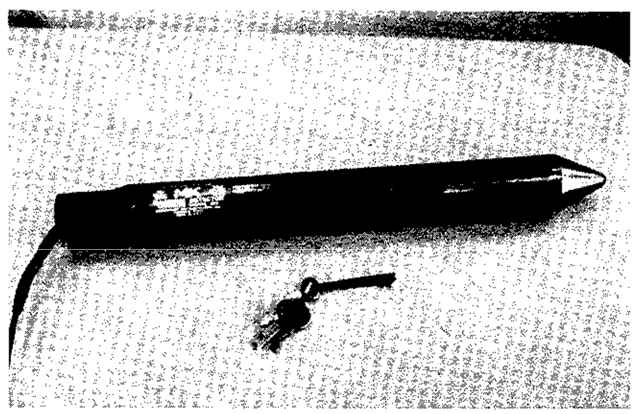


Figure 3. Magnetic detector probe.

Magnetometer probes (Figure 4) are small cylinders (no larger than 2 in (5 cm) in diameter or more than 4.25 in (11 cm) in length) embedded vertically in the surface of the roadway. The presence of a vehicle is detected by measuring the focusing effect of the Earth's magnetic field that occurs when the vehicle is near the detector. These detectors are particularly effective for use on bridge structures and with chronically poor pavement surfaces. Magnetometers can be used instead of or in combination with loop detectors.

Another device similar to the magnetometer is the microloop. It is a small, passive, cylindrical probe

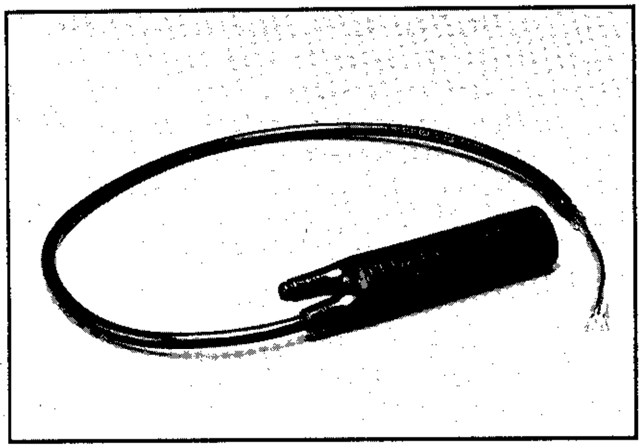


Figure 4. Magnetometer probe.

(0.88 in (2.2 cm) in diameter and 3.63 in (9.2 cm) long) buried beneath the roadway surface. A sample probe is shown in Figure 5. It transforms changes in the Earth's magnetic field intensity into changes in inductance. As a vehicle passes the microloop, the change in inductance is sensed by a conventional loop detector electronic unit.

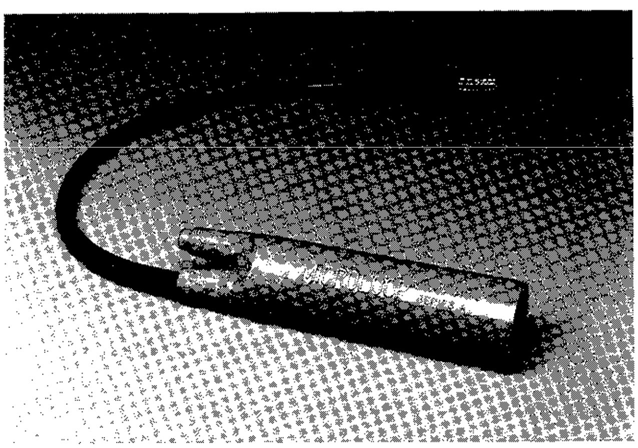


Figure 5. Microloop probe.

Other detector types that have been used in the past are still utilized in special situations. Radar detectors were quite popular in the fifties and sixties, with many installations still in existance. A radar installation is shown in Figure 6. The sonic detector also had a period of popularity. It used the same principles as radar, but in the sonic freequency range rather than in the radio frequencies. A typical sensor head (shown in Figure 7) was mounted either overhead or in a sidefire position. Both of these

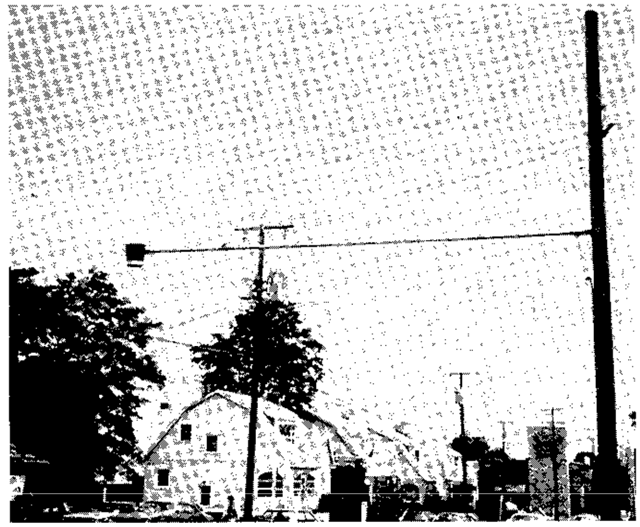


Figure 6. Overhead-mounted radar detector.

types of detectors are being revived using modern technology (see Chapter 7).

The Handbook will concentrate on inductive loops, magnetometers, and magnetic detectors. The main emphasis is on detection for traffic signal installations. There is, however, a growing need for accurate, dependable detectors for traffic surveillance and control.

In recognition of the importance of accurate detection in these applications, manufacterers have developed new models that take advantage of advanced technology. Others concentrate on developing new detection techniques and methodology.

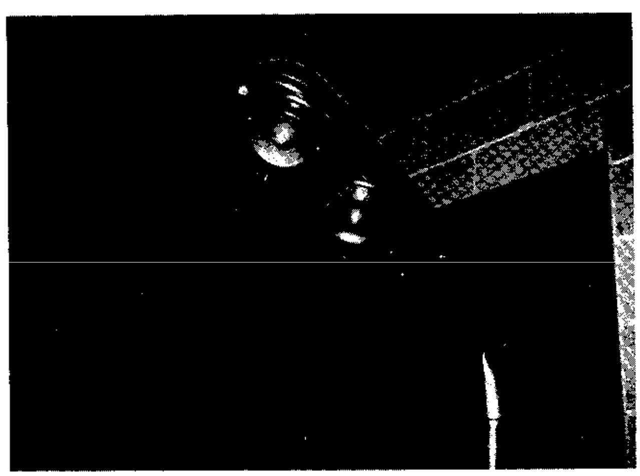


Figure 7. Sonic detector sensor unit.

DEFINITION OF TERMS

One of the major difficulties in explaining detector application and design theories is the abundance (and redundancy) of terms used in current literature. That is, a number of terms meaning the same thing may be used interchangeably and indiscriminately among various reference sources and even within a single document. This can create confusion for even the most experienced traffic engineer.

To avoid any potential confusion, the basic terminology used in this Handbook is defined below. Terms meaning the same (or nearly the same) thing are appended for easy reference. To the extent possible, the term shown in bold type was used consistently throughout the text. A more complete listing of terminology is incorporated in the Glossary at the end of the Handbook.

Detector: A device for indicating the presence or passage of vehicles. This general term is usually supplemented with a modifier indicating type (e.g., loop detector, magnetic detector, etc.); operation (e.g., point detector, presence detector, etc.); or function (e.g., calling detector, extension detector, etc.).

Detector Amplifier: A device that is capable of intensifying the electrical energy produced by a sensor. An example is a magnetic detector amplifier. A loop detector unit is commonly called an amplifier, although its electronic function actually is different.

Detector Unit: The portion of a detector system other than the sensor and lead-in cable, consisting of an electronic assembly.

Large Area Detector: (Area Detector) A detector or series of detectors wired together in series or series/parallel covering an area in the approach to an intersection. Detection area varies from 6 x 40 ft (1.8 x 12 m) to 6 x 100ft (1.8 x 30 m) or larger. One of the more common configurations is four 6- x 6- ft (1.8- x 1.8- m) loops spaced 9 or 10 ft (2.75 or 3 m) apart for a length of 51 or 54 ft (15.5 or 16.5 m).

Small Area Detector: (Point Detector) A detector that measures the passage of vehicles past a point (i.e., a small area usually not exceeding 6 x 6 ft (1.8 x 1.8 m)).

Loop Detector Unit: An electronic device which is capable of energizing the sensor loop(s), of monitoring the sensor loop(s) inductance, and of responding to a predetermined decrease in inductance with an output which indicates the passage or presence of vehicles in the zone of detection. It is the electronics package, exclusive of the loop(s) and lead-in cable.

Loop Detector: A detector that senses a change in inductance of its inductive loop sensor caused by the passage or presence of a vehicle near the sensor.

Magnetic Detector: A detector that senses changes in the Earth's magnetic field that are caused by the movement of a vehicle near its sensor. It is a vehicle detector placed under the roadway which makes use of both the Earth's magnetic field and the energy change created by the passage of a vehicle over the detector to produce an output.

Magnetometer Detector: A detector that measures the difference in the level of the earth's magnetic forces caused by the passage or presence of a vehicle near its sensor. It is a device capable of being activated by the magnetic disturbance caused by the passage or presence of a vehicle. A magnetic flux generator/sensor is installed in the roadway and connected to sensor amplifier electronics.

Passage Detector: (Motion Detector, Dynamic Detector, Movement Detector) A vehicle detector that has the ability to detect the passage of a vehicle moving through the detection zone and to ignore the presence of a vehicle stopped within the detection zone.

Presence Detector: A traffic detector which is able to detect the presence of a vehicle and hold the call for a specified minimum period of time that the vehicle is within its field of detection.

Lead-In Wire: (Loop Lead-In) That portion of the loop wire between the physical edge of the loop and the pull box; for a magnetic detector and magnetometer it is the wire which runs from the sensor (probe) to the pull box.

Lead-In Cable: (Feeder Cable, Home-Run Cable, Transmission Line) The electrical cable which serves to connect the lead-in wire to the input of the loop detector unit.

Pull Box: (Hand Hole, Junction Box, Junction Well, Splice Box) A container usually at least 1 cubic ft (0.028 cubic m) in size that is placed underground with a removable cover flush with the ground surface. Splices between lead-in cable and loop lead-in wire are located here.

Crosstalk: The adverse interaction of any channel of a detector unit with any other detector channel in that unit or another unit. It is the mutual coupling of magnetic fields that produces an interaction between two or more detector units in the same cabinet when the units are operating at similar frequencies. Crosstalk results in a detector outputting an actuation in the absence of a vehicle.

Splashover: An unwanted actuation caused by a vehicle in a lane adjacent to that in which the detector is located.

Zone of Detection: (Area of Detection, Effective Loop Area, Field of Influence, Sensing Zone) That area of the roadway within which a vehicle is to be detected by a vehicle detector system.

ORGANIZATION OF HANDBOOK

This Handbook has been structured to parallel the progression of decisions, activities, and functions related to the design, installation, and maintenance of detector systems. This introductory chapter discussed the evolution of detector technology, the basic types of detectors in use today, the emerging types of detectors under development, and the special terminology as it applies to this Handbook.

Chapter 2 provides the technical information basic to the theory of operation for the various types of detectors. It is specifically addressed to traffic or electric engineers with responsibility for selecting or specifying the proper detector design to meet specific operational requirements. It also covers the roles of the NEMA Standards and the Type 170 Specification.

Chapter 3 provides an overview of detection applications used in traffic control and identifies the wide range of choices involving operational features of the detector component of traffic control.

Design considerations in terms of detector configuration and placement for the various applications are discussed in Chapter 4. It should be of particular interest to traffic engineers involved in developing plans and specifications for local intersections, traffic signal systems, and freeway surveillance and control systems.

Chapter 5 stresses the importance of proper installation procedures and describes the best current practices. This chapter is primarily addressed to project engineers, contractors, inspectors, field crew supervisors, and traffic technicians.

Chapter 6 covers the broad spectrum of detector maintenance activities. It will provide general information of value to management and supervising engineers as well as detailed guidelines for maintenance supervisors and technicians.

Finally, Chapter 7 provides an overview of new technology currently under development in terms of new concepts, hardware, and applications. It also includes a review of relatively new products and applications that have recently been introduced into general usage. The Glossary and List of References follow the appendixes which include supplemental technical information that may be of use by those who are interested in more detail.

2. DETECTOR TECHNOLOGY

This chapter provides technical information basic to the "how" and "why" detectors work, including the theory of operation, the characteristics of the roadway sensing element, and the functional characteristics of the various electronic units for inductive loop detectors, magnetic detectors, and magnetometer detectors. The information summarized in this chapter is intended to provide the practicing traffic engineer or electrical engineer with the background needed to select the proper detector design to meet specific operational requirements.

INDUCTIVE LOOP DETECTORS

Since its introduction in the early 1960's, the inductive loop detector has become the most popular form of detection system. The principle components of an inductive loop detector system include one or more turns of insulated loop wire wound in a shallow slot sawed in the pavement, a lead-in cable from the curbside pull box to the intersection controller cabinet, and a detector electronics unit housed in the intersection controller cabinet. Figure 8 provides a simple schematic of an inductive loop detector system model.

Simply stated, the detector electronics unit drives energy through the loop system at frequencies in the normal range of 10 kHz to 200 kHz. The loop system forms a tuned electrical circuit of which the loop wire is the inductive element. When a vehicle passes over the loop or is stopped within the loop, it decreases the inductance of the loop. This decrease in inductance then actuates the detector electronics output relay or solid state circuit which, in turn, sends an impulse to the controller unit signifying that it has detected the passage or presence of a vehicle.

This section describes in more detail the loop system theory, loop characteristics, and the basics of the detector electronic unit.

BASIC PRINCIPLES AND THEORY OF OPERATIONS

The basic principles of the inductive loop detector system discussed below are common to all of the inductive loop system designs described later in Chapter 4. In all systems, the loop wire and lead-in cable possess a combination of resistance, inductance, and capacitance (both inter-wire and wire-to-earth capacitance).

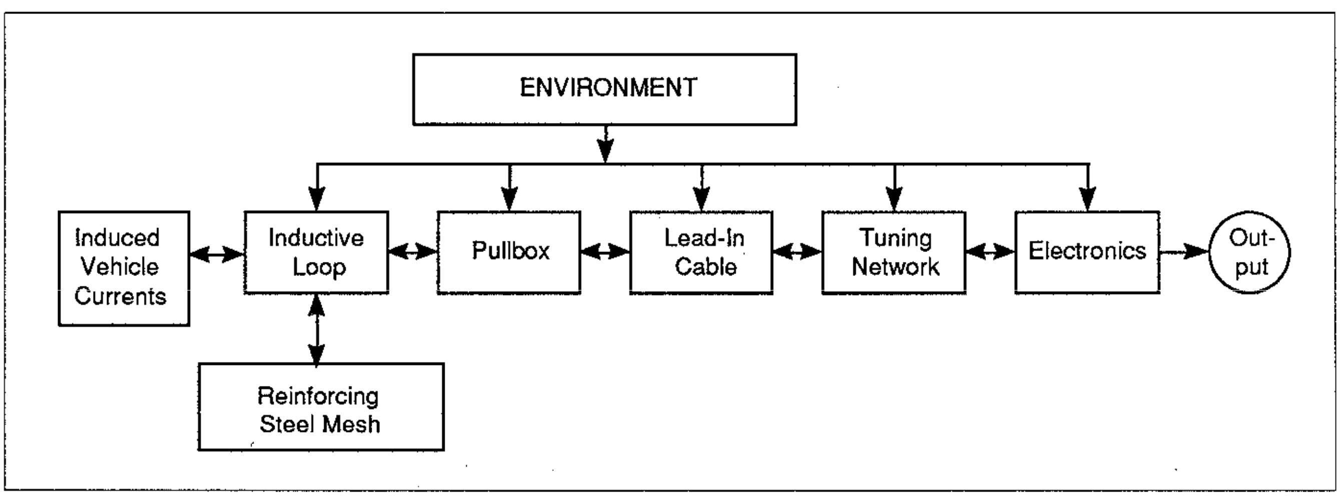


Figure 8. Inductive loop detector system model.

Loop System Resistance

Inductive loops, lead-in wires, and lead-in cables typically use #12, #14, or #16 AWG wire with the low frequency or direct current resistance in units of ohms.

This wire resistance is inversely proportional to the square of the wire diameter and increases as the wire diameter decreases. A Volt Ohm Meter (VOM) measures direct current resistance. The wire resistance to alternating current increases as the frequency increases because the conducting area of the wire decreases due to the non-uniform flux inside the wire. This high frequency resistance cannot be measured with a VOM, but can be obtained from a measurement of quality factor to be defined later.

The loop in the roadway also contains an induced resistance (called the ground resistance) due to transformer action between the loop and induced current flowing in the roadway and subgrade materials. Appendix A provides a detailed derivation of ground resistance. Table 1 provides DC/low frequency resistance values for various commercially available loop wire and lead-in cables.

Table 1. Loop system wire DC resistance.

Type Manufacturer's Model #	Function L = Loop LI = Lead- In	Gauge # AWG	DC Resistance Ohms/ft
9438	L	14	0.0025
8718	LI	12	0.0019
8720	LI	14	0.0029
8719	LI	16	0.0045

Loop Inductance

All conductors or wires carrying an electrical current produce magnetic flux which links with (i.e., encircles) the current. The effect of this flux is the electrical property called inductance, measured in Henrys (h). The inductance of the wire is called self-inductance. If the flux from current flowing in the wire couples to other wires, the resulting inductance is called mutual inductance. Figure 9 illustrates the flux around a single turn loop. Notice that the plane containing the flux is normal to the current in the wire and the flux has a direction determined by the "right hand rule." Place the right hand under the wire with fingers in the direction of the flux. The thumb points in the direction of current flow. All flux is in the same direction inside the loop.

Figure 10 illustrates the magnetic flux lines for a solenoid or coil whose length is greater than the diameter. The magnetic flux is uniform inside the coil except near the ends. The magnetic field for this coil geometry is given by

$$H = \frac{N I}{\ell} \tag{1}$$

where:

H = Magnetic field, Ampere turns per m
N = Number of turns
I = Coil current, Amperes
ℓ = Length of coil, m

Because the magnetic flux is uniform inside the coil, the flux is given by:

$$\Phi = B A \tag{2}$$

where:

Φ = Magnetic flux, Webers
B = Magnetic flux density, Webers per m^2
A = Cross sectional area of coil, m^2

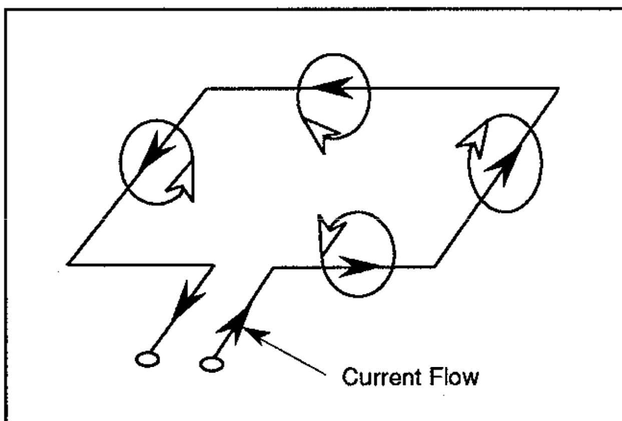


Figure 9. Magnetic flux around loop.

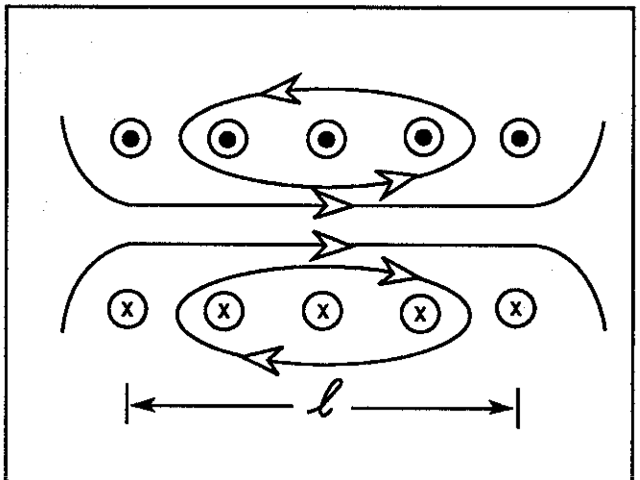


Figure 10. Magnetic flux for solenoid (coil).

The magnetic flux density is related to the magnetic field by:

$$B = \mu_r \mu_o H \tag{3}$$

where:

μ_r = Relative permeability of material (1 for air)
μ_o = $4\pi \times 10^{-7}$, h per m

The inductance of a coil is defined as:

$$L = \frac{N\Phi}{I} = \frac{NBA}{I} \tag{4}$$

where:

L = Inductance, h
N = Number of turns
I = Coil current, Amps

The inductance of a coil, with a length much greater than the coil area to ensure uniform magnetic flux inside the coil, is given by:

$$L = \frac{N\mu_r \mu_o HA}{I} = \frac{\mu_r \mu_o N^2 A}{\ell} \tag{5}$$

This simple equation shows that coil inductance is proportional to the turns squared and the coil area, and inversely proportional to coil length. Although the inductance formula as written is not directly applicable to a roadway inductive loop, the formula can be modified by a factor F_1 to account for non-uniform flux in the inductive loop.

$$L = \frac{\mu_r \mu_o N^2 A F_1}{\ell} \tag{6}$$

This inductance formula is applied to an example loop inductance calculation in Appendix B. Note that ℓ is called the "length of the current sheet." The relative μ_r term in the formula shows that iron with a relative μ_r greater than one will increase the loop inductance. Although the greatest increase in inductance would occur when an iron core passes directly through the loop, the iron mass of a vehicle engine, transmission, or differential will slightly increase the loop inductance. This condition is called the "ferromagnetic effect."

Ferromagnetic Effect

Because of the phenomenon known as the ferromagnetic effect, it is incorrect to assume that it is the mass of the vehicle that is causing the actuation. Actually, the heavy, ferrous engine in the loop increases the inductance. The insertion of an iron core into the field of any inductor acts to reduce the reluctance of the flux path and, therefore, increase the net inductance. The peripheral metal of the vehicle has an opposite effect due to the eddy currents. The decrease in inductance from the eddy currents more than offsets the increase from the ferrous mass, and the net effect is an overall reduction.

LOOP CHARACTERISTICS

One of the advantages of the inductive loop detector is the wide range of permissible geometries available to the design engineer. These design options are discussed in detail in Chapter 4. The size and the number of turns of a loop or combination of loops, together with the length of the lead-in cable, must produce an inductance within a range that is compatible with the design of the detector unit and with the goals of the design engineer. NEMA (See Appendix J) specifies that a detector unit must be capable of operating satisfactorily over a range of 50 to 700 µh. Some units can accept much higher inductances; for example, from several loops wired in series. While the higher inductances are technically feasible, NEMA has specified a conservative upper limit to promote conservative practices.

Loop Capacitance

Figure 11 shows that capacitance coupling exists between the loop turns and loop slot. The major component of capacitance is due to the capacitance between the loop conductors and slot side wall. The capacitance is directly proportional to the dielectric constant of the slot sealing material. Figure 12 presents a schematic diagram of the loop installed in the roadway pavement. The inductance seen at the loop terminals is modified by the capacitance and results in an inductance which increases with increased operating frequency as shown in Figure 13. If the slot sealing material is hygroscopic (i.e., readily absorbs and retains water) or incomplete (does not fill the slot or encapsulate the wires), allowing water to enter the slot and penetrate between the loop conductors, the capacitance will change greatly because of the high dielectric constant of water.

Too many loop turns on large area loops will increase the loop capacitance and lower the self-resonant frequency of the loop (i.e., no loop inductance is measured at the loop terminals when the loop is self resonant). The capacitance change (due to water) will cause an inductance change, resulting in unstable loop detector operation. At frequencies of 1 kHz the capacitance is insignificant. At frequencies of 10 kHz or greater, the capacitance is important. When loop inductance is measured at 20 kHz or greater, the measurement frequency must be specified since the measured inductance is frequency dependent.

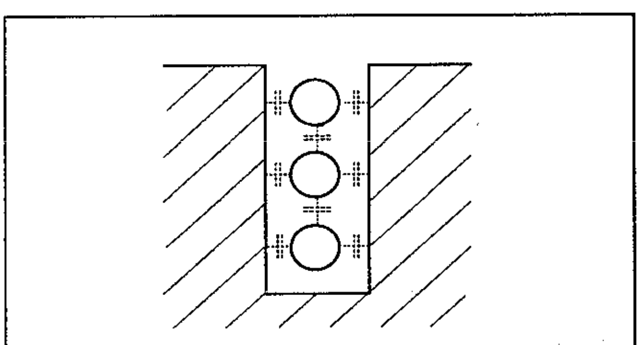


Figure 11. Loop wire capacitance coupling.

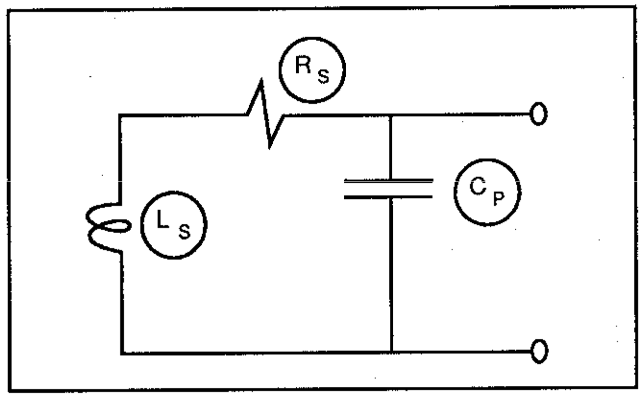


Figure 12. Roadway loop circuit.

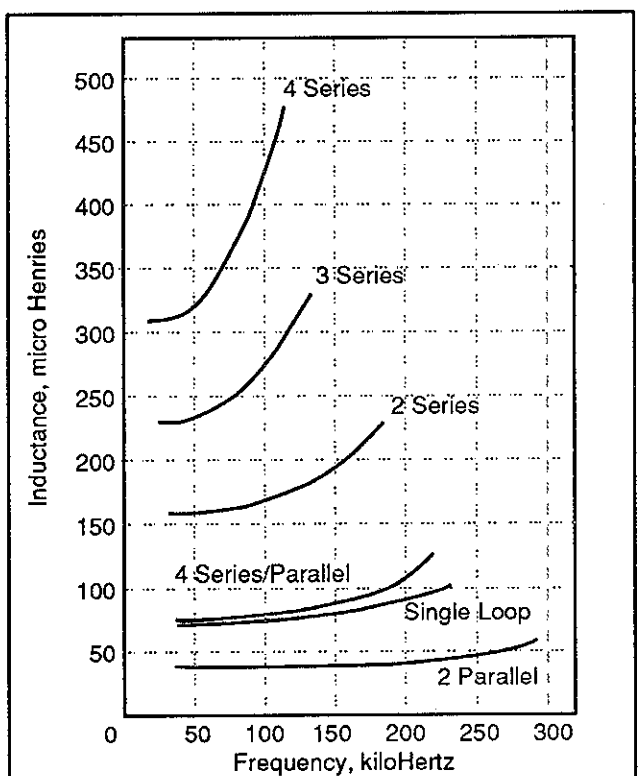


Figure 13. Inductance of loop vs measuring frequency.

Loop Quality Factor, Q

The factor that measures the resonant efficiency of a circuit is the "Q" or quality factor. It is a dimensionless index. If the losses of the inductor are too great, the Q will be low. A perfect inductor has no losses; that is, there is no dissipation of energy within the inductor and the Q is infinite.

All of the energy losses in an inductor may be represented by a resistor in series with the inductor. The ratio of the inductive reactance to the resistive losses may be expressed as Q. Since inductive reactance is a frequency-dependent measure, the frequency must be specified for a series circuit when considering the performance of an inductor. The formula for Q is:

$$Q = \frac{2\pi \; f L_S}{R_S} = \frac{\omega L_S}{R_S} \tag{7}$$

where:

Q	=	Quality factor
π	=	3.14159 (a constant)
f	=	Series inductance frequency, Hz
L_S	=	Series inductance, h
R_S	=	Resistance, ohms
ω	=	$2\pi f$

The formula for the resonant frequency (ω_O in radians) of the circuit in Figure 12 is:

$$\omega_O = \frac{1}{\sqrt{L_S C_P \left(1 + \frac{1}{Q_O^{\,2}}\right)}} \tag{8}$$

Since:

$$\omega_O = \frac{Q_O R_S}{L_S} \tag{9}$$

The formula for the quality factor, Q_O, of the resonant circuit is:

$$Q_O = \sqrt{\frac{1}{R_S^{\,2}} \frac{L_S}{C_P} - 1} \tag{10}$$

In an inductive loop detector system, the circuit in Figure 12 will have some load resistance, R_L, shunted across the capacitor, C_P, which will reduce the value of Q_O.

The quality factor, Q_P, of the parallel circuit is:

$$Q_P = \omega_O C_P R_L \tag{11}$$

Since:

$$Q_O = \omega_O C_P R'_P \tag{12}$$

Where R'_P is the transformed series resistance in parallel with R_L.

The loaded quality factor, Q, of the circuit in Figure 12 with a load resistance, R_L, shunted across the capacitor, C_P, is:

$$Q = \frac{Q_P \; Q_O}{Q_P + Q_O} \tag{13}$$

The resonant loop quality factor, Q_O , is reduced by the shunt load resistance, R_L. A sample calculation of loop system quality factor, Q, is shown in Figure 14.

In the case of loop detectors, it is recommended that the Q be greater than 5. Moisture in the pavement and subgrade can increase the loop ground resistance to the point that the Q of the loop system falls below 5, thereby reducing the sensitivity of most detector units. Loop capacitance will also reduce Q. The oscillators in most detectors will not operate with low Q.

The Q formula is intended for straight-forward applications in which losses are low, Q is high, and f, L, and R can be readily measured. Detector loops, on the other hand, are not so clear-cut, as the inductance is distributed over the loop and lead-in cable and is hard to measure. The Q factor is further complicated by the fact that the resistance of the loop wire and lead-in cable is larger than the series value measured with an ohm-meter. The extra losses are due to high frequency operation and ground currents in the pavement associated with the circuit configuration and the roadway environment near the wire. The Q will vary from location to location.

LOOP SYSTEM QUALITY FACTOR, Q, CALCULATION

Assumptions:

Loop Type: 3-turn, 6 x 6 ft (1.8 x 1.8 m) of #14 AWG wire
Loop Inductance: 74 μh at 20 kHz from Appendix C
Loop Resistance (in air): 0.0025 Ω/ft (.0083 Ω/m) from Appendix D
Lead-In Cable Type: 100 ft (30 m) of Belden 8718
Lead-In Cable Inductance: 0.20 μh/ft (0.67 μh/m) from Appendix D
Lead-In Cable Resistance: 0.0031 Ω/ft (0.0103 Ω/m) from Appendix D
Operating Frequency: 20 kHz

Total Loop System Series Inductance: 74 μh + 20 μh = 94 μh
Total Loop System Series Resistance: 0.25 Ω + 0.62 Ω = 0.87 Ω
Note: Wire length for resistance calculation is per wire (i.e., twice the cable length).

Total Loop System Capacitance:

$$C_P = \frac{1}{\omega_O^2 \, L_S} = \frac{1}{(2\pi * 20 * 10^3)^2 \, (94 * 10^{-6})}$$

$$C_P = 6.74 * 10^{-7} \text{ Farad}$$

Quality Factor of Loop System:

$$Q_O = \sqrt{\frac{1}{R_S^2} \frac{L_S}{C_P} - 1} = \sqrt{\frac{94 * 10^{-6}}{(0.87)^2 \, (6.74 * 10^{-7})} - 1}$$

$$Q_O = 13.54$$

This value is the unloaded loop system quality factor with 100 ft (30 m) of Belden 8718 #12 AWG lead-in cable. Assume that the detector electronics adds a shunt parallel resistance of 1,000 ohms.

$$Q_O = \omega_O \, C_P \, R_P = (2\pi * 20 * 10^3) \, (6.74 * 10^{-7}) \, (1{,}000)$$

$$Q_O = 84.70$$

The total loaded loop system quality factor is:

$$Q = \frac{Q_P \; Q_O}{Q_P + Q_O} = \frac{(84.70)\,(13.54)}{84.70 + 13.54}$$

$$Q = 11.67$$

Figure 14. Loop system quality factor sample calculation.

Tables 2 through 4 present calculated quality factors. Loops operate at 20 kHz in these tables, with conductor and/or quadrupole lateral spacing of 200 mils. All inductance and quality factors are apparent values (i.e., loop capacitance and resistance is included).

Loop Lead-In Wire

The lead-in wire from the roadway loop to the pull box at the roadside is formed by twisting the "start" and "finish" wires of the loop. Most manufacturers recommend at least five turns per foot (16.5 turns per meter).

The wire twists form small loops along the twisted wire which alternate in winding direction. An external magnetic field from a noise or crosstalk source induces voltages in the small loops which almost cancel, thus reducing interference. The importance of these twists in the lead-in wire is stressed in Chapters 4 and 5. Typical loop-to-pull box lead-in wire characteristics are presented in Table 5.

Table 2. Rectangular loop parameters.*

Wire Gauge (AWG)	1 Turn		2 Turn		3 Turn		4 Turn		5 Turn	
	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)
12	10	20	35	30	73	37	123	43	184	47
14	11	16	36	24	74	30	125	35	186	40
14**	63	12	89	14	128	18	180	21	243	25
16	11	12	37	18	75	23	126	28	188	31
18	11	8	37	13	77	17	127	20	189	23

* 6 x 6 foot (1.8 x 1.8 m) loop   ** With lead-in cable

Table 3. Quadrupole loop parameters.*

Wire Gauge (AWG)	1 Turn		2 Turn		3 Turn		4 Turn		5 Turn	
	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)
12	17	22	60	33	125	40	211	46	315	50
14	18	17	61	27	127	33	213	38	317	43
16	18	13	62	20	129	26	215	30	320	34
18	19	9	63	14	130	19	217	22	323	25

* 6 x 6 foot (1.8 x 1.8 m) loop

Table 4. Circular loop parameters.*

Wire Gauge (AWG)	1 Turn		2 Turn		3 Turn		4 Turn		5 Turn	
	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)	Inductance (µh)	Quality Factor (Q)
12	10	20	34	31	71	38	120	44	179	49
14	10	16	35	25	72	32	121	37	181	41
16	10	12	35	19	73	24	122	29	182	32
18	11	8	36	13	74	17	123	21	184	24

* 7 foot (2.1 m) diameter loop

Table 5. Twisted loop lead-in wires.

Wire Manufacturer Type	Wire Insulation Type	AWG number	Jacket Diameter Mils	Number of Twists per foot	Inductance µh / ft	Capacitance pF / ft	Resistance Ω / ft
XHHW	Cross Linked Polymer	14 Stranded	130	3 - 4	0.24	10	0.006
Belden 9438	High Density Polyethylene	14 Stranded	139	5.5	0.22	10	0.00252

Lead-In Cable

The lead-in cable (home run cable) from the pull box to the detector terminals in the controller cabinet is composed of a shielded, twisted pair of wires. The conducting shield reduces interference from external electric fields. Typical lead-in cable characteristics are presented in Table 6.

In Appendix D, measurements of loop system quality (with 100 ft (30 m) of shielded lead-in cable connected to a loop) show that little benefit is gained from using larger conductor diameters in the shielded lead-in cable. In other words, the decrease in quality factor caused by using #14 AWG shielded lead-in cable is not substantially reduced by substituting #12 cable. The principal loss results from the type of

Table 6. Commercial lead-in cable characteristics.

Cable Manufacturer /Type	Wire Insulation Type	AWG number	Insulation Diameter, Mils	Cable Insulation Type	Inductance µh / ft	Capacitance pF / ft	Resistance Ω / ft
Belden							
8718	Polyethylene	12	37	Vinyl	0.2	25	0.0019
8720	Polyethylene	14	32	Vinyl	0.2	24	0.0029
8719	Polyethylene	16	32	Vinyl	0.2	23	0.0045
Clifford							
IMSA	Polyethylene	12	30	Polyethylene	0.2	25	0.0016
Specification	Polyethylene	14	30	Polyethylene	0.2	24	0.0025
50-2-1984	Polyethylene	16	30	Polyethylene	0.2	23	0.0040

shielding rather than the conductor diameter. Table 7 shows how lead-in cable type and length affect the quality factor.

DETERMINATION OF INDUCTANCE

There are several simplified formulas that provide "rule of thumb" approximations of the inductance of a loop. However, more accurate inductances have been obtained by a mutual coupling method discussed in Appendix A.

This method provides acceptable accuracy for calculating the self inductance of multi-turn, rectangular, quadrupole, and circular loops which have a large area relative to the conductor spacing. The method gives results that compare favorably with a range of measured loop inductances.

Appendix C presents the calculated loop inductances for various size loops and shapes (rectangular, quadrupole, and circular). Inductance and quality factor, for various turns of wire, are calculated using the mutual coupling formula.

Loop System Inductance Calculations

Inductance of the lead-in cable is added to the loop inductance at the rate of 22 µh per 100 ft (30 m) of #14 AWG lead-in cable. For example, a 6- x 6- ft (1.8- x 1.8- m) rectangular loop should have three turns, according to Appendix C, and will then have an inductance of 74 µh. If the lead-in is 200 feet (61 m) in length, the total inductance will be:

$$L = 74 + \frac{200}{100} * 22 = 74 + 44 = 118\ \mu h \quad (14)$$

If two or more loops are wired together in series, their inductances are additive. That is, $L = L_1 + L_2 \pm 2M$, where M is the mutual inductance between the two loops and the sign of M is positive if flux is increased by the current flowing in the same direction in the closest spaced loop wires.

For a large separation the mutual inductance is negligible, therefore $L = L_1 + L_2$ (series connection). Thus, series connection provides the maximum loop inductance.

Table 7. Lead-in cable type and length effect on Q.

Loop Turns #14 AWG	Lead-In Cable Type Belden	Lead-In Cable Length (ft)	Cable Wire Gauge (AWG)	Total Parallel Capac. (µF)	Series Loop Induct. (µh)	Lead-In Cable Induct. (µh)	Total Series Induct. (µh)	Loop Resist. (Ω) *	Lead-In Cable Resist. (Ω) **	Total Series Resist. (Ω)	Loop System Q	Loop System Loaded (1,000Ω) Q
3	8718	100	12	0.674	74	20	94	0.25	0.62	0.87	14	12
3	8720	100	14	0.670	74	21	95	0.25	0.80	1.05	11	10
3	8719	100	16	0.670	74	21	95	0.25	1.00	1.25	10	9
4	8718	100	12	0.437	125	20	145	0.33	0.62	0.95	19	14
4	8720	100	14	0.434	125	21	146	0.33	0.80	1.13	16	13
4	8719	100	16	0.434	125	21	146	0.33	1.00	1.33	14	11
5	8718	100	12	0.312	186	20	206	0.42	0.62	1.04	25	15
5	8720	100	14	0.306	186	21	207	0.42	0.80	1.22	21	14
5	8719	100	16	0.306	186	21	207	0.42	1.00	1.42	18	12
5	8718	1,000	12	0.172	186	200	386	0.42	6.20	6.62	7	5
5	8720	1,000	14	0.160	186	210	396	0.42	8.00	8.42	6	5
5	8719	1,000	16	0.160	186	210	396	0.42	10.00	10.42	5	4

Loop Size is 6 x 6 feet (1.8 x 1.8 m)
Frequency is 20 kHz
* Measured Series resistance of loop 3 feet (0.9 m) above the laboratory floor
** 8719 resistance value estimated

If the loops are wired together in parallel, then the combined inductance is calculated from the formula $1/L = 1/L_1 + 1/L_2$ (parallel connection). For example, two 6- x 6- ft (1.8- x 1.8- m) loops of three turns each, connected in parallel give the following combined inductance:

$$\frac{1}{L} = \frac{1}{74} + \frac{1}{74} = \frac{2}{74} \qquad (15)$$

$$2\,L = 74 \text{ and } L = 37\ \mu h$$

It is seen that parallel connection of loops reduces the inductance. Care must be exercised to assure that the inductance does not fall below the lower limit of 50 μh as is the case in the above example.

In some cases, both series and parallel connections are desirable. Consider, for example, four 6- x 6- ft (1.8- x 1.8- m) three-turn loops installed 9 ft (2.7 m) apart to provide detection in a left-turn lane. Three types of connection are shown in Figure 15. Connection in series produces an inductance of 4 x 74 = 296 μh. Parallel connection produces only 18.5 μh (4L = 74, L = 18.5 μh). A series/parallel scheme where the upper two loops are connected in series as are the bottom two loops. The two pairs are then wired in parallel to produce 74 μh.

Required Number of Turns

All loops should have a sufficient number of turns to provide a nominal minimum of 100 microhenries per loop. This minimum value ensures stable operation of the system. A simple rule of thumb that can be applied to determining the number of turns that will provide an inductance within the required range. This rule of thumb states that if the loop perimeter is under 30 ft (9 m), three turns of wire are indicated. If the loop perimeter is over 30 ft (9 m), use two turns of wire.

Loop Sensitivity

The current flowing through the loop wire creates a magnetic field around the wire as illustrated in Figure 9. If a vehicle (or any other electrically conductive object) enters this magnetic field and the magnetic field or a component of the magnetic field is normal to the area of the object, eddy currents will be induced in the conducting object. The eddy currents generate a magnetic field which opposes the magnetic field of the loop causing a decrease in the total magnetic field around the loop. Since the loop inductance is proportional to magnetic flux, the loop inductance decreases.

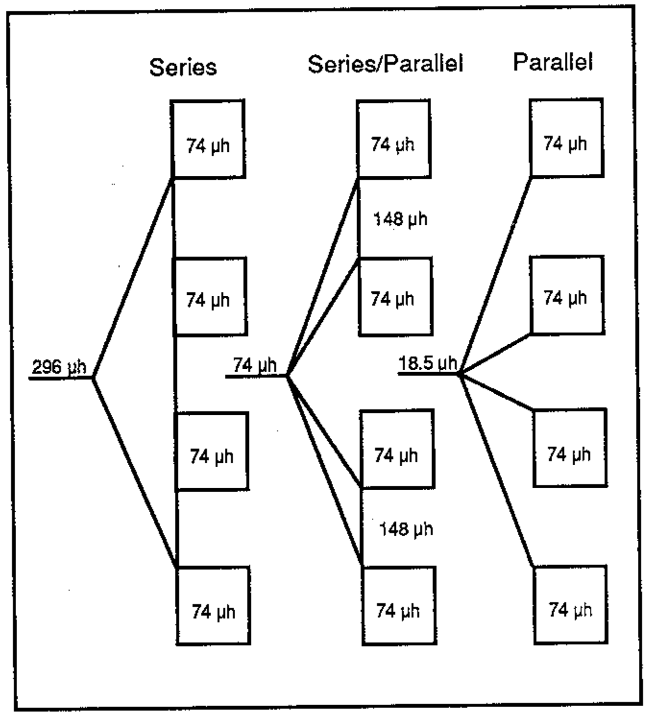


Figure 15. Four small loops connected in various ways.

A 12- in (30- cm) wire can be formed into a circle about 4 in (10 cm) in diameter. Hold this loop by hand so that the ends do not quite touch one another, forming an open circuit, then rapidly thrust this circle over the loop in a level position. No actuation will occur. When the ends of the circle are made to touch forming a closed circuit before being thrust over the loop, an actuation will occur because of the flow of eddy currents. It is the "shorted turn," not the mass, that is important in producing the actuation.

Bicycle Detection

Figure 16 illustrates the detection of a bicycle. When the bicycle travels along the loop wire, eddy currents are induced in the conducting wheel rims and frame.

The eddy currents travel in an opposite direction from the loop currents, thus the dotted eddy current magnetic field opposes the loop's magnetic field. The inductance of the loop is reduced and detection results.

The loops magnetic field is normal to the conducting perimeter of the wheels and frame. If the bicycle travels normal to the loop wire, the magnetic field of the loop does not link the wheels and frame so no eddy currents are induced and the bicycle is not detected.

The magnitude of induced current, and thus sensitivity, is proportional to the cosine of the angle between the bicycle's direction and loop wire. A diamond loop couples a normal component of the loop's magnetic field to the bicycle (cosine 45°) resulting in detection at reduced sensitivity.

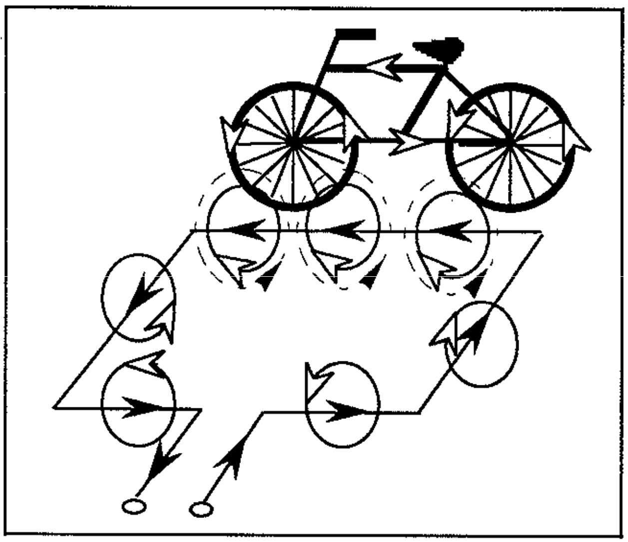


Figure 16. Bicycle detection.

Detection with Rectangular or Square Loops

A bicycle can be considered a vertical conducting target or object relative to the plane of the loop. A vehicle undercarriage is a horizontal target. The undercarriage is modeled as a conducting rectangular sheet of width and length of the vehicle at some average undercarriage height.

The continuous sheet is approximated by a conducting mesh. When the mesh is symmetrically located over the loop (maximum sensitivity), all induced internal mesh currents cancel, leaving a single induced current flowing around the perimeter of the mesh which is equivalent to a single turn rectangular wire loop or shorted turn. Figure 17 illustrates this principle.

Maximum vehicle detection sensitivity results from a shorted turn with minimum distance from the loop wires. As a consequence, the ideal loop should have a shape that approximates the vehicle's periphery. That is, a 6- x 6- ft (1.8- x 1.8- m) square loop would be preferable to one the size of an engine.

Because of undercarriage height, high bed trucks are most difficult to detect. The width of the loop should be the width of the truck if lane width permits. The length of the loop should not be less than the width or a loss of sensitivity will result.

Mutual Inductance

Loop self inductance was defined using the loop's magnetic flux. When the magnetic flux of a loop couples to a vehicle, the coupled flux is used to define mutual inductance.

Figure 17 shows the magnetic coupling between a loop and shorted turn, which is equivalent to an air core transformer. The mutual inductance between the primary circuit (loop) and secondary circuit (shorted turn) is given by:

$$M_{21} = \frac{N_2 * \Phi_{21}}{I_1} \qquad (16)$$

where:

M_{21} = mutual inductance between circuit one (loop) and circuit two (shorted turn), h

N_2 = Number of turns (1 for shorted turn)

Φ_{21} = magnetic flux normal to shorted turn area (Webers)

I_1 = current in loop (Amps)

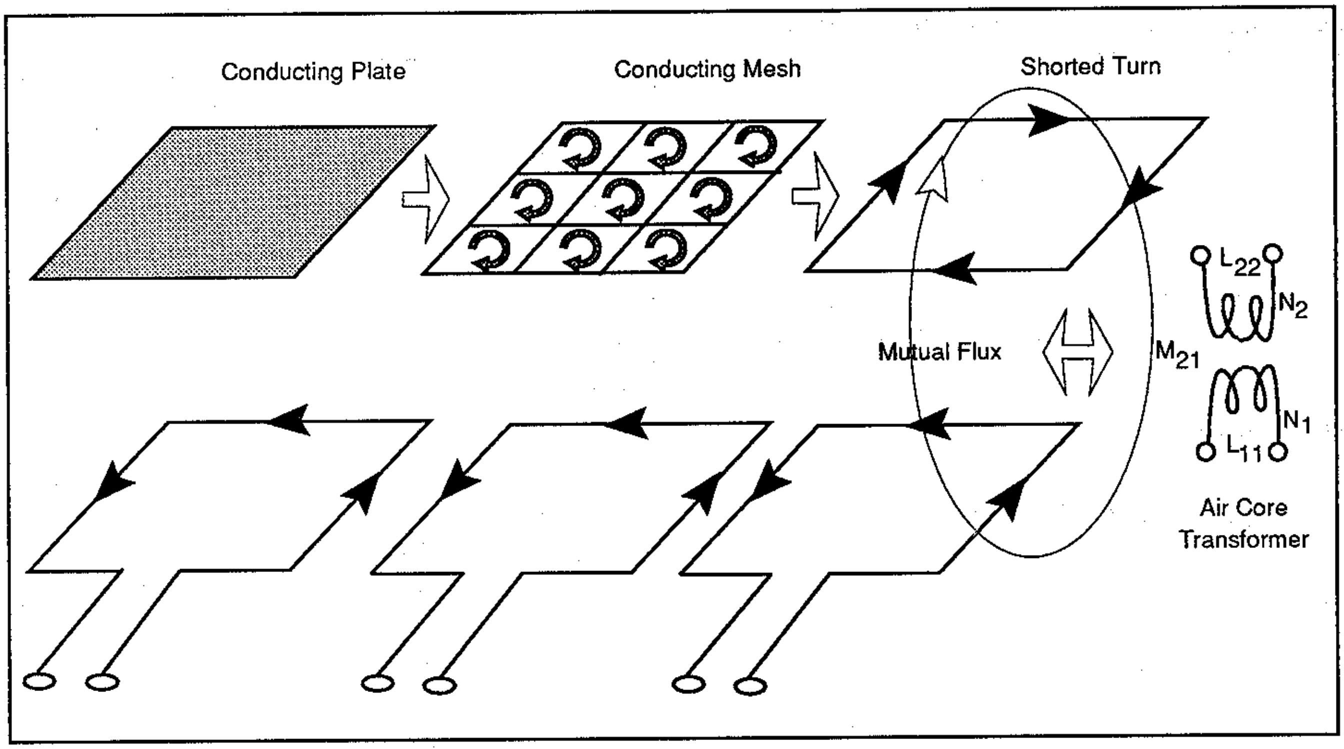


Figure 17. Vehicle undercarriage model.

NORMALIZED LOOP INDUCTANCE (SENSITIVITY)

The loop sensitivity, S_L, of an inductive loop is defined as:

$$S_L = 100 * \frac{L_{NV} - L_V}{L_{NV}} = 100 * \frac{\Delta L}{L} \quad (17)$$

where:

L_{NV} = Inductance with no vehicle
L_V = Inductance with vehicle

The sensitivity, S_L, for the air core transformer of Figure 17 and for a quality factor (Q) greater than 10 is given by:

$$S_L = 100 * K = 100 * \frac{M_{21}^2}{L_{11} * L_{22}} \quad (18)$$

where:

K = Coefficient of coupling
M_{21} = Mutual coupling between loop and shorted turn, h
L_{11} = Self inductance of loop, h
L_{22} = Self inductance of shorted turn, h

Assume the effect of vehicle iron is negligible. Then μ_r = 1 and the self inductance of the roadway loop is:

$$L_{11} = \frac{\mu_0 N_1^2 A F_1}{\ell_1} \quad (19)$$

The inductance of the shorted turn loop is given by:

$$L_{22} = \frac{\mu_0 N_2^2 A_V F_2}{\ell_2} \quad (20)$$

The mutual inductance between the shorted turn loop and roadway loop is given by:

$$M_{21} \cong \frac{\mu_o N_1 N_2 A_V F_1}{d_{21}} \qquad (21)$$

where:

A_V = area of vehicle undercarriage
d_{21} = distance between loop and shorted turn, m

The sensitivity is given by:

$$S_L = 100 * \frac{A_V \ell_1 \ell_2 F_1}{A\, d_{21}^2 F_2} \qquad (22)$$

where:

$A_V \leq A$

This formula shows that the sensitivity decreases for loop areas larger than the vehicle undercarriage area.

The sensitivity decreases as the square of the vehicle undercarriage distance from the loop. The sensitivity is also independent of the number of loop turns; however, pulling the turns apart slightly increases sensitivity by increasing ℓ_1 at the expense of a deeper sawcut slot in the roadway.

Appendix E shows a more complex formula useful for calculation of S_L. Figure 18 shows how loop sensitivity varies versus vehicle undercarriage height for 6- x 2- ft (1.8- x 0.6- m), 6- x 4- ft (1.8- x 1.2- m), and 6- x 6- ft (1.8- x 1.8- m) 3-turn loops. Note the low sensitivity of the 6- x 2- ft (1.8- x 0.6- m) loop.

Figure 19 illustrates how loop sensitivity decreases when a 200- ft (60- m) lead-in cable is added to the loops in Figure 18. The 6- x 2- ft (1.8- x 0.6- m) loop will probably double count a high-bed truck.

Figure 20 shows the decrease in loop sensitivity for a vehicle centered in 2-turn long loops. A further decrease in loop sensitivity will result when a lead-in cable is added.

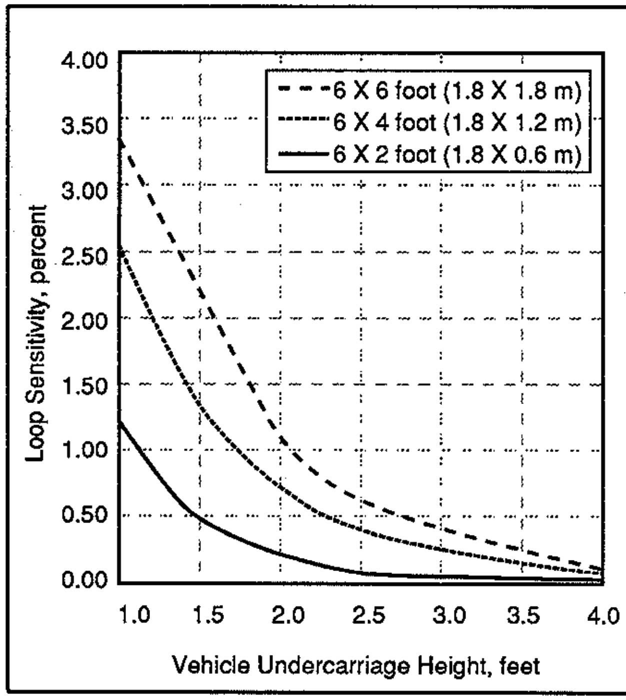


Figure 18. Calculated sensitivity of 3-turn loops.

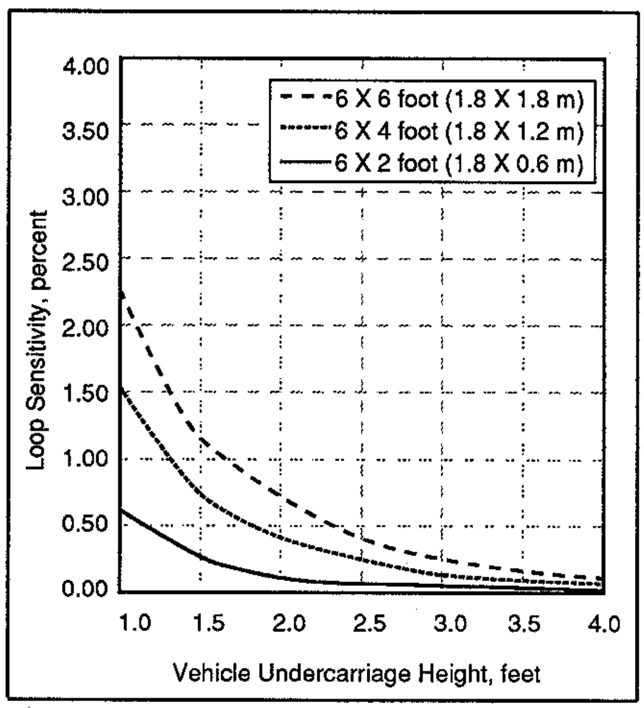


Figure 19. Calculated sensitivity of 3-turn loops with 200 ft (60 m) lead-in cable.

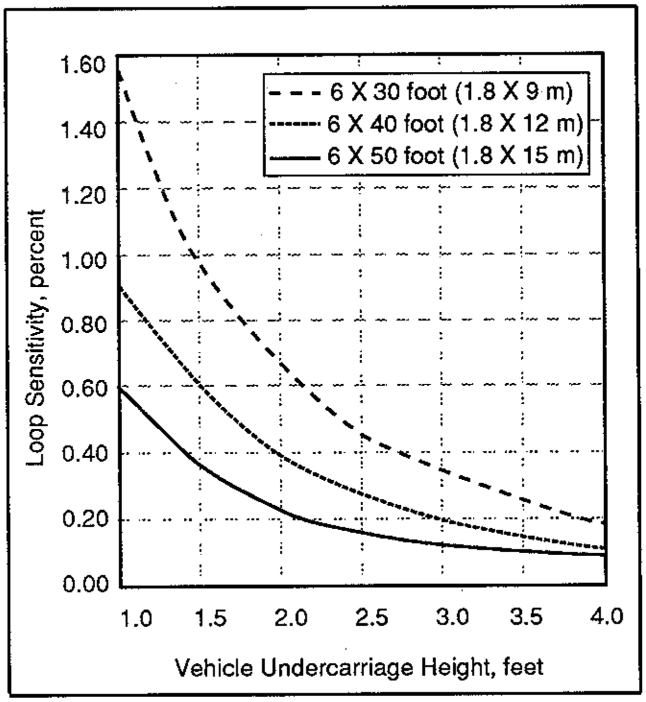


Figure 20. Calculated sensitivity of 2-turn long loops.

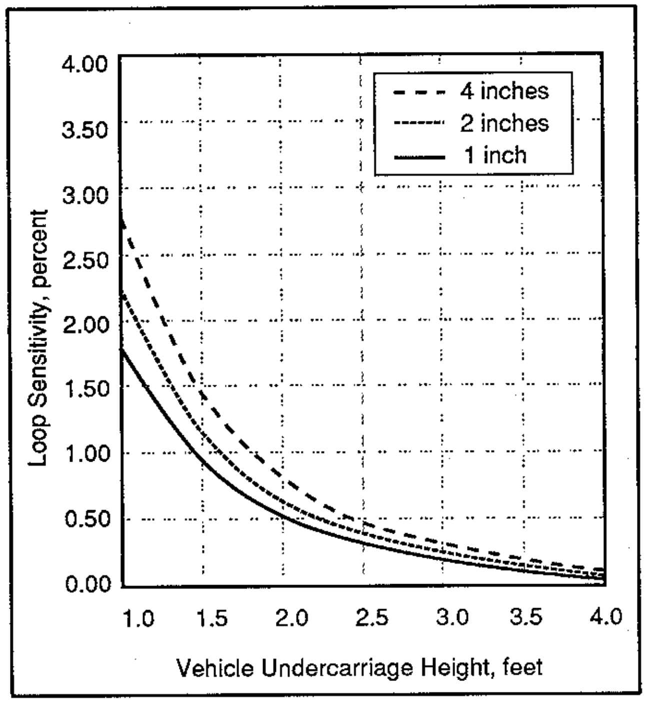


Figure 21. Calculated sensitivity of 6 x 6 foot loop over reinforcing steel.

Effect of Reinforcing Steel

Figure 21 shows that a loop over reinforcing steel mesh has lower sensitivity. The effect of the reinforcing steel is modeled as a shorted turn at twice the mesh spacing from the loop. The effect of the reinforcing steel is to reduce the magnetic field around the loop conductors (wire) which causes a decrease in loop inductance and in sensitivity to vehicles. Table 8 presents the inductance for a typical loop with and without reinforcing steel. The values are expected to be conservative since the mesh is assumed to be a perfect conductor. Modern detectors are capable of detecting vehicles even though the loop wire is laid on the rebars before concrete is poured.

Loop System Sensitivity

Loop system sensitivity may be defined as the smallest change of inductance at the detector terminals that will cause the detector to actuate. This sensitivity must be equal to or greater than the detector threshold. Many States have specified that the detector unit must respond to a 0.02 percent change in inductance. NEMA Standards (See Section 15.3.2 of Appendix J), recognizing the differences in detector unit design ($\Delta L/L$ or ΔL), have specified the sensitivity threshold for three classifications of test vehicles when they are centered in a single 6- x 6-ft (1.8- x 1.8-m), three turn loop with 100 ft (30.5 m) of lead-in cable:

- Class 1: 0.13 percent ($\Delta L/L$) or 0.12 µh (ΔL) inductance change (small motorcycle).
- Class 2: 0.32 percent ($\Delta L/L$) or 0.3 µh (ΔL) inductance change (large motorcycle).
- Class 3: 3.2 percent ($\Delta L/L$) or 3.0 µh (ΔL) inductance change (auto).

An inductance in series or parallel with an inductive loop will reduce the loop system sensitivity at the detector electronics terminals.

Table 8. Calculated effect of reinforcing steel on loop inductance.

Number of Turns	Loop Inductance, µh			
	Reinforcing Steel			
	None	1 inch	2 inches	4 inches
1	11	9	10	10
2	35	28	31	33
3	73	56	63	68
4	121	89	103	112
5	179	127	151	166
6	248	167	206	228
7	325	206	266	298

Sensitivity of Two Series Inductors

Figure 22 shows how the loop sensitivity of two series inductors is expressed as an equivalent inductor. The equivalent total series inductance, L_{TS}, is:

$$L_{TS} = L_A + L_B \tag{23}$$

The equivalent total series sensitivity, S_{TS}, is:

$$S_{TS} = S_L^A \left[\frac{1}{1 + \frac{L_B}{L_A}} \right] \tag{24}$$

where:

S_L^A = Loop sensitivity as vehicle enters loop A

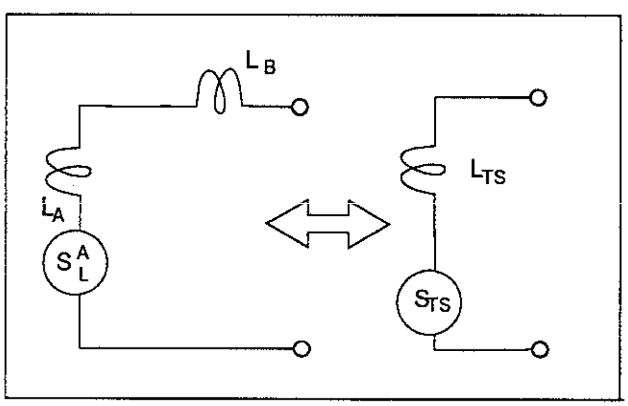


Figure 22. Equivalent total series inductor sensitivity.

Sensitivity of Two Parallel Inductors

Figure 23 shows how the loop sensitivity of two parallel inductors is expressed as an equivalent inductor. The equivalent total parallel inductance, L_{TP}, is:

$$L_{TP} = \frac{L_A * L_B}{L_A + L_B} \tag{25}$$

The equivalent total parallel sensitivity, S_{TP}, is:

$$S_{TP} = S_L^A \left[\frac{1}{1 + \frac{L_A}{L_B}} \right] \tag{26}$$

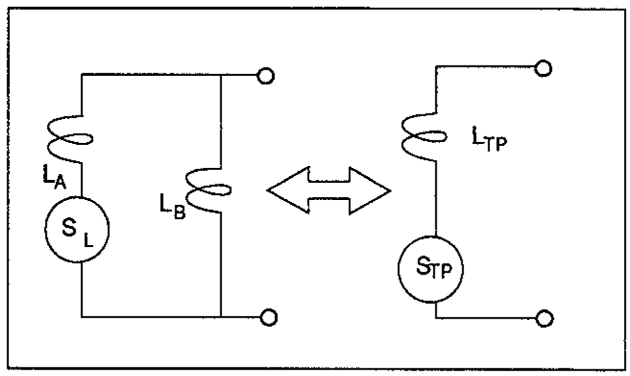


Figure 23. Equivalent total parallel inductor sensitivity.

Single Loop Example

1. What is the loop sensitivity at the pull box assuming a high-bed vehicle (4-ft (1.2-m) undercarriage) passes over the loop? Figure 24 illustrates this case and shows lead-in wire lengths. The circuit diagram is shown in Figure 25. The sensitivity, S_L, for a 4-ft (1.2-m) high undercarriage and a 3-turn, 6- x 6-ft (1.8- x 1.8-m) loop of #14 AWG wire is 0.1 percent from Figure 18. The twisted loop wires form an approximately 24-ft (7.3-m) lead-in wire to the pull box. The inductance per foot for #14 AWG loop wire with 5 twists per foot is 0.22 µh/ft. The lead-in inductance, L_S, is:

$$L_S = (0.22\ \mu h/ft) * (24\ ft) = 5.3\ \mu h \tag{27}$$

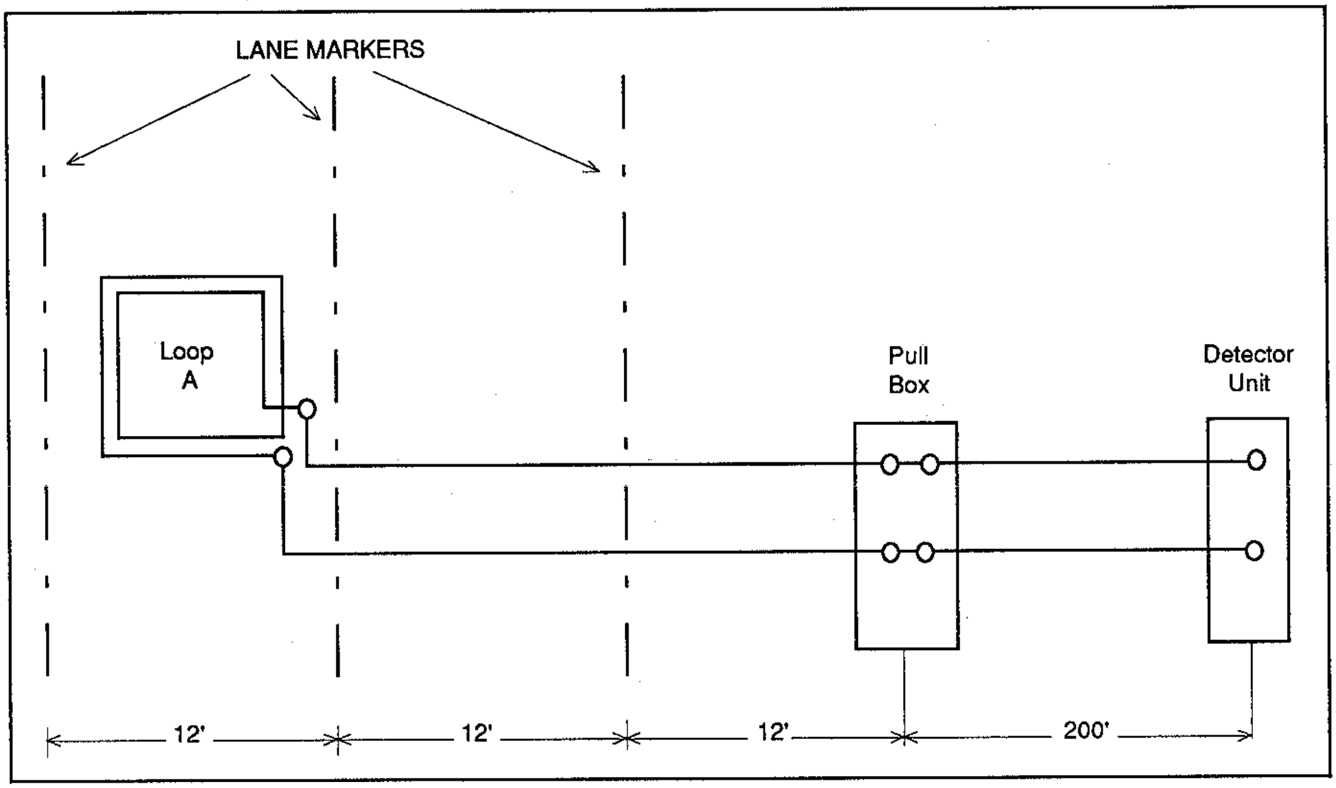


Figure 24. Single loop connected to pull box.

The self inductance, L_L, of a 3-turn, 6- x 6-ft (1.8- x 1.8-m) loop of #14 AWG wire at 20 kHz from Appendix C is 74 µh.

$$S_P = \left[\frac{S_L}{1 + \frac{L_S}{L_L}} \right] = \left[\frac{0.1\,\%}{1 + \frac{5.3\ \mu h}{74\ \mu h}} \right]$$

$$= 0.093\,\% \qquad (28)$$

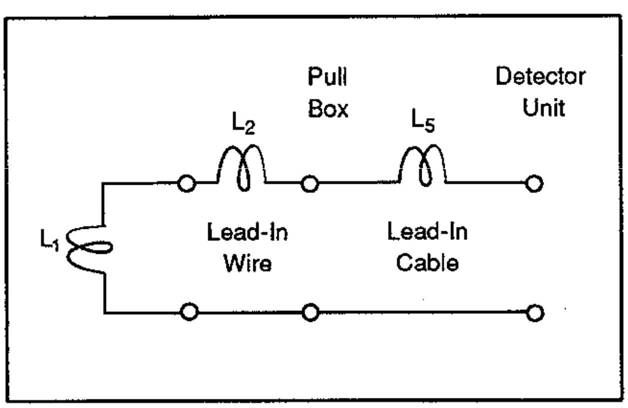


Figure 25. Single loop circuit.

where:

S_P = Sensitivity at the pull box, %

2. What is the loop system sensitivity at the detector terminals with a 200-ft (61-m) length of Type 8720 shielded lead-in cable between the pull box and detector electronics?

From Table 6, the inductance per foot of type 8720 cable is 0.22 µh/ft. The total series inductance between the loop and the detector terminals is:

$$L_S = [(0.22) * (24)] + [(0.22) * (200)] \qquad (29)$$

$$L_S = 5.3\ \mu h + 44\ \mu h = 49.3\ \mu h$$

Then:

$$S_D = \left[\frac{S_L}{1 + \frac{L_S}{L_L}} \right] = \left[\frac{0.1\,\%}{1 + \frac{49.3\ \mu h}{74\ \mu h}} \right]$$

$$= 0.060\,\% \qquad (30)$$

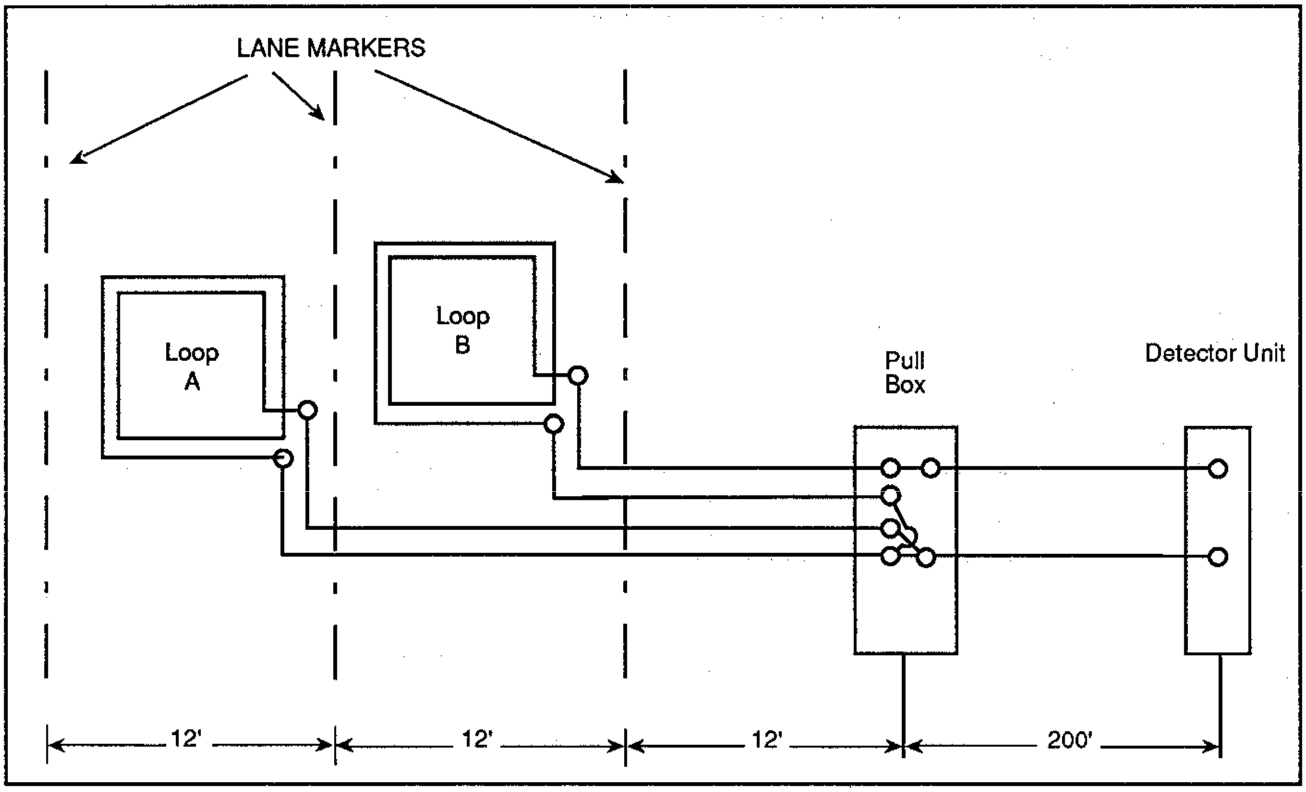


Figure 26. Two loops connected in series.

where:

S_D = Sensitivity at detector electronic unit, %

3. What is the loop system sensitivity at the detector terminals with a 200-ft (61-m) length of Type 8720 shielded lead-in cable between the pull box and detector electronics if a 4-turn, 6- x 6-ft (1.8- x 1.8-m) of #14 AWG wire is used?

The sensitivity, S_L, for a 4-ft (1.2-m) high undercarriage and 4-turn, 6- x 6-ft (1.8- x 1.8-m) loop is 0.1 percent. From Appendix C, the loop self inductance is 125 µh at 20 kHz. The series inductance is the same as in the previous case.

Therefore:

$$S_D = \left[\frac{S_L}{1 + \frac{L_S}{L_L}} \right] = \left[\frac{0.1\,\%}{1 + \frac{49.3\,\mu h}{125\,\mu h}} \right]$$

$$= 0.072\,\% \qquad (31)$$

Two Loops in Series Example

1. What is the loop system sensitivity at the detector terminals when a second identical loop is placed in series with the loop sensing the vehicle? Figure 26 illustrates this case and shows lead-in wire lengths. The series connection is made in the pull box. Figure 27 shows the circuit. The sensing loop is a 6- x 6-ft (1.8- x 1.8-m), 3-turn loop of #14

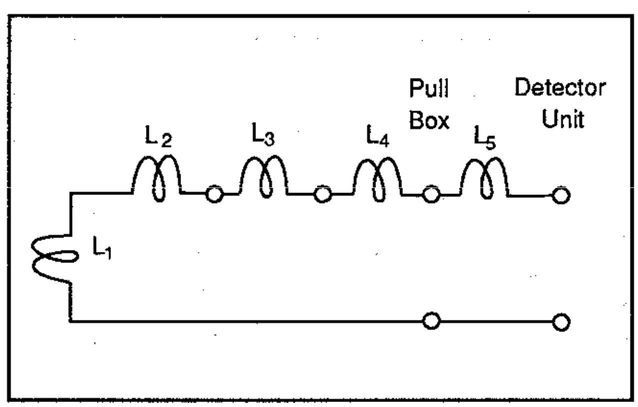


Figure 27. Two loops in series circuit.

AWG. The self inductance of the series loop B is 74 μh. The second (B) loops' lead-in wire inductance is:

$$L_4^B = (0.22\ \mu h/ft) * (12\ ft) = 2.6\ \mu h \qquad (32)$$

The total series inductance of loop B and lead-in wire to pull box is:

$$L_T^B = 2.6\mu h + 74\ \mu h = 76.6\ \mu h \qquad (33)$$

and:

$$L_T^S = L_T^B + L_T^A + L_S \qquad (34)$$

$$= 76.8 + 79.3 + 47.6 = 203.7\mu h$$

Then:

$$S_D = \left[\frac{S_L}{1 + \frac{L_T^S}{L_L}}\right] = \left[\frac{0.1\ \%}{1 + \frac{203.7\ \mu h}{74\ \mu h}}\right]$$

$$= 0.066\ \% \qquad (35)$$

Two Loops Connected in Parallel Example

1. What is the loop system sensitivity at the detector terminals with two identical loops connected in parallel? Figure 28 illustrates this case and shows lead-in wire lengths. The circuit for this case is illustrated in Figure 29. All parameters are the same as the previous series example. The procedure is as follows:

$$L_{TS} = L_1 + L_2 \qquad (36)$$

$$S_{TS} = S_L\left[\frac{1}{1 + \frac{L_2}{L_1}}\right] \qquad (37)$$

Let:

$$L_A = L_1 + L_2 \qquad (38)$$

$$L_B = L_3 + L_4 \qquad (39)$$

Then:

$$L_{TP} = \frac{L_A * L_B}{L_A + L_B}$$

$$= \frac{(L_1 + L_2) * (L_3 + L_4)}{L_1 + L_2 + L_3 + L_4} \qquad (40)$$

$$S_{TP} = S_{TS}\left[\frac{1}{1 + \frac{L_A}{L_B}}\right]$$

$$= S_{TS}\left[\frac{1}{1 + \frac{L_1 + L_2}{L_3 + L_4}}\right] \qquad (41)$$

and:

$$L_D = L_{TP} + L_S = \frac{L_A * L_B}{L_A + L_B} + L_S \qquad (42)$$

$$L_D = \left[\frac{(L_1 + L_2) * (L_3 + L_4)}{L_1 + L_2 + L_3 + L_4}\right] + L_S \qquad (43)$$

Therefore:

$$S_D = S_L\left[\frac{1}{1 + \frac{L_2}{L_1}}\right] * \left[\frac{1}{1 + \frac{L_1 + L_2}{L_3 + L_4}}\right] * \left[\frac{1}{1 + \frac{L_S}{\frac{(L_1 + L_2) * (L_3 + L_4)}{L_1 + L_2 + L_3 + L_4}}}\right]$$

(44)

Resonant Circuit

Many self-tuning loop detector electronics use the shift of frequency or period of an oscillator in the electronics. The frequency determining the tank circuit of the oscillator is typically a parallel resonant circuit comprised of the equivalent loop system inductance and detector tuning capacitance. The equivalent loop system inductance includes the effect of loop system capacitance and has an equivalent quality factor due to system resistance losses. If the equivalent loop system inductance is too small,

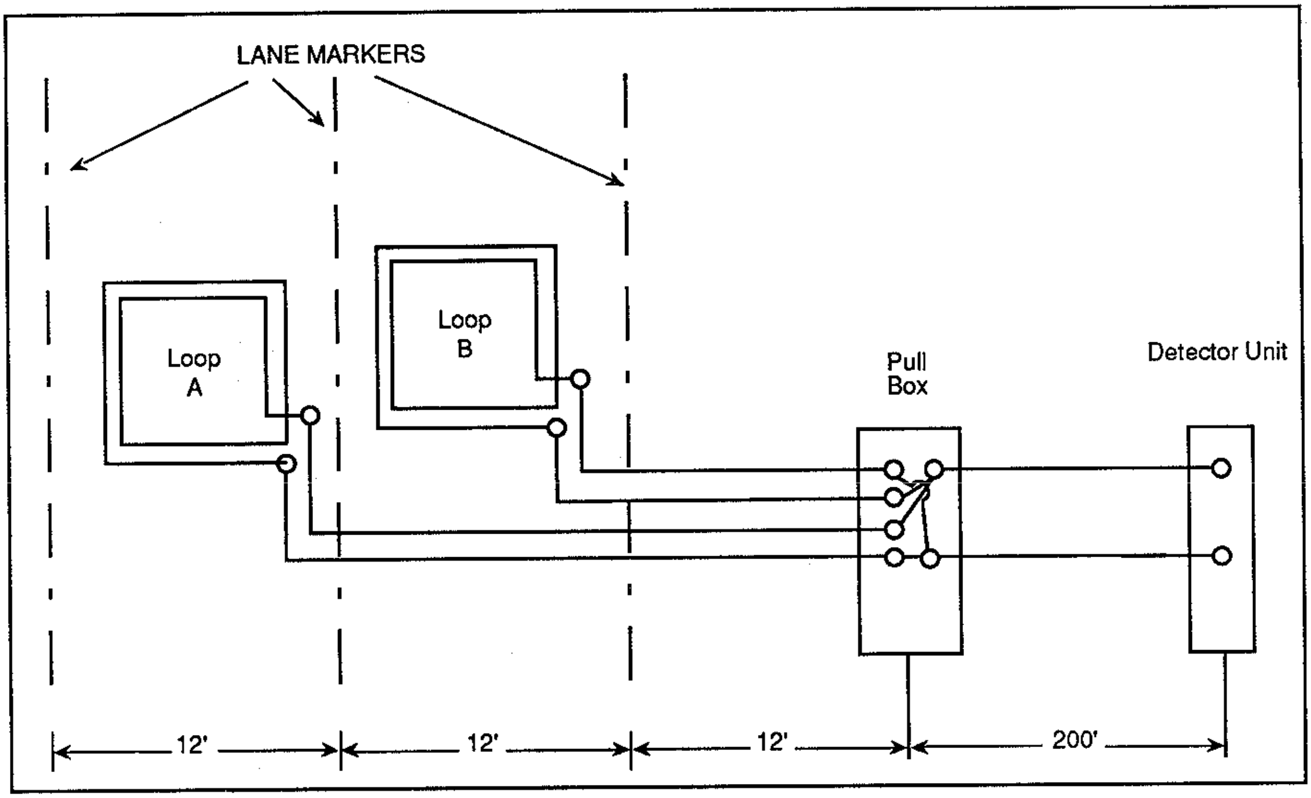


Figure 28. Two loops connected in parallel.

the oscillator will not oscillate. The range of loop system inductance and minimum loop system quality factor is specified by the manufacturer.

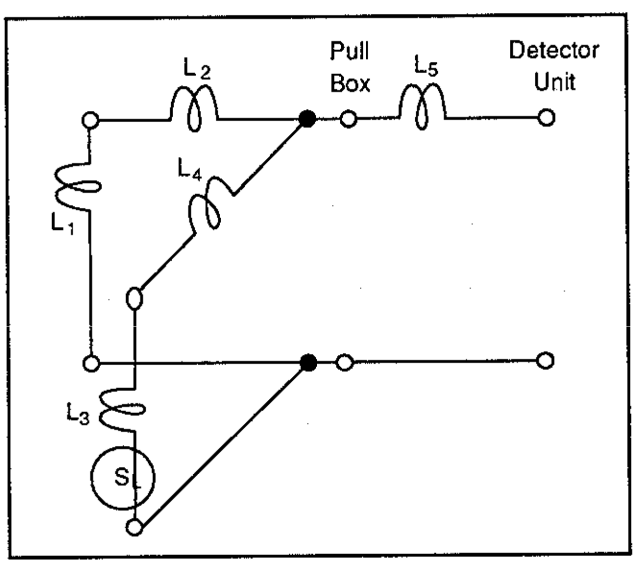


Figure 29. Two loops in parallel circuit.

The tuned tank circuit has a resonant frequency calculated as:

$$f_D = \frac{1}{2\pi\sqrt{L_D\, C_D\left(1 + \frac{1}{Q_D^{\,2}}\right)}} \qquad (45)$$

where L_D, C_D, and Q_D are respectively the inductance, capacitance, and quality factor of the tank circuit.

It is clear from this equation that a decrease in the inductance will increase the resonant frequency and a quality factor greater than five will have negligible effect.

DETECTOR ELECTRONIC UNIT

The electronic unit which generates the energy and monitors the loop system has changed significantly since the 1970's. Early versions of loop electronic units were fixed-frequency units which used a crystal to produce a fixed frequency of oscillation. There were many problems with the crystal detectors, particularly when used with long lead-in cables.

Another serious problem was with resonant-frequency drift due to environmental changes in temperature and moisture. These units were phased out of service in the 1970's and were initially replaced with analog phase shift detectors which were capable of compensating for (or tracking) drift caused by environmental changes. Today, the commonly used units include Digital Frequency Shift Detectors, Digital Ratioed Frequency Shift Detectors, Digital Period Shift Detectors, and Digital Ratioed Period Shift Detectors. The design theory of these units is described below. Analog Phase Shift Detectors are still in limited use for vehicle classification.

Analog Phase Shift Detector Unit

This unit was developed to meet the demands of the European market, where bicycles must be detected. Like the crystal model, it is a phase shift detector, but uses two oscillators rather than one and the oscillators are variable rather than crystal controlled. The loop oscillator operates at a frequency determined by the loop and lead-in wire (in the range of 25 to 170 kHz). The loop oscillator is coupled to a second internal oscillator in such a way that the initial, manual tuning procedure brings the two oscillators into synchronization in frequency and phase.

The tuning knob moves a ferrite core back and forth inside an inductor, causing the oscillator connected to it to change its frequency (and phase) to match that of the loop oscillator. Arrival of a vehicle into the loop decreases loop inductance and the loop oscillator attempts to pull out of synchronization with its companion oscillator. It is not able to do so in frequency because of a cross-coupling resistor, but a phase shift is developed that is the basis for detection.

With this design concept, the detector electronic unit is able to compensate for (or "track") environmental drift. As the temperature within the controller cabinet changes, the two oscillators drift identically. The output of the two oscillators are fed to a phase comparison circuit which develops a DC voltage proportionate to the amount of shift; thus, the term "analog" detector, because it uses varying voltages rather than numerical counts.

When there are no vehicles within the detection zone, the DC voltage is stored and remembered by a memory capacitor. When a vehicle causes a change in the phase comparator output, the difference between it and the memory capacitor causes relay operation. Very slow changes in the DC voltage are followed by the memory capacitor, which allows the circuit to track for drift due to environmental changes. The memory circuit will ultimately forget a vehicle parked over the loop and drop that call. Detail on tracking environmental drift is included later under "Digital Frequency Shift Detector Unit."

Overview of Digital Detector Units

With the introduction of electronic digital processing techniques, most detector electronic unit manufacturers are currently producing digital type vehicle detectors. Digital techniques allow more reliable, accurate, and precise measurements than the analog techniques.

Understanding how digital detectors operate is important because increased detector sensitivity results in increased detector response time. A large detector response time can result in significant error in vehicle velocity measurements using two loops in a speed trap (i.e., a measured distance). Response times vary with the different manufacturers.

Digital vehicle detectors sense either a change in the frequency or period of a waveform. The oscillator frequency or period shift is caused by a decrease in loop inductance when a vehicle is within the detection zone. The detector oscillator frequency for a quality (Q) factor of 5 or greater is:

$$f_D = \frac{1}{2\pi\sqrt{L_D\, C_D}} \tag{46}$$

where:

f_D = Detector oscillator waveform frequency, Hz

L_D = Total inductance across detector terminals, h

C_D = Total capacitance across detector terminals plus internal tuning capacitance

The normalized oscillator frequency change due to a normalized change in detector inductance for a Q factor of 5 or greater is given by:

$$\frac{\Delta f_D}{f_D} = -\frac{1}{2}\frac{\Delta L_D}{L_D} = -\frac{1}{2} S_D \tag{47}$$

where:

Δf_D = Change in detector oscillator frequency, Hz

ΔL_D = Change in detector terminal inductance, h

S_D = Sensitivity of detector to inductance change

It appears to be universally accepted that vehicle proximity to a buried inductive wire loop predominantly causes a change in the loop inductance parameter of the LC tank circuit formed by the loop, lead-in cable, and detector input capacitor. Some manufacturers use the percent change of loop inductance, $\Delta L/L$, while others simply use the change of loop inductance, ΔL. Neither of these can be measured directly at the loop input terminals. However, to indicate sensitivity, several manufacturers provide frequency meters to measure the resonant frequency and the amount of frequency change.

Experience has shown that the percentage change of inductance ($\Delta L/L$) from an unoccupied loop to an occupied loop is extremely repeatable for a given loop size and geometry, for a given vehicle size and geometry, and for a given location of the vehicle with respect to the loop. Since parameters such as actual loop inductance and loop operating frequency do not affect $\Delta L/L$ and do affect ΔL, the following discussions and computations address the $\Delta L/L$ concept. The term "detector sensitivity," in the context of this discussion, is defined as the value of $\Delta L/L$ which actuates the detector with the smaller values interpreted to mean greater sensitivity.

For short lead-in cables with negligible series cable inductance:

$$\frac{\Delta L_D}{L_D} = \frac{\Delta L_L}{L_L} = S_L \tag{48}$$

where:

ΔL = Change in loop inductance when sensing a vehicle, h

L = Loop inductance, h

S_L = Sensitivity of loop to vehicle

The period of the detector oscillator (T_D) is the inverse of the frequency. For a Q factor of 5 or greater, the T_D is given by:

$$T_D = \frac{1}{f_D} = 2\pi\sqrt{L_D C_D} \tag{49}$$

where:

T_D = Detector oscillator waveform period, sec

The normalized oscillator period change due to a normalized change in detector inductance for a Q factor of 5 or greater is approximately:

$$\frac{\Delta T_D}{T_D} = -\frac{1}{2}\frac{\Delta L_D}{L_D} = -\frac{1}{2} S_D \tag{50}$$

With the advent of sophisticated electronic digital microprocessors and the availability of loop network resonant frequency information at the detector input terminals, extremely precise measurements of the following parameters can be accomplished with relative ease:

- Frequency shift measurements (Δf_D)
- Ratioed frequency shift measurements ($\Delta f_D/f_D$)

- Period shift measurement ($\Delta f_D / f_D$)
- Ratioed period shift measurement ($\Delta T_D / T_D$)

Each of the four types of digital vehicle detectors units is introduced below. Detailed analyses and block diagrams of each type are provided in Appendices F through I.

Digital Frequency Shift Detector Unit

This type of detector unit is not manufactured. The theory and characteristics of this detection principal are included to assist in the understanding of the operation of the digital ratioed frequency shift detector.

The digital processor of this detector concept compares counts proportional to oscillator frequency when sensing a vehicle to a reference count taken periodically when no vehicles are present. The reference count is stored in a memory. During vehicle detection, when the count exceeds the reference count by a preset sensitivity threshold count, a vehicle call is initiated.

The frequency shift detector sensitivity, (S_D^f), from Equation 47 is:

$$S_D^f = 2 \frac{\Delta f_D}{f_D} \tag{51}$$

Appendix F shows that:

$$S_D^f = K_f \sqrt{L_D C_D} = \frac{2 N_{ft}}{N_{fc}} \tag{52}$$

where:

N_{ft} = Fixed frequency threshold count selected by sensitivity switch

N_{fc} = Variable frequency counter count

K_f = Frequency sensitivity constant

In the above described method, the term S_D is proportional to the square root of the $L_D C_D$ product. Since larger values of S_D represent decreased sensitivity, it follows that sensitivity decreases proportional to the square root of the $L_D C_D$ product with a Δf_D measurement. Hence, every time the frequency switch is changed to a new position (e.g. to avoid crosstalk), the sensitivity would change and, if critical, would necessitate a new setting of the sensitivity switch.

With increased lead-in cable length, the added inductance of the lead-in cable would cause some loss of sensitivity and the increased $L_D C_D$ product would cause even more loss of sensitivity. Overall, this type of measurement does not appear to be very useful.

Digital Ratioed Frequency Shift Detector Unit

For this type of detector unit, the digital processor compares counts proportional to the oscillator frequency when sensing a vehicle to a reference count taken periodically when no vehicle is present. The reference count is stored in a memory. When the count during vehicle detection exceeds the reference count by a preset sensitivity threshold count, a vehicle call is initiated.

The ratioed frequency shift detector differs from the frequency shift detector because the frequency counter is held approximately constant (see Appendix G).

The sensitivity, S_D^f, is independent of the inductance, L_D, and the capacitance, C_D, across the detector terminals and is calculated as follows:

$$S_D^f = \frac{2 N_{ft}}{N_{fc}} \tag{53}$$

where:

N_{ft} = Fixed frequency threshold count

N_{fc} = Fixed frequency counter count

From Appendix G, the measurement response time is:

$$t^f = \frac{2\,N_f\,t}{m\,f_D\,S_D^f} \qquad (54)$$

The advantage of having the detector sensitivity independent of the inductance and capacitance across the detector terminals is illustrated by the following example. (This example also applies to the Digital Ratioed Period Shift Detector Unit discussed later.)

For this example, assume four equal size loops, say, 6 x 6 foot (1.8 x 1.8 m) with an equal number of turns, say three. Wire the loops as follows (these configurations are shown in Figure 15):

- All series (288 µh).
- Series/parallel (72 µh).
- All parallel (18 µh).

For simplicity, lead-in cable length is not considered. The sensitivity of the ratioed frequency or ratioed period shift detector is identical for all three of the above wiring schemes. Accordingly, a sensitivity threshold sufficient to detect a small motorcycle over one of the four loops when wired in series need not be changed when rewired in series/parallel or all parallel.

Although lead-in cable length was not considered above, an extra long lead-in cable will produce varying changes in inductance due to inductance sharing. The amount of change depends on the length of the lead-in cable and the wiring scheme used for the multiple loops. Figure 30 provides an indication of the signal amplitude that may be expected at the detector input terminals from a small motorcycle traveling over one of the four loops.

Digital Period Shift Detector Unit

In the digital period shift detector concept, the "period" of a waveform is the time required for one full cycle. It is calculated by dividing one by the frequency in cycles per second (cps). The unit makes use of a high-speed reference clock with a frequency in the megahertz range to measure the loop period precisely in terms of the number of cycles from the clock. That is, the count is proportional to the period. Precision is enhanced without sacrificing too much speed by actually measuring the time for 32 cycles for sensitivity one, 64 cycles for sensitivity two, etc.

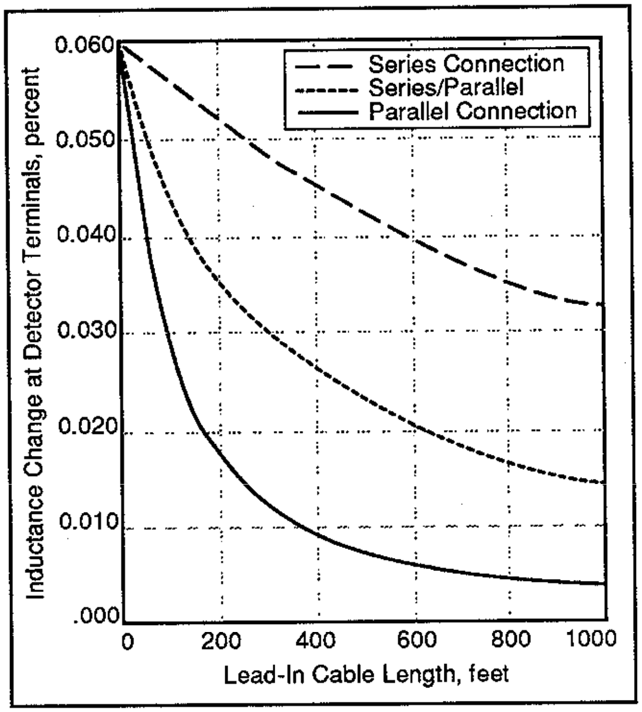


Figure 30. Inductance change as a function of lead-in cable length.

When a vehicle enters the loop, the inductance is decreased, the loop frequency increases, and the loop period shortens. Therefore, there is a reduction in the measured time duration of a fixed number of loop cycles. A reduction in the measured time duration by an amount greater than a preselected threshold value produces an output signal (call) to indicate the vehicle's presence. With careful choice of reference clock frequency and the threshold value (4 counts ± 2 counts), this design is practical at any frequency encountered in practice. The time to detect is so short that it is feasible for the electronics to sequentially scan or operate four small loops, one at a time, several times a second. (Multichannel operation is discussed later.)

The period shift detector is entirely self-tuning on installation and, like most other designs, is able to track environmental drift. Like the digital frequency shift model, most models stop tracking for a time after a vehicle enters the loop, to guarantee that the call of a small vehicle will be held long enough to bring the green to that approach.

The period shift detector sensitivity, S_D^p, from Equation 50 is:

$$S_D^p = 2\frac{\Delta T_D}{T_D} \quad (55)$$

Appendix H shows that:

$$S_D^p = \frac{K_p}{\sqrt{L_D C_D}} = \frac{2\,N_{pt}}{N_{pc}} \quad (56)$$

where:

N_{pt} = Fixed frequency threshold count selected by sensitivity switch

N_{pc} = Variable frequency counter count

K_p = Frequency sensitivity constant

The term S_D^p is inversely proportional to the square root of the LC product. Because of the small values of S_D^p, this represents increased sensitivity. It also follows that sensitivity increases proportional to the square root of the LC product with a ΔT measurement. Hence, with increased lead-in cable length, part of the loss of sensitivity due to the added lead-in cable inductance would be automatically compensated by the increase in the LC product. Unfortunately, the compensation is not one to one because of the square root relationship.

The detector response time (t^p) from Appendix H is:

$$t^p = \frac{2\,N_{pt}}{f_C\, S_D^p} \quad (57)$$

Most vehicle detectors use a transformer to connect the external detector loop terminals to the internal loop oscillator. If the transformer is loosely coupled, a series leakage or swamping inductance results. This inductance reduces the effect of lead-in cables on sensitivity at the expense of overall sensitivity.

If a swamping inductance, L_T, is used in the detector electronics, then:

$$t^p = \frac{2\,N_{pt}}{f_C\, S_D^p\left[\dfrac{1}{1+\dfrac{L_T}{L_D}}\right]} = \frac{2\,N_{pt}\left[1+\dfrac{L_T}{L_D}\right]}{f_C\, S_D^p} \quad (58)$$

For example, let:

N_{pt} = 4
L_T = 150 µh
L_D = 75 µh
f_C = 2.22 mHz
S_D^p = 0.005 %

Then:

$$t^p = \frac{2 * 4 * \left[1+\dfrac{(150\ \mu h)}{(75\ \mu h)}\right]}{(2.22 * 10^6\ Hz) * (5 * 10^{-5})} = 216\ ms \quad (59)$$

The percentage error in vehicle velocity obtained from a speed trap using two spaced inductive loops is given by:

$$\frac{\Delta V}{V} = 100 * \frac{\Delta T\, V}{X} \quad (60)$$

where:

$\frac{\Delta V}{V}$ = Error in vehicle velocity, %
ΔT = Error in measured time, secs
X = Spacing between leading edges of the loops, feet
V = Vehicle velocity, feet/sec

The maximum time error in vehicle speed or occupancy measurements is assumed to be the detector response time. The speed trap error caused by detector response times is illustrated by the following example.

Let:

$\Delta T = 2 * 216 \text{ ms} = 432 \text{ ms } (0.432 \text{ sec})$
$V = 60 \text{ mph } (96.6 \text{ kph}) = 88 \text{ ft/sec } (26.8 \text{ m/sec})$
$X = 100 \text{ feet } (30.5 \text{ m})$

$$\frac{\Delta V}{V} = 100 * \frac{(0.432) * (88)}{100} = 38.0\ \% \qquad (61)$$

This example clearly indicates that the loop system should be designed so that the system sensitivity is as large as possible. By using the detector electronics on a less sensitive range, the detector time response is decreased, allowing more accurate vehicle speed detection.

An increase in the detector electronics clock frequency from 2.22 mHz to 22.2 mHz will reduce the percentage velocity error from 38.0 percent to 3.8 percent. Many of the newer detectors use clock frequencies in the 20 to 25 mHz range.

Digital Ratioed Period Shift Detector Unit

The digital processor of this type of detector design compares counts proportional to the oscillator period when sensing a vehicle to a reference count taken periodically when no vehicle is present. The reference count is stored in a memory. When the count during detection is less than the reference count by a preset sensitivity threshold count, a vehicle call is initiated. The ratioed period shift detector differs from the period shift detector in that the threshold count, N_{pt} is not fixed.

The threshold count (see Appendix I) is given by:

$$N_{pt} = S_T\ N_{pc} \qquad (62)$$

Thus:

$$S_D^p = \frac{2\ S_T\ N_{pc}}{N_{pc}} = 2\ S_T \qquad (63)$$

Since the detector sensitivity is independent of the period counter count, the detector sensitivity is independent of detector frequency. The response time is identical to that of the digital period shift detector.

Comparison of Digital Detectors

A summary comparison of the various detector electronic unit concepts in terms of sensitivity and response time is presented in Table 9.

Multichannel Digital Models

Controller cabinet space can be conserved if the detector unit can operate more than one loop. Most

Table 9. Comparison of detector sensitivity and response time.

Digital Detector Type	Detector Sensitivity (S_D)	Detector Response Time	Comments
Frequency Shift	$S_D^f = K_f\sqrt{L_D C_D}$	t^f = frame time	Sensitivity is deceased by an increase in induction from the larger loop or longer lead-in cable. Response time is fixed by detector frame time.
Ratioed Frequency Shift	$S_D^f = \frac{2\,N_{ft}}{N_{fc}}$	$t^f = \frac{2\,N_{ft}}{m\,f_D\,S_D^f}$	Sensitivity is independent of inductive value at detector terminals. Response time increases for increase in inductance at detector terminals and detector sensitivity.
Period Shift	$S_D^p = \frac{K_p}{\sqrt{L_D C_D}}$	$t^p = \frac{2\,N_{pt}\left(1 + \frac{L_T}{L_D}\right)}{f_c\,S_D^p}$	Sensitivity is increased by increase in inductive loop from larger loop or longer lead-in; however, available inductive change is decreased when L_T is present. Response time is dependent on loop inductance.
Ratioed Period Shift	$S_D^p = 2\,S_T$	$t^p = \frac{2\,N_{pt}}{S_D^p}$	Sensitivity is independent of inductive value at detector terminals.

digital detector manufacturers offer detector units which can operate four or more loops. Some models address the crosstalk problem by providing a frequency-separation switch, while others separate the loops by a time-division "scanning" process.

One manufacturer's scanning detector energizes and analyzes each of the four or more channels sequentially, one at a time, up to 100 times per second. The digital period shift type of detector is inherently fast enough to permit scanning. The time to analyze a channel depends on the sensitivity desired, as high precision in thresholding demands more time for counting reference pulses.

For example, if three 150 μh loops were connected and used with sensitivities of 1, 4, and 6, and the fourth channel was switched to off, then the four channels would require 2.3, 9, 63, and 0.9 ms respectively, for a total of 75 ms. Each channel would be energized and analyzed a number of times per second calculated as $1{,}000 \div 75 = 13$. The use of loops of larger L will reduce the scan rate, as will the selection of the highest sensivity settings on the unit.

If more than four similar and nearby loops are involved, the frequency switch can be used or the size and/or number of turns of the loops can be varied to provide crosstalk protection. Equation 39 and Tables 2, 3, and 4 can be used to design frequency separations of 7 percent or more.

Another manufacturer utilizes a much higher clock speed. This provides much faster scanning rates. For example, on the lower sesitivity settings, the sample time is 0.5 ms per channel. Therefore, the total time to scan all four channels is 2 ms. Also, when a channel is switched off, the the scan time for that channel is zero.

Recent Advances in Digital Detectors

During the 1980's several refinements have been incorporated into digital detector systems. Recognizing the heavy demand on maintenance dollars, some manufacturers have added circuitry to their detectors to reduce the frequency of trouble calls to reset detector units attached to faulty loops. These features, intended to reduce maintenance costs and maximize traffic performance, include Open Loop Test capability and Automatic and Remote Reset as discussed below.

Open Loop Test Feature

This feature allows the detector to continue to operate an intermittently open loop system. A momentary open caused by a broken wire, poor splice, or loose connection will be stored in memory. If the connection remakes, the unit will promptly retune and continue to operate properly. If the open continues, it will result in a constant call.

When making a service call to the intersection, the technician may observe an indicator light that will flash a distinct pattern if an "open" has occured. Or, on other brands of detectors, the technician presses the "Open Loop Test" button on the detector unit to determine whether an opening has occurred since the last service call. The open loop memory can be queried repeatedly as it can be reset only by power interruptions (such as removing the module from its card rack and reinserting) or by pressing the common reset button on the detector. This constitutes a system reset which will clear the open loop memory.

Automatic Reset Feature

Some detectors can be programmed such that, if a call (detector output) exceeds the programmed time, the detector will generate an internal reset. This reset is controlled by the termination of the associated phase green. One agency claims that this feature reduced their detector maintenance costs by 42 percent.

Remote Reset Feature

Remote reset allows automatic investigation of suspicious detector calls in computer or software program control systems. A remote master monitoring the actuations of each system sensor may suspect that a detector is malfunctioning. By asserting the Reset command, the detector can frequently be returned to normal operation. The reset causes presence calls to be cleared, but it does not clear Open Loop Memory nor does it prevent an open loop from calling.

If the Reset fails to restore normal operation, the fault can be recognized and printed out for maintenance attention. An open loop that is constantly calling can be taken off line so that it does not falsely influence system operating parameters.

Independant Loop Fail Output

In addition to the normal detector output, a second output for loop status is provided on some models of detectors. Whenever the loop inductance takes a step change of ± 25 percent or more, the Loop Fail Output is turned on. If the inductance returns to a value less than ± 25 percent of the reference, the Loop Fail Output turns off. This enables remote interrogation of the loop status.

NEMA STANDARDS

As with traffic signal controllers, loop detectors were developed and marketed by numerous manufacturers, each using a different type of harness connector and detector technique. To overcome the subsequent interchangeability problems, NEMA developed a set of standards known as "Section 7. Inductive Loop Detectors" released early in 1981. This section of the NEMA Standards defined functional standards, physical standards, environmental requirements, and interface requirements for several loop detector unit configurations.

Section 7 covered only the basic functions associated with loop detectors. Users identified the need for additional functions for specific locations, particularly delay and extension timing. To cover this gap, NEMA developed, and in 1983 released Section 11 entitled "Inductive Loop Detectors with Delay and Extension Timing." This section was basically identical to Section 7 with the addition of requirements for the timing of delayed call and extended call features. A further revision resulted in a new Section 15 released February 5, 1987 (a reproduction is provided in Appendix J). This new standard combines, updates, and supersedes Sections 7 and 11.

Detector Unit Configurations

The NEMA Standards define two basic types of detector unit configurations: shelf mounted and card-rack mounted. Shelf mounted detector units are commonly used in NEMA controller installations, and are available in both single channel and multi-channel (two or four channel) configurations. These shelf mounted units as shown in Figure 31 are powered by the 120 volt AC supply in the cabinet. Outputs are generated by electromechanical relays or by electrically isolated solid-state circuits. Physical dimensions and connector requirements are included in the NEMA Standards in Appendix J.

Card-rack mounted detector units, illustrated in Figure 32, fit into a multiple card rack and operate

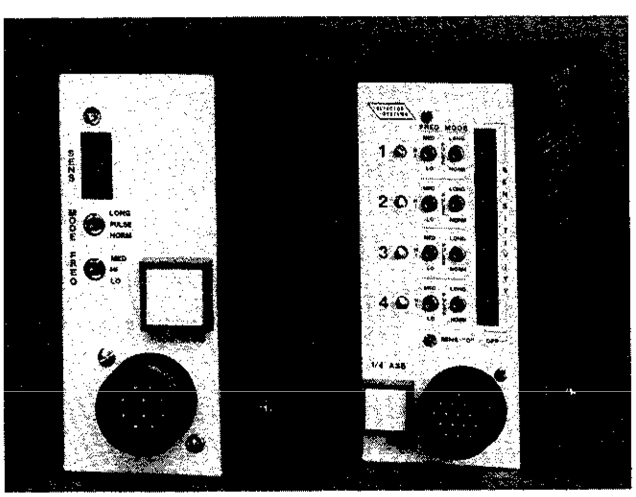


Figure 31. Shelf mounted detector units

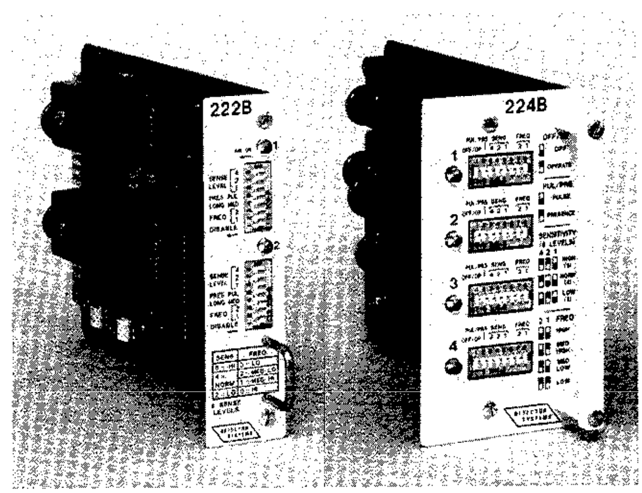


Figure 32. Card-rack mounted detector units

off an external 24 volt DC power supply generated in the rack assembly or elsewhere in the controller cabinet. Use of these devices are an effective way to reduce cabinet space requirements where large numbers of detectors are needed.

Modes of Operation

There are two modes of operation selectable for each detector channel: presence and pulse. Presence detection implies that a detector output will remain on while a vehicle is over the loop.

NEMA Standards require the detector unit to be able to sustain a presence output for a minimum of 3 minutes before tuning out the vehicle. Most units will maintain the call for periods up to 10 minutes. This mode is typically used with long loop installations on intersection approaches with the controller in the non-locking detection memory mode.

Non-locking detection memory is a controller function whereby the controller retains a call (vehicle detection) only as long as the presence detector is occupied (vehicles are passing over or stopped on the detector). If the calling vehicle leaves the detector, the call is dropped (forgotten) by the controller.

Pulse detection requires the detector to generate a short pulse (between 100 and 150 ms) every time a vehicle enters the loop area. This mode would typically be used where detectors are located well upstream of the intersection with the controller in the locking detection mode. That is, the vehicle call is not dropped by the controller when the calling vehicle leaves the detector. For more information on these modes, see Chapter 3.

Output Types

Two types of outputs are available for detector units: relay and solid state. Relay type outputs use electromechanical relays to generate a circuit closure and thus, a detection call to the controller. Solid-state outputs have no moving parts, and are therefore generally more reliable and considerably more accurate in tracking the actual presence of vehicles. This is a very important factor in some aspects of timing traffic signals.

The relay type outputs are designed to fail "on" (contacts closed) when power to the detector is interrupted. The solid state output fails "off" (nonconducting) in the same circumstances. Therefore, a relay type output may be more desirable for use with intersection actuation because a constant-call would be safer than the no-call situation, and a solid-state output more desirable where accurate presence detection is desired.

Crosstalk

When two loops are the same size and have the same number of turns and the same lead-in length, they have the same resonant frequency. Should these two loops be near each other or should the lead-ins from these loops be in close proximity (perhaps running in the same conduit), a phenomenon know as "crosstalk" can occur. This occurrence is an electrical coupling between the two loop channels and will often manifest itself as brief, false and/or erratic actuations when no vehicles are present.

NEMA Standards require some means to prevent crosstalk, either inherent, automatic, or manual. The most common feature is a frequency selection switch used to vary the operating frequency of the adjacent loop channels.

Timing Features

As contained in Section 15 of the NEMA standards (Appendix J), the timing features include delay and extension timing. Delay timing can be set from 0 to 30 seconds, indicating the time which the detector waits, from the start of the continuous presence of a vehicle, until an output begins (see Figure 33). The output terminates when the vehicle leaves the detection area. If the vehicle leaves the loop before the delay time has expired, no output is generated. Extension time, defines the amount of time the output is extended after the vehicle leaves the zone of detection (see Figure 34), and can be set from 0 to 15 seconds.

Timing features can be controlled by external inputs to the detector. For detectors with relay type outputs, a Delay/Extension Inhibit Input is provided and requires 110 Volts to activate. Detectors with

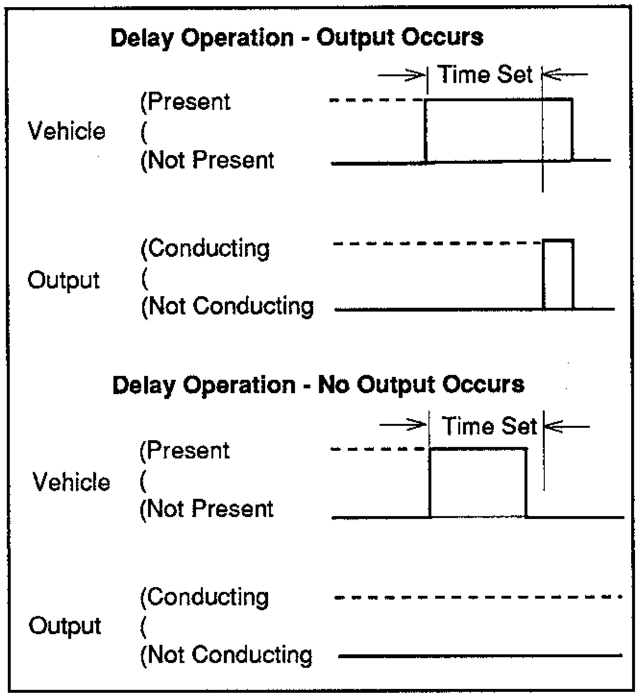


Figure 33. Delay operation.

solid state outputs have a Delay/Extension Enable Input, which requires a "low" state DC voltage (0 to 8 Volts).

A typical delayed call installation might be a semi-actuated intersection with heavy right-turns-on-red from the side street which has long loop presence detection. Using a relay output detector, the side street green field output (110 Volts AC) is connected to the Delay/Extension Inhibit input. Thus, a delay is timed, allowing right-turns-on-red to be made without unnecessarily calling the controller to the side street. (Heavy right-turn movements will bring up the green anyway, as the loop will be occupied by following vehicles.) However, when the side street has the green, the delay is inhibited, permitting normal extensions of the green.

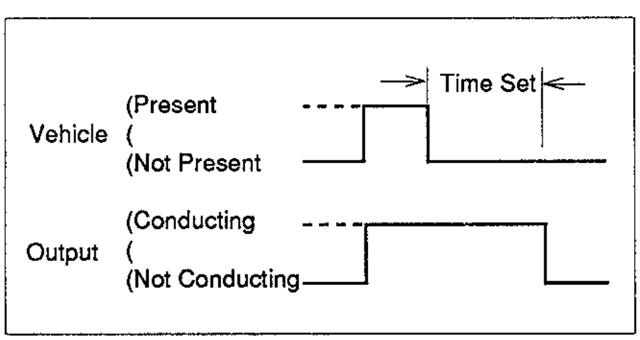


Figure 34. Extension operation.

Conversely, extended call detectors could be used on high-speed approaches to an intersection operated by a basic (non-volume-density) actuated controller. Using this technique, the apparent zone of detection is extended, and a different "gap" and "passage" time can be created without the volume-density controls (this does not, however, replace volume-density functions). The Delay/Extension Enable Input on a solid-state output detector could be tied to the controller's "Phase On" output (Ref. 1).

TYPE 170 SPECIFICATION

Simultaneously with the evolution of the NEMA Standards, the States of California and New York developed the Type 170 controller specification. As with the NEMA Standards, the development of this new controller was a direct response to the problems of non-interchangeability. The system developed was to be interchangeable between all manufacturers suppling equipment for either state.

Unlike the NEMA Standards which standardize *functions,* the Type 170 Specification standardizes *hardware.* The Type 170 is defined as a system involving cabinet, controller, and all required accessories including detectors. The California system (Figure 35) specifies a large, base-mounted cabinet with full component layout for 28 two-channel detector units, while the New York system features a smaller, pole-mounted cabinet with 14 two-channel detector units. New York has subsequently revised its specification to require a new microprocessor. This system, labeled a Type 179, covers the same cabinet and detectors as the original Type 170.

As the Type 170 Controllers are housed in standardized cabinets, all components are modular or card rack-mounted. The detector sensor unit is mounted on a edge-connected, printed circuit board. Two channel detectors take up one card slot, four channel detectors take two slots. The detector module front panel is provided with a hand pull for insertion and removal from the input file.

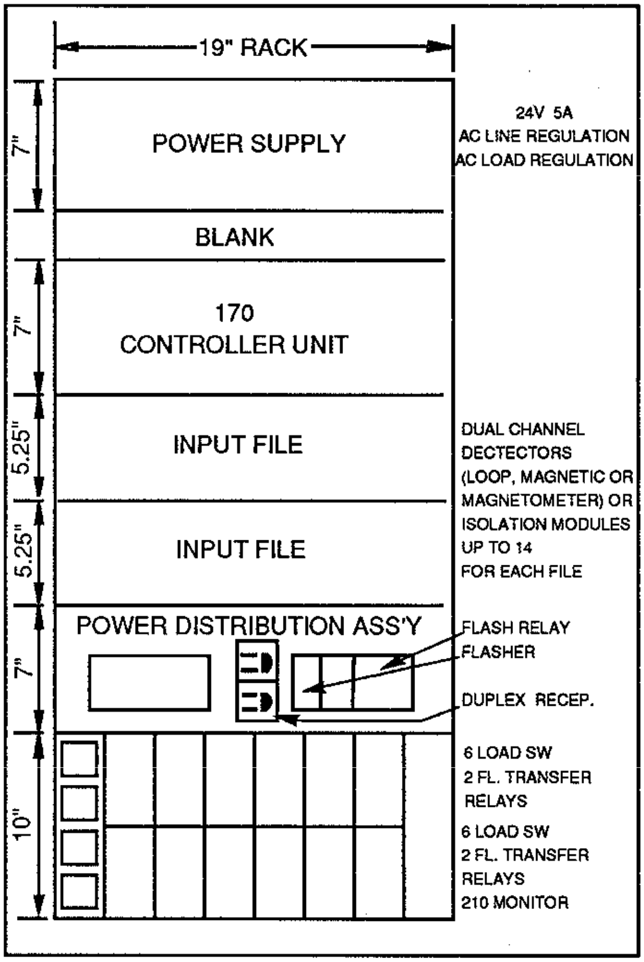


Figure 35. Type 170 cabinet layout (California).

Model 222 / 224 Loop Detectors

Chapter 4 of the Type 170 Specification (reproduced in Appendix K) defines the specification applicable to the Model 222, Two-Channel Loop Detector Sensor Unit and Model 224, Four-Channel Loop Detector Sensor Unit (See Figure 32). Specifically, this chapter sets forth the general description, functional requirements, and electrical requirements.

Each detector channel is equipped with panel selectable sensitivity settings for both presence and pulse modes of operation. As with the NEMA Standards, the Type 170 Specification requires some means to prevent crosstalk with other modules. It also requires that the detector channel shall not detect moving or stopped vehicles at distances of 3 feet or more from any loop perimeter. The timing features are incorporated into the various Type 170 software programs such as the Caltrans Local Intersection Program (LIP).

SELECTION FACTORS

There are several important considerations that should be evaluated before selecting a appropriate detector unit model. The importance of these factors depend on the particular requirements of a given situation.

Tuning Range

NEMA requires that a detector unit be capable of tuning and operating as specified over a range of inductance from 50 µh to 700 µh. For most applications, this range is adequate. Some units, however, are capable of tuning and operating over a range of 1 µh to 2,000 µh. This larger operating range permit extra long lead-in cables and/or several loops to be wired in series to one unit.

Response Time

The time required for a detector unit to respond to the arrival and departure of a vehicle is of importance when the output is used to calculate speed and occupancy. Systems for the surveillance and control of surface street traffic signals and freeway flow usually perform these calculations.

If the time for vehicle call pick-up is close to the time for drop-out, little or no bias in the time of vehicle occupancy is introduced. If there is significant difference, but the difference is about the same from unit to unit, a correction for the bias is easy to apply.

NEMA specifies that a detector unit respond to the arrival or departure of a small motorcycle into and out of a 6- x 6-ft (1.8- x 1.8-m) loop within 125 ms. An automobile call must be initiated or terminated within 50 ms. NEMA also states that for certain specific surveillance applications which involve vehicle speeds in excess of 45 mph (72 kph), more precise response times might be required.

It should be emphasized that response time is becoming more important. What the user accepted in the past, was speed and occupancy measurements that averaged out over many vehicles to a marginal accuracy. Now, and in the future, more emphasis is being placed on faster responce times to provide greater accuracy to meet the needs of advanced traffic control algorithms. Many of the manufacturers are responding to this need by supplying new madels with enhanced capabilities.

A study performed for the SCANDI project in Detroit found that the duration of a call is impacted by the height of the flux field, which, in turn, depends on the presence and depth of reinforcing steel and other location-specific factors (Ref. 2). The study indicated that adjustable, diamond-shaped loops compensate for such factors at each location, resulting in a uniform duration from loop to loop for a given vehicle at a given speed.

Recovery from Sustained Occupancy

Recovery time can become critical when the unit is operated in the presence mode with a long loop, say 6- x 50-ft (1.8- x 15-m), at the stop line, or four 6- x 6-ft (1.8- x 1.8-m) loops in a left-turn lane wired in a combination of series/parallel. NEMA requires that after a sustained occupancy of 5 minutes by any of the three test vehicles, the detector shall recover to normal operation at least 90 percent of the minimum specified sensitivity within one second after the zone of detection is vacated. If a detector unit does not recover quickly enough, the next vehicle may not be detected at all and will be trapped until a new vehicle arrives on the loop.

Loss of Detection during Saturated Flow

During peak periods, a long loop or combination of loops may be held in detection without a break for an hour or more. In these situations, it is important that the detector unit be designed to continue outputting for at least an hour without dropping the detection because of an environmental tracking feature or other design defect. NEMA does not address this important point.

Sensitivity with Pavement Overlay

Depth of loop wires has traditionally been considered to be a critical factor when the pavement is overlayed. However, tests conducted in Texas suggest that, with high sensitivity, proper installation, and calibration, the depth at which a loop is buried should have little effect on auto detection. In these tests, a 6- x 6-ft (1.8- x 1.8-m), 5-turn loop was buried at a depth of 18.5 in (50 cm) and encased in a 1/2-in (1.2-cm) PVC conduit with no filler. There was no appreciable difference in the detection of large cars between the near-surface mounted loops and the deep buried loops.

Bicycle detection was only slightly less efficient with deep buried loops. The difference occurred at the medium sensitivity setting. The surface loop detected the bicycle 1 ft (0.3 m) outside the loop at the medium setting, while the deep buried loop did not. The rectangular 6- x 6-ft (1.8- x 1.8-m) did not detect bicycles in the center portion of the loop on either the surface mounted or deep buried loops regardless of the detector setting.

Pulse-Mode Reset

The pulse mode of operation provides an output (100 to 150 ms) that is useful in counting vehicles. A detector unit should be capable of resetting or rephasing correctly to avoid either overcounts or undercounts under certain conditions. NEMA requires only that a detector produce one, and only one, output pulse for a test vehicle moving at 10 mph in the detection zone of a 6- x 6-ft (1.8- x 1.8-m) loop.

For users wishing to count vehicles in two or more lanes at the same time, a separate detector and loop is recommended for each lane to ensure accuracy. This approach can be implemented for a small additional cost over the use of a single detector and a wide loop.

Operation with Grounded or Open Loops

Although NEMA does not address this point, some detectors provide failsafe operation with faulty loops; i.e. grounded or open loops. The use of a loop isolation transformer permits these models to operate if the loop insulation is leaky or even shorted completely to ground at a single location.

Isolation allows "balanced to ground" operation of the loop circuit. This reduces the effect of the loop and lead distributed capacitance and hence the effects of thermal and moisture changes in the capacitance. The balance also minimized loop circuit coupling from lead-in cables in common conduits. If the loop breaks, this design will fail in a "safe" way by holding a constant call, thus keeping traffic moving and avoiding trapping any vehicles. Such operation is, however, very inefficient.

Lightning Damage/Electrical Interference

An extensive study into the effects of lightning related electrical surge problems was conducted by the Ontario Ministry of Transportation and Communications (Ref. 3). The major conclusions of the study were:

- Most problems occured on common grounding systems.
- If changed to isolated grounding, maintenance problems are reduced almost 80 percent.
- If system using isolated grounding is also upgraded to include both primary and secondary surge protection, maintenance problems are reduced by more than 90 percent.

NEMA requires that detector units withstand the same power-line transients specified for controller units. The detector loop input terminals must be able to withstand 3,000 volts. The primary to secondary insulation of the input (loop-side) transformer protects against "common mode" lightning voltages.

With one model, differential lighting protection consists of a four-element protective circuit composed of the input resistors, the neon tube, the transformer leakage inductance, and the diode path across the secondary. Differential lightning-induced currents are also potentially damaging. These currents are shunted through the neon bulbs, limiting the voltage across the transformer.

In Model 170 contoller cabinets, the specifications require lightning protection be installed within the loop detector unit. The protection is to enable the detector to withstand the discharge of a 10 microfarad capacitor charged to ±1000 volts directly across the detector input pins with no loop load present. The protection must also withstand the discharge of a 10 microfarad capacitor charged to ±2000 volts directly across either the detector input inductance pins or from either pin to earth ground. The detector chasis is grounded and a dummy resistive load of 5.0 ohms is attached to the pins.

The Model 170 specifications also include provisions for preventing interference between channels in a given unit as well as between units. The prevention means may be either manual or automatic.

MAGNETOMETER DETECTORS

The magnetometer consists of a small in-road sensor about the size and shape of a small can, a lead-in cable, and an amplifier. A typical installation is shown in Figure 36.

The magnetometer detector was introduced in the 1960's as an alternative to the loop detector in specific situations. It is a special type of magnetic detector designed to detect the presence of a vehicle by measuring the focusing effect of the Earth's magnetic field which results when ferrous metal (e.g. the vehicle) is in the vicinity of the detector.

The magnetometer is normally used where the only information required is that the vehicle has arrived at a "point" or small-area location. Therefore, it is used to actuate controller phases operated in the locking detection memory mode. It is also effective in counting vehicles. Unlike the loop detector, the magnetometer will usually work on bridge decks where steel is present and cutting the deck pavement for loop installation is not permitted.

The magnetometer probe and its lead-in wire (which is polyeurathane jackted) tend to survive in crumbly pavements longer than ordinary loops. In addition, they require fewer linear feet of saw cut. Both magnetometers and loop detectors have their respective applications and tend to complement each other.

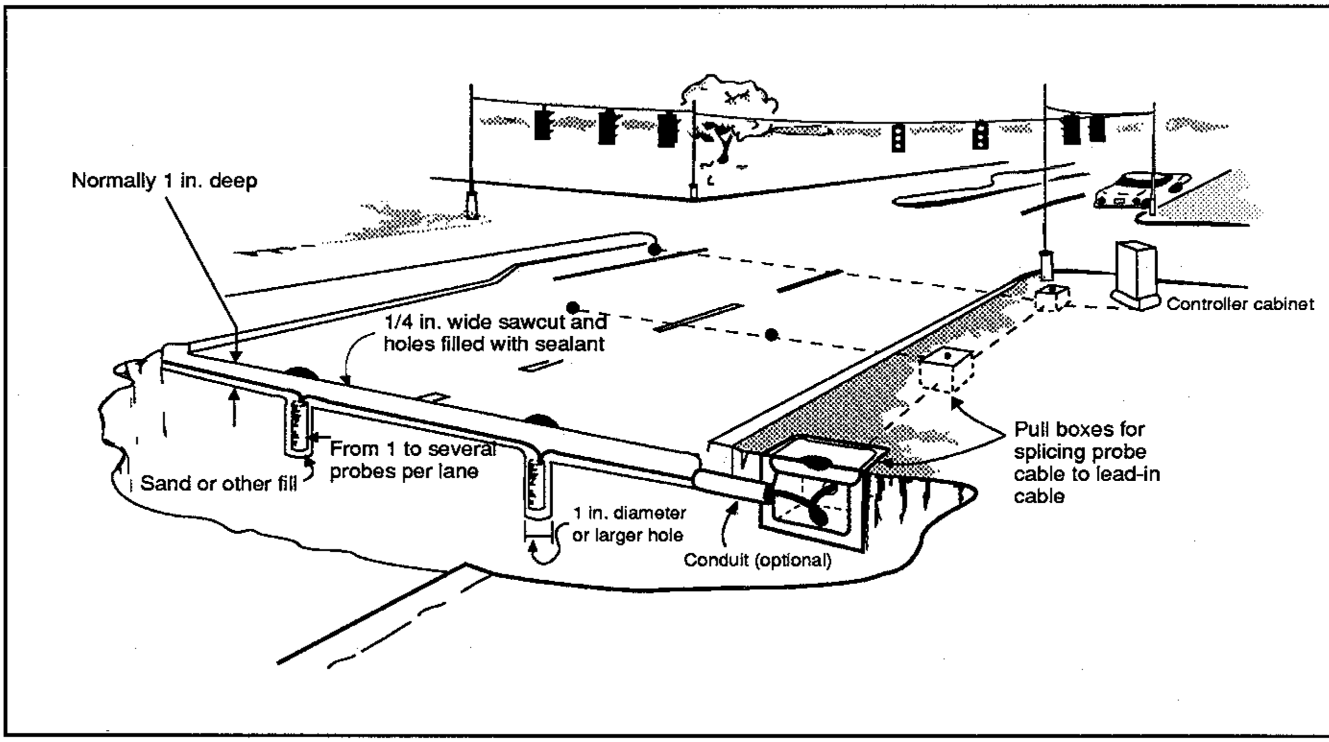


Figure 36. Typical magnetometer installation

MODEL 228 MAGNETOMETER DETECTOR

Chapter 6 of the Type 170 Specification (see Appendix K) addresses specifications applicable to the Model 228 two-channel magnetometer detector control unit and the Model 227 magnetometer sensing element. The magnetometer control unit is specified only in the two channel version. Each channel operates with from one to six probes or sensors (Model 227). The control unit produces an output signal whenever a vehicle passes over one or more of the probes.

A magnetometer measures the passage or presence of a vehicle. Two modes of operation are provided: pulse mode which gives an output closure of 125 ± 25 ms for each vehicle entering the zone of detection, and presence mode which gives a continuous output as long as a vehicle occupies the zone of detection.

THEORY OF OPERATIONS

The Earth is a large bar magnet with lines of flux running from pole to pole as shown in Figure 37. For

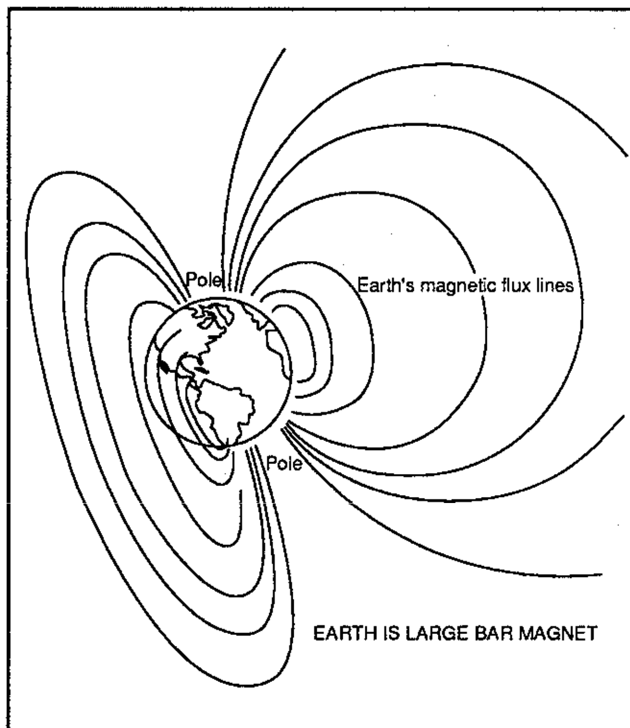


Figure 37. Earth's magnetic flux lines.

a vertical axis magnetometer to function, the vertical component of the Earth's magnetic field must exceed 0.2 oersteds; therefore, vertical axis magnetometers cannot be used near the equator where the magnetic field lines are horizontal.

Figure 38 presents a map of the angle of the earth's magnetic field and defines the area (crosshatched) which is not suitable for using magnetometers

A vehicle of iron or steel distorts the flux lines because ferrous material is more permeable to flux lines than is air. That is, the flux lines prefer to pass through the ferrous vehicle. As the vehicle moves along, it is always accompanied by a concentration of flux lines known as its "magnetic shadow" as illustrated in Figure 39.

There is reduced flux to the sides of the vehicle, and increased flux above and below it. A magnetometer probe installed within the pavement detects the increased flux below. Vehicles traveling between zero to 100 mph (0 to 160 kph) can be detected.

PROBE CHARACTERISTICS

A typical magnetometer probe is cylindrical and approximately 1 in (2.5 cm) by 4 in (10 cm). It is installed in a drilled hole in the pavement generally about 1-ft (0.3-m) deep. A general arrangement of the components of the magnetometer probe is shown in Figure 40.

The core and the windings comprise a small, stable, transformer-like element. It consists of sets of windings placed over a core material that has been treated to obtain special saturable magnetic properties. The core is a single strip of Permalloy, around which are wrapped primary and secondary windings.

The operation relies on the second-harmonic technique applied to an open saturable core which is oriented so as to be sensitive to the magnetic disturbances in the Earth's ambient magnetic field. A triangular wave excitation current of suitable

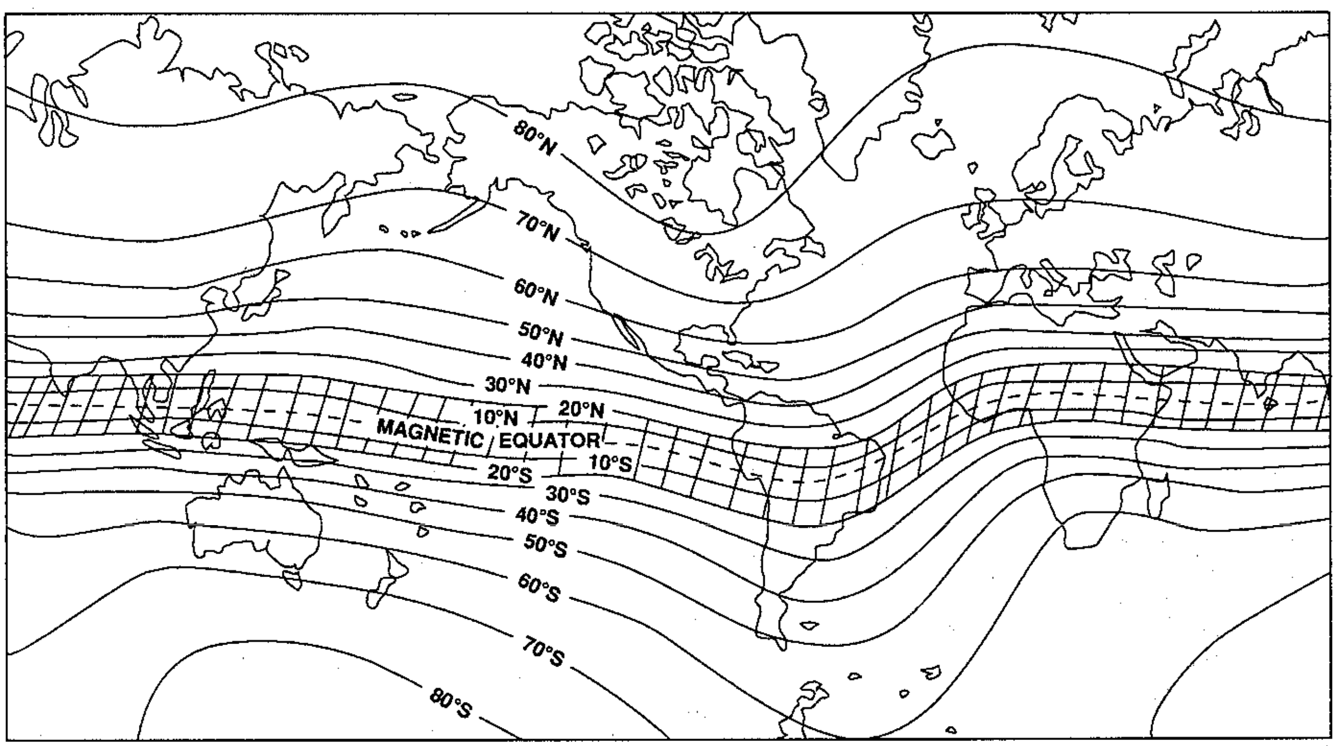


Figure 38. Equatorial belt not suitable for vertical axis magnetometers.

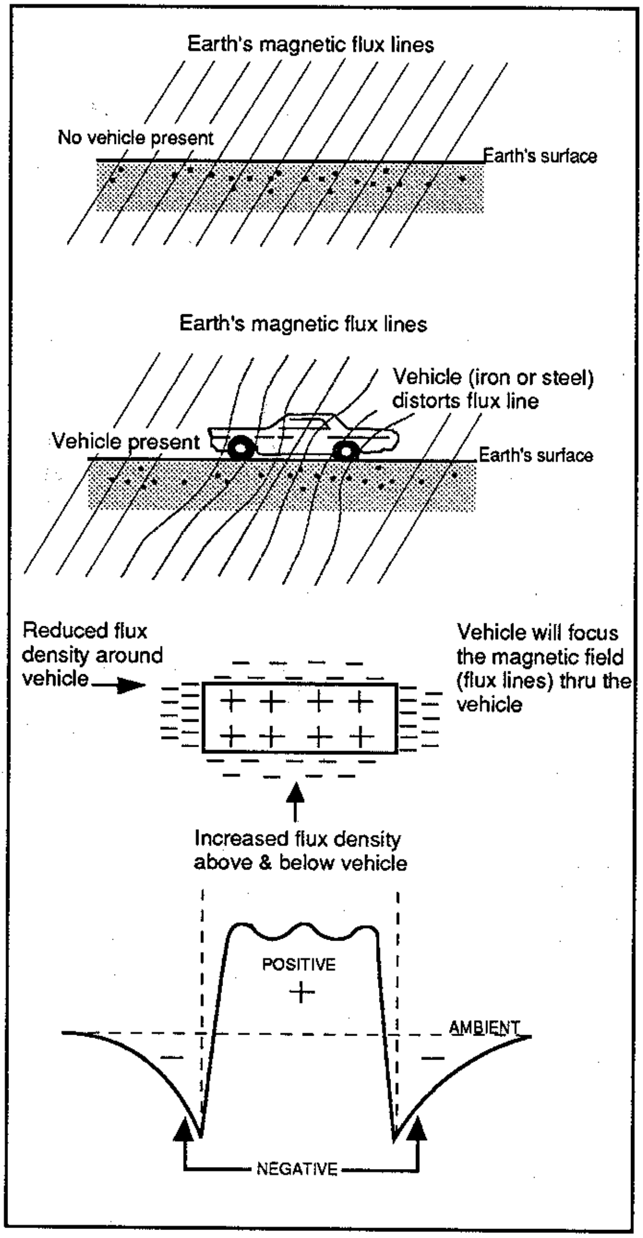


Figure 39. Vehicle's magnetic shadow.

frequency (typically 5 kHz) is applied to the two primary windings connected in series opposition. The secondary windings, which also carry the DC bias to neutralize the ambient field, are connected in series, aiding to supply a second-harmonic signal into the electronic circuit of the detector.

A polyurethane casing is used for abrasion resistance. It also makes the probe impervious to moisture and chemically resistant to all normal motor vehicle petroleum products. If the pavement is soft, the probe may tilt causing a drifting out of tune. A length of PVC pipe can be used to hold the probe vertical.

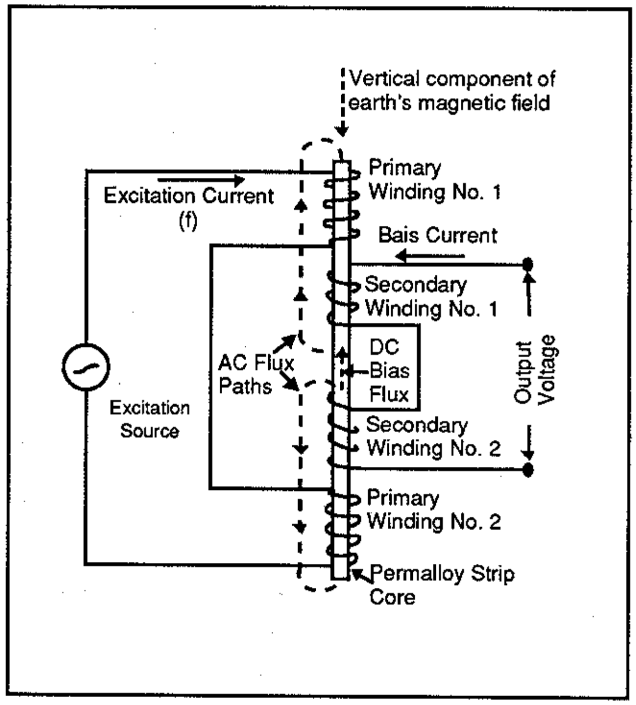


Figure 40. Magnetometer probe components.

OVERVIEW OF MAGNETOMETER DETECTOR SYSTEM

A block diagram of a magnetometer detector system is shown in Figure 41. Provided the ambient magnetic field is stable and exceeds about 16 ampere/m (20,000 gamma), the magnetic shadow cast by a vehicle causes a local field increase of the order of 20 percent and the switch-like action of the magnetic material of the probe causes a signal change several times this figure. The important aspect of this detection principle is its high sensitivity and signal-to-noise ratio.

SENSITIVITY AND THRESHOLDING

Magnetometers are passive devices. There is no radiated "field" or core of detection. Therefore, a portion of the vehicle must pass over the probe.

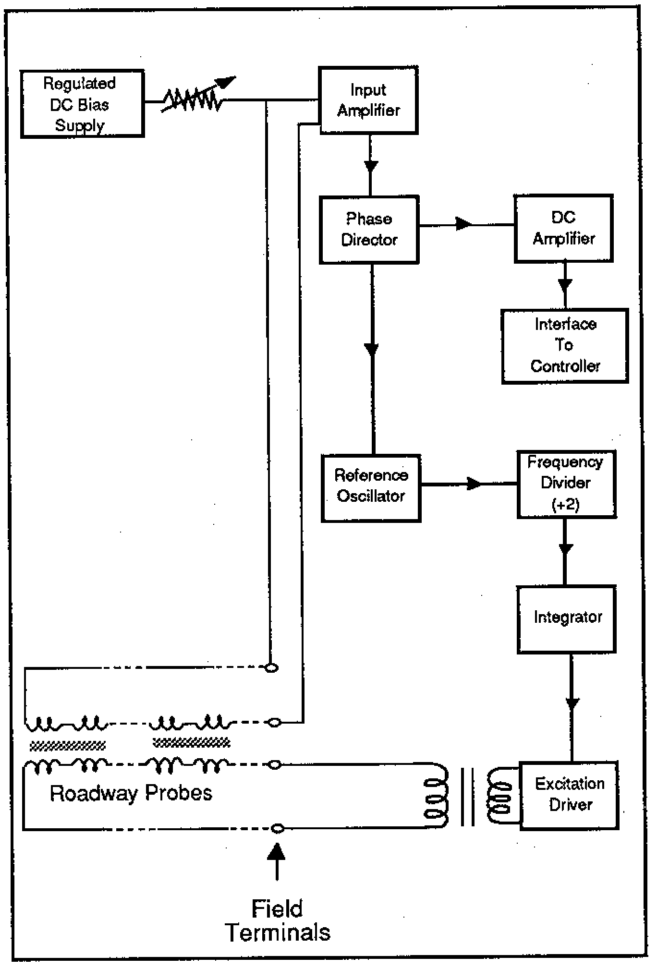


Figure 41. Magnetometer system diagram.

Consequently, a magnetometer can detect separately two vehicles that are a foot apart. This makes the magnetometer better at counting vehicles than the loop detector.

Conversely, the magnetometer is not a good "locater" of the perimeter of the vehicle. There is an uncertainty of about ± 1.5 ft (45 cm). A single magnetometer is therefore seldom used for determining occupancy and speed in a surveillance application. Two closely spaced probes are preferred for that function.

Magnetometers are sensitive enough to detect bicycles. A detection channel is sensitive enough to detect bicycles passing across a 4-ft (1.2-m) span when the channel is connected to two probes buried 6 in (16 cm) deep and spaced 3 ft (0.9 m) apart. They can hold the presence of a vehicle for a considerable length of time, and cannot crosstalk with one another. No motion is required.

As many as 12 probes can be connected in series to one channel of a detector unit. However, the sensitivity is divided among the probes so there is a loss in sensitivity per probe when more than one is used per channel. The unit will detect with a vehicle over one out five probes in the series (20 percent sensitivity on each probe).

ELECTRONICS AND CONTROL

The electronics unit normally includes two complete, independent detection channels with from 1 to 12 series-connected probes on each channel.

The calibration procedures adjust the operation of the electronic unit to accommodate the magnetic environment of the sensing probes. Prior to tuning, a check must be made to assure that there are no vehicles or movable equipment within 20 ft (6 m). A calibration knob for each channel is turned until a pilot light flashes, indicating that the ambient field has been neutralized. Magnetometer detectors do not offer a delayed-call timing feature.

Four operating modes are available. These are selected on the front panel and include:

- **Presence** - Output is maintained throughout the time the vehicle is over the probe. Hold time is unlimited.
- **Extended Presence** - Output is held for a pre-selected time interval of up to 5 seconds after each vehicle departs.
- **Pulse** - A single output occurs during the first 40 ms a vehicle presence is sensed. A subsequent output cannot occur while that presence is maintained.
- **Inhibited Pulse** - Subsequent output pulses are inhibited for pre-selected time up to 5 seconds after each vehicle departs. This eliminates multiple pulses from trailers, etc.

MAGNETIC DETECTORS

The magnetic detector is a simple, inexpensive and rugged device that is useful only for pulse output in traffic-acctuated signal control. These devices are mostly used in the snow belt States of the northeast because of the harsh winters and deteriorating pavements It consists of a bullet shaped detector sensor tunneled under the roadway inside a non-ferrous conduit. The detector consists of a highly permeable magnetic core on which are located several coils in series, each consisting of a large number of turns of fine wire. The motion of a vehicle causes a change in the lines of the Earth's magnetic flux which induces a tiny voltage in the coil which, in turn, is amplified by an electronic unit located in the controller cabinet thus producing a call.

MODEL 232 / 234 MAGNETIC DETECTORS

Specification for the magnetic loop detector, as defined in Chapter 5 of the Type 170 Specification (see Appendix K), applies to three units of the detection system: the sensing element, Model 231; the two-channel magnetic detector amplifier, Model 232; and the four-channel magnetic detector amplifier, Model 234.

Each individual detector channel operates independently with its associated magnetic detector sensing element and shall produce an output signal when a vehicle passes over the embedded sensing element. The solid state amplifier, located in the controller cabinet, is designed to render reliable detection when a voltage is induced in the sensing element by a passing vehicle.

THEORY OF OPERATIONS

Figure 37 showed that the Earth is in effect a large bar magnet with flux lines running from pole to pole. The axis of the coil in all magnetic detectors is perpendicular to traffic flow and has an associated spherical zone of influence.

Disturbed lines of magnetic flux cut the turns of the coil and create an output for as long as the vehicle is in motion through the zone of influence. Minimum speeds of 3 to 5 mph (5 to 8 kph) are required to produce an actuation. Stopped vehicles are not detected, therefore, the magnetic detector cannot be used as a presence detector. However, where simple detection is needed to actuate a traffic signal, a magnetic detector installation can be both economical and reliable.

PROBE CHARACTERISTICS

The magnetic detector probe is simply a coil of fine wires encased in a metal housing. As the device is passive, it creates no field around it. It is only produced as a non-directional, uncompensated detector. There are two types available differing only in their installation requirements. One type is installed below the surface (subsurface mounted) and the other type is installed flush with the pavement (surface mounted).

The subsurface unit is 2 in (5 cm) in diameter by 20 in (50 cm) long and weighs 8 lb (3.6 kg) as depicted in Figure 42. The surface-mounted model is approximately 3 in (7.5 cm) by 5 in (12.5 cm) by 20 in (50 cm) long with the sensing unit encased in a cast aluminum housing. These models are responsive to flux changes over a large area, covering up to three conventional lanes. If the lanes are considerably wider than 12 ft (3.6 m), several probes may be needed if small vehicles and motorcycles are to be detected.

The signal voltage level emitted from the probe must be high enough to avoid being mistaken as noise. On the other hand, the signal level must be a minimum of 0.2 mV into 1,000 to 2,000 ohms to ensure against noise disturbances induced in the installation and wiring by other adjacent electrical circuits. The required sensitivity is such that it should operate on a single cycle of a sine wave of between 0.25 and 1.0 Hz with an amplitude of 2 mV and should operate with a single cycle of 0.1 Hz with an amplitude of 5 mV.

ELECTRONICS UNIT

The electronics unit is essentially an amplifier that is tuned by adjusting the amplification gain to a level sufficient to detect vehicles.

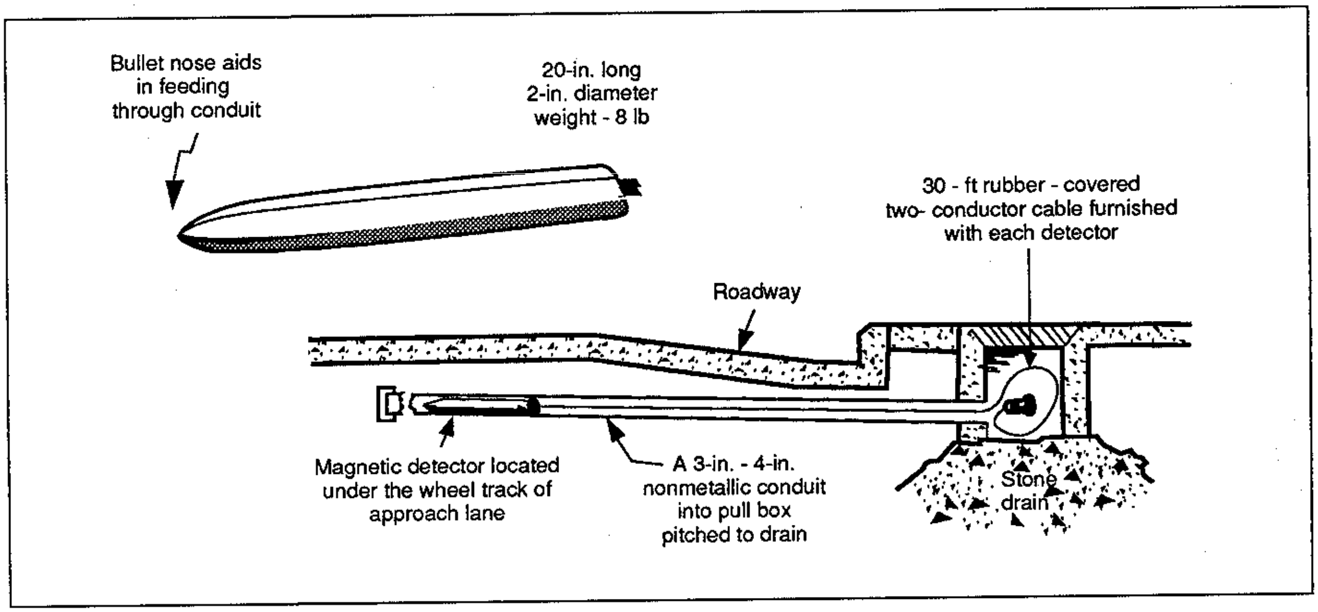


Figure 42. Magnetic detector probe.

3. DETECTOR APPLICATIONS

The application of traffic detectors to various forms of traffic control continues to escalate. Best known for signalized intersection control, use of detectors for additional operations such as ramp metering control, and freeway surveillance and control, is becoming increasingly commonplace. Advances made in traffic control system technology during the past decade are primarily a result of microprocessor usage and advances in electronics. Research and widespread user experience is now available to assist agencies in selecting the most appropriate operational configuration to satisfy their detection needs.

This chapter describes the wide range of choices involving operational features of the detector component of traffic control. Although emphasis is placed on the application of the most commonly used inductive loop detector, applications for magnetometer and magnetic detectors are also considered.

OVERVIEW OF TRAFFIC CONTROL CONCEPTS

Traffic control concepts involving a detection element fall into two general classifications: control concepts for city streets, and control concepts for freeways. To provide a basic understanding of these concepts, a brief overview is presented covering the functional characteristics of detectors, and the interrelationships and interdependence between and among the various traffic control components. For those seeking additional background on traffic responsive traffic control, two standard references are recommended: The Manual of Traffic Signal Design (Ref. 4) and the Traffic Control System Handbook (Ref. 5).

CONTROL CONCEPTS FOR CITY STREETS

Traffic signal control concepts for city streets are primarily involved with signalized intersections, which may be grouped into the following categories:

- Isolated Intersection Control: The flow of traffic is controlled without considering the operation of adjacent traffic signals. (See Figure 43).
- Arterial Intersection Control (Open Network): Major consideration is given to progressive flow of traffic along an arterial and to operating arterial signals as a system. Figure 44 illustrates both an open and a closed network.
- Closed Network Control: Includes a group of adjacent signalized intersections in a network whose operations are coordinated (e.g. the control of signals in the Central Business District (CBD)).

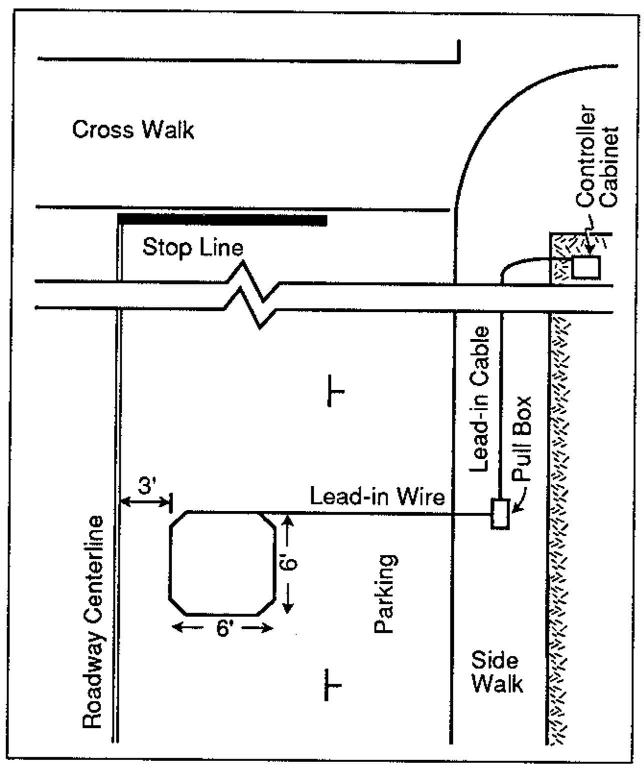


Figure 43. Isolated intersection control.

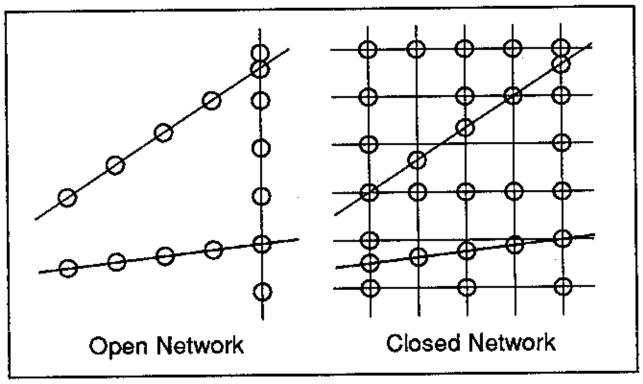


Figure 44. Arterial networks.

- Areawide System Control: Treats all of the traffic signals within an area, a city, or a metropolitan area as a total system. Individual signals within an area may be controlled by isolated, open network, or closed network concepts.

Other signal-related control concepts that may be applied for special functions include:

- Priority Vehicle System Control: Assigns priority for the movement of priority vehicles such as emergency vehicles and buses.

- Diamond Interchange Control: Improves efficiency of freeway diamond interchanges.

Each of these concepts has a unique set of operational requirements, performance objectives, and functional requirements. The hardware and software components necessary to satisfy these requirements are discussed later in this chapter.

CONTROL CONCEPTS FOR FREEWAYS

As originally conceived, freeways were considered as limited access, free flowing facilities with little need of traffic control. The rapid growth in freeway traffic demand and the resulting congestion have led to the development of Freeway Surveillance and Control Systems. These systems are designed to specifically address ramp control, mainline control, and corridor control. The concepts that have been brought to bear on the freeway congestion problem include:

- Restricted Entry (ramp closure, ramp metering).

- Priority Treatment (high occupancy vehicle (HOV) operation).

- Surveillance.

- Incident Management (detection and response).

- Advisory Information (speed, travel time, route guidance, diversion).

For each of these concepts, control principles and parameters have been developed. Each have their own set of functional components. Detectors play an important role in most of these concepts.

FUNCTIONAL DESCRIPTION OF DETECTORS

Most vehicle detectors are used to identify the movement of vehicles past a given point on the road. This information is transmitted to a traffic signal controller, traffic counter, or other device. If a detector is equipped with a directional feature, it will record the passage of vehicles in the specified direction and not that of vehicles in the opposite direction. For locations where vehicular speeds are extremely low, or where vehicles may be standing and the directional feature is not required, a presence detector is generally used.

A passage (motion) detector will record the passage of a vehicle in the detection zone as long as it is moving above 2 to 3 mph (3 to 5 kph). These detectors are used with semi-actuated or full-actuated controllers. To record slow moving or standing vehicles, a presence detector is necessary.

When vehicles are forced to stop or move very slowly in approaching a traffic actuated signalized intersection, it is desirable to use presence detection to assure that stopped vehicles waiting on the detectors will be recorded. Presence detectors do not have a directional feature and cannot differentiate between vehicles entering or leaving the detection zone. However, there is less need for the directional feature as the call is not normally retained in the controller once the vehicle leaves the detection zone. The call will not be retained by passage detectors either, once the vehicle leaves the detection zone. The difference is in controller operation (i.e., whether the controller is in locking or non-locking mode).

For traffic counting, a passage detector is generally used. These detectors can be used to count traffic in individual lanes, lanes in a particular direction simultaneously, or all lanes in both directions continuously. As the number of lanes counted by a single detector increases, the accuracy of the count decreases as multiple vehicles can occupy the same detector at the same time.

Passage detectors are also used for measuring traffic speed and volume. They can record the traffic information in individual lanes, or on all lanes of traffic in one direction. In the past, separate detection equipment and recording mechanisms were required to retain traffic data in both directions. Equipment is now available that will record separately by direction and/or by lane. To obtain accurate vehicle count and speed data, detectors must be located sufficiently in advance of the signalized intersection so that traffic is never backed up to, or over the detection zone. If traffic backs up to the detector, only volume is counted.

Of the three types of detectors (loop, magnetometer, and magnetic detectors), the magnetic detector is the most limited. It can only operate in a pulse mode. That is, the detector produces a short output pulse (100 ms) when detection occurs. Accordingly, it can only be used to detect motion at an intersection approach and as a counting device. Magnetometer and loop detectors can be used to detect either presence or passage. Magnetometers work well for counting vehicles provided that the detection zone is adequately defined. The detection zone for magnetometers is generally less than 3 ft (1 m) in diameter, which can cause some missed detections.

The inductive loop detector is the best type of sensor r detecting vehicle presence. Loop size can be varied to accommodate different applications. For small area detection, the conventional loop and the magnetometer may be interchanged. For motion (pulse) detection only, all three types are interchangeable.

Some schemes for high-speed intersections use conventional loops or magnetometer detectors with normal output. Other designs use detector units that "stretch" or hold the call of the vehicle after it leaves the detection zone (Extended Call Detectors). Still another design incorporates detectors that delay an output until the detection zone has been occupied for a preset period of time (Delayed Call Detectors). These detectors are discussed later in this chapter and in Chapter 4.

LOCAL INTERSECTION CONTROL

The functional requirements of the detector element of local intersection control are primarily based on the operational decisions made early in the design process. The design engineer must first determine the appropriate method of control and the associated operational elements to establish the functional requirements of the hardware (and software) components.

CONTROL MODES

The two basic types of control are pretimed and actuated. Since pretimed control assigns the right of way at an intersection according to a predetermined schedule, detectors are not required. The length of time interval for each signal indication in the cycle is fixed based on historic time patterns. In actuated control, signal phases are not of fixed length, but the right of way is assigned on the basis of actual traffic conditions (vehicle demand) as provided by inputs from the detection element.

There are several types of actuated control. In semi-actuated control, one phase (usually the major street) operates in a non-actuated mode. In this type of operation, detectors are required only on the cross street (and, perhaps, on other minor phases), and is best suited to intersections where the major street has a relatively uniform flow and the cross-street has low volumes with unpredictable peaks.

Full-actuated control is primarily used at the intersection of streets with sporadic and varying traffic distribution. Detectors are required for all phases with each phase timed according to preset timing parameters. Full-actuated control may allow skip phasing (omitting phases when there is no demand), split phasing, overlap timing (allowing nonconflicting phases to operate concurrently), and pedestrian timing.

Volume-density control is a variation of actuated control and provides a complex set of criteria for allocating green time ("Added Initial" and "Time Waiting–Gap Reduction"). This mode can be utilized in both semi-actuated and full-actuated modes. It normally operates on a continuously variable cycle length and requires accurate traffic information to react in time to accommodate existing conditions. Although the "time waiting-gap reduction" aspect of volume density control can be utilized with presence detectors, normally this means that point detectors on volume density approaches are installed far in advance of the intersection (from 200 to 600 ft (60 to 180 m) depending on approach speed).

DETECTION OF PRIORITY VEHICLES

There are a number of situations which require special assignment of the right-of-way at a signalized intersection. For these situations, several forms of priority control have been developed. For the purposes of this discussion, a distinction is made between preemption and priority control.

In this context, *preemption* may be defined as an operation in which the normal signal sequence at an intersection is interrupted and/or altered in deference to a special situation, such as the passage of a train, a bridge opening, or the granting of the right of way to an emergency vehicle such as a fire engine, ambulance, or police car. In *priority* operations, the green is held longer than normal or will go to green as soon as possible in order to provide priority treatment for transit vehicles.

In the case of railroad preemption, train predictors (detectors provided by the railroad) are used to detect the approach of a train and to trigger a control reaction which first clears the track area and then allows non-conflicting green phases to operate during the passage of the train. Preemption for emergency vehicles at an individual intersection depends on an ability to detect individual emergency vehicles, typically by using modulated light. When an emergency vehicle is detected, a special signal control procedure assigns the right-of-way to the emergency vehicle. After a preset time period, the signal returns to normal operation.

In some emergency systems, a green indication is displayed at all signalized intersections along a selected route to be traveled by the emergency vehicle. The right-of-way assignment along the route is accomplished by activating a switch at a central location such as a fire station. In some centrally controlled computerized signal systems, the emergency progression is a programmed feature which operates more efficiently than the manual technique described above.

The essential objective in transit priority control is assigning priority to person movement as opposed to vehicle movement. This can be accomplished in a number of ways such as: exclusive bus lanes, assignment of transit priorities at signalized intersections through signal timing optimization programs (e.g.. TRANSYT 7F), or through bus priority systems.

There are several categories of equipment that may be used for these purposes. The most prevalent type of active system is based on an optical principle as described below.

Light Emitter/Receiver

This system, used for both preemption and priority control for emergency and transit vehicles, is a special purpose high-intensity light detector system. It utilizes a high-intensity light emitted at a specific frequency from a transmitter mounted on the vehicle (a forward-facing white strobe light on emergency vehicles and the same light with an infrared filter on transit vehicles).

The light is programmed to flash a high frequency code to distinguish it from other flashing lights or lightning. A different code is used for the various types of vehicles to distinguish between emergency vehicles which command preemption and transit vehicles that may only receive a priority from the signal controller.

Each intersection to be preempted is equipped with one or more optical receivers, depending on the number of approaches that are to provided with preemption capabilities As the emergency vehicle with the light emitter approaches the intersection, the appropriate directional receiver senses the coded light, triggering the preemption circuitry in the intersection controller. When the light from an emergency vehicle is detected, a signal is relayed to a phase selector (connected to the controller) or directly to the controller. The status of the controller is examined and the controller either holds the green interval for the emergency vehicle or terminates the green on the opposing street(s), thus transferring the green to the direction of travel of the emergency vehicle. The various components of this system are shown in Figure 45.

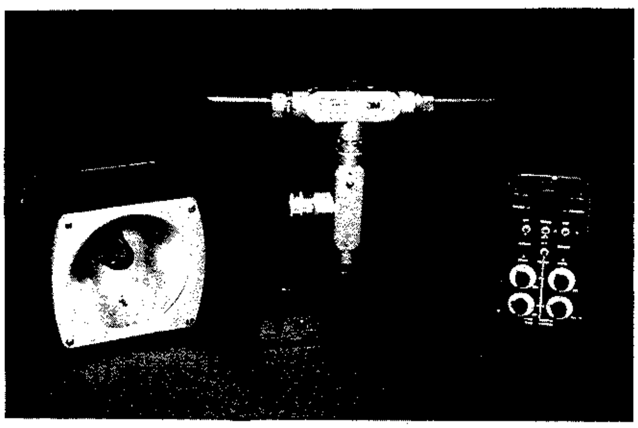


Figure 45. Light emitter/receiver preemption system.

The operation for priority vehicles is essentially the same except that the control function is not preempted. If the signal is green, the controller attempts to hold the green long enough for the priority vehicle to enter. If the light is not green, the controller attempts to bring the phase up as quickly as possible.

This system allows for two priorities so that both emergency vehicles and transit vehicles can use the same intersection hardware. Transit vehicles are equipped with a light emitter with an infrared filter and a different light coding sequence. The electronics at the intersection can differentiate between the two codes, and implement the appropriate preemption or priority sequence.

Vehicle Identification Concept

This concept, introduced in 1989, utilizes a small transmitter located on the emergency, transit, or commercial vehicle; an existing or new loop in the roadway; and a standard detector unit with the addition of a discriminator module. The system recognizes the emergency vehicle and provides a separate output while still operating as a normal vehicle detector. In addition to preemptive and priority control, the system has other applications such as overriding gate control, recognition of vehicles at control positions or gasoline pumps, relating bus passage with schedules, etc.

The vehicle transmitter, shown in Figure 46, is mounted on the underside of the vehicle. It is designed to continuously transmit a unique code that identifies the vehicle. This code is received by any standard loop in the roadway. A special digital loop detector unit detects the vehicle and decodes the vehicle's identification.

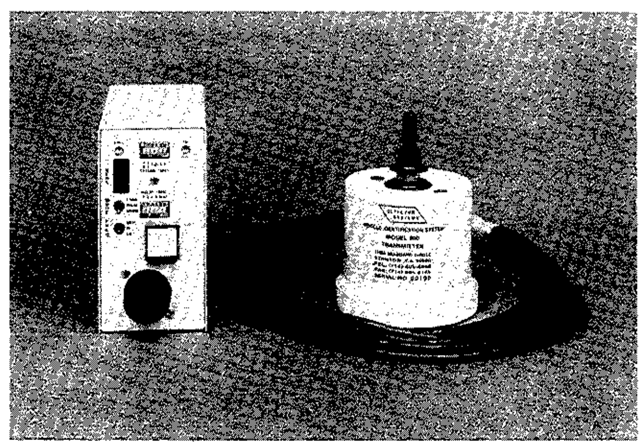


Figure 46. Transmitter and detector unit for vehicle identification system.

Transit Vehicle Signature - Loop Detector

To eliminate the need for equipping priority vehicles with a special transmitter, recent focus has been placed on developing a passive system that would not require a transmitter on board the vehicle. Systems currently on the market consist of a conventional loop buried in the roadway and a specially adapted digital detector unit which provides a unique wave form (also termed "signature" or "footprint") of each vehicle it detects.

For bus detection systems, the digital signal is input to a microprocessor module which analyzes the shape and characteristics of the signature created by the involved vehicle. The signature is then compared to known bus profiles held in the processor's memory. If a bus is identified, an output is generated to provide priority treatment. A block diagram of this system is shown in Figure 47. Typical signatures for various classes of vehicles are shown in Figure 48.

Radio Transmitter/Receiver

Similar in operation to the light emitter system described above, this technique uses a radio transmitter mounted on each emergency or transit vehicle, and a radio receiver at each involved intersection. However, as radio waves are not directional, the system must either include a directional command from the approaching vehicle, or provide limited preemption or priority capabilities (one approach preemption, all-red flash, etc.) and a reduced detection zone to avoid preempting all adjacent signals unnecessarily.

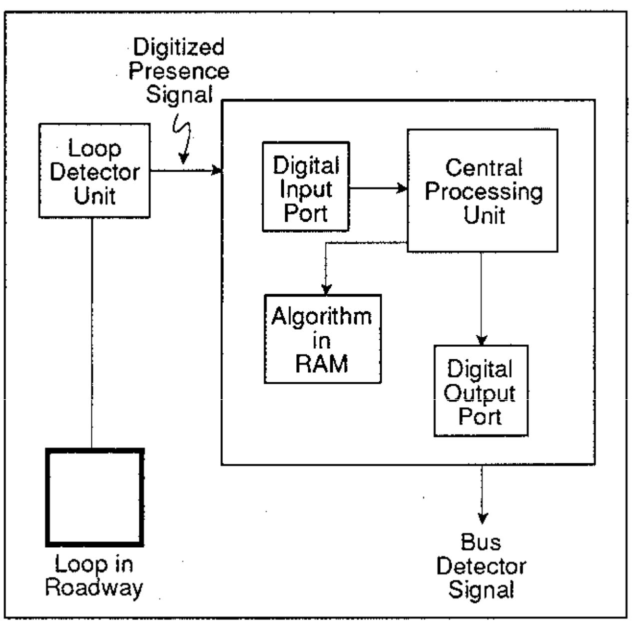


Figure 47. Bus detection system.

One system currently available includes an on-board device to automatically determine the heading of the vehicle, which is then coded into the radio transmission to the signal being approached. By coding emergency and transit vehicles separately, a dual preemption/priority system can be implemented.

SIGNAL SYSTEM CONTROL

Detectors are used as system sensors to acquire the data needed for a number of system functions. In this sense, detectors constitute the surveillance subsystem to provide the traffic flow information for use in computing signal timing for system functions such as critical intersection control (CIC), selecting timing plans, and for both on-line and off-line development of timing plans using optimization programs. A distinction should be made between system sensors (detectors) and detectors used for local actuation. A local intersection detector is connected directly to an actuated controller, whereas the system sensor is connected to the central computer or arterial master.

Typically, system sensors sample traffic at strategic locations. The precise detector type, placement, and configuration of the detector subsystem is dependent upon the variables to be measured and the configuration of the control system. The system may be for the control of arterial streets, closed networks,

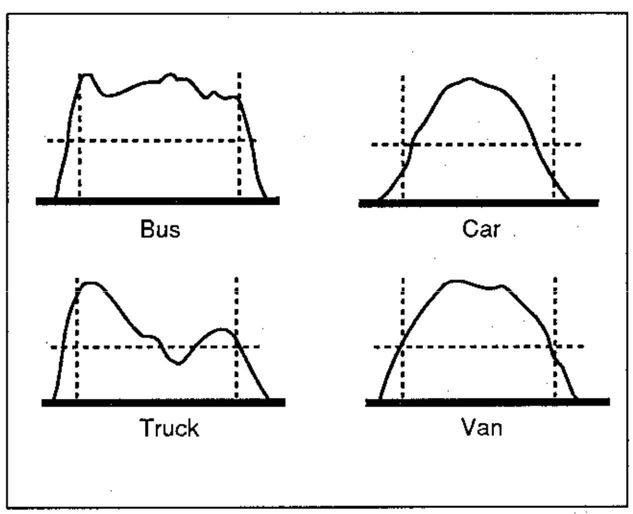


Figure 48. Typical vehicle signatures.

diamond interchanges, or area control. On a per intersection basis, fewer system sensors are used than for local intersection control.

For data acquisition, the loop detector is best suited to computerized traffic signal control because of its reliability, accuracy, and ability to detect both presence and passage. Using these two outputs, a number of variables can be derived with varying degrees of accuracy, such as volumes, occupancy, speed, delay, stops, queue lengths and travel times. These variables are related to either traffic flow along the length of the detectorized roadway or in the immediate vicinity of the detectors.

The most easily obtained quantity is the volume. This quantity is the number of pulses measured during a given time period. That is, a 15-minute volume would be the number of pulses from the detector in a 15-minute period. Occupancy is the percent of time that a detector is indicating a vehicle presence over a total time period, and can range from zero to 100 percent, depending on vehicle spacing.

Volume and occupancy are the most important variables for use in selecting traffic responsive timing plans and for many operating thresholds. In many cases, volume can be used without occupancy. When the intersection approaches saturation, however, volume will level off to a constant value that is proportional to the green time divided by the average vehicle headway, while the occupancy will continue to increase. It generally follows that occupancies of over 25 percent are a reliable indicator of the onset of congestion.

Speed is another useful variable in the on-line or off-line computation of signal timing plans using optimization programs such as TRANSYT. With a fixed volume, speed is inversely proportional to occupancy because the faster a vehicle is traveling, the lower its occupancy. But, since occupancy is the accumulated value of several vehicle presence measurements, the inverse of occupancy must also be divided by volume.

Speed computations typically will be subject to error. For example, vehicles are not all the same length; occupancy measurements also will contain error as the detector output is sampled rather than measured continuously; all vehicles are not properly positioned in their lanes when they cross the detector; and speed measurements are made at a point instead of along the link. A 20 to 30 percent error in speed computations is not uncommon. Newer detectors, operated in pairs, can provide much more accurate speed measurements. Speed detection using two loops is discussed later in this chapter.

The remaining variables (delay, stops, travel time, and queue lengths) are used primarily for the evaluation of system operation and are very difficult to measure accurately. Stops and queues require multiple detectors in each lane to obtain acceptable measurements. The number and location of loops depend on the individual software programs that are being used.

ARTERIAL STREET SYSTEMS

Volume and occupancy are the two basic variables used in arterial street system control. The objective is to adjust signal timing to reflect the major traffic flow. To establish progression along a major arterial, a few system detectors are strategically placed at free-flowing midblock locations. By sampling inbound and outbound traffic conditions, control parameters can be computed by a master supervisory unit. Cross-street approaches are detectorized as they would normally be for local intersection control. The arterial master controller selects a traffic pattern based on measures of directional volume and/or occupancy as measured by the detectors on the arterial street.

NETWORK CONTROL

The type of control specified for network control systems will define the type of data to be acquired by the detector surveillance subsystem. For example, time-of-day control does not require detectors because it is basically a time-clock operation. Conversely, first generation traffic-responsive operation is based on the timely identification of traffic trends within the network and will therefore require, as a minimum, detectorization on the heavily traveled links.

For traffic responsive generation-type plans, detectors are nominally required on all approaches. Criteria for several optimization programs can help reduce the number of detectors while retaining adequate accuracy for preparing on-line signal timing plans. A more definitive discussion of the location of detectors for a traffic-responsive system is provided in Chapter 4.

FREEWAY SURVEILLANCE AND CONTROL

Detectors are generally used in freeway surveillance and control to detect two types of congestion: recurring and nonrecurring congestion. Congestion is termed *recurring* when both the location and time of congestion are predictable such as weekday peak periods. *Nonrecurring* congestion is defined as that caused by random, temporary incidents such as stalled vehicles, accidents, spilled loads, or other unpredictable events.

Recurring congestion results when the traffic demand exceeds freeway capacity. Measures to help reduce congestion involve decreasing peak period demand by managing vehicle activity through such techniques as entrance ramp metering, mainline metering, freeway-to-freeway connection control, and corridor control. Detectors play a major role in alleviating recurring congestion, particularly in entrance ramp metering.

Nonrecurring congestion is more difficult to manage because of its unpredictability. It is obvious that the effects of these nonrecurring events can best be minimized by detecting the incident and removing the cause as quickly as possible.

Incident detection techniques consist of a variety of advanced and/or expensive techniques, including closed-circuit television, aerial surveillance, emergency call boxes, patrols, etc. The lower cost mainline detectors in the lanes are not as effective in incident identification, but are often used to detect the beginning of congestion at off peak hours, which usually indicates some type of incident has occurred. They can also be used to determine the extent of the incident's impact.

This section discusses those techniques using detectors for managing traffic in freeway surveillance and control systems.

ENTRANCE RAMP CONTROL

Controlling freeway ramp entrances is one of the most effective and commonly used methods of limiting the number of vehicles entering a congested freeway during peak periods. Ramp control is generally accomplished through ramp closures (which do not require detectors) and various ramp metering control modes (e.g. pretimed, traffic responsive, gap-acceptance merge control, and integrated ramp control).

The *Traffic Control Systems Handbook* (Ref. 5) provides a comprehensive discussion of the applications, strategies, and methods used in entrance ramp control. The following provides a brief summary of those applications.

Ramp Closure

Closing an entrance ramp during peak period is a simple and positive technique for limiting the number of vehicles entering a congested freeway. It is, however, the most restrictive and least popular with the public. If applied in an inappropriate situation, it could result in under-utilization of the freeway and the overloading of alternative routes. The most effective usage is where the entrance ramp introduces serious weaving or merging problems under congested conditions.

Ramp closure is accomplished with manually-placed barriers, automated barriers, and/or signing. In any case, detectors are not required for this entrance ramp control technique except, perhaps, during the change-over operation of automated barriers.

Ramp Metering

Ramp metering is rapidly becoming an integrated component of freeway surveillance and control systems. Essentially, ramp metering consists of limiting the rate at which traffic can enter a freeway through the use of traffic signals usually located on the ramp just prior to the freeway entrance. A typical ramp meter installation is shown in Figure 49. Metering rates may range from a minimum of 180 to 240 vph to a practical maximum of 750 to 900 vph. When the metering rate is not directly influenced by mainline traffic conditions, the control is referred to as "pretimed control", but this does not necessarily imply the absence of detectors.

Figure 49. Typical ramp meter site (Los Angeles).

Other types of ramp metering control techniques include traffic-responsive metering, gap acceptance merge control, and integrated ramp control.

In a *pretimed system*, depending on the purpose of the control and the strategy employed, the following type of detectors may be used. (These detectors are generally located as shown in Figures 50 and 51.)

- **Check-in (Demand) Detector:** Signal remains red until vehicle is detected at the stop bar on the approach and turns green after minimum red.

- **Checkout (Passage) Detector:** Placed just beyond the stop bar, it is used to assure single vehicle entry by terminating green as soon as vehicle is sensed.

- **Queue Detector:** Placed well in advance of signal, it is used to prevent blockage of surface streets or frontage road by sensing vehicles occupying the loop for a selected period indicating need for a higher metering rate to shorten the queue and clear the blockage.

- **Merge Detector:** Placed in the primary merge area to sense the presence of vehicles attempting to merge into the main freeway lanes.

The pretimed metering system operates with a constant cycle and can be set for single entry metering or platoon metering. Timing may be set to release the desired number of vehicles per cycle. There are a number of documented advantages of this system including reduction in congestion, travel time improvement, providing the driver with a dependable situation, and relatively low installation costs. The major disadvantage is that the system can not respond automatically to changes in traffic conditions. A typical layout of a pretimed, entrance ramp metering system is shown in Figure 50.

Unlike pretimed metering control, *traffic-responsive metering* is directly affected by the mainline and ramp traffic conditions. In this system, metering rates are selected on the basis of real-time measurements of traffic variables indicating the relation between upstream demand and downstream capacity. The same types of detectors are used as defined above. In addition, some systems include detectors used to determine traffic composition and weather conditions to enable the system to account for the effects of these factors on traffic flow. A layout of a traffic-responsive entrance ramp metering system is shown in Figure 51.

Gap-Acceptance Merge Control is another form of entrance ramp control intended to allow a maximum number of vehicles to merge safely from the ramp into the mainline without causing significant disruption to the flow of freeway traffic. The gap-acceptance merge control system does not generally operate with a constant metering rate for a specific control interval, as do the pretimed and traffic-responsive metering systems. Rather, it operates in response to the availability of acceptable gaps in the freeway lane into which the ramp vehicles are to merge.

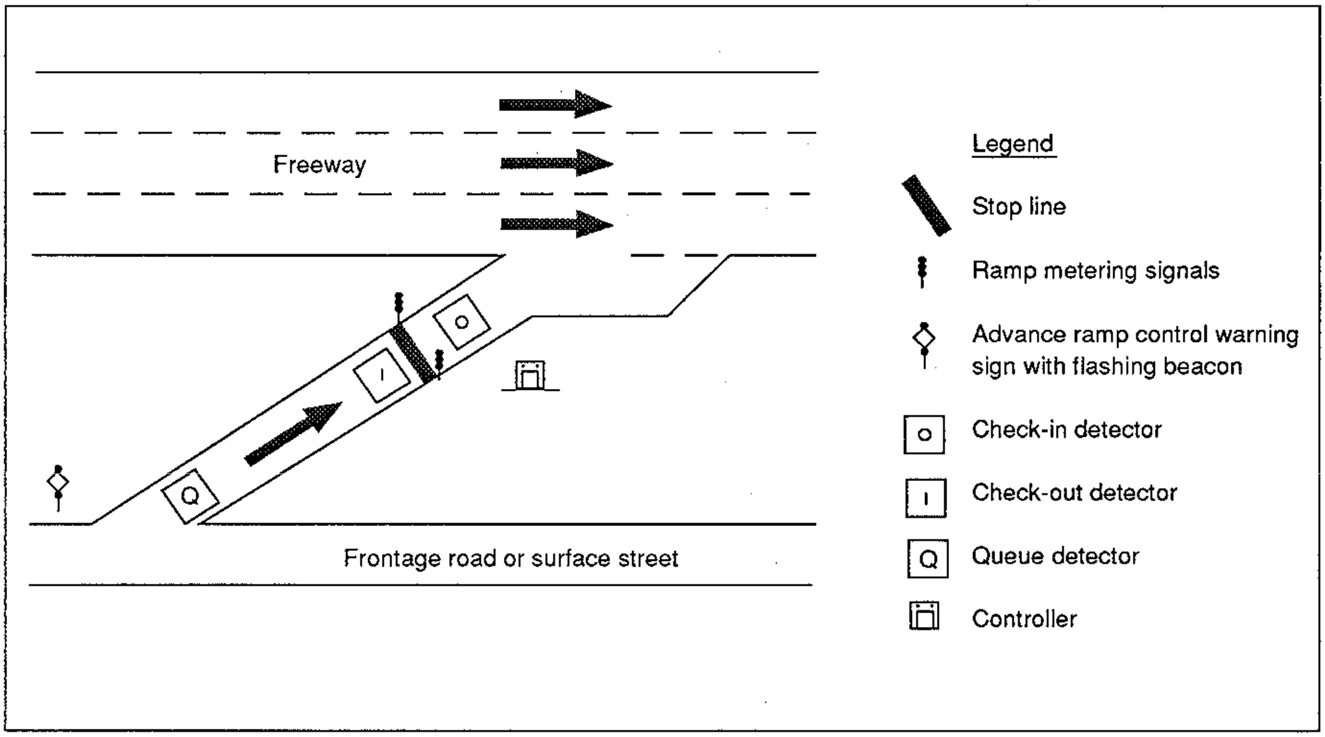


Figure 50. Pretimed ramp metering system.

In addition to the detectors used in pretimed and traffic responsive systems (Figures 50 and 51), a main line gap/speed detector is located in the shoulder lane of the freeway, upstream of the ramp merge area to provide the data necessary to determine presence and approach speed of available gaps. Some systems may include a slow vehicle detector to sense the presence of a slow vehicle on the entrance ramp between the metering signal and the merge detector.

Integrated Ramp Control

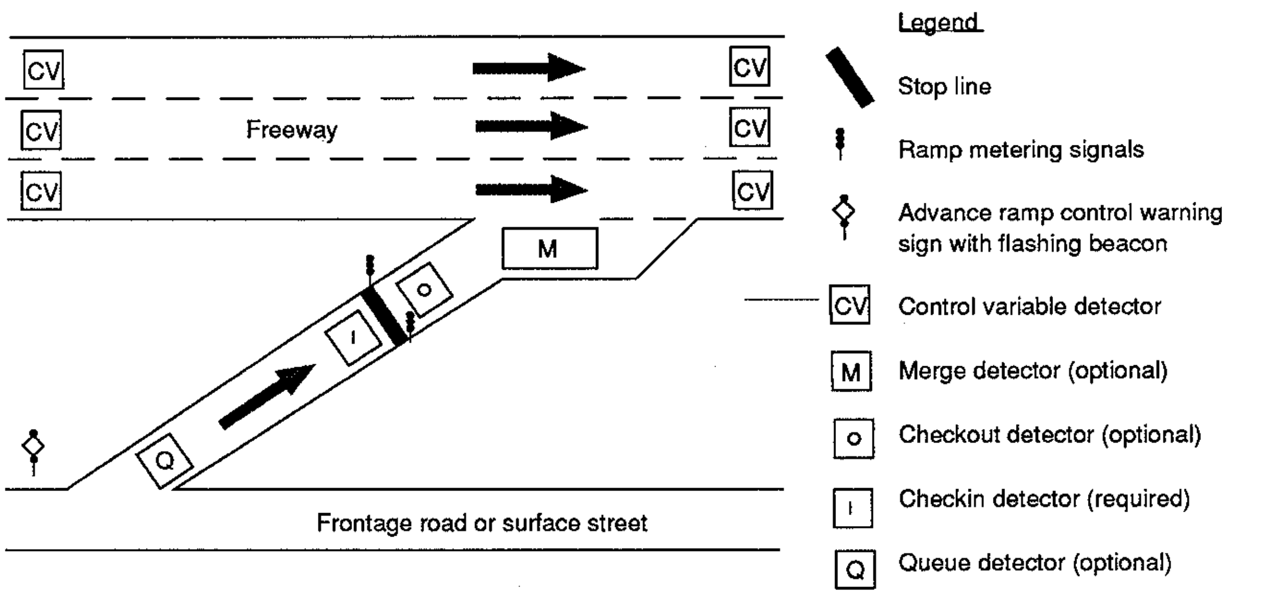
Integrated ramp control, by definition, is the application of ramp control to a series of entrance ramps taking into account the interdependency of the controlled ramps. That is, the control of each ramp is based on the demand-capacity considerations for the whole system rather than on the demand-capacity constraint at each individual ramp.

A significant feature of integrated ramp control is the interconnection among local ramp controllers which permits conditions at one entrance ramp to affect the metering rate imposed at one or more other locations. Real time metering plans are computed and updated by a central master controller, based on freeway traffic information obtained from vehicle detectors (sensors) located throughout the system. A schematic representation of a typical integrated ramp control system is given in Figure 52.

MAINLINE CONTROL

Although considerable interest has been expressed in the concept of freeway mainline control (i.e., actually controlling or metering the through lanes on a freeway), until recently, the application of these concepts in the United States has been limited to a few specialized sites, to research efforts, and to selected demonstration projects. There have, however, been extensive applications of various types of mainline control strategies in West Germany, Japan, and the United Kingdom.

Mainline control usually involves such means as driver information systems, variable-speed control,



Note: For isolated traffic-responsive ramp meter control, a minimum of one CV detector is needed either upstream or downstream of the ramp, but not both. It may be desirable to install two detectors, one in each of the right lanes, to and choose the best for use with ramp meter control.

Complete mainline coverage of all lanes is provided only in interconnected control systems, usually at 2-3 mile spacing.

Figure 51. Traffic-responsive ramp metering system.

lane closure, mainline metering, and/or reversible lane control. Individually or in combination, these control techniques are rapidly gaining acceptance at many highly congested freeway locations throughout the Nation. The role of detectors in these techniques will vary considerably depending on the operational needs and the data requirements.

The basic principle involved in most vehicular detector-based surveillance systems is that changes in the percentage of time that a vehicle is present between adjacent detectors (lane occupancy) are used to sense congestion and to indicate that an incident has occurred. A computer calculates the difference in occupancy between adjacent detector stations. At the end of a sampling period when the occupancy of that period and the preceding sample for the downstream detector exceeds a certain value, an alert is signaled automatically by the computer. Additional information immediately upstream of the incident is then obtained and a judgment decision is made as to what response is required.

One mainline freeway metering system has been in operation since 1978 on Route 94 just before its junction with Route 125 in San Diego, California. Ramps on Route 94 upstream of the junction have not been metered, while the ramps on Route 125 have been metered. To offset this unbalance in upstream control, the mainline lanes on Route 94 are metered.

A gantry which contains a separate signal head for each of the three lanes (two conventional lanes and one HOV lane) is mounted over the roadway. When the system is operating (normally from 6 to 9 A.M.), each signal head turns green to allow one vehicle at a time to proceed in that lane. A passage detector is located immediately downstream of the stop line. As the vehicle is detected, the signal turns red (no

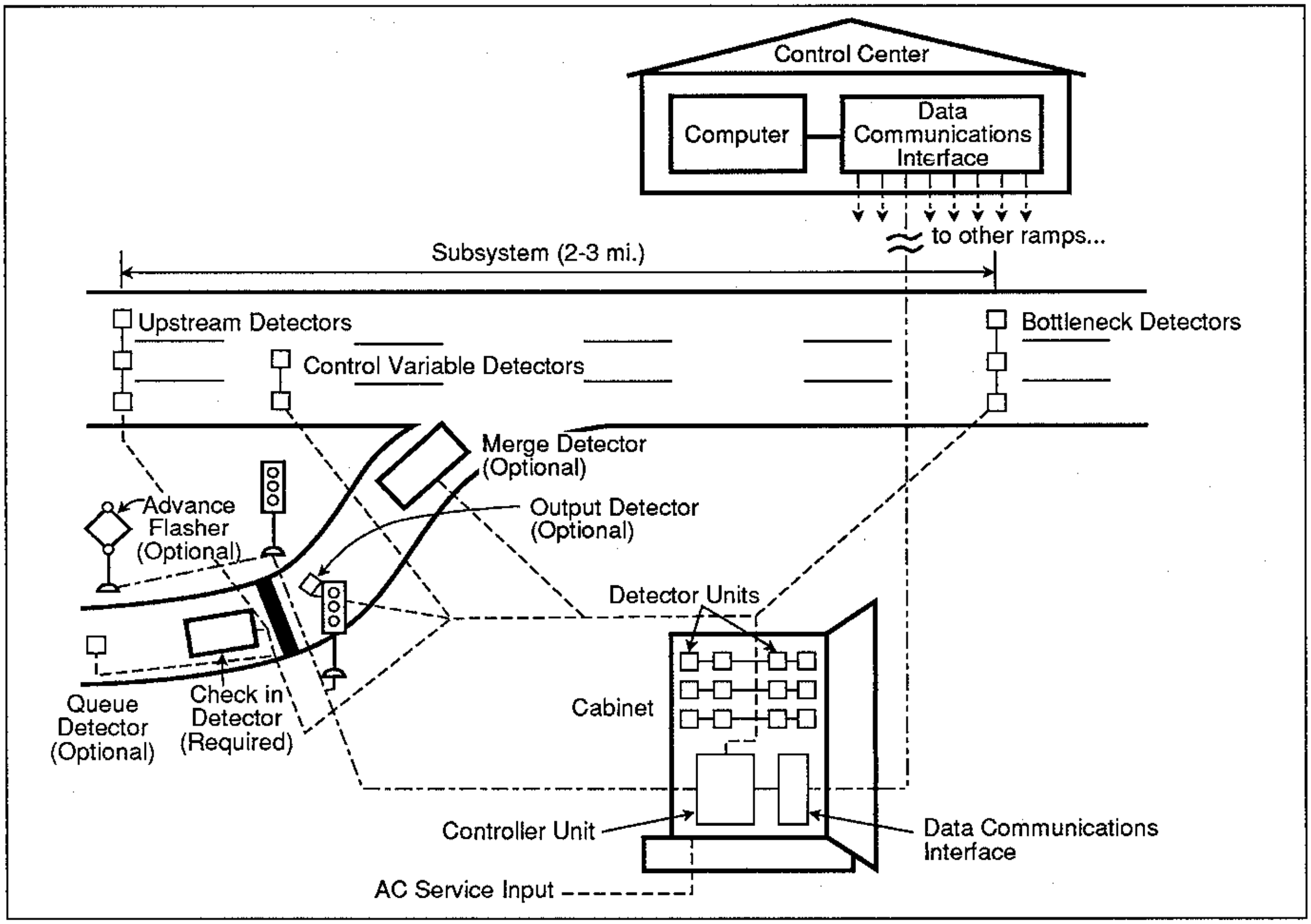


Figure 52. Typical integrated ramp control system.

yellow interval is used during the metering operation, only during startup). The signal then remains red for the remainder of the metering cycle, which is set to achieve the desired flow rate. Extensive signing is placed in advance of the metering station to warn freeway traffic of the unusual event that they are about to encounter.

The metered freeway (Route 94) has no ramp meters upstream of the mainline meters, while the joining freeway (Route 125) does have upstream ramp meters. Therefore, at the junction, one freeway has already been metered through entrance ramp meters while the other freeway is metered just prior to the merge. The system has been operating effectively since 1978 and has encouraged the use of three other mainline metering stations on the San Diego area freeway system.

One of these, located in El Cajon, is shown in Figure 53. Three lanes of southbound State Route 67 are metered as they join westbound Interstate 8. An internally illuminated sign displays the message "Prepare to Stop" during the metering operation. The metering signals are 12-in (300-mm) standard 3-section heads centered on each lane and mounted on a 50-ft (15-m) mast arm.

Another mainline metering station is located on the west bound lanes approaching the San Francisco-Oakland Bay Bridge, a 7-mile (11.2-km) toll bridge across San Francisco Bay in California. This metering station (shown in Figure 54) is located 800 ft (240 m) west of the 17 toll booths and the 2 HOV bypass lanes in the toll plaza. All 19 lanes must be accommodated in 5 lanes on the bridge. During the A.M. peak, one of the toll booths is closed and the lane is

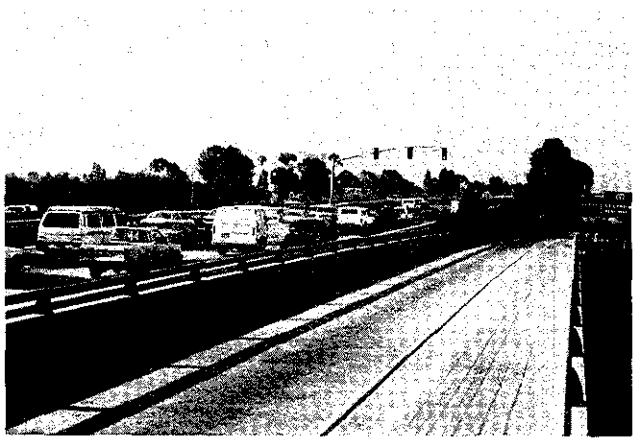


Figure 53. San Diego freeway metering system.

converted to a third HOV lane. The remaining 16 lanes are reduced to 12 lanes at the metering station.

The metering signals, mounted on a gantry, individually control the 12 lanes from the toll booths and allow the 3 HOV lanes to pass freely. Again, the green indications in each lane are terminated as soon as the vehicle crosses the stopline and is detected by a passage detector. Metering rates are kept at a level to maintain smooth flow on the bridge. The meters are only operated during periods of heavy traffic (primarily in the A.M. peak) or when a major incident has occurred on the bridge. There is no need for extensive advance warning prior to the signal gantry because of the proximity of the toll booths. No significant speed is attained by vehicles as they leave the toll booth before they encounter either the signal itself, or the queue backed up from the signal. During off-peak periods, the signals remain green continuously.

Detectors are used in this application to measure volumes and occupancy. which determines whether there is congestion and, if so, activates the metering system. Magnetometers are in place under the upper (westbound) bridge deck which, together with side-mounted infrared detectors, monitor traffic on the approach as well as on the bridge itself. The level of congestion defines the metering rate.

OTHER APPLICATIONS

Detectors are used for a number of applications other than traffic detection at signalized intersections or freeway control. These applications include speed monitoring, traffic counting, vehicle classification, and safety applications. Highly specialized applications, such as detection of vehicles at drive-through fast food, retail, or banking facilities and gate control, are not addressed in this Handbook. These

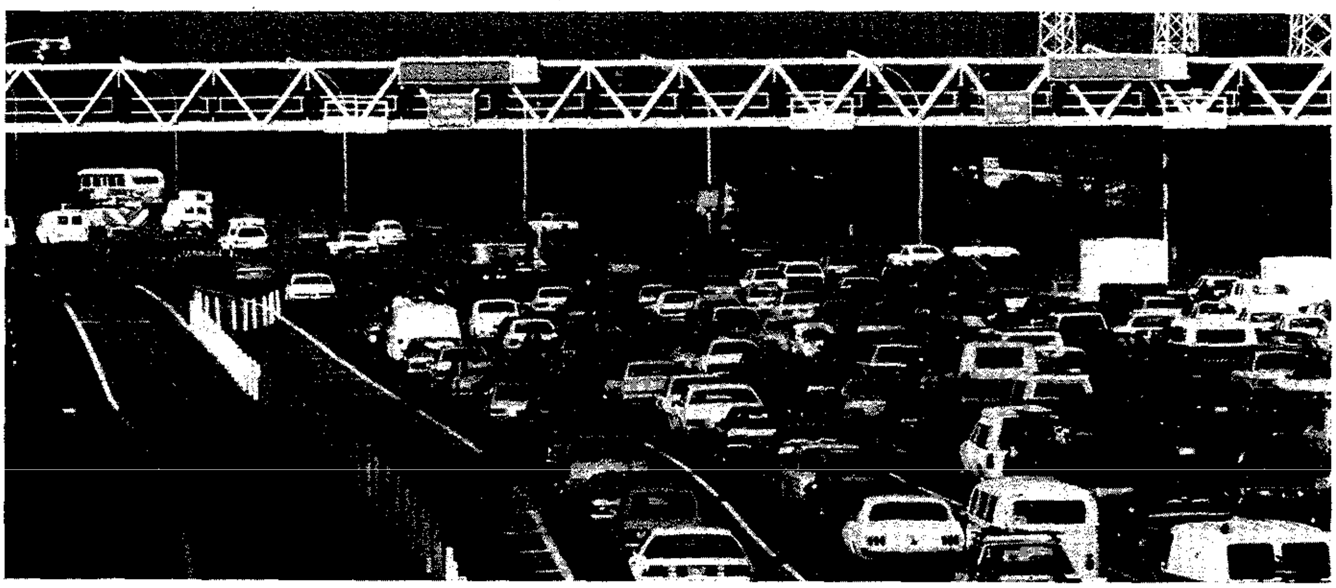


Figure 54. San Francisco-Oakland Bay Bridge metering system.

usages, per se, do not fall under the classification of roadway traffic detection and are used primarily on private property.

SPEED MONITORING

When 55 mph (88.5 kph) became the national speed limit, a study was conducted to evaluate the equipment available for use by the States to certify compliance with this law (Ref. 6). Four different types of sensors were analyzed: the loop detector, pneumatic tubes, piezo-electric cable, and tapeswitches. This study concluded that the loop detector was the best alternative available. It was suggested that the optimum characteristics of a detector unit for vehicle speed measures were:

- Self tuning to reduce drift.
- Short response time from intercept to output.
- High sensitivity without appreciable time delay.
- Consistency of vehicle location at beginning and end of detection, independent of vehicle speed or length of lead-in cable.

When using two loops to measure speed, the loops should be large enough to sense high-body vehicles and to provide a sharply defined wave front output as the vehicle passes over the loop with as little time difference as possible between different sizes of vehicles. The loops should be spaced sufficiently far apart so that any difference in the time of intercept of the two loop detector circuits is small when compared to the time of transit from the first loop to the second loop.

A general rule of thumb that may be applied states that the height of the field to be intercepted by the vehicle is two thirds the distance of its shorter dimension. That is, a 6- x 6-ft (1.8- x 1.8-m) loop would have intercepts of approximately 4 ft (1.2 m) as would a 6- x 100-ft (1.8- x 30.5-m) loop. Both 5 ft (1.5-m) wide and 6 ft (1.8 m) wide loops have proven effective. The choice depends on lane width. A spacing of at least 2-1/2-ft (0.8-m) should be allowed from the center line to the edge of the loop to avoid actuation by traffic in adjacent lanes. In a 12-ft (3.6-m) lane, the 6-ft (1.8-m) loop should be used to ensure no counts are missed.

The spacing between loops for speed measurements is often specified as 16 ft (4.9 m) between the leading edges of two 6-ft (1.8-m) loops. The sensitivity of both detector units must be set for the same value. If this is not done, the point over the loops at which the inductance change reaches the turn-on point (i.e., the response time which is directly related to the sensitivity of the detector) will vary — thereby, introducing an error. In the late 1980's, the attainment of very fast response times at sensitivity levels appropriate for roadway vehicles was made achievable by new electronic component technology. A typical loop placement for speed measurement is diagrammed in Figure 55.

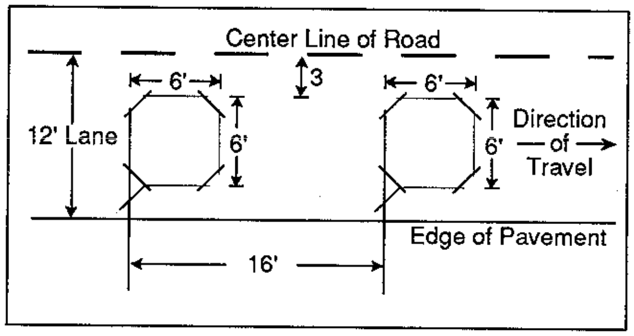


Figure 55. Speed measuring loop placement.

TOO FAST WHEN FLASHING

Speed monitoring, as described above, may also be applied on the freeway system. There can be a considerable safety problem when the design speed for certain curves is below that of other portions of the freeway. To lessen the accident potential at such locations, a system of speed measurement, with a flashing display to alert the driver of an unsafe speed, can be used. That is, if it is determined that a vehicle is traveling faster than the desired (safe) speed, a flashing sign or signal would be activated to advise the driver to reduce the speed of the vehicle (Figure 56).

One system that was evaluated (Ref. 7) used loops spaced 16 ft (4.8 m) apart to measure speed. A display was attached to a bridge structure downstream of the loop to alert the driver. If the vehicle was detected traveling 62 mph (100 kph) or less, only the speed would be displayed. If the vehicle was traveling faster, an additional message "SLOW DOWN" would be displayed along with the speed. The study concluded that a speed detection system can be effectively utilized.

Unfortunately, at one such installation, drivers were observed deliberately accelerating to see how high a reading they could achieve on the speed sign. A potential solution to this problem would be to display speed values only up to the existing speed limit. Any speed above the limit would receive the message "SLOW DOWN" or "YOU ARE EXCEEDING SPEED LIMIT."

PREPARE TO STOP

In many instances, the geometrics of intersections are such that the signal display cannot be seen in time for drivers to react. In addition, there may be sight-distance restrictions due to overhead obstructions such as bridges and large trees which cannot be removed. Intersections located on a downgrade may increase the actual required stopping distance.

Another such situation may exist at vertical curves that may hide the queue at a signal although not obstructing the signal itself. Still another important area of need is locations subject to dense ground fogs that reduce signal visibility below normal minimums.

To alleviate these obviously dangerous situations, additional information may be provided to the driver to assist in determining the best course of action. To modify driver behavior, the information should not be limited to merely warning the driver of the existence of a signal.

A more appropriate response is to provide a changeable message advance warning sign. This type of warning sign could alter the information provided based on whether the driver should slow or proceed. The warning sign shown in Figure 57 is used to warn approaching drivers that a hidden signal around a curve is red and that they must stop.

The criteria used in developing this type of warning system include:

- The sign should be mounted adjacent to the roadway or overhead (at least 17 ft (5.2 m) above the pavement). The lettering should be at least 12 in (30 cm) high with 12-in (300-mm) alternating beacons.
- The legend should read "PREPARE TO STOP WHEN FLASHING."

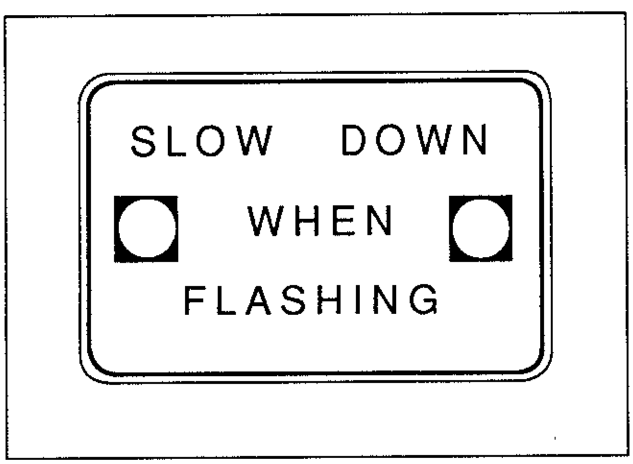


Figure 56. Unsafe speed sign.

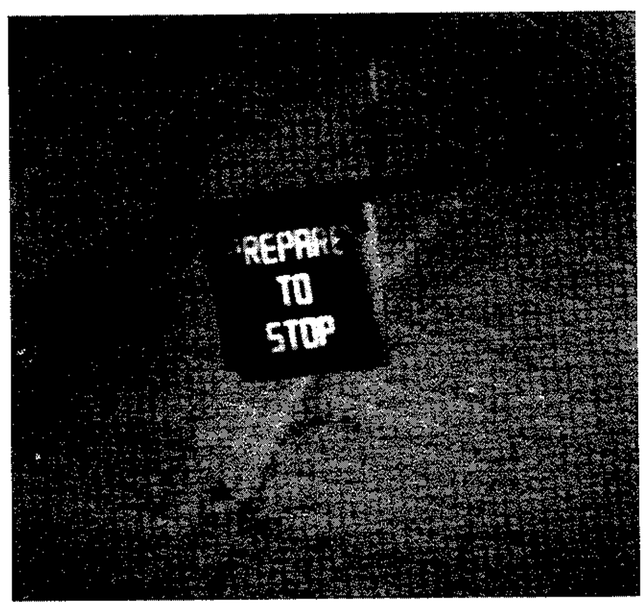


Figure 57. PREPARE TO STOP sign.

- The warning sign message and beacons should begin to flash (50 to 60 times per minute) just prior to the signal display of the yellow change indication so that the driver will observe the signal display just after it has turned yellow. The Last Car Passage feature of some of the early density controllers can be used for this purpose.
- The sign should continue to flash except when the approach signal is green.

With this system, additional control logic should be provided that will ensure safety. That is the sign must go to flash if the signal should fail, be in conflict, or be placed in either a manual or red flashing mode.

When warranted, the use of this type of flashing sign has proved to be an effective solution to the problem of rear-end accidents. When actuated in such a manner that it provides the approaching drivers with accurate information as to whether they will have to stop for the signal, it is a beneficial addition to the signal installation.

TRAFFIC COUNTING AND VEHICLE CLASSIFICATION

In recent years, loop detectors have been replacing pneumatic tubes for counting vehicular traffic. As the tubes are laid over the roadway, they are especially vulnerable to the wear and tear of passing traffic. The buried loops provide a better means of counting. Moreover, should the loop experience a failure, all counting would stop; whereas the tube tends to distort counts prior to failure. Another favorable aspect is that the loop detector will give only a single output for most vehicles, regardless of the number of axles, thus providing a more accurate count.

In addition to conventional traffic counts, a growing number of computerized signal systems are using loop detectors to provide volume data. The data collected by the detectors are output directly to the system computers which control signal timing throughout the system.

Counts by Loop Detectors

When counts are to be made in multiple lanes, it is not appropriate to extend a single loop across the several lanes. If a second vehicle in a different lane moves over part of a loop before the first vehicle has left its part of the loop, only one continuous output will be registered. This could lead to significant undercounting.

When lane discipline is good (i.e., traffic stays in its own lane), a separate loop should be placed in each lane. However, when lane discipline is not very good (i.e., traffic is continually changing lanes), an additional loop should be placed between the lanes as shown in Figure 58. Ideally, the loops should be placed according to the following constraints:

- The widest vehicle will not straddle more than two loops.
- The narrowest vehicle will not pass between any two loops.
- Two side-by-side vehicles must cross three loops.

Figure 58 depicts the three loop layout for a two lane roadway. The logic that would be inserted into the logic model is described as follows (Ref. 8): The operation of loops A or B or C produces one count immediately. Operation of loop A and C together or A, B, and C together produces one count and a second count after a short delay. Basically, the operation of single loops or adjacent pairs (A and B, or B and C) produces only one count, but the operation of A and C together produces the first count followed by a second count a short time later.

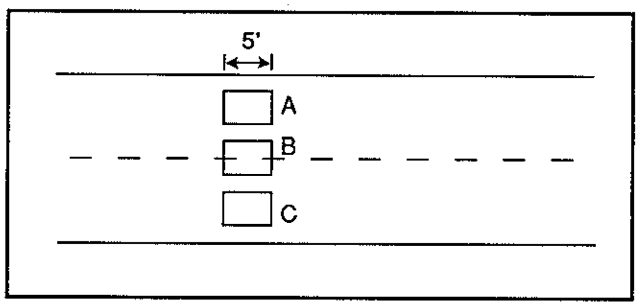


Figure 58. Three loop layout for counts.

Counts Using Long Loops

One manufacturer has introduced a detector which will provide normal detector operation with timing functions (if desired) and will also provide a secondary output of one pulse per vehicle in a single long loop or in a series of sequential short loops. Count accuracy for a single loop of any size is claimed to be greater than 95 percent. Accuracy for the four loops in series is lower because this configuration presents a very complex analysis problem which reduces the count accuracy. This capability may prove to be a major development in loop detector technology.

Directional Detection

When it becomes necessary to distinguish between the direction of travel (such as where two directions of traffic must use the same area of roadway as on a reversible lane), two loops, two detector channels, and a "directional logic" can be used (see Figure 59). With this system, separate counts will be obtained according to the direction of travel. An alternative is to activate the appropriate loops by time-of-day along with the reversible lane control signal.

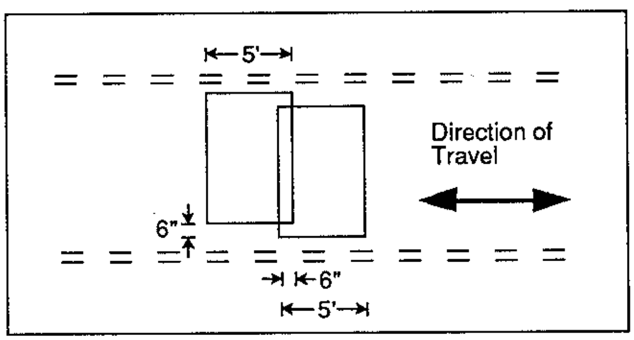


Figure 59. Directional detection.

TEMPORARY LOOPS

Several manufacturers and State agencies have sought to develop a durable and cost effective loop that would satisfy the needs of speed monitoring, vehicle counting, vehicle classification and portable Weigh-in-Motion (WIM) programs. Two types of temporary and/or portable loop systems are described below.

Mat-Type Loops

This type of temporary loop consists of a durable rubber mat into which a multiple turn loop has been embedded. The mats are usually smaller in width than the typical loop installation. Standard sizes vary, ranging from 4 x 6 ft (1.2 x 1.8 m) to 3 x 6 ft (0.9 x 1.8 m). The mats are positioned in the center of the traffic lane with the longer dimension parallel to the flow of traffic so that most traffic will straddle the mat, thereby extending the life of the mat. A typical installation is shown in Figure 60. Nails and washers are typically used to secure the mat to the road surface. A wide, (3-in (7.6-cm)) heavy duty adhesive tape is used to prevent the edges of the mat from lifting. The lead-in wires from the mat to the data collection equipment at the roadside is encased between two layers of tape.

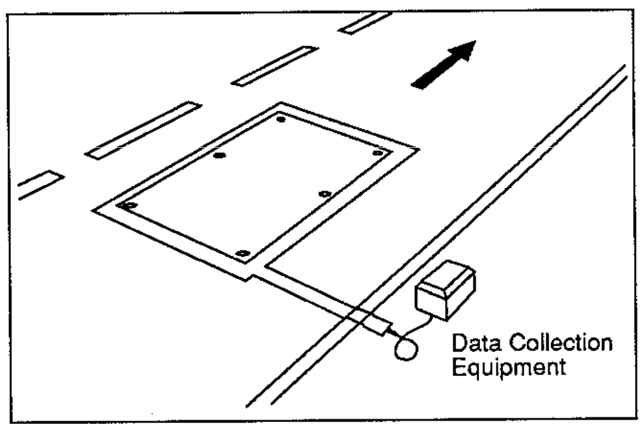


Figure 60. Typical mat type loop detector.

Some agencies have produced this type of system in their own shop. However, hand-producing these mats was found to be too labor intensive to be cost-effective. The mats were reliable, but with heavy truck traffic, some of the mats did not last more than a few hours.

Open Loop Configuration

One manufacturer produces a preformed temporary portable loop that is 4 x 6 ft (1.2 x 1.8 m). The loop is sandwiched with five components. On the bottom, there is a 4-in (101.6-mm) wide paper release sheet to protect the 2–in (50.8-mm) wide strip of adhesive bituminous rubber compound. Its upper surface is finished with a high-density polyethylene film. This padding strip is the bed for three turns of #22 AWG loop wire. An identical 2-in (50.8-mm) padding strip covers the loop wires. The top layer is a 4-in (101.6-mm) wide strip of adhesive bituminous compound reinforced with an overlay of woven polypropylene mesh. This concept is illustrated in Figure 61.

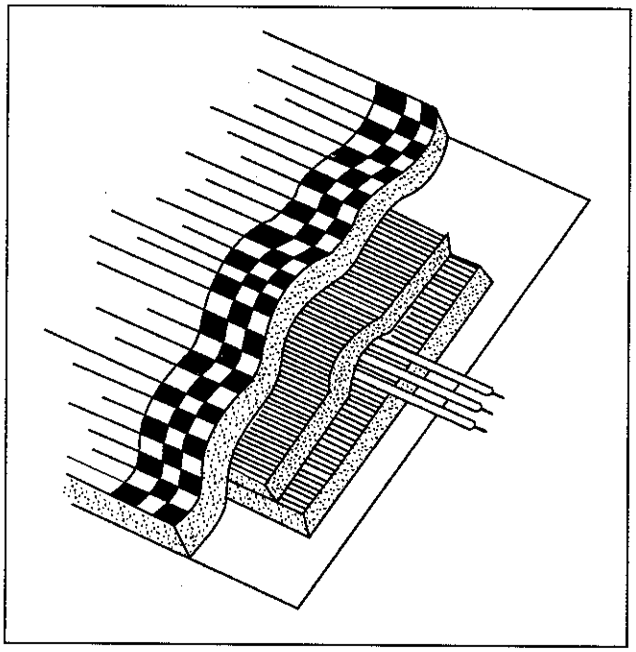


Figure 61. Open loop temporary detector.

The preformed, open loop configuration can be transported to the selected location and installed by one man in a few minutes. The bottom backing is removed and the loop is positioned on the roadway with sufficient pressure to ensure adhesion. Five feet of protected lead-in wire is standard. Omensions and protected lead-in lengths are available.

Another approach to the open loop configuration has been developed by the Special Study Section of the Nevada Department of Transportation (Ref. 9). The Nevada DOT previously used a 6- x 6-ft (1.8- x 1.8-m) portable loop constructed of three turns of #14 gauge stranded copper wire wrapped with black duct tape. Problems with durability and maintenance became very time consuming as the use of the portable loops increased. This led to the testing of a variety of materials to replace the duct tape covering of the original loops, such as several types of tape, rubber tubing, and a rubber mat material.

The material finally chosen was a bitumen tape manufactured by Polyguard Products. It is a fabric-reinforced rubber-like material with one adhesive side. The final configuration consists of four turns of #14 AWG copper wire, wound in the shop, and taped together for easy handling The loops are encased in two wraps of the polyguard material and installed as shown in Figure 62.

A number of tests were conducted to test the durability and accuracy of the loops as compared with conventional loops installed in saw cut slots. Other tests compared the 4- x 6-ft (1.2- x 1.8-m) configuration to the 6- x 6-ft (1.8- x 1.8-m) configuration. The test loops were installed on a rural two lane FAP roadway with a high percent of multiple unit trucks. Both series of tests used the same counter/classifier recorder.

After almost 5,000 actuations, it was found that there was less than 1 percent difference in the number of vehicles counted by this type of portable loop as compared to the saw-cut installed loop. It was also found that the 4- x 6-ft (1.2- x 1.8-m) loop

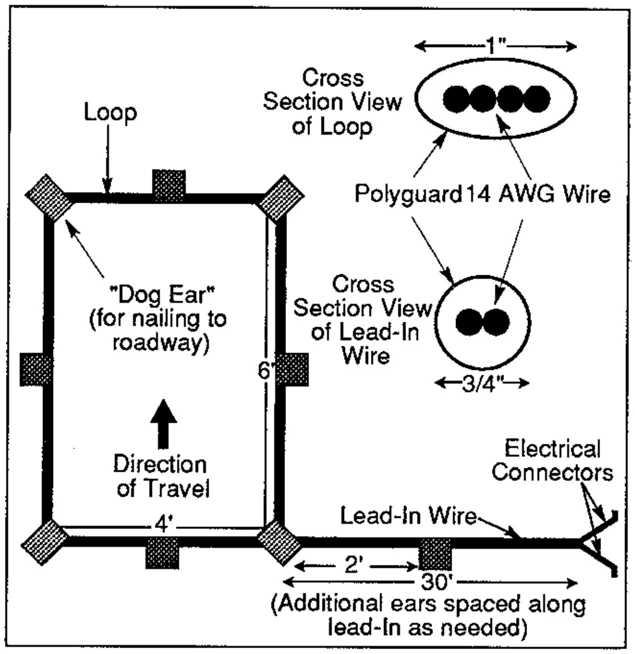


Figure 62. Portable loop installation.

size performed virtually the same as the 6- x 6-ft (1.8- x 1.8-m) size whether the loop was in a saw-cut or in the portable form.

A product durability test was conducted for over a year and after over a million activations, the portable loops are still functioning. The test, conducted on U.S. 395 between Reno and Carson City, Nevada, has shown the loops to be extremely durable and capable of withstanding a wide range of weather conditions. It should be noted that the roadway at this location has an asphalt surface and, after several months, the loops became embedded in the pavement, which may have contributed to their longevity. On a concrete surface, these loops are expected to last well past one-half million activations. The loops have also been used with overlays and were able to withstand the heat involved in this process.

Also of note is that these loops were tested in a semi-permanent situation and were not subjected to repeated removals and reinstallations which may also have affected their longevity. However, other loops of the same type have been repeatedly installed without sign of undue wear. As a result of these tests and the experience with these loops, the Nevada DOT is now using the polyguard loop in all of their portable loop installations.

Vehicle Classification Devices

As part of the traffic counting process, many agencies wish to obtain vehicle counts by class of vehicle. There are several vehicle classifications counters commercially available. Most of these devices use loops and axle detectors to obtain the information required to classify vehicles.

One relatively new product that is capable of counting and classifying vehicles also monitors and reports weather conditions. The road unit of this system consists of an electronic sensor, a high-speed microcomputer and a weather monitor to measure surface temperature, wet or dry pavements, and visibility. The electronic sensor operates by detecting small disturbances in the energy field which are then processed by the high-speed microcomputer. As the vehicle passes over or near the road unit, a real-time record is made of the vehicle's profile throughout its entire length. When the vehicle is detected, a count is made and speed is calculated. Knowing the speed, the computer then calculates the length in determining the class of vehicle.

When the device is removed from the roadway, data from the unit is optically transferred to a Interrogator-Programmer (IP) which can store 32 bytes of data. After the data are retrieved from the road unit, the data may be transferred to a printer, to a PC computer, or over a telephone modem to the central office (Ref. 10).

PEDESTRIAN DETECTORS

The applications described above all involve the detection of various types of vehicles. However, properly timed actuated signal control also requires the detection of pedestrians. Unlike vehicles, pedestrians do not change magnetic fields or cause inductive variations. Moreover, pedestrians cannot be depended on to follow a specific path toward their intended direction of travel, nor can they be expected to take a specific action to make their presence known to the signal controller.

The push-button detector is the most common form of detection used for pedestrians (see Figure 63). The detector is actuated by a pedestrian pushing the button which causes a contact (microswitch) closure.

Figure 63. Passive pedestrian push button.

This closure allows a low-voltage current to flow to the controller to register a "demand" for pedestrian service.

The weak link in the pedestrian push-button system is the pedestrian. The pedestrian push-button requires a specific action to be taken to register a demand. Unfortunately, many pedestrians do not make the necessary effort and, in those cases, are likely to cross the intersection illegally and/or unsafely.

Many pedestrians do not realize that pushing the button will extend their green time as well as servicing their needs faster. Where two buttons for crossing in different directions are located on the same support, care must be taken to clearly indicate the button's relationship to each crosswalk. Although the Manual of Uniform Traffic Control Devices (MUTCD) specifies a series of standard signs for use with pedestrian push-button devices, many agencies augment these standard signs with additional instructional signs.

Active pedestrian push buttons have been used in the past and are common in Europe. These devices provide a response when activated by turning on a small light (usually green) or illuminating a small sign that flashes the message "WAIT PLEASE" or "WAIT FOR WALK." An example from England is shown in Figure 64. Such a response is a confirmation of the pedestrian's call for service similar to that of an elevator button. When used, this type of pedestrian pushbutton appears to alleviate pedestrian anxiety and promotes understanding of the pedestrian phasing of the traffic signal.

When push buttons are used by visually impaired pedestrians, some type of guiding device can be used to enable the pedestrian to locate the button. Texturing the concrete on the sidewalk approaching the push-button, audible locators, or handrails can be used for this purpose. Audible signals are sometimes used at such locations, with distinctive sounds (e.g., bird calls) for each walk indication.

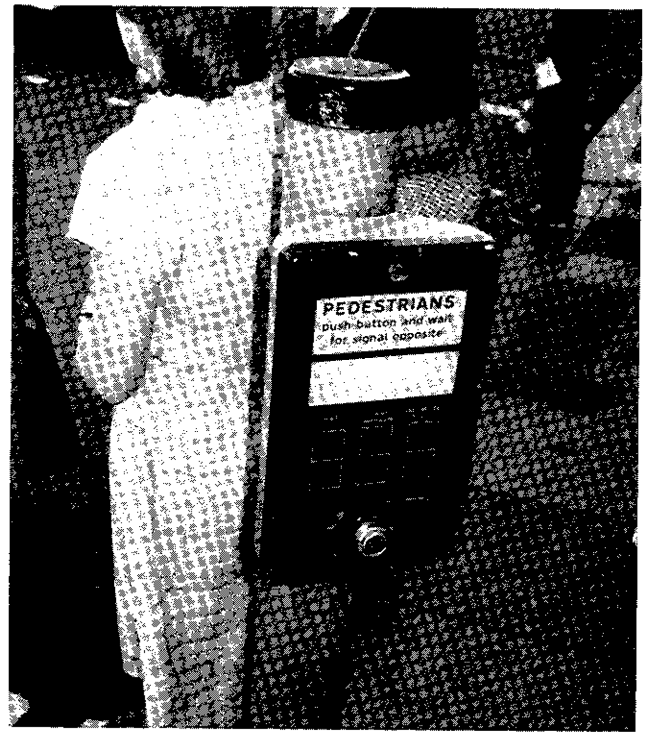


Figure 64. Active pedestrian push button.

Recent developments in microwave technology indicate that an effective presence detector for pedestrians may be viable. A sensor using this technology is installed overhead or in a sidefire position and is designed to detect the continuous presence of an object (i.e., a pedestrian) within its detection field.

Pressure mats similar to those used in automatic doors have been used in some locations to detect pedestrians. These mats are installed on the sidewalk near the end of the crosswalk in the path of approaching pedestrians. When a pedestrian steps on the mat, a continuous contact switch is closed relaying the pedestrian call to the controller unit. The mats are non-directional; consequently, if a pedestrian exiting the crosswalk steps on the mat, an undesired false call will be registered. A guide rail system can be used to alleviate this problem.

4. DETECTOR DESIGN

This chapter will focus on design considerations in terms of detector size, shape, and location for various applications and configurations. It is intended to provide guidelines for traffic engineers involved in developing plans and specifications that include detection for local intersections, traffic signal systems, and freeway surveillance and control systems. Although the primary emphasis is placed on inductive loops as they are the predominant type of detectors in use today, magnetometer and magnetic detectors will also be addressed.

The first step in the design process is to determine the type of detector suited for the purpose at hand. Some agencies have predetermined policies or standard plans. These standards have been developed based on various selection criteria. Unfortunately, many of these standard plans have not been updated to reflect recent improvements in technology. Where standard plans are not requisite, or are not available, the following criteria may be used as a guideline for selecting the type of detector.

SELECTION CRITERIA

The decision as to whether a particular detector is appropriate for a specific purpose depends on its operational characteristics, its adaptability to the particular application, the location-specific details of the installation requirements, and the acceptability of the maintenance burden it will impose. Each of these criteria, separately and in combination, should be carefully examined and evaluated in this decision process.

SELECTION BASED ON OPERATIONS

The operating theory and concepts as described in Chapter 2 indicate that the three principal types of detectors (loop, magnetic, and magnetometer detectors) are inherently unsuitable for certain applications. For example, magnetometers cannot be used with NEMA controllers where delayed-call capability is required, since this feature is not available in magnetometers. (Note: In Type 170 controllers, timing is done by the controller, therefore, magnetometers can be used.) Magnetic detectors must be excluded from consideration for operations requiring presence detection because the magnetic detector is only capable of detecting a vehicle in motion (passage detection).

Loop detectors are not always appropriate for some uses in traffic signalization. For example, a design that requires detection of over-saturated flow and/or long queues may not appropriately use long loops. Loops are more applicable than other forms of detection for freeway surveillance and control where the size of the field must be closely controlled and the times required for output, pick-up, and drop-out need to be predictable.

SELECTION BASED ON APPLICATION

The choice range of detectors for specific applications is further narrowed by the practical uses of the three major types of detectors. In theory, both the loop detector and magnetometer are suitable for large area detection on an approach to a signalized intersection. The loop detector, however, is significantly less expensive. Conversely, for an approach where it is not important to screen out false calls for the green (i.e. right turns on red) and only rudimentary traffic detection is adequate, any of the three may be installed, but the magnetic detector might be chosen first for its ruggedness and low cost/useful life ratio.

SELECTION BASED ON INSTALLATION

In the 1960-70's, it was common for large cities such as New York or Atlanta to select radar or ultrasonic detectors because they could be installed on a suitable pole already in place and not disrupt traffic or break the pavement. A crew could install one of these in about 45 minutes. Although these particular types have fallen into disuse, ease of installation is no less important. However, recent developments in electronics have encouraged a new interest in above ground detectors.

Today, users are more alert to the possibility of eliminating a saw cut or by replacing it with a drilled hole. The problem with deteriorating pavements has produced more interest in installing preformed loops, microloops, or pavement slabs with detectors in place. Another technique is the placement of preformed loops or prewound loops in conjunction with repaving. Chapter 7 details some of the new approaches to simplifying installation and new detectors that do not disturb the pavement.

SELECTION BASED ON MAINTENANCE

Most traffic engineering agencies are aware of the cost differences in maintaining various forms of detectors (See Chapter 6). For example, the magnetic detector, with its limited application, has managed to retain some popularity largely because of its ruggedness and long life with minimum maintenance. The advances in loop detector electronic units have resulted in improved reliability to the point where the loop sensor (the wire loop in the pavement) and problems with its installation remain the primary sources of failure. The thrust toward more rugged loop detector installations is testimony to the need to reduce maintenance costs in terms of frequency of failures and resulting maintenance calls.

DESIGN CONSIDERATIONS

The type of timing intervals of the intersection controller have an explicit relationship to the detection techniques employed and should be selected early in the design process. The following discussion is intended to provide a general structure and background for subsequent chapters. Specifically, it defines the various timing parameters, the effect of short loop and long loop configurations, and the detection alternatives for low-speed and high-speed approaches.

TIMING PARAMETERS

Normally, in an actuated phase, there are three timing parameters in addition to the yellow change and all-red clearance intervals. These are the minimum green (also known as initial interval), the passage time (also called the vehicle interval, extension interval, or unit extension), and the maximum interval (Ref. 4). The relationships among these intervals is shown in Figure 65. These intervals are timed as a function of the type and configuration of the intersection's detector installation.

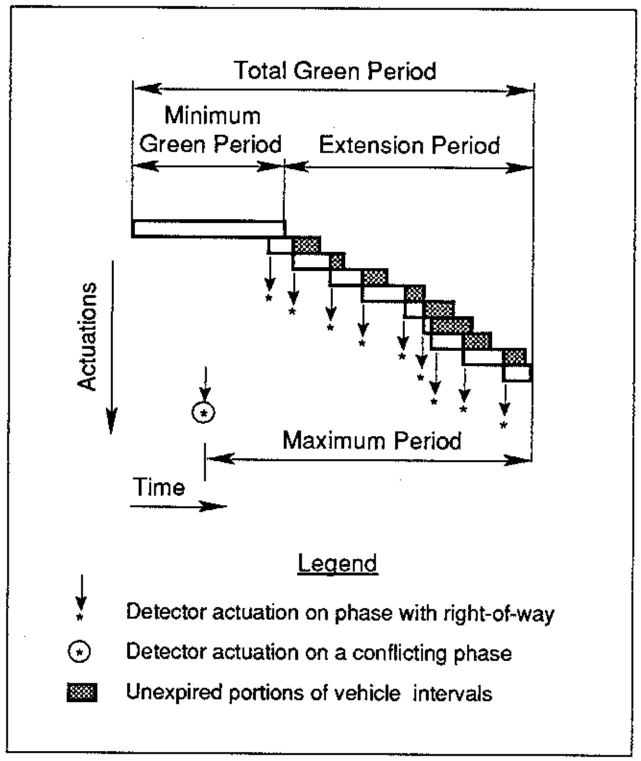


Figure 65. Actuated controller intervals.

Minimum Green Interval

In the early stages of detector technology, most detectors were "point" detectors and consisted of treadles or pressure plates in the roadway. Today's 6- x 6-ft (1.8- x 1.8-m) loop detector is also a form of point detector. When point detection is used, the minimum green interval is established to allow vehicles stopped between the detection point and the stop line to get started and move into the intersection. Table 10 shows the minimum green interval for various distances from the stop line. The data are based on an average vehicle headway distance of 20 ft (6 m) and the average times for vehicles from a queue to enter the intersection.

Table 10. Minimum green vs distance.

Distance Between Stop Line and Detector		Minimum Green
Feet	Meters	Seconds
0 to 40	0 to 12.2	8
41 to 60	12.5 to 18.3	10
61 to 80	18.6 to 24.4	12
81 to 100	24.7 to 30.5	14
101 to 120	30.8 to 36.6	16

A different timing approach is used to establish minimum green intervals for presence detection. When long loops (or a series of short loops) which end at the stop line are used, the initial interval is set as low as zero seconds for "snappy" response for left-turn phases or possibly longer for through movements where driver expectancies may be for a longer green. If the loop ends some distance from the stop line, this distance is used to calculate the interval time in the same way as for point detection.

Passage Time Interval

The passage time interval is timed to permit a vehicle to travel from the detector to the intersection. This is particularly important where point detectors are used and are located some distance from the stop line. The passage time also defines the maximum apparent time gap between vehicle actuations that can occur without losing the green indication to a call waiting. As long as the interval between vehicle actuations is shorter than the passage time, the green will be retained on that phase (subject to the maximum interval described in the following section).

The apparent time gap in a single stream of vehicles passing over a loop detector is somewhat shorter than the actual time gap. A vehicle activates the loop upon entry over the loop and the loop does not deactivate until the vehicle leaves the loop. The true time gap is reduced by the time it takes the vehicle to traverse the loop.

Another factor to be considered in determining an appropriate vehicle interval is the number of approach lanes containing detectors. Detectors for the same phase and function installed in adjacent lanes are often connected to the detector amplifier by means of a single lead-in cable. This may present a distorted representation.

Current NEMA controllers (identified as "Advanced Design," "Exceeds," or "Beyond" NEMA Controllers) have a predefined minimum green time. If no further actuations occur, the minimum green is the total green. If, on the other hand, there are further actuations, the passage time interval extends the green until a gap exceeds the passage time or the maximum green time is reached. The relationship of these elements was shown previously in Figure 65.

When long loops are used in approaches, especially when used in left turn bays, the minimum green and the passage time intervals are generally set to zero or near zero. The long loop operates in the presence mode and the controller continuously extends the green as long as the loop is occupied. The critical gap is not a preset value, but is an equivalent space gap equal to the length of the loop. In other words, no following vehicle has entered the loop prior to the departure of the previous vehicle.

When a series of short loops is used, the series acts as a single long loop, provided that the space between loops is less than the length of a vehicle. If the spacing is greater than the length of a vehicle, a short vehicle interval can be used to provide the same effect as a single long loop.

Maximum Green Interval

The maximum green interval limits the time a phase can hold the green. The maximum green begins timing at the first call received from an opposing (or conflicting) phase. Ordinarily, maximum intervals for through movements are set between 30 and 60 seconds. When the signal is properly timed with appropriately short passage times (vehicle intervals), the maximum interval will not consistently time out unless the intersection is badly overloaded. Some actuated controllers are capable of providing two maximum intervals per phase. This allows longer maximums to be used during peak periods (or shorter maximums for selected phases) when very heavy traffic flows are expected on the major street.

Volume Density Mode

Volume density phases have more timing parameters than are used in the standard actuated phase. For this type of operation, detectors are generally placed further back from the intersection, particularly on high-speed approaches. The value of the minimum green interval, as described above, can be increased to provide longer initial green times for those instances when the minimum green is not adequate to serve the actual traffic present. The variable initial is governed by three settings—the Minimum Green, Seconds per Actuation, and Maximum Initial. The procedure is illustrated in Figure 66. This variable initial interval is provided as defined in the NEMA Standards (Ref. 1) summarized below.

> *"In addition to MINIMUM GREEN, PASSAGE TIME, and MAXIMUM GREEN timing functions, phases provided with VOLUME DENSITY operation shall include VARIABLE INITIAL timings and GAP REDUCTION timings. The effect on the INITIAL timing shall be to increase the timing in a manner dependent upon the number of vehicle actuations stored on this phase while its signal is displaying YELLOW or RED. The effect on the extensible portion shall be to reduce the allowable gap between successive vehicle actuations by decreasing the extension time in a manner dependent upon the time waiting of vehicles on an opposing RED phase."*

In volume-density phases, the extended green time (passage time) created by each new actuation after the initial green time has elapsed is normally set based on the time required to travel from the detector to the stop line. Because this distance can be relatively long, the passage time can be more than the desired allowable gap. The NEMA gap reduction procedure mentioned above consists of four time settings—Time before Reduction, Passage Time, Minimum Gap, and Time to Reduce. The time before reduction begins when there is a call on a conflicting phase. Once the time before reduction has expired, the allowable gap reduces on a linear scale until the minimum gap is reached at the end of the time-to-reduce interval. The process is portrayed in Figure 67. The maximum green extension, as well as the yellow change and all-red clearance intervals, are predetermined (precalculated) and set on the controller.

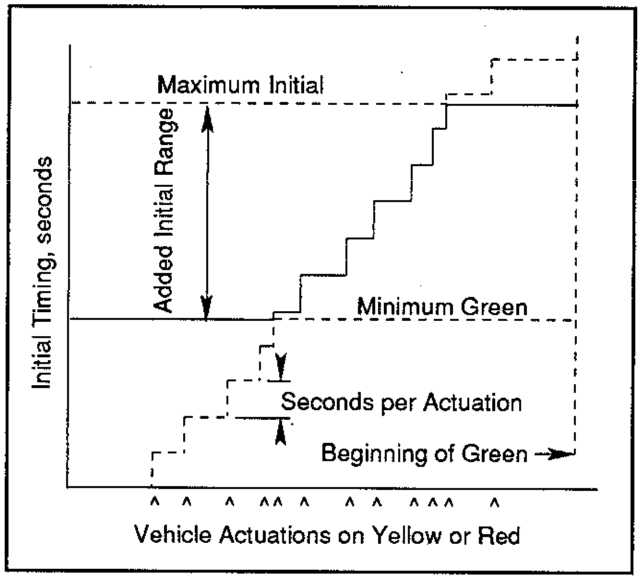


Figure 66. Variable initial NEMA timing.

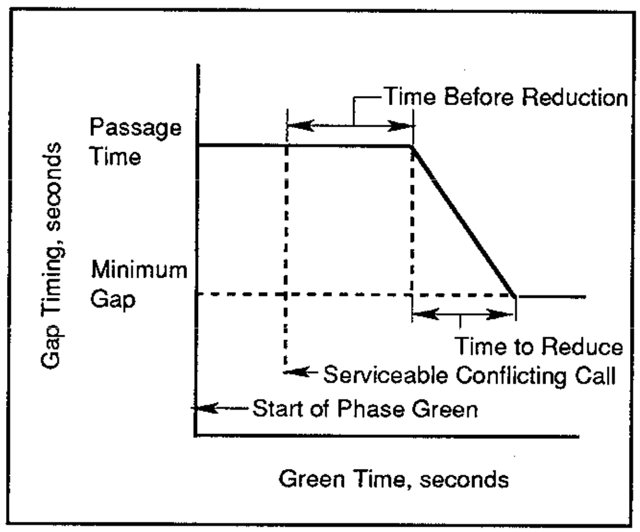


Figure 67. NEMA gap reduction process.

LOW SPEED APPROACHES

Approaches with speeds of less than 35 mph (55 kph) are considered low-speed approaches. The detector design for a given approach depends on whether the controller phase has been set for "locking" or "non-locking" detection memory. (This is also referred to as "memory ON" or "memory OFF"). The locking feature means that a vehicle call for the green is remembered or held by the controller until the call has been satisfied by the display of the green indication, even if the calling vehicle has left the detection area (e.g. right turn on red). In the nonlocking mode, a waiting call is dropped (or forgotten) by the controller as soon as the vehicle leaves the detection area.

Locking Memory with Point Detection

Locking detection memory is associated with the use of small-area ("point") detectors such as a 6- x 6-ft (1.8- x 1.8-m) loop and is frequently referred to as "conventional control." The minimum green interval (or initial interval) is preset to provide sufficient time to clear a standing queue between the detector and the stop line. The passage time or unit extension fixes both the allowable gap (to hold the green), and the travel time from detector to stop line, at one common value.

The allowable gap is usually 3 or 4 seconds. This indicates that the detector might be ideally located 3 or 4 seconds of travel time back from the intersection. This detector position would appear to be the most efficient for accurately timing the end of green after passage of the last vehicle of a queue. However, a long minimum green (assured green) is created at approaches with speeds higher than 25 to 30 mph (40 to 50 kph) because of the longer detector setback. Therefore, the principle is amended to locate detectors 3 to 4 seconds of travel time, but not more than 170 ft (52 m), from the stop line. Some agencies limit this distance to 120 ft (37 m). Applying this principle, the detector location and the associated timing parameters as a function of speed are presented in Table 11.

The advantage of this single detector approach is that the cost of installation is minimized. However, this type of control is incapable of screening out false calls for green such as would occur with right turns on red.

Table 11. Detector location and timing parameters.

Approach Speed		Detector Set-Back Stop Line to Leading Edge of Loop		Minimum Green	Passage Time
mph	kph	Feet	Meters	Seconds	Seconds
15	24	40	12	9	3.0
20	32	60	18	11	3.0
25	40	80	24	12	3.0
30	48	100	30	13	3.5
35	56	135	41	14	3.5
40	64	170	52	16	3.5
45+	72+	Volume Density or Multiple Detectors Recommended			
Note: Volume density could be considered at speeds of 35 mph (56 kph) or above					

Nonlocking Memory with Presence Detection

Nonlocking detection memory is associated with the use of large area detectors such as a 6- x 50-ft (1.8- x 15.2-m) loop. This scheme is often called "loop-occupancy control" (Figure 68). By providing infor-

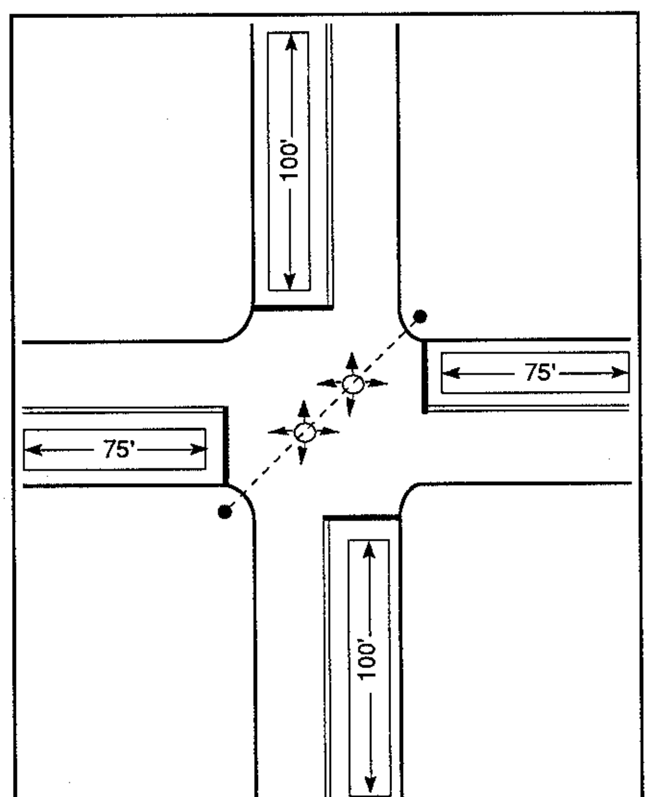


Figure 68. Loop occupancy control.

mation on the presence of vehicles in the detection area, many of the false calls for green can be screened out, thus avoiding the display of an unnecessary green indication to an approach with no waiting vehicles. The disadvantage of this configuration is the higher initial cost of installation and the higher replacement cost when maintaining large area detectors.

The use of nonlocking detection memory is particularly appropriate for use in left-turn lanes with separate signal control for the left turns. The green arrow is terminated as soon as the loop is cleared by the turning vehicle. In addition, a call placed during the yellow change interval by a vehicle that clears on the yellow does not bring back the green to an empty approach. Another potential advantage is gained when the left turn is permitted; that is, the left turn is allowed to filter across oncoming traffic on the circular green shown to the through movement. In this case, left turns may be serviced during the through phase and, therefore, do not require the display of a left arrow.

The left turn bay may use a delayed-call detector which is designed to output to the controller only if a vehicle is continuously detected beyond a preset period (say, 5 seconds). This allows the detector and controller to ignore vehicles that are in transit over the loop if oncoming traffic is light enough to allow a left turn without the protective left-turn arrow. If oncoming traffic is so heavy that left turning vehicles queue up over the loop, then the green arrow would be called. This type of operation is often used with lagging left-turn phasing.

A similar operation occurs on a single lane approach from the cross street where a right-turning vehicle approaches on the red. Again, the use of a delayed call detector will avoid calling the green to the side street if the right turn on red can be made during the delay time set on the detector.

Loop-occupancy control is also often used for through lane control on low-speed approaches. The technique minimizes delay by allowing the use of short passage times (unit extensions) in the range of 0 to 1.5 seconds. The length of the detection zone obviously depends on the approach speed and the controller unit time settings. For approach speeds under 30 mph (50 kph), Figure 69 indicates the length of the long-loop presence detector for various

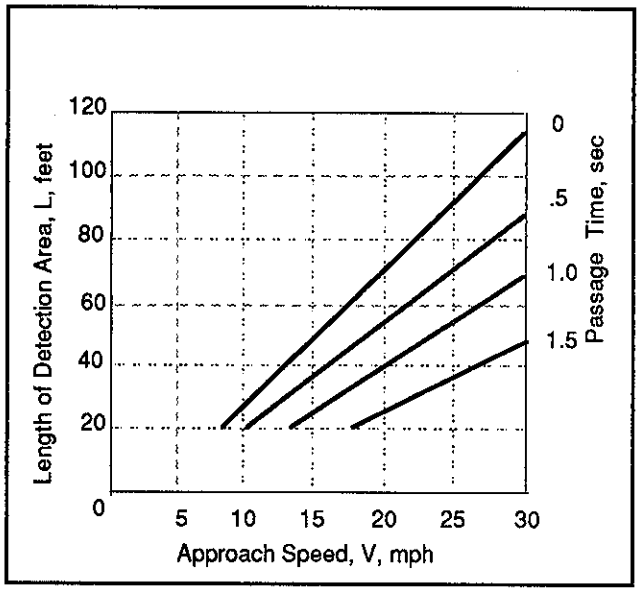


Figure 69. Detector length for loop occupancy control.

passage time settings on the controller. The chart is based on a desired allowable gap of 3 seconds and an average vehicle length of 18 ft (5.5 m). The formula is:

$$L = 1.47\,V\,(3 - P_t) - 18 \qquad (64)$$
$$L = 0.277\,V\,(3 - P_t) - 5.5 \text{ (in metric)}$$

where:

L = Length of detection area, ft (m)
V = Approach speed, mph (kph)
P_t = Passage time (unit extension), secs

HIGH-SPEED APPROACHES

Approaches with speeds in excess of 35 mph (56 kph) are considered high-speed approaches. There are a number of problems associated with these high-speed approaches that require careful consideration. At these speeds, it may be difficult for the driver to decide whether to stop or proceed when approaching a yellow change indication. An abrupt stop may result in a rear-end collision, while the decision to proceed through the intersection may cause a right-angle accident or a traffic violation.

That portion of the roadway in advance of the intersection within which the driver is indecisive (as to stopping or proceeding into and through the intersection at the onset of the yellow change interval) is called the "dilemma zone." Some researchers (Refs. 11 and 12) have defined the dilemma zone as that area of the approach between a point where 90 percent of the drivers will stop on yellow and a point where 90 percent of the drivers will go (i.e., 10 percent will stop).

Table 12 shows these boundaries for various speeds. Figure 70 illustrates a typical dilemma zone. To minimize the untimely display of yellow (and thus the creation of a dilemma zone problem), a number of techniques have been devised for controllers with locking and nonlocking detection memory, basic actuated and volume-density controller circuitry, and various detector configurations.

Table 12. Dilemma zone boundaries.

Approach Speed		Distances from Intersection for Probabilities of Stopping			
		Feet		Meters	
mph	kph	90 %	10 %	90 %	10 %
35	56	254	102	77	31
40	64	284	122	87	37
45	72	327	152	100	46
50	80	353	172	108	52
55	88	386	234	118	71

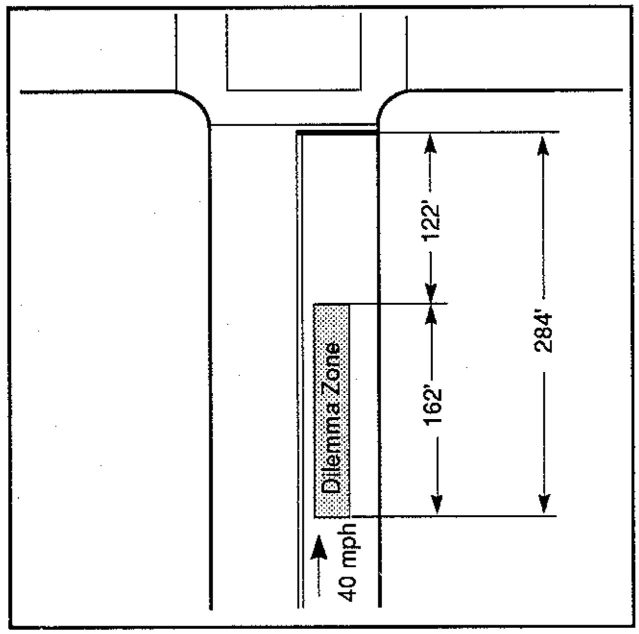


Figure 70. Typical dilemma zone.

The most straightforward conventional design for a high-speed approach uses a controller with a volume-density mode. This type of actuated operation can count waiting vehicles beyond the first because of the "added initial" feature. It also has a timing adjustment to reduce the allowable gap based on the time vehicles have waited on the red on a conflicting phase.

More efficient operation can be achieved with this controller mode than is possible with the normal full-actuated control because of these features and because detection is farther back on the approach–400 ft (120 m) is typical. This approach detection is often supplemented by a calling detector near the stop line which operates only when the phase is red or yellow. This calling detector is disabled when the signal turns green so that it cannot extend the green time inappropriately.

Full-actuated controllers have been used for a number of years (since at least 1982) with an extended-call detector just upstream of the dilemma zone. Designs for high-speed approaches using nonlocking detection memory include a long loop at the stop line as well as one or more small loops upstream. The long loop improves the controller's knowledge of traffic at the stop line, but tends to increase the allowable gap.

Detector designs for both normal full-actuated and volume-density controllers have been developed. A more definitive discussion of these designs and of solutions to the dilemma zone problem is presented later in this chapter.

Rural High-Speed Roadways

For isolated high-speed rural intersections, an extinguishable message sign, "PREPARE TO STOP," is frequently used when the signal site experiences periods of poor visibility caused by dense ground fog or by the orientation of the sun. These signs are also used where the geometry is such that the signal is not visible far enough in advance to ensure safety. For this situation, vehicle detectors are located further in advance of the intersection than normal.

Using the "last car passage" feature of some density controllers, the gap in the traffic flow can be identified to allow the last car in the platoon to go through the signal and presumably give the next vehicle sufficient time to stop. The sign (Figure 71) would flash "Prepare to Stop" at the appropriate time, but would be blank or unreadable at other times.

Essentially, the controller picks up a gap in the traffic, but does not change the signal until a preset time has elapsed to allow the last car to clear the intersection. The "Prepare to Stop" is illuminated when the gap is selected, so that the next vehicle following the platoon will see the sign. Thus, the driver will know he will be required to stop even though the signal ahead is still green. A typical layout for a similar installation or application is shown in Figure 72.

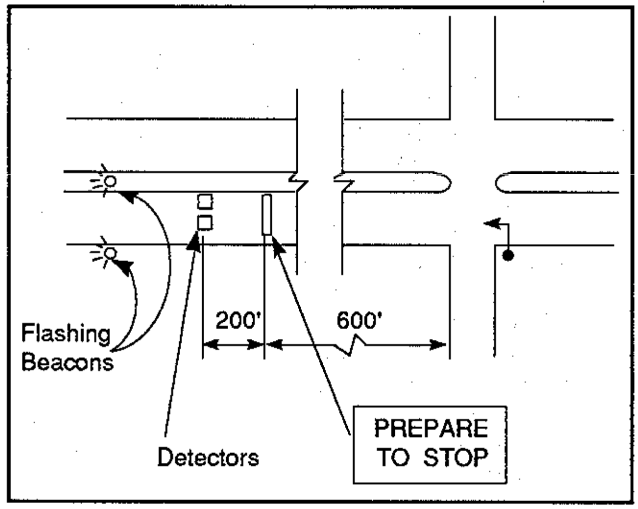


Figure 72. Prepare to Stop detection system.

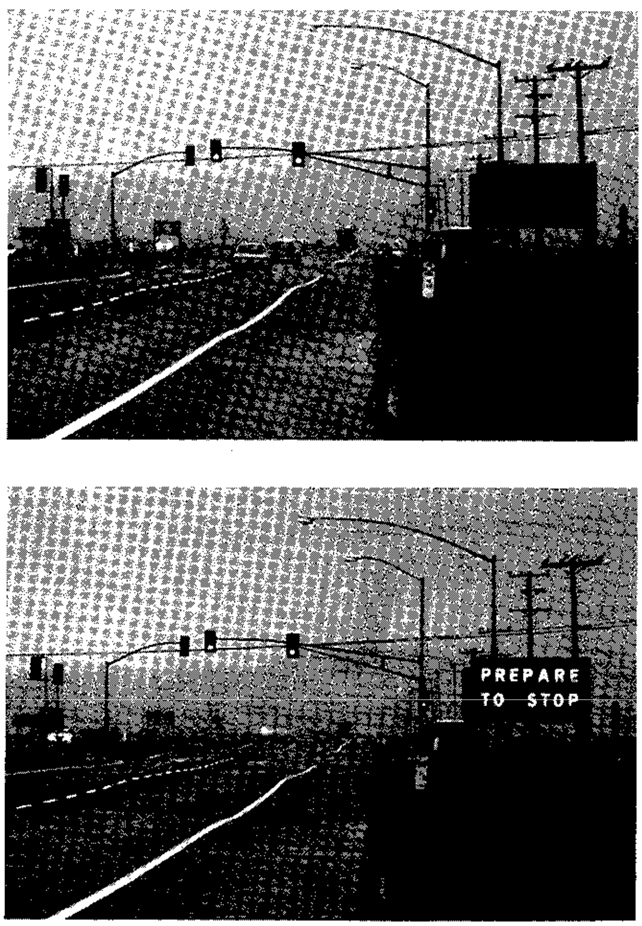


Figure 71. "PREPARE TO STOP" sign.

A simple display is used by some jurisdictions. They use flashing beacons together with a diamond or rectangular sign with the message "PREPARE TO STOP WHEN FLASHING."

REST-IN-RED SPEED CONTROL

Frequently, the commuting driver will use residential roadways as a legitimate time-saving route for reaching destinations particularly when the residential street is parallel to congested arterial streets. This through traffic in residential areas is generally perceived by residents as a threat to the safety of children and pets, particularly where speeding is a problem.

To control traffic speeds in residential areas, traffic engineers have used a variety of traffic control devices such as stop signs, warning signs, speed bumps, and coordinated traffic signals with vigorous enforcement of posted speed limits. While these measures are often successful, there are drawbacks associated with their use.

For example, the use of unwarranted stop signs to control vehicular speeds imposes delay penalties on all drivers and it only affects speeds within 200 ft (60 m) of the stop sign. Unwarranted stop signs may also encourage drivers to ignore the stop sign, which is even more dangerous.

One approach to the problem of high speed traffic is to install two speed measuring loop detectors approximately 180 ft (54 m) in advance of the intersection. These advance loops measure the speed (or, more accurately, the elapsed time between loops) of an approaching vehicle and register a call on the controller only if the vehicle is traveling at or below the speed limit. Assuming the signal is resting in four-way red, and if the vehicle is not speeding, a green is displayed and the driver may proceed through the intersection without being delayed. If, on the other hand, the approaching vehicle is exceeding the speed limit, no call is placed and the driver must slow down until he reaches a loop near the intersection. A call will then be placed and the green interval activated.

With this system, a vehicle crossing the first advance loop starts a timing device and a call is initiated. If the vehicle speed is low enough, the predetermined interval will time out before the vehicle reaches the second loop. Then the call will be passed on to the controller. When the vehicle reaches the second loop, the timing device is reset, and any call being held at the timing device is cancelled. Thus, a vehicle exceeding the speed limit is never detected by the advance loop, and each succeeding vehicle is timed independently. This method is simple, economical, adjustable, and not dependent on vehicle size or length.

The spacing between the initiating and resetting advance loops is approximately 1 second of travel distance at the speed limit. The distance from the advanced loop to the first intersection loop is predetermined from the lowest travel speed to be accommodated (normally 20 mph (32 kph)), and the maximum desirable passage time interval (4 seconds). The minimum distance from a stop line to the advance detector loop is determined by a comfortable reaction time and the stopping distance at the design speed.

LOOP DETECTOR DESIGN ALTERNATIVES

In this general discussion, detector design will be described first in terms of "small area" (for point or passage detection) and then in terms of "large area" (for area or presence detection). Inductive loops can be applied in either case. Magnetic detectors can only be used for point detection because they cover a small area and require vehicle motion (passage) to activate the system. Magnetometers are basically point detectors, but can be used as area detectors by using multiple sensors to cover a larger detection area.

Typical design configurations for detector locations in through lanes and in left turn lanes are also presented. Both simple and complex designs are described along with the type of controller operation, if appropriate. Treatments to alleviate the "dilemma zone" problem are also discussed.

SMALL AREA DETECTION

Small area detection usually consists of a single short loop. Although the literature defines short loops as being up to 20 ft (6.1 m) in length, by far the most common short loop application is the 6- x 6-ft (1.8- x 1.8-m) loop in a 12-ft (3.6-m) lane. For narrower lanes, 5- x 5-foot (1.5- x 1.5-m) loops should be used to avoid adjacent lane pickup (splashover). Smaller loops are not recommended in areas where high bed vehicles must be continuously detected.

The short loop is intended to detect a vehicle upstream of the stop line. When a vehicle passes over the detector loop, a call is output to the controller. Timing of the green interval is commonly based on preset controller settings, not by the length of time the detection area is occupied by vehicles approaching the intersection. In most cases, the controller operates with locking detection memory circuits to insure calling the appropriate phase.

Short loop detectors may be used in a variety of ways and may be located at varying distances from the stop line depending on the operational requirements. A typical application may consist of one or more short loops near the stop line on the actuated approach of a low speed intersection. Another typical application is to space a number of these loops well back of the stop line to act as extension detectors for higher speed approaches.

The shape of the loop in the roadway has been the subject of a great deal of research during the 1970's and 1980's. The desire to detect all forms of vehicles, from bicycles and motorcycles to high-bed trailer trucks, while avoiding detection of vehicles in adjacent lanes has led to a proliferation of loop designs. Each design purports to have advantages over other designs. Examples of various short loop shapes are shown in Figure 73. Some of these configurations are in common use, while others have been developed specifically for either a site-specific location or to detect a particular range of vehicles.

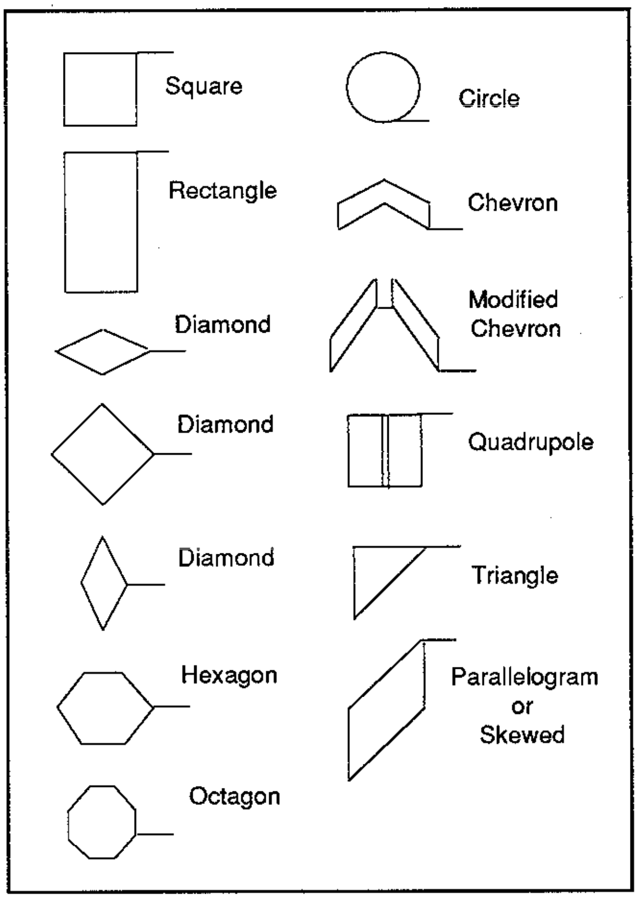


Figure 73. Small loop shapes.

A number of agencies and universities have conducted tests to determine an optimum loop shape (e.g., Refs. 13, 14, 15). Typically, these projects involved installing several different loop shapes then testing and comparing the sensitivity of the loops in detecting several types of test vehicles. None of these projects tested all of the loop designs currently in use. In some cases, one loop design would test better when compared to one or two different loop designs. In most instances, the difference in sensitivity among loops was not significant, given the state of the art in detector electronic units. It is therefore difficult to cite one particular design as superior to all others. However, it is generally accepted that some loop designs are better suited than others for detecting small vehicles or high-bed trucks as discussed in later sections.

Many States specify the acceptable loop shapes to be used within their jurisdiction. An example of one State's (California's) specified shapes is shown in Figure 74. In this particular example, each unique shape is given a letter designation (i.e., Type A is a typical 6- x 6-ft (1.8- x 1.8-m) loop, etc.).

LARGE AREA DETECTION

Large area detection normally consists of a detection zone covering an area of at least 20 ft (6 m) or more in a traffic lane. It is primarily presence detection in that it registers the presence of a vehicle as long as the detector zone is occupied. This concept originally utilized a single loop encompassing the entire detection zone. However, the long loop, as a single entity, is being supplanted by a sequence of short loops which emulate the long loop. In this Handbook, "long loop" is intended to mean either a single long loop or multiple short loops acting as a single long loop.

Long Loops

Traditionally, the long loop has been defined as a single loop that was 6 ft (1.8 m) wide by 20 to 80 or more ft (6 to 24 m) long. Figure 75 illustrates various long loop shapes. These long loops generally have only one or two turns of wire. If the rectangular, powerhead, or trapezoidal loop needs to reliably detect all roadway vehicles, the sensitivity level must be set high which, in turn, will detect adjacent lane vehicles (splashover). The quadrupole loop is an appropriate design to eliminate this problem, however, due to its limited height of field, it may have difficulty in continuously detecting high-bed vehicles. Quadrupoles are excellent wheel and axle detectors. The lengths associated with long loops increase the vulnerability to failure caused by pavement cracks and joint movement. In response to

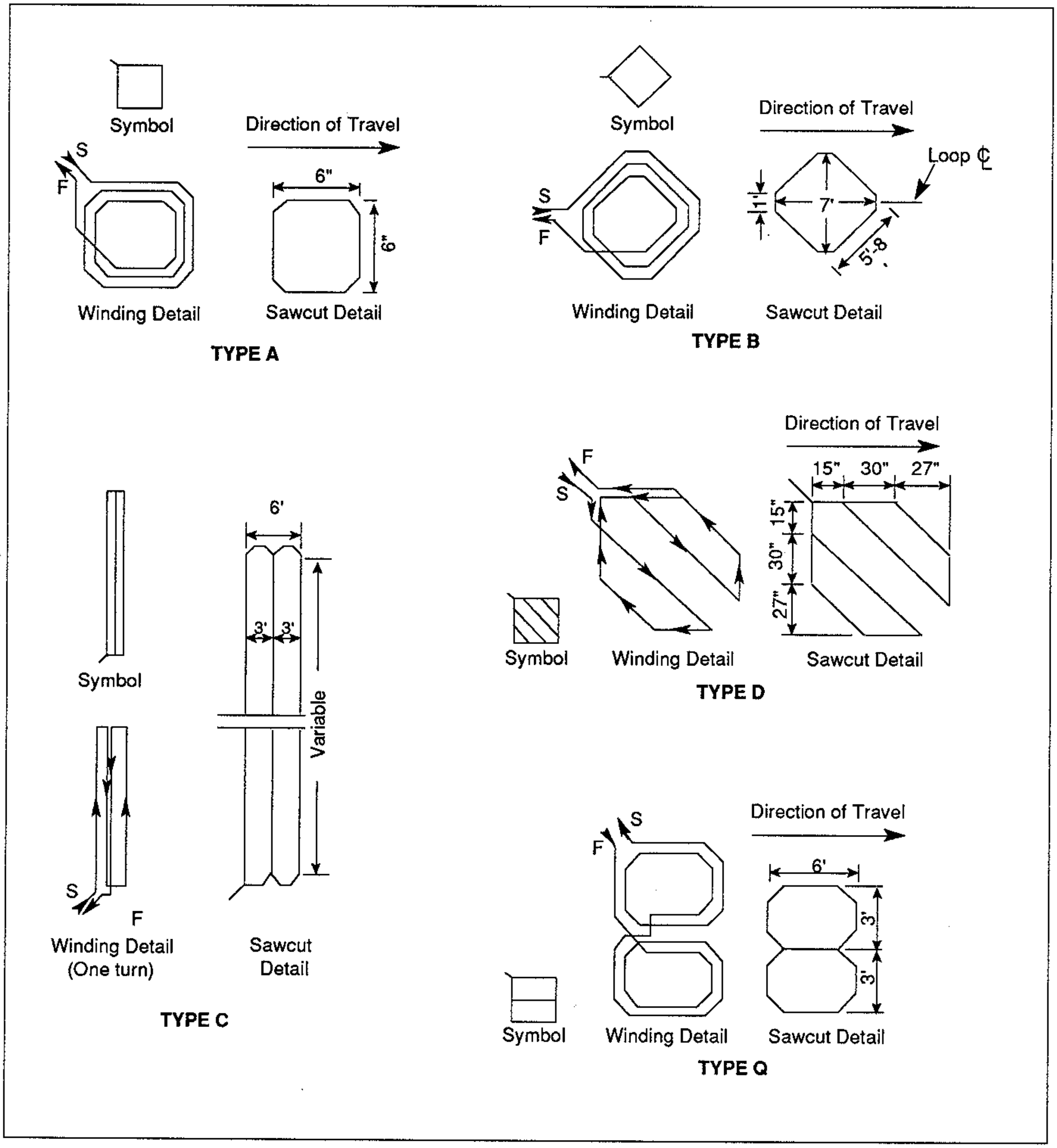


Figure 74. Example of state-specified loop shapes (California).

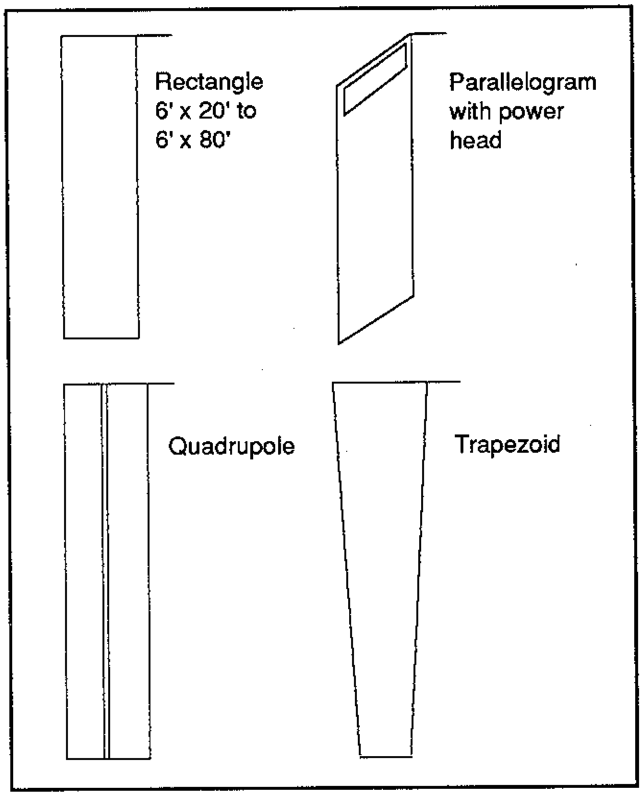


Figure 75. Long loop shapes.

these problems, many agencies are using sequential short loops as described later.

The long loop normally provides input to the controller for what is termed "loop occupancy control." In this form of control, the minimum green interval (or initial interval in older controllers) is set to zero, or near zero, and the passage time or vehicle interval is set to a short interval as was shown in Figure 69. When the green interval appears for the subject phase, it will remain green as long as the detector is occupied (subject, of course, to the maximum green). As soon as the detector loop is cleared, the passage time is timed and, if no further actuation occurs during the passage time, the yellow change interval appears.

The effective time gap is equal to the travel time required to traverse the length of the loop plus one vehicle length plus the passage time. Therefore, the length of the loop is a critical measure for providing appropriate operation. Care should be exercised to ensure that the length of the loop is sufficient for a following car to brake to a stop if the yellow interval appears just before the following vehicle reaches the loop or, conversely, to allow the vehicle to proceed through the intersection on the yellow.

If heavy trucks are included in the traffic stream, there may be a start up problem if a long queue exists. Passenger cars in front of the truck may accelerate and clear the detector loop before the truck can accelerate and reach the detector.

One researcher (Ref. 16) studied the relationship between detector length and the time settings of vehicle interval and maximum green for intersections where vehicle approach speeds were less than 35 mph (56 kph). The purpose of the study was to determine the optimal combinations of detector length, vehicle interval, and maximum green for a wide range of flow conditions (i.e. flow rate per lane, distribution of traffic among lanes, and temporal variations in flow rates). Both two- and four-phase operations of presence mode control were analyzed for each flow pattern.

Optimal vehicle intervals are a function of detector length and flow rate. The study suggests that for detectors 30 ft (9 m) long, the use of 2 second vehicle intervals can lead to the best signal performance over a wide range of operating conditions. For 50-ft (15-m) detectors, 1 second vehicle intervals are desirable under a variety of flow conditions. When detectors 80 ft (25 m) long are used, 0 second vehicle intervals can minimize delays. The use of longer vehicle intervals for such detector lengths is not desirable unless the combined critical flow at an intersection exceeds 1,400 vph.

The study concluded that maximum green for the presence mode control is generally longer than optimal green durations for pretimed control. Flow patterns with higher degrees of concentration of traffic in short periods of time need longer maximum greens. The optimal maximum greens for hourly flow patterns with a peaking factor of 1.0 (a uniform flow rate) are about 10 seconds longer than the corresponding optimal pretimed greens. With a peaking factor of 0.85 (a higher concentration of traffic in a short period), the optimal maximum greens are approximately 80 percent longer than the corresponding optimal pretimed greens.

The study further concluded that detectors 80 ft (25 m) long can consistently produce the best signal performance. However, for a combined critical flow of less than 1,100 vph, 65-ft (20-m) detectors can produce comparable performance. For a combined critical flow of less than 900 vph, the use of 50-ft (15-m) detectors rather than the 80 ft (25 m) length would incur a delay of up to 2 seconds per vehicle. For a combined critical flow of less than 600 vph, 30-ft (9-m) detectors may be used instead of the 80-ft (25-m) detectors without incurring undue delays.

Sequential Short Loops

The use of sequential short loops to emulate a long loop is the preferred treatment in many agencies. The advantages of this configuration result primarily from the fact that they are less subject to failure because of their shorter length; therefore they are less vulnerable to the problems of crossing pavement cracks and joints and to adjacent lane pickup (splashover). Long loops are more subject to adjacent lane splashover since the entire length of the vehicle is exposed to the side of the long loop (approximately 17 ft (5 m)) as compared to less than a third of the vehicle length of about 6 ft (1.8 m) for a short loop. The short loops also provide superior detection of small vehicles as explained later.

The sequential short loops commonly consist of four 6- x 6-ft (1.8- x 1.8-m) square or diamond loops separated by 9 or 10 ft (2.7 or 3.0 m). This configuration is equivalent to a 51- or 54-ft (15.3- or 16.2-m) long loop. Various configurations of sequential loops are shown in Figure 76. This California standard

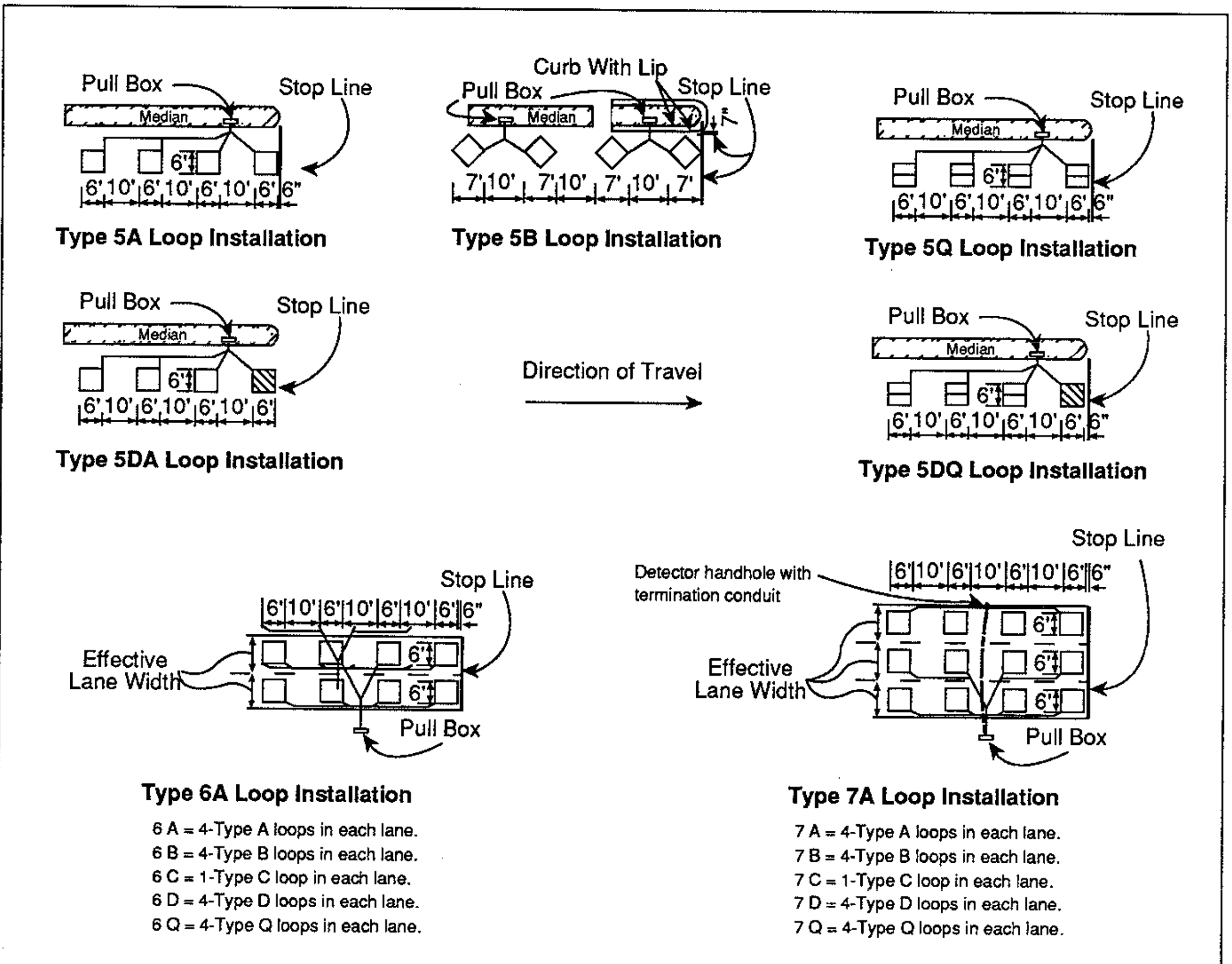


Figure 76. Sequential loop configurations (California).

uses loop type designations such as those shown in Figure 74.

On the other hand, Figure 77 defines a different spacing pattern that is used by the Pennsylvania Department of Transportation. This spacing normally requires a passage time or vehicle interval greater than zero to provide proper signal operation. Various spacing arrangements are used by other agencies around the country.

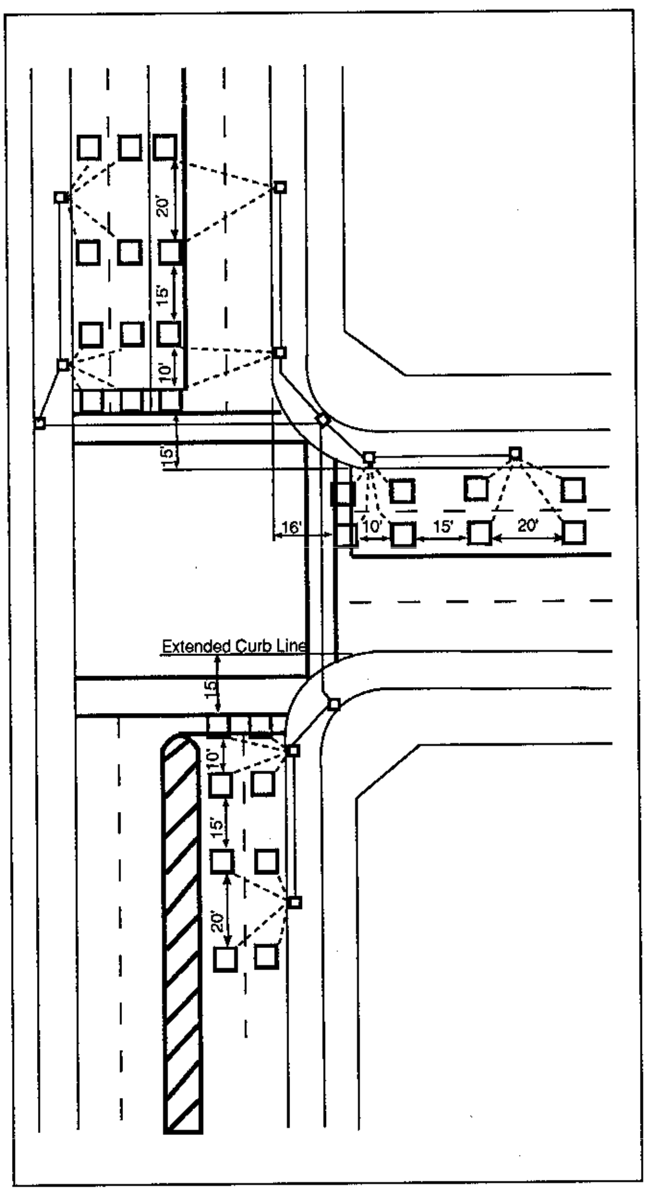


Figure 77. Series of short loops (Pennsylvania).

Wide Loops

Some agencies use wide loops to cover wide lane or multiple lane approaches. These loops are normally 6 ft (1.8 m) in length in the direction of traffic flow and up to 46 ft (13.8 m) for a four-lane approach. The basic layout of a wide lane is shown in Figure 78. The number of turns of wire varies according to the number of lanes covered. Table 13 indicates the number of turns as well as the dimension ranges for the loop. Wide loops are not recommended. In fact, many agencies do not permit the use of wide loops. They are subject to more frequent failure because they generally cross pavement joints and fractures. A failure anywhere on the perimeter takes the entire loop out of operation which in turn removes all detection capability for that approach. Separate loops in each lane are less susceptible to failure and even if a failure in one loop occurs the remaining loops can provide approach detection.

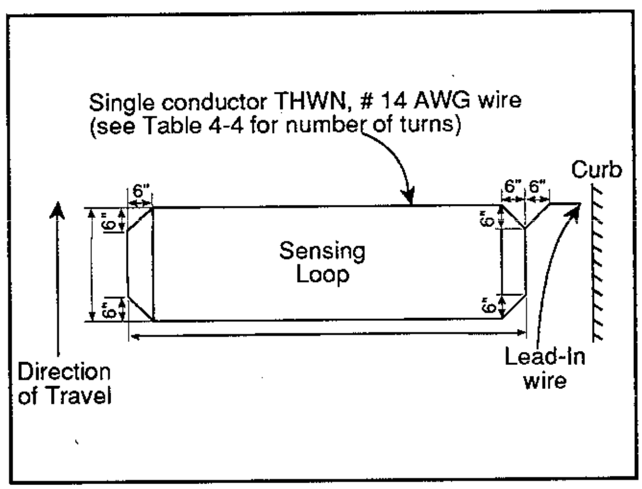


Figure 78. Wide loop detector layout.

Very large loops of up to 30 ft (9 m) in width and 50 to 60 ft (15 to 18 m) in length have been used to provide an extension of green time when occupancy increases to a saturation point in a given direction. The detector unit is adjusted to be sensitive to more than a certain number of vehicles in the loop. In other words, the detector only responds to a saturated condition. No additional green extension is given to the approach unless there is a congested

Table 13. Wide loop detector dimensions.

Number of lanes	Approach width ft	Loop width ft	Loop length ft	Turns of wire
1	12-18	6-12	6	4
2	19-32	13-26	6	3
3	33-45	27-39	6	2
4	46-52	40-46	6	1

situation. If no extensions are present (i.e., there is no saturation or congestion), the opposing street green receives the excess time. This application cannot be used for call initiation and is intended for use only in locations where unpredictable and extreme fluctuations of traffic are present, such as shopping center exits, some freeway exits into main street flow, and industrial plant parking lot exits.

LEFT-TURN LANE DETECTION

Vehicle detectors in left-turn lanes can affect the capacity of an intersection by reducing unnecessary green time and left turn arrow indications. When the last vehicle proceeds a block or so past the signal before the conflicting phase begins, the travel time represents lost green time which could more appropriately be used to increase the green time available to other phases. The design of left-turn detection is generally based on the premises discussed below.

At the start of the green indication, it normally requires 3 to 5 seconds for the first vehicle in a queue to start up, with an average headway of 2 to 3 seconds between following vehicles. These times are average; consequently, longer times must be accounted for by providing an appropriate length of loop to maintain the green for slower starting vehicles. Moreover, trucks and other slow vehicles require a longer start-up time which frequently leaves a three or four car-length gap ahead of them. Loop length also needs to account for these gaps.

Because green time is based on vehicular demand, only a short green time is needed for one or two vehicles. For example, a rapidly starting single vehicle can clear the turn lane with a green time of under 5 seconds. A driver of a following vehicle just entering the left turn lane may be confused by the short green. The length of the detector loop should be such as to allow the following car to reach the loop in time to enter the intersection on the green indication or brake to a stop. This length is based on the equation for maximum deceleration rates, which indicate that a vehicle traveling at 30 mph (48 kph) can stop in 83 ft (25 m).

To accommodate these conditions, a loop length of 80 ft (24 m) from the stop line and a controller passage time of 1 second is frequently used. Shorter loops must be compensated for by adding more passage time on the controller. Controller passage time is the time a controller will hold the green after actuation. A passage time of 1.0 second permits most motorists to almost complete their turning radius before the onset of the yellow change interval is displayed.

Another problem occurs when vehicles are permitted to turn on the circular green (green ball) indication. Drivers will usually proceed past the stop line and wait for a gap in the opposing traffic. If a gap does not occur, or a vehicle ahead prevents the turn, the driver may be left stranded beyond a detection zone that ends at the stop line. In this case, the controller may skip the turn arrow in the next cycle because the vehicle is positioned ahead of the detector. Some agencies feel that it is a good practice to extend the loop beyond the stop line 1 to 6 ft (0.3 to 2 m) to prevent this situation.

To detect small vehicles (e.g., motorcycles), the detector must be set for high sensitivity. However, this high sensitivity will frequently cause detection of vehicles in adjacent lanes (splashover). Many agencies use quadrupole loops to avoid splashover. As the quadrupole requires an additional sawcut the length of the loop, it is desirable to limit the quadrupole design to the area near the stop line. (See later discussion "Detection of Small Vehicles.")

One method, used by the Illinois Department of Transportation (Ref. 14), for designing a minimum left-turn loop is illustrated in Figure 79 and procedurally described as follows:

- Locate the stop line in relation to cross-street turning radius.

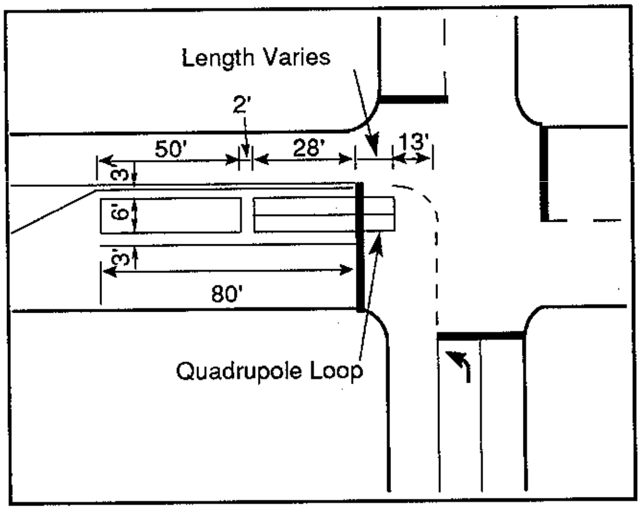


Figure 79. Left turn detection procedure (Illinois).

- Measure back 80 ft (24 m) from the stop line to establish the back loop.
- Measure 50 ft (15 m) toward the stop line to establish front edge of the back loop.
- Allow 2-ft (0.6-m) gaps between loops and measure 28 ft (8.4 m) to the stop line.
- The front of the front loop should be within 13 ft (4 m) of the edge of the cross street traffic lane.
- Design the front loop as a quadrupole to detect small vehicles.

When the left-turn demand requires 150 ft (45 m) or more of storage length, or when higher approach speed require long deceleration lanes, the loop layout should include an advanced detection loop. This advanced detector with a call extension feature will extend the effective detection zone to accommodate heavy traffic volumes or high-speed traffic.

THROUGH LANE DETECTION

Detection of vehicles in through lanes depends on the approach speed and the type of controller operation being used. It can be a single point detector, a long loop, a combination of long and short loops, or a sequence of short loops. Each of these types is discussed below.

Single Point Detection

This form of detection is the simplest form used for actuated controllers. It is used primarily for low speed approaches; that is, less than 35 mph (56 kph). It may also be used on side street approaches, with another form of detection on the major street.

A point detector (e.g., a 6- x 6-ft (1.8- x 1.8-m)) is located 2 to 4 seconds of travel time in advance of the stop line. As this is the only detector in the approach lane, controller timing must be appropriately set to utilize the information. The actual distance divided by 25 ft (7.6 m) (length of vehicle plus the space between vehicles) indicates the number of vehicles that can be queued between the detector and the stop line when the light turns green. This is used to establish the minimum green interval setting on the controller. The distance between the detector and the stop line divided by the 15th percentile speed is a good first estimate of the passage time. This passage time is also the allowable gap that will lose the green indication. If this setting is too long or short to be acceptable as an allowable gap, the position of the detector should be moved to ensure an appropriate gap size.

Loop Occupancy Detection

The loop occupancy form of detection is generally used on low speed approaches. This normally consists of a single loop 50 ft (15 m) or more in length or a sequence of short loops (usually four) located immediately upstream of the stop line. Loop occupancy timing is used on the controller as described earlier. This type of operation is most effective when speeds are 25 mph (40 kph) or less. Even at this speed there is some potential for the light turning yellow just before an approaching vehicle reaches the detector. In this case, the vehicle will probably cross the intersection on the yellow indication.

As speeds increase, the detection zone must also lengthen to accommodate the increased stopping distance. One jurisdiction uses the combination o approach speeds and detection lengths shown in Table 14. These loop lengths appear to be excessively long, resulting in long minimum gaps.

Table 14. Loop occupancy detector lengths.

Speed		Detector Length	
mph	kph	Feet	Meters
30	48	120	37
35	56	160	49
40	64	200	61
45	72	250	76

The 120-ft (36.6-m) detection area is measured from the stop line and consists of two 56-ft (17.1-m) loops. Where greater detection areas are required, either additional long loops or small loops may be used. If additional small loops are chosen, they must be connected to separate detector units with the extension time programmed into the detector. The long loops are set to presence mode.

High-Speed Point Detection

For high-speed approaches (those with speeds greater than 30 mph (48 kph)), detection becomes more complex. Volume density control is one technique used that relies on the controller functions rather than extensive detectorization. Normally only one detector is used for each lane. This point detector is placed much farther from the intersection than the 2 to 4 seconds of travel time used for normal actuated operation. The detector is usually placed at least 5 seconds and as much as 8 to 10 seconds from the stop line.

This detector is active at all times rather than just during the green interval. During the red interval, each actuation increments the variable initial timing period. After the variable initial exceeds the minimum green, each additional actuation adds more time to the initial interval. During the green interval, the detector acts to extend the green. At first the extension is equal to the passage time, but after a conflicting phase has registered a call, the extension is reduced, eventually reaching a minimum gap.

A concern with this type of operation is the potential for a vehicle being in the dilemma zone at the onset of yellow. The following section presents a discussion of dilemma zones and describes how multiple detectors are utilized to alleviate the dilemma zone problem.

DETECTION FOR DILEMMA ZONES

One problem that has plagued designers and operations and safety engineers involves intersection approaches where the speeds of approaching traffic are greater than 30 mph (48.3 kph). Drivers approaching at these higher speeds are frequently faced with a "dilemma"–whether to stop or proceed through the intersection at the onset of the yellow change interval. The placement of detectors to ameliorate this problem has received serious consideration and research. This section defines the many variables that affect the dilemma zone problem and describes several detector placement schemes that have proven effective.

Definition of Dilemma Zone Problem

When a vehicle traveling at a constant speed (V) approaches an intersection and is positioned at distance (X) from the intersection at the beginning of the yellow change interval, the driver is faced with a decision. He may decelerate and stop the vehicle before entering the intersection; or continue and enter the intersection, accelerating if necessary, before the red interval begins. In some States, the driver is required to clear the intersection before the red appears. Depending on the distance from the intersection and the speed of travel, drivers may not be certain that they can stop in time, or they may be unsure that they can clear the intersection before conflicting vehicles enter. This creates the "dilemma." Some drivers will opt to stop, while others may accelerate and continue through the intersection.

If the choice is to stop, after a short perception/reaction time, the driver will decelerate. The distance the vehicle will travel after the beginning of the yellow change indication includes the distance traveled during the perception/reaction time (t), and the distance traveled during deceleration. The following inequality must be maintained to ensure a safe and complete stop.

$$X \geq V \times t + \frac{V^2}{2d} \quad (65)$$

where:

X	=	Distance from stop line at start of yellow interval, ft (m)
V	=	Approach speed, fps (mps)
t	=	Perception/reaction time (typically one second)
d	=	Constant deceleration rate, fps ^{2} (mps ^{2})

Safety and comfort require that the vehicle's deceleration rate not exceed one third to one half the acceleration of gravity. Using d* to represent a critical deceleration rate under prevailing roadway conditions, the stopping distance (X_s) for speed V may be defined by:

$$X_s = V \times t + \frac{V^2}{2d^*} \quad (66)$$

The quantity X_s is the minimum distance from the stop line where the vehicle can stop completely after the beginning of the yellow interval. That is, if a vehicle is closer to the stop line than X_s when the yellow begins, the driver will be unable to stop safely or comfortably before the intersection. The area between the stop line and the point X_s is an area in which drivers should not be expected to stop ("cannot stop") (see upper portion of Figure 80).

If the driver decides to accelerate and pass through the intersection, the following inequality must be maintained:

$$X_c \leq V(Y+R) + \frac{a(Y+R-t)}{2} - (W+L) \quad (67)$$

where:

X_c	=	Clearance distance, ft (m)
t	=	Perception/reaction time (typically one second)
a	=	Acceleration rate, fps ^{2} (mps ^{2})
Y	=	Yellow change interval, seconds
R	=	Red clearance interval, secs
W	=	Effective width of intersection, ft (m)
L	=	Length of vehicle, ft (m)
V	=	Approach speed, fps (mps)

The above equation will take the driver completely through the intersection before the appearance of the red signal. Many traffic engineers do not feel that a driver must clear the intersection on the yellow. In fact, most State Vehicle Codes do not require the vehicle to clear the intersection prior to the onset of the red indication but merely to enter prior to the red. Therefore, these same engineers may eliminate the last term (W + L) from the equation or, they may use 1/2 or 1/4 of this term. In some cases, the red clearance interval is increased to assure clearance when needed rather than include the W + L term in the equation.

The constant acceleration rate (a) available to the driver in Equation 67 may be estimated using Gazi's equation:

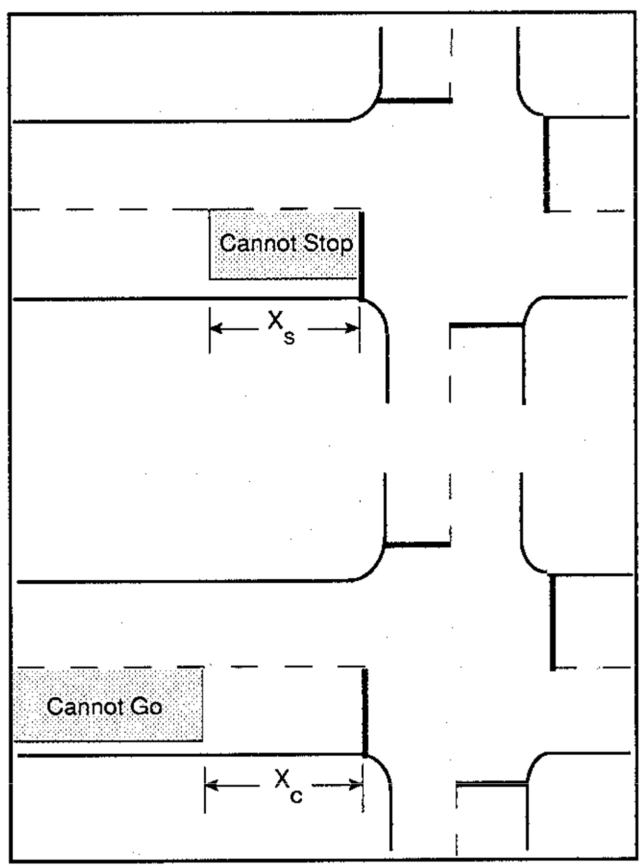


Figure 80. Region of "Cannot Stop" or "Cannot Go."

$$a = 16.0 - 0.213\,V \qquad (68)$$
$$(a = 4.9 - 0.213\,V \quad \text{(in metric)})$$

From this equation, it can be seen that higher acceleration rates can be attained when the vehicle is traveling at lower speeds. Clearance distance (X_C) is the maximum distance from the stop line from which a vehicle is able to clear the intersection. X_C can be defined by the following:

$$X_C = V(Y+R) + \frac{a(Y+R-t)}{2} - (W+L) \qquad (69)$$

Again, the last term (W + L) is often omitted from the equation. Since X_C is the maximum distance upstream of the stop line from which a vehicle can clear the intersection during the yellow interval, any vehicle positioned at a point beyond X_C (i.e., further upstream), would not be expected to clear the intersection during the yellow interval and is thus in a region in which the driver "cannot go" without violating the red indication (see lower portion of Figure 80).

As both X_S and X_C are measured distances from the stop line, the relationship of these two quantities should be defined by one of the following:

- $X_S > X_C$
- $X_S = X_C$
- $X_S < X_C$

In the case where $X_S > X_C$, the overlapping area in which a vehicle can neither stop nor go if faced with a yellow indication is termed the "dilemma zone" (Figure 81). In this case, a driver of a vehicle within the dilemma zone at the onset of yellow would have to accelerate or decelerate at an unsafe rate; and consequently, would be vulnerable to a right angle or rear-end accident.

In the case where $X_S = X_C$, the dilemma zone disappears, and therefore, presents no problem (Figure 82). A driver in the "cannot go" zone would be able to stop safely, whereas a driver in the "cannot stop" zone could successfully accelerate through the intersection.

In the third case where $X_S < X_C$, in the area between X_S and X_C the driver may either stop or go safely.

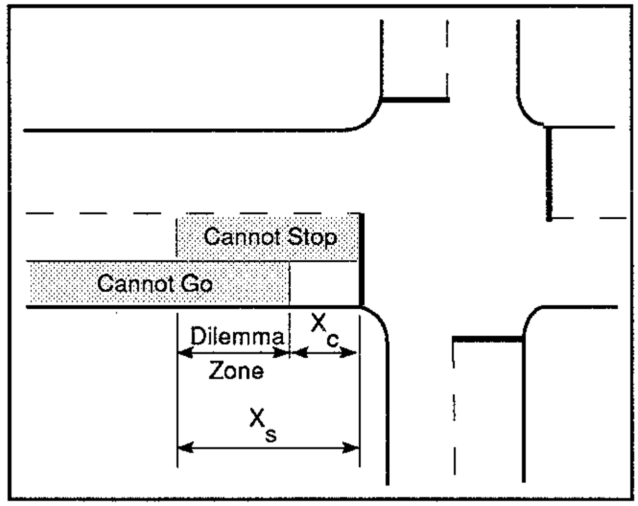


Figure 81. Dilemma zone ($X_S > X_C$).

Therefore, this zone is considered an optional zone as shown in Figure 83.

It can be seen from this relatively simply analysis that a dilemma zone is only formed when $X_S > X_C$. From Equation 66 and 69, it is seen that X_S is a function of speed, perception/reaction time, and deceleration rate, while X_C is a function of speed, perception/reaction time, acceleration rate, yellow interval time, and effective width of the intersection. Tables 15 and 16 present stopping distance X_S and clearance distance X_C for deceleration rates of 10 and 16 fps (3.0 and 4.9 mps), and intersection widths of 48 and 76 ft (14.6 and 23.2 m), respectively. The tables are based on the following assumptions:

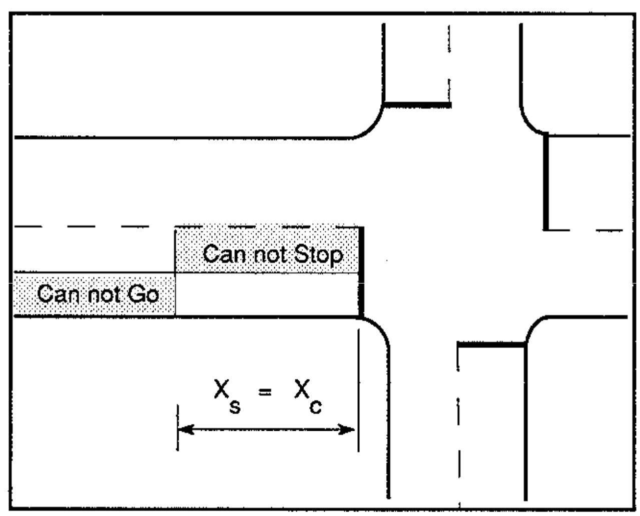


Figure 82. No dilemma zone ($X_S = X_C$).

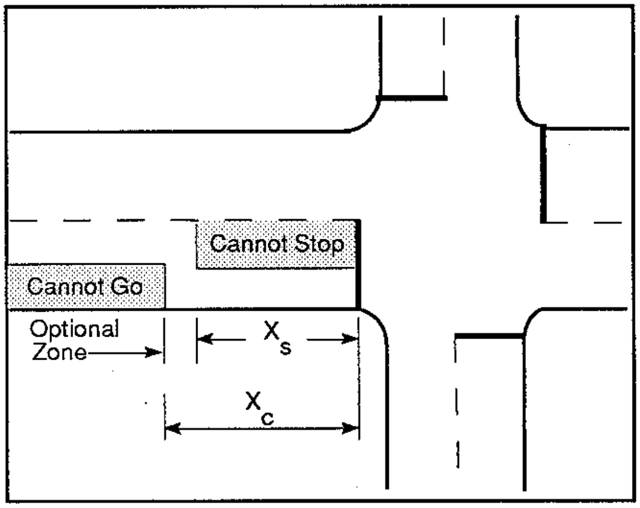


Figure 83. Optional zone ($X_s < X_c$).

- All distances are measured from the stop line in the upstream direction.
- Vehicle length is 20 ft (6 m).
- Acceleration rate = a = 16.0 – 0.213 x speed, fps^2.
- Perception/reaction time equals 1 second.

From this analysis, several general statements may be developed :

- For a given yellow interval, as speed increases, the dilemma zone becomes longer.
- For a given speed and yellow interval, increases in the deceleration or acceleration rate will result in a reduction of the dilemma zone.
- Increases in the effective width of the intersection will directly increase the length of the dilemma zone if the total width of the intersection is included in the calculation.

In pretimed signal control, the appropriate strategies for controlling the dilemma zone problem consist of providing a consistent yellow change interval and incorporating an appropriate red clearance interval. This strategy will, however, increase vehicular delay.

In actuated signal controlled intersections, the most appropriate strategy for resolving the dilemma zone problem involves detector placement before, within, and after the dilemma zone in such a way as to

Table 15. Stopping and clearance distances for intersection width of 48 feet.

Decel. Rate	Speed	Stopping Distance	Clearance Distance (feet) for Yellow equal to:		
ft/sec ^{2}	mph	feet	3 sec	4 sec	5 sec
10	20	73	44	102	173
	25	104	64	127	201
	30	141	84	152	229
	35	184	103	176	258
	40	232	123	201	286
	45	285	143	226	314
	50	344	163	250	342
	55	408	183	275	370
	60	477	203	299	399
16	20	56	44	102	173
	25	79	64	127	201
	30	105	84	152	229
	35	134	103	176	258
	40	167	123	201	286
	45	203	143	226	314
	50	242	163	250	342
	55	285	183	275	370
	60	331	203	299	399

Table 16. Stopping and clearance distances for intersection width of 76 feet.

Decel. Rate	Speed	Stopping Distance	Clearance Distance (feet) for Yellow equal to:		
ft/sec ^{2}	mph	feet	3 sec	4 sec	5 sec
10	20	73	16	74	145
	25	104	36	99	173
	30	141	56	124	201
	35	184	75	148	230
	40	232	95	173	258
	45	285	115	198	286
	50	344	135	222	314
	55	408	155	247	343
	60	477	175	271	371
16	20	56	16	74	145
	25	79	36	99	173
	30	105	56	124	201
	35	134	75	148	230
	40	167	95	173	258
	45	203	115	198	286
	50	242	135	222	314
	55	285	155	247	343
	60	331	175	271	371

reduce the probability of entrapment of a vehicle in the dilemma zone at the onset of the yellow interval. The various methods of detector placement for dilemma zones are discussed below.

Multiple Point Detection

As mentioned above, the dilemma zone problem can be ameliorated by the strategic placement of multiple detectors at high speed approaches to intersections controlled by actuated controllers. These methods also assume the use of loop detectors. It should be noted that, as inventive as these methods are, because of maximum greens, force-offs, etc., vehicles will still get caught in the dilemma zone. Adequate change intervals (yellow and all-red displays) must be provided to ensure motorist safety.

There are three general detector placement strategies in general use. These may be defined as:

- Green extension systems (for semi-actuated controllers).
- Extended call detector systems (for basic controllers).
- Multiple detection systems.

Green Extension System

This system is an assembly of extended call detectors and auxiliary logic (Ref. 17). The logic can monitor the signal display, enable or disable selected call detectors, and hold the controller in green. Although two loop detectors are normally used, three detectors may be used at high-speed intersections. The concept of this system is simply that of detecting the vehicle before it enters the dilemma zone and then extending the green until the vehicle clears the dilemma zone.

This placement scheme is shown in Figure 84 (Ref. 18). The location of the loops in this case is governed by the 85th percentile speed. The following equations are used to calculate the appropriate distances for the loops.

$$D = 1.47\,V_1 t + \frac{V^2}{30\,f} \tag{70}$$

$$D_2 = 1.47\,V\left(\frac{V}{30} + 1\right) \tag{71}$$

$$D_1 = D - D_2 \tag{72}$$

where:

V	=	85th percentile speed, mph
t_1	=	Perception-reaction time, secs
f	=	Coefficient of friction
D	=	Stopping distance, ft
D_1	=	Clearing distance, ft
D_2	=	Separation between loops, ft

With the loops positioned as shown, a vehicle passing over loop S_1 would actuate an electronic timer which would extend the green for the vehicle to reach loop S_2 in time T_1. Similarly, when the vehicle passes over loop S_2, a second timer would maintain the green while the vehicle proceeds toward the intersection. This design does not insure that vehicles traveling at speeds less than the 85th percentile speed would not be trapped in the dilemma zone.

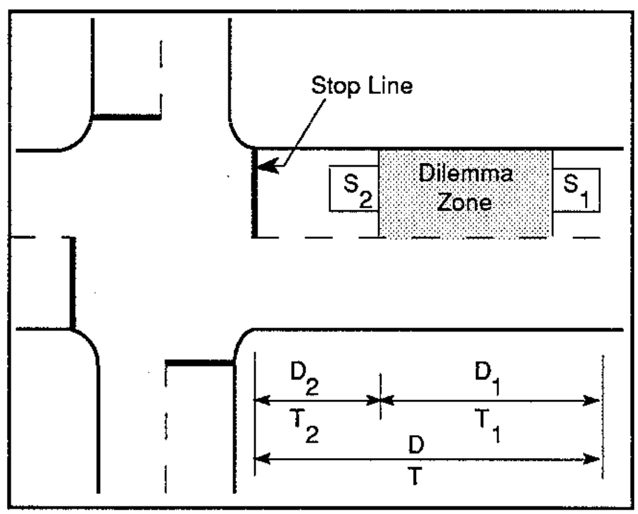


Figure 84. Green extension system – two detectors.

Extended Call Detector System

This concept uses a 70- ft (21-m) presence loop extending upstream from the stop line and a small extended call detector 250 to 500 ft (75 to 150 m) upstream of the stop line as shown in Figure 85. The

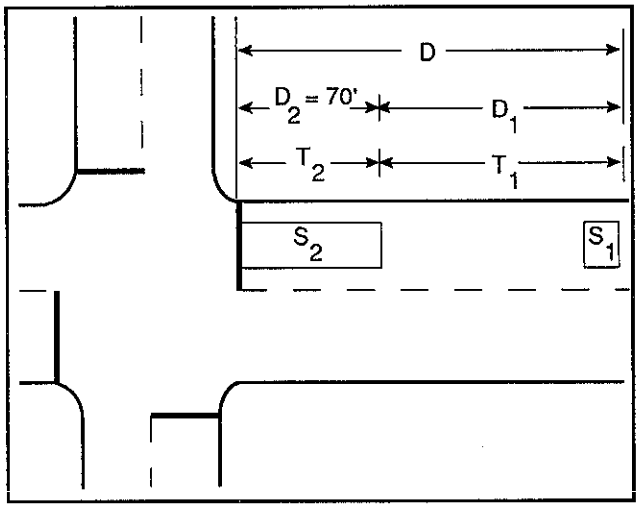


Figure 85. Extended call detector system.

magnitude of D is calculated based on Equation 70 and the speed limit or the 85th percentile speed. D_2 is set at 70 ft (21 m). T_1 is set equal to D_1 (which is $D - D_2$) divided by a lower limit approach speed which is generally assumed to be the 15th percentile speed. This time is set on the extended call detector. The controller is operated in the loop occupancy control mode.

This design ensures that the last vehicle, and those vehicles traveling below the speed limit, will not be trapped in the dilemma zone. A trailing vehicle may be trapped at the end of the maximum extension limit (maximum green time after an actuation on an opposing phase). The 70-ft (21.3-m) presence loop ensures that stopped vehicles queued behind the stop line will move forward and enter the intersection without triggering a premature gap out.

Multiple Point Detector Methods

The two methods described previously utilized two or (at most) three detectors. These techniques can be effectively employed at intersections with relatively low speeds. As discussed earlier, when speeds are high, the dilemma zone becomes longer and more detectors are needed to accommodate a wide range of approach speeds. There are three commonly used techniques for determining the placement of detectors. (These methods are identified by the name of the person, agency, or group which developed the technique.)

<u>The Beirele Method:</u> This method (originated by Harvey Beirele of the Texas State Department of Highways and Public Transportation, Ref. 19) uses a 1-second vehicle interval setting on a controller operating with locking detection memory. The detectors are 6- x 6-ft (1.8- x 1.8-m) presence mode loop detectors.

The outermost detector upstream of the intersection is placed at a safe stopping distance from the intersection for highest normal approach speed. Safe stopping distances are based on a 1-second perception/reaction time plus braking distances resulting from coefficients of friction between 0.41 and 0.54 for speeds between 55 and 20 mph (90 and 30 kph). The next detector is tentatively located at a safe stopping distance for a vehicle traveling 10 mph (16 kph) less than that assumed for the first detector. If the travel time between the two detectors is greater than 1 second, the downstream detector is relocated to allow the vehicle to reach the second detector within the 1 second vehicle interval set on the controller.

This location procedure is repeated for each successive detector until the last loop is within 75 ft (23 m) of the stop line, each time subtracting 10 mph (16 kph) from the maximum considered speed. The minimum assured green time is set on the controller to permit vehicles stopped between the last detector and the intersection to enter the intersection.

The Texas State Department of Highways and Public Transportation has also investigated a modification to the Beierle procedure which uses AASHTO stopping distance criteria. Figure 86 illustrates the detector spacing for various speeds used in the State of Texas.

<u>The Winston-Salem Method:</u> The second method of multiple detector placement was developed by Donald Holloman for that agency (Ref. 17). This is basically the same as the Beierle Method. The only difference is the Winston-Salem Method uses slightly shorter stopping distance for the outermost and innermost detector and incorporates speeds up to 60 mph (96.6 kph).

<u>The SSITE Method:</u> The third method was developed by the Southern Section of the Institute of Transportation Engineers (Refs. 20 and 21). This method uses an iterative process and engineering

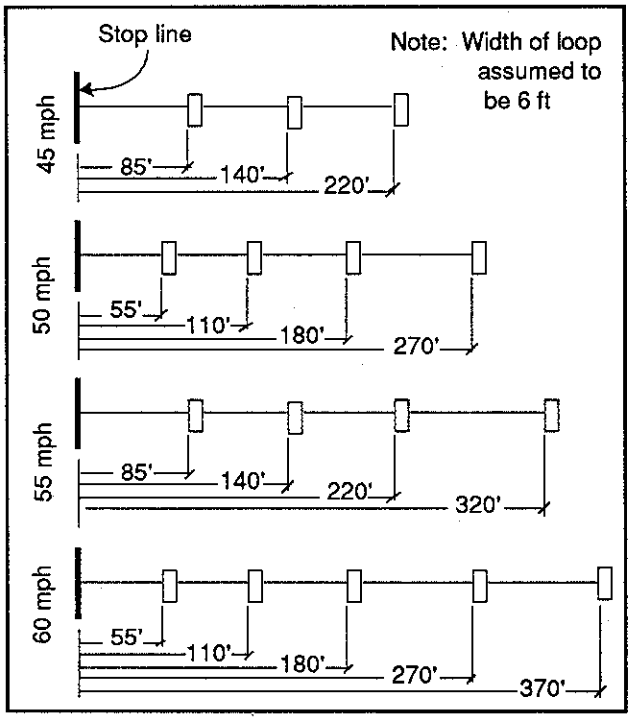


Figure 86. Multiple loop detector placement (Texas).

judgment in locating the detectors. The outermost loop is positioned to provide safe stopping distance as determined by data collected by the Southern Section. The other differences are that the spacing between successive loops is 2 seconds and the innermost loop is located at the stop line. The system also uses an allowable gap between five and seven seconds which is greater than other methods.

These methods differ primarily in the number of loops used and in the spacings. Table 17 presents a summary of the different placement mode methods and their characteristics.

Since the length of the dilemma zone becomes larger as speed increases, more detectors are required to track the vehicle through the dilemma zone. Moreover, the longer the spacing between detectors, the longer the vehicle interval and the less efficient the controller is likely to be.

In general, it appears that the multiple detection systems are more appropriate for use with high mean approach speed and high variability.

Table 17. Summary of detector placement methods for dilemma zones.

Design / Method		Green Extension Systems for Semi-Actuated Control	Extended Call Detector Systems for Basic Controllers	Multiple Detection Systems		
				Beierle Method	Winston-Salem Method	SSITE Method
Controller Memory		Non-Locking	Non-Locking	Locking	Locking	Non-Locking
Detector Type		Presence	Presence	Presence	Presence	Presence
Speed Range		V = 85th Percentile	V = 85th Percentile	$V \leq 50$	$V \leq 60$	$V \leq 60$
Loop Lay-out	Outer-most Loop*	$D=1.47Vt+\frac{V^2}{30f}$	$D=1.47Vt+\frac{V^2}{30f}$	Use Stopping Distance from Ref. 19	Use Stopping Distance from TEH, Ref. 17	Use SSITE Report Ref. 20
	Inner-most Loop	$D_1=1.47V(\frac{V}{30}+1)$	0	Within 75 feet of the Approach Stop Line	86 feet	0
	Spacing Between Loops°	$\frac{D-D_1}{V} > 2$ seconds	$\frac{D-70}{V_{low\ limit}} > 2$ sec	1 second	1 second	2 seconds
	Number of Loops†	2 (or 3)	2	$\left\|\frac{V}{10}\right\|-1$	$\left\|\frac{V}{10}\right\|-2$	≤ 6
Allowable Gap		5 to 6 seconds	5 to 6 seconds	2 to 5 seconds	2 to 5 seconds	5 to 7 seconds

* - The distance is measured from the stop line

° - $V_{low\ limit}$ = low speed limit, for example use 15th percentile speed

† - $\left|\frac{V}{10}\right|$ represents the integer part of $\frac{V}{10}$ for example $|3.7| = 3$

Typical Design Options

To simplify their detector design process, the Pennsylvania Department of Transportation has defined seven basic design options together with an evaluation of the characteristics of each option. The following excerpt presents these options from the PennDot Traffic Signal Design Handbook (Ref.22).

Option 1: Consists of a long loop 6 ft x 50 ft maximum for each approach lane. This enables individual lane detection in the presence mode. Although it requires more loop wire than the other options, its initial cost is the lowest as less lead wire and fewer pull boxes are required. Construction cost is lowest of all options. The disadvantages include: all detection for a lane is lost should the loop break; and long loops are the least sensitive of all loop configurations. When the sensitivity is increased, the loop becomes more susceptible to detecting vehicles in adjacent lanes.

Option 2: Consists of sequential short loops for individual lane detection in either the pulse or presence mode. They may be wired either in series or parallel; however, best results are achieved when alternate loops are paired and wired in parallel to separate input channels. There is an added safety feature inherent to this option in that should one loop fail, detection is not completely lost. Although the initial cost is higher than that for long loops, maintenance is easier, as only a small loop need be replaced in case of damage.

Like the long loop, the short loops are susceptible to detecting vehicles in adjacent lanes; however, they are more sensitive and are better suited for sensing small vehicles.

Option 3: Consists of a long quadrupole loop for each approach lane. Its operation is identical to that of Option 1. The major advantage of this option is it is sensitive enough to detect bicycles and small motorcycles, yet it does not detect vehicles in adjacent lanes. Like Option 1, detection for an entire lane is lost should the loop be severed. Construction cost is approximately 20 percent greater than for Option 1.

Option 4: Consists of one short loop per lane located in advance of the intersection based on normal approach speeds. This option, which operates in pulse mode only, is best suited for providing extension intervals on roads with higher travel speeds.

They can also be used for individual lane counting and gap determination. There are two disadvantages with this option. First, should the loop fail, detectorization for the approach would be lost. Second, since there are no loops near the stop line, any vehicle entering the approach from a driveway between the loop and the stop line would not be detected and would have to wait for another vehicle to place a call for the necessary phase unless calling detectors are used.

Option 5: Is basically the same as Option 4 except a single wide loop is used for multi-lane detection instead of individual lane detectors. Construction is less expensive than Option 4; however, should breakage occur, detection on that approach would be completely lost.

Option 6: Consists of a single short loop per approach lane for use where a driveway is located between the intersection and the area of detection for Options 4 or 5. Traffic generated by the driveway would be unable to actuate its phase without the additional detectors placed near the stop line. A 6- x 6-ft (1.8- x 1.8-m) calling detector is used in these cases.

FUNCTIONAL APPLICATIONS

There are several conditions that may require detectors to perform special functions. These applications include small vehicle and bicycle detection, detection of long vehicles or large trucks, queue detection at freeway off-ramps, vehicle counting, and special safety applications to prevent accidents and reduce speeds.

A summary of the various loop shapes and their operating characteristics is given below in terms of the functional requirements determined by the operating agency. These requirements are typically based on the type of application (e.g., intersection control, freeway surveillance and control, etc), traffic or vehicle mix, climate, and other site specific conditions.

DETECTION OF SMALL VEHICLES

The cost of fuel has increased steadily during the 1980's. As a result, the trend toward smaller, fuel-conserving vehicles has become more pronounced. These vehicles range from the small compact automobiles to the 100 cc motorcycle, and even to the moped and light-weight bicycle. The increasing number of these small vehicles and their behavior patterns often necessitates their detection with existing standard detector configurations.

A presence detector should be able to detect a small motorcycle and hold its call until the display of a green signal. If a call is dropped prematurely by the detector, the motorcyclist could be trapped on the red phase. The required time of hold should at least match the shortest cycle time observed at the intersection. The NEMA Standards (see Appendix J) specify a minimum hold period of 3 minutes. The FHWA Type 170 Hardware Specification also requires that the detector system be capable of holding the call of a 100 cc Honda motorcycle for a period of 3 minutes (see Appendix K).

Calls may be dropped prematurely in some older detectors that include circuitry intended to compensate for environmental drift, primarily due to changes in temperature and moisture. This circuitry will frequently neutralize a weak detection from a small vehicle within a period of less than a minute. Newer detectors do not have this problem and all meet the NEMA Standards and the Type 170 Specification which both require a minimum hold of 3 minutes.

In California and other parts of the country with temperate climates, the bicycle has become a significant mode of transportation. As such, it has become necessary for proper operation and safety, to detect bicycles at signalized intersections. The inherent problems associated with bicycle detection include:

- Locating the loop on the street to assure the rider will be within the zone of detection. A separate bike lane is ideal, but not always possible.

- Sequencing the traffic signal to accommodate a detected bicycle. This cannot be done with some control techniques.

- Providing sufficient signal timing to avoid trapping the bicyclist in the intersection. This also can be a problem with some intersection designs.

In response to these problems, it has been suggested that the detector electronic unit have extension timing and delay features. In such a system, one loop is located about 100 ft (30 m) from the stop line and the second loop is located at the stop line. When a bicycle is detected at the first loop, the extension time is provided to hold the green to allow the bicycle to reach the loop at the stop line.

When the detection is made at the stop line, extension time is provided to allow the bicycle to move far enough into the intersection to safely clear before the end of the yellow indication. If the detection occurs when the light is red, the minimum timing feature assures that when the light turns green, the minimum green time will allow safe crossing of the intersection. This type of operation works best in a bike lane. The loop in the bike lane with a standard detector unit could be wired to call the pedestrian timing which would allow adequate time for the cyclist to cross the intersection.

A delay feature is used for cases where vehicles merge into the bike lane to turn right. The detection is not immediately registered so that the vehicle may complete a right turn without creating delay for other traffic including bicycles.

There are a number of factors that must be considered in determining the most effective detection configuration to be used when policy dictates that small vehicles including bicycles must be detected. Important determinants that must be carefully weighed include: the shape of the loop, the width of the lane, and the loop placement within that lane. Loop configurations that can be used to enhance the ability to detect small vehicles are described below.

Multiple Interconnected Small Loops

One configuration that is frequently used for the detection of small vehicles is multiple interconnected small loops or, as it is often to, sequential short loops. The sensitivity can be controlled better with the multiple loops than with the conventional single long loop that must be set so high to detect small vehicles that false calls from the adjacent lanes (splashover) result. With the small loops, total loop inductance very close to optimum can be achieved by connecting the loops in series. In the past, series/parallel connections were mandated, however, newer detector units have obviated this need. Moreover, the small vehicle will be detected when it reaches the first small loop rather than at the stop line, as is the case with the long loop with a power head described later. Also, should one loop fail, there would still be some detection capability in that lane.

Quadrupole Loop Configuration

The quadrupole loop configuration was first used in the early 1970's. As shown in Figure 87, this configuration adds a longitudinal saw cut in the center of the lane. The loops are wired in a figure eight pattern so that the center wires have current flowing in the same direction. Their fields reinforce each other, improving the capability to detect small vehicles. The center wires counteract the fields of the outer wires, which have their current flowing in the opposite direction from the center wires. The influence of the outer fields is diminished, reducing the possibility of splashover.

The single wire configuration ("1-2-1" with one layer in the perimeter slots and two layers in the center slot) shown in Figure 87 is used for the detection of automobiles, trucks, and the larger motorcycles. A double layer design ("2-4-2") is recommended to include the detection of small motorcycles and bicycles. Some agencies wind the 2-4-2 as two, 2-turn loops rather than the traditional figure eight winding pattern. No definitive tests were found to favor either method.

Placement in the lane is another important consideration. Installations placed in the center of the lane may fail to detect the small motorcycle if the travel path is outside the quadrupole field. For example, motorcyclists waiting to turn left will usually stop on the left side of the lane and may be outside of the quadrupole field. In the case of a lane where detection is required for a left turn, it is recommended that the left edge of the quadrupole be located no further than 2 ft (61 cm) from the left edge of the left turn lane.

The quadrupole is used as a short or long loop and as a single element, or in combinations such as series, or series/parallel. This configuration is used effectively in many installations across the country not only to detect small vehicles, but to eliminate the problem of adjacent lane detection (splashover) in high sensitivity inductive loop systems.

Short quadrupoles (less than 30 ft (9 m)) tend to lose high-bed sections of trucks. The quadrupole is really two loops whose height of field will be approximately 2/3rds of the short leg of the loop. In this case the approximate height will be 2 ft (0.6 m). In the longer loops (greater than 30 ft (9 m)), there are always one or more wheels or axles over the loop.

It is generally agreed that the 6-ft (1.8 m) quadrupole loop detects bicycles better than most other loop configurations. The major problem with this configuration and the small bicycle is the need for the bicyclists to ride close enough to a wire within

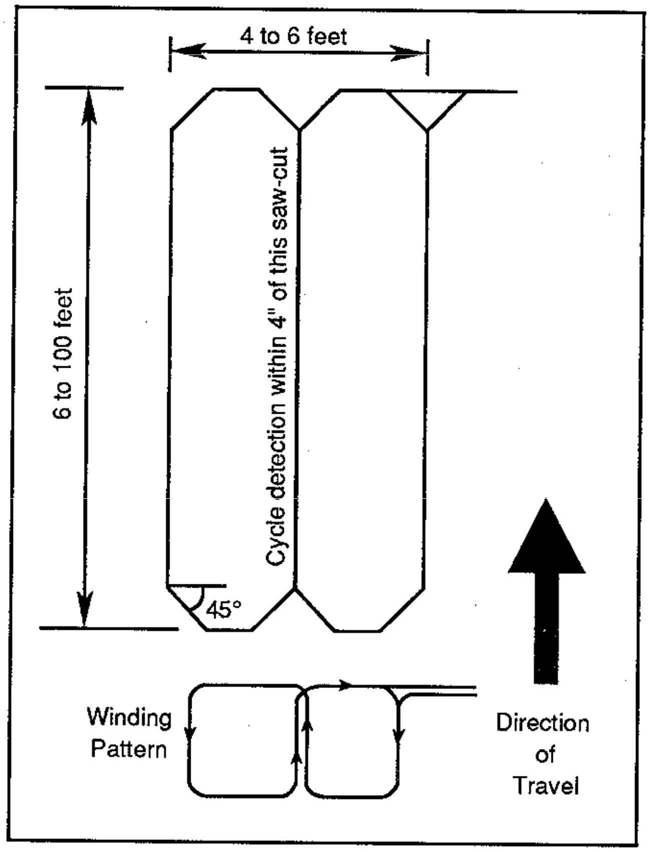


Figure 87. Quadrupole loop configuration.

the quadrupole to be detected. A number of unique pavement markings and signs have been used for this purpose. The pavement marking identifies the location of the wire and the sign explains the markings to the cyclist.

Figure 88 diagrams one such system used in Clarke County, Georgia. In this system, a pattern of 4- x 18-in (10- x 46-cm) white strips were placed 18 in (46 cm) apart starting at the stop line. The length was kept short since only one actuation is necessary to call the green indication.

In the City of San Luis Obispo, California, an aggressive public information program was mounted to inform bicyclists that they could make the red light turn green by traveling over the pavement markings shown in Figure 89. These markings were painted on all appropriate through, right, and left turn lanes at all signalized intersections that contained loop sensors.

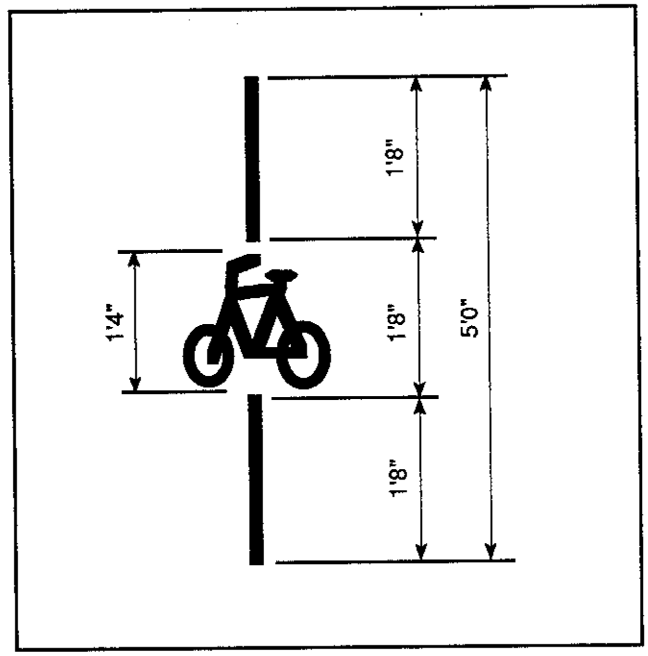


Figure 89. Special bicycle pavement marking.

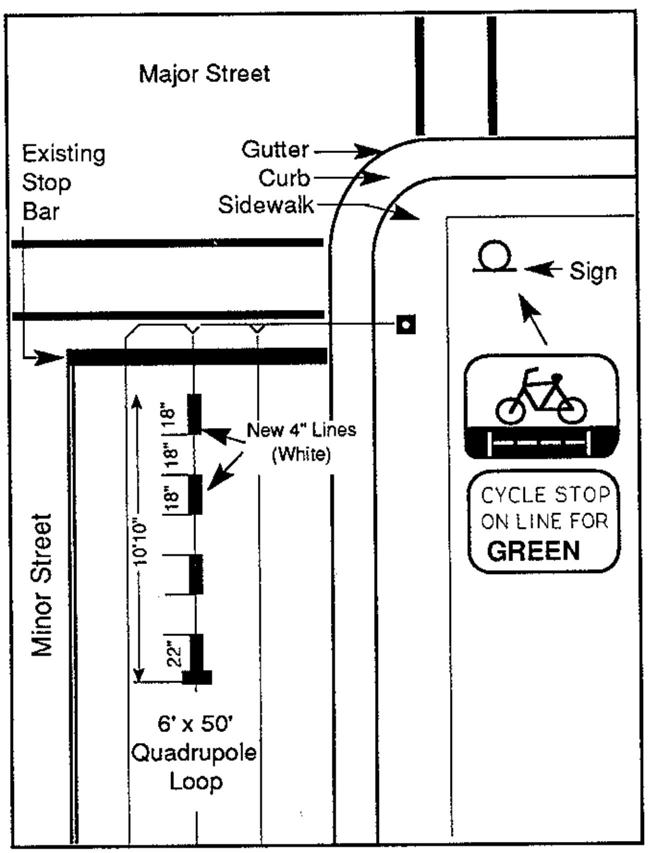


Figure 88. Bicycle detector sign and markings.

Chevron Loop Configuration

The chevron configuration used to detect small vehicles is shown in Figure 90 and consists of one or more four-turn parallelogram loop(s) with the short section in the direction of traffic. The long side of the parallelogram makes a 30 degree angle with the

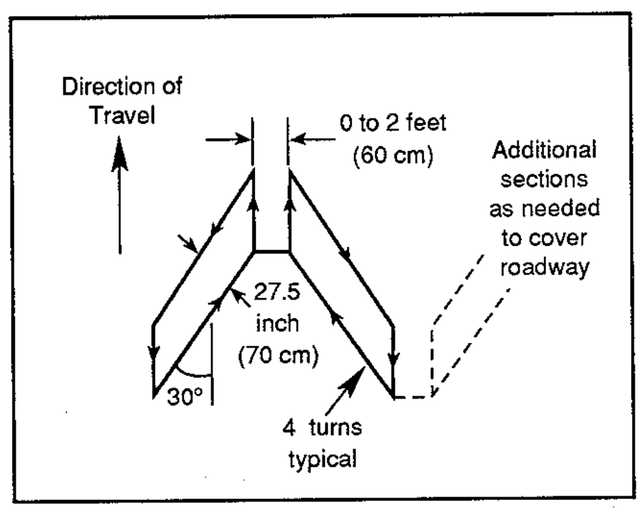


Figure 90. Chevron loop configuration.

short section. The long sides of the loop sections are 27-1/2 in (70 cm) apart. Adjacent ends of the successive loop sections may be in a single slot or separated by 2 ft (60 cm). This alignment allows a smaller vehicle to cut the lines of flux more efficiently (Ref. 23).

Loop sections are wound alternately clockwise and counterclockwise so that currents in adjacent loop ends are always in the same direction. Successive sections wound in the same direction would produce dead-paths where the sections are joined.

Long Loop with Power Head

Frequently, a small motorcycle or bicycle will not produce a sufficient shift of inductance in a one-turn 6 x 20 ft (1.8 x 6.1 m) or longer loop. Some detector units will detect these small vehicles with two or more turns of wire although there are dead areas in the center of the loop.

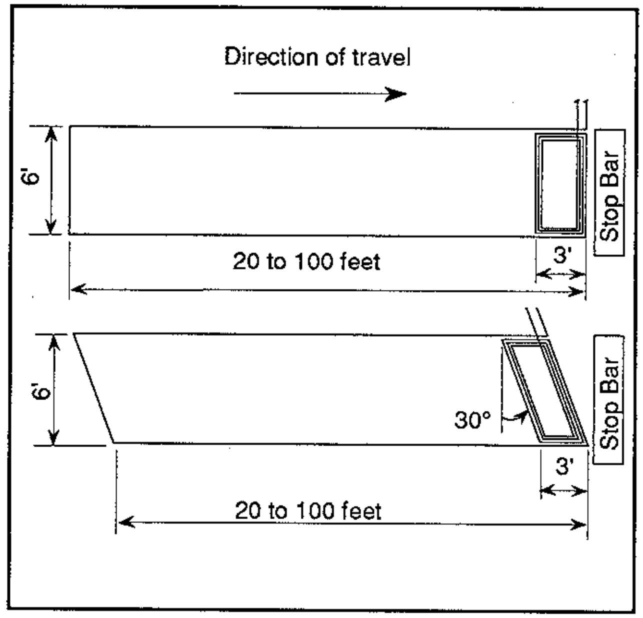


Figure 91. Long loop with powerhead.

One approach is to use a small power head at the stop line with the long loop. This configuration is shown in the upper portion of Figure 91. The standard power head can be improved by angling the transverse wires as shown in the lower portion of Figure 92. The angling will cause the small vehicle to cut the lines of flux more efficiently; thereby increasing the signal by as much as 25 percent. The disadvantage to this concept is that the vehicle may not stop on the powerhead unless it is clearly indicated by paint or signs.

There has been some concern expressed that there may be some liability because small vehicles are not detected throughout the zone of detection. Although these vehicles are detected at the stop line, the controller operation is based on the detection of vehicles in the approach. Other engineers feel that the important element is to detect the small vehicles to ensure that they will receive the green signal, not to ensure that the signal operation is optimized for these vehicles. They do not believe that any liability is incurred.

A way to avoid the problem of not detecting small vehicles throughout the detection zone is to use sequential short loops in the lane rather than a single long loop. Also, modern detectors have the ability to detect small vehicles without the resultant splashover that occurs when using the single long loop with high sensitivity settings. These two factors have reduced the need for the powerhead design.

Bicycle Detectors

The State of California has developed what is termed a Type D loop configuration to better detect bicycles (Ref. 24). This configuration, shown in Figure 92, is a palm shaped loop that fits into a 6-ft (1.8-m) square. The loop has three turns of wire when a single Type D loop is connected to a detector channel, and five turns of wire if one Type D loop is connected in series with three 6- x 6-ft (1.8- x 1.8-m) loops on a detector channel (see Type 5DA or 5DQ installations in Figure 76). At the acute corners of this loop, measures must be taken to protect the wire in the bend. Drilling a hole in the corner or chipping out the inner angle to provide a radius will prevent kinking the wire. This loop may be used in either traffic or bike lanes.

In some applications, it is desirable to detect the presence of a bicycle across a greater portion of a full width traffic lane. One loop configuration that is

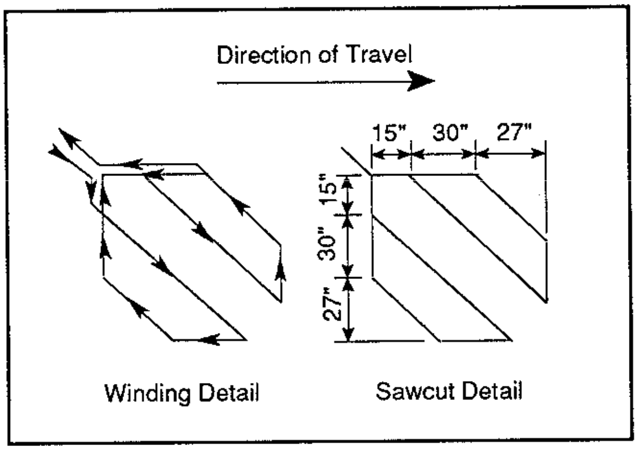


Figure 92. Type D loop configuration.

used is an 8-ft (2.4-m) square with three diagonal saw cuts traversing the square. Two layers of wire are used and are wound so that the current flow is in the same direction for both layers. This results in four layers of wire in each diagonal. The acute angle corners are rounded to prevent damage to the wires. This is a special configuration that is used in areas of heavy bicycle traffic such as near the University of California at Davis.

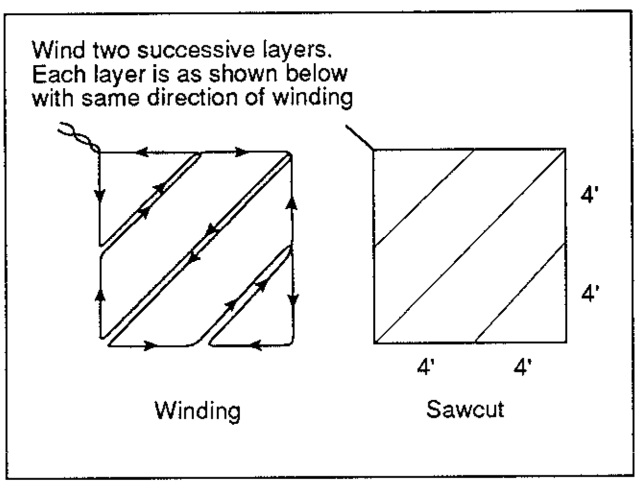


Figure 93. Wide coverage bicycle loop.

One method of bicycle detection is to place loops within the traveled area of a bike lane that will reliably detect bicycles and provide an adjustable timed call extension to hold the call to the controller long enough for the bicycle to clear the intersection when operating in a Loop Occupancy mode. An appropriate design that is essentially two quadrupoles side by side is shown in Figure 94. The 4 1/2- x 6-ft (1.4- x 1.8-m) configuration provides assurance of detecting all bicycles and complete adjacent lane rejection.

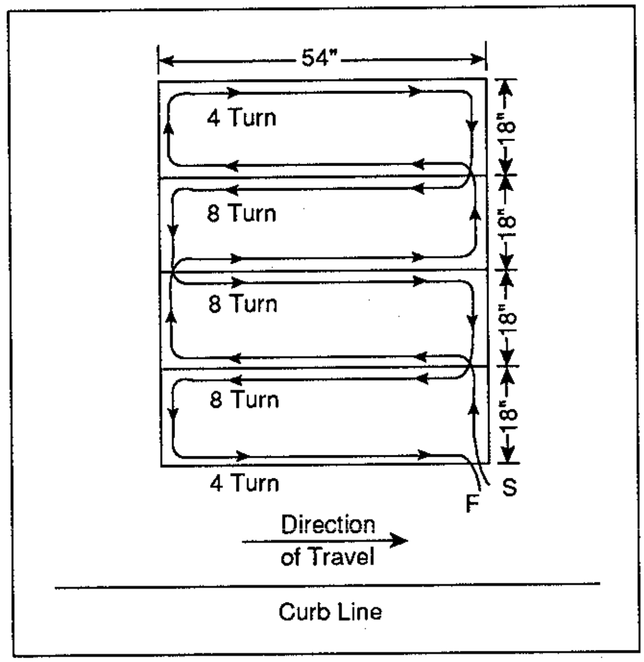


Figure 94. Bicycle lane loop layout.

DETECTION OF LONG, HIGH BED VEHICLES

It is generally a good idea to allow long, high bed vehicles (e.g., tandem trucks, semi-trailer trucks, and cars pulling trailers) to travel through the intersection without stopping. There are three strong reasons why long vehicles should not be stopped:

- Jack-knifing of truck-trailers tends to occur under heavy braking conditions.
- After stopping, a large vehicle requires a longer start-up time delaying following traffic.
- Increased noise and air pollution are associated with heavy truck start-up.

One detection alternative for trucks consists of two loops spaced 30 ft (9 m) apart and located 302 ft (90.6 m) from the stop line (Ref. 25). This is the distance that would be required for a loaded semi-trailer traveling 45 mph (72 kph) to come to a safe stop. The detector logic requires that the second loop be activated before the first loop is vacated.

One freeway program (in Detroit) required that all vehicles be detected as a single entity, including high-bed trucks, semi-trailers, and tanker trucks as well as conventional vehicles. Their test of three turn 6- x 6-ft (1.8- x 1.8-m) loops did not adequately satisfy their requirement. After numerous trials, the agency determined that a seven turn 6- x 6-ft (1.8- x 1.8-m) loop rotated 45 degrees to form a diamond shape was superior particularly in their accuracy in detecting trucks. The diamond shape was further refined by carefully adjusting the angles of the diamond to avoid splashover (Ref. 25).

One manufacturer states that the ability to detect trucks reliably due to configuration change is not due to the diamond shape of the loop as suggested above. Rather it is due to the increased number of turns which increases the inductance of the loop. The amount of signal received by the detector is dependent on the loop inductance to lead-in cable inductance ratio. Simply stated, when the loop inductance to lead-in cable inductance ratio is equal to one, then the amount of change seen by the detector is 1/2 the change occurring in the loop. By increasing the loop inductance (by increasing the number of turns to seven), Detroit has greatly increased the amount of change received at the detector, thereby, resulting in more reliable detection of high bed trucks.

QUEUE DETECTION

Freeways that are operating under congested conditions are likely to periodically result in heavy volumes on off-ramps. When these off-ramps terminate at a signalized intersection, backups can extend to the freeway lanes, causing even more congestion. Depending upon agency policy, it may be desirable to detect and discharge such queues before they become a freeway problem.

One solution uses an actuated controller with a queue discharge system consisting of a queue detector with a built-in delay time (Ref. 21). As shown in Figure 95, the queue detector loop is located at a strategic position at the upstream end of the off-ramp. A timer starts when a vehicle enters the detection zone of the queue detector and resets to 0 when the vehicle exits the zone of detection. If the system times a predetermined number of seconds, the detector's normal output relay is energized.

If the queue of vehicles waiting at the red indication extends upstream to the queue detector, a vehicle will be over the loop longer than the selected delay time. When the delay timer times out, the detector logic issues a signal to discharge the queue. The green signal will remain on until all vehicles are moving with gaps longer than the loop itself.

The detection loop must be long enough to span the distance between standing vehicles. Concomitantly, it must be shorter than the shortest gap in moving traffic so that the breaks between moving vehicles will cause the delay timer to reset. This latter consideration can be critical when the queue detector covers two or more lanes. A loop length of 30 ft (9 m) will generally satisfy this criteria.

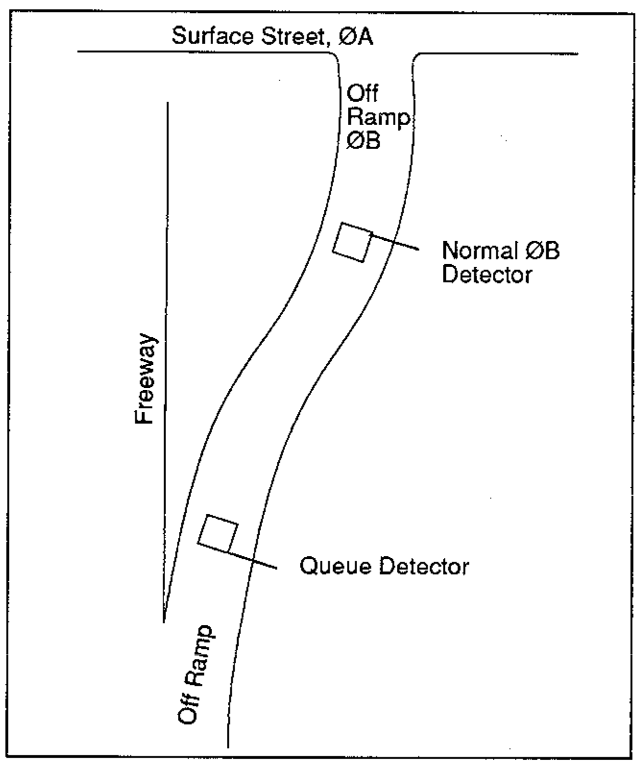


Figure 95. Queue discharge system.

DETECTOR DESIGN FOR TRAFFIC CONTROL SYSTEMS

The detector requirements for area-wide traffic control systems are dependent on the type of control to be implemented. Time-of-day control does not require detectorization as it is basically a time-clock operation. First generation traffic responsive control and other advanced control strategies do require a system of detectors capable of early identification of traffic trends within a system. It must provide an early indication of a peak period for the beginning of heavy traffic. Thus, the detectors must be placed on heavily traveled links with traffic patterns representative of the significant flows within a section of the area-wide system.

The application of detectors in various forms of traffic control systems was defined in Chapter 3. Detector design considerations for traffic responsive traffic control systems are discussed below.

Accuracy Goals

When designing a detector surveillance system for use in computerized traffic control systems, the use of the gathered data and measures to be collected must be considered. As discussed in Chapter 3, volume and occupancy can be measured effectively. The remaining variables are only rough approximations of the actual conditions. In estimating link-specific volumes, three components of error combine to limit the accuracy potential of each of the control variables. These are:

- A measurement error in the data on which the predictor operates.
- A prediction error in estimating the underlying mean.
- A component reflecting the randomness of traffic.

The data error can be expressed as X percent probability that the error would be within Y percent. A normal distribution is assumed for the mean value of a large sample. The count error for First Generation UTCS critical intersection control was plus or minus three vehicles 90 percent of the time (Ref. 26).

For determining measures of effectiveness, several filtering and smoothing techniques may be used. A filtering equation is used which takes the old smoothed value (like volume) and determines the difference between it and the latest unsmoothed value. The difference is used to update the value of the smoothed data.

Another error is introduced for vehicle presence because the computer is not observing vehicle presence continuously, but is sampling. This results in an error in occupancy and speed computations. There will always be a sampling error that increases as vehicle speed increases. This error cannot be eliminated, but can be decreased by increasing the sampling rate. Ref. 27 describes how to compute the percent sampling rate as well as filtering and smoothing techniques.

Link Selection for CIC

The location of detectors in a traffic control system is a three step process. First, links are selected for detectorization. The lateral and longitudinal detector placements are then determined. The link selection must consider each function in the sequence, beginning with intersections which are candidates for Critical Intersection Control (CIC). Candidate intersections are those that could take advantage of variable split, but which operate in an unsaturated condition. When detectorizing an intersection to operate under CIC, all approaches served by phases with variable green times must be detectorized. The step-by-step process for determining CIC candidates is given in Ref. 28.

The need for measuring general traffic trends will probably be satisfied by the CIC detectors in area-wide surveillance systems. If this type of detectorization has not been installed, detectors should be located on major collectors or distributors to the network to obtain system trends with a minimum of instrumentation. Another group of candidates for this type of detectorization are entrances and exits of large parking facilities that would have a significant effect on local traffic conditions.

The location of detectors to evaluate system operation is, to a large extent, dependent upon the degree of accuracy required by the evaluation. If a general evaluation of changes in system operations is desired, the detector placement for traffic responsive operation would be adequate. If a more detailed evaluation is required such that speed and delays can be determined, it will be necessary to increase the number of detectors within the system. The cost of this degree of detectorization may suggest that other techniques be employed.

Lane Selection

It has been demonstrated that a single detector in the lane carrying the maximum through volume will be the most representative of the traffic to which the signal must respond. Moreover, the signal should be timed for critical lane volumes. However, it is not possible to derive reliable total volumes from a single detector. Yet, multiple loop detectors located in noncritical lanes may introduce errors that exceed the value of the data they provide as they are measuring parking vehicles, turning vehicles, etc. (unless individual lane detection is used). Thus, the most reliable data is derived from the critical lane. The critical lane (defined as the one carrying the greatest volume) is usually easy to identify by observing the length of queues at the intersection.

At locations where the critical lane changes with time of day, multiple lanes should be detectorized and the time of day factors used in the software to select the detector currently measuring true critical lane volumes.

Field measurements should be made of the traffic volumes on each lane of an approach (Ref. 5). Average lane volumes per cycle are computed and compared with the tentative critical lane. There are four conditions that will require engineering judgment, including project priorities and a knowledge of individual link traffic. These conditions include:

- Approaches where one lane is always critical.
- Approaches where the critical lane shifts between two lanes, but the difference in volume is not great or the shift is infrequent.
- Approaches where shifts in critical lanes are significant.
- Approaches exhibiting specific critical lanes during peak hours, but, for various reasons, erratic shifts in critical lanes occur during non-peak periods.

It is unusual for more than two lanes to require detectorization and most often only one lane will need a detector. After the critical lanes have been identified for the links to be detectorized, it is necessary to determine the longitudinal placement of the detectors on the links.

Longitudinal Placement

There are two guidelines for the longitudinal placement of detectors for signal system control. One relates to the upstream intersection and the second refers to the downstream intersection. From the upstream intersection, a detector should be downstream from the zone of acceleration of vehicles entering the link. A distance of approximately 230 ft (69 m) is recommended.

From the downstream intersection, the detector should be upstream from the point beyond which standing queues of vehicles do not usually extend. Although this distance is a function of the cycle length, split, and offset, it is recommended that values of 200 to 250 ft (60 to 75 m) be used in urban grid areas and values of 300 to 350 ft (90 to 105 m) be used in suburban arterial systems. When both criteria cannot be met, the criteria based on typical queue size is considered the more critical.

One additional longitudinal detector placement issue is in the location with respect to traffic sinks and sources (e.g., parking facilities). Detector placement research has shown that a sink/source has a minimal effect on traffic measured in the critical lane when the facility is operated as a sink such as a parking garage during the morning peak. Turns into the garage are made from the curb lane which is not usually the critical lane.

Only during the evening peak hour when the garage is functioning as a source are there measurable effects on the critical lane. An evaluation of the paths of vehicles entering the lane from a source showed that most vehicles wait for a sufficient gap to enter the specific lane within the link. It is suggested that a critical lane detector be located at least

50 ft (15 m) downstream from the source, provided that the downstream intersection criteria is not violated. In general, unless the source contributes more than 40 vehicles per hour to the critical lane, the effect of a source on the link demand is not significant.

System Detector Location Summary

The information developed in earlier tasks will result in the selection of links to be detectorized, the lanes in which the detector should be placed, and an approximate location with respect to the upstream and downstream intersections. With this information shown on a map, a field visit should be conducted for each link.

A "walk through" by the designer will permit the selection of final locations considering access to the control equipment, special driveway problems, or other roadway or parking conditions. Each location must pass a reasonableness test as well as the analytical test.

Several general guidelines have been suggested concerning the field location of individual loop detectors (Ref. 28):

- A detector should be located in the center of the traffic flow, not necessarily in the center of the marked lane. The center of the traffic flow can usually be identified by the oil markings or tire tracks on the pavement.

- The detector should be located in the areas of stable traffic flow. Sections of a link with excessive weaving or heavily impacted by entering and exiting driveways should be avoided.

- Where a major driveway is located within a link, the detector should be located at least 50 ft (15 m) downstream from the driveway provided the detector is at least 200 ft (60 m) upstream of the stop line.

- Traffic detectors should not be located within 10 ft (3 m) of any manhole, water valve, or other appurtenance located within the roadway. This distance is required to permit sufficient clearance for work on the manhole without disturbing the detector.

In summary, the final decision concerning the location of detectors for advanced traffic control strategies is a blend of analytical procedures coupled with engineering judgment. It must be recognized that not all links can be instrumented to yield input measures within the accuracy required by the algorithms. Short links, and links with extremely poor lane discipline are typical of those that are not compatible with accurate instrumentation.

LOOP DETECTOR ELECTRONIC UNIT

The operational characteristics of the various types of detector electronic units being manufactured today are discussed in detail in Chapter 2. Requirements for loop detector electronic devices are included in both the NEMA Standards and the Type 170 Specifications (see Appendices I and J). The NEMA Standards define a series of self-contained loop detector units designed for shelf mounting. It also describes a card-type detector unit designed to insert into a multi-card detector housing rack. The revised NEMA Standards (TS-2) are expected to emphasize card-rack mounted units. The Type 170 Specifications define card-type detector modules only, that are designed for insertion into the input file of the cabinet system.

The NEMA detector units are available with either one, two, or four independent detector channels per unit. Some agencies insist on using only single channel detector units because they believe that failures in the unit can be more easily corrected by replacing a single unit rather than having to replace a multiple channel unit for a single channel failure. Current reliability of detector units makes this argument obsolete. The rack-mounted modules used in the Type 170 system contain either two or four independent channels.

The NEMA Standards also define optional timing features, allowing for the delaying or the extension of the detector output. In the delayed call mode, the detector will wait a user-defined period after a vehicle enters the detection area, before it starts the output signal. In the extended call mode, the detector will extend the output after the vehicle leaves the detection area. The Type 170 detector does not provide this capability as it is normally performed by software in the controller unit itself.

MAGNETOMETER CONFIGURATIONS

The magnetometer detector system consists of one or more magnetometer sensors (probes), the magnetometer detector unit, and the lead-in cable between the sensor and the detector unit. A typical magnetometer installation was shown earlier in Figure 36. The probe sensor installation is shown in Figure 96.

As described in Chapter 2, the magnetometer is a passive device. There is no radiated field or cone of detection. The probe-type sensor detects a change in the vertical component of the Earth's magnetic field caused by the passage or presence of a vehicle. The magnetometers, like the inductive loop detector, can be used for either passage or presence detection.

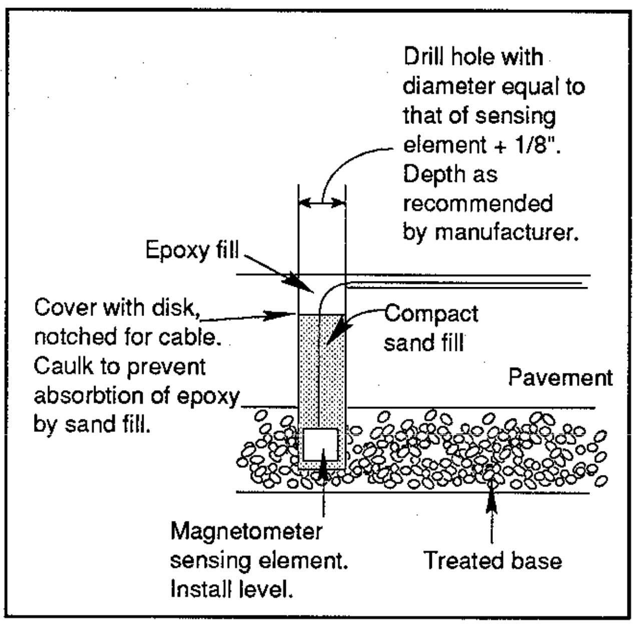


Figure 96. Typical magnetometer probe installation.

Because the probes are buried in a drilled hole approximately 18 in (0.5 m) below the surface, they are primarily used in the northeastern United States where the pavement deteriorates more rapidly due to thermal expansion and contraction and suffers damage from snow-removal equipment. They are also used in areas where loops cannot be cut in the road surface, such as on steel bridge decks.

The configuration for a magnetometer installation is dependent on a number of factors that must be considered. In designing the optimum configuration for a specific location, it is necessary to determine the best tradeoff between these factors. The following section discusses these factors and their impact on the ultimate configuration.

SITE SELECTION

Magnetometers will detect a vehicle whenever a sufficiently intense portion of its magnetic shadow falls on a probe. The dimensions of a vehicle's magnetic shadow generally approximates the geometric dimension of the vehicle. In some cases, the magnetic shadow may be offset by a few feet in any direction.

SENSITIVITY

Detection units for the magnetometers typically provide two independent detection channels. Each channel may have up to 6 probes connected to its input device. If only one probe per channel is installed in the street, the entire channel sensitivity is available to that single probe. However, as the number of probes per channel is increased, the sensitivity is divided among the probes, thus decreasing the sensitivity of each separate probe. For example, when four probes are connected to a single channel, the total channel sensitivity remains the same, but the sensitivity at each probe will be reduced to one-fourth of the channel sensitivity.

It is therefore necessary to determine what type of vehicles are to be detected in order to select the proper spacing between probes and to define how many probes might be tied in together per channel. The number of probes required per lane and their optimum cross-lane position is determined by the lane width and the size of the vehicles to be detected. As a general rule, some portion of the vehicle must pass over a probe to be detected. Some general guidelines for the number of probes for a given type of vehicle and the number of probes per channel are given below.

- **Auto, Trucks, and Buses:** Install probes at 5 ft (1.5 m) intervals. Six probes per channel maximum.

- **Motorcycles (300 cc and larger):** Install probes at 4- ft (1.2-m) intervals. Four probes per channel maximum.

- **Motor Bikes (70-300 cc):** Install probes at 3-ft (0.9-m) intervals. Three probes per channel maximum.

- **Bicycles:** Install probes at 3-ft (0.9-m) intervals. Two or three probes per channel.

The magnetometer detection system will operate properly at latitudes north and south of the narrow equatorial band. Sites should be chosen to avoid conditions that would adversely affect operation, such as: adjacent to manholes or large pipes; near very high current transmission lines, trolley lines, or underground power lines; or within tunnels or other enclosing iron structures.

Magnetometers are frequently the detector of choice on bridge decks. Figure 97 illustrates a typical bridge deck installation. The presence of the steel deck over or under the probe has little effect on system performance. However, vertical structural steel members may detract from performance by reducing the intensity of the adjacent ambient magnetic field. As with loops, the most appropriate location for the probes is at the maximum distance from the steel supports or columns as shown in the illustration.

A magnetic field analyzer should be used to measure the intensity of the magnetic environment at the selected location. This instrument measures geomagnetic field intensity, magnetic noise, and a.c. magnetic field strength. It is especially useful at locations where the use of magnetometers is questionable (e.g. within tunnels, near large electrical devices, etc). A typical magnetic field analyzer is shown in Figure 98.

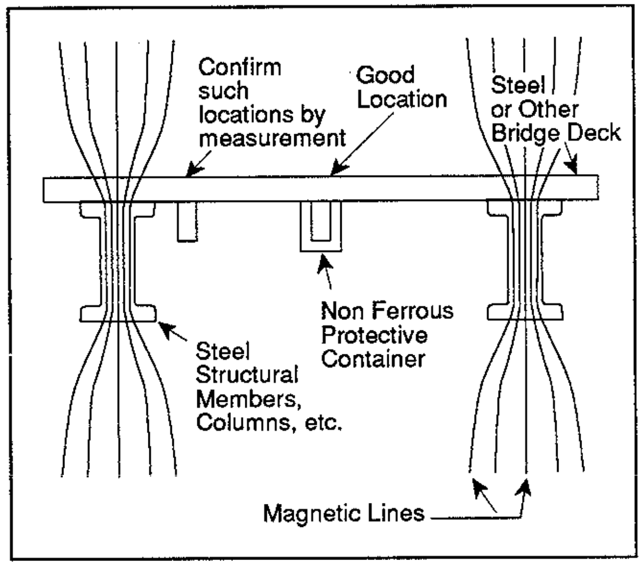


Figure 97. Typical bridge deck installation.

There are some situations where manmade magnetic noise is of sufficient intensity to impair performance of the magnetometer. These situations

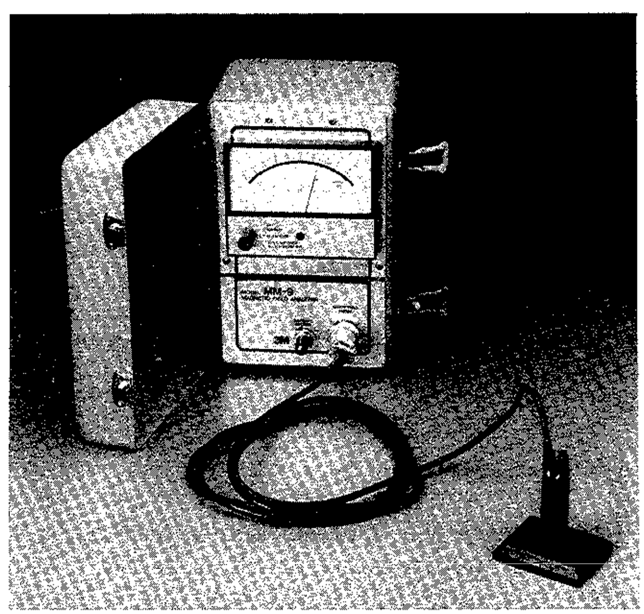


Figure 98. Magnetic field analyzer.

occur at sites where non-vehicular induced magnetic field changes exceed 5.0 millioersted. Magnetic field changes of this magnitude are almost always man-made, such as street car lines, some trolley bus lines, subway trains, or nearby elevators. However, few sources are of sufficient intensity to affect a detector probe located more than 30 ft (9 m) from the source.

PROBE PLACEMENT

The optimum lateral placement of probes in a lane is determined by such factors as the width of the narrowest vehicle to be detected, the lane width, and the detection quality required. Some part of the magnetic shadow of the vehicle must fall on one or more of the probes for detection to occur. Consequently, the maximum probe spacing is equal to the width of the narrowest vehicle to be detected. Since most autos, trucks, and buses are wider than 5 ft (1.5 m), a single probe centered in a 10-ft (3-m) lane would generally provide adequate performance. In a 12-ft (3.7-m) lane, a single probe may fail to detect some of the small vehicles traveling near the edge of the lane.

By increasing the number of probes to two per lane, virtually all four-wheeled vehicles within a 12-ft (3.7-m) lane would be detected. In this type of configuration, probes should be placed no further than 5 ft (1.5 m) from each lane boundary. Furthermore, if bicycles are to be detected, more probes per lane may be needed.

In general, the quality of detection improves as the number of probes per lane is increased because of the special averaging which results when the magnetic shadow of a vehicle falls on several probes judiciously spaced. Reduction in field intensity at one lateral position may be compensated for by increases at other positions.

PROBE DEPTH

Vertical placement of probes is an important determinant of system performance properties. Deep placement such as 18 in (45 cm) to 24 in (60 cm) provides good single count vehicle presence detection, but results in a lower signal level. Conversely, shallow placement, say 6 in (15 cm), provides higher signal levels, but with an increased incidence of multiple counts per vehicle. Multiple counts with shallow placement result primarily from the passage of major components of the vehicle such as engine, transmission, and differential, each of which may produce a separate magnetic perturbation. By increasing the depth to 18 to 24 in (45 to 60 cm), most vehicles yield a single perturbation of the magnetic field as the deeply buried probes sense the overall magnetic bulk of the vehicle rather than details of the understructure.

In summary, for detection application where only passage information is required and where multiple counts are not detrimental, probes should be located near the surface. Similarly, in constant speed applications where the time extension feature of the extendable presence mode can be used effectively, probes may be located near the surface. Small two-wheeled vehicles such as bicycles or motorbikes develop narrow, low intensity shadows. Their detection also requires shallow place of probes.

SUGGESTED CONFIGURATIONS

There are a number of configurations of probe placements. Some typical designs are presented in Appendix L. These examples illustrate the various tradeoffs that are available with probe depth and lateral distances between the probes. The examples include configurations for single lane, two, and three lane detection, wide lane detection, and detection for two-wheeled vehicles. Also shown are some suggested configurations for left turn lanes with zones of detection ranging from 30 to 70 ft (9 to 21 m). Figure 99 depicts detector configurations for various modes of operation.

WIRE SIZE AND CABLE SELECTION

Minimum wire size is determined by the cable length and the number of probes per channel. The probe excitation circuit provides current at a constant 125 milliamperes peak-to-peak, but is limited to a 15 volt peak-to-peak swing (see Chapter 2). Maximum allowable probe-cable assembly resistance is therefore 125 ohms. At resistance levels below this limit, system operation is normal. At higher resistance levels, instability and performance degradation will occur.

Effective resistance of each probe is approximately 4 ohms. Probes on the channel are connected in series electronically so their resistance is additive. Allowable cable resistance is 120 ohms less the sum of the probe resistances. AWG #22 copper wire pairs have a loop resistance (going and returning total) of 35 ohms per 1,000 ft (300 m), AWG #20 pairs have 20 ohms, and AWG #18 pairs have 13 ohms. Because of the changes in wire resistance with temperature, it is recommended that #18 AWG wire be used on cable runs exceeding 2,000 ft (600 m) in climates where extreme temperature ranges are typical.

Interconnection of the magnetometer detector and probes requires two pair of conductors per channel. One pair supplies the probe excitation current and the other carries the return signal. Properties of the cable become especially significant in long transmission distances of over 2,000 ft (600 m). The cables should combine distance capability with high noise immunity and environmental tolerance.

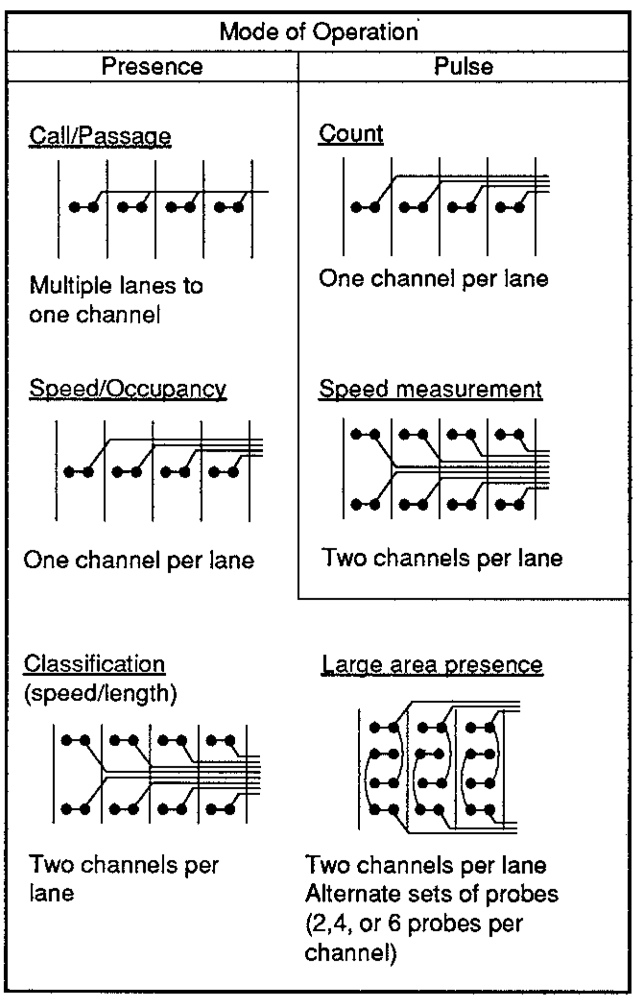


Figure 99. Magnetometer probe placement.

As discussed earlier, up to 12 probes per channel can be used. However, as the number of probes increases, the allowable lead-in length decreases. Generally, the lead-in length should not exceed 4,000 ft (1,200 m) for a 12 probe per channel installation. If, on the other hand, 6 probes per channel are used, the lead-in length should not exceed 5,000 ft (1,500 m).

MAGNETIC DETECTOR CONFIGURATION

Although the magnetic detector was developed in the 1930's, it is still in use today particularly where deteriorated pavement and/or frost activity tend to contribute to the failure of loop detector wires. It is also used where it is desirable to install detection without cutting the pavement. While this form of detection is inexpensive, reliable, and simple, it is suitable only for pulse output in traffic actuated signal control and traffic volume counting.

As described in Chapter 2, the magnetic detector operates on the basis of a change in the lines of flux from the Earth's magnetic field. A typical magnetic detector probe is shown in Figure 100. A coil of wire with a highly permeable core is placed below the surface of a roadway. When a metallic object such as a vehicle comes near or passes over the coil, the constant lines of flux passing through the coil are deflected by the vehicle, thus inducing a voltage in

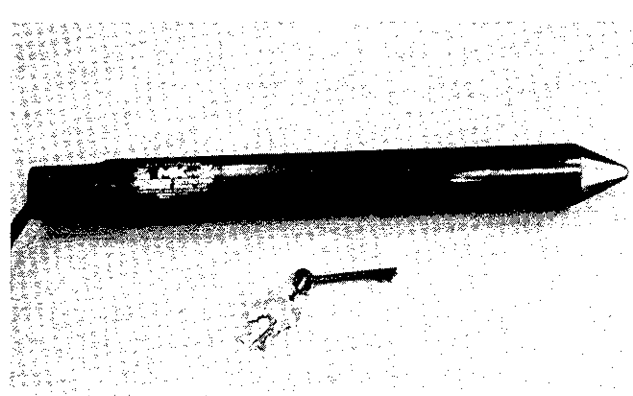


Figure 100. Typical magnetic probe.

the coil. A high-gain amplifier then enables this voltage to operate a relay which sends a message to the controller that a vehicle has been detected.

The following discussion is limited to the non-compensating form of magnetic detectors. The non-compensating detector is a tube approximately 2 in (5 cm) in diameter and 20 in (50 cm) long placed below the surface of the pavement.

MAGNETIC DETECTOR PROBE PLACEMENT

The placement of the probe is particularly important to the proper operation of this detector system. Since the probe detects changes in the magnetic field, a vehicle must be moving at a speed greater that 5 mph (8 kph). This means that it must be placed far enough back from the stop line where vehicles are normally in motion (generally at least 50 ft (15 m)). It must also be placed in the most appropriate location in the lane to generate a sufficiently strong impulse to register a detection.

Distance from the Stop Line

The set-back distance of the probe from the stop line is based on the desirable allowable gap. For example, assume an allowable gap (therefore passage time) of 3 seconds. Then, on a street with an observed speed of 30 mph (48 kph), the probe would be located 182 ft (55 m) from the stop line.

The graphs shown in Figure 101 identifies the proper location of the probe relative to the stop line based on an allowable gap of 2, 3, 4, or 5 seconds.

Lateral Placement of Probe

In a single lane approach, the optimal location is under the path normally followed by the right wheels of the vehicle as shown in Figure 102. On a two lane approach where a single probe is used, the probe should be placed between the lanes to provide satisfactory coverage. If the right lane of a multi-lane approach is designated for right turning traffic, the probe should be located in the middle of the through lane to minimize the effect of vehicles in the right turn lane.

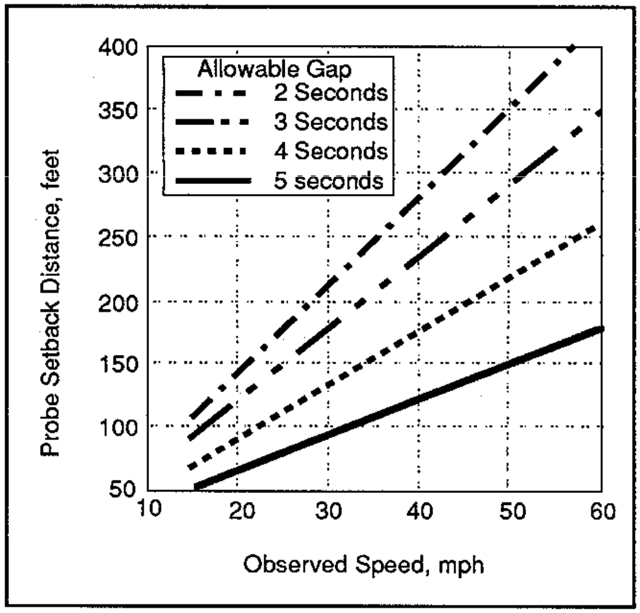


Figure 101. Proper location of magnetic probe.

A common practice for multi-lane approaches, is to place a probe in each lane. In such designs, the probe should be placed under the right wheel track in each lane. Up to three probes can be placed in a conduit. When the magnetic probes are to be placed in a new roadway, multiple conduits should be used, one probe per conduit. In an existing road, conduit runs should be kept to a minimum; thus more than one probe may be placed in a conduit.

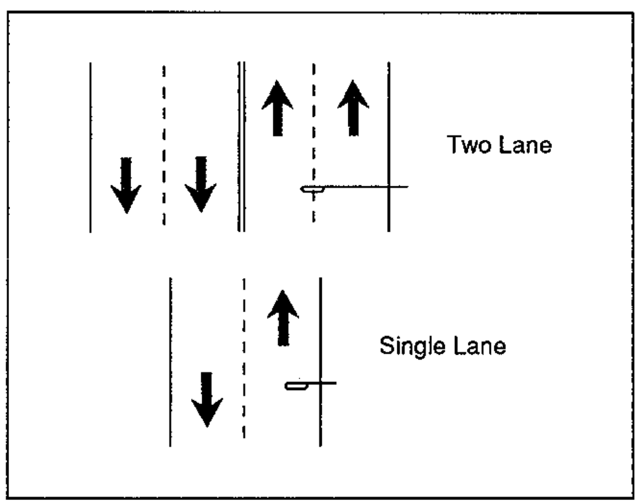


Figure 102. Magnetic probe location.

SENSITIVITY

When two or more probes are used on different approaches of the same traffic phase, they should be placed in similar locations (if possible) so the distance each probe will have to cover will be the same. This will allow for the sensitivity of all detectors to be adjusted by the single sensitivity adjusting knob on the detector unit.

The probe sensor will generate an impulse in response to any change in the magnetic conditions surrounding it. The strength of the impulse is proportional to the change in the magnetic field. Changes in the magnetic field can be caused by movement of iron or steel objects in the vicinity or by changes of current in power wires. With the probe placed as close as possible to the path of the vehicles, the strength of the impulses caused by these vehicles will be maximized. Impulses caused by traffic moving in other lanes or by current changes in nearby wire will be minimized. The sensitivity of the detector can be turned down until the unwanted impulses are not strong enough to actuate the relay, while the impulses from vehicles in the proper lanes will be strong enough to actuate.

5. INSTALLATION

Installation may be considered by some as the simplest, most straightforward activity in the process of implementing detection capabilities. When detector theory and application have been reviewed and the design, specifications, and plans have been developed, installation may appear relatively easy. Among all the complicated engineering activities already undertaken, surely the mechanical task of cutting a slot in the pavement, laying turns of wire in the slot, covering it with sealant, splicing it to the cable, and connecting the cable to the electronic unit in the controller cabinet would not seem to present a difficult challenge.

In reality, this seemingly uncomplicated activity is the most crucial process in the chain of events. Improper or "sloppy" installation causes many of the detector failures and signal malfunctions. There is no more important activity in the system to ensure effective operation.

For example, consider that the detection element represents about 4 to 10 percent of the cost of implementing intersection traffic control, yet accounts for a significant portion of maintenance dollars. Moreover, as traffic congestion and delay become a more urgent problem, and traffic control equipment becomes more sophisticated to better manage this traffic, dependence on properly functioning detectors becomes more important.

This chapter is specifically addressed to project engineers, contractors, inspectors, field crew supervisors, and traffic technicians. It begins with a discussion of pre-installation activities, regardless of the type of detector selected. To underscore the criticality of the installation process, the magnitude and causes of loop detector failure are then addressed.

The various activities comprising the process of installing loop detectors in existing roadways are then described, followed by a discussion of loop installation in new roadways or as part of a repaving process. Installation of magnetometers and magnetic detectors is discussed later in the chapter.

TYPICAL PRE-INSTALLATION ACTIVITIES

The design of the detector system (see Chapter 4) involves a number of decisions that must be made previous to installation. These decisions include specifications for the type and configuration of the detector hardware necessary to meet previously identified operational requirements, and a preliminary plan of the location.

Pre-installation activities should include a thorough review of the design documents, preparation of scale drawings, and field visits to the location. Upon completion of these activities, the engineer is ready to hand the job over to the installation crew foreman or the contractor who must then develop manpower estimates, and material and equipment requirements. All information should be clearly defined and complete so that installation can proceed in an orderly manner.

SCALE DRAWING OF LOCATION

A scale drawing of the location showing the correct geometry of the roadway and the exact location of the in-road sensor element in relation to the pavement markings should be prepared. The drawing should also show the location and content of conduit, manholes, power sources, pavement materials, and electrical equipment that would interface with the installation. The accuracy of this drawing is of great importance to effective installation as it will become the basic guideline for the installation crew as well as a part of the procurement package if the installation is to be performed by a contractor.

The completed drawing should be reviewed with the design engineer to insure that the loops (or probes) are located as specified in the configuration design and in areas free of underground or underpavement hardware that could interfere with proper operations.

FIELD VISITS

Field visits to the site of the installation should be made before and after the scale construction drawing is made. Prior to preparing the drawing, a field visit should be made to inventory the existing conditions and to identify any potential problem areas such as pavement joints, which may affect loop design.

As a result of this visit, the project engineer should then determine the method for burying cables and the types of equipment needed for the installation strategy. The method of traffic routing and control during installation should also be determined including the position and quantity of barricades or cones that may be needed for traffic control. Finally, the permits and licenses required for installation should be identified.

The information obtained from the initial visit should be incorporated into the plan drawings. After the drawings are completed, a second field visit should be made to verify their accuracy.

MANPOWER ESTIMATES

If the installation is to be preformed by an in-house (force account) crew, the next step would be to estimate manpower requirements. The plans will provide sufficient information to determine the scope of the installation work, the amount of time required, and the size of the crew necessary to perform the installation. Depending upon the size of the crew, many of the tasks can be performed simultaneously to reduce the total time that traffic would be disrupted.

EQUIPMENT REQUIREMENTS

It is also necessary to determine the equipment required for the installation. The type and configuration of the detector system will, in effect, dictate the equipment necessary for installation. Table 18 lists the commonly used equipment for a normal installation of loop detectors. Barricades, signs, cones, safety vests, and other devices will also be required to control traffic safely during the installation procedure.

Table 18. Equipment for typical loop installation.

Item	Description
Power Saw	Self-propelled 18-65 hp saw equipped with 1/4 to 3/8 in (6.4 to 9.5 mm) thick blade (abrasive or diamond), water valve, depth gauge, and horizontal guide
Water Supply	For use with diamond blade to cool blade and clean out saw slots
Jackhammer	For boring holes through concrete curb
Air Compressor	For use with jackhammer and to clean and dry sawed slots
Chisel & Hammer	For removal of sharp edges at corners of saw cuts
Blunt Tool	Such as a wooden stirring stick for seating wire in saw slot
Twister	To provide symmetrical twists of the lead-in wires
Template/ Straight Edge	For marking outlines of loops on pavement
Trenching machine	For burying cable in dirt
Megohmeter & Volt/Ohm Meter	For inspecting and testing wire continuity and resistance
Loop Analyzer	To test continuity and inductance of the loop
Soldering Iron	Either a butane torch with a soldering tip or an electric soldering iron for solder connections
Measuring Tape	Minimum 100-ft (33-m) tape for exact measurements for placement of loops

In addition to the equipment listed in Table 18, the installation of magnetometers requires a drill and bit to bore the vertical hole in the roadway for the probe. Additional equipment required for installing magnetic detectors includes: a backhoe, a horizontal boring machine, a level, and a tamping machine.

MATERIAL REQUIREMENTS

As with manpower and equipment, the type and amount of material that will be needed should be determined. Care should be exercised to assure that all materials are provided in ample quantities to avoid any interruptions of work on the street due to lack of materials. A typical material list for loop installations is provided in Table 19.

Table 19. Typical required materials.

Item	Usage
Detector Wire	To form the loop and the lead-in wires
Lead-In Cable	To connect the detector lead-in wire in the pull box to the electronic unit in the controller cabinet
Pull Boxes	To house and provide access to the connection (splice) between the lead-in wire and the lead-in cable
Sealant	To seal saw cuts
Cement, Sand, or Talc	To dust on saw cut after sealant has been emplaced to prevent tracking
Concrete	For setting pull boxes
Surge Voltage Protector	If necessary, to provide protection in the controller cabinet
Solder	For making splices
Splice Kits (or equivalent)	For environmentally sealing splices
Spray Paint or Chalk and Line	For outlining loop for sawcutting

LOOP DETECTOR INSTALLATION

The loop detector system is composed of a wire loop(s) embedded in the pavement (the sensor), a splice between the lead-in wire and the lead-in cable in the pull box, the lead-in cable (usually in a conduit) running to the terminal strip in the controller cabinet, a cable from the terminal strip to the electronic detector unit, and finally, the detector unit itself. The relationship of these various components is illustrated in Figure 103.

This section will initially present an overview of installation techniques. Loop failures as they relate to installation will then be discussed. Finally, conventional loop installations in existing roadways will be addressed in terms of the most commonly used techniques and materials. Unique installations are discussed later in this chapter.

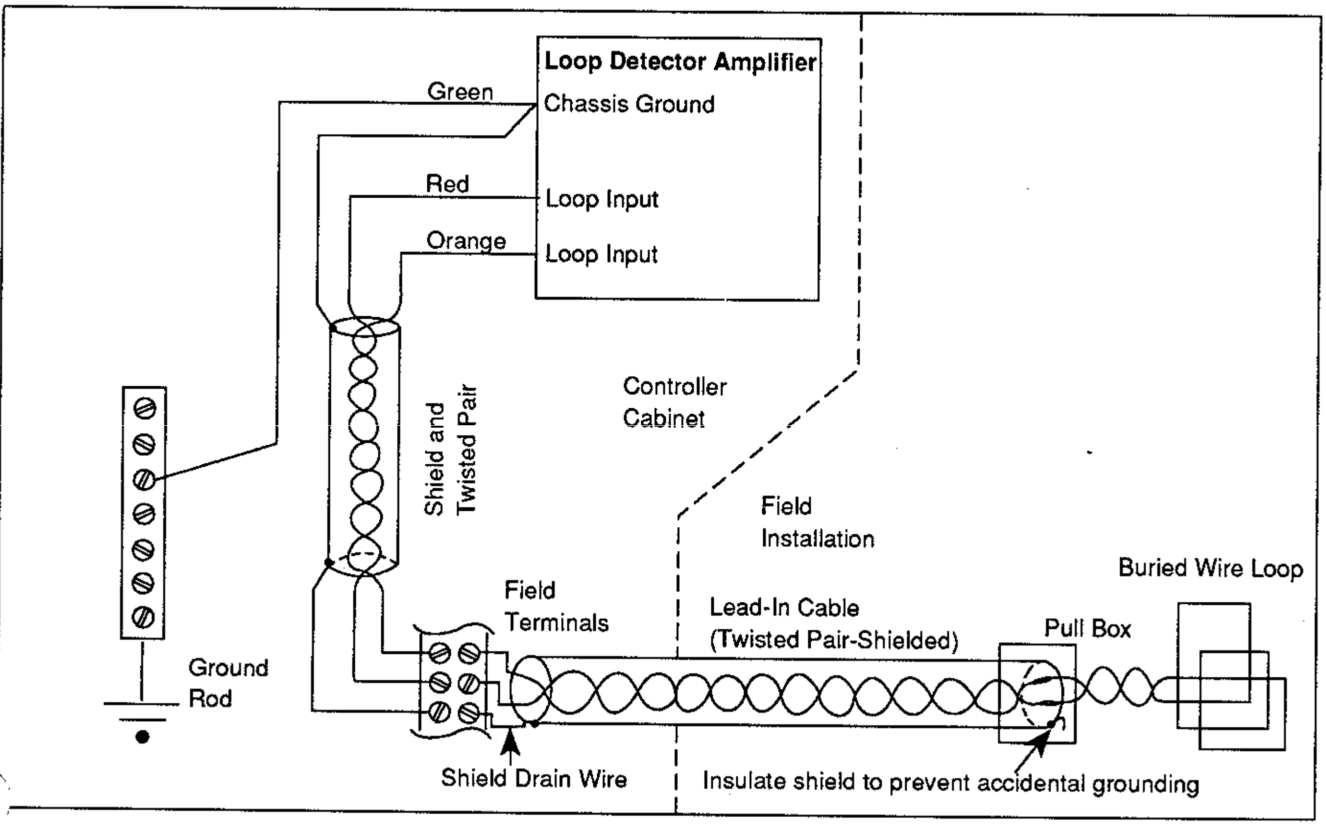


Figure 103. Loop system schematic.

INSTALLATION TECHNIQUES

Loop detectors are installed in pavement, either asphalt or concrete, by cutting a slot, cleaning and drying the slot, laying in the detector wire, sealing the sawcut, connecting the wire to the lead-in cable, connecting the cable to the terminal strip in the cabinet, and ensuring that the harness connects the terminal strip to the electronic unit. The major field steps in this process are shown in Figure 104. Differences in installation techniques usually involve the treatment of the corners where two saw cuts intersect, splicing techniques, the type of sealant, and the method of applying the particular sealant. Even with this relatively simple installation process, there are many different techniques used.

Installation techniques and theories vary widely among traffic agencies. For example, a survey of western states (Ref. 29) provided the variations shown in Table 20. Procedures developed over the years are frequently out-of-date or are no longer effective, yet there is often great resistance to change. In many cases, the installation of detectors is performed by contractors who have their own shortcuts (and shortcomings). The importance of appropriate

Table 20. Installation practices in western States.

State	Type of Loop	Saw Cut Dimensions	Cleaning Method	Loop Wire	Lead-In Cable	Detector Mounting
Alaska	6 x 6 ft square (3 turns) 6 x 20 ft (2 turns)	—	—	# 14 THNN Stranded	IMSA 50-2 or # 12 twisted pair w/ shield & drain	Shelf
California	6 x 6 ft square or diamond (3 turns) 6 x 6 - 50 ft Quadrupole (2-4-2 or 1-2-1)	W = 1/4 - 1/2 inch D = 1 3/4 inch	Flush w/ water and blow out and dry w/ air	# 12 RHW-USE (Neoprene or x-link polyethelene stranded	2 # 12 solid unshielded 2 # 14 or # 16 stranded, shielded 4 # 18 stranded, shielded	Rack
Idaho	6 x 6 ft square (2 turns)	W = 3/8 inch D = 1 1/2 inch (minimum)	Blow out w/ air	Model 20002 vehicle home-run cable (4 # 18 conductors)	Belden 8227	Rack
Montana	6 x 6 ft square 6 x 20 ft quadrupole (various # of turns)	Asphalt W = 1/4 inch D = 2 inch Concrete W = 1/4 inch D = 1 1/4 inch	Blow out w/ air	# 12 XHHN stranded	Belden 8720	Shelf
Nevada	6 x 6 ft square (3 turns) 6 x 25 ft rectangle (2 turns) 6 x 70 ft rectangle (1 turn) 6 x 75 ft Quadrupole (1-2-1)	W = 1/4 inch D = 2 inch	Blow out w/ air	# 12 RHW and XHHW N. Nev - solid S. Nev - stranded	IMSA 19-2 (Pair communication cable w/ shield)	Mostly Shelf
Oregon	Single loop - 4 x 4 ft diamond Series of loops - 3 x 3 ft diamonds (both 4 turns)	W = 1/4 inch D = 1 inch	Flush w/ water and blow out w/ air	# 14 THWN stranded	IMSA 50-2, Belden 8720, or equivalent	Rack
Utah	6 x 6 ft square (3 turns) 6 x 16 ft rectangle (3 turns) 6 x >16 ft (2 turns)	W = 1/4 inch D = 2 inch	Blow out w/ air	# 14 THHN or THNN stranded	Belden 8720, or equivalent	Shelf
Washington	6 x 6 ft square (4 turns) 6 x 50 ft Quadrupole (2-4-2)	W = 1/4 inch D = 2 1/2 to 3 inch	Blow out w/ air	# 14 XLP, RHH, or RHW or # 12 XLP stranded	AIW 7311 or Belden 8718	Shelf and Rack

NOTE: All states splice loop lead-in wire to lead-cable in the pull box. Lead-in cable runs to the controller are in conduit.

1 in = 2.54 cm 1 ft = 0.3 m
Date of Survey: January, 1984

Figure 104. Typical loop installation details.

installation procedures in the long term operational effectiveness of detectors cannot be overstressed. Given that loop detectors are primarily installed by contractors, it follows that construction supervision and inspection by the responsible agency is a critical factor.

Recently, detector installations have become even more varied. Because of the high failure rates attributed to moisture or breaks in wire, the trend is to encase and seal the loop wires in some type of protective covering prior to sealing the sawcut. Some agencies choose to prewind and bundle the loops in the shop to ensure the proper number of turns and to save on-street time. Other agencies use preformed loops (i.e., the loop consists of 1/2- or 3/4-in (12- or 19-mm) PVC pipe with the wire enclosed). These loops require at least a 1-in (25-mm) wide slot in the pavement rather than the narrow saw cut used for conventional loops. Some agencies have used wider slots (up to 4 in (100 mm)) to facilitate placement of the preformed loop.

Because of their relatively harsh weather, Alaska uses a very protective grade of preformed loop enclosed in 1-in (25-mm) PVC pipe. They use Schedule 80 (instead of Schedule 40) PVC pipe with a #12 AWG crosslinked polyethelene wire with backer rod fill to prevent damage caused by water encroachment followed by freezing.

In addition, a great many detectors are now being set in place during construction of a new roadway or during repaving. In Puerto Rico, concrete slabs with the detector loops in place are being used (see discussion later in this chapter under Loop Installation Alternatives). In this case, instead of a sawcut to house the loop wires, a section of roadway is removed and replaced with a slab already containing the loop. The slab concept can also be used with new road construction.

DETECTOR FAILURES

The number of loop detector failures nationwide has created deep concern in the traffic engineering community and an aggressive effort has been undertaken to determine the major causes of these failures so that they may be eliminated or minimized. During the 1980's, FHWA, in cooperation with various State agencies, funded a number of studies of detector failures. The objectives of these studies were to quantify the scope of detector failures, to identify the causes of failure, and to evaluate the various installation procedures (e.g. sawcutting and cleaning slots) and materials (e.g. sealant, conduits, wires and cables). The results of these studies are briefly discussed below and are presented in Appendix M.

Causes of Detector Failure

In loop detectors, the failure of the detector system can likely be traced to the in-road detector sensor (loop wire) or to the splice between the loop wire lead-in with the lead-in cable. Since the introduction of the digital self-tuning electronic units, failure attributed to the amplifier/oscillator unit has all but disappeared. Failures continue to plague agencies still using the older units that are unable to adjust to changes in temperature, moisture, or changes within the loop and lead-in.

Loop failure literature is difficult to synthesize because of the different terminology used to define failures. For example, one report may categorize a failure as "break in loop wire." This may be caused by crumbling pavements, failure of the sealant, a foreign substance in the slot, or any number of other reasons. A report from another agency may report this failure as "deteriorated pavement."

No matter how failures are categorized, the inescapable conclusion is that the predominant causes for failures in the loop detector system can be ameliorated by improved installation techniques and vigilant supervision and inspection.

Frequency of Failures

Considering the number of variables that may contribute to loop detector failure, it is apparent that failure rates will differ from agency to agency. In addition, until recently, very few agencies maintained comprehensive records. If a loop failed, it was repaired or replaced as a signal maintenance activity. The cause of the failure, the age of the loop, the condition of the pavement, etc. were not recorded. Consequently, many of the surveys reported in the literature were based on subjective, after-the-fact judgments.

Perhaps the largest of the FHWA studies was conducted by the State of New York. It was found that of the 15,000 existing loop detectors maintained by the State, 25 percent were not operating at any given time. It was also found that, on the average, loop installations generally operated maintenance free for only 2 years (Ref. 30). This high failure rate encouraged New York State to develop improved installation methods described later.

The failure rate reported by New York is consistent within the literature. For example, one district in Minnesota reported an annual failure rate of 24 percent and Cincinnati, Ohio reported 29 percent failures per year. It should be noted that these areas have basically cold weather climates. Failure rates in the sun-belt States are about the same, but the causal factors differ.

Failure Mechanisms

As mentioned earlier, most failures originate in the loop wire. In reality, although the wire is where the failure occurs, it, in itself, is not necessarily the precipitating cause of the failure. It may be considered as the *effect* of the failure *caused* by any one of several breakdown mechanisms, such as poor pavement, or poor installation of sealant which allows the wire to float to the top and thus become vulnerable to traffic.

Table 21 summarizes the results of a detector failure survey of eight western States (Ref. 15). A more definitive discussion of loop failures is presented in Appendix M.

LOOP LAYOUT AND SAW CUTS

After securing the work zone with appropriate barricades, cones, etc. to divert traffic from the work area, the first step is to carefully mark the pavement for the size and shape of the loop to be installed. This is usually accomplished with either a lumber crayon, chalk, or can of spray paint. If available, a template of the proper size and shape should be used. However, a straight edge or a tightened string can be used as a marking guide. It is critical that the marking reflect the exact location as shown on the construction plans.

Corner Treatment

Corner treatments vary among agencies. Traditionally, a chamfer cut such as shown in Figure 105 has been used to ease the stress on the wire of a 90 degree bend. These diagonal cuts are overlapped so that the slot is at full depth at the turn points. The diagonal cut should be far enough back from the corner to prevent pavement breakout at these corners.

Table 21. Summary of loop detector failure survey.

State	Percent Installed by		Major Failures	Remarks
	State	Contractor		
Alaska	10	90	No loop failures reported	Exclusive use of preformed loops
California	5	95	Improper sealing and foreign material in saw slot	Uses preformed loops in poor pavement and dirt detours
Idaho	10	90	Improper sealing	No failure for loops made of # 20002 cable
Montana	10	90	Improper sealing	—
Nevada	5	95	Improper sealing and pavement deterioration	—
Oregon	10	90	Improper sealing	—
Utah	70	30	Improper sealing and pavement deterioration	Used some preformed loops with no failures
Washington	10	90	Improper sealing and foreign material in saw slot	Need better inspection to improve loop performance

Approximately 12 in or more is recommended. Some agencies use a hexagonal, octagonal, or round loop design in order to eliminate the sharp turn as well as reducing "splashover." A new technique for installing round loops is presented later in this chapter under Loop Installation Alternatives.

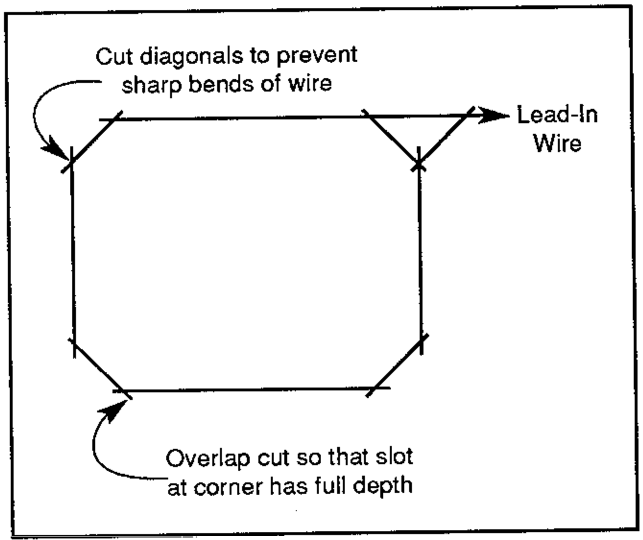


Figure 105. Chamfer cut corner treatment.

Many agencies have found that diagonal cuts across the corners of loops cause the triangular portion of the pavement to break up. Instead, 1-1/4-in (3.1-cm) holes are drilled at the loop corners before the slots are saw cut. Core drilling the corners is also faster (15 seconds per drilled hole) and the integrity of the pavement is preserved. This technique is illustrated in Figure 106. The State of New York uses an alternative to core-drilled corners (Ref. 30). With this technique, straight sawcuts overlap at the corners (i.e., no diagonal sawcuts) and then the inside corner is chipped out using a small hand chisel and hammer or small air-powered impact chisel to cut a smooth curve for the wire to follow.

Saw Cutting Operations

The sawing of the slot for the loop wire is one of the most time-consuming parts of the installation process. The cost effectiveness of the saw-cutting operation is dependent on selecting the most appropriate equipment and making sure that the equipment is in good operating condition.

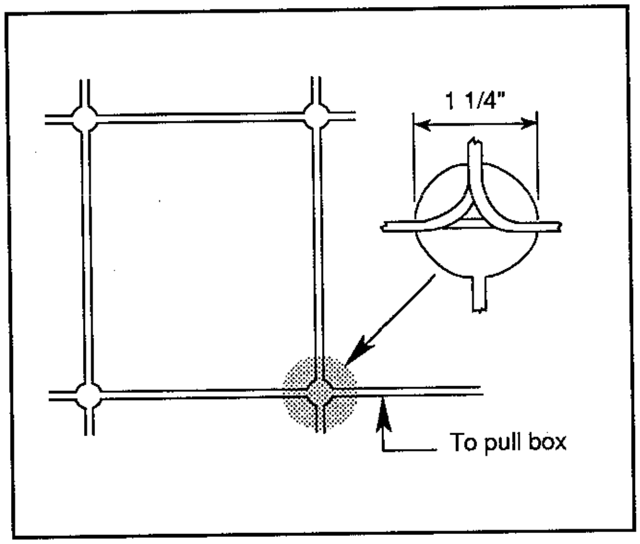


Figure 106. Core drilled corner treatment.

Overview of Saw Cutting Equipment

Many saw types and sizes are available for cutting slots. Formerly, many specifications for saw-cutting equipment called for at least an 8 or 9 hp gasoline engine powered saw with a 1/4- or 3/8-in (64- or 96-mm) abrasive or diamond blade. The abrasive blade was favored by some agencies as it was perceived to be more economical. It could also be used for dry cutting and therefore did not require a water supply or produce a wet slurry that had to be cleaned out with compressed air. Most agencies, however, argue that the dust created by the dry-cutting method using the abrasive blade was irritating and dangerous to the workers, motorists, and pedestrians. Further, loop installers report that the abrasive blade wears out quickly, requires too much time for the cutting operation, and is difficult to maintain at a constant depth in the slot.

Although abrasive blades are less expensive than diamond blades on a per blade basis, the service life is very short and is therefore not cost effective when compared with the diamond blade. After a comprehensive evaluation of saw blades by the State of New York, it was concluded that by using water cooling, a diamond blade, and a higher horsepower saw, cutting time could be reduced by two-thirds (when compared to a dry cutting system) with only a slight increase in initial saw costs. Increased material cost could be reclaimed in a savings of time, labor, and equipment longevity.

Diamond Blade Design

The design of the diamond blade is a specialized area of expertise. There are a number of manufacturers with their own proprietary design. Generalization concerning the best design is difficult because of the difference in aggregate used in pavement surfaces. The best blade for a specific site is one that matches the cutting requirements (speed and pavement hardness) to the requirements and condition of the particular saw being used. The objectives guiding diamond blade design include: 1) maximize blade life, and 2) expose new diamond cutting edges only after the surface chips are rounded to the point that the blade no longer cuts efficiently.

The diamond chips are set in a matrix which is laser-welded to the blade blank. The requirement to cut faster means exposing new diamond chips more quickly. This, in turn, means a reduction in the life of the blade. The matrix used to hold the diamond chips must be matched to the speed of the saw. The centrifugal force throws the diamond chips out when the edges become rounded. By making the matrix softer, cutting diamonds are released sooner and a faster cutting rate is possible. Increasing or decreasing the power of the saw will require a change to a blade suited for the particular saw and the speed at which it will operate.

Saw Blade Trouble Shooting

Some of the problems that are experienced with saw blades used in cutting pavements for loops and/or magnetometers are presented in Table 22 (compiled

Table 22. Saw blade trouble shooting.

PROBLEM	POSSIBLE CAUSE	SOLUTION
Loss of cutting element - 1 or more	Blade temperature too high and/or inadequate water supply	Return to Manufacturer for repair
Blade stops cutting, but cutting elements appear ok	Blade too hard for application	Periodically redress blade on Haydite block or silica brick
Vertical hair line cracks appear in cutting elements	Blade matrix metal too hard for application or saw RPM's too high	Purchase new blade to match job requirements and saw to be used
Vertical hair line cracks appear in core below air gap	Cutting element bond too hard or improper blade tension for RPM's being used	Purchase blade with softer bond or drill a hole at base of crack to check its growth
Horizontal hair line crack appears at base of air gap	Blade wobbling due to improper blade tension, or cutting element bond too hard, or bent arbor not tracking blade path	Replace blade and/or have blade reblanked
Arbor hole out of round	Saw mandrel scored or too small for blade	Replace or reblank blade. For minor damage, ream out and use a reducer bushing
Under cutting of core below the cutting element	Material being cut is excessively abrasive	Remove blade before cutting elements are lost. Replace blade or have it reblanked if cutting is to continue. A wear guard may be added in reblanking process
Core dished - blade tension lost	Bond may be too hard for RPM's or incompatible blade dimension	Reset tension on blade. If problem persists, replace with blade better suited to job and saw
Inconsistent blade life	Blade used for various applications, blade not suited to application	Ensure proper blade for job requirements
Short blade life	Wrong RPM's, inadequate water, blade not suited to job, or excessive friction	Ensure adequate water supply and that water strikes blade near the arbor on each side. Check saw RPM's against blade requirements

from Ref. 31). The probable cause of the problem and potential solutions are also presented.

Saw Horsepower

The horsepower (hp) of the saw is a critical factor in the cost of the saw cut. The speed of cutting is directly proportional to the hp of the saw and is influenced by the hardness of the surface to be cut. Essentially, a 65 hp saw will cut almost twice as fast as a 35 hp saw and four times as fast as an 18 hp saw. While there is slightly more wear on the blade, the advantage of these higher speeds is the decrease in the time the lane must be closed to traffic.

The saw must be large enough to provide the power necessary to keep the blade from "bogging" down (Ref. 31). Other indications of an under-powered saw or the improper match of the blade to the saw are described below:

- A white or blue smoke emitted from the front of the saw indicates that the blade is excessively hot. Blue to black discoloration of the blade core just below the cutting edges is another indicator of excessive heat. Water can be used to reduce blade temperature. A more appropriate blade may be necessary. Failure to correct will result in excessive diamond chip loss and short blade life.

- Break-up of part, or complete loss of the cutting edge indicates excessive pressure on the blade during cutting. To avoid this problem, reduction in cutting speed or selection of a better suited blade is required.

On the basis of its 1983 study (Ref. 29), the State of New York revised its recommendation for its saw from 9 hp to 18 hp. However, most contractors and a number of State agencies favor a more powerful saw. Wet cut tests conducted in Texas, using a 65 hp saw with a diamond blade, cut at speeds ranging from 37- to 82-in-ft (28- to 62-cm-m) per minute for a 1-in (2.5-cm) deep cut in asphaltic concrete. The average rates are given in Table 23. Ten tests were run on AC (Asphaltic Concrete) surfaces and four runs were made on PCC (Portland Cement Concrete). All tests were cut to a 1-in (2.5-cm) depth. The table also presents the average projected rate for various slot depths.

Table 23. Saw slot cutting rates.

Type of Surface	Number of Test Cuts	Average Cutting Rate* per Slot Depth, inches			
		Actual	Projected		
		1	$1\,^1/_2$	2	$2\,^1/_2$
AC	10	55.7	37.1	27.9	22.3
PCC	4	9.0	6.1	4.5	3.5

* Inch-feet per minute

During these tests with the 65 hp saw, the blade tended to ride up out of the slot resulting in a substantial variation in the depth of the cut. A difference of up to 1/2 inch (1.3 cm) was common. Further testing in the cutting speed range of 25 to 30 in-ft (19 to 23 cm-m) per minute showed that this problem can be reduced by adding a 50 lb (23 kg) dead weight directly over the blade drive shaft.

Wet versus Dry Cutting

Today, particularly with the use of the higher speed saws, the preponderant evidence suggests that wet cutting is necessary in Portland Cement Concrete (PCC) and is desirable for asphaltic surfaces. While asphaltic concrete (AC) can be successfully dry cut at high speed, it would be accomplished at the expense of blade life. It is estimated that dry cutting reduces the life of a diamond blade by one third.

Simply adding water to the saw cutting operation does not guarantee that the blade will not overheat and cut inefficiently. A poor water distribution system can simulate a dry cutting situation and should be avoided. The water jets must direct the water so that it strikes the blade near the center of the core. The centrifugal force will then throw the water out to the edge of the blade. The water should be directed so that it arrives at the cutting edge of blade just as the edge point goes down into the pavement surface. This maximizes cooling and lubrication.

Saw Cut Depth

Regardless of the type of saw used, it should be equipped with a depth gauge and a horizontal guide to assure proper depth and alignment. The appropriate depth is dependent on the type of pavement and the number of turns of wire. A general guide for slot depth is given in Table 24 (Ref. 32). The depth of the sawcut should be checked frequently during cutting to assure a constant value. It is generally accepted that a minimum depth of 1-1/4 in (32 mm) and a maximum depth of 2 in (50 mm) should be maintained. Some agencies specify adequate depth to allow for a 1/2-in (13-mm) sealant cover over the wires, while some manufacturers recommend planning for at least a 1-in (25-mm) of cover.

Table 24. Saw cut slot depth guide.

Turns of Wire	Slot Depth	
	Inches	Millimeters
1	1-3/16	30
2	1-3/8	35
3	1-9/16	40
4	1-3/4	45
5	2	50
6	2	50

Finishing the Saw Cut

The saw cut should be a clean, well-defined cut. All jagged edges and protrusions should be removed with a small chisel and hammer. It is crucial that the saw cut be clean and dry. Cleaning should take place immediately after the cutting is complete. There should be no cutting dust, grit, oil, or contaminants in the slot. It should be flushed clean with pressurized water and then dried with compressed air.

Many agencies only require that the slot be cleaned with compressed air. If these agencies experience an inordinate rate of wire failure, they should consider flushing the slot with pressurized water as well as with compressed air. Care should be exercised to avoid blowing the debris in the direction of passing pedestrians or vehicles.

Only one saw cut along the marking should be made. If the saw cut is out of alignment, another cut *should not be made* near the first cut as this will significantly weaken the pavement. If another cut is necessary, at least 4 to 6 in (10 to 15 cm) should be allowed between the old cut and the new cut.

INSTALLING LOOP WIRE

After the slot is saw cut and cleaned, it is now ready for the installation of the loop wire. The following discussion describes common practices followed by a number of loop installers. Many contractors specializing in installing loop detectors have developed their own individual methods and short cuts, some of which are highly effective while others are merely expedient for their purpose but, in the long run, costly to the agency. This underlies the need for careful inspection procedures during the installation process.

It should be recognized that field crew personnel are not always as vigilant or careful in handling the wire as would be desired. Accordingly, the installation supervisor and/or inspector should stress that the wire must not be damaged during the process as it could cause detector malfunction and would ultimately have to be replaced. Should any damage occur to the wire during handling, it should be pulled up immediately and replaced.

Wire Type

Wire sizes are classified in accordance with the American Wire Gauge (AWG), originally called Brown & Sharpe Gauge. The AWG is a system of numerical wire sizes starting with the lowest numbers for the largest sizes. The gauge designations are each 20.6 percent apart based on cross-sectional area. That is, AWG #12 is 20.6 percent larger than AWG #14, etc.

Wire is further described by type of insulation. Definitions of some of the more commonly used wire for detector applications are provided in Table 25.

The most commonly used wire size ranges from #12 to #16 AWG. Agencies that use the larger wire are about equally divided between #12 and #14 AWG.

Table 25. Definition of wire standards.

Designation	Description
TFF	Stranded copper conductor insulated with thermoplastic lead wire
THHN	Building wire, plastic insulated, 90° C, 600 volt, nylon jacketed
THW	Building wire; plastic insulated; heat, flame, and moisture resistant, 75° C
THWN	Same as THW with overall nylon jacket
TW	The UL designation for thermoplastic insulated wire for use in conduit, underground, and in wet locations. It is a common building wire having a bare soft copper solid or stranded conductor
XHHN	Cross-linked polyethelene insulated wire rated at 90° C in dry locations and at 75° C in wet locations
Note: Building wire is defined as a commercial wire used for light and power in permanent installations using 600 volts or less. Typically used in an enclosure which will not be exposed to outdoor environments.	

However, some manufacturers recommend #16 AWG. Their position is that the difference in wire size is not as critical as the quality and thickness of the wire insulation. The insulation used on the wire may be rubber, thermoplastic, or synthetic polymer. Cross-linked polyethylene appears to be the most popular insulation and is strongly recommended by detector manufacturers. The insulation must withstand wear and abrasion from shifting streets, moisture, and attack by solvents and oils as well as withstand the heat of high temperature sealants. Stranded loop wire is preferred over solid wire. Because of its mechanical characteristics, a stranded wired is more likely to survive bending and stretching than a solid.

Ducted Wire

There is a growing tendency to use insulated loop wire encased in continuous cross-linked polyethylene tubing. There are a number of manufacturers of these loop materials. Brand names include Detecta-Duct, Power Loop, Signal Duct, Electroloop, etc.

A typical product uses a flexible ducting encasing THHN type #14 gauge AWG stranded wire conductors. The use of ducted loop wire has the following advantages:

- The conductor wires are able to move freely within the duct, compensating for the shearing stress caused by pavement displacement.
- The duct protects against moisture penetration and temperature extremes.
- The ducting maintains its integrity when in contact with high temperature (400 °F (149 °C) or more) sealing compounds.
- The ducted loop wire retains its flexibility over a wide range of temperatures.

Prewound Loops

Some agencies prewind and bind loop wire (or ducted wire) to exact specifications in their shops, making a prefabricated loop for transport to the site. This is accomplished by winding the loop wire around carefully spaced pegs on a wall or table. This minimizes the tendency of the wire to spring into a coil after removing it from the supply reel. The completed loop consists of the proper number of turns and the required length of lead-in to the pull box bound together. Although prewinding appears to be a labor-intensive operation, it can cut installation time significantly. This procedure seems to be best suited for smaller loops. A prewound loop ready for installation in the sawcut is shown in Figure 107.

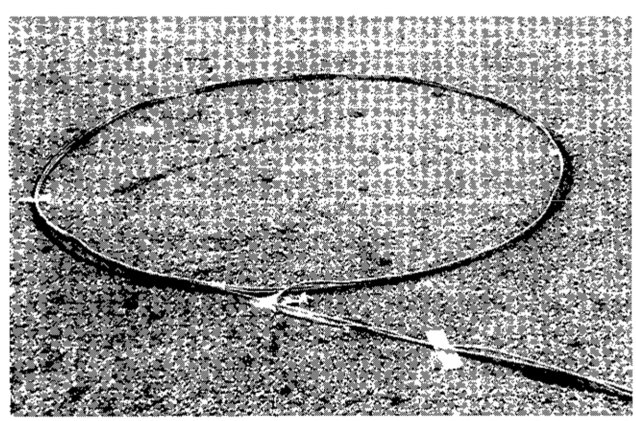


Figure 107. Prewound loop installation.

Preformed Loops

For a number of years, several detector manufacturers have offered a preformed loop assembly consisting of a continuous unspliced length of #14 AWG THHN wire completely enclosed in a 1/2-in (13-mm) heavy wall PVC pipe. The assembly comes complete with twisted lead-in wire of specified length to reach the first pull box. The water-tight assembly is sealed at the Tee fitting where the lead-in exits. The lead-in portion of the Tee is provided with a short stub of 1/2-in (13-mm) PVC pipe to enable the installer to add the necessary additional 1/2-in (13-mm) PVC and couplings to seal and protect the twisted lead-in to the pull box. Some models are supplied with watertight slip joints at the four corners. This allows the preformed loops to be folded for shipment. A typical preformed loop assembly is illustrated in Figure 108.

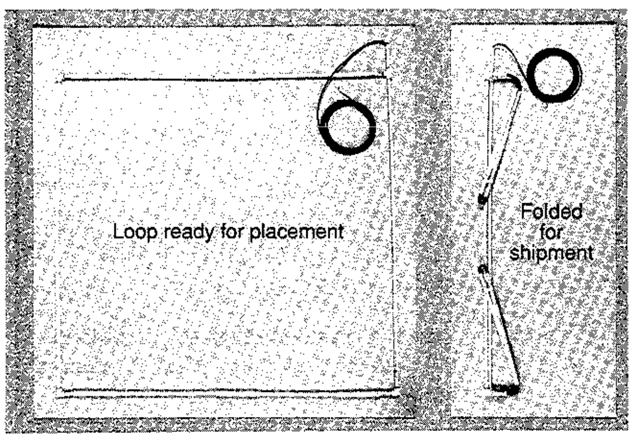


Figure 108. Preformed loop assembly.

The loops should be constructed within PVC conduit of the size necessary to contain the number of turns shown on the plans. The wire within the loop should be installed such that there will be no movement of individual conductors with respect to each other and no movement of the bundle of wire within the conduit. The loops may be fabricated from multiconductor cable (untwisted) with 40 mil (1 mm) polyethylene insulation on all conductors and a 40 mil (1 mm) polyethylene outer jacket. Lead-in wire to the loop wire splice should be soldered, covered with heat shrink tubing, and waterproofed with sealant within a section of PVC pipe.

This type of installation has demonstrated: (1) improved environmental stability, (2) no problems from wire movement, (3) higher dielectric characteristics when tested with a 500-volt megger to ground, and (4) much longer physical life. These installations have been used in concrete, asphalt pavements, and even in dirt and gravel roadways. Preformed loops can be installed in the following situations:

- Placed in a 1-in (25-mm) or wider slot in existing pavements in much the same way that conventional loops are installed.
- Placed on top of the base course before paving with bituminous surface.
- Installed 2 to 3 in (5 to 6 cm) beneath the untreated base course of a concrete roadway.
- Anchored to existing pavement and overlaid by at least 2 in (5 cm) of asphalt paving.
- Included in the pour of a concrete bridge deck.

The County of Los Angeles found that, when preformed loops were laid on top of an existing roadway and then a hot asphalt overlay was applied with a steel tracked vehicle, the PVC pipe was likely to be damaged. However, when the hot asphalt overlay was applied with a rubber-tired vehicle, the PVC was not damaged.

The use of PVC pipe in the assembly also presents some problems for extreme cold-weather applications, particularly in the presence of heavy equipment traffic. Even the heavy-duty Schedule 40 PVC will shatter under these conditions. Alaska uses extra-heavy-duty PVC (Schedule 80) to alleviate this problem.

The electric characteristics of this factory assembled, heavy-duty loop installation is normally guaranteed by the supplier. The installation mistakes typical of the saw-cut embedded loops are avoided. Although the cost is higher, and shipping and handling a bit inconvenient, user agencies report that the longer life makes the preformed loop an attractive alternative. The total installed cost of the preformed loop is likely to be lower in an overlay situation than the cost of labor and installation of a standard loop. Caution should be exercised in using preformed loops in wide sawcuts because of the difficulty in sealing the wide cuts and in preserving the integrity of the pavement.

Metal Sheathed Loop Cable

A metal sheathed loop known as mineral insulated cable (MI) was first included in National Electrical Code (NEC) in 1953, and was approved for use in many applications, most specifically for use in hazardous locations or difficult environments. MI cable is an assembly of one or more conductors insulated with a highly compressed refractory mineral insulation and enclosed in a liquid-tight seamless metallic sheath with a polyethylene jacket. The mineral insulation is magnesium oxide and the seamless sheath is phosphorus deoxidized copper.

MI installations are found in many industries, including mining, aerospace, marine, petrochemical, cryogenic, and in blast furnaces. It has recently been used for loop detector installations, after it was discovered that loop detector wires would operate efficiently encased in metal. These installations appear to be best suited to situations where the loops are installed on the base course previous to covering with the asphalt or concrete surface course. The loop is factory-assembled. The conductors are installed in the tubing parallel to each other,permitting the formation of a loop of the desired number of turns using one cable.

Among the advantages inherent in this type of loop cable is the excellent shielding system. The shield system starts at the detector unit, continues through the detector wiring harness to the controller cabinet field terminals. The shielding continues through the lead-in cable to the corner of the loop, and finally terminates at the opposite corner of the loop. To realize the advantage of the shielding, the metal shield must be opened at the far corner of the loop. It is recommended that 1/2 to 1 in (12 to 19 cm) of the metal shield be removed and the exposed material and sheath waterproofed at this corner. The lead-in cable shield needs to be connected to both sides of the exposed sheath at the connection corner of the loop in the pull box. All loop and sheath connections must be waterproofed to ensure that the shielding system is insulated from ground except at the detector unit end.

The State of Illinois developed a regulated procedure for installation when they found that haphazard construction procedures seriously degraded performance. It should be noted that Illinois DOT uses the MI cable loops primarily in new pavements and for replacing loops that are destroyed by widening and resurfacing projects. Figure 109 presents the installation detail suggested by the State of Illinois. Their specification is repeated here as Figure 110 for the information of those agencies interested in using this type of product (Ref. 14).

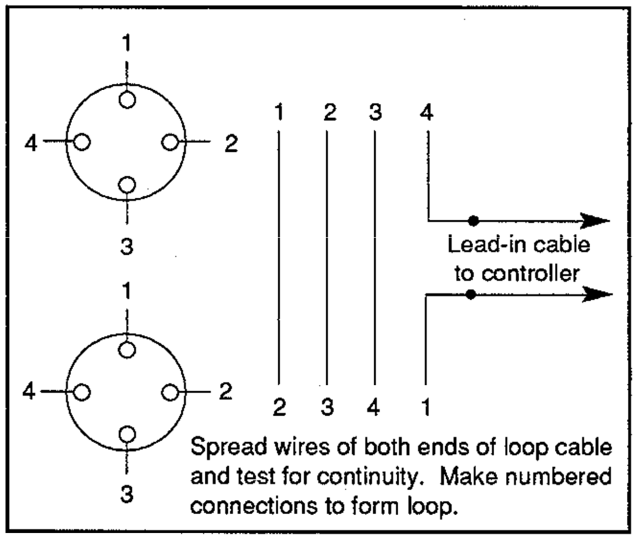


Figure 109. Metal sheathed loop cable installation.

Wire Insertion

The loop wire must be one continuous wire from the pull box through the curb, around the loop the designated number of turns, and back to the pull box. The supply reel should be checked before installation to ensure that there is a sufficient amount of wire on the reel for the particular installation. Careful count must be made of the turns of wire installed in the slot. This is a common error; the workmen simply lose count, particularly when four or more turns are required. Prewound and preformed loops, created in the shop, help ensure the proper number of turns in the loop.

SPECIFICATION FOR METAL SHEATHED LOOP CABLE

The cable shall be #16 AWGwith two, three, or four conductors as shown on the plans rated for 300 volts with outside diameters of 0.306, 0.337, and 0.353 inches respectively. The cable shall be furnished with a terminal subassembly kit composed of a pot, cap, sealer, and sleeves.

Installation shall consist of furnishing and installing MI Cable Detector Loop on a bituminous or PCC base course and covering it with bituminous surface course as described and detailed herein and in the plans.

To install the cable, slanted holes of 1-inch diameter shall be drilled through the base course. Where curb and gutter is present, the hole shall begin where the base course and gutter meet and where curbs are not present, the hole shall begin about 1-foot from the edge of the pavement. The cable shall not be installed until the loop area is ready to be covered (by the surface course) to minimize the traffic or asphalt truck running over the cable.

The installation of the cable requires the forming of the loop size including the leads to terminal end with some spare, cutting the cable and immediately sealing the terminal ends to prevent absorption of moisture by the mineral. The leads shall be bound together and inserted through the hole and positioned in place to make splices in the proposed junction box.

The cable shall be secured to an asphaltic base course including the leads. The corner radius for the loop shall not be less that 6 inches. The leads shall be bound together with straps or fish tape rope (do not use wire) to prevent cutting or damaging the polyethylene cover. Shovels of asphalt can be used to hold the cable in place.

The termination of the cable involves the stripping of the cable ends, installation of fittings, application, or insulating compound and installing the sleeve assembly according to manufacturer's instructions. When the stripping is completed, the exposed MI material should be sprayed with an insulating spray. The termination procedure must be completed to avoid leaving the magnesium oxide exposed and the conductor sleeves open to allow moisture to enter them.

The sleeved conductors shall be spliced together and metered to ensure a proper connection. The conductors must be cleaned of the material coating to ensure a good connection while metering. The conductors must be soldered together and each conductor wrapped with two layers of rubber or vinyl electrical tape. The wrapping shall completely cover the soldered connection and the conductor sleeves for 1/2 inch.

A loop test meter is used to ensure the loop will perform for detecting vehicles and after obtaining an acceptable reading, the spliced conductors and then sealed by centering them in a bottle mold and fill the mold with epoxy type resin. The resin must completely cover the tapes on the sleeves.

Any exposed copper sheath and the end seal pot shall be taped and coated with a silicone spray to prevent any moisture contact with their surfaces. Any electrical contact between the copper sheaves and the ends of the cables will destroy the inductance reading.

No splice shall be permitted in the loop wire beyond the lead-in cable splice or controller terminal when the loop wire is connected directly to the controller terminal.

The inductance and resistance of the loop as metered shall be within 10% of the calculated values for that loop as shown on the loop detail sheet.

Figure 110. Example specification for MI loop cable (Illinois Department of Transportation).

The wire should be laid in the slot so that there are no kinks or curls. A blunt tool such as a paint stirrer may be used to push the wires to the bottom of the slot. Some agencies use a narrow blunt wheel rolled along the slot. A sharp instrument (e.g. screw driver) should never be used as it easily penetrates the wire insulation.

CROSSING PAVEMENT JOINTS

A special installation problem is encountered when the wire has to cross a pavement joint. When the loop is placed in a concrete roadway and crosses a pavement joint, particularly an expansion joint, the movement of one slab relative to another will cause the wire to break if some special treatment is not used to protect the wire. Additionally, one of the most common failure points is where the road surface meets the curb line. This area is subjected to both vertical and horizontal shifting.

There are two basic treatments for crossing the pavement joint. One method is to encase the portion of wire crossing the joint in some type of conduit as shown in Figure 111. Many agencies use rigid plastic conduit or flexible tubing. The State of Illinois has used common rubber garden hose in some of their installations.

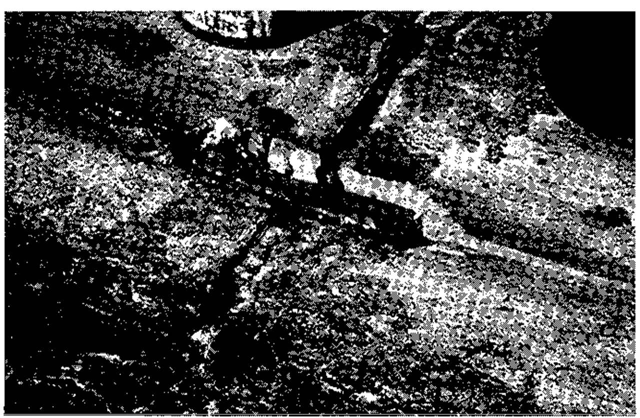


Figure 111. Crossing pavement joints using rigid tubing.

The material that is used should be approximately 3/4-in (1.9-cm) in diameter and at least 1 ft (30 cm) long. The conduit is placed in a cut which measures 1-1/4 in (3.1 cm) wide and is 16 in (40 cm) long. The details of this type of installation are shown in Figure 112.

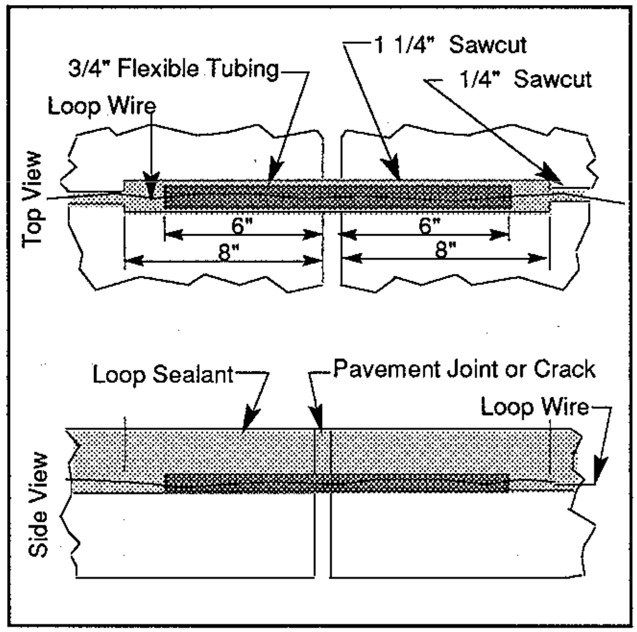


Figure 112. Pavement joint crossing details.

An alternative method is to provide an excess of wire at the pavement joint. The most common method for providing additional space for the extra wire is to make the cut in the shape of a diamond. The cut should be small, 2 in (5 cm) from edge to edge, excavated to the full depth of the sawed slot. This allows sufficient space for an "S" shape of excess wire to be placed in the cut out diamond as shown on Figure 113. The diamond (and the adjacent joint, if necessary) is filled with an appropriate sealant.

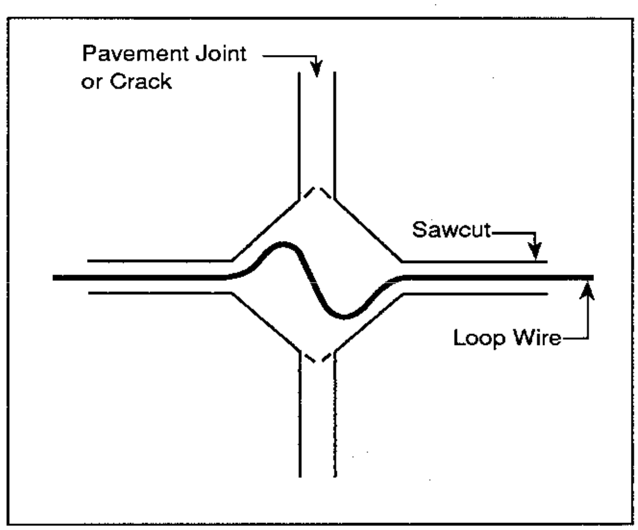


Figure 113. Crossing pavement joints using diamond cut.

HANDLING THE LOOP WIRE LEAD-IN

The two lead-in wires from the beginning and ending of the loop turns should be twisted together to form a symmetrically twisted pair from the loop to the pull box. Depending on agency policy, an additional 3 to 5 ft (0.9 to 1.5 m) of lead-in pair slack should be provided in the pull box.

Lead-in wire must be twisted to avoid crosstalk. Agencies vary on the specified number of twists per foot, ranging from two twists per foot to five twists per foot. Manufacturers feel strongly that wires should be twisted a minimum of five to six twists per foot. Some agencies or contractors do not twist the wires because the twisted wires require a wider slot for the lead-in wires, necessitating a larger saw blade than that required for the loop saw cut. Agencies that do not twist the lead-in wires usually allow only one pair of lead-ins per lead-in slot.

The correct and incorrect ways of twisting the lead-in wires are shown in the top portion of Figure 114. Although wires may be twisted by hand, more effective methods are also shown. The use of a twister shown at the bottom of the illustration will significantly speed up the process.

A multiple loop configuration is frequently used to emulate a long loop. For this type of loop system, the loops may be wired in series, in parallel, or in series-parallel as discussed in Chapter 2. The wiring alternative to be used is determined by the loop system designer by considering such factors as system configuration, system requirements, and the recommendations of the selected electronic unit manufacturer. The proper connections for each of the wiring alternatives are shown in Figure 115.

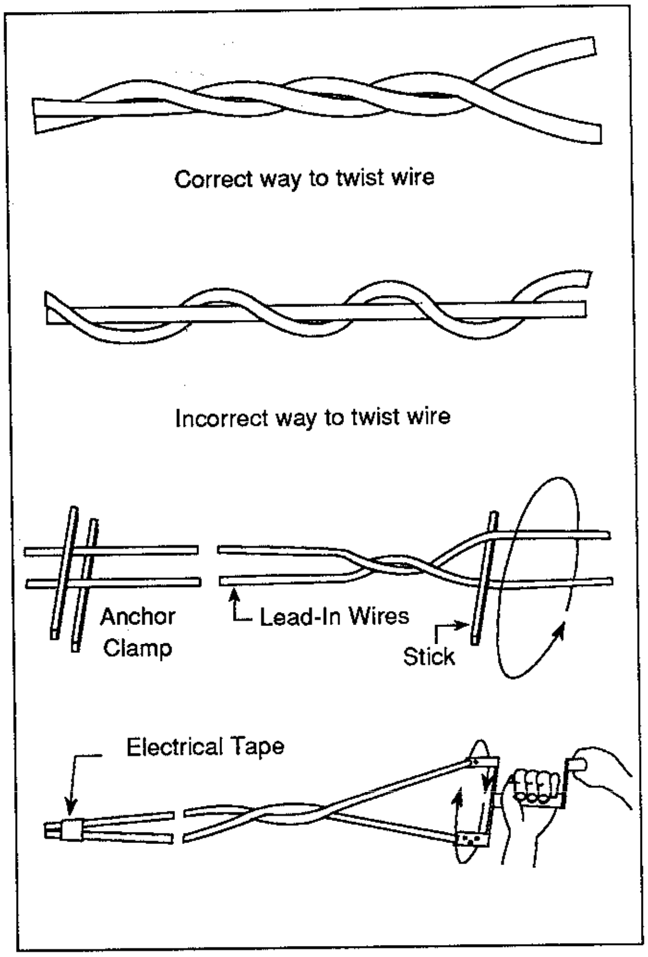


Figure 114. Method of twisting lead-in wires.

CROSSING CURBS

Typically, the twisted lead-in wire must extend from its lane location in the roadway across the curb or shoulder to the pull box. If a curb is present, passage through the curb is usually accomplished by using a jackhammer drill or punch-type tool to make the entry as shown in Figure 116. Liquid-tight flexible conduit is then installed in the hole so that it receives the twisted loop lead-in wire from the sawcut. The conduit should terminate in the pull box above the drainage to prevent moisture from entering the conduit. Figure 117 shows a cross-section view of the conduit connecting the saw cut to the pull box. This conduit should be installed at the same time that the pull box is installed.

Where the curb and gutter section is relatively shallow, the lead-in wire is placed in rigid conduit near the edge of the roadway. The conduit is inserted under the curb and gutter as is shown in Figure 118. The roadway end of the conduit is normally 2 in (5 cm) below the roadway surface.

In some cases, the crew will simply cut the curb and pass the lead-in wire through the curb. Unless the cut is made to a minimum depth of 18 in (45 cm) below the surface, this practice is not recommended. When the wires remain too close to the surface, they could be severed by grass trimming or other maintenance activities

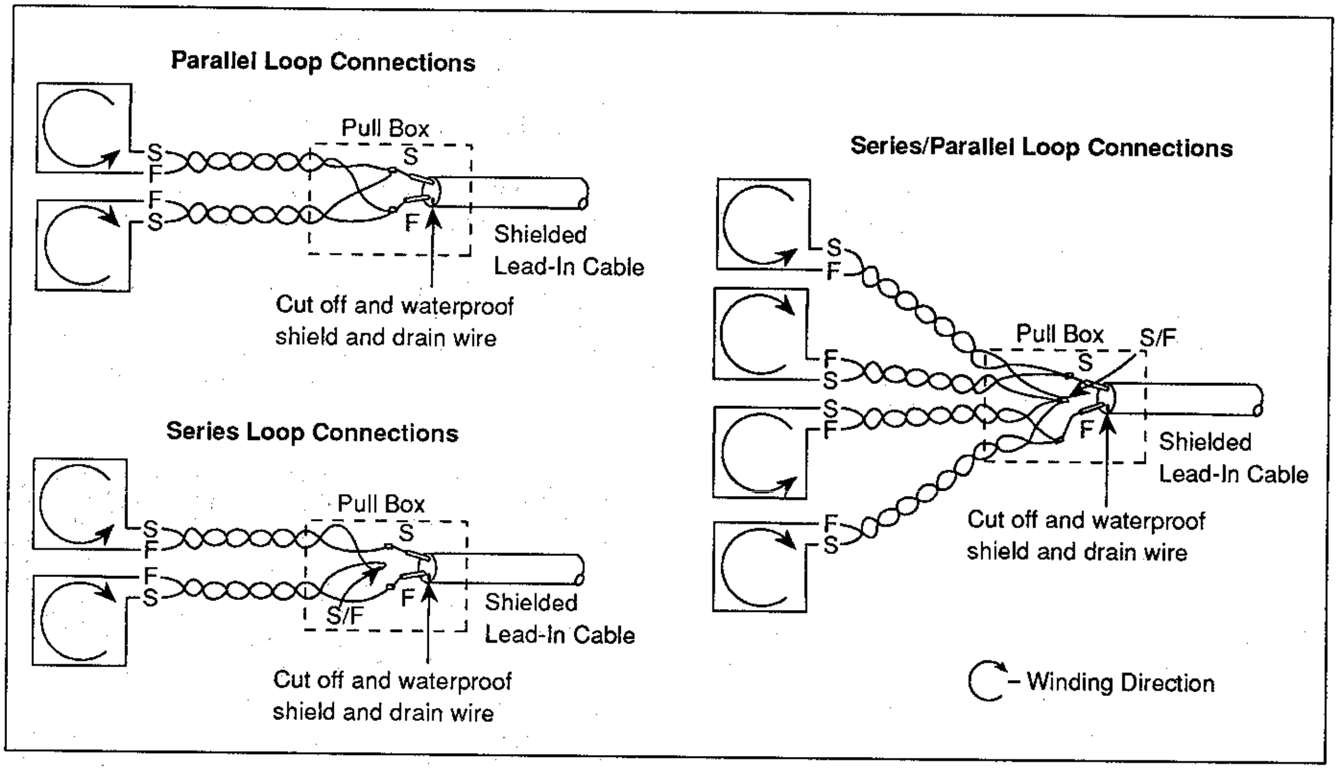


Figure 115. Loop wire winding diagrams for mutiloop installations.

Some agencies will drill through pavement before reaching the curb and gutter and will install a conduit beneath the curb section enroute to the pull box. These agencies believe this to be a simpler installation process than drilling through the concrete curb. Other agencies claim it to be more disruptive to the pavement integrity. It does, however, avoid any problems with the joint between the pavement slab and the curb/gutter.

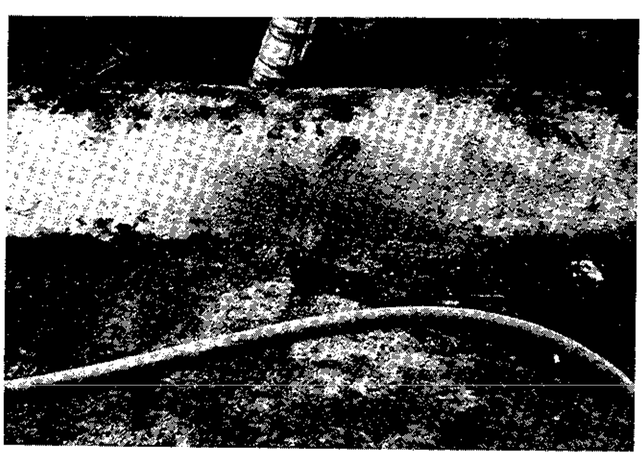


Figure 116. Entry hole for curb crossing.

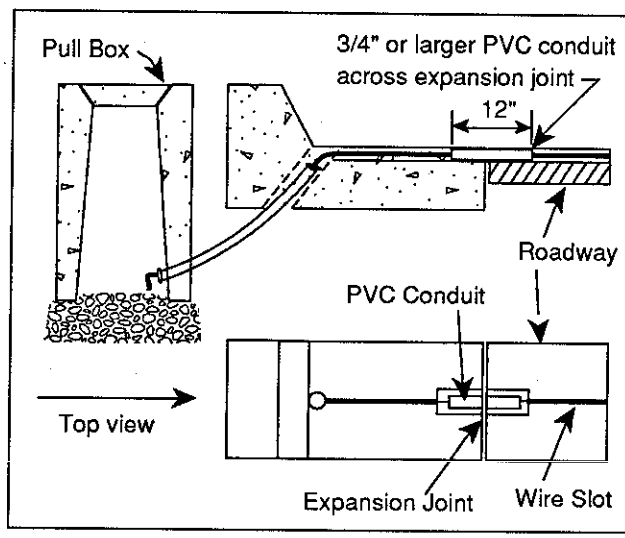


Figure 117. Loop lead-in wires at curb section.

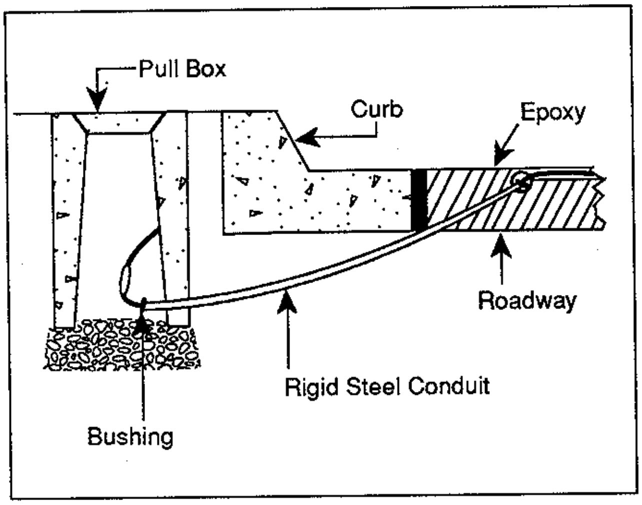


Figure 118. Detail for shallow curb section.

When a curb is not present, a hole is drilled through the edge of the pavement at a 45° angle. The top of the hole should be at least 6 in (15 cm) from the edge of the pavement. The hole should be aligned with the pull box and be of sufficient size to accept an appropriately sized conduit. Figure 119 illustrates the recommended procedure.

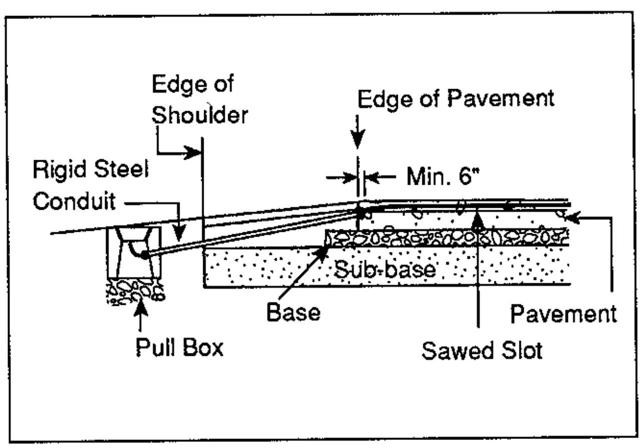


Figure 119. Loop lead-in wires at pavement edge.

INSTALLATION OF PULL BOX AND CONDUIT

The purpose of the pull box (also referred to as a "splice box," "handhole," or "junction box") is to house the splices between the lead-in wires from the loop and the lead-in cable to the controller cabinet. Additional pull boxes may be required at specified intervals on long runs to the electronic units in the controller housing. Pull boxes can be made of concrete, plastic, metal, or fiberglass.

For most installations, a standard No. 3 or No. 5. pull box, as shown in Figure 120, is used. The type of box and its location should be specified and shown on the construction plans. Many agencies specify that the pull boxes, conduits, and curb cuts must be completed before beginning the loop wire installation. Typical installation details are shown in Figure 121.

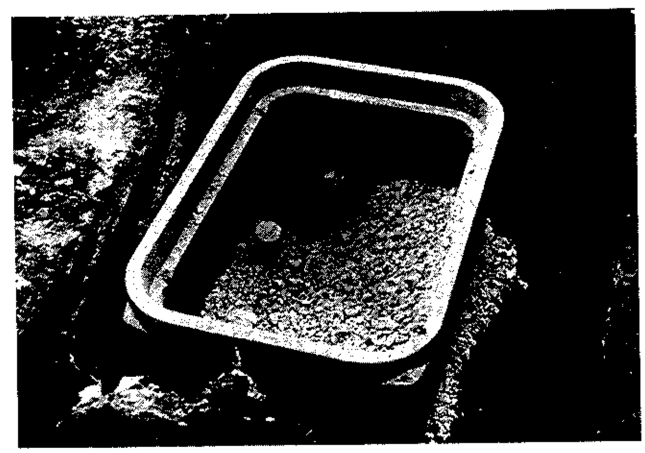


Figure 120. Standard pull box.

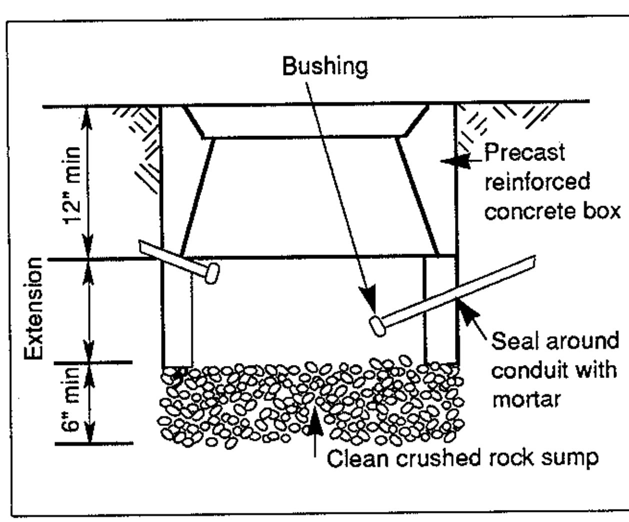


Figure 121. Pull box installation detail.

Conduit is used to protect the lead-in wires and is connected to the pull box during installation. The conduit is inserted into the hole through the curb or pavement and is connected to the pull box.

Although a 3/4-in (1.9-cm) conduit is adequate for a single pair of lead-in wires (one loop), it is common to use a 1-in (2.5-cm) minimum conduit. Table 26 provides the size of conduit for the number of loop conductors. Normally, no more than two twisted pairs are installed in one sawcut slot; however, sometimes loop lead-ins are collected at an in-street pull box (i.e., a pull box located in the travel way) and then carried to the terminal pull box in a conduit under the pavement.

At the roadway end, the conduit should be terminated 2 in (5 cm) below the pavement surface and a non-metallic bushing should be attached to protect the lead-in wires. For further protection, the lead-in wires should be taped for several inches on each side of the bushing.

It is important to tag each loop lead-in wire identifying the loop number and the start ("S")and finish ("F") of each individual loop.

Table 26. Conduit size.

Conduit size inches	Loop Conductors # of pairs
1	1 to 2
1-1/2	3 to 4
2	5 or more

TESTING THE LOOP

Before the loop wires are sealed in the pavement, the loop and lead-in wire should be checked for continuity and resistance. Tests should be run with a loop tester instrument capable of measuring electrical values of the wires and lead-ins. Measurements should be made of the induced AC voltage, inductances in microhenries, and the resistance of the conductors in ohms.

There are several types of loop testers to measure inductance, such as the one shown in Figure 122. In addition, the integrity of the wire insulation should be checked. This can be accomplished with a megohmeter (popularly called a "megger"). Applying a megger between each end of the lead-in and the nearest reliable electrical ground (e.g. street light, fire hydrant, etc) the megger reading should be in excess of 100 megohms under any condition.

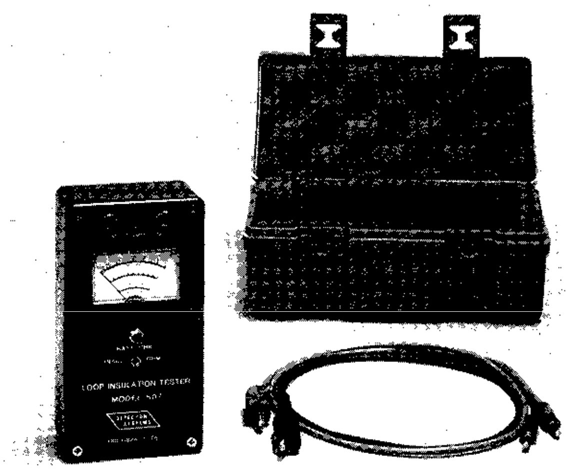


Figure 122. Loop tester.

The wiring diagram of the plan set or the inspection report should include a table of calculated values of the inductance in microhenries and resistance in ohms for each loop. Two values should be shown: one at the pull box without the lead-in cable, and the second at the controller cabinet with the lead-in cable connected. The loop installation is acceptable under the following conditions:

- **Induced Voltage:** There is no deflection of the pointer of a volt meter.
- **Inductance:** The inductance reading on the loop tester is within 10 percent of calculated value.
- **Leakage to Ground:** Using a 500 V megger, the resistance to ground of a newly installed loop exceeds 100 megohms.
- **Loop Resistance:** The reading on an ohm meter is within 10 percent of the calculated value.

The metered values obtained from the test should be recorded on the wiring plan (or on an Inspection Report described later under Final Tests and Record Keeping). This information will be used for future testing and maintenance. Ref. 32 describes a procedure used by the California Department of Transportation to test the operation and sensitivity of a new loop installation.

SEALING THE SAW CUT

One of the major challenges in detector technology has been to protect the loop wires from breakage, moisture, and from floating to the top of the sawcut and becoming vulnerable to the ravages of traffic. The sealant used is of primary importance, as is the technique of its application.

The several types of sealants, the application of the sealant, and the alternative methods of protecting the wire within the slots are discussed below. Again, it should be stressed that matching the proper sealant with the type and condition of the roadway, together with appropriate, well supervised installation techniques, are the key factors to effective, maintenance-free detector operation.

Types of Sealants

During the 1970's, the types of sealants used were about equally divided between asphalt-type and epoxy-type sealants. Early asphalt-based sealants had to be heated before application. These were soon replaced with gun-grade asphalts marketed as caulking compounds. These, in turn, were replaced by epoxy sealants. The early epoxies were too hard and brittle to adapt well to shifts in pavements and were expensive and difficult to apply.

Today, there is a wide variety of sealants produced based on each manufacturer's proprietary formula. These suppliers strive to produce a sealant that performs according to various desirable characteristics. For example, the sealant should be hard enough to resist the penetration of foreign materials and street debris such as nails or metal fragments that might pierce or break the wire, yet the sealant should be flexible enough to deform without cracking during thermal expansion and contraction. Sealants should be able to withstand the corrosive effects of road salts, gasoline, anti-freeze, transmission fluids, brake fluid, etc. commonly found on roadway surfaces.

Another critical characteristic is that the sealant should have good adhering properties with similar contraction and expansion characteristics to that of the highway material in which it will be installed. For asphalt-type roads which tend to move, rubberized asphalt, polysulfide-based sealants, and flexible epoxies are usually recommended. These types can also be used with concrete along with the more brittle-type epoxy.

Other advantages sought in selecting sealants are rapid curing rate and the ability to be applied to damp surfaces. A rapid curing rate is desirable because it will minimize the amount of time that a lane must be closed to traffic. During the saw cutting operation, a water-cooled blade is generally used, and even though the slot may be cleaned with compressed air, some residual dampness may remain. In such cases, it is desirable to be able to apply the sealant directly to damp surfaces rather than first drying them with butane torches, which is time consuming and may damage the asphalt surfaces.

Sealant applications are characterized as either cold pour or hot pour types. Cold pour types include polyester resin, epoxies, polysulfide bases, and rubberized asphalt. The hot pour varieties include hot pitch, asphalt, and rubberized asphalt. Both sealant types must not revert to their liquid state during hot weather, because this will allow the loop wire to float to the surface. Sealant should always be fluid enough during application to level itself on a horizontal surface, but should not run when applied on an inclined surface. Careful attention must always be paid to applying the sealant in strict adherence to the manufacturer's instructions.

Hot tar continues to be used because of its low initial cost. Several States, however, have prohibited its use due to the high percentage of failures and the danger and inconvenience to workers during application. The heat involved (sometimes exceeding 500 °F (260 °C)) in the application frequently breaks down or deforms the insulation of the loop wire, diminishing its insulating integrity. In addition, hot tar sealant becomes soft in hot weather and allows vehicles to track the tar from the sawcut. Rocks and other debris can penetrate the soft surface and eventually damage the loop wire insulation.

Rubberized asphalt appears to be the sealant of choice, particularly for asphalt pavements. It is necessary to ensure that the wire specified for the loop has insulation capable of withstanding the 400 °F (205 °C) application temperature of the rubberized asphalt sealant. Epoxies, however, have overcome some of their early drawbacks and are now formulated to provide a greater degree of flexibility.

A number of States have conducted extensive tests of the various, commercially available sealants prior to listing the acceptable sealant products in their specifications. A typical State specification is presented in Figure 123 (adapted from Ref. 33). In reviewing the documentation of these State tests, it was interesting to note that a product that scored highest in one State test was considered unacceptable in anotherState test. This leads to the conclusion that the disparity in test results is most probably caused by differences in geographic and climatic conditions, as well as methods of testing the products. However, most agencies are consistent in product approval criteria. This, in turn, suggests that agencies should periodically validate their tests and test procedures to ensure that their specifications are appropriate.

TRAFFIC LOOP SEALANT SPECIFICATION

Section XXX.XX Traffic Loop Sealant Material shall be an epoxy resin system or a polyester system designed specifically to meet the physical properties for sealing traffic loop pavement cuts. The epoxy resin system shall be an unfilled system intended to be used with an equal volume of clean, oven-dry sand. The system shall bond to either portland cement concrete or bituminous concrete, shall be unaffected by environmental conditions, and shall have a dielectric strength sufficient to allow the traffic loop to operate as intended. Viscosity of the mixture shall be such that it is easily pourable into the saw slot and sufficiently flowable to encase the electrical wiring.

(a) Epoxy Resin System shall be a two component material conforming to the following requirements based on the epoxy without sand (except for the pot life requirement):

PROPERTY	TEST METHOD	MEASUREMENT	REQUIREMENT
Pot Life at 77° F w/Sand	ASTM C881; ¶ 11.2	Minutes	12 Minimum
Initial Cure Time at 77° F		Hour	1 Maximum
Hardness, Shore D	ASTM D2240	Number	25 to 65
Elongation	ASTM D 638	Percent	50 Minimum
Water Absorbtion in 24 hours	ASTM D 570	Percent	0.5 Maximum
3% NaCl Absorbtion in 24 hours	ASTM D 570	Percent	0.5 Maximum
ASTM #3 Oil Absorbtion in 24 hours	ASTM D 570	Percent	0.1 Maximum
Gasoline Absorbtion in 24 hours	ASTM D 570	Percent	1.0 Maximum

(b) Polyester System shall be a two component material conforming to the following requirements:

PROPERTY	TEST METHOD	MEASUREMENT	REQUIREMENT
Pot Life at 77° F w/Sand	ASTM C881; ¶ 11.2	Minutes	12 Minimum
Initial Cure Time at 77° F		Hour	0.75 Maximum
Hardness, Shore D	ASTM D2240	Number	25 to 65
Elongation	ASTM D 638	Percent	15 Minimum
Water Absorbtion in 24 hours	ASTM D 570	Percent	0.2 Maximum
3% NaCl Absorbtion in 24 hours	ASTM D 570	Percent	0.2 Maximum
ASTM #3 Oil Absorbtion in 24 hours	ASTM D 570	Percent	0.02 Maximum
Gasoline Absorbtion in 24 hours	ASTM D 570	Percent	0.8 Maximum

Figure 123. Typical State sealant specification.

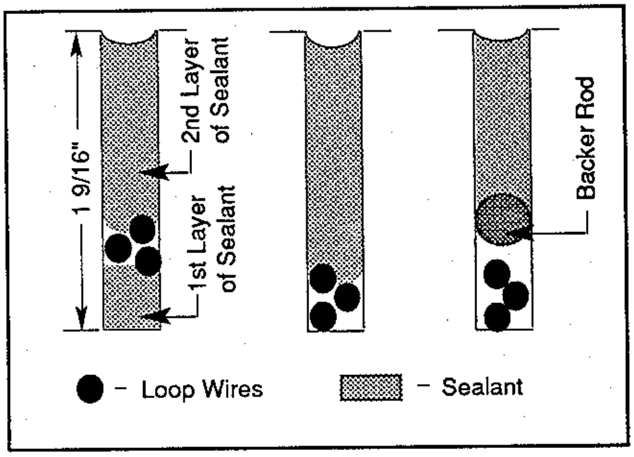


Figure 124. Methods of applying sealant.

Techniques for Sealant Application

The commonly used practices for sealing the loop wire are depicted in Figure 124. One procedure (Figure 124 left view) consists of applying a layer of sealant to the floor of the saw cut after thoroughly cleaning and drying the slot. The loop wires are then laid in the slot and covered with a second, final layer of sealant. This method tends to fix the position of the loop wires in the middle of the saw cut, protecting them on the top and bottom. Some agencies believe that this procedure, although more costly, protects the loop wires from water intrusion.
In the technique shown in the middle of Figure 124, the wire is simply laid in the slot and covered with sealant. There is no way to control the positioning of the wire in the slot. In a three-wire installation, the three layers of wire may form a triangle on the bottom of the slot or may stack over each other.

The backer rod/sealant combination shown in Figure 124 (right view) is based on the theory that stresses on sealant during elongation are reduced if the sealant has less depth. With this method, the wires are placed in the slot and then a backer rod (generally a closed-cell polyethylene rope) is forced into the slot over the wires. The remainder of the slot is then filled with sealant. The backer rod assures a shallow layer of sealant reducing tensile stresses and leaving the wires free to adapt to shifting of the pavement. An alternative method that is becoming increasingly popular is to insert short pieces of the backer rod (approximately one inch) every foot or two to anchor the wire in the slot before applying the sealant.

There seems to be no published evidence of the superiority of one method over the other. In reality, most detector installers agree that the neat arrangement of wires as shown in many published illustrations is simply not indicative of actual installations, rather, the lay of the wires is random in the slot. They agree that complete encapsulation by the sealant is seldom achievable. Some installers also argue that placing sealant in the bottom of the saw cut (left view in Figure 124) before laying the wire is time-consuming and requires more road-closure time. Installers indicated that even when this method of installation is specified, it is unlikely to be followed unless an agency inspector was actually overseeing the installation. This is another illustration of the need for careful installation inspection.

On the other hand, proponents of this method report that the extra protection of the bed of sealant on the bottom of the sawcut prevents the intrusion of water through small pavement cracks. It also avoids the possibility of sharp edges or rocks becoming dislodged and piercing the installation. Others feel that this is a remote possibility, particularly if the sawcut is well cleaned of debris. On the other hand, some agencies specify the use of a layer of sand rather than sealant at the bottom of the saw cut. This does provide a smooth bed at the bottom of the saw cut but does not prevent the intrusion of water through pavement cracks.

The amount of sealant to be applied should be sufficient to completely fill the saw cut, but not overfill. A trowel or other tool should be used to ensure that the sealant is slightly below the pavement surface and that any excess sealant is removed. Figure 125 shows the result of poor installa-

Figure 125. Example of poor sealant application.

Figure 126. Crew applying sealant.

tion procedures. It shows overfilling, underfilling, and air bubbles in the sealant. All three conditions can lead to detector failure and should have been corrected during the installation process.

Sealant may be applied with a special applicator as shown earlier in Figure 104 or by hand directly from a container as shown in Figure 126. In this illustration, one member of the crew is placing the lead-in wires in the slot, while another worker is pouring the sealant into the sawcut. Note that a paint stirrer has been inserted in the slot to hold the wire down while the sealant is being applied. Other techniques can be used (e.g., backer rod strips, nylon rope, etc.) to hold the wire securely in place as sealant is added. Figure 127 shows the crew properly finishing the sealant application. The sealant has been trowelled in the slot to remove any excess, talc is being dusted on the fresh sealant, and splashes of sealant are being removed from the pavement area.

Figure 127. Finishing the sealant application.

After the sealant has been applied and before opening the lane to traffic, a number of agencies and loop installers coat the newly applied sealant with sand or talc. This prevents tracking of the sealant during its curing process and allows earlier opening of the traffic lane.

Some sunbelt agencies use sand as the sealant. After the wire is placed, sand is tamped into the slot. The sand is easily tracked out of the slot and the wires may become dislodged. Therefore, this practice is not recommended.

SPLICING THE WIRE

The splice between the loop lead-in wire and the lead-in cable to the detector unit in the controller housing is a critical step in the installation process. The splice should be located in the pull box and should be the only splice in the loop system. The splice is frequently the cause of detector failure; however, if proper splicing procedures are used, the splice connection should not be a problem. There are two basic steps to a splice; the physical connection of the wires and the environmental sealing of the connection.

Connecting the Wires

The methods used to physically connect the lead-in wires from the loop with the lead-in cable vary among agencies. The two preferred methods are twisting and soldering or crimping and soldering. Most detector manufacturers specify a solder connection in their installation procedures. The argument for soldering is that it provides a connection with lower resistance and has less susceptibility to corrosive degradation. The soldered connection will, therefore, require less maintenance in the long run.

While pressure connectors (crimping) without soldering may have been generally acceptable in the past, the use of solid state electronic apparatus now makes soldered connections preferable. These electronic devices operate at very low voltage levels and minimum current loads. Because of this, they are susceptible to even slight voltage drops which occur where poor electrical connections cause high resistance in a circuit.

To make the physical connection, about 8 in (20 cm) of the outer covering of the lead-in cable is stripped away. One wire is clipped about 3 in (7.5 cm) shorter than the other. About 1-1/2 in (4 cm) of the wire insulation must be stripped away from the cable wires and the loop lead-in wires. The appropriate wires are then twisted together (end to end) or crimped with a non-insulated butt connector. Care must be exercised to assure that the correct wires are connected.

If the connections are to be crimped, it is strongly recommended that a high quality pressure crimping tool be used to provide a uniform 360° crimp. Care must be exercised to ensure that only bare wire, and not the adjacent insulation, is in the connector. The individual connected splices should be staggered so that the spice does not become too bulky. Each connection should then be soldered using 60/40 (tin/lead) resin core solder. The Ontario Ministry of Transport, on the other hand, specifies the use of 60/40 (lead/zinc) resin core solder (Ref. 31). The procedures for both twisted and crimped splices are detailed in Figure 128.

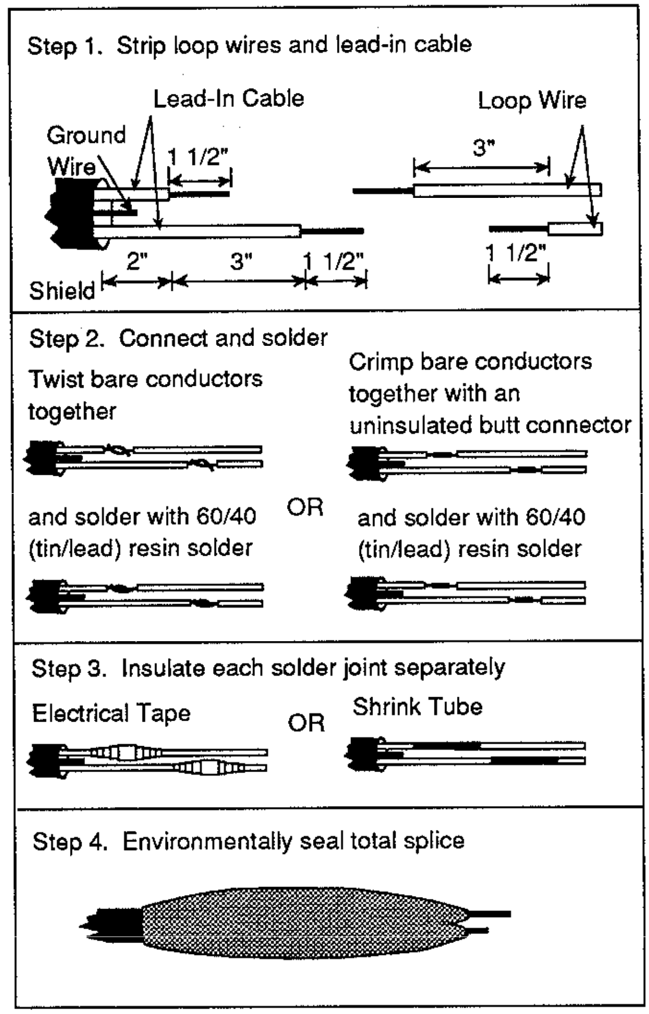


Figure 128. Splicing loop wire at pull box.

Environmentally Sealing the Splice

Once the wires are firmly spliced, it is essential that the splice be environmentally sealed against weather, moisture, abrasion, etc. A variety of methods are used, including heat-shrinkable tubing, special sealant kits, special forms to be filled by sealant, pill bottles with slot sealant, tape and coating, etc. Any method is acceptable as long as it provides a sound environmental seal.

When using heat shrinkable tubing, the wires must be inserted in the tubes before they are joined. Two small tubes are used for the individual wires and one large tube to cover the entire splice area. The wires are connected and soldered as described earlier, and the small tubes are centered over the connections and are gradually heated by an electric heat gun or butane torch until the tubes have shrunk uniformly around the wires. The larger tube is now positioned over the splice and heated in the same manner. Care must be exercised to avoid burning the wire insulation or the cable jacket. Once the tubes have been shrunk over the splice area including the cable end, a secure environmental seal has been established.

Special sealant kits are commercially available. These kits may have one-part or two-part sealants. One-part sealants are ready to use. Two-part sealant kits usually contain the resin and hardener in separate compartments of a plastic package. The seal between the two parts is broken and the two components mixed. The package is then cut open and the sealant is formed over the splice area. It is important to ensure that the mixture penetrates between the wires.

An alternate process uses a form around the splice area. A liquid or pourable sealant is introduced into the form. Care should be exercised to ensure that the form is totally filled with sealant and there are no voids within the splice area.

A very simple encapsulation process consists of using a common drug store pill bottle as shown in Figure 129. The wires are spliced side by side rather than end to end. After the wires are twisted and soldered (some agencies add a wire nut or tape the joint), the completed splices are inserted into a pill bottle that has been filled with sealant or electrical epoxy. The details of the pill bottle splice are illustrated in Figure 130.

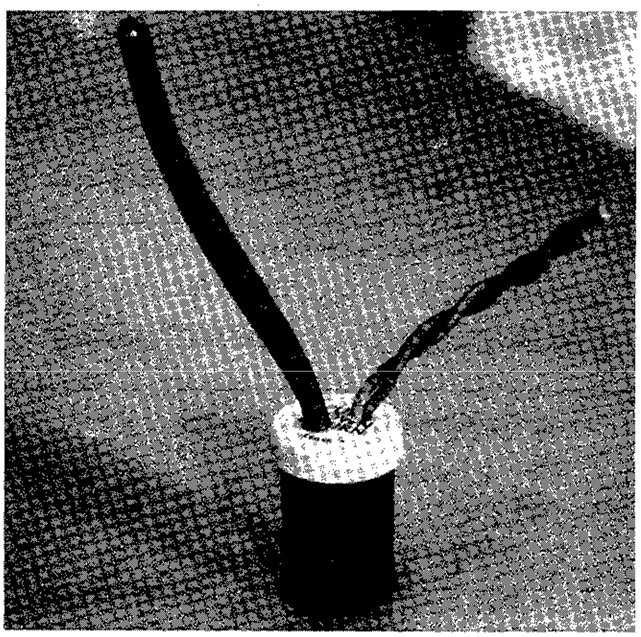


Figure 129. Pill bottle splice.

Some agencies still use electrical tape to seal the splices. This procedure is not recommended. However, if tape is used, it should be high quality electrical tape. Each wire connection should be taped separately and then the entire splice area covered by several layers of overlapped tape. A waterproof sealant should then be applied to the entire taped area.

LEAD-IN CABLE INSTALLATION

In general practice, the lead-in cable from the pull box to the controller cabinet is buried bare or placed in conduit below the surface of the ground. In either case, the cable should be buried in a trench at least

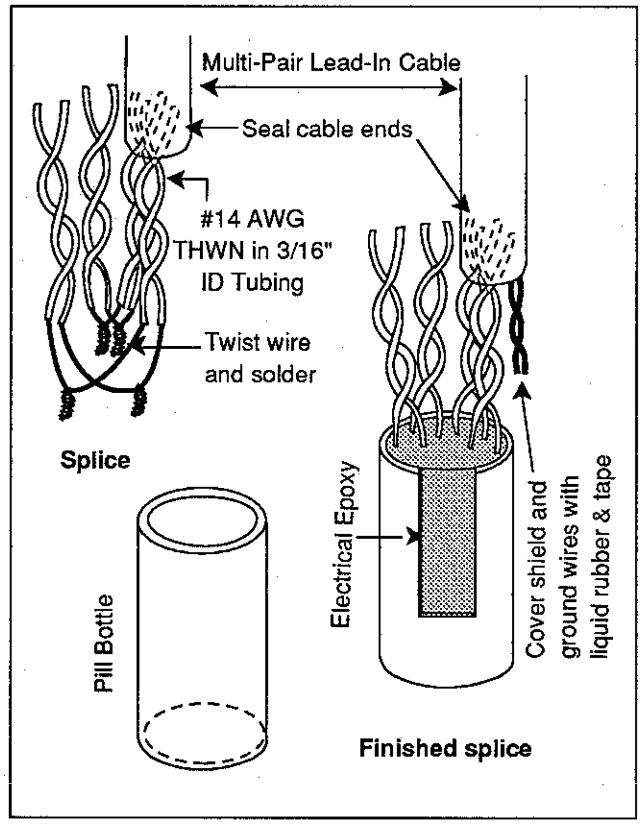


Figure 130. Pill bottle splice details.

18 in (45 cm) below the surface. If conduit is used, it should be waterproofed.

Trenching is the most common method for installing underground cable (see Figure 131). The construction plans should specify how deep to trench. After placing the cable in the trench, it should be backfilled in layers not to exceed 6 in (15 cm). Each layer

Figure 131. Cable trenching.

should be compacted with mechanical tampers to the approximate density of the surrounding ground. When the backfill is complete, there should not be any extra material left over.

The lead-in cable will end inside the controller cabinet at the field terminal strip as shown in Figure 132. An excess of 18 in (45 cm) of cable should be provided in the cabinet housing. Note that the shield of the cable in this example is connected to the third terminal adjacent to the loop terminations. A different procedure is espoused by one manufacturer who states that the cable shield should be insulated from ground and floating at both ends (at the cabinet and in the pull box).

Most manufacturers recommend grounding at the cabinet (i.e., connecting the shield to the terminal in Figure 132) and insulating the end of the cable in the pull box. This allows any electrical disturbance or interference to be safely grounded without affecting the loop lead-in cable.

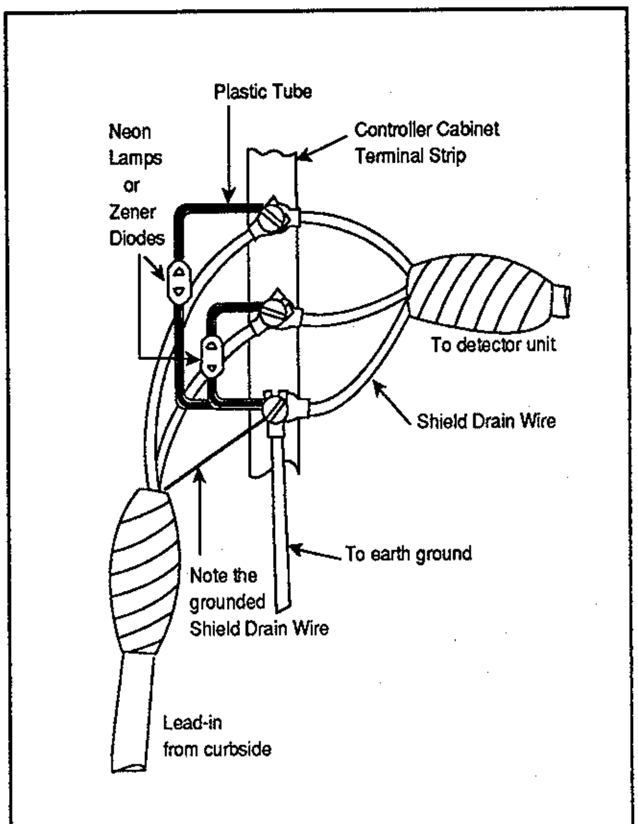


Figure 132. Field terminal strip.

The Ontario Ministry of Transport (until 1990) recommended a contrary procedure, that is, grounding at the splice point in the pull box and cutting off the shield in the cabinet. (See Appendix N, page 9-36.) They reversed this procedure in 1990, to ground the shield in the cabinet and insulate the shield in the pull box.

NEMA avoids the issue by indicating that "Field installation practices or detector unit design may require grounding the shield of the loop lead-in cable. Such grounding should be in accordance with the detector manufacturer's recommendation."

The loops are capacitively coupled to the earth and receive a voltage surge whenever lightning currents enter the ground nearby and cause an earth voltage rise. These surges may need to be suppressed where the cable enters the controller cabinet or where these circuits enter the detector units. Back-to-back zener diodes or neon lamps usually provide adequate protection.

Most modern detector units have built-in lightning protection features. Even so, some agencies in lightning prone areas (specifically Ontario, Canada (Ref. 31) and Florida) recommend that additional protection be added, such as two neon lamps or two gas filled, surge voltage protectors connected to the terminal strip as shown in Figure 132.

FINAL TESTS AND RECORD KEEPING

Final tests should be conducted after all loops and cables have been installed. The initial tests, described previously in this section, should be repeated to ensure the detector installation is performing as expected and is fully operational after all cables have been buried.

The result of the tests should be recorded on an installation data sheet such as that shown in Figure 133. Any modification made to the original plan drawings should be noted, dated, and retained as "As Built" plans.

Exact readings from the tests and the modified plans should be verified by the inspector. These records will comprise the history of the particular detector system and will form the basis for any future maintenance or repair activity.

LOOP INSTALLATION DATA

Date: ____________________

Weather: ____________________

Approximate Temperature: __________

Pavement Condition: Wet (___) Dry (___)

Location: ____________________

Drawing Number: ____________________

Contractor: ____________________

Material:

Loop Wire: ____________________

Lead-In Cable: ____________________

Pull Box: ____________________

Splice Kit: ____________________

Conduit:

Curbside to Pull Box: ____________________

Pull Box to Cabinet: ____________________

Sealant: ____________________

Loop System:

Position: ____________________

Configuration: ____________________

	Estimated	Measured
Twisted Lead-In Length:	______	______
Lead-In Cable Length:	______	______
Inductance:	______	______
DC Resistance:	______	______
Leakage Resistance:	______	______

Comments on Workmanship: ____________________

____

Remarks: ____________________

____

Recommendation: ____________________

Inspected By: ____________________

Figure 133. Typical installation sheet.

GENERAL INSTALLATION GUIDELINES

A set of general installation guidelines is presented in Table 27. It is emphasized that these are general guidelines for the installation of loop detectors at signalized intersections under a wide variety of circumstances. For specific installations, the actual design, installation procedures, testing, etc. should be followed. These guidelines were developed from Refs. 34 and 35.

Table 27. General installation guidelines.

Design

- The width of the loop should be tailored to the width of the lane
- Loops should not be over 6 feet (1.8 m) wide in a 12 foot (3.7 m) lane.
- Loops should not be less than 5 feet (1.5 m) wide (height of detection is approximately one half to two/ thirds of the loop width).
- All loops should have a minimum of two turns of wire in any sawcut except in a quadrupole.
- One additional turn of wire may be specified for loops installed in reinforced concrete or over 2 inches (5 cm) deep.

Installation of Loop Wire and Lead-in Cables

- The corner of loop sawcuts should be cored, chiseled, beveled, or diagonally cut to eliminate sharp turns.
- Sawcut should be deep enough to provide for a minimum of 1 inch (2.5 cm) of sealant over uppermost wire.
- If 1/4 inch sawcut is to be used, select wire size to allow encapsulation of the wires (AWG #14 or #16).
- Loop wires should have a high quality insulation such as cross-linked polyethylene or polypropelene.
- Wire should be laid in sawcuts in the same rotation (clockwise or counter-clockwise) in a loop.
- Loop wires should be tagged to indicate start (S) and finish (F) and should indicate the loop number in the pull box to facilitate series splicing with alternate polarity connections.
- Sawcuts for the loop lead-in wire should be at least 12 inches (2.5 cm) from adjacent loop edges.
- The loop lead-in wire from the loop to the pull box should be twisted a minimum of 3 to 5 turns per foot.
- Splices of loop lead-in wire to lead-in (home-run) cable must be soldered, insulated, and waterproofed to ensure environmental protection and proper operation.
- The lead-in cable should be twisted, shielded, and waterproofed.
- The cable selected should have a polyethylene jacket.
- For most installations, the lead-in cable should not be connected to earth ground at the pull box, only insulated and floating. Manufacturer's recommendations should be followed concerning whether the cabinet end is grounded or not (per NEMA).

Table 27. General installation guidelines. (Continued)

Testing

- Prior to filling sawcuts with sealant, loops should be checked with an ohm-meter for continuity and loop and lead-ins in pull boxes should be checked with a 500 V DC megger to confirm insulation resistance >100 megohms.

- Loops should be checked with a direct reading inductance meter at the pull box to confirm the number of turns of wire in any loop. The following formula was developed to provide a simple method to calculate the approximate inductance of any loop configuration and/or confirm the number of turns in the loop.

  Inductance (L) = K x feet of sawcut

No. of Turns	K, μh/ft
1	0.5
2	1.5
3	3.0
4	5.0
5	7.5

- Inductance meter should also confirm electrical splice configuration of multiple loops to allow selection of proper sensitivity setting on detector unit.

Sealant

- Loop sealant should be selected to insulate and protect wires.
- Loop sealant should encapsulate loop wires to the fullest extent possible.
- At least 1 in (25 mm) of sealant should cover the loop wires (i.e., do not allow wires to float).
- The sealant selected should adhere to asphalt or concrete, but not necessarily to both.
- For installation in an existing roadway, loop sealant should be poured to within 1/8 inch of surface. For installation prior to overlay, the sawcut should be filled completely before paving.

Connections

- All spade lug connections in the loop circuit should be soldered.
- Multiple loops connected to the same detector channel should be connected in series or series/parallel. (Some manufacturers dispute the use of series/parallel.)
- Confirm series splice with inductance measurement prior to connecting to lead-in cable.
- Multiple loops connected to the same detector channel should be connected with alternate polarity (clockwise - counter clockwise) to improve noise immunity and stability.
- Loops in adjacent lanes should be connected to the same multiple channel detector unit.

Note: For more exact values of inductance, use Appendix C.

DETECTOR INSTALLATION ALTERNATIVES

Agencies and manufacturers continue to search for better ways to install detectors. The following section describes two methods that have been developed, tested, and are currently operational. Note that conventional loop details such as splicing, testing, etc. described earlier also apply to the following alternative methods.

SLAB LOOPS

In the early 1980's, the Puerto Rico Highway Authority and the Department of Transportation and Public Works began to experiment with placing loop detectors in heavily reinforced precast concrete slabs for installation in bituminous pavements (Ref. 36). Earlier experimentation with loop detectors placed in cast-in-place concrete slabs 12 ft (3.7 m) in width and 6 ft (1.8 m) in length were unsuccessful due to the difficulties in maintaining traffic during the relatively long curing period. Because of the size and weight, these slabs could not be precast.

The use of magnetometer detectors was also tried. They were found to be unsatisfactory because of the proximity of the Island of Puerto Rico to the equatorial line, which resulted in erratic behavior of the detectors.

Smaller unitized slabs were selected as an effective design for use in Puerto Rico. They have been used extensively for left-turn lane detection, off-ramp detection, arterial detection, and system detection.

The final design of the precast or cast-in-place loop slabs (both types are used) is 4 ft (1.2 m) square and 8 in (20.3 cm) deep. A circular slot 40 in (102 cm) in diameter, 3 in (7.6 cm) deep, and 1/2 to 3/4 in (13 to 19 mm) wide is impressed in the concrete to house the conductors forming the loop.

Five turns of wire are standard in these installations with three turns considered to be the minimum acceptable. (Adequate detection has been obtained with up to 1,000 ft (300 m) of lead-in cable between the pull box and the detector unit.) After the wire is wound in the slot, a 5/8- to 7/8-inch (16- to 22- mm) nylon rope is forced into the slot on top of the loop wires and then the slot is filled with an asphalt sealant. A 1-in (25-mm) flexible metallic conduct is used to house the lead-in wires leading to the pull box.

As shown in the plan details in Figure 134 (from Ref. 36), the slabs are provided with four lift point devices for handling during the original installation and for resetting in the case of overlays. These slabs can be easily handled bytwo men and a small loader-backhoe combination.

Hot-poured asphaltic sealant and silicone sealant have both been used successfully. An emulsified asphalt sealant is also being tested as it is less expensive and does not need to be heated. Epoxy sealant has not been used for this purpose as this type of sealant may make reentry into the slot for repairs more difficult.

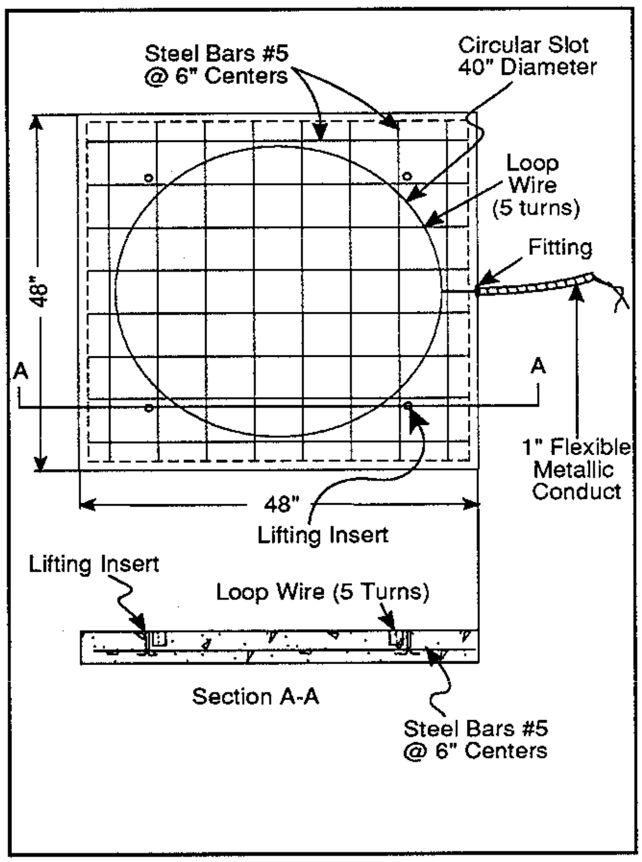


Figure 134. Plan details of slab loop installation.

Although these slabs were originally intended for use on bituminous pavements, their performance and ease of maintenance have led to the use of slabs on new and existing PCC pavements. On existing PCC pavements, an oversize square is cut out of the pavement and the precast slab is installed with concrete backfill.

Puerto Rico uses non-reinforced concrete pavements. Therefore, on new PCC pavements, a grid of reinforcing bars is placed at the bottom of the new slab where the loop is to be placed prior to the pouring of the concrete. After the pour, a form for the slot is impressed into the fresh concrete.

Precast loop slabs have been used successfully in four basic configurations as shown in Figure 135: actuation (LC-1), directional (LC-2), presence (LC-4), and high-speed detection (not shown on drawings). The loops have been connected in series and in parallel and have been used with standard and self-tuning detector units.

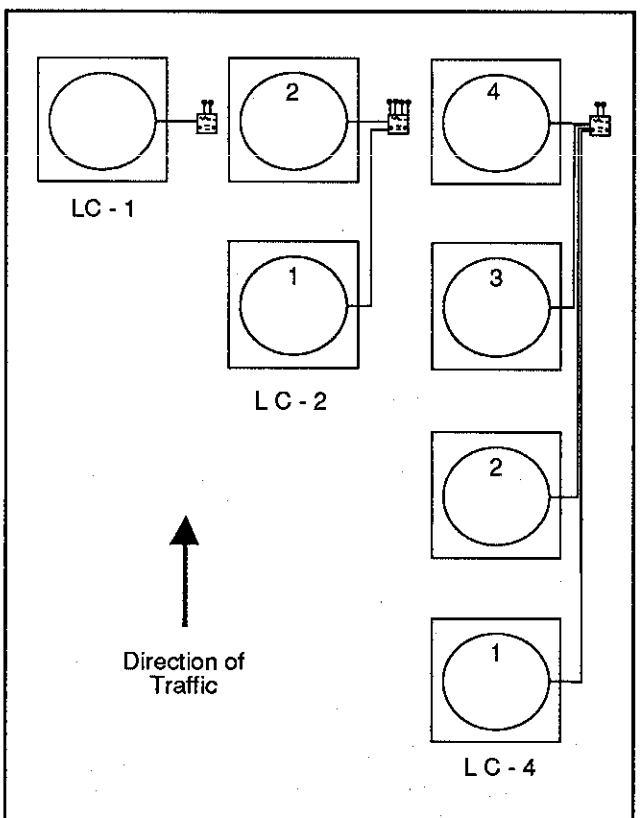


Figure 135. Precast loop slab configurations.

They have been installed at isolated intersections as well as in coordinated systems. In coordinated systems, they have been used for both local detection and as strategic system sensors to feed information to the master controller for traffic responsive operation.

By 1988, there were more than 1800 slab loop detectors installed in Puerto Rico. Over a 5 year period there had been no traffic or pavement-induced failures. On three occasions the lead-in wires had been damaged by excavations in the sidewalk or adjacent pavement areas. There were also 13 incidences of failure in the wire insulation caused by a manufacturing error.

It is important to note, that, although Puerto Rico experiences heavy rainfall, the annual temperature ranges between a low normally about 60 °F (16 °C) and a high normally below 97 °F (36 °C); consequently, there is no freeze-thaw problem. This could possibly affect the use of these slabs in colder climes.

The failures that occurred provided the opportunity to demonstrate the ease with which loops can be repaired. With a screwdriver or similar tool, the nylon rope is pried from the slot and, by pulling on the rope, the rope and sealant are removed. The conductor wires are then removed from the slot. New conductors, rope, and sealant are then installed and an epoxy-encapsulated splice is made at the nearest pull box. This completes the repair with little disruption to traffic.

Experience with the loop slabs have been very successful in Puerto Rico. A typical installation on an off ramp and in a left turn lane is shown in Figure 136. In the mid-80's the cost in Puerto Rico was approximately $350 per loop including the slab, installation, conduit, wiring to the nearest pull box, and the splice at that pull box.

Older signal projects with sawed slots in the pavement are being retrofitted with precast slabs to prevent the deterioration and interruption of service due to loop failures. Although a formal benefit/cost comparison between the precast and the sawed loop detectors has not been conducted, the zero failure rate of the precast system during a 5 year operating period is considered sufficient justification for Puerto Rico to adopt the precast loop as standard practice.

Figure 136. Slab loop installations.

ROUND LOOPS

Although square or rectangular loops are the most commonly used shapes, many loop designers have theorized that circular loops would provide optimum detection characteristics. In theory, the round loop will produce a uniform magnetic field without dead spots.

Proponents of the round loop argue that the circular design maximizes loop sensitivity for detection of motorcycles as well as high bed trucks while eliminating splashover from adjacent lanes. Other advantages cited include the elimination of sharp corners and the reduction in wire stress. The most critical disadvantage is the difficulty associated with cutting the circular shape in the pavement.

In addressing this problem, one manufacturer has developed a patented vehicle, designed specifically to saw a circular slot 6 ft (1.8 m) in diameter that is 1/2 in (1.25 cm) wide and 3 in (7.6 cm) deep for the installation of circular loop detectors in either asphalt or concrete road surfaces (Ref. 37). The self-contained vehicle is equipped with a 6-ft (1.8-m) diameter bit to cut the circle, a 500-gallon (1.9- kl) water supply, central vacuum system, a 6.5 KVA generator, arrow boards front and rear, portable hot sealant unit, and a 35 hp flat saw for cutting the slot from the loop to the pull box. The loop wire used in this installation is encased in continuous PVC tubing and prewound for the specified number of turns, stacked, and taped at the factory.

A typical installation is illustrated in Figure 137 and is described as follows. The truck arrives at the site and the two-man crew sets out cones to divert traffic. The liftgate is used to off load the hot rubberized sealant machine and the flat saw. The sealant material is placed in the machine to melt to pumping consistency. A center mark for the drilling bit is marked on the roadway. The truck is positioned to center the bit over the mark and the platform, housing the bit, is lowered. The drive button on the control panel is depressed to activate the bit. The depth gauge on the bit allows the operator to monitor the accuracy of the depth of the cut. When the proper depth is reached, the drive button is released and the bit comes to a stop. The platform is raised and the truck can be repositioned for the next cut. The average cutting time is 5 minutes.

The flat saw is used to cut the slot from the loop to the pull box. A 3–in (7.6-cm) core is drilled at the point where the lead-in slot joins the circle. After all cuts have been made, the slots are washed down to remove debris and vacuumed dry.

The prewound loop and its lead-in wires are then installed. All loops are wound in a clockwise pattern and are connected in series. The top wire is wound around the 3-in (7.6-cm) core to reduce bending stress. The installation is now ready to be sealed. The sealant is pumped into the slot after reaching its melting point. The installation is completed and the lane may be opened to traffic immediately as the sealant hardens as soon as it is exposed to air.

The manufacturer of this unit reports that since the truck and cutting tool are a totally self contained unit, the loop cutting operation can be confined to a single lane at a time. The body of the truck faces oncoming traffic which provides an added measure of protection for the operator and others working in the area. Thus the loop cutting can be accomplished safely, in minimal time, and with minimum disruption to traffic flow in the area.

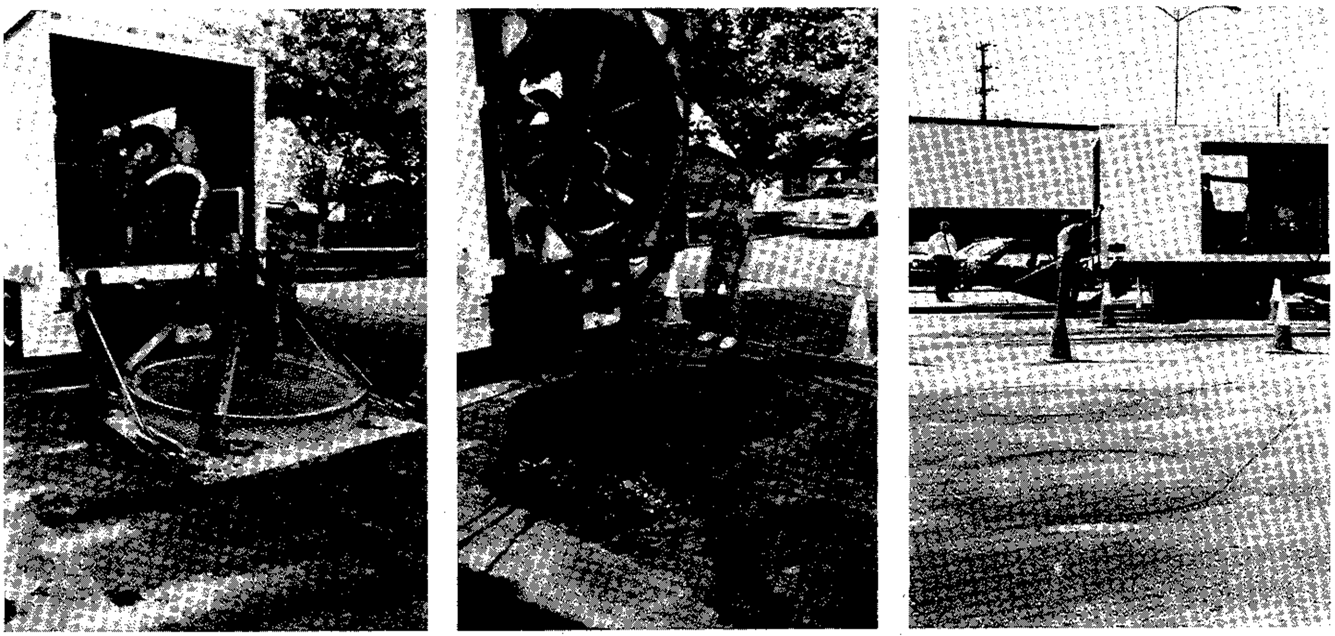


Figure 137. Installation of round loops.

INSTALLATION OF MAGNETOMETER DETECTORS

Typical magnetometer installations for various lane configurations are illustrated in Figure 138. The probes are placed beneath the roadway surface in cored holes. The optimum depth and placement of the probes depends on the type of detection required (see Chapter 4).

After the pre-installation activities (described earlier in this chapter) have been completed, installation usually follows the step-by-step procedures discussed below.

INSTALLATION OF SENSING PROBE

After securing the work zone with appropriate barricades, cones, etc. to divert traffic from the area, the first step is to lay out and mark the detection area with spray paint or chalk markers to match the construction plans. A magnetic field analyzer should be placed over each marked probe location to verify that the area is free of adverse elements that would degrade performance (see Chapter 4).

Holes for the probes are then drilled through the roadway to the proper depth as defined in the construction plans. The general rule for the diameter of the hole is to use the diameter of the sensing probe plus 1/8 in (3.2 mm).

Slots for the connecting cable are then sawed in the pavement to the adjacent pull box and blown clean and dry with compressed air. The pull box is installed using the same procedures as previous described for loop detectors.

The probe should be installed with the long dimension vertical and with the cable ends at the top. The probe should be firmly supported in the hole so it will not shift from its vertical position.

There are several approaches for placement of the probe in the hole. Manufacturers indicate that the probe is made so that it can be placed in the hole without any protective housing and a number of agencies follow this procedure.

Other agencies prefer to provide some type of housing (e.g. PVC conduit) for placing the probe while others choose to secure the probe by tightly packing

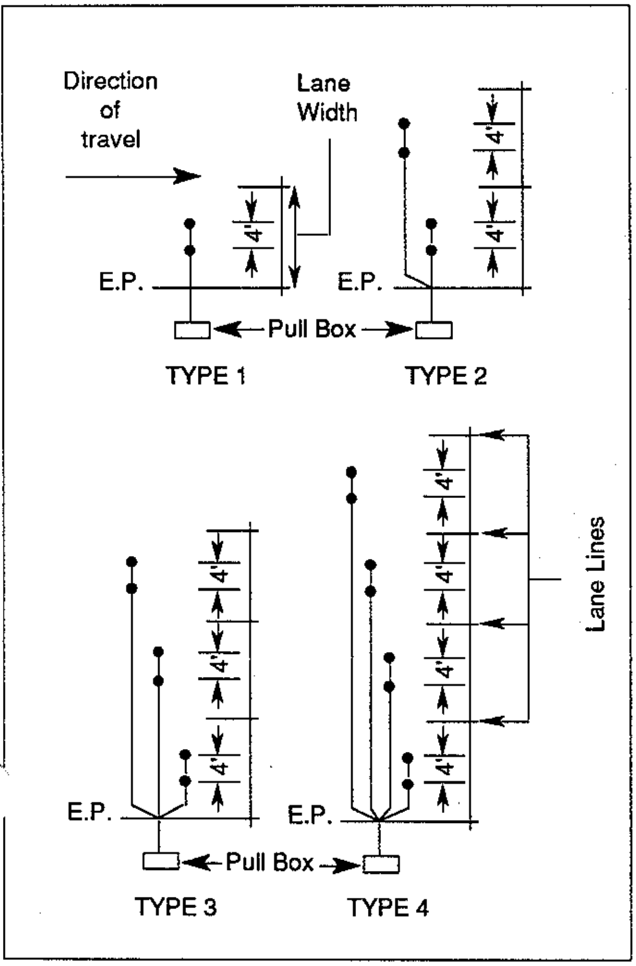


Figure 138. Typical magnetometer installation.

sand or using sealant around it. A typical standard plan for magnetometer installation is shown in Figure 139.

The cables from the probe to the pull box are installed in the sawed slot. A 3/16- to 1/4-in (4.8- to 6.4-mm) wood paddle is used to seat the cable in the sawed slot. A 5-ft (1.5-m) slack of cable should be allowed at the pull box. The cables should be identified by lane or by probe designation.

Using a volt ohmmeter, the series resistance (continuity) of the probe and cable should be checked. This value should be the resistance of each probe (4 to 6 ohms per probe) plus the resistance of the cable. The value should be within 10 percent of the calculated value. Resistance to ground should also be checked. The value should be high, indicating that there are no breaks in the probe or wire insulation. A megger should ***not*** be used to check resistance to ground as the high induced voltage will destroy the probe.

SPLICING THE CABLES

Splicing of the sensing element cable to the lead-in cables to the controller cabinet should be soldered using resin core solder. The techniques for splicing are the same as those used for loop detectors. The lead-in cable should not be spliced between the pull box and the controller cabinet.

The same precautions that were stressed for loop detectors should be addressed when installing magnetometers. The following is a recommended procedure for splicing probe cables to the lead-in (home-run) cable. This method uses two types of heat shrinkable polyolefin tubing. Small diameter tubes insulate the individual conductors and a single large tube is used to seal and protect the splice. A butane hand torch or electric heat gun is required to make the splice.

- Strip both cable jackets back 8 in (27 cm).

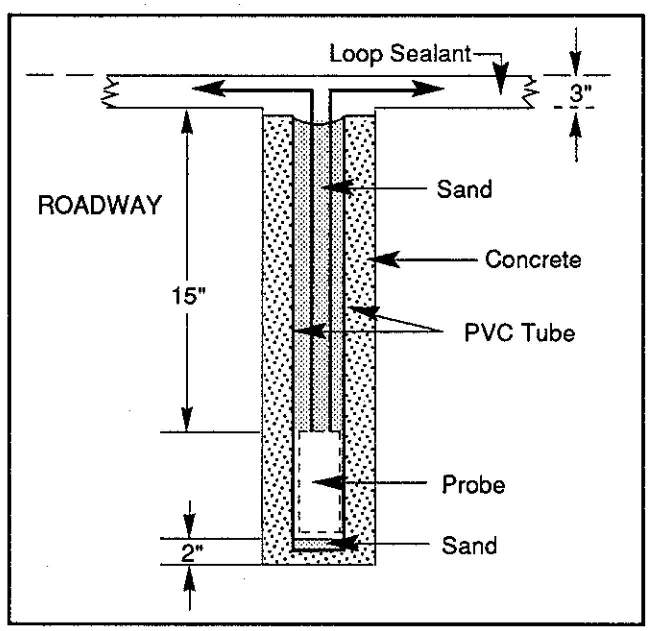


Figure 139. Standard plan.

- Clip 3 in (7.6 cm) from one colored wire of one cable and clip 3 in (7.6 cm) from the other colored wire of the second cable.
- Strip individual conductors back 1-1/2 in (38 mm).
- Install large and small diameter heat shrink tubing over either of the cables to be joined.
- Matching color for color, twist together each of the individual conductors.
- Using an electric or butane solder iron, solder the twisted joints (avoid excessive heat which could melt or burn the wire insulation).
- Slide the small diameter tubes over the soldered joints.
- Using an electric heat gun or butane torch, gradually heat the small diameter tubes until they have shrunk uniformly and the inner wall melts and begins to ooze.
- Slide the large diameter tube over the entire cable splice.
- Heat the larger tube in the same manner. Proper heat exposure in this case is indicated by a color change. Stop heating when the blue strip changes to brown and, as before, avoid burning the cable jacket.

TESTING THE SYSTEM

Each probe element circuit should be tested at the controller cabinet before filling holes and slots. The same measurements described earlier should be made with a low range ohmmeter. In this test, the series resistance will be higher because of the added resistance of the lead-in cable.

An operation check should also be made at the controller cabinet. This may be accomplished by connecting the probe cables to a detector unit and applying power. The detector unit should then be calibrated following the manufacturers guidelines. Check each probe using a bar magnet oriented in a direction which aids the vertical component of the Earth's magnetic field intensity. The channel indicator should light up when the bar magnet is located over any probe in the set being tested.

Record the measurements taken. One additional measurement should be made using a yard stick with 1/16-in (1.6-mm) increments and the bar magnet. Stand the yardstick vertically over the probe, place the magnet at the top of the yard stick, and slowly move the magnet down toward the probe until the indicator light on the detector lights up. If, at a later time, the system experiences a failure, this same measurement can be repeated. If the magnet must be closer to the probe to light the indicator, this means that the probe has rotated.

SEALING THE HOLES AND CUTS

At this point, the probe holes and the saw cuts containing the cables are sealed in the same manner used for loop detectors. This completes the installation of the magnetometer detector system.

INSTALLATION OF MAGNETIC DETECTORS

The pre-installation activities for magnetic detectors are much the same as those described for loop detectors. When the magnetic detector probe is installed 12 to 30 in (30 to 76 cm) under the roadway, the long axis is generally horizontal and is at a right angle to the direction of travel. The conduit, housing the probe, can be installed by either drilling or trenching under the pavement surface as described below.

INSTALLATION PROCEDURE

The preferred method of installation is to tunnel a hole under the pavement from the side of the road and push the conduit into the hole as shown in

Figure 140. For installation in a four lane divided roadway with a median, many agencies have found it desirable to install from the median. The median area is preferable as these areas have fewer sign posts, guard rails, and utility activities.

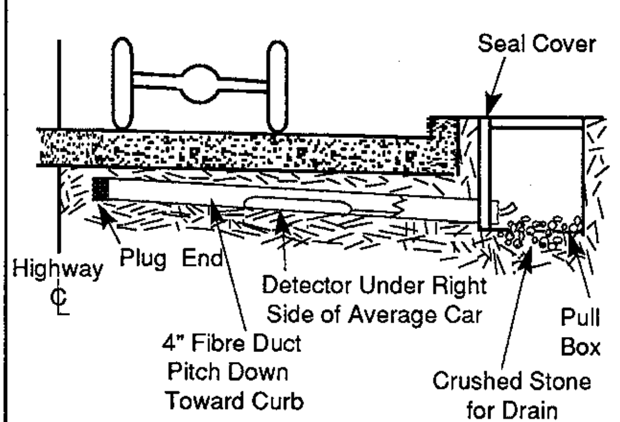


Figure 140. Magnetic probe installation.

After locating and marking the proper area for the placement of the probe, a measurement is made from the pull box to a point on the road where the conduit ends. Using a backhoe, a pit 3 ft (.9 m) deep, 2 ft (.6 m) wide, and 10 ft (3 m) long is dug. A horizontal boring machine is then placed in the pit, leveled, squared, and secured. The hole is then bored under the pavement, taking care that the drill does not stray from the desired path.

When the drilling is complete, the machine is removed and the pit is backfilled to a level just below the bore hole. A 3- or 4-in (7.6- to 10.2-cm) schedule 40 PVC is capped and placed in the hole section by section. It is critical that each section of pipe be fitted squarely and glued. Before the final section of PVC is fitted, the pull box is placed in the trench and set so that the hole in the box lines up with the pipe. The pipe should fit flush with the wall of the pull box.

TRENCHING

An alternative to the boring method of installing a conduit to hold the magnetic detector, is trenching. The first step in this procedure is to mark the boundary of the trench. The pavement is then cut and a trench is excavated including the area for the pull box. A 3- to 4-in (7.6- to 10.2-cm) plastic conduit or fiber duct is laid in the trench and sloped to drain into the pull box in case of water leakage or condensation. The outer end of the conduit should be capped before placing in the trench.

To prevent damage to the probe by the pressure of traffic above it, the conduit should be covered with a minimum of 6 in (15 cm) of concrete. When the conduit is to be covered by dirt or stone, as is the case of macadam roads, the probe should be at least 1 ft (30 cm) below the surface. A sand cushion should be placed immediately below it and above it to prevent stones from being driven into the conduit by impact from the vehicles traveling on the road above.

CONNECTING THE SYSTEM

The probe sensor lead-in wire should be marked when measuring the correct position by laying the probe on the road in the desired position. This is marked so that when the wire reaches the edge of the pull box, the detector will be in the correct position. The sensor is inserted into the conduit and pushed into position using a steel (3/8-in (9-mm) span wire).

After the probe has been placed in the conduit, the next step is to install the pull box in the same way as that described for loop detectors. A drain should be provided in the bottom of the box and the cover should be sealed to prevent the entrance of surface water.

The probe lead in wire should be spliced to the lead-in cable running to the controller. Splices should be soldered because the magnetic detector generates an extremely small current. Procedures for splicing and environmentally sealing splices have been presented previously in this chapter for both loop detectors and magnetometers.

There are two conductors required for each magnetic sensor. Since magnetic detectors generate extremely small currents, any size copper wire in the cable is satisfactory. Magnetic detector circuits should not be run in the same cable sheath with wires carrying signal currents. Leakage between wires carrying signal currents. Leakage between the signal wires and detector wires will cause erratic operation of the detectors. Electromagnetic or electrostatic induction between signal wires and detector wires could cause false calls. However, any number of detector wires can be housed in the same cable sheath without causing interference.

TESTING THE SYSTEM

Two tests should be conducted with a volt-ohm meter during installation to determine the series resistance (continuity) and ground resistance. For each probe in the series circuit, the series resistance should register 3800 ohms, plus or minus 10 percent. If there are two probes, the reading should be around 7600 ohms. If the meter reads several times the normal resistance, a check should be made of the wiring and splicing, and each probe should be tested individually.

Resistance to ground should measure several megohms. Low resistance indicates leakage through the wire insulation or the probe. Such leakage will not prevent relay response unless it is sufficient to reduce the probe output.

When the gain is set on the amplifier, it should be set at the lowest value possible to insure proper operation. The reason for this is to avoid spurious detection of vehicles in other lanes.

The test readings and gain settings should be recorded on the construction plans and on forms which are stored in the controller cabinet, as well as those filed in the maintenance office. This information should always be referred to when maintenance is required.

6. DETECTOR MAINTENANCE

Most agencies responsible for traffic detector operations readily agree that proper and adequate maintenance is critical to effective traffic signal control systems and surveillance and control systems. Central to this is the careful installation and the use of appropriate materials and products. However, even with both superior design and installation, the system will not operate as intended if the basic fundamentals of maintenance management are not applied. Unfortunately, there are many factors that impede the best intentions.

Problems of inadequate budget and staffing deficiencies have a profound effect on the level and quality of maintenance activities. Budgetary problems that continue to plague traffic agencies have resulted in cost-consciousness that frequently focuses only on initial cost, rather than on lifetime cost. Consequently, less expensive products, materials, and/or processes are used in the original installation because of their lower initial cost. However, this is not always a cost-effective solution.

While budgetary/funding problems may not be easily resolved, they may be ameliorated by increased attention to cost-effectiveness in all phases of design, installation, operation, and maintenance. Staffing problems, in terms of numbers and skill levels of maintenance personnel, may be reduced somewhat by selecting only the equipment that can be realistically maintained by available personnel.

This chapter is addressed to those responsible for the management of the maintenance operations as well as to maintenance supervisors and technicians. Design engineers and those responsible for installation and operations should be fully cognizant of the cause and effect relationship between their activities and the maintenance problem.

Please note that there are a number of excellent reference sources addressing the maintenance process. Recommended sources for further details concerning comprehensive maintenance programs include ITE's *Traffic Signal Installation and Maintenance Manual* (Ref. 38), TRB's *Maintenance Management of Traffic Signal Equipment and Systems* (Ref. 39), and FHWA's *Traffic Control Devices Handbook* (Ref. 40).

NATURE OF THE PROBLEM

The nature of the problems associated with detectors has changed considerably over the years. For example, the detector electronics unit, which formerly accounted for a considerable portion of detector malfunctions, has progressed to the point where many currently available digital models seldom experience failure. As stressed continually throughout this manual, proper installation using appropriate materials and processes is the key to longer detector life, lower failure rates, and less required maintenance.

There is little question that detector malfunctions and the associated signal failures increase motorists' time and delay, maintenance costs, accidents, and liability. For example, a simple failure of a detector loop can induce delay in the traffic flow. If a call is locked in to the controller, it will cause the green to extend to its maximum limit regardless of traffic demand.

In cases where the detector fails without a call, the common temporary "fix" is to place the phase on Maximum Recall in the controller. This can increase intersection delay by 50 percent or more.

Although failures cannot be totally eliminated, adherence to proper installation and maintenance procedures can assuredly reduce the incidence of failure and the number of unnecessary maintenance calls. Some of the common causes of failure are discussed below.

FAILURES IN LOOP DETECTOR SYSTEMS

When a detector system experiences a failure, it exerts a negative effect on the total traffic signal control system. As discussed in Chapter 5, failures can be categorized by the failure mechanism and by the cause for failure.

FAILURE MECHANISMS

A failure mechanism may be defined as the effect of a problem occurring in the detector system. Among the common failure mechanisms, are the following:

Omitted Phase

The signal does not service one phase due to the lack of detector calls. This is usually caused by a loop failure. Earlier detector units with solid state outputs would fail in the "open" position resulting in no call to the controller. Newer units have circuitry that provides a continuous call if the loop circuit is incomplete. (See Phase Extending to Maximum below.)

Stuck Signal

A stuck signal is characterized by a signal indication (or phase) not changing as programmed. In most instances, a stuck signal is not caused by the detector system, but by a controller failure. On occasion it may be caused by a vehicle not being properly detected, or when a detector unit, operating with the delay feature, does not retain the call for a sufficient amount of time to be transmitted to the controller.

Phase Extending to Maximum

This situation occurs when a specific phase of the signal operation extends to the maximum time set on the controller regardless of traffic demand. This is typically caused by a continuous call from the detector unit and can generate extra delays of up to one-half the normal daily delay. The continuous call may be caused by a faulty detector unit or by an open loop circuit.

Intermittent Problems

Low sensitivity of the loop or the detector unit (or combination of both) can result in intermittent problems. Unstable oscillators in the detector unit may also cause intermittent problems during periods of rapid temperature shifts. However, many of the current detector units are capable of retuning. When the problem persists for no apparent reason (termed "ghost problems"), the detector unit is usually replaced.

A broken loop wire that will ordinarily cause a malfunction may reconnect itself with shifts in pavement and cause intermittent operations. The only cure for this situation is to replace the loop when it has been determined by a process of elimination that the only remaining problem could be a broken wire.

External devices, installed to provide additional lightning protection, may have been damaged by a power surge. This may result in intermittent operation. Since this damage may not be visible, these devices should be checked if intermittent operation occurs.

Crosstalk

Crosstalk is the result of inductive or capacitive coupling between loops or lead-in wiring. Crosstalk may produce false detections when there are no vehicles in the detection zone. It may also result in lock-up following a vehicle detection. It is usually associated with motion in either the generating or receiving loop channels due to transient frequency alignment caused by a vehicle signal.

Crosstalk occurs when the frequency of one loop installation is influenced by the frequency of another. This normally occurs when the frequency of one loop system is decreasing and passes through or near the frequency of the other loop. Electrical engineers refer to this as a "frequency lock" between two oscillators.

This condition occurs only when the frequencies of the two oscillators are close and electronic coupling exists between the two oscillators. There are numerous sources of electronic coupling. Some of the more common sources include:

- Poor quality connections in the loop system.
- Field coupling due to close physical proximity of two loops.
- Coupling between two closely spaced lead-in wires.
- Coupling between lead-in cables sharing a common conduit.
- Grounding of the lead-in cable shield at controller cabinet field terminals.
- Coupling between closely spaced harness wires from the field terminals to the detector.

Splashover

The false detection of vehicles outside the zone of detection is termed "splashover." This problem often occurs when long loops are operated at a level of sensitivity required to detect small vehicles (i.e. motorcycles). With this high level of sensitivity, vehicles from adjacent lanes may be falsely detected. This problem also occurs when the loop is placed too close to the lane line. Splashover is a problem between lanes controlled by different phases. It is not a problem between lanes on the same phase unless accurate vehicle counts are desired.

CAUSES OF LOOP SYSTEM FAILURE

As discussed in Chapter 5 and detailed in Appendix M, surveys of traffic agencies indicate that there are eight primary causes of loop failure:

- Pavement problems (cracking and moving).
- Breakdown of wire insulation.
- Poor sealants or inadequate sealant application.
- Inadequate splices or electrical connections.
- Damage caused by construction activities.
- Improper detector unit tuning.
- Detector unit failure.
- Lightning/electrical surges.

FACTORS AFFECTING NEEDED MAINTENANCE

Many agencies report that most of their maintenance problems involving detectors can be traced directly to installation errors. These errors can be a direct result of sloppy installation, poor inspection, and the use of low-grade components not suited to the particular environment.

Many agencies do not use their own forces to install detectors. In these cases, the contract to install detectors is usually awarded to the lowest bidder. The "lowest bidder" concept has been very successful in encouraging competitive bidding and generally lowering costs. To be effective, however, a procuring agency needs to apply stringent prequalification guidelines to avoid awarding the contract to an electrical contractor with inadequate experience and/or knowledge.

If inspection is inadequate, the potential for contractor expediency and error is enormous. The consequences of these improper short cuts or errors may not surface until the contractor's responsibility has elapsed and must therefore be repaired at the expense of the agency. For example, piercing, cutting, or otherwise damaging the insulation on the loop wire by the use of improper tools or careless handling may not show up until some time after the wire is sealed in the slot.

In Chicago, the Illinois DOT maintains over 18,000 loop detectors. Because of their past experience with loop failure, they initiated an active inspection and maintenance program to monitor each loop. This program has reduced replacements to about 35 recuts per year. They report that no more than 5 percent of their loops are inoperative at any given time (Ref. 14).

TROUBLE SHOOTING PROCEDURES FOR LOOP DETECTORS

The analysis of a malfunctioning detector can be a difficult task. The root cause of the failure may be associated with environmental conditions or other conditions built into the installation. All of the various causes of failures defined above should be considered by the technician analyzing a faulty loop system. Initially, of course, it is necessary to isolate the problem as one associated with the detector system.

An experienced technician is frequently able to pinpoint the troubled area or faulty part by visual examination. As shown in Figure 141, it is readily apparent that pavement failure has occurred along the saw slot exposing the loop wires. When visual inspection does not immediately disclose the problem, systematic trouble shooting is required. Procedures that may be applied in identifying and correcting malfunctioning detector systems are discussed below.

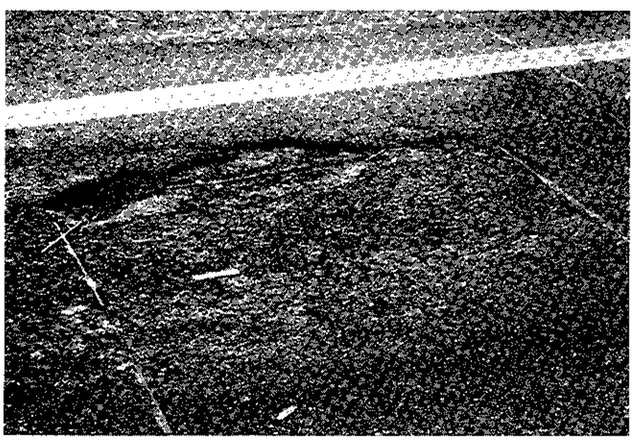


Figure 141. Example of pavement failure.

SAWCUT MAINTENANCE

A visual inspection of the roadway at and around the sawcut should be made to determine if the integrity of the pavement, the sealant, or the slot has been violated. The inspection should include looking for wires that have floated to the top of the sealant. A loop installation with exposed or shallow-buried wires should be replaced.

If the sealant appears to be unstable, a blunt instrument may be used to remove any cracked or deteriorating sealant. The slot should be blown clean with compressed air and new sealant poured over the old. This is especially important in areas when snow removalequipment is used and salt applications are prevalent.

Pot holes within the loop area should also be repaired. Some agencies use a cold mix compound. A thin blanket overlay covering the area has proved effective for patching deteriorating pavement. FHWA Reports (Ref. 41 and 42) provide detailed instructions for repairing pot holes.

As the loop wire is the most vulnerable component in the hostile environment of the street, a scheduled visual inspection of the saw slots should be conducted every 6 months. Early detection and correction of saw slot problems can avoid many potential detector malfunctions.

REARRANGEMENT OF LOOP CONNECTIONS

When the loop does not have sufficient sensitivity to detect a vehicle, this usually means that the inductance is too low. This situation could be caused by an insufficient number of turns of wire, by turns of wire shorted together, or by steel mesh in the roadway that has produced a shorted-turn effect. If this occurs in a multiple loop configuration, it may be temporarily corrected by eliminating the defective loop.

Multiple loops can be connected in series or series/parallel to maintain an equivalent inductance within the range of the detector unit. Quantitative measurements are made to determine if the inductance of a malfunctioning system has dropped below the acceptable value. There are several test meters commercially available that will determine inductance. Some of these meters directly measure inductance, while others measure frequency. In the latter case, accompanying charts or graphs are used to determine inductance.

ELIMINATING CROSSTALK

As defined earlier, crosstalk can result when two loop lead-in cables share a common conduit, operate at close to the same frequencies, or the cable shields are not properly connected. Crosstalk may also occur when two loops are installed within a few feet of each other, or when two sets of lead-in wires occupy the same saw slot. Other causes include poor quality splices and coupling between closely spaced wires in the cabinet harness. Potential solutions to these problems are listed below.

- Poor quality connections in the loop system: Solutions include use of high quality soldered joints, soldering of all crimp connections, minimizing the number of joints, use of high quality connectors and replacement if worn, safeguards against corrosion, tight terminal block screws, and twisting an soldering of wire ends together and placing under one terminal block screw rather than two individual screws.

- Field coupling due to close physical proximity of two loops: Not much can be done to eliminate this source. However, frequency separation and/ or use of a multichannel multiplexed detector are effective solutions.

- Coupling between two closely spaced lead-in wires: Solutions include independent routing in slots physically separated by at least 1 ft (0.3 m), twisting loop wire pairs a minimum of 5 turns per foot (16.5 turns per meter), use of multichannel multiplexed detectors, and frequency separation.

- Coupling between lead-in cables sharing a common conduit: Solutions include the use of individual, shielded, twisted-pair cables; proper grounding of cable shields; use of multichannel multiplexed detectors; and frequency separation.

- Grounding the lead-in cable shield at controller cabinet field terminals: A potential solution is the use of the three terminal method (see Figure 132). This procedure is to strip the individual lead-in cables back a maximum of 2 to 3 in (5 to 8 cm) and ground each lead-in cable independently. (Note: Until1990, the Ontario Ministry of Transport (Appendix N, page 9-36) specified that the shields should be grounded at the pull box and *not* in the cabinet.)

- Coupling between closely spaced harness wires from the field terminals to the detector: The solution is to either use shielded twisted cable with proper grounding of the shield or use twisted wire pair.

One agency (California Department of Transportation, Ref. 32) described a procedure for identifying and correcting crosstalk. They used a modified loop tester for the following four-step procedure.

1. Using the auxiliary input to the tester, measure the operating frequency of the loop detector suspected of crosstalking.

2. If the operating frequencies of two or more detectors are less than 2 kHz apart, and they share one or more conduit runs, they are likely to crosstalk. This can usually be corrected by grounding the cable shields at the controller cabinet.

3. If the amplifiers have a range switch or other means of selecting frequencies, adjust so that operating frequencies are separated by at least 2 or more kHz.

4. If adjustments cannot be made, adding parallel capacitors to the field terminals may shift the operating frequencies. A quality capacitor such as a polycarbonate or ceramic capacitor may be used. It should have a reasonable temperature stability coefficient and should be of a size ade-

quate to shift the resonant frequency by about 2 kHz. This procedure cannot be used on detectors where the operating frequency is independent of loop inductance. Some manufacturers recommend against added capacitance external to the detector unit because temperature stable capacitors are difficult to procure and are still prone to value change with rapid temperature shifts.

If the loop sensors are causing the crosstalk problem, they can be reassigned to different channels, or the lead-in wires in the pull box can be retwisted and respliced, thus eliminating one form of potential crosstalk.

A general procedure to identify which detector unit is cross-talking consists of disconnecting all detectors except the units which have the most frequent false calls. If no new false calls or lock-ups occur, then crosstalk from another unit is indicated. By selectively reconnecting the other units, the unit causing the crosstalk between detectors can be identified.

Certain of the multichannel detectors have a scanning feature that reduces potential crosstalk effects. In these units, the sequential scanning system activates one loop channel at a time, while the remaining loops, connected to other channels, are de-energized and thus unable to provide coupling to the active channel. This does not, however, eliminate crosstalk between channels on different detector units. Frequency separation will reduce crosstalk between adjacent loops as well as with other detectors.

SUBSTITUTION OF DETECTOR UNITS

Experience shows that older detector units could not be freely substituted for each other. After conducting tests in Los Angeles (Ref. 43) it was found that "...there are some brands of detectors that appear...to have more sensitivity than others...Certain brands and/or types will not operate with adverse conditions such as very low circuit Q or a low value of shunt resistance to the conduit ground." It was concluded that the inductance value at the cabinet end of the loop system must fall within the operating range of the units if they are to be interchanged. With the newer products, units with the same characteristics and quality can generally be interchanged without problem. That is, different manufactured units operate on different frequencies; however, any unit which passes the NEMA tests can usually be interchanged.

Each unit within an agency's inventory should be checked for sensitivity to ensure that minimum sensitivity is achieved by all detector units. After this check has been made, the substitution process can be used to determine if the detector unit at the malfunctioning installation is the cause of the failure. That is, if the detector unit is replaced and the system functions normally, this may indicate a failure in the detector unit. Conversely, if the loop system still does not operate better with the substituted unit, then the original detector unit is reinserted and another problem source must be sought to resolve the problem.

In substituting detector units, it should be recognized that many malfunctions are crosstalk related. Hence, any change that will affect the loop frequency will improve the situation, at least temporarily. Substitution of another detector, even of the same model and frequency setting, will often work well due to the subtle differences in the values of the detector input capacitors. Substitution of a different model (especially of a different manufacturer) stands a good chance of being successful due to differences in front end design. The best solution is to eliminate, to the maximum practical extent, those elements that contribute to crosstalk.

OPERATIONAL CHECK OF MALFUNCTIONING DETECTOR

There are several operational checks that can be conducted to expedite the analysis of a malfunctioning detector system. These checks can be accomplished using a maintenance vehicle and a vehicle simulator. With this equipment, tests can be performed to analyze adjacent lane detection, motion in the loop wire, intermittent detection, and sensitivity of the loop system.

Adjacent Lane Detection

At locations where adjacent lane detection is suspected (such as where long loops are used on left turn lanes), one technique is to maneuver the maintenance vehicle close to the lane and monitor the detector unit. The sensitivity is then adjusted so that the maintenance vehicle does not cause an output. Care must be exercised to assure that the detector unit will still register a small vehicle in the detection zone.

It should be noted that this procedure does not test the worst case. The worst case is when several vehicles are stopped in the adjacent lane and occupy the entire length of the long loop.

There are several loop configurations that can be used to avoid adjacent lane detection (i.e., series of small loops, quadrupole loops, adjustable diamond loops, and others as described in Chapter 4). When it is not possible to change loop configurations, delay timing can be used so that a vehicle would only be detected if it were present in the detection zone for a specified amount of time (say, 5 seconds). With this approach, passing vehicles in an adjacent lane would not be detected, although stopped vehicles may present a signal strong enough to hold the call in the empty lane.

Intermittent Operation

The beginning of loop failure is often associated with intermittent operation. As discussed earlier, causes of this type of operation are generally poor connections, open loops, short circuits, or leakages to ground. These, in turn, may cause the detector to lock-up when a motor vehicle passes over the point of the fault.

To identify this problem, the operation of the detector is observed while the maintenance vehicle is driven over the various loops suspected of having intermittent operation. Operation of the vehicle in the detection area can also assist in identifying problems associated with wire motion. Another approach to identifying sources of intermittent operation is to visually inspect all connections and test with a 500 volt megger and a low ohm midscale ohmmeter.

System Sensitivity

A device to simulate vehicles can be used to determine if the detector system's sensitivity is in balance. The same procedure is used to test new installations. The State of California uses a shorted-turn vehicle model to simulate a 100 cc Honda motorcycle. Ref. 32 provides the construction details and their procedures for using this model.

The simulated vehicle is used to measure the change in inductance, which is a measure of the sensitivity. For this purpose, a frequency reading is made with no vehicle present, then the simulated vehicle is introduced into the detection area and a new frequency reading is made.

The difference between the two frequencies is a measure of the change in inductance due to the presence of the vehicle according to the relationship of $\Delta f/f = 1/2\ \Delta L/L$. This is an approximate relationship valid for percentage changes in inductance up to 10 percent and for loop Q greater than 5. The percent change in frequency is multiplied by 2 to get the percent change in inductance.

The simulated vehicle represents the smallest detectable vehicle and is also used to determine the minimum sensitivity required of a loop system. The simulator is placed in the detection zone and the detector unit is observed to determine if it is detected.

ELECTRICAL TESTS OF DETECTOR SYSTEM

Table 28 identifies some of the probable causes for specific malfunctions. The maintenance of proper resistance values and knowledge of inductance values for proper hookup to detector units will eliminate many of the problems associated with loop operation. Basically, four devices are desirable to analyze loop systems. A high voltage resistance tester (megger), used to measure insulation resistance; a frequency tester (see Figure 142) or inductance meter, used to measure inductance; a digital volt-ohm meter, used to measure series resistance; and a low ohm (about 2 to 3 ohms) midscale ohmmeter, used to measure the dynamic change in the series resistance.

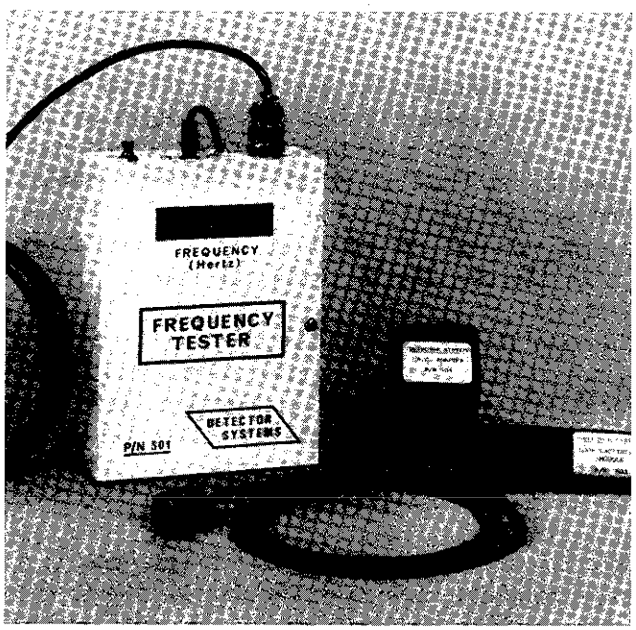


Figure 142. Typical frequency tester.

Both low resistance-to-ground and high series resistance are major factors in loop system malfunctions. Low resistance-to-ground can result from poor insulation on the loop or lead-in wire, or inadequate sealing of splices. These problems should not occur if, during installation, proper care was taken in handing the materials and following appropriate splice sealing methods. Low resistance-to-ground can also occur when wires are exposed as a result of pavement cracking, sealant cracking, frost action, and from studded tires wearing down pavement. In addition, excess wire coiled in the pull box or controller cabinet can add inductance to the circuit. This may result in tuning problems. There is also an increased potential for coupling to another loop system.

High series resistance can be caused by poor splices, corroded or loose screw terminals, poor crimping, or inadequate wire size. The high series resistance problem is sensitive to humidity, temperature, and vibration, which will cause drifting and false calls. These are the same problems that occur when the system has low resistance-to-ground.

TEST PROCEDURES

To isolate the causes of erratic operation or system malfunction in a detector system, the tests from Ref. 43 presented below should be performed sequentially.

Table 28. Loop malfunctions and possible causes.

Possible Cause	Malfunction						
	No Call	Constant Call	False Call	Drifting	Crosstalk	Will Not Tune	Unbalanced Sensitivity
Low Q		X				X	X
Low Resistance to Ground		X	X	X		X	X
High Series Resistance		X	X	X		X	X
Improper Inductance	X	X				X	X
Poor Ground			X		X		
Improper Installation	X	X	X	X	X		X
Detector Malfunction	X	X	X	X		X	

Equipment Required

These tests require the following equipment:

- Ohmmeter, battery operated.
- AC Voltmeter, high impedance input to 100 kHz.
- Digital Frequency Counter, input impedance > 50 K to 200 K.
- Q Test Meter.
- Loop Tester Meter.
- Data Recording Forms for Q and Sensitivity (see Figures 144 and 145).
- Vehicle Simulator, Sensitivity Standard.

In cases where pavement overlays have covered the loop installation, a loop finder such as that shown in Figure 143 can be used to identify the location of the loop.

Figure 143. Loop finder.

Sequential Test Procedure

The following tests, when performed sequentially, should isolate the causes for a detector system becoming inoperative or experiencing erratic operation. The Quality (Q) data form is illustrated in Figure 144. The Sensitivity (S) data form is portrayed in Figure 145.

Step 1. Visual Inspection

Check for indication of broken or cut loop or lead-in wires. Check for open leads within the controller and for the availability of power to the detector.

Step 2. Check Detector Unit

To rule out the detector unit as the source of the problem, replace the existing detector unit with one having a known sensitivity. If the operation is not considerably improved, remove the substituted unit, replace the original unit and continue to Step 3.

(One manufacturer notes that since many problems are crosstalk-related, any change that will affect the loop frequency will improve the situation, at least temporarily. Substitution of a detector unit, even of the same model and frequency switch settings, will frequently work successfully due to subtle difference in the values of detector input capacitors. Substitution of different models (especially from different manufacturers) will have an even greater chance of success because of the difference in front-end design. Therefore, substitution of detector units may solve the problem temporarily but, in actuality, the real problem has not been resolved. If the problem is crosstalk-related, the most effective solution is to identify and eliminate the causes of the crosstalk.)

Step 3. Measure Q Factor

Measure and record the following data on the Quality (Q) data form (Figure 144).

QUALITY (Q)

Location: ______________________________ Date: __________

Description: ______________________________ By: __________

Position	Connection	E_{lps}	f_{LT}	L (µh)	f_r	f_h	f_l	Bw	Q calc.	R_P	Remarks

Analysis:

E_{lps} = voltage across loops; f_{LT} = frequency of Loop Test Unit; f_r, f_h, f_l = frequency for resonance, high, low; Bandwidth (Bw) = (f_h - f_l); Q calculated = (f_r / Bw); R_P = resistance to ground.

Figure 144. Quality (Q) data form.

SENSITIVITY (S)							
Location: ____________						Date: ________	
Description: ____________						By: ________	
Loop Position	Sensitivity Standard	Frequency (kHz)			Sensitivity S (%)	Presence Minutes	Remarks
		f_r	f_2	$f_2^2 - f_r^2$			
Analysis:							
f_r = resonant or tuning frequency; f_2 = loop frequency with test standard or vehicle; $S = [(f_2^2 - f_r^2) / f_2^2] * 100 \approx$ the change in inductance in percent.							

Figure 145. Sensitivity (S) data form.

- With the detector disconnected and power removed from the loop, measure the resistance from either loop terminal to the bus or conduit ground. Record as R_p in the Q data form. Check for series continuity between the terminals.

- With the Loop Test Meter attached to the controller tie points and the detector disconnected, measure the inductance of the loop system. Record the frequency (f_{LT}) and the inductance (L) on the form.

Step 4. Determine Q

To determine the Q Factor of the loop system, follow the procedure described below and record the results on the Quality (Q) form (Figure 144):

- Attach the Q Test Unit to the existing cable or adaptor cable as required.

- Connect the AC voltmeter and digital frequency counter to the Q Test Unit to read loop voltage and frequency in kHz.

- Adjust the frequency for maximum voltage across the loops; record the frequency as (f_r) and the voltage across the loops as (E_{lps}).

- Adjust the frequency higher and lower to obtain the frequency points having 70 percent of the resonant voltage value. Record these as higher (f_h) and lower (f_l).

- Calculate and record the bandwidth (Bw) and compute Q. That is, $Bw = f_h - f_l$ and $Q = f_r / Bw$.

Step 5. Measure Sensitivity of Loop System

Record the frequencies obtained from either of the following methods on the Sensitivity (S) data form (Figure 145).

<u>*Method 1*</u>

- Set the function switch to "Q MEAS" on the Q Test Unit.

- Adjust the frequency to obtain resonance and record as (f_r).

- Record the reference number of the Sensitivity Standard to be used.

- Place the simulator or vehicle on the desired loop.

- Retune the frequency of the detector to the new resonant point and record as (f_2).

- Calculate the sensitivity as indicated on the data form.

<u>*Method 2*</u>

- Set the function switch to "INTERNAL" and the mode switch to "S" on the Q Test Unit.

- Allow the detector to tune downward in frequency to the "lock-on" point.

- Note the frequency and record as (f_r) on the form.

- Place the Sensitivity Standard on the desired loop.

- Note the new lock-on point frequency. Record as (f_2) on the form.

- Calculate the sensitivity as indicated on the data form.

Step 6. Analysis

Conduct the analysis by comparing the values obtained for each of the system characteristics with the acceptable limits listed in the Loop Trouble Shooting Chart (see Table 29). Determine the required maintenance from the suggested corrective actions from the form.

Table 29. Loop trouble shooting chart.

Item	Indicated Conditions	Corrective Action
Loop wires	Broken, cut, or exposed Insulation worn away	Install new loops shifted by 6 in (15 cm) from the old loop and cut each old loop at least twice
Loop slots	Sealant missing Wire exposed Surface eroded	Clean slot of loose material and refill or replace entire loop and lead-in as required above Street surface patch if loop wire is not exposed
Resistance to ground	100 MΩ or more Shorted	Acceptable if Q >5 Replace as required
Series Loop Resistance	Open circuit Greater than specified (based on wire size and length)	Locate and correct open circuit Isolate cause (poor splice, inadequate crimp, etc.) and repair as required
Q Factor	>5, R_p >l00 M <5, any R_p	Acceptable with modern detector units Replace detector unit
Sensitivity of Loop System	Measures lower than design value for the configuration	Consider Q, shunt R_p, and series R as possible causes and correct as indicated Determine loop interconnection and rework to accepted design values
Sensitivity of detector	Remains actuated Does not actuate Insufficient sensitivity	Substitute known serviceable detector Substitute known serviceable detector Substitute and return unit removed to shop
The limits placed on the characteristics are nominals determined from the original investigation. They may require modification to reflect additional experience.		

MAINTENANCE OF MAGNETOMETER SYSTEMS

The magnetometer detector system is made up of the probe, probe cable, lead-in cable, and the detector electronic unit. The same precautions should be observed for the probe cable and lead-in (home run) cable as for the loop lead-in wire and lead-in cable.

The probe cable is placed in a slot in the road surface and should be sealed with the same care as for loop detector lead-ins. The splices connecting the probe cable and the lead-in cable must be mechanically and electrically sound and environmentally protected as described in Chapter 5.

Failure can occur in any of the subsystems. The principal causes of magnetometer failures are described below.

CAUSES OF MAGNETOMETER FAILURES

There are four key areas that can affect the operation of the magnetometer detector system. These are: proper burial depth of the probe, stability of the probe in the pavement, characteristics of the probe cable with regard to moisture penetration, and saw slot maintenance.

Probe Burial Depth

The vertical placement of the probe is critical to system performance. Deep placement of approximately 24 in (60 cm) will provide good single count detection, but will result in lower signal levels. Shallow placement of about 6 in (15 cm) will provide a stronger signal, but there is a greater potential for double counting. Therefore, the burial depth must be appropriate for the intended application as described in Chapters 4 and 5.

Probe Movement

The probes must be firmly supported in their holes. Any displacement of the vertical alignment of the probes may result in performance instability. PVC conduit as a shell, with sand tamped around the probe to prevent lateral displacement, is recommended.

Probe Cable

The cable must be water-blocked cable to prevent moisture penetration. Any moisture can cause excessive capacitance or leakage between wires or to ground. In addition, moisture across the leads of a magnetometer may induce drift. Wherever possible, it is recommended that the probe cable run directly to the detector unit, thus eliminating the use of splices. If this is not possible, the splices must be electrically sound and environmentally protected.

Sawcut Maintenance

The sawcut for the magnetometer should be visually inspected every 6 months to evaluate the condition of the sealant and the surrounding roadway. As with the loop detector sawcut, any cracking or deteriorating sealant should be chipped away, blown clean, and replaced with new sealant.

TROUBLE SHOOTING PROCEDURES

The initial step for troubleshooting problems with the magnetometer system is to visually inspect all elements of the system, including the connections at the terminal strip in the controller cabinet, any splices in pull boxes, and the street installation of the probe and probe cable. These elements should be examined to detect any loose connections, poor sealant, exposed wires, bad splices, or evidence of recent construction.

If none of these elements show any evidence of problems, the next step is to examine the probe for tilting. Without retuning the detector unit, use the bar magnet oriented in a direction which aids the vertical component of the earth's magnetic field intensity (as described in Chapter 5) to measure the distance from the road surface that will cause the detection to occur. Compare this measurement with the one taken at the time of installation.

If the distance is smaller than the original measurement, then the probe may have tilted due to pavement movement. If the probe has tilted, the detector unit may be retuned and this location monitored frequently for evidence of further tilting. If the unit cannot be retuned, the probe should be pulled and reinstalled in the proper vertical alignment.

One way to compensate for the tilting problem is to use a Digital Nulling Loop such as that developed for the City of Baltimore (Ref. 44). This device has an automatic compensating circuitry which is incorporated into the detector unit. It works like a loop detector in tracking environmental changes. One of these devices is required for each channel in the detector unit.

If detection does not occur during the test for tilting, the problem could be in the cable, wire, probe, splice, or detector unit. Series resistance and resistance-to-ground measurements should then be made at the controller cabinet with a volt-ohmmeter. The series resistance should be within 10 percent of the measurements made at installation, and the other readings should be high, indicating no breaks in the insulation or in the integrity of the environmental splice.

If the measurements do not fall within these ranges, the next step is to determine whether the problem lies: in the probe, the probe cable, the splice, or the lead-in cable.

The splice should be taken apart and the following tests conducted. A series resistance and resistance-to-ground measurement toward the probe should be made and compared with measurements taken during installation. Large variations indicate faulty probe or probe cable. The best solution is to replace the probe and probe cable.

On the other hand, if the measured values compare favorably with the original values, the top pair of the lead-in cable wires should be tied together and the volt ohmmeter read. This should be repeated with the bottom two wires. If these values are high, this means that the lead-in cable should be replaced. If not, the problem undoubtedly originates in the splice and a careful reconnection of the splice should eliminate the problem.

If this systematic method is used, the problem will usually be identified. The original reference sheet should always be referred to during this process to compare measurements. When the problem has been rectified, new values should be noted and retained for future reference.

MAGNETIC DETECTOR MAINTENANCE

Magnetic detectors have an extremely good maintenance record. As they are installed under the road surface, and all lead-in wires are in the form of cable encased in conduit underground, the opportunity for failure is relatively small. User surveys indicate that these detectors do not present any major maintenance problems, and that some of these devices have been installed for more than 20 years without a failure.

In the rare case where a magnetic detector fails, the first step is to examine the amplifier. In cases of a false response (the amplifier output relay closes when no cars are crossing the detection area), replace the existing unit with another tested unit, tune, and monitor. If the system then works, it can be assumed that the original amplifier was at fault. If the system still does not work, a series resistance test and then a resistance-to-ground test should be performed. This should identify any leakage in the system.

The total detector circuit resistance to ground should be measured after disconnecting all of the jumpers to ground and the leads to the relay. In cases where leakage is between detector cables and signal cables, a 1 megohm leakage may result in erratic operation. This can be avoided by proper cable layout and good splicing. Occasionally, one probe circuit will pick up more disturbance than another probe circuit on the same phase. If this is the case, interchange probes at the terminal strip so that the probe circuit picking up the most disturbance is at the "Magnetic Detector Minus" side of the system.

If the voltmeter needle is jumpy when there are no vehicles passing the probes, it generally indicates surges in nearby power wires. If the probe can be located closer to the traffic, the sensitivity of the amplifier can be turned down and the power lines will have less effect. By changing the orientation of the detector axis, the effect of a particular power line can be eliminated or reduced significantly. For minimum disturbance, the detector axis should be parallel to the power lines.

The relay unit is designed to be immune to all line voltage changes except for very violent ones. If it is suspected that the line voltage changes are causing the voltmeter needle to jump, disconnect the "Magnetic Detector Plus" and the "Magnetic Detector Minus" leads and short them together. If the voltmeter needle is still jumpy, the trouble is due to line voltage changes. In this case, examine the joints in the power service to make sure they are properly soldered and insulated. If there are no obvious problems, request the power company to check the regulation of the power supply and make the necessary changes in their equipment.

If the voltmeter needle tends to jump only when the signals change (with the magnetic detector terminals short circuited), the trouble is insufficient current-carrying capacity in the service wires between the cabinet and power source.

If the voltmeter needle stays steady when the amplifier operates (with the detector leads shorted) and tends to jump when the signal lights change (with the detectors reconnected), the difficulty is caused by electromagnetic or electrostatic induction between the wires carrying signal currents and the wires leading to the magnetic detectors. Make sure that the condensers are in place across the terminals to which the magnetic detectors are connected, as these condensers tend to absorb such surges.

Intermittent response might also be caused by the neutral fluctuating with respect to ground. This can be stabilized by making a connection to a driven round ground rod (that is required in most modern installations). If the connections are stable, check for leakage in the detector circuit by making the same tests that were described above with a volt-ohm meter.

Other problems could involve induced voltage response, which can occur when the detector leads are included in the conduit with the power supply leads. Induced voltage can cause false responses. Consequently, the lead-in cable should not be included in conduit with other signal wiring. Another cause of false response occurs when the gain is set too high. An adjustment of the gain on the amplifier will generally solve this problem.

7. EMERGING TECHNOLOGY

Urban traffic congestion is one of the major problems requiring immediate action in the 1990's. On the U.S. freeways alone, congestion increased by 54 to 68 percent between 1983-85. Traffic volumes are expected to continue to increase by as much as 45 percent by the year 2005. A reduction in the level of congestion would yield truly impressive savings in terms of fuel, travel time, and accidents.

To tackle the problem, the U. S., European countries, Australia, and Japan are all investing in high technology solutions for hardware and software development involving a coalition of government, university, and private industry. One of the most promising concepts for alleviating urban traffic congestion is effective traffic surveillance and control.

This chapter reviews emerging technology as it relates to the detector requirements of intersection control and traffic surveillance and control systems. The new technology includes new concepts, new products, new applications, and new procedures. Some of the products are already in use in selected locations but have not, as yet, been applied fully, while others are still in the research and development phase.

DETECTOR DEVICES UNDER DEVELOPMENT

In the United States, the quest for a reliable vehicle detector that can be installed and maintained without disrupting traffic, while providing traffic data at least as accurate as the loop detector, is continuing. The following section summarizes the major ongoing developments.

SELF POWERED VEHICLE DETECTOR

The Self-Powered Vehicle Detector (SPVD) has been under development by the Federal Highway Administration since 1973. Basically, this system consists of a cylindrical in-road sensor containing a transducer, a RF transmitter with antennas, and a battery. The in-road sensor operates on the same principle as the magnetometer sensor. It is powered by an internal battery and its connection to the relay is a radio link. The roadside receiver includes a commercially available FM receiver and a tone decoder electronics package. No lead-in or interconnecting cables are needed. The concept is illustrated in Figure 146.

The SPVD can measure vehicle passage, presence, count, and occupancy. Speed measurements are possible using two SPVDs set a predetermined distance apart.

Development History

The SPVD's transducer initially consisted of two single-axis fluxgate magnetometers. These were replaced with a single, dual-axis "Brown" magnetometer oriented to detect changes in the horizontal and vertical components of the Earth's magnetic field. A vehicle passing or stopping over the detector disturbs both of these components, changing the operating level of the magnetometer's core. This change induces a voltage that enables the RF transmitter, which sends two 30-ms tone-coded pulses, indicating the entrance and exit of the vehicle. (See Ref. 45.)

The RF telemetry link was redesigned in 1978 by FHWA and the Naval Surface Weapons Center (NSWC). NSWC was contracted to develop 20 prototype systems. Three of these units were tested by the City of Kettering, Ohio during the period 1978 to 1979 (Ref. 46). Two of the units were installed at a line-of-sight distance 500 ft (150 m) from their receiver antennas. These two units failed to function even when varying distances were used. Electronic malfunctions were suspected.

The third unit was installed in a left-turn lane 118 ft (35.4 m) from the receiver antenna. This unit operated flawlessly during the year long test period

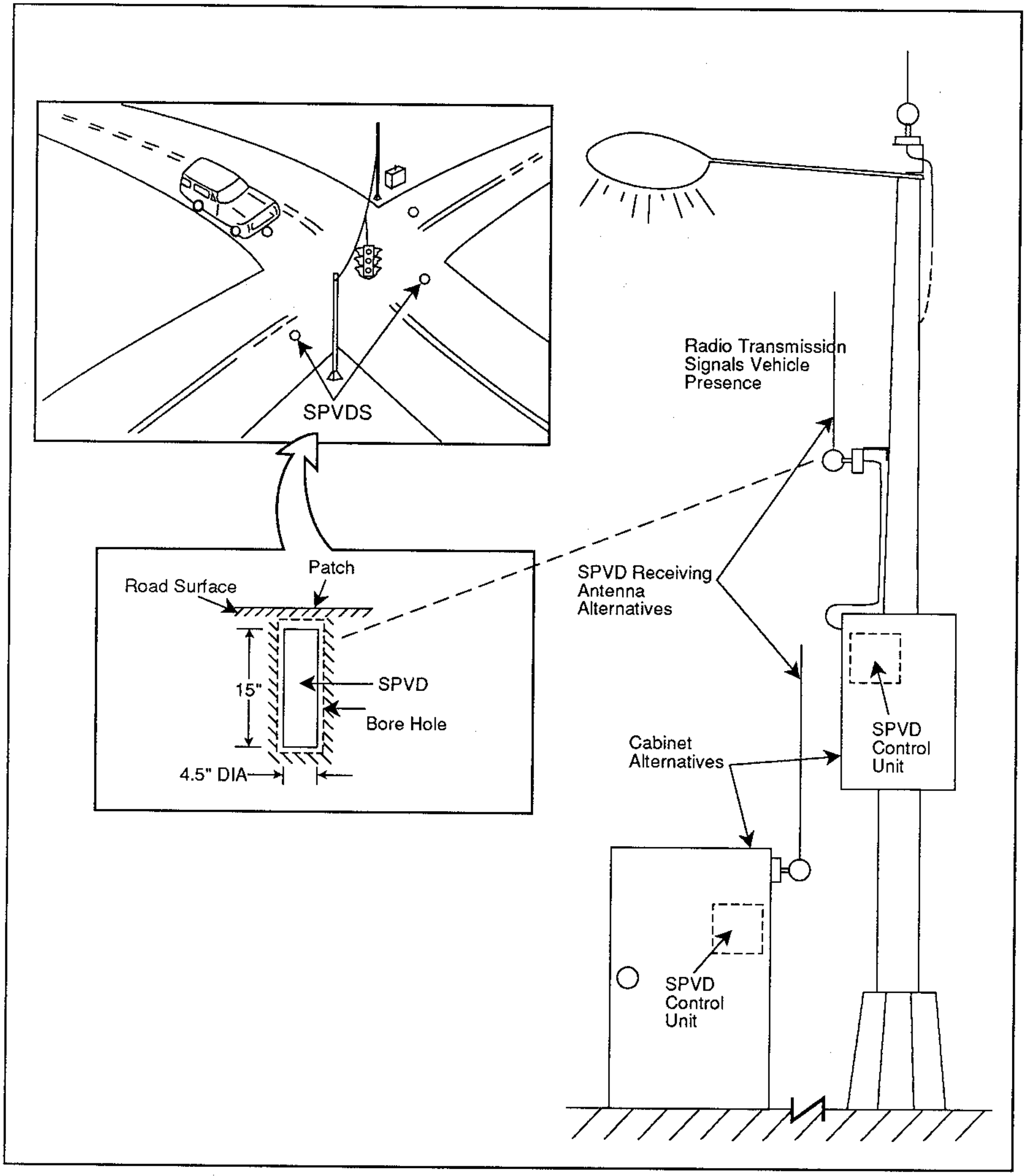


Figure 146. Self-powered vehicle detector concept.

despite temperatures sometimes approaching 0 °F. This unit was located 10 ft (3 m) from the stop line in the center of a 6- x 6-ft (1.8- x 1.8-m) loop operated for comparative purposes.

Volumes from the SPVD prototype and the installed loop detector were extremely similar over the 1 year test period, except that the SPVD yielded higher volumes during congested periods because its zone of influence provided separate counts for closely following vehicles. The City concluded that the concept was cost effective and worthy of further development.

Although the lack of lead-in or interconnecting cables reduced the installation cost and traffic disruption associated with loop detectors, the specified 1-year battery life was considered a drawback. Accordingly, batteries have since been developed with a 2-year life.

Current Status

Development has been on-going and, in 1987, the FHWA contracted to develop nine production models utilizing small-scale integrated circuit designs, and nine systems utilizing large-scale integrated circuit designs. Figure 147 portrays the SPVD system under development.

These production models are scheduled for acceptance testing during the period 1990-91. They will be designed to transmit at least 500 ft (150 m).

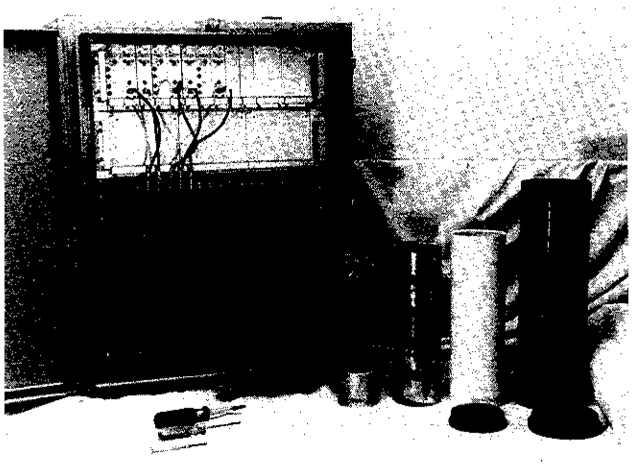


Figure 147. Self-powered vehicle detector.

WIDE AREA DETECTION SYSTEM (WADS)

In Freeway Surveillance and Control Systems, a detector system is needed that can provide vehicle detection, automatic surveillance, and the extraction of data (volume, speed, occupancy, etc.) necessary for advanced control strategies in real-time. As algorithms become more complex, the need for more accurate data is critical.

With existing loop detector technology, the detector processing algorithms must extrapolate the received data to derive the required traffic flow statistics. These extrapolations can result in critical errors which contribute to unreliable incident detection.

Video cameras have been used for roadway surveillance for many years. However, these cameras required a human operator to interpret the images generated. An alternative technique for interpreting the video images is through image processing or "machine vision." This technique uses a computer and software to analyze the roadway images and extract the information needed for traffic surveillance and control.

Evolution of WADS

The use of video technology and image processing techniques that could be used as a substitute for loop detectors was first investigated during the mid-1970's (Ref. 47). This work initially was promoted and funded by the Federal Highway Administration.

The purpose of this initial project was to combine the television camera with video processing technology to identify and track vehicles traveling within the camera's field of view. The initial system was of limited success because of the difficulties with continuously tracking a vehicle through varying background and lighting conditions.

During the 1970's and 1980's parallel efforts were undertaken in Japan, the United Kingdom, Germany, Sweden, and France. The purpose of these activities was to address the problems and limitations of existing roadway detectors and fulfill the requirements of modern control technology for improved detection. A typical WADS set-up is show in Figure 148.

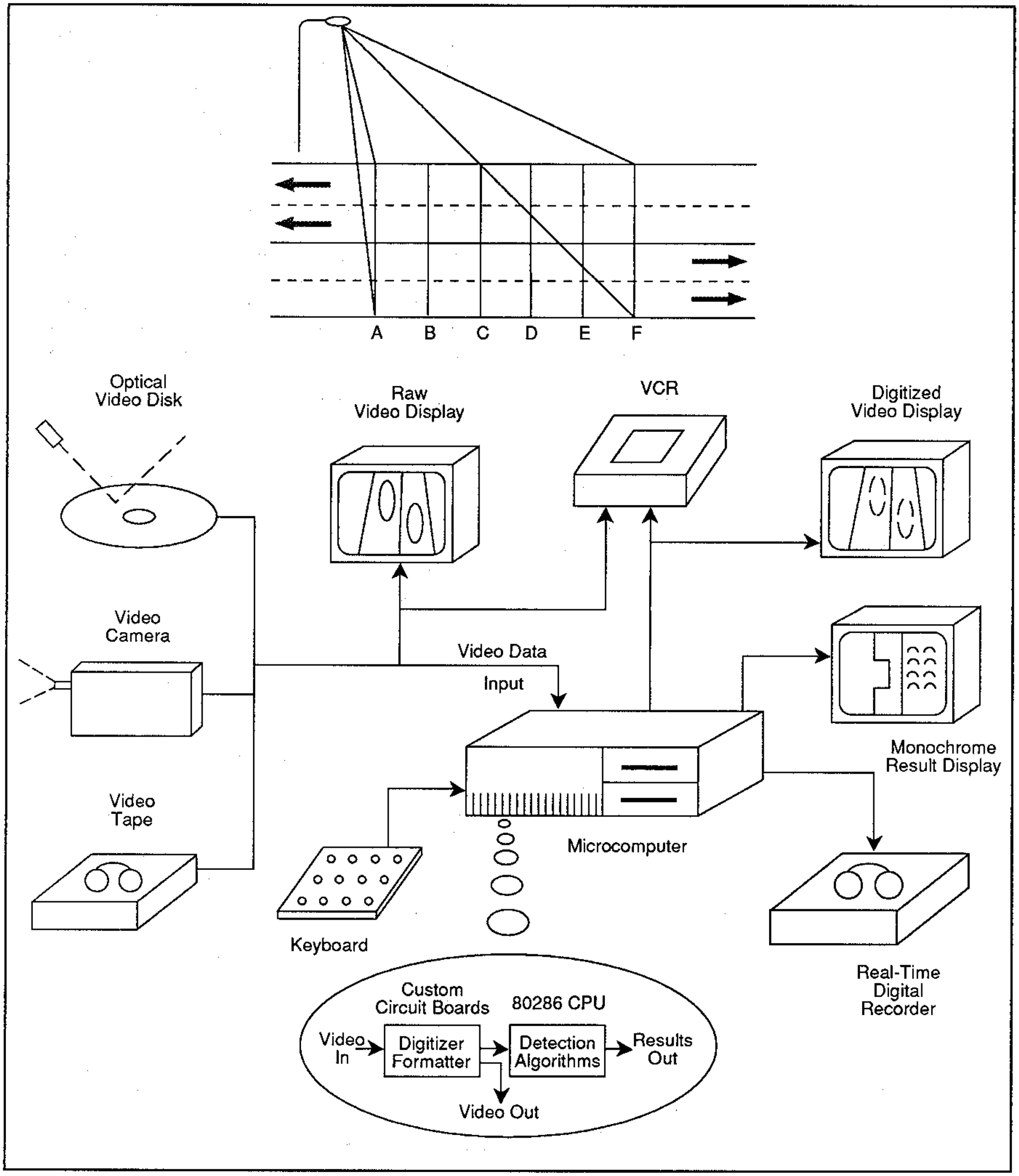


Figure 148. Wide area detection system.

Video/Image Processing Systems

As a follow-on to the initial FHWA WADS research project, a subsequent system was developed by Dr. Panos Michalopoulos at the University of Minnesota (Ref. 48). This system, known as VIDS (Video Detection System) was designed to use a single video camera with associated processing hardware and software to provide outputs equivalent to those of multiple loop detectors. This joint project was funded by the FHWA, the Minnesota DOT, and the University of Minnesota.

The operation of this real-time video imaging detection system is depicted in Figure 149. Video cameras are installed at selected locations on the freeway and/or signalized intersections to collect traffic data in real time. Cameras installed on freeway systems or on signal systems with central control capability transmit their images to a central location for processing. Cameras serving isolated signalized intersections transmit their images to local processing hardwarein the control cabinet (or in a separate cabinet) installed at the intersection.

The system can detect traffic at a number of locations (multiple spots) within the camera's field of vision. These locations are specified by the user with interactive graphics and can be changed as often as desired. To achieve this flexible detection point placement, detection lines along or across the roadway lanes (as depicted in the traffic scene appearing on the TV monitor screen) are inserted on the screen by means of a mouse or keyboard. Every time a vehicle crosses a detection line, a detection signal is generated.

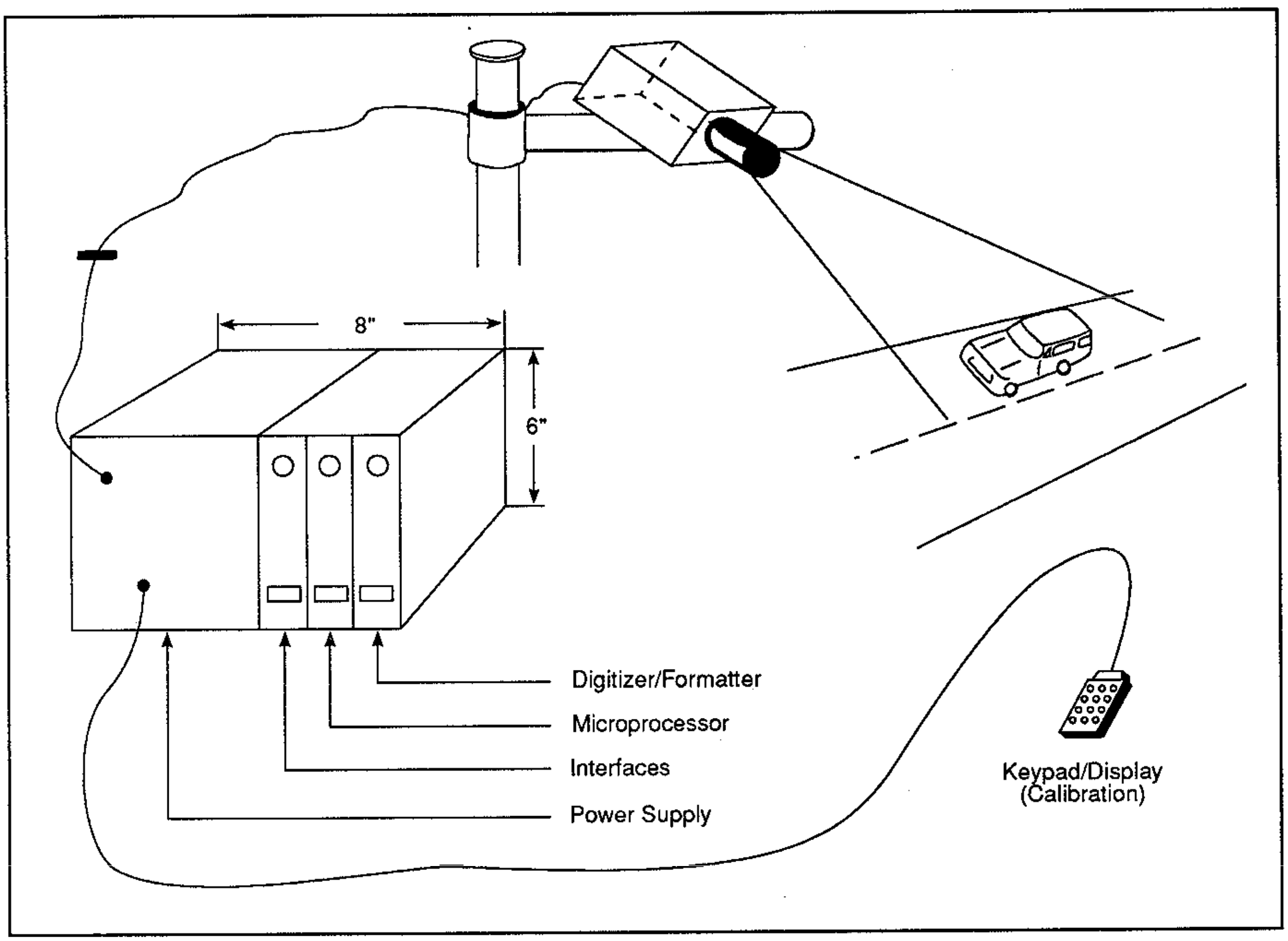


Figure 149. Wide area video imaging system.

The processing system provides outputs comparable to loop detectors; that is, presence and passage as well as speed. From these measurements, other traffic parameters can be extracted, including occupancy, volumes, queue lengths, etc. The output of the system can be connected to an existing control system (either freeway or signal control) or to a local signal controller where the detected traffic will be processed by the traffic control application software. The advantage is that, in addition to wireless detection, a single camera can replace many loops, thereby providing true wide area detection.

VIDS Development Status

A real-time version of VIDS has been developed and successfully demonstrated for a variety of roadway, environmental, and traffic conditions (Ref. 49). The algorithms have been developed to generate presence and passage detection signals and vehicle speed estimates for multiple detection spots in the camera field-of-view. The first step in the algorithm approach is to reduce the image data (from the video digitizer) so that only the data needed for detection is processed by the microprocessor, thus reducing the amount of data to be processed by two to three orders of magnitude.

The data reduction or "image formatting" is done in hardware to allow the algorithms to be done in real-time. This data reduction hardware is implemented on a single circuit card in the microprocessor called the formatter. Once the data are reduced by the formatter hardware, spatial and temporal features are extracted for each detection location. These spatial and temporal elements are combined using sequential decision processing to generate either presence or passage signals. Speed is estimated by using pairs of closely spaced detection lines and then measuring the time between adjacent passage signals for these detection spots. This is very similar in concept to speed traps used with loop detectors.

The algorithms have been optimized to deal with artifacts such as shadows, illumination changes, and reflections. The resulting system has produced vehicle detection accuracy in excess of 95 percent for all of the conditions studied. The conditions that degraded the performance in earlier video detection systems appear to be resolved. These include congestion, shadows, poor lighting, and adverse weather.

Although this is still a new and experimental approach to traffic surveillance, using advanced image processing techniques, research and development are continuing and demonstration projects are ongoing.

MICROWAVE/RADAR DETECTORS

The use of microwave radar during World War II led to the use of this technique for detecting traffic. Microwave energy is beamed toward an area of roadway from an antenna mounted overhead or in a sidefire position on a pole (Figure 150). When a vehicle passes through the beam, the energy is reflected back to the sensing unit (antenna) at a different frequency. The detector senses the change in frequency, which denotes the passage of a vehicle.

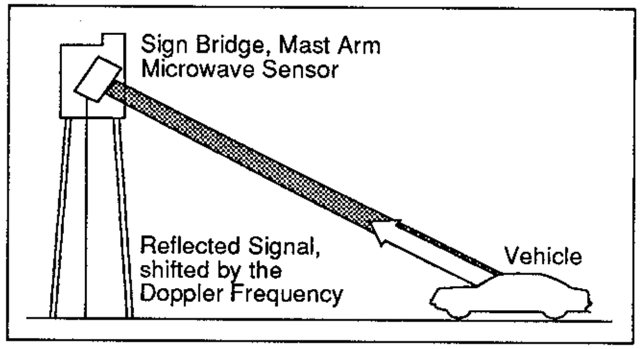


Figure 150. Microwave/radar detector concept.

The operating frequency of the signal is normally in the K-band (24 gHz) or the X-band (10 gHz). The antenna is angled slightly toward traffic, creating a Doppler effect on the reflected signal. Therefore, vehicles must be traveling at least 3 mph (5 kph) to be detected.

Radar detectors have been commercially available for a number of years. Their use, however, has been limited to special applications because they were relatively complex to maintain, were vulnerable to vandalism, and, most importantly, could only be used as passage (motion) detectors (Ref. 50).

Newly developed radar detectors promise to give true presence detection and correct many of the previous problems. One new type of radar detector, developed for the FHWA and the City of Baltimore, uses a 24 gHz signal and is expected to be capable of detecting presence as well as passage. Despite a high initial cost ($1,000 to $4,000 per unit, depending on the features and frequency used), the manufacturer claims that the life cost will be comparable to loop detectors. Field testing was planned for 1989-90 (Ref. 51).

Another relatively new microwave detector, commercially available, is shown in Figure 151. This small unit can be mounted in either a sidefire or overhead mount. It detects traffic moving in one direction using a very low power microwave beam. A single unit will cover more than one lane of traffic. It was designed primarily for use when a conventional loop detector is disabled or in construction zones. It may also be used during bridge repair work which necessitates lane closure, as it is easily removed and re-used when the job is completed. It may also be used in permanent installations for small intersections.

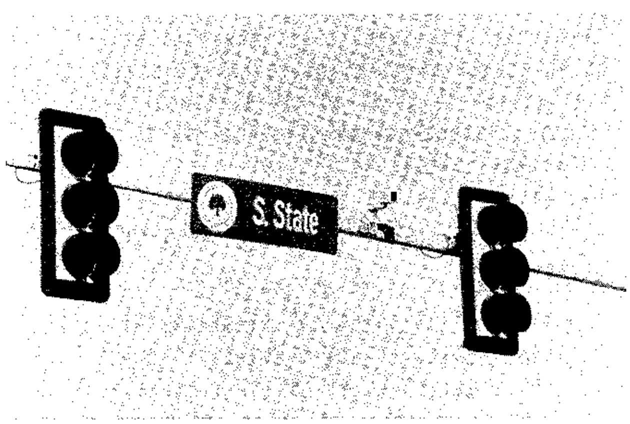


Figure 151. Commercially available microwave detector.

The unit is housed in an anodized aluminum casing and is mounted on a pole near the intersection approach (sidefire). The overhead mounted unit is only recommended when one lane is to be detected. It is mounted by means of a universal mounting bracket 12 to 18 ft (3.7 to 5.5 m) above the surface of the roadway aimed toward the flow of traffic. A four conductor cable is run from the unit to the controller cabinet: two wires are run to 10 to 24 V AC power and two wires are connected to detector inputs. Five different operating frequencies in the range of 10.525 gHz eliminate cross talk between units. Monitoring circuits for relay and transceiver failure will cycle the controller to recall (Ref. 52).

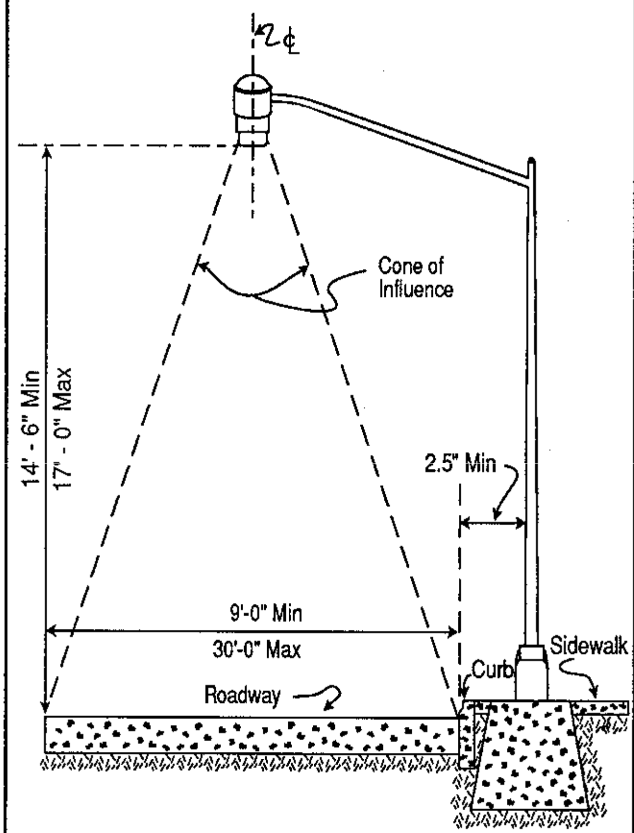
Another new radar device is under development in Germany. This development is part of a new traffic data acquisition system which uses a 61 gHz microwave detector to gather real-time data on the spacing and speed of vehicles. The prototype is being tested at a research facility in Ulm, West Germany (Ref. 51).

ULTRASONIC DETECTORS

Ultrasonic vehicle detectors were initially developed in the mid-1950's. Many agencies used them but most experienced problems and abandoned their use. These detectors operate on the same principle as radar detectors. That is, both transmit a beam of energy into an area and receive a reflected beam from a vehicle. The sonic detector transmits pulses of ultrasonic energy (20 to 50 kHz at 20 to 25 times per second) through a transducer. A typical installation is shown in Figure 152.

The passage of a vehicle causes these beams to be reflected back to the transducer at a different frequency. The transducer then senses the change and converts it to electrical energy. This energy is relayed to a transceiver, which then sends an impulse to the controller to denote the passage of a vehicle. The transducer is mounted over the roadway, while the transceiver is mounted in the controller or in a separate cabinet.

Michigan, Illinois, New York, and California were among the early users of this type of detector. In the 1960's the Michigan DOT tested several ultrasonic detectors in Detroit and found problems with controlling the conical detection zone. They also found that salt on the road would alter the signal. The Illinois DOT (Chicago) experience with ultrasonic detectors, also in the 1960's, indicated that they were neither reliable nor cost effective. Caltrans found them to be unreliable in conditions of extreme heat, and the vacuum tubes used in the early detectors would fail due to vibration. The State of New York continues to use ultrasonic detectors in remote areas with bad pavement. They estimate that 10 percent of their highway surveillance is provided by ultrasonic detectors.



No. of Lanes	℄
1	4' from curb (or edge of roadway)
2	Between lanes
3	Center line of middle lane

Figure 152. Ultrasonic vehicle detector.

Recently, there has been renewed interest in this concept, which has resulted in several major new activities. One major university program has developed modified prototypes of an ultrasonic vehicle detector to resolve some of the problems reported above (Ref. 53). After laboratory and field testing indicated that it was well suited for use as an overhead vehicle sensor, several prototypes were placed in operation in 1986. After over a year of continuous operation with periodic accuracy checks against data collected by loop detectors, the device continued to show promise.

The Port Authority of New York and New Jersey plans to use ultrasonic detectors for a new surveillance and control program at the Holland Tunnel. Originally, photoelectric cells were used to count vehicles. They were replaced with loop detectors because the dirt and grime in the tunnel caused the photoelectric cells to be unreliable. The planned system will use ultrasonic detectors placed in pairs at regular intervals to monitor and track individual vehicles moving through the tunnel. The pairs of sensors will provide vehicle classification information as well as speed, occupancy, vehicle length, and counts. This is believed to be the most intensive use of ultrasonic detectors for freeway surveillance and control in the United States.

Ultrasonic detectors are, however, used extensively in Japan in keeping with government policy which does not permit cutting the pavement (Ref. 54). These detectors are a major component in the Tokyo traffic control system. A central control computer monitors traffic signals and vehicle motion throughout Tokyo, resets timing patterns, activates motorist information display signs, and relays real-time information to both motorists and police. This appears to be most extensive use of ultrasonic detectors anywhere. The detectors used in this application are slated for testing by the Institute of Transportation Studies at the University of California (Berkeley) in their study to evaluate several forms of detector sensors for freeway surveillance and control.

Another ultrasonic device to be tested in this study provides a circular zone of detection (5 to 6 ft (1.5 to 1.8 m)) located 10 to 20 ft (3 to 6 m) from the detector. The unit can be mounted in an overhead or sidefire position and will provide continuous detection of any licensed vehicle entering the zone of detection at any speed up to 70 mph (112 kph). The transducer is recessed into the housing of the device to provide an environmental shield. It uses the principle of electrostatic detection rather than the traditional doppler effect.

INFRARED DETECTORS

Infrared detectors are used extensively in England for both pedestrian crosswalks and signal control They are also used on the San Francisco-Oakland

Bay Bridge. Here, they are side-mounted at 600-ft (18-m) intervals on the upper deck of the bridge. The detectors establish the presence of vehicles across all five lanes, thus providing an occupancy measurement.

The following disadvantages of infrared detectors are often cited. Changes in light and weather will cause scatter of the infrared beam. The lens system is sensitive to water and environmental constraints. Their reliability in high flow conditions has been questioned. In addition, earlier infrared detectors were not capable of providing vehicle counts (Ref. 51).

One infrared detector product line consists of both *active* and *passive* models. In the active system (see Figure 153), detection zones are illuminated with low power infrared light. The infrared light reflected from vehicles traveling through the zone of detection is focused by an optical system onto a sensor matrix. A real-time signal processing technique analyzes the received signal and determines the *presence* of a vehicle. Environmental shifts are tracked automatically. One version of this active infrared detector is primarily used for stop-line presence detection, while a second version is used for presence detection in the intersection approach (e.g., a detection zone 68 to 100 ft (20 to 30 m) in advance of the stop line).

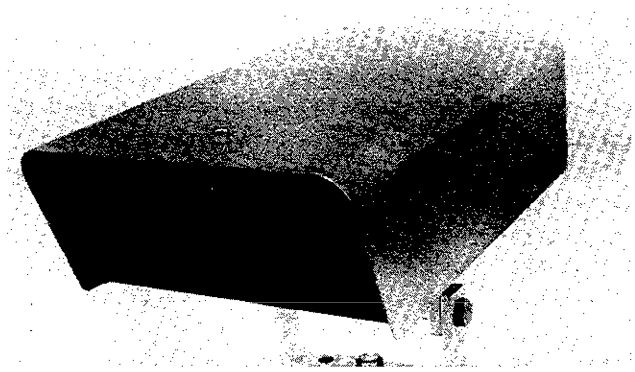


Figure 153. Active infrared detector.

The manufacturer reports that their active infrared detectors can provide vehicle presence detection for traffic signals, vehicle counting, speed measurement, length assessment, and queue detection information. Their units are designed to accommodate mounting heights of between 15 and 30 ft (4.5 to 9 m). An overhead mounting is shown in Figure 154. Multiple units can be installed within the same intersection without interference and with no interaction between units. The optical system design provides sharp edged zones of detection. Vehicles outside of the defined zone have no effect (Ref. 55).

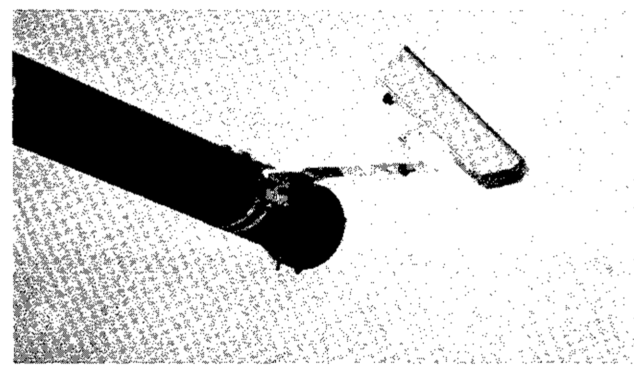


Figure 154. Overhead mounted infrared detector.

The passive system measures passage (motion) only. The unit (illustrated in Figure 155) contains a lens configuration that provides detection of moving vehicles within a 3° zone of detection which may be up to 300 ft (91 m) from the unit. Wider detection zones are available by selecting the optional medium or short focal length lenses. To eliminate adjacent lane detection when detecting vehicles over 100 ft (30 m) from the unit, the long length lens option is recommended. For detection close to the unit (e.g., for side-fire detection) a medium or short focal length lens is used.

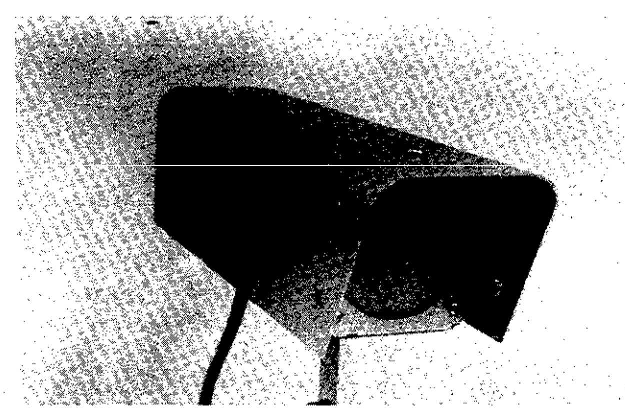


Figure 155. Passive infrared detector.

DIGITAL LOOP TEST INSTRUMENT

A 1989 test instrument which uses digital signal processing and sampled data techniques to measure a broad range of loop system parameters has been developed and is in the prototype phase of testing and calibration prior to production (see Figure 156). The application for this loop tester includes testing of new loop installations, preventive maintenance, diagnostics and repair of failed loops, and data collection and statistics. The theory of operation, design philosophy, and the operational features attributed to this product are summarized below from Ref. 56.

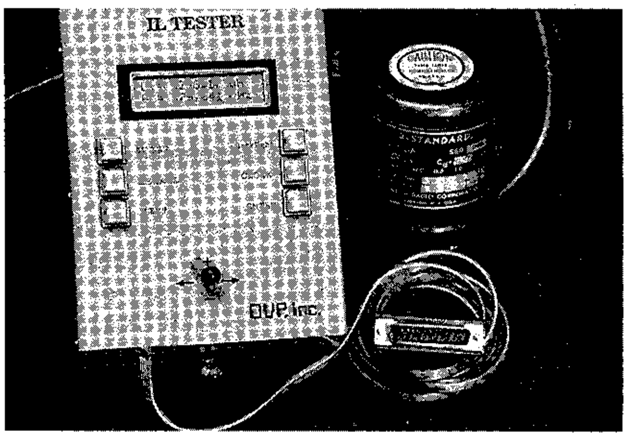


Figure 156. Digital loop test instrument.

THEORY OF OPERATION

Until recently, the construction of an all-digital device that would operate in the ranges necessary to fully diagnose loop detector systems has been constrained by limitations in the technology. The new technology applied in this evolving product is described as follows. To take measurements in a non-energized loop, an interactively programmable frequency is generated by a high-speed digital signal processor (DSP). Time critical math functions are performed on the DSP chip and post-processing is conducted on a general purpose microprocessor.

The microprocessor also controls the display. All components are CMOS (Ceramic Metal Oxide Silicon), which is a low-powered integrated circuit technology. This allows low-powered battery operation over a broad range of temperatures. A flexible power converter/charging unit permits operation over an extended voltage range from a variety of input sources.

Even with this technology, it is critical to have the proper algorithms and software to produce the correct results. This loop test instrument combines a precision phase/gain meter with a frequency synthesizer. By accurately measuring the phase and gain of an oscillator driving a coil, the inductance, resistance, and Q factor can be computed.

To accommodate a broad range of inductance values and operating frequencies, the test instrument can autorange the source impedance and input signal gain (with auto gain control). Noise reduction is accomplished through the use of dynamically reconfigurable digital filters and averaging.

FREQUENCY MEASUREMENT

At frequencies above 20 kHz, the effective loop inductance becomes more frequency dependent. For this reason, it is important to measure the loop inductance at its operating frequency. This requires measuring the loop frequency when connected to the detector electronics, then disconnecting the loop to directly measure the inductance at the measured frequency.

Many of the newer loop detector units use multichannel techniques to operate four or more loops. This conserves controller cabinet space and can minimize crosstalk problems by using a time-division scanning process. Because the scanning detector energizes each of the four channels sequentially (up to 100 times per second), conventional frequency counters cannot be used to accurately measure the loop operating frequency.

Some loop detectors require 10 or more cycles to stabilize after being switched on during a scanning cycle. The detector electronics mask these cycles out when switching from channel to channel. A conventional frequency counter would give an erroneous reading due to the short frequency burst of the detector oscillator and the stabilization time required. This instrument is designed to accurately measure the frequency and it is reported that the measurement circuitry requires only a few cycles of frequency to make a measurement. Initial cycles can be gated out and the measurement can be triggered from the signal burst. A summary of the performance characteristics of this instrument is given in Table 30.

Table 30. Summary of loop tester performance.

Measurement	Range	Units
Inductance	10 - 2,000	microhenries, µh
Loop Quality	1 - 300	dimensionless, Q
Level/Frequency		
Range	1 - 150	kilohertz, kHz
Freq. Level	– 40 - 150	decibels, dB
Signal/Noise Ratio	40	decibels, dB
Frequency Generator		
Range	1 - 150	kilohertz, kHz
Resolution	1.0	Hertz, Hz
Level	– 40 - 0	decibels, dB
Resistance	1 - 10,000	Ohms, Ω

DESIGN PHILOSOPHY

Failures of inductive loops can be caused by a variety of problems. The loop wires may become shorted from worn or stressed insulation. They may break or short to ground. The lead-in wire may become damaged through corrosion. Any number of failures may eventually occur; consequently, reliable test equipment is required for routine maintenance to detect failing or failed loop circuits.

The typical electrical parameters needed to diagnose a loop system are resistance, frequency, impedance, capacitance, Q factor, and inductance. Some of these factors can be measured directly, while others require computation from separate tests. Of the many different loop detector systems, all possess a combination of resistance, inductance, and capacitance. These characteristics, within certain parameters, determine whether the detector system will or will not operate properly. There is a wide variety of acceptable limits for these measurements depending the geometry, length and type of lead-in cable, location of loop, external interference, system tuning, etc.

Historically, loop diagnostics for problem loops, as well as testing new installations, relied heavily on rule-of-thumb and trial-and-error approaches. There are, however, certain measurements that can be taken to increase confidence in the quality of the installation and to help diagnose faulty loops. For example, a simple resistant-to-ground and "open loop" determination can easily be preformed with a specialized megameter and a simple volt ohmmeter (VOM). The megameter uses a high voltage to check for leakage to ground, while the VOM is used to check for shorts and open circuits. These two instruments have provided the majority of field diagnostic information and have proved adequate for many older loop installations.

Today's loop installations operate with far greater sensitivities than their older counterparts and have a higher operational demand. Todays loops must provide accurate information dealing with multi-lane inputs and must be able to detect vehicles from large trucks to bicycles. Problems such as crosstalk, environmental drift, operational frequency, and intermittent sensitivity variations have now become significant factors. A typical VOM is no longer adequate. For example, the loop is actually operating at relatively high frequencies (the wire resistance to alternating current increases as the frequency increases), and these high frequencies cannot be measured with a VOM. A more sophisticated instrument is required to accurately assess the quality of the loop. Measurement at these operational frequencies becomes important.

APPENDIXES

INDUCTIVE LOOP SYSTEM EQUIVALENT CIRCUIT MODEL

Abstract

This paper describes the development and application of an equivalent circuit model and computer program to calculate the apparent self inductance and quality factor versus frequency of square, rectangular, quadrupole, and circular loops of round wire buried in a roadway. The effect of transmission lines and matching transformers between the loop in the roadway and roadside vehicle detector electronics is included in the model. The capacitance between the loop conductors and surrounding pavement material is shown to have a major effect on the magnitude of the loop's apparent self inductance.

Inductive loop detectors are presently used in most actuated and computer controlled traffic surveillance systems. The design of the loop's size and shape, and number of turns of wire should provide adequate vehicle detection sensitivity and prevent the transmission line from reducing sensitivity. The magnitude of inductance seen by the detector electronics must be in a range specified by the detector manufacturer. The computer program calculates the loop apparent inductance and quality factor versus operating frequency (20-60 kHz) for a selected loop size, shape, conductor size, number of turns, turn spacing, slot width, pavement loss tangent, and slot sealant material dielectric constant.

Introduction

The inductive loop detector system is comprised of a buried loop of round wire in the roadway pavement which is connected with a transmission line to roadside vehicle detector electronics. When a vehicle is sensed by the loop, a small decrease in loop inductance is detected by the detector electronics. Since the series inductance of the transmission line decreases the loop inductance change available to the detector electronics, the loop inductance should be larger than the transmission line series inductance. The loop inductance can be increased by winding additional turns to the loop and/or adding a transformer between the loop and transmission line. The frequency range of typical vehicle detector electronics is 20 kHz to 60 kHz. The inductance seen by the vehicle detector electronics can change significantly versus frequency if too many turns are used on the roadway loop because of loop capacitance. An equivalent circuit model of the inductive loop system was developed and programmed on a computer. The computer program allows inductive loop system designers and maintenance technicians to calculate the loop system inductance and quality factor as a function frequency, wire gauge size, wire spacing, etc.

The equivalent loop system model is comprised of a roadway inductive loop model, a transformer model, and a transmission line model. The calculation of the self inductance of square, rectangular, and quadrupole loops is described in previous papers [1,2]. King [3] describes the calculation of the self inductance of circular loops. This paper includes the calculation of the internal and external capacitance of such loops to determine high frequency performance. A wide band transformer model is used. The transmission line model uses a complex characteristic impedance. All equations used in the loop computer program are included in this paper.

Loop Capacitance Theory

Internal Loop Capacitance

The capacitance between loop turns was calculated using a low frequency, multi-layer, transformer model [4]. This model assumes uniform flux coupling through the loop turns with minimum leakage flux. Figure 1 illustrates the capacitance between two adjacent isolated loop turns.

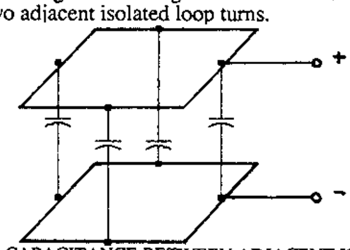


FIGURE 1. CAPACITANCE BETWEEN ADJACENT ISOLATED LOOP TURNS.

The loop is comprised of parallel transmission lines with a capacitance [5] per unit length, C', given by

$$C' = \frac{(\varepsilon/\varepsilon_0) \times 10^{-9}}{36 \cosh^{-1}(D/2a)} \tag{1}$$

where

C'	=	capacitance (F/m)
D	=	spacing between conductor centers (m)
a	=	conductor radius (m)
$\varepsilon/\varepsilon_0$	=	relative dielectric constant (1 for air)

The total capacitance between adjacent, isolated loop turns is given by

$$C^i = C'P \tag{2}$$

where P is the loop perimeter (m). A similar method was used by Palermo [6]. The actual loop turns are connected as shown in Figure 2.

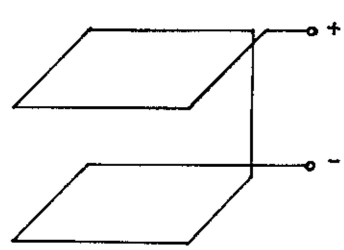


FIGURE 2. CAPACITANCE BETWEEN ADJACENT LOOP TURNS.

The parallel transmission line is shorted at the end. The input capacitance of the shorted transmission line is given by

$$C_T^i = \int_0^P \left(\frac{x}{P}\right)^2 C'dx = \frac{1}{3} C'P \qquad (3)$$

Figure 3 shows the circuit model for a multi-turn loop where L_L is the low frequency inductance of the loop and C^i_L is the lumped internal capacitance across the loop terminals.

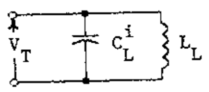


FIGURE 3. LOOP INTERNAL CAPACITANCE.

The total internal capacitive energy is

$$E_T = \frac{1}{2} C_L^i V_T^2 = \frac{1}{2} \sum_{j=2}^{n} C_j^i V_j^2 \qquad (4)$$

where assuming a linear voltage drop

$$V_j = \frac{2}{n} V_T \qquad (5)$$

and n is equal to the number of loop turns, then

$$C_L^i = \sum_{j=2}^{n} \frac{C'P}{3} \left(\frac{2}{n}\right)^2 \qquad (6)$$

The lumped internal capacitance across the loop terminals is given by

$$C_L^i = \frac{4}{3} \frac{(n-1)}{n^2} C'P \qquad (7)$$

This equation is identical to the equation [7] for the capacitance between transformer winding layers with the exception of C'.

External Loop Capacitance

Capacitive coupling exists between the loop conductors and edge of pavement slot containing the conductors. Figure 4 illustrates the capacitive coupling. Since loop wires are typically closer to the top of the slot (*i.e.*, sealant in bottom of slot supports conductors), the capacitive coupling between the conductors and bottom of the slot was neglected.

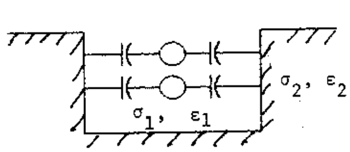


FIGURE 4. CAPACITANCE BETWEEN LOOP CONDUCTORS AND SLOT.

The external capacitance exists between a conductor and a material with variable dielectric constant and conductivity rather than metal. Galejs [8] determines the impedance of a buried insulated wire. The capacitance is calculated assuming the region surrounding the slot or cavity is finitely conducting where region one is a low loss dielectric [9] or

$$|j\omega\epsilon_1| > \sigma_1 \qquad (8)$$

Stratton [10] also shows that a perfectly conducting outer conductor for a coaxial line provides a good approximation to a finitely conducting one when calculating shunt admittance. The slot walls are approximated by infinite conducting ground planes as illustrated in Figure 5.

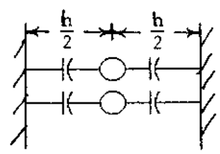


FIGURE 5. CAPACITANCE BETWEEN LOOP CONDUCTORS AND INFINITE CONDUCTING PLANES.

The characteristic impedance [11] of this conductor geometry is

$$Z_o = \frac{138}{\sqrt{\epsilon_r}} \log_{10}\left(\frac{4h}{d}\right) \qquad (9)$$

The capacitance per unit length of a TEM transmission line is

$$C' = \frac{120\pi\,\epsilon_o \sqrt{\epsilon_r}}{Z_o} \qquad (10)$$

Then

$$C' = \frac{2\pi\,\epsilon_o\,\epsilon_r}{\ln\left(\frac{4h}{d}\right)} \qquad (11)$$

or

$$C' = \frac{1}{18}\,\frac{\epsilon_r \times 10^{-9}}{\ln\left(\frac{4h}{d}\right)} \text{ (Farads/meter)} \qquad (12)$$

The total external capacitance for the loop conductor is

$$C = C'P \qquad (13)$$

Inductive loops are typically balanced as shown in Figure 6.

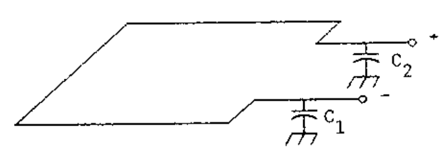


FIGURE 6. BALANCED INDUCTIVE LOOP.

Because of the balanced configuration and zero potential point at conductor perimeter center

$$C_1 = C_2 = \left(\frac{C'}{3}\right)\left(\frac{P}{2}\right) = \frac{C'P}{6} \quad (14)$$

thus,

$$C_L^e = C_1 \| C_2 = \frac{C'P}{12} \quad (15)$$

If one side of the loop is grounded

$$C_L^e = \frac{C'P}{3} \quad (16)$$

Loop Resistance Theory

Loop Resistance

The series loop resistance, R_L, is comprised of the direct current wire resistance, R, the high frequency of skin effect resistance, Rac, and the ground resistance, Rg. The most important resistance is the ground resistance which is caused by currents induced in the conductive pavement and subgrade material. The ground resistance may limit loop sensitivity in locations with a large moisture content. The ground resistance is calculated by assuming the pavement and subgrade material causes a magnetic loss similar to that of a ferrite or iron core in an inductor. The permeability, μg, of the pavement and subgrade material is assumed to be one. Appendix I presents a derivation of the ground resistance.

The series loop resistance is:

$$R_L = R + Rac + Rg \quad (17)$$

$$Rg = \tan\delta g \omega L_L \quad (18)$$

where

- R_L = series loop resistance (Ω)
- R = direct current loop resistance (Ω)
- Rac = skin effect resistance (Ω)
- Rg = ground resistance (Ω)
- r = loop wire radius (m)
- $\tan\delta g$ = loss tangent of pavement material
- L_L = loop self inductance (Hy)
- ω = operating frequency (radians)

Internal Inductance and Resistance Per Unit Cylindrical Conductor Length

Johnson [12] shows that the ratio of actual internal inductance to low-frequency internal inductance and internal resistance to low-frequency internal resistance is given by:

$$\frac{L_i}{L_{io}} = \frac{4}{q}\left[\frac{\text{beiq}\,\text{béiq} + \text{berq}\,\text{bérq}}{(\text{béiq})^2 + (\text{bérq})^2}\right] \quad (19)$$

and

$$\frac{R}{R_o} = \frac{q}{2}\left[\frac{\text{berq}\,\text{beíq} - \text{beiq}\,\text{ber}'\text{q}}{(\text{beíq})^2 + (\text{ber}'\text{q})^2}\right] \quad (20)$$

where

$$q = \frac{\rho\left(\sqrt{2}\right)}{\delta} \quad (21)$$

where

$$d = \frac{1}{\sqrt{\mu_r \mu_o \pi f \sigma}} \quad (22)$$

- Li = internal inductance (Hy/m)
- δ = skin depth (m)
- μo = permeability of fre space = $4\pi \times 10^{-7}$ Hy/m
- μr = relative permeability of copper wire = 1
- f = frequency (Hz)
- σ = conductivity of copper wire = 0.58×10^8 (mhos/m)
- ρ = radius of wire (m)
- ρr = resistivity (ohm-meter)

$$L_{io} = \frac{\mu_o \mu_r}{8\pi} \text{(Hy/m)} \quad (23)$$

$$R_0 = \frac{\rho_r}{\pi \rho^2} \quad (24)$$

ρr = 1.74×10^{-8} ohm-meters for copper wire

Appendix II presents the formulas [13] for the complex Bessel Functions and their derivatives.

Loop Inductance Theory

Self Inductance of Single Turn Circular Loop

The self inductance [14] of a single turn circular loop is given by

$$L_o = \mu_r \mu_o (2r\text{-}a)\left[\left(1 - \frac{k^2}{2}\right)K(k) - E(k)\right] \quad (25)$$

where

$$k^2 = \frac{4r(r-a)}{(2r-a)^2} \quad (26)$$

- Lo = self inductance (H)
- E(k) = complete elliptic integral of first kind
- K(k) = complete elliptic integral of second kind
- r = radius of loop conductor center (m)
- a = loop conductor radius (m)

The formula for E(k) [15] and K(k) [16] is given in Appendix III.

Self Inductance of Multi-Turn Circular Loop

The inductance formula for a circular coil with N equal spaced, identical turns following King [17] is given by:

$$L_T = NLo + 2(N-1)M_{12} + 2(N-2)M_{13} + \ldots.. \quad (27)$$

or

$$L_T = NL_o + 2\sum_{i=1}^{n}(n-1)M_{1,(i+1)} \quad (28)$$

where following Ramo [18]

$$M = \mu_r \mu_o \sqrt{ab}\left[\left(\frac{2}{k} - k\right)K(k) - \frac{2}{k}E(k)\right] \quad (29)$$

$$k^2 = \frac{4ab}{d^2 + (a+b)^2} \qquad (30)$$

with

M = mutual inductance (H)
a = radius of turn one (m)
b = radius of turn two (m)
d = spacing between turns (m)

External Inductance of Single Turn Rectangular Loop

The external inductance of a single turn, rectangular loop is given by the sum of the inductance of two pairs of conductors. Then:

$$L_o^e = L_{pl}^e + L_{p2}^e \qquad (31)$$

The external inductance of a single turn, rectangular loop is:

$$L_o^e = \frac{\mu_o}{\pi} \{ l_1 \ln\left[\frac{l_1}{\rho} + \sqrt{1 + \left(\frac{l_1}{\rho}\right)_2}\,\right]$$

$$- l_1 \ln\left[\frac{l_1}{l_2} + \sqrt{1 + \left(\frac{l_1}{l_2}\right)^2}\,\right]$$

$$+ l_2 \ln\left[\frac{l_2}{\rho} + \sqrt{1 + \left(\frac{l_2}{\rho}\right)^2}\,\right]$$

$$- l_2 \ln\left[\frac{l_2}{l_1} + \sqrt{1 + \left(\frac{l_2}{l_1}\right)^2}\,\right]$$

$$- \sqrt{l_1^2 + \rho^2} - \sqrt{l_2^2 + \rho^2}$$

$$+ 2\sqrt{l_1^2 + l_2^2} - \left(l_1 + l_2\right) + 2\rho\} \qquad (32)$$

where

l_1 = width of loop (m)

l_2 = length of loop (m)

This equation can be written in more compact form by combining logarithms.

Self Inductance of Single Turn Rectangular Loop

The self inductance of a single turn rectangular loop is given by the sum of internal and external inductance and is:

$$L_o = L_o^i + L_o^e \qquad (33)$$

where

$$L_o^i = 2\left(l_1 + l_2\right) L^i \qquad (34)$$

and L^i is given by equation (19) and $L^e{}_o$ is given by equation (32).

Self Inductance of Multi-Turn Rectangular Loop

The general inductance formula for a coil with N equal spaced, identical turns is:

$$L_T = NLo + 2(N - 1)M_{12} + 2(N - 2)M_{13} + \ldots\ldots \qquad (35)$$

Mutual Inductance of Two Coaxial, Parallel, Rectangular Loops

The total mutual inductance of th rectangular loops in Figure 7 is given by the sum of the mutual inductances between the parallel sides and using formula (37) is

$$M = 2\,[\,M_{13}\left(A, \sqrt{H^2 + B^2}\right) - M_{11}\,(A, H)$$

$$+ M_{24}\left(B, \sqrt{H^2 + B_2}\right) - M_{22}\,(B, H)] \qquad (36)$$

where M_{11} is the mutual inductance between side 1 of the bottom loop turn and side 1 of the top loop turn under consideration as shown. Note that all mutual inductances are symmetrical (*i.e.*, $M_{13}, = M_{31}$, etc).

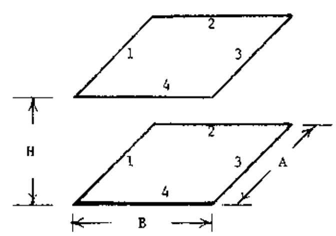


FIGURE 7. LOOP TURN GEOMETRY.

Mutual Inductance of Parallel Filamentary Circuits

The mutual inductance [19] between the pair of filamentary circuits located in free space and illustrated in Figure 8 is:

$$M\,(l,d) = + \frac{\mu_o l}{2\pi} \left\{ \begin{array}{l} \ln\left[\frac{l}{d} + \sqrt{1 + \left(\frac{l}{d}\right)^2}\,\right] \\ - 1 + \sqrt{\left(\frac{d}{l}\right)^2 + \frac{d}{l}} \end{array} \right\} \qquad (37)$$

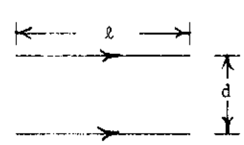


FIGURE 8. PAIR OF PARALLEL CURRENT ELEMENTS.

where

μo	=	permeability of free space = $4\pi \times 10^{-9}$ Hy/m
l	=	filamentary length (m)
d	=	filamentary spacing (m)
M(l,d)	=	mutual inductance (Hy)

A plus sign is used when the direction of current in the filaments is the same and a minus sign is used when the direction of current in the filaments is opposite.

Self Inductance of Multi-Turn Quadrupole Loop

Figure 9 presents an illustration [20] of a two turn quadrupole loop.

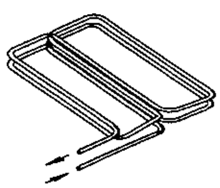


FIGURE 9. TWO TURN QUADRUPOLE LOOP.

The external inductance of an N turn quadrupole loop is:

$$L_T = 2NL_o + 2NM_{12} + 4(N-1)M_{13} + 4(N-1)M_{14} + 4(N-2)M_{15} + 4(N-2)M_{16} + \ldots\ldots \quad (38)$$

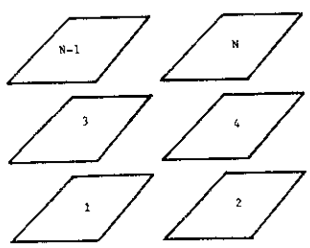


FIGURE 10. MULTI-TURN QUADRUPOLE LOOP.

General Formula for Mutual Inductance of Parallel Filaments

In order to calculate the mutual inductance between the offset loops in the quadrupole loop model, a general formula for the mutual inductance of parallel, offset filaments is required.

Following Jefimenko [21], the mutual inductance (Henry's) between the two parallel current filaments (meters) illustrated in Figure 11 is given by:

$$M_{ik} = \pm \frac{\mu_o l}{4\pi}\left[\ln\left(\frac{(a+A)^a (b+B)^b}{(c+C)^c (d+D)^d}\right) + (D+C) - (B+A)\right]_{ik} \quad (39)$$

where the positive sign is used for elements with currents in the same direction.

This formula, assumes that the elements lengths are much less than the wavelength divided by 2π and the conductor radius is much less than the element length.

It should be noted that Grover [22] shows that this type of general formula can also be expressed by applying the laws of summation of mutual inductance to equation (37).

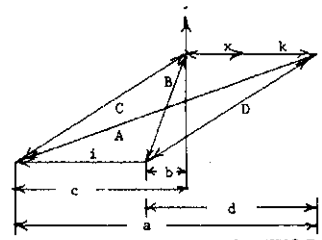


FIGURE 11. MUTUAL INDUCTANCE OF TWO PARALLEL SEGMENTS.

Loop Circuit Model

Inductive Loop Circuit Model

Figure 12 presents a circuit model of an inductive loop.

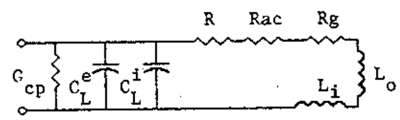


FIGURE 12. INDUCTIVE LOOP CIRCUIT MODEL.

Let

$$Ls = Lo + Li \quad (40)$$

$$Rs = R + Rg \quad (41)$$

$$Cp = C^i{}_L + C^e{}_L \quad (42)$$

Following Johnson [23], the slot dielectric loss conductance is

$$G = \tan \delta_c \omega Cp \quad (43)$$

where $\tan \delta_c$ is the loss tangent of the slot sealer material.

Appendix IV shows the inductive loop circuit model of Figure 12 reduces to the circuit model of Figure 13 where

$$R^L_{in} = \frac{G_p}{G_p^2 + \left(\omega C_p - \dfrac{1}{\omega L_p}\right)^2} \quad (44)$$

and

$$X^L_{in} = \frac{\dfrac{1}{\omega L_p} - \omega C_p}{G_p^2 + \left(\omega C_p - \dfrac{1}{\omega L_p}\right)^2} \quad (45)$$

The loop quality factor is given by

$$Q^L_{in} = \frac{X^L_{in}}{R^L_{in}} = \frac{\dfrac{1}{\omega L_p} - \omega C_p}{G_p} \quad (46)$$

The self resonant frequency of the loop is given by

$$fo = \frac{1}{2\pi}\sqrt{L_p C_p} \quad (47)$$

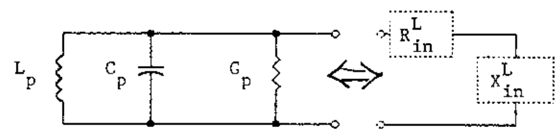


FIGURE 13. EQUIVALENT LOOP CIRCUIT MODEL.

Loop Transmission Line Theory

Loop Transmission Line Model

A transmission line connects the roadway loop with roadside detector electronics. The complex impedance (Z_L) of the loop is transformed to a complex impedance, Z_{in}, by the transmission line cable by the following equation [24].

$$Z_{in}^{c} = Z_o \frac{Z_L + Z_o \tanh \gamma l}{Z_o + Z_L \tanh \gamma l} \tag{48}$$

where

$$Z_L = R_L + j\omega L_L \tag{49}$$

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{50}$$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{51}$$

with

- R = transmission line per unit resistance (Ω/m)
- G = transmission line per unit conductance (Ω/m)
- L = transmission line per unit inductance (H/m)
- C = transmission line per unit capacitance (F/m)
- R_L = loop equivalent resistance (Ω)
- L_L = loop equivalent inductance (H)
- ω = radian frequency

A useful equation [25] for computing Zin is given by

$$\tanh(x \pm jy) = \frac{\sinh 2x \pm j \sin 2y}{\cosh 2x + \cos 2y} \tag{52}$$

Frequency Shift Detector System Sensitivity

The frequency shift, Δf_D, at the detector terminals is required as a function of loop and cable parameters.

Let $\quad f_V - f_{NV} = -\Delta f_D \quad (53)$

and $\quad f_{NV} = f_D \quad (54)$

Then

$$\frac{\Delta f_D}{f_D} = -\frac{1}{2} S_D \tag{55}$$

Since $\quad L_D = L_L + L_C \quad (56)$

and $\quad \Delta L_D = \Delta L_L \quad (57)$

$$\frac{\Delta f_D}{f_D} = -\frac{1}{2} S_L \left(\frac{1}{1 + \frac{L_c}{L_L}} \right) \tag{58}$$

where

$$S_L = \frac{\Delta L}{L} \tag{59}$$

This equation shows that the cable inductance, L_C, is important relative to frequency shift detection sensitivity. If the cable inductance is one tenth or less of the loop inductance, the transmission line has a negligible effect on Inductance Loop Detector (ILD) sensitivity provided the quality factor, Q_D, is five or greater. The frequency shift detector system sensitivity results also apply to period shift detector systems.

Loop Transformer Theory

Inductive Loop Transformer Model

A transformer [26] with low leakage inductance (*i.e.*, total series leakage inductance less than transmission line inductance) can be placed between the loop and transmission line to transform the loop inductance to a value larger than the transmission line inductance. The transformer will remove the reduction in sensitivity caused by the transmission line.

The transformer model [27] used is shown in Figure 14.

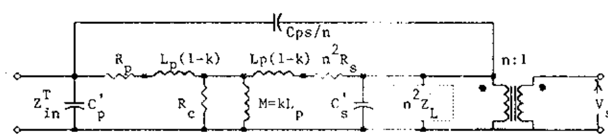


FIGURE 14. LOOP TRANSFORMER MODEL.

where all parameters are referred to the primary

- R_p = primary winding resistance
- R_c = resistance corresponding to core loss
- n^2R_s = referred secondary winding resistance
- n^2Z_L = referred load impedance
- C_p = primary capacitance
- C_s = secondary capacitance
- C_s' = modified secondary shunting capacitance

$$C_s' = \frac{C_s}{n^2} + \frac{C_{ps}}{n}\left(\frac{1}{n} - 1\right) \tag{60}$$

- C_{ps}/n = referred primary to secondary capacitance
- C_p' = modified primary capacitance

$$C_p' = C_p + C_{ps}\left(1 - \frac{1}{n}\right) \tag{61}$$

- n = ratio of primary to secondary turn

$$n = \frac{\sqrt{L_p}}{\sqrt{L_s}} \tag{62}$$

- L_p = open circuit primary inductance at low frequency
- $L_p(1-k)$ = one-half total leakage inductance
- K = coupling coefficient

$$K = \frac{\text{mutual inductance}}{\sqrt{L_p L_s}} = \frac{M}{\sqrt{L_p L_s}} \tag{63}$$

The equivalent transformer model of Figure 15 was used to determine the transformed load impedance

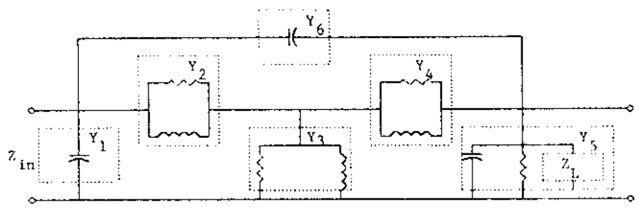


FIGURE 15. EQUIVALENT TRANSFORMER MODEL.

The comparison of measured and calculated results is seen to be favorable. Measured loop inductance and quality factor data versus frequency was unavailable for quadrupole and circular loops.

In Appendix V it is shown that

$$Z^{T}_{in} = \frac{(Y_2+Y_3+Y_4)(Y_4+Y_5+Y_6) - Y_4^2}{(Y_1+Y_2+Y_3)\left[(Y_2+Y_3+Y_4)(Y_4+Y_5+Y_6)-Y_4^2\right] - 2Y_2Y_4Y_6 - Y_6^2(Y_2+Y_3+Y_4) - Y_2^2(Y_4+Y_5+Y_6)} \tag{64}$$

Loop Computer Program

Loop Detector Analysis System (LDAS) Program

The LDAS computer program calculates loop inductance and quality factor for rectangular, quadrupole, and circular loops. The loop inductance and quality factor is transformed by the transmission line, (non-shielded twisted loop wire) to roadside junction box and transmission line (shielded twisted pair) between junction box and detector electronics in controller box. The program also allows a transformer between the loop and transmission line or between the two types of transmission lines.

The LDAS program is menu driven and written in Microsoft Quick Basic. All mathematical functions are computed using double precision calculations.

Measured Data and Calculated Results

Comparison of Calculated and Measured Loop Self Inductance and Quality Factor

Table I presents measured self inductance and quality factor data for a 1.83m (6ft) by 1.83 m (6ft) three turn inductance loop. A comparison between measured and LDAS computed data is presented in Table II.

Results and Conclusions

Tables III through V present calculated loop inductance and quality factor as a function of conductor size. The quality factor decreases with increasing wire gauge as expected. The addition of a transmission line of 240 feet length approximately halves the quality factor. Detector applications requiring transmission lines over 200 feet in length should use number 12 AWG wire for the loop and non-shielded transmission line. Three to four turns of loop wire have an adequate quality factor. One to two turn loops should be used with a transformer.

Loop inductance should be measured at 1 kHz to remove effects of capacitance when determining the number of turns of a buried loop. All loop measurements at frequencies of 20 kHz or greater should be made with a balanced instrument since the loop detector electronics is balanced. An unbalanced measurement will result in wrong values because of the different capacitance to ground. Since the external capacitance is determined by the dielectric constant of the slot sealing material, the loop conductors should be completely sealed to prevent water in the loop slot. The high dielectric constant of water will cause a significant change in the external capacitance causing the apparent loop inductance to change. Unstable loop detector operations results from incomplete sealing of the loop slot.

Table I. Measured inductive loop parameters with vehicle not present.

f_o	f_2	f_1	$Q=\frac{f_o}{f_2 - f_1}$	C	$L=\frac{1}{(2\pi f_o)^2 C}$	$R=\frac{2\pi f_o L}{Q}$
(KHz)	3db(KHz)	3db(KHz)		(mF)	(μH)	(Ω)
20	20.334	19.702	31.7	0.856490	73.9	0.29
25	25.372	24.688	35.5	0.548109	73.9	0.33
30	30.388	29.644	40.3	0.380000	74.1	0.35
35	35.427	34.607	42.7	0.278693	74.2	0.38
40	40.470	39.573	44.6	0.212056	74.3	0.42
45	45.514	49.472	45.7	0.167887	74.5	0.46
50	50.571	49.472	45.5	0.135704	74.7	0.52
55	55.633	54.407	44.9	0.111845	74.9	0.58
50	60.704	59.342	44.1	0.093450	75.3	0.64

Comments:

Loop Size: 1.83m (6ft) by 1.83m (6ft)
Loop Number of Turns: 3
Loop Wire Size: 14 Gauge
Loop Lead in Length: 1.52m (60in)
Loop Self-Resonant Frequency: 697.06 kHz
Note: 50 pf residual capacitance in decade box neglected in C value.

Table II. Comparison of Calculated and Measured Loop Parameters.

F_O (KHz)	Measured L (μH)	Calculated L (μH)	Measured Q	Calculated Q
20	73.9	74.4	31.7	30.4
25	73.9	74.4	35.5	33.9
30	74.1	74.3	40.3	36.6
35	74.2	74.3	42.7	38.8
40	74.3	74.3	44.6	40.6
45	74.5	74.3	45.7	42.2
50	74.7	74.3	45.5	43.7
55	74.9	74.3	44.9	44.9
60	75.3	74.3	44.1	46.1

Calculated Loop Parameters:

- pavement loop slot width (mils): 375
- loop slot sealant dielectric constant: 6
- pavement material loss tangent: .01
- loop wire insulation dielectric constant: 2.5
- effective loop wire insulation loss tangent: .001
- loop conductor spacing (mils): 200
- American wire Gauge, AWG: 14

Table III. Rectangular Loop Parameters

Wire Gauge (AWG)	1 Turn Inductance (μH)	1 Turn Quality Factor	2 Turn Inductance (μH)	2 Turn Quality Factor	3 Turn Inductance (μH)	3 Turn Quality Factor	4 Turn Inductance (μH)	4 Turn Quality Factor	5 Turn Inductance (μH)	5 Turn Quality Factor
12	10.13	19.68	35.22	29.88	73.28	37.13	123.14	42.65	184.00	47.03
14	10.50	15.61	35.96	24.06	74.39	30.40	124.62	35.41	185.85	39.51
14*	63.45	11.59	89.16	14.11	128.18	17.51	179.61	21.20	242.96	24.86
14**	351.70	1.77	853.20	4.90	1433.69	9.99	1985.51	17.24	2464.16	26.76
16	10.85	11.57	36.68	18.10	75.46	23.25	126.04	27.50	187.62	31.09
18	11.20	8.11	37.37	12.84	76.50	16.73	127.42	20.05	189.34	22.95

*Transmission Line
**Transformer Loop

Note: 1. 20kHz, other parameters given for Table II
2. All inductance and quality factors in Table III are apparent values (i.e., the effect of loop capacitance and resistance is included)
3. Transformer Parameters

Primary Resistance (OHMS)	= 1
Primary Capacitance (PICOFARADS)	= 10
Primary Inductance (MILLIHENRY'S)	= 5
Secondary Resistance (OHMS)	= 1
Secondary Capacitance (PICOFARADS)	= 10
Primary to Secondary Turns Ratio	= 5
Core Loss Resistance (OHMS)	= 1000000
Coupling Coefficient	= .99
Primary to Secondary Capacitance (PF)	= 10

4. Transmission Line Parameters:

• length (ft):	240
• resistance (milliohms/ft):	2.5
• inductance (microhenry's/ft):	0.22
• conductance (micromhos/ft):	0.000076
• capacitance (picofarads/ft):	26

Table IV. Quadrupole Loop Parameters

	1 Turn		2 Turn		3 Turn		4 Turn		5 Turn	
Wire Gauge (AWG)	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor
12	17.14	21.72	60.15	32.74	125.42	40.32	210.78	45.93	314.77	50.27
14	17.69	17.26	61.26	26.53	127.08	33.28	212.98	38.48	317.49	42.64
16	18.22	12.81	62.32	20.07	128.67	25.67	215.09	30.18	320.10	33.91
18	18.74	8.99	63.36	14.32	130.22	18.61	217.15	22.21	322.65	25.29

Note: 1. 20 kHz, lateral conductor spacing, 200 mils, other parameters given for Table II
2. All inductance and quality factors in Table III are apparent values (i.e., the effect of loop capacitance and resistance is included)

Table V. Circular Loop Parameters

	1 Turn		2 Turn		3 Turn		4 Turn		5 Turn	
Wire Gauge (AWG)	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor	Inductance (µH)	Quality Factor
12	9.70	20.39	33.95	30.95	70.91	38.42	119.50	44.07	179.00	48.53
14	10.04	16.19	34.63	24.98	71.93	31.55	120.86	36.73	180.69	40.95
16	10.37	12.00	35.29	18.83	72.91	24.21	122.16	28.63	182.31	32.36
18	10.68	8.42	35.92	13.38	73.86	17.47	123.43	20.96	183.89	24.00

Note: 1. 20 kHz, Loop diameter: 7 feet, other parameters given for Table II
2. All inductance and quality factors in Table III are apparent values (i.e., the effect of loop capacitance and resistance is included)

Appendix I

Loop Ground Resistance Derivation

The complex impedance, Z_L, of the loop results from a complex permeability, μg, and is:

$$ZL = j\,\omega\mu g L_L \qquad \text{(I-1)}$$

$$= j\,\omega(\mu g' - j\,\mu g'')L_L \qquad \text{(I-2)}$$

The material loss tangent, $\tan \delta g$, is:

$$\tan \delta g = \frac{\mu'' g}{\mu g} \qquad \text{(I-3)}$$

Letting $\mu g' = 1$

the loss tangent is

$$\tan \delta g = \mu g''$$

Then

$$Z_L = j\,\omega(1 - j\tan \delta g)L_L \qquad \text{(I-5)}$$

$$Z_L = \omega \tan \delta g L_L + j\,\omega L_L \qquad \text{(I-6)}$$

$$Z_L = Rg + j\,X_L \qquad \text{(I-7)}$$

$$Rg = \tan \delta g\, \omega L_L \qquad \text{(I-8)}$$

Appendix II

Real Part of complex Bessel Function of First Kind

$$\text{ber } x = 1 - \frac{\left(\frac{1}{2}x\right)^4}{(2!)^2} + \frac{\left(\frac{1}{2}x\right)^8}{(4!)^2} - \ldots\ldots$$

$$\text{ber } x = 1 + \sum_{n=1}^{\infty} (-1)^n \frac{\left(\frac{1}{2}x\right)^{4n}}{(2n!)^2} \qquad \text{(II-1)}$$

Derivative of Real Part

$$\text{ber}'x = -\frac{\left(\frac{1}{2}x\right)^3}{1!\,2!} + \frac{\left(\frac{1}{2}x\right)^7}{3!\,4!} - \frac{\left(\frac{1}{2}x\right)^{11}}{5!\,6!} + \ldots\ldots$$

$$\text{ber}'x = \sum_{n=1}^{\infty} (-1)^n \frac{\left(\frac{1}{2}x\right)^{(4n-1)}}{(2n-1)!\,2n!} \qquad \text{(II-2)}$$

Imaginary Part of complex Bessel Function of First Kind

$$\text{bei } x = \frac{\left(\frac{1}{2}x\right)^2}{(1!)^2} - \frac{\left(\frac{1}{2}x\right)^6}{(3!)^2} + \frac{\left(\frac{1}{2}x\right)^{10}}{(5!)^2} - \ldots..$$

$$\text{bei } x = \sum_{n=1}^{\infty} -(-1)^n \frac{\left(\frac{1}{2}x\right)^{(4n-2)}}{\left[(2n-1)!\right]^2} \quad \text{(II-3)}$$

Derivative of Imaginary Part

$$\text{bei}'x = \frac{1}{2}x - \frac{\left(\frac{1}{2}x\right)^5}{2!3!} + \frac{\left(\frac{1}{2}x\right)^9}{4!5!} - \ldots... \quad \text{(II-4)}$$

$$\text{bei}'x = \sum_{n=1}^{\infty} -(-1)^n \frac{\left(\frac{1}{2}x\right)^{(4n-3)}}{(2n-2)!\,(2n-1)!}$$

Appendix III

Complete Elliptic Integral of First kind

$$K(k) = \frac{\pi}{2} \prod_{m=o}^{\infty} (1 + k_{m+1}) \quad \text{(III-1)}$$

$$k_{m+1} = (1 - k_{m'})/(1 + k_{m'}) \quad \text{(III-2)}$$

$$k_{m'} = \sqrt{1 - k_m^2} \quad \text{(III-3)}$$

$$k_o \equiv k \quad \text{(III-4)}$$

Complete Elliptic Integral of Second Kind

$$E(u) = \frac{\pi}{2(1-u)} \left[1 + \frac{u^2}{2^2} + \frac{1^2}{2^2 \cdot 4^2} u^4 + \frac{1^2 \cdot 3^2}{2^2 \cdot 4^2 \cdot 6^2} u^6 + \ldots.. \right]$$

$$E(u) = \frac{\pi}{2(1-u)} \left[1 + \sum_{N=1}^{\infty} \left[\frac{(2N-3)!!}{2N!!} \right]^2 u^{2N} \right] \quad \text{(III-5)}$$

$$u = (1 - k')/(1/k') \quad \text{(III-6)}$$

$$k' = \sqrt{1-m} \quad \text{(III-7)}$$

$$M = k^2 \quad \text{(III-8)}$$

Note: $2N!! \equiv 2^n N!$ (III-9)

Appendix IV

Series to Parallel Circuit Transformation

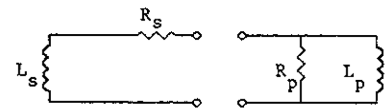


FIGURE IV-1. SERIES/PARALLEL CIRCUIT EQUIVALENCY

From Figure IV-1

$$Zin = Rg + j\omega L_S \text{ and } Yin = \frac{1}{R_p} - j\frac{1}{\omega L_p}$$

Setting (IV-1)

$$\frac{1}{Zin} = Yin \quad \text{(IV-2)}$$

$$R_p = \frac{R_s^2 + \omega^2 L_s^2}{R_s} \quad \text{(IV-3)}$$

$$L_p = \frac{R_s^2 + \omega^2 L_s^2}{\omega^2 L_s} \quad \text{(IV-4)}$$

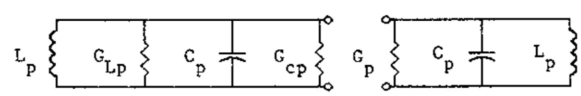


FIGURE IV-2. LOOP SERIES/PARALLEL CIRCUIT EQUIVALENCY.

From Figure IV-2

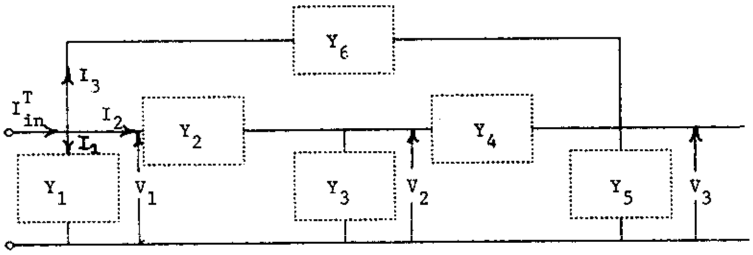
$$Gp = GLp + Gcp \quad \text{(IV-5)}$$

$$Y_{in}^L = Gp + j\left(\omega Cp - \frac{1}{\omega Lp}\right) \quad \text{(IV-6)}$$

$$Z_{in}^L = \frac{1}{Y_{in}} \quad \text{(IV-7)}$$

Appendix V

Transformer Model Input impedance



$$\begin{bmatrix}1\\0\\0\end{bmatrix} = \begin{bmatrix} Y_1+Y_2+Y_6 & -Y_2 & -Y_6 \\ -Y_2 & Y_2+Y_3+Y_4 & -Y_4 \\ -Y_6 & -Y_4 & Y_4+Y_5+Y_6 \end{bmatrix}\begin{bmatrix}V_1\\V_2\\V_3\end{bmatrix} \tag{V-1}$$

$$I_{in}^T = I_1 + I_2 + I_3 \tag{V-2}$$

$$I_{in}^T = Y_1V_1 + Y_6(V_1 - V_3) + Y_2(V_1 - V_2) \tag{V-3}$$

$$Z_{in}^T = \frac{V_1}{Iin} = \frac{1}{Y_1+Y_6\left(1-\frac{V_3}{V_1}\right)+Y_2\left(1-\frac{V_2}{V_1}\right)} \tag{V-4}$$

$$\begin{bmatrix}V_1\\V_2\\V_3\end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix}^{-1}\begin{bmatrix}1\\0\\0\end{bmatrix} = \begin{bmatrix} Y_{11}' & Y_{12}' & Y_{13}' \\ Y_{21}' & Y_{22}' & Y_{23}' \\ Y_{31}' & Y_{32}' & Y_{33}' \end{bmatrix} = \begin{bmatrix}1\\0\\0\end{bmatrix}$$

$$V_1 = Y_{11}' = \frac{V_{22}Y_{33} - Y_{23}Y_{32}}{|Y|}$$

$$V_2 = Y_{21}' = \frac{-(Y_{21}Y_{33} - Y_{23}Y_{31}}{|Y|}$$

$$V_3 = Y_{31}' = \frac{Y_{21}Y_{32} - Y_{22}Y_{31}}{|Y|}$$

where

$$Y_{21} = -Y_2$$
$$Y_{22} = Y_2 + Y_3 + Y_4$$
$$Y_{23} = -Y_4$$
$$Y_{31} = -Y_6$$
$$Y_{32} = -Y_4$$
$$Y_{33} = Y_4 + Y_5 + Y_6$$

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APPENDIX B.

CURRENT SHEET FORMULA FOR CALCULATION OF LOOP INDUCTANCE

A general inductance formula using a rectangular current sheet was cited by Mills in Ref. B-1. The primary formula for inductance (L (in μh)) is as follows:

$$L = 0.004\ \pi\ N^2 \left(\frac{a\, a_1}{b}\right) - F^1 \tag{B-1}$$

where:

$$F^1 = \beta_1 \gamma + \beta_1{}^1 \gamma \ \ln\left(\frac{1}{\gamma}\right) + \beta_2 \gamma^2 + \beta_3 \gamma^3 - \beta_5 \gamma^5 + \ldots \tag{B-2}$$

and:

$$\gamma = \left(\frac{b}{a}\right) = \left(\frac{\text{length of current sheet}}{\text{longer side of rectangle}}\right) \tag{B-3}$$

The term "length of current sheet" means the axial length of a coil or solenoid. For a detection loop, it is the height of the wires in the slot, as made clear in the example below. It is very small as compared to the "longer side of the rectangle", so γ is very small. The factor F^1 adjusts for the fact that detector loops are very short solenoids.

Also:

$$K = \left(\frac{a_1}{a}\right) \tag{B-4}$$

The values of β are obtained from Table B-1 below.

Table B-1. Niwa's coefficients for short rectangular solenoids (Ref. B-2).

K	β_1	$\beta_1{}^1$	β_2	β_3	β_5	β_7
1.00	0.4622	0.6366	0.2122	-0.0046	0.0046	-0.0382
0.95	0.4574	0.6534	0.2234	-0.0046	0.0053	
0.90	0.4512	0.6720	0.2358	-0.0046	0.0064	-0.0525
0.85	0.4448	0.6928	0.2496	-0.0042	0.0080	
0.80	0.4364	0.7162	0.2653	-0.0031	0.0103	-0.0831
0.75	0.4260	0.7427	0.2829	-0.0010	0.0141	
0.70	0.4132	0.7730	0.3032	0.0026	0.0198	-0.1564
0.65	0.3971	0.8080	0.3265	0.0085	0.0291	
0.60	0.3767	0.8488	0.3537	0.0179	0.0432	-0.3372
0.55	0.3500	0.8970	0.3858	0.0331	0.0711	
0.50	0.3151	0.9549	0.4244	0.0578	0.1183	-0.7855
0.40	0.1836	1.1141	0.5305	0.1697	0.3898	-2.403
0.30	-0.0314	1.3359	0.7074	0.5433	2.0517	-7.85
0.20	-0.6409	1.9099	1.0610	2.3230	14.507	15.51
0.10	-3.2309	3.5014	2.1220	22.548	497.36	14280

An example (from Ref. B-1) is shown of the next page for the calculation of the self inductance for a three-turn, 6 x 6 foot (1.8 x 1.8 m) loop using the current-sheet formula described above.

SAMPLE CALCULATION

Calculation of the self inductance of a three-turn, six-foot by six-foot (1.8 m by 1.8 m) loop using the current-sheet formula (Equation B-1).

a_1 = 6 feet = 183 cm

a = 6 feet = 183 cm

N = 3 turns

P = turn spacing = 150 mils = 0.38 cm

b = N x P = (3) x (0.38) = 1.14 cm

$$\gamma = \left(\frac{b}{a}\right) = \left(\frac{1.14}{183}\right) = 0.0062$$

$$K = \left(\frac{a_1}{a}\right) = 1$$

From Table B-1:

β_1 = 0.4622

$\beta_1{}^1$ = 0.6366

β_2 = 0.2122

β_3 = 0.0046

β_5 = 0.0046

β_7 = 0.0382

Solving Equation B-2 yields:

$$\ln\left(\frac{1}{\gamma}\right) = 5.0754$$

$$F^1 = \beta_1 \gamma + \beta_1{}^1 \gamma \ \ln\left(\frac{1}{\gamma}\right) + \beta_2 \gamma^2 + \beta_3 \gamma^3 - \beta_5 \gamma^5 + \ldots \qquad \text{(B–2)}$$

$$F^1 = 0.0029 + 0.0200 + 8.16 \times 10^{6} = 0.0229$$

Using Equation B-1:

$$L = 0.004 \ \pi \ N^2 \left(\frac{a \ a_1}{b}\right) - F^1 \quad \text{(B-1)}$$

$$L = 0.004 \ \pi \ (3)^2 \left(\frac{(193)\ (193)}{1.14}\right) - (0.0229) = 75.8 \ \mu h$$

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 1 kHz

Apparent Rectangular Loop Inductance

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	10.53	36.02	74.46	124.67	185.81	257.24	338.44
7	11.52	39.49	81.72	136.94	204.23	282.91	372.40
8	12.51	42.94	88.94	149.12	222.52	308.38	406.08
9	13.50	46.38	96.12	161.25	240.71	333.71	439.58
10	14.48	49.80	103.28	173.32	258.83	358.94	472.94
11	15.46	53.22	110.42	185.37	276.90	384.09	506.20
12	16.44	56.63	117.54	197.39	294.93	409.19	539.38
13	17.42	60.04	124.65	209.39	312.93	434.25	572.51
14	18.40	63.44	131.76	221.38	330.91	459.27	605.59
15	19.37	66.84	138.85	233.35	348.87	484.27	638.63
16	20.35	70.23	145.95	245.32	366.81	509.24	671.64
17	21.32	73.63	153.03	257.27	384.74	534.09	704.63
18	22.30	77.02	160.12	269.22	402.66	559.13	737.59
19	23.27	80.41	167.20	281.16	420.57	584.06	770.54
20	24.25	83.80	174.27	293.10	438.47	608.97	803.47
25	29.12	100.74	209.63	352.73	527.89	733.42	967.96
30	33.98	117.66	244.95	412.31	617.22	857.75	1132.29
35	38.84	134.57	280.25	471.85	706.51	982.00	1296.52
40	43.71	151.48	315.55	531.38	795.76	1106.21	1460.70
45	48.57	168.38	350.83	590.89	885.00	1230.40	1624.85
50	53.43	185.28	386.11	650.39	974.22	1354.56	1788.98

Apparent Rectangular Loop Quality Factor

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	1.07	1.81	2.48	3.09	3.67	4.21	4.72
7	1.08	1.83	2.51	3.14	3.72	4.27	4.79
8	1.09	1.85	2.54	3.17	3.76	4.32	4.85
9	1.09	1.87	2.56	3.20	3.80	4.36	4.90
10	1.10	1.88	2.58	3.22	3.83	4.40	4.94
11	1.11	1.89	2.59	3.24	3.85	4.43	4.97
12	1.11	1.90	2.61	3.26	3.87	4.45	5.00
13	1.11	1.91	2.62	3.28	3.89	4.47	5.03
14	1.12	1.91	2.63	3.29	3.91	4.49	5.05
15	1.12	1.92	2.64	3.30	3.92	4.51	5.07
16	1.12	1.92	2.65	3.31	3.94	4.53	5.09
17	1.13	1.93	2.65	3.32	3.95	4.54	5.11
18	1.13	1.93	2.66	3.33	3.96	4.56	5.12
19	1.13	1.94	2.67	3.34	3.97	4.57	5.14
20	1.13	1.94	2.67	3.35	3.98	4.58	5.15
25	1.14	1.96	2.70	3.38	4.02	4.62	5.20
30	1.15	1.97	2.71	3.40	4.05	4.66	5.23
35	1.15	1.98	2.73	3.42	4.07	4.68	5.26
40	1.15	1.98	2.73	3.43	4.08	4.70	5.28
45	1.16	1.99	2.74	3.44	4.09	4.71	5.30
50	1.16	1.99	2.75	3.45	4.10	4.72	5.31

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 20 kHz

Apparent Rectangular Loop Inductance							
Length, feet	Number of Loop Turns						
	1	2	3	4	5	6	7
6	10.50	35.96	74.39	124.62	185.85	257.48	339.07
7	11.49	39.43	81.65	136.90	204.32	283.27	373.23
8	12.48	42.88	88.87	149.10	222.66	308.88	407.26
9	13.46	46.31	96.05	161.24	240.92	334.37	441.10
10	14.44	49.73	103.21	173.34	259.12	359.80	474.86
11	15.42	53.15	110.35	185.42	277.28	385.17	508.58
12	16.40	56.56	117.48	197.47	295.41	410.53	542.29
13	17.37	59.96	124.60	209.51	313.54	435.87	576.01
14	18.35	63.36	131.71	221.54	331.65	461.22	609.76
15	19.32	66.75	138.82	233.57	349.76	486.58	643.54
16	20.30	70.15	145.92	245.59	367.87	511.95	677.38
17	21.27	73.54	153.02	257.61	385.99	537.35	711.28
18	22.24	76.93	160.12	269.62	404.11	562.78	745.24
19	23.21	80.32	167.21	281.65	422.25	588.24	779.28
20	24.19	83.71	174.31	293.67	440.40	613.73	813.41
25	29.04	100.65	209.79	353.85	531.41	741.89	985.51
30	33.90	117.58	245.31	414.22	622.99	871.46	1160.59
35	38.75	134.52	280.89	474.83	715.29	1002.77	1339.33
40	43.60	151.47	316.54	535.75	808.46	1136.14	1522.43
45	48.45	168.43	352.28	597.01	902.63	1271.89	1710.61
50	53.30	185.41	388.13	658.67	997.93	1410.37	1904.64

Apparent Rectangular Loop Quality Factor							
Length, feet	Number of Loop Turns						
	1	2	3	4	5	6	7
6	15.61	24.06	30.40	35.41	39.51	42.95	45.87
7	15.75	24.28	30.67	35.73	39.85	43.30	46.24
8	15.86	24.46	30.90	35.98	40.12	43.59	46.52
9	15.95	24.61	31.08	36.18	40.35	43.81	46.75
10	16.03	24.73	31.23	36.36	40.53	44.00	46.93
11	16.10	24.84	31.36	36.50	40.68	44.16	47.08
12	16.15	24.93	31.48	36.63	40.82	44.29	47.21
13	16.20	25.01	31.58	36.74	40.93	44.40	47.31
14	16.25	25.08	31.66	36.83	41.03	44.49	47.39
15	16.29	25.14	31.74	36.92	41.11	44.57	47.46
16	16.32	25.20	31.81	36.99	41.18	44.64	47.51
17	16.36	25.25	31.87	37.06	41.25	44.69	47.55
18	16.39	25.30	31.93	37.12	41.30	44.74	47.59
19	16.41	25.34	31.98	37.17	41.35	44.78	47.61
20	16.44	25.38	32.02	37.22	41.39	44.81	47.62
25	16.54	25.53	32.20	37.39	41.53	44.88	47.59
30	16.60	25.63	32.31	37.48	41.58	44.85	47.44
35	16.65	25.71	32.38	37.53	41.57	44.74	47.18
40	16.69	25.76	32.43	37.54	41.51	44.57	46.84
45	16.72	25.80	32.46	37.53	41.42	44.34	46.43
50	16.75	25.83	32.47	37.49	41.29	44.07	45.95

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 40 kHz

Apparent Rectangular Loop Inductance

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	10.44	35.86	74.28	124.61	186.13	258.43	341.24
7	11.43	39.33	81.55	136.94	204.76	284.58	376.22
8	12.41	42.77	88.78	149.19	223.28	310.63	411.12
9	13.39	46.20	95.97	161.40	241.75	336.65	446.04
10	14.37	49.62	103.14	173.59	260.21	362.21	481.07
11	15.34	53.03	110.30	185.76	278.66	388.76	516.24
12	16.32	56.43	117.45	197.92	297.14	414.92	551.61
13	17.29	59.83	124.60	210.09	315.64	441.17	587.21
14	18.26	63.23	131.74	222.27	334.18	467.54	623.08
15	19.23	66.62	138.88	234.46	352.77	494.04	659.24
16	20.20	70.02	146.03	246.66	371.42	520.68	695.72
17	21.17	73.41	153.18	258.89	390.13	547.49	732.56
18	22.14	76.81	160.33	271.13	408.91	574.47	769.77
19	23.11	80.20	167.48	283.40	427.76	601.63	807.38
20	24.07	83.59	174.64	295.69	446.70	628.99	845.42
25	28.91	100.57	210.56	357.63	542.74	769.19	1043.04
30	33.75	117.57	246.71	420.50	641.54	916.19	1255.80
35	38.58	134.62	283.16	484.52	743.73	1071.72	1488.10
40	43.42	151.72	319.96	549.90	849.98	1237.75	1745.46
45	48.25	168.88	357.16	616.85	961.04	1416.63	2035.03
50	53.09	186.12	394.82	685.62	1077.75	1611.21	2366.36

Apparent Rectangular Loop Quality Factor

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	22.45	33.19	40.64	46.18	50.48	53.89	56.63
7	22.63	33.46	40.95	46.51	50.80	54.19	56.89
8	22.78	33.67	41.19	46.76	51.05	54.41	57.07
9	22.90	33.85	41.39	46.97	51.24	54.57	57.18
10	23.01	33.99	41.56	47.13	51.38	54.68	57.24
11	23.09	34.12	41.70	47.27	51.50	53.76	57.26
12	23.17	34.23	41.82	47.38	51.59	54.80	57.24
13	23.24	34.32	41.92	47.47	51.65	54.82	57.19
14	23.30	34.41	42.01	47.55	51.70	54.82	57.12
15	23.35	34.48	42.08	47.61	51.73	54.80	57.02
16	23.39	34.54	42.15	47.66	51.75	54.76	56.90
17	23.44	34.60	42.21	47.70	51.75	54.71	56.77
18	23.48	34.65	42.25	47.73	51.74	54.64	56.61
19	23.51	34.70	42.30	47.75	51.72	54.56	56.44
20	23.54	34.74	42.33	47.76	51.69	54.46	56.25
25	23.67	34.90	42.45	47.75	51.44	53.83	55.08
30	23.76	35.00	42.48	47.61	51.01	52.96	53.59
35	23.82	35.05	42.45	47.39	50.46	51.89	51.80
40	23.87	35.09	42.28	47.10	49.78	50.64	49.74
45	23.91	35.10	42.27	46.74	49.00	49.21	47.41
50	23.94	35.09	42.14	46.33	48.11	47.61	44.82

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 60 kHz

Apparent Rectangular Loop Inductance							
Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	10.40	35.79	74.25	124.77	186.85	260.30	345.26
7	11.38	39.25	81.53	137.19	205.75	287.11	381.59
8	12.36	42.69	88.78	149.56	224.60	313.94	418.12
9	13.34	46.12	96.00	161.90	243.46	340.88	454.97
10	14.31	49.54	103.21	174.24	262.36	367.98	`492.24
11	15.28	52.95	110.41	186.59	281.34	395.31	530.03
12	16.25	56.36	117.61	198.96	300.41	422.89	568.41
13	17.22	59.76	124.81	211.37	319.59	450.76	607.46
14	18.19	63.16	132.02	223.81	338.89	478.96	647.24
15	19.16	66.57	139.24	236.29	358.34	507.52	687.83
16	20.12	69.97	146.47	248.83	377.94	536.47	729.31
17	21.09	73.37	153.70	261.41	397.71	565.85	771.74
18	22.05	76.78	160.96	274.06	417.66	595.69	815.22
19	23.02	80.18	168.23	286.77	437.80	626.02	859.83
20	23.98	83.59	175.51	299.55	458.15	656.87	905.65
25	28.81	100.67	212.62	364.62	563.43	820.32	1156.67
30	33.63	117.83	249.52	432.01	675.89	1003.04	1456.51
35	38.45	135.10	287.53	502.29	797.51	1211.88	1828.33
40	43.28	152.49	326.39	576.05	930.74	1456.41	2312.27
45	48.11	170.04	366.24	653.98	1078.66	1750.56	2979.87
50	52.95	187.75	407.21	736.88	1245.26	2115.67	3977.12

Apparent Rectangular Loop Quality Factor							
Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	26.56	38.32	46.10	51.65	55.77	58.86	61.17
7	26.77	38.60	46.40	51.94	56.02	59.04	61.24
8	26.93	38.82	46.64	52.16	56.19	59.13	61.21
9	27.07	39.01	46.83	52.33	56.30	59.15	61.10
10	27.18	39.16	46.98	52.46	56.37	59.12	60.93
11	27.28	39.29	47.11	52.55	56.39	59.04	60.71
12	27.37	39.40	47.21	52.61	56.39	58.93	60.44
13	27.44	39.49	47.30	52.66	56.36	58.78	60.12
14	27.51	39.58	47.37	52.68	56.30	58.60	59.77
15	27.56	39.65	47.42	52.69	56.22	58.39	59.37
16	27.62	39.71	47.46	52.68	56.12	58.15	58.94
17	27.66	39.76	47.50	52.66	56.01	57.89	58.48
18	27.71	39.81	47.52	52.63	55.88	57.61	57.99
19	27.74	39.85	47.54	52.59	55.73	57.30	57.46
20	27.78	39.89	47.55	52.53	55.57	56.98	56.91
25	27.92	40.01	47.51	52.14	54.56	55.05	53.70
30	28.01	40.06	47.36	51.56	53.26	52.67	49.83
35	28.08	40.07	47.12	50.82	51.69	49.87	45.34
40	28.13	40.03	46.81	49.95	49.88	46.68	40.25
45	28.16	39.97	46.43	48.94	47.84	43.10	34.59
50	28.19	39.87	45.99	47.81	45.56	39.15	28.35

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 1 kHz

Apparent Quadrupole Loop Inductance

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	17.73	61.33	127.13	212.86	316.90	438.00	575.12
7	20.06	69.53	144.29	241.80	360.23	498.17	654.45
8	22.38	77.72	161.44	270.73	403.55	558.32	733.75
9	24.70	85.91	178.59	299.65	446.85	618.46	813.03
10	27.02	94.09	195.74	328.57	490.15	678.59	892.31
11	29.34	102.28	212.88	357.49	533.45	738.71	971.58
12	31.67	110.47	230.03	386.41	576.75	798.84	1050.85
13	33.99	118.65	247.18	415.33	620.05	858.96	1130.11
14	36.31	126.84	264.32	444.24	663.34	919.08	1209.38
15	38.63	135.03	281.47	473.16	706.64	979.20	1288.65
16	40.95	143.21	298.61	502.08	749.93	1039.33	1367.91
17	43.27	151.40	315.76	530.99	793.23	1099.45	1447.18
18	45.60	159.59	332.91	559.91	836.52	1159.57	1526.45
19	47.92	167.77	350.05	588.83	879.82	1219.70	1605.73
20	50.24	175.96	367.20	617.74	923.12	1279.82	1685.00
25	61.85	216.89	452.92	762.33	1139.61	1580.47	2081.42
30	73.45	257.83	538.65	906.92	1356.11	1881.15	2477.90
35	85.06	298.76	624.38	1051.52	1572.63	2181.88	2874.48
40	96.67	339.69	710.11	1196.12	1789.18	2482.66	3271.16
45	108.28	380.63	795.85	1340.73	2005.75	2783.49	3667.95
50	119.89	421.56	881.59	1485.36	2222.35	3084.39	4064.88

Apparent Quadrupole Loop Quality Factor

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	1.20	2.06	2.82	3.52	4.16	4.77	5.33
7	1.22	2.10	2.88	3.59	4.25	4.87	5.45
8	1.24	2.13	2.93	3.66	4.33	4.96	5.55
9	1.25	2.16	2.97	3.71	4.39	5.03	5.63
10	1.26	2.18	3.00	3.75	4.44	5.09	5.70
11	1.28	2.20	3.03	3.79	4.49	5.14	5.76
12	1.28	2.22	3.05	3.82	4.52	5.19	5.81
13	1.29	2.23	3.07	3.84	4.56	5.22	5.85
14	1.30	2.25	3.09	3.87	4.59	5.26	5.89
15	1.30	2.26	3.11	3.89	4.61	5.29	5.93
16	1.31	2.27	3.13	3.91	4.46	5.32	5.96
17	1.31	2.28	3.14	3.93	4.66	5.34	5.98
18	1.32	2.29	3.15	3.94	4.68	5.36	6.01
19	1.32	2.29	3.16	3.96	4.69	5.38	6.03
20	1.33	2.30	3.17	3.97	4.71	5.40	6.05
25	1.34	2.33	3.21	4.02	4.77	5.47	6.13
30	1.35	2.35	3.24	4.06	4.81	5.52	6.19
35	1.36	2.36	3.26	4.08	4.84	5.56	6.23
40	1.36	2.37	3.28	4.10	4.87	5.59	6.26
45	1.37	2.38	3.29	4.12	4.89	5.61	6.29
50	1.37	2.39	3.30	4.13	4.90	5.63	6.31

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 20 kHz

Apparent Quadrupole Loop Inductance

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	17.69	61.26	127.08	212.98	317.49	439.56	578.46
7	20.01	69.45	144.26	242.03	361.15	500.51	659.37
8	22.32	77.64	161.44	271.10	404.88	561.64	740.66
9	24.64	85.82	178.63	300.21	448.71	622.98	822.40
10	26.96	94.01	195.83	329.35	492.64	684.58	904.66
11	29.28	102.20	213.05	358.53	536.70	746.45	987.48
12	31.59	110.40	230.27	387.77	580.88	808.63	1070.92
13	33.91	118.59	247.51	417.05	625.20	871.14	1155.04
14	36.23	126.79	264.76	446.39	669.68	934.00	1239.90
15	38.55	134.99	282.03	475.79	714.33	997.25	1325.55
16	40.86	143.19	299.32	505.25	759.15	1060.91	1412.05
17	43.18	151.40	316.62	534.78	804.16	1125.01	1499.47
18	45.50	159.61	333.95	564.38	849.37	1189.58	1587.86
19	47.82	167.82	351.29	594.05	894.79	1254.64	1677.30
20	50.14	176.03	368.66	623.81	940.43	1320.24	1767.86
25	61.73	217.17	455.85	773.93	1172.42	1657.20	2239.86
30	73.32	258.42	543.75	926.67	1411.89	2012.31	2751.56
35	84.92	299.81	632.50	1082.59	1660.59	2390.42	3315.54
40	96.53	341.36	722.23	1242.29	1920.49	2797.33	3948.06
45	108.14	383.08	813.10	1406.39	2193.80	3240.10	4670.95
50	119.75	425.01	905.26	1575.59	2483.09	3727.59	5514.46

Apparent Quadrupole Loop Quality Factor

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	17.26	26.53	33.28	38.48	42.64	46.05	48.87
7	17.51	26.91	33.74	38.98	43.16	46.56	49.37
8	17.71	27.22	34.10	39.38	43.57	46.96	49.73
9	17.88	27.47	34.40	39.70	43.89	47.26	50.00
10	18.02	27.69	34.65	39.97	44.15	47.50	50.20
11	18.14	27.87	34.87	40.18	44.36	47.68	50.33
12	18.25	28.02	35.04	40.37	44.52	47.81	50.42
13	18.34	28.16	35.20	40.52	44.66	47.91	50.46
14	18.42	28.28	35.33	40.65	44.77	47.98	50.47
15	18.49	28.38	35.45	40.76	44.85	48.02	50.44
16	18.55	28.47	35.55	40.85	44.92	48.04	50.39
17	18.61	28.55	35.63	40.93	44.96	48.03	50.31
18	18.66	28.63	35.71	40.99	45.00	48.01	50.21
19	18.71	28.69	35.78	41.04	45.01	47.97	50.08
20	18.75	28.75	35.84	41.09	45.02	47.92	49.94
25	18.91	28.98	36.04	41.18	44.89	47.44	48.95
30	19.03	29.12	36.14	41.12	44.56	46.68	47.58
35	19.11	29.21	36.15	40.96	44.07	45.68	45.88
40	19.17	29.27	36.12	40.71	43.44	44.48	43.86
45	19.22	29.30	36.04	40.38	42.69	43.08	41.56
50	19.26	29.31	35.92	39.99	41.82	41.49	38.97

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 40 kHz

Apparent Quadrupole Loop Inductance

Length, feet	Number of Loop Turns						
	1	2	3	4	5	6	7
6	17.61	61.14	127.09	213.56	319.54	444.65	589.12
7	19.92	69.33	144.35	242.97	364.23	508.03	675.03
8	22.23	77.52	161.64	272.50	409.28	572.25	762.72
9	24.54	85.72	178.97	302.18	454.75	637.45	852.47
10	26.85	93.92	196.35	332.02	500.67	703.75	944.54
11	29.16	102.14	213.77	362.04	547.11	771.28	1039.25
12	31.47	110.36	231.25	392.26	594.11	840.17	1136.92
13	33.78	118.59	248.78	422.70	641.74	910.56	1237.90
14	36.09	126.83	266.38	453.37	690.03	982.62	1342.58
15	38.40	135.08	284.04	484.29	739.06	1056.49	1451.40
16	40.71	143.34	301.78	515.49	788.88	1132.37	1564.81
17	43.02	151.61	319.59	546.97	839.56	1210.42	1683.35
18	45.33	159.90	337.48	578.76	891.16	1290.86	1807.62
19	47.64	168.20	355.46	610.89	943.75	1373.91	1938.27
20	49.96	176.51	373.53	643.36	997.41	1459.80	2076.06
25	62.53	218.33	465.40	811.78	1284.60	1942.02	2907.06
30	73.11	260.61	560.30	992.54	1612.56	2548.33	4123.51
35	84.72	303.46	658.95	1189.34	1998.78	3357.78	6162.33
40	96.40	346.97	762.14	1406.81	2466.77	4524.99	10461.3
45	107.99	391.24	870.79	1650.98	3058.41	6402.00	26153.2
50	119.66	436.39	985.93	1929.88	3841.27	10005.70	68070.5

Length, feet	Number of Loop Turns						
	1	2	3	4	5	6	7
6	24.62	36.14	43.82	49.33	53.42	56.48	58.74
7	24.95	36.58	44.31	49.79	53.81	56.76	58.85
8	25.21	36.94	44.68	50.14	54.08	56.89	58.80
9	25.43	37.23	44.98	50.40	54.24	56.91	58.61
10	25.61	37.47	45.22	50.58	54.33	56.83	58.31
11	25.77	37.67	45.41	50.72	54.34	56.68	57.90
12	25.90	37.84	45.57	50.80	54.31	56.45	57.41
13	26.02	37.99	45.69	50.85	54.22	56.16	56.84
14	26.12	38.11	45.78	50.86	54.09	55.81	56.18
15	26.21	38.22	45.86	50.85	53.93	55.41	55.46
16	26.29	38.31	45.91	50.81	53.72	54.96	54.67
17	26.36	38.39	45.95	50.75	53.49	54.47	53.82
18	26.42	38.46	45.97	50.66	53.22	53.93	52.90
19	26.48	38.52	45.98	50.56	52.92	53.34	51.92
20	26.54	38.57	45.98	50.44	52.60	52.72	50.88
25	26.74	38.72	45.81	49.59	50.61	49.02	44.85
30	26.88	38.75	45.44	48.40	48.04	44.43	37.50
35	26.97	38.70	44.91	46.91	44.96	39.01	28.93
40	27.04	38.59	44.25	45.14	41.38	32.80	19.22
45	27.08	38.43	43.46	43.11	37.11	25.85	8.45
50	27.11	38.22	42.55	40.83	32.83	18.19	-3.31

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 60 kHz

Apparent Quadrupole Loop Inductance

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	17.55	61.08	127,31	214.81	323.36	453.84	698.32
7	19.85	69.28	144.73	244.86	369.89	521.58	703.48
8	22.15	77.50	162.23	275.21	417.28	591.44	803.28
9	24.46	85.73	179.82	305.90	465.67	663.76	908.57
10	26.76	93.97	197.52	336.98	515.20	738.91	1020.35
11	29.06	102.23	215.32	368.49	566.00	817.32	1139.78
12	31.37	110.52	233.25	400.48	618.23	899.44	1268.22
13	33.68	118.82	251.32	432.99	672.04	985.81	1407.32
14	35.98	127.15	269.53	466.07	727.63	1077.63	1559.08
15	38.29	135.50	287.90	499.78	785.18	1173.78	1725.94
16	40.60	143.88	306.43	534.17	844.91	1276.87	1910.97
17	42.90	152.28	325.15	569.29	907.05	1387.23	2118.05
18	45.21	160.72	344.06	605.20	971.87	1505.96	2352.17
19	47.53	169.18	363.18	641.98	1039.65	1634.37	2619.87
20	49.84	177.68	382.51	679.68	1110.73	1774.02	2929.90
25	61.41	220.74	482.97	884.97	1530.25	2725.24	5781.94
30	73.02	264.88	591.16	1127.49	2116.11	4590.35	24158.9
35	84.67	310.38	709.46	1425.35	3027.21	10214.52	-14095.7
40	96.36	357.47	840.85	1808.24	4699.56	-77203.2	-5948.3
45	108.11	406.48	989.27	2329.10	8926.13	-10112.4	-3900.7
50	119.91	457.72	1160.02	3093.03	40376.3	-5506.1	-2956.9

Apparent Quadrupole Loop Quality Factor

Length, feet	Number of Loop Turns 1	2	3	4	5	6	7
6	28.99	41.41	49.24	54.51	58.09	60.40	61.66
7	29.35	41.87	49.68	54.85	58.23	60.25	61.11
8	29.64	42.23	50.00	55.05	58.22	59.91	60.32
9	29.88	42.52	50.24	55.15	58.08	59.41	59.32
10	30.08	42.75	50.42	55.17	57.83	58.77	58.14
11	30.25	42.94	50.53	55.12	57.50	58.01	56.79
12	3.40	43.09	50.61	55.01	57.08	57.13	55.28
13	30.52	43.22	50.64	54.84	56.58	56.14	53.62
14	30.63	43.32	50.65	54.63	56.02	55.05	51.82
15	30.73	43.40	50.62	54.38	55.38	55.39	49.88
16	30.82	43.47	50.57	54.09	54.69	52.59	47.81
17	30.89	43.52	50.49	53.76	53.94	51.22	45.61
18	30.96	43.56	50.40	53.39	53.14	49.77	43.28
19	31.03	43.58	50.28	53.00	52.27	48.23	40.83
20	31.08	43.60	50.15	52.57	51.36	46.61	36.26
25	31.29	43.54	49.24	49.97	46.02	37.30	23.69
30	31.42	43.32	47.99	46.69	39.49	26.15	6.52
35	31.50	42.97	46.42	42.78	31.85	13.30	-12.97
40	31.54	42.51	44.57	38.28	23.18	-1.11	-34.45
45	31.56	41.96	42.46	33.21	13.53	-16.91	-57.64
50	31.56	41.31	40.08	27.59	2.97	-33.96	-82.23

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 1 kHz

Apparent Circular Loop Inductance

Diameter, feet	Number of Loop Turns 1	2	3	4	5	6	7
4	5.32	18.10	37.28	62.23	92.52	127.80	167.79
5	6.87	23.49	48.53	81.21	120.99	167.44	220.21
6	8.45	29.02	60.12	100.80	150.42	208.47	274.51
7	10.07	34.68	71.99	120.91	180.66	250.65	330.38
8	11.71	40.46	84.12	141.46	211.58	293.82	387.60

Apparent Circular Loop Quality Factor

Diameter, feet	Number of Loop Turns 1	2	3	4	5	6	7
4	1.03	1.74	2.37	2.95	3.49	4.00	4.48
5	1.06	1.81	2.47	3.08	3.65	4.19	4.69
6	1.09	1.86	2.55	3.18	3.78	4.34	4.87
7	1.11	1.90	2.61	3.27	3.88	4.46	5.01
8	1.13	1.94	2.67	3.34	3.98	4.57	5.14

Frequency = 20 kHz

Apparent Circular Loop Inductance

Diameter, feet	Number of Loop Turns 1	2	3	4	5	6	7
4	5.31	18.07	37.24	62.18	92.47	127.76	167.79
5	6.85	23.45	48.47	81.15	120.94	167.44	220.30
6	8.43	28.98	60.06	100.75	150.40	208.54	274.78
7	10.04	34.63	71.93	120.86	180.69	250.85	330.93
8	11.68	40.40	84.05	141.43	211.68	294.21	388.55

Apparent Circular Loop Quality Factor

Diameter, feet	Number of Loop Turns 1	2	3	4	5	6	7
4	15.16	23.32	29.46	34.34	38.35	41.72	44.61
5	15.57	23.99	30.31	35.32	39.42	42.86	45.79
6	15.90	24.53	30.99	36.09	40.26	43.75	46.72
7	16.19	24.98	31.55	36.73	40.95	44.47	47.46
8	16.43	25.37	32.03	37.26	41.53	45.07	48.07

LOOP INDUCTANCE AND QUALITY FACTOR TABLES

Frequency = 40 kHz

Apparent Circular Loop Inductance							
Diameter,	Number of Loop Turns						
feet	1	2	3	4	5	6	7
4	5.28	18,02	37.16	62,09	92.40	127.75	167.92
5	6.81	23.38	48.38	81.07	120.92	167.58	220.76
6	8.39	28.90	59.96	100.68	150.48	208.94	275.80
7	9.99	34.54	71.83	120.84	180.92	251.66	332.81
8	11.62	40.30	83.96	141.48	212.16	295.61	391.66

Apparent Circular Loop Quality Factor							
Diameter,	Number of Loop Turns						
feet	1	2	3	4	5	6	7
4	21.85	32.30	39.59	45.08	49.38	52.86	55.74
5	22.40	33.11	40.56	46.13	50.47	53.97	56.83
6	22.84	33.77	41.33	46.95	51.31	54.80	57.63
7	23.21	34.31	41.95	47.61	51.98	55.44	58.23
8	23.53	34.77	42.48	48.16	52.52	55.95	58.66

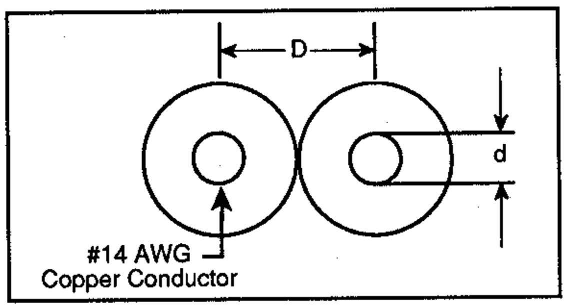
Frequency = 60 kHz

Apparent Circular Loop Inductance							
Diameter,	Number of Loop Turns						
feet	1	2	3	4	5	6	7
4	5.26	17.98	37.10	62.05	92.40	127.89	168.30
5	6.79	23.33	48.32	81.05	121.04	167.99	221.73
6	8.35	28.84	59.90	100.72	150.79	209.83	277.76
7	9.95	34.48	71.79	120.98	181.53	253.27	336.29
8	11.58	40.23	83.95	141.76	214.20	298.26	397.32

Apparent Circular Loop Quality Factor							
Diameter,	Number of Loop Turns						
feet	1	2	3	4	5	6	7
4	25.89	37.38	45.06	50.65	54.92	58.28	60.99
5	26.50	38.25	46.05	51.69	55.95	59.26	61.88
6	27.00	38.94	46.83	52.47	56.70	59.95	62.45
7	27.42	39.51	47.45	53.09	57.27	60.41	62.76
8	27.77	39.99	47.97	53.59	57.70	60.71	62.89

ELECTRICAL CHARACTERISTICS OF WIRE AND CABLE

Calculation of electrical characteristics of twisted lead-in wire composed of Belden # 14 AWG copper conductor wire.



Capacitance of parallel Conductors

$$C = \frac{\left(\frac{\epsilon}{\epsilon_o}\right) * 10^{-9}}{36 \cosh^{-1}\left(\frac{D}{d}\right)} \text{ Farads (F) / meter}$$

For Belden 9438

$$C = \frac{2.3 * 10^{-9}}{36 \cosh^{-1}\left(\frac{139 \text{ mils}}{64.1 \text{ mils}}\right)}$$

where:

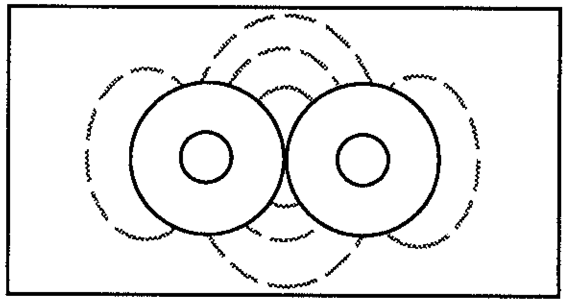
2.3 is dielective constant of polyethylene

$$C \cong \frac{2.3 * 10^{-9}}{36 \ln\left(\frac{139 \text{ mils}}{32.05 \text{ mils}}\right)}$$

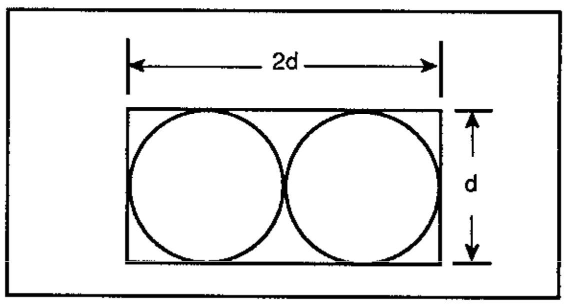
$$C = 4.355 * 10^{-11} \text{ Farads / meter}$$

$$C = 13.3 \text{ pF / ft}$$

Formula assumes all fields in dielectric. We have



Assume this geometry contains most fields



$$A_{cable} = \frac{\pi d^2}{4} + \frac{\pi d^2}{4} = \frac{\pi d^2}{2}$$

$$A_{rectangle} = (2d) * (d) = 2d^2$$

$$\text{Ratio of Areas} = \frac{\left(\frac{\pi d^2}{2}\right)}{2d^2} = \frac{\pi}{4} = 0.79$$

Then

$$C = (0.79) * (13.3 \text{ pF/ft}) = 10.45 \text{ pF/ft}$$

For 100 feet (30 m)

$$C = 1{,}045 \text{ pF}$$

Inductance of Parallel Conductors

$$L = 0.4 \ \ln\left(\frac{2D}{d}\right) + 2L_i \qquad \mu h/m$$

The internal inductance, L_i, of copper at 1 kHz is 0.05 Mh/m

$$L = 0.4 \ \ln\left(\frac{2D}{d}\right) + 0.1 \qquad \mu h/m$$

For Belden 9438

$$L = 0.4 \ \ln\left(\frac{2\,(139 \text{ mils})}{64.1 \text{ mils}}\right) + 0.1 \quad \mu h/m$$

$$L = 0.69 \ \mu h/m$$

$$L = 0.21 \ \mu h/ft$$

For 100 feet (30 m)

$$L = 21 \ \mu h$$

Table D-1

Measured Lead-In Cable Electrical Characteristics

14 AWG twisted pair lead-in cable

Frequency (kHz)	Open Circuit Measurements		Short Circuit Measurements	
	Capacitance (pF)	Conductance (µS)	Inductance (µh)	Resistance (Ω)
0.1	997	-0.0005	22.87	0.57
1.	999	-0.0082	22.95	0.57
5.	1000	-0.056	22.97	0.58
10.	1001	-0.14	22.91	0.60
15.	1002	-0.24	22.83	0.63
20.	1002	-0.36	22.72	0.67
25.	1002	-0.51	22.60	0.72
30.	1002	-0.67	22.47	0.77
35.2941	1003	-0.85	22.33	0.82
40.	1003	-1.02	22.21	0.87
45.4545	1003	-1.21	22.09	0.92
50.	1003	-1.40	21.99	0.97
54.5454	1003	-1.58	21.90	1.01
60.	1003	-1.77	21.80	1.06
66.6666	1003	-2.03	21.69	1.12
71.4286	1003	-2.26	21.62	1.16
75	1004	-2.43	21.57	1.19
80	1004	-2.67	21.51	1.24
85.714	1004	-2.95	21.44	1.28
96	1004	-3.46	21.33	1.37
100	1005	-3.79	21.29	1.40
120	1005	-4.74	21.12	1.56
125	1006	-5.02	21.09	1.59
150	1006	-6.52	20.93	1.78

Type: Twisted Wire Pair of Belden 9438 wire (not shielded)
Guage: # 14 AWG
Twists per Foot: 5.5
Pair Length: 100 feet (30 m)
Wire location: Laboratory Floor
Measuring Instrument: HP 4284 A
Note: Balun unavailable, instrument unbalanced during measurements

Table D-2
Measured Lead-In Cable Electrical Characteristics

Shielded cable lead-in

Frequency (kHz)	Belden 8718 Cable (# 12 AWG) Inductance (µh)	Belden 8718 Cable (# 12 AWG) Resistance (Ω)	Belden 8720 Cable (# 14 AWG) Inductance (µh)	Belden 8720 Cable (# 14 AWG) Resistance (Ω)
0.1	19.78	0.35	21.00	0.59
1.	19.96	0.35	21.14	0.59
5.	19.94	0.37	21.16	0.60
10.	19.78	0.43	21.07	0.64
15.	19.54	0.51	20.94	0.71
20.	19.26	0.62	20.76	0.80
25.	18.96	0.74	20.56	0.91
30.	18.65	0.87	20.33	1.04
35.2941	18.33	1.02	20.08	1.19
40.	18.05	1.16	19.84	1.33
45.4545	17.74	1.33	19.57	1.50
50.	17.49	1.47	19.34	1.64
54.5454	17.24	1.62	19.11	1.79
60.	16.96	1.79	18.84	1.97
66.6666	16.63	2.00	18.51	2.20
71.4286	16.39	2.16	18.28	2.36
75	16.23	2.27	18.11	2.48
80	16.00	2.43	17.88	2.65
85.714	15.75	2.60	17.78	2.89
96	15.32	2.91	17.18	3.18
100	15.16	3.03	17.01	3.30
120	14.43	3.58	16.25	3.90
125	14.27	3.71	16.07	4.04
150	13.52	4.29	15.27	4.67

Type: Shielded Cable
Length: 100 feet (30 m)
Wire Location: Laboratory Floor
Measuring Instrument: HP 4284 A
Note: Balun unavailable, instrument unbalanced during measurements.
Conductance and capacitance measurements not made due to unbalance.

Table D-3
Measured Inductive Loop Electrical Characteristics

Loop with Belden 8718 shielded lead-in cable

Frequency (kHz)	Inductance (μh)	Resistance (Ω)	Quality Factor (Q)
0.1	94.80	0.53	0.1
1.	94.52	0.53	1
5.	94.08	0.56	5
10.	93.27	0.63	9
15.	93.37	0.73	12
20.	92.98	0.86	14
25.	92.59	1.01	15
30.	92.21	1.16	15
35.2941	91.81	1.34	15
40.	91.47	1.49	15
45.4545	91.09	1.68	16
50.	90.79	1.84	16
54.5454	90.50	2.00	16
60.	90.17	2.18	16
66.6666	89.79	2.41	16
71.4286	89.53	2.57	16
75	89.34	2.69	16
80	89.09	2.85	16
85.714	88.82	3.03	16
96	88.36	3.33	16
100	88.20	3.44	16
120	87.47	3.93	17
125	87.31	4.03	17
150	86.65	4.44	18

Loop Size: 6 x 6 foot (1.8 x 1.8 m)
Number of Turns: 3 (close wound)
Gauge: # 14 AWG
Location: 3 feet (0.9 m) above Laboratory Floor
Lead-In Cable Type: Belden 8718 (# 12 AWG)
Lead-In Cable Length: 100 feet (30 m)
Measuring Instrument: HP 4284 A
Note: Balun unavailable, instrument unbalanced during measurements

Table D-4
Measured Inductive Loop Electrical Characteristics

Loop with Belden 8720 shielded lead-in cable

Frequency (kHz)	Inductance (µh)	Resistance (Ω)	Quality Factor (Q)
0.1	96.80	0.77	0.1
1.	95.78	0.77	0.8
5.	95.37	0.79	4
10.	95.10	0.85	7
15.	94.85	0.94	10
20.	94.59	1.05	11
25.	94.29	1.18	13
30.	94.00	1.33	13
35.2941	93.67	1.49	14
40.	93.38	1.65	14
45.4545	93.04	1.84	14
50.	92.76	2.00	15
54.5454	92.48	2.17	15
60.	92.16	2.37	15
66.6666	91.78	2.60	15
71.4286	91.51	2.77	15
75	91.20	2.90	15
80	91.06	3.07	15
85.714	90.77	3.26	15
96	90.28	3.59	15
100	90.10	3.70	15
120	89.30	4.24	16
125	89.12	4.35	16
150	88.35	4.80	17

Loop Size: 6 x 6 foot (1.8 x 1.8 m)
Number of Turns: 3 (close wound)
Gauge: # 14 AWG
Location: 3 feet (0.9 m) above Laboratory Floor
Lead-In Cable Type: Belden 8720 (# 14 AWG)
Lead-In Cable Length: 100 feet (30 m)
Measuring Instrument: HP 4284 A
Note: Balun unavailable, instrument unbalanced during measurements

Table D-5
Measured Inductive Loop Electrical Characteristics

Loop with Belden 9438 twisted pair lead-in cable

Frequency (kHz)	Inductance (µh)	Resistance (Ω)	Quality Factor (Q)
0.1	98.19	0.75	0.1
1.	97.83	0.75	0.8
5.	97.43	0.77	4
10.	97.20	0.81	8
15.	97.04	0.86	11
20.	96.88	0.92	13
25.	96.74	0.99	15
30.	96.61	1.06	17
35.2941	96.50	1.14	19
40.	96.43	1.21	20
45.4545	96.37	1.30	21
50.	96.34	1.36	22
54.5454	96.34	1.43	23
60.	96.36	1.51	24
66.6666	96.43	1.60	25
71.4286	96.50	1.67	26
75	96.56	1.72	27
80	96.68	1.78	27
85.714	96.83	1.86	28
96	97.18	2.00	29
100	97.34	2.05	30
120	98.34	2.31	32
125	98.63	2.38	33
150	100.42	2.70	35

Loop Size: 6 x 6 foot (1.8 x 1.8 m)
Number of Turns: 3 (close wound)
Gauge: # 14 AWG
Location: 3 feet (0.9 m) above Laboratory Floor
Lead-In Cable Type: Belden 9438 twisted pair (5.5 twists per foot (15 per meter))
Lead-In Cable Length: 100 feet (30 m)
Measuring Instrument: HP 4284 A
Note: Balun unavailable, instrument unbalanced during measurements

Table D-6
Measured Inductive Loop Electrical Characteristics

Loop with no lead-in cable

Frequency (kHz)	Inductance (µh)	Resistance (Ω)	Quality Factor (Q)
0.1	75.02	0.18	0.3
1.	74.33	0.19	3
5.	74.35	0.20	12
10.	74.15	0.21	22
15.	74.04	0.23	30
20.	73.95	0.25	37
25.	73.86	0.28	42
30.	73.79	0.30	46
35.2941	73.71	0.33	50
40.	73.66	0.36	52
45.4545	73.61	0.39	55
50.	73.57	0.41	57
54.5454	73.53	0.43	59
60.	73.48	0.46	61
66.6666	73.44	0.49	63
71.4286	73.41	0.51	64
75	73.39	0.53	65
80	73.36	0.55	67
85.714	73.34	0.58	68
96	73.30	0.62	71
100	73.29	0.64	72
120	73.25	0.73	76
125	73.25	0.75	77
150	73.25	0.84	82

Loop Size: 6 x 6 foot (1.8 x 1.8 m)
Number of Turns: 3 (close wound)
Gauge: # 14 AWG
Location: 3 feet (0.9 m) above Laboratory Floor
Lead-In Cable Type: None
Lead-In Cable Length: 0 feet (0 m)
Measuring Instrument: HP 4284 A
Note: Balun unavailable, instrument unbalanced during measurements

VEHICLE DETECTION SENSITIVITY FORMULAS FOR MULTI-TURN RECTANGULAR LOOPS

ABSTRACT

This paper describes the derivation and application of a formula to calculate the vehicle detection sensitivity of a multi-turn, rectangular loop of round wire. The effect on detection sensitivity of reinforcing steel mesh in the pavement and "lead in" cable inductance is also considered. The loop is installed in the roadway pavement and connected to roadside detection electronics by a transmission line, "lead in", cable. When a vehicle passes over the loop, Eddy currents induced in the vehicle undercarriage cause a decrease in loop inductance which is sensed by the detector electronics.

The multi-turn rectangular loop is modeled as a number of series connected, single-turn, rectangular loops which exhibit mutual coupling between each other. This loop is the primary of an air core transformer with two secondary windings comprised of shorted turns simulating the vehicle undercarriage and reinforcing steel mesh. The derived formulas are used to calculate tables of vehicle detection sensitivity versus loop turns, loop size, wire size, vehicle undercarriage height, etc.

INTRODUCTION

The inductive loop detector (ILD) system is used nationwide to detect stopped or moving vehicles for traffic surveillance and control systems. A typical ILD system consists of a 6 foot (1.83m) by 6 foot (1.83m) loop of 3 turns of 14 AWG wire embedded in the pavement, a "lead in" cable to roadside, and roadside vehicle detection electronics. The vehicle detection sensitivity is the normalized inductance change at the terminals of the detector electronics when a vehicle is sensed by the loop. High ground clearance vehicles such as trucks cause a small change in loop inductance which sometimes results in non-detection of part of the vehicle. Increasing the sensitivity of the detector electronics to sense such small inductance changes usually increases the response time of the detector which causes errors in detector applications for measuring vehicle speed.

This paper will show that the vehicle detection sensitivity of an inductive loop detection system is increased when the spacing between loop turns is correctly selected. The increased sensitivity should improve detection of high ground clearance trucks. At the present time, spacing between loop turns is not considered important.

This paper is based on a previous paper[1] which developed a detection sensitivity formula for a single-turn rectangular loop. It was shown that with no reinforcing steel, the sensitivity is proportional to the mutual inductance squared divided by the product of the self-inductance of the single-turn loop and the self-inductance of the shorted turn loop simulating the vehicle. If the loop turns of a multi-turn rectangular loop are tightly coupled, the sensitivity is independent of loop turns. A formula for the self inductance of a multi-turn rectangular loop which accounts for leakage flux was developed in a second paper[2]. As the loop turns become more widely spaced, the increased leakage flux causes the loop self-inductance to decrease which results in increased detection sensitivity until the decrease in mutual coupling to the shorted turn becomes significant.

VEHICLE DETECTION SENSITIVITY THEORY

Vehicle Model

The vehicle is modeled as a flat, perfectly conducting plate at a height above the loop approximately equal to the average undercarriage height of the vehicle. The width and length of the plate are equal to the width and length of the vehicle. The continuous, perfectly conducting plate can be simulated by a wire grid provided the mesh elements are sufficiently small.

In order to simplify the calculation of loop system sensitivity, the wire grid simulating the vehicle was set equal to the size of the inductive loop in the roadway. When the wire grid is coaxially located over the loop, the interior currents induced in the grid by the loop cancel, leaving a current flowing around the perimeter of the grid provided the grid width and length are equal to those of the loop. Thus, the grid can be replaced with a wire loop or shorted turn equal to the grid perimeter. This case represents a vehicle centered over the loop (i.e., maximum percentage inductance change of the loop). Magnetic effects on the loop due to the permeable material of the vehicle are assumed to be negligible.

Reinforcing Steel Model

The mesh elements of the reinforcing steel in the pavement are considered sufficiently small and the size of the mesh sufficiently large compared to the loop so that the steel mesh can be replaced with a perfectly conducting plane of infinite extent. Based on image theory, the infinitely conducting plane is replaced with an image loop at twice the distance from the loop to the reinforcing steel. Figure 1 illustrates the geometry of the vehicle and reinforcing steel shorted turn model for a two-turn rectangular inductive loop. The direction of induced currents determines the sign of the mutual inductance terms used in the following circuit model.

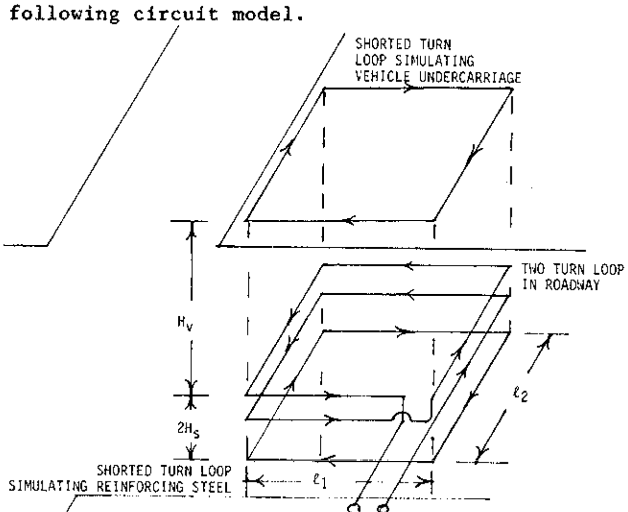


FIG. 1 TWO TURN LOOP IN ROADWAY

Circuit Model for One-Turn Loop

Figure 2 shows the one-turn inductive loop, loop simulating the vehicle, and loop simulating the reinforcing steel mesh, modeled as an air core transformer. The inductive loop is the primary winding of the transformer with the shorted turn secondary winding modeling the vehicle. This shorted turn winding is movable to simulate changes in vehicle undercarriage height. The shorted turn secondary winding modeling the reinforcing steel mesh is located at a distance of twice the steel mesh to inductive loop spacing.

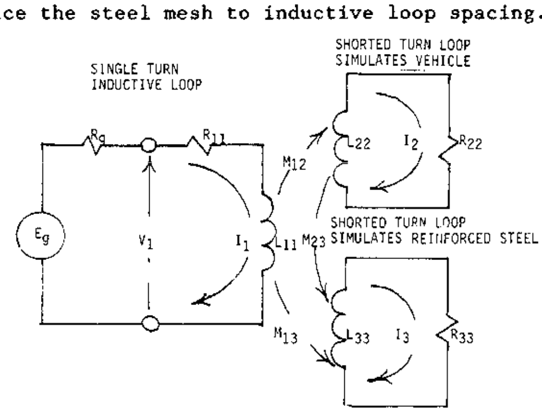


FIG. 2 SINGLE TURN INDUCTIVE LOOP CIRCUIT MODEL

Circuit Equations for One-Turn Loop

The circuit equations for Figure 2 are:

$$V_1 = Z_{11}I_1 + Z_{12}I_2 + Z_{13}I_3 \qquad (1)$$

$$0 = Z_{21}I_1 + Z_{22}I_2 + Z_{23}I_3 \qquad (2)$$

$$0 = Z_{31}I_1 + Z_{32}I_2 + Z_{33}I_3 \qquad (3)$$

where

$$Z_{11} = R_{11} + j\omega L_{11} \qquad (4)$$

$$Z_{22} = R_{22} + j\omega L_{22} \qquad (5)$$

$$Z_{33} = R_{33} + j\omega L_{33} \qquad (6)$$

$$Z_{12} = j\omega M_{12} \qquad (7)$$

$$Z_{13} = j\omega M_{13} \qquad (8)$$

All mutual impedances are symmetrical (i.e.,

$$Z_{12} = Z_{21},\ Z_{13} = Z_{31},\ \text{etc.})$$

Experimental measurements show that the quality factor, $\omega L_{11}/R_{11}$, of the loop driving point impedance, Z_{11}, is ≥ 10.

Assuming small circuit loss to simplify calculations

$$Z_{11} = j\omega L_{11} \qquad (9)$$

$$Z_{22} = j\omega L_{22} \qquad (10)$$

$$Z_{33} = j\omega L_{33} \qquad (11)$$

Inductive Loop Driving Point Impedance

The loop driving point impedance, Z_1, from equations 1, 2, and 3 is:

$$Z_1 = \frac{V_1}{I_1} = \frac{Z_{11}Z_{22}Z_{33} - Z_{31}^2 Z_{22} - Z_{32}^2 Z_{11} - Z_{21}^2 Z_{33} + 2\,Z_{21}Z_{31}Z_{32}}{Z_{22}Z_{33} - Z_{32}^2} \qquad (12)$$

If the reinforcing mesh is spaced a great distance from the inductive loop

$$Z_{13} = Z_{23} = 0$$

then

$$Z_1 = \frac{Z_{11}Z_{22} - Z_{21}^2}{Z_{22}} \qquad (13)$$

The loop driving point impedance, Z_1, depends only on the effect of the vehicle.

Inductive Loop Sensitivity

The sensitivity, S_L, of an inductive loop is defined as:

$$S_L = \frac{\Delta Z_1}{Z_1^{NV}} \qquad (14)$$

The change in loop driving point impedance, ΔZ_1, is given by:

$$\Delta Z_1 = Z_1^{NV} - Z_1^{V} \tag{15}$$

where Z_1^{NV}, is the loop driving point impedance with no vehicle present and Z_1^{V} is the loop driving point impedance when sensing a vehicle.

The loop driving point impedance, Z_1, can be put in the following form:

$$Z_1 = Z_{11} - \frac{Z_{13}^2 Z_{22} + Z_{12}^2 Z_{33} - 2\, Z_{12} Z_{13} Z_{23}}{Z_{22} Z_{33} - Z_{23}^2} \tag{16}$$

Then if no vehicle is present

$$Z_{12} = Z_{23} = 0$$

$$Z_1^{NV} = Z_{11} - \frac{Z_{13}^2}{Z_{33}} = \frac{Z_{11} Z_{33} - Z_{13}^2}{Z_{33}} \tag{17}$$

$$Z_1^{V} = Z_{11} - \frac{Z_{13}^2 Z_{22} + Z_{12}^2 Z_{33} - 2\, Z_{12} Z_{13} Z_{33} Z_{23}}{Z_{22} Z_{33} - Z_{23}^2} \tag{18}$$

$$\Delta Z_1 = \frac{Z_{13}^2 Z_{23}^2 + Z_{12}^2 Z_{33}^2 - 2\, Z_{12} Z_{13} Z_{33} Z_{23}}{Z_{33}\,(Z_{22} Z_{33} - Z_{23}^2)} \tag{19}$$

The loop sensitivity, S_L, is given by:

$$S_L = \frac{\Delta Z_1}{Z_1^{NV}} = \frac{Z_{13}^2 Z_{23}^2 + Z_{12}^2 Z_{33}^2 - 2\, Z_{12} Z_{13} Z_{33} Z_{23}}{(Z_{11} Z_{33} - Z_{13}^2)\,(Z_{22} Z_{33} - Z_{23}^2)} \tag{20}$$

if

$$Z_{13} = Z_{23} = 0$$

$$S_L = \frac{Z_{12}^2}{Z_{11} Z_{22}} \tag{21}$$

Applying equations 9, 10, and 11 to equation 20 the loop sensitivity, S_L, in percent is:

$$S_L = 100\, \frac{M_{12}^2 L_{33}^2 + M_{13}^2 M_{23}^2 - 2\, M_{12} M_{13} M_{23} L_{33}}{(L_{11} L_{33} - M_{13}^2 - M_{13}^2)\,(L_{22} L_{33} - M_{23}^2)} \tag{22}$$

where

S_L = inductive loop sensitivity (%)

M_{12} = mutual inductance between inductive loop and loop simulating vehicle (Hy)

M_{13} = mutual inductance between inductive loop and loop simulating reinforcing mesh (Hy)

M_{23} = mutual inductance between loop simulating vehicle and loop simulating reinforcing mesh (Hy)

L_{11} = self inductance of inductive loop (Hy)

L_{22} = self inductance of loop simulating vehicle (Hy)

L_{33} = self inductance of loop simulating reinforcing mesh (Hy)

When no reinforcing steel mesh is present

$$S_L = 100\, \frac{M_{12}^2}{L_{11} L_{22}} \tag{23}$$

Circuit Model for Two-Turn Loop

Figure 3 shows the two-turn inductive loop, loop simulating vehicle, and loop simulating reinforcing steel mesh, modeled as an air core transformer.

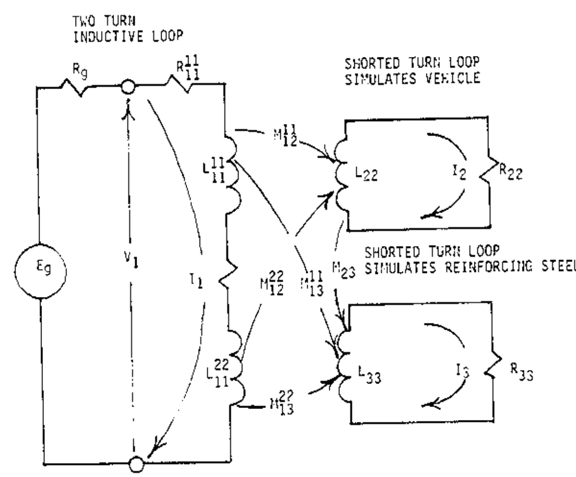


FIG. 3 TWO TURN INDUCTIVE LOOP CIRCUIT MODEL

Circuit Equations for Two-Turn Loop

$$V_1 = (Z_{11}^{11} + Z_{11}^{22} + Z_{11}^{12} + Z_{11}^{21})I_1 + (Z_{12}^{11} + Z_{12}^{22})I_2 + (Z_{13}^{11} + Z_{13}^{22})I_3 \quad (24)$$

$$0 = (Z_{21}^{11} + Z_{21}^{22})I_1 + Z_{22}^{22}I_2 + Z_{23}^{22}I_3 \quad (25)$$

$$0 = (Z_{31}^{11} + Z_{31}^{22})I_1 + Z_{32}^{22}I_2 + Z_{33}^{33}I_3 \quad (26)$$

Where Z_{12}^{11} is the mutual impedance between primary turn 1 of the transformer and secondary shorted turn 2 which models the vehicle. Z_{12}^{22} is the contribution of primary turn 2. Z_{11}^{12} is the mutual impedance between primary turn 1 and primary turn 2.

then

$$Z_{11} = Z_{11}^{11} + Z_{11}^{22} + Z_{11}^{12} + Z_{11}^{21} \quad (27)$$

$$Z_{12} = Z_{12}^{11} + Z_{12}^{22} \quad (28)$$

$$Z_{13} = Z_{13}^{11} + Z_{13}^{22} \quad (29)$$

$$Z_{21} = Z_{21}^{11} + Z_{21}^{22} \quad (30)$$

$$Z_{22} = Z_{22}^{22} \quad (31)$$

$$Z_{23} = Z_{23}^{22} \quad (32)$$

$$Z_{31} = Z_{31}^{11} + Z_{31}^{22} \quad (33)$$

$$Z_{32} = Z_{32}^{22} \quad (34)$$

$$Z_{33} = Z_{33}^{33} \quad (35)$$

The self impedance, Z_{11}, is replaced by the total two turn loop impedance. Each mutual impedance is replaced by the sum of the mutual impedances from each turn.

Circuit Equations for Multi-Turn Loop

$$V_1 = ZI_1 + \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{12}^{ij} I_2 + \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{13}^{ij} I_3 \quad (36)$$

$$0 = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{21}^{ij} I_1 + Z_{22}I_2 + Z_{23}I_3 \quad (37)$$

$$0 = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{31}^{ij} I_1 + Z_{32}I_2 + Z_{33}I_3 \quad (38)$$

Where δ_{ij} is the Kronecker Delta function, then (i.e., $\delta_{ij} = 1$ for $i=j$ and $\delta_{ij} = 0$ for $i \neq j$)

$$Z_{11} = Z_N = \text{multi turn loop self impedance} \quad (39)$$

$$Z_{12} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{12}^{ij} \quad (40)$$

$$Z_{13} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{13}^{ij} \quad (41)$$

$$Z_{21} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{21}^{ij} \quad (42)$$

$$Z_{31} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{31}^{ij} \quad (43)$$

Sensitivity for Multi-Turn Loop

Equation (22) is generalized for the multi-turn case by letting

$$L_{11} = L^{*}_{N} \quad (44)$$

$$M_{12} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{12}^{ij} \quad (45)$$

$$M_{13} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{13}^{ij} \quad (46)$$

<u>Formula for Vehicle Detection Sensitivity for a Multi-Turn Loop</u>

$$S_L(\%)=100\,\frac{\left(\delta_{ij}\sum_{i=1}^{N}\sum_{j=1}^{N}M_{12}^{ij}\right)^2 L_{33}+\left(\delta_{ij}\sum_{i=1}^{N}\sum_{j=1}^{N}M_{13}^{ij}\right)^2 M_{23}-2\left(\delta_{ij}\sum_{i=1}^{N}\sum_{j=1}^{N}M_{12}^{ij}\right)\left(\delta_{ij}\sum_{i=1}^{N}\sum_{j=1}^{N}M_{13}^{ij}\right)M_{23}L_{33}}{\left[L_N^*L_{33}-\left(\delta_{ij}\sum_{i=1}^{N}\sum_{j=1}^{N}M_{13}^{ij}\right)^2\right]\left[L_{22}L_{33}-M_{23}^2\right]} \quad (47)$$

For a two turn (N=2) loop

$$S_L(\%)=100\,\frac{(M_{12}^{11}+M_{12}^{22})^2L_{33}+(M_{13}^{11}+M_{13}^{22})^2M_{23}-2(M_{12}^{11}+M_{12}^{22})(M_{13}^{11}+M_{13}^{22})M_{23}L_{33}}{\left[L_N^*L_{33}-(M_{13}^{11}+M_{13}^{22})^2\right]\left[L_{22}L_{33}-M_{23}^2\right]} \quad (48)$$

The formula for multi-turn loop sensitivity can be applied to any loop geometry provided the vehicle and reinforcing steel mesh can be modeled as shorted turns.

When no reinforcing steel mesh is present,

$$S_L(\%)=100\,\frac{\left(\delta_{ij}\sum_{i=1}^{N}\sum_{j=1}^{N}M_{12}^{ij}\right)^2}{L_N^*L_{22}} \quad (49)$$

Equation (47) is applied to a multi-turn rectangular loop with N coaxial, equal spaced, identical[3] turns. The low frequency inductance, L_N, formula for such a loop is:

$$L_N = NM_{11} + 2(N-1)M_{12} + 2(N-2)M_{13} + \cdots \quad (50)$$

$$L_N = NM_{11} + 2\sum_{i=1}^{N}(N-i)M1,i+1 \quad (51)$$

Where M_{11} is the inductance of a single turn and M_1,i+1 is the mutual inductance between turn one and the i+1 turn. This formula assumes that the smallest dimension of a loop turn length or width is much greater than the largest spacing between loop turns.

For a two turn loop

$$L_N = 2M_{11} + 2M_{12} \quad (52)$$

The total self inductance, L_N^*, of the loop is given by the sum of the low frequency inductance, L_N, and the high frequency, skin effect inductance, L_H

$$L_N^* = L_H + L_N \quad (53)$$

$$L_H = 2(l_1 + l_2)L^i \quad (54)$$

Where l_1 and l_2 are turn width (m) and turn length (m) and the internal inductance, L^i is 0.036 micro Henries/meter @ 47kHZ.

<u>Inductive Loop Detector Sensitivity</u>

The series inductance, L_c, of the transmission line connecting the loop in the roadway to the vehicle detector electronics reduces the loop sensitivity, S_L, to the detector sensitivity available to the electronics.

$$S_p = S_L\left(\frac{1}{1+\frac{L_c}{L_N^*}}\right) \quad (55)$$

LOOP DETECTOR SENSITIVITY
MEASURED DATA AND CALCULATED RESULTS

Loop Detector Sensitivity Computer Program

Equations (47), (51), (53) and (55) were programmed in BASIC and run on an IBM AT Computer. The main program calls a subroutine which calculates the sum of the mutual inductance from each loop turn to the image loop simulating the vehicle and image loop simulating the reinforcing steel. The main program also calls a subroutine which calculates the external, or low frequency inductance of a coaxial, multi-turn, rectangular loop of round wire. This low frequency inductance subroutine calls a subroutine which calculates the mutual inductance between two coaxial, single turn, rectangular loops. The single turn, mutual inductance subroutine calls a subroutine which calculates the mutual inductance between two parallel current elements.

Measured Loop Detector Sensitivity Data

The only known measured loop detector sensitivity data[4] versus the number of loop conductor turns is presented in Table I. This data was measured with a Ford Falcon over a 6 foot (1.83m) by 6 foot (1.83m) loop with 10 feet (3.05m) of number 14 underground feeder (UF) cable connected between the loop and the laboratory equipment. The loop sensitivity versus loop turns was calculated from the change in loop inductance with and without the vehicle. The sensitivity magnitude increased by approximately 5 percent when the operating frequency changed from 15 to 100 kiloHertz for four or more loop turns.

Comparison Between Measured and Calculated Sensitivity Data

Since the average undercarriage height of the Ford Falcon is unknown, the Falcon was modeled with a 6 foot by 6 foot shorted turn coaxially located 0.71 feet (216mm) over the loop of number 14 AWG wire. A loop wire spacing of 150 mils (38mm) and "lead in" cable inductance of 0.22 microHenries per foot was assumed. A comparison of measured and calculated loop sensitivity data is presented in Table II. The agreement between measured and calculated loop detector sensitivity is good.

Effect of Loop Turns on Sensitivity

A survey by Dorsey[5] found that 15 of 21 States cut loop slots in the pavement greater than 2 inches (50.8mm). The spacing between the center of the conductor of the top loop turn and the center of the conductor of the bottom loop turn was assumed to be 2 inches (50.8mm) for analysis. In actual practice a much closer top to bottom turn spacing is used. A loop slot depth of 1-3/8 inches (35mm) is recommended in the Traffic Detection Handbook[6] for a two turn loop. A nominal sensitivity level of 0.098 percent was assumed for detection threshold.

A "lead in" cable length of zero was used so that the effect of loop turns on sensitivity would be independent of "lead in" cable length.

The effect of the reinforcing steel mesh was removed by spacing the mesh 1000 feet (304.8m) from the loop. The results of the loop detector sensitivity, computer program are presented in Table II. The vehicle height sensitivity is approximately proportional to the volume contained by the loop conductors and for a given volume is approximately independent of the number of loop turns. For example, the volume of the 6 ft. (1.83m) by 6 ft.(1.83m) by 2000 mils (0.051m) loop analyzed in Table II is 6 ft.^{3} (0.171m^3).

Effect of Loop Volume on Sensitivity

Since Table II shows that the sensitivity is approximately independant of the number of loop turns for three or more turns, the effect on loop sensitivity by increasing the spacing between turns in a three turn loop was calculated and is presented in Table III. The vehicle height detection sensitivity slowly increases when the turn spacing exceeds 1 inch (25.4mm). The volume of the 6 ft.(1.83m) by 6 ft.(1.83m) by 300 mil (7.6mm) loop is 0.90 ft^3 (0.25m)^3 with a height detection sensitivity of 4.7 ft.(1.43m). Increasing the loop volume by a factor of 10 results in a 0.3 ft. increase in vehicle height detection.

Effect of Lead in Cable on Sensitivity

The lead in cable inductance reduces the vehicle height detection sensitivity. Additional loop turns increase the loop inductance which reduces the detrimental effect of the lead in cable inductance. Table IV clearly shows this effect.

Effect of Mesh on Sensitivity

The reinforcing steel mesh reduces the vehicle height detection sensitivity. Additional loop turns have little effect on the reduced sensitivity caused by the mesh as shown in Table IV.

Effect of Lead in Cable and Mesh on Sensitivity

The lead in cable and mesh substantially reduces vehicle height detection sensitivity. Table IV shows that loop turns should be five or more if 4 ft.(1.22m) high ground clearance trucks are to be detected.

TABLE I COMPARISON OF MEASURED AND CALCULATED LOOP DETECTOR SENSITIVITY DATA

Loop Turns (No)	Measured Loop Detector Sensitivity Data** (%)	Calculated Loop Detector Sensitivity Data (%)	Difference (%)
1	3.25	3.72	14.47
2	4.75	4.75	0.00
3*	5.20	5.20	0.00
4	5.50	5.47	-0.55
5	5.60	5.68	1.43
6	5.65	5.83	3.19
8	5.75	6.07	5.57
10	6.05	6.25	3.31

* The height of 0.71 feet was selected so that this difference is zero.
** Measured data @ 50 kHz

TABLE II LOOP TURNS VERSUS VEHICLE UNDERCARRIAGE HEIGHT DETECTION
WITHOUT LEAD IN CABLE AND REINFORCING STEEL MESH

Loop Turns	Loop Turn Spacing		Vehicle Height Detection Loop Size: 5ft.(1.52m) x 5ft.(1.52m)		Loop Inductance for 6ft.(1.83m) x 6ft.(1.83m)	Vehicle Height Detection Loop Size: 6ft.(1.83m) x 6ft.(1.83m)	
Number	(mils)	(mm)	(ft.)	(m)	(μH)	(ft.)	(m)
1	NA		3.8	1.16	10.42	4.5	1.37
2	2000	50.8	4.1	1.25	29.15	4.8	1.46
3	1000	25.4	4.2	1.28	60.15	5.0	1.52
4	660	16.8	4.3	1.31	103.47	5.0	1.52
5	500	12.7	4.3	1.31	158.72	5.0	1.52
6	400	10.2	4.3	1.31	226.48	5.0	1.52
7	330	8.4	4.3	1.31	307.23	5.0	1.52
8	286	7.3	4.3	1.31	399.10	5.0	1.52

CONDUCTOR TYPE: *#14 AWG CABLE*
LEAD IN LENGTH: 0 FT
MESH SPACING: 1000 FT (305m)
DETECTION SENSITIVITY THRESHOLD: 0.098%

TABLE III LOOP TURN SPACING VERSUS
VEHICLE UNDERCARRIAGE HEIGHT
DETECTION FOR 3 TURN LOOP

Loop Turn Spacing		Vehicle Height Detection Loop Size: 6ft.(1.83m) x 6ft.(1.83m)	
(mils)	(mm)	(ft)	(m)
150	3.8	4.7	1.43
300	7.6	4.8	1.46
450	11.4	4.8	1.46
600	15.2	4.9	1.49
750	19.1	4.9	1.49
900	22.9	4.9	1.49
1050	26.7	5.0	1.52
1200	30.5	5.0	1.52
1350	34.3	5.0	1.52
1500	38.1	5.0	1.52

CONDUCTOR TYPE: #14 AWG
LEAD IN CABLE LENGTH: 0
MESH SPACING: 1000 FT (305m)
DETECTION SENSITIVITY *THRESHOLD: 0.098%*

TABLE IV LOOP TURNS VERSUS VEHICLE UNDERCARRIAGE HEIGHT DETECTION
FOR 6 FT(1.83m) x 6 FT(1.83m) LOOP WITH LEAD-IN CABLE AND REINFORCING STEEL MESH

Loop Turns	Loop Turn Spacing		Vehicle Height Detection with Lead in Cable*		Vehicle Height Detection with Mesh **		Vehicle Height Detection with Lead in Cable* and Mesh**	
(Number)	(mils)	(mm)	(ft)	(m)	(ft)	(m)	(ft)	(m)
1	-		2.3	0.70	3.9	1.19	1.9	0.58
2	2000	50.8	3.5	0.94	4.3	1.31	3.0	0.91
3	1000	25.4	4.1	1.25	4.4	1.34	3.6	1.10
4	660	16.8	4.4	1.34	4.4	1.34	3.9	1.19
5	500	12.7	4.6	1.40	4.5	1.37	4.1	1.25
6	400	10.2	4.7	1.43	4.5	1.37	4.2	1.28
7	330	8.4	4.8	1.46	4.5	1.37	4.3	1.31
8	286	7.3	4.9	1.49	4.5	1.37	4.3	1.31

CONDUCTOR TYPE: #14 AWG WIRE
* LEAD IN LENGTH: 250 FT(76.2m)
** MESH SPACING: 3000 MILS (72.6mm)
DETECTION SENSITIVITY THRESHOLD: 0.098%

RESULTS AND CONCLUSIONS

A formula for calculating the vehicle detection sensitivity for a mult-turn loop is presented. Results from this formula indicate that the vehicle detection sensitivity for a 6 ft.(1.83m) by 6 ft.(1.83m), 3 turn loop of number 14 AWG wire is increased as the spacing between turns is increased. Although a maximum height sensitivity of 5.05 ft.(1.54m) occurs at a turn spacing of 2 in. (50.8mm), a height sensitivity of 4.99 ft. (1.52m) occurs at the more practical turn spacing of 1 in.(25.4mm). A very small increase in height sensitivity 5.06 ft.(1.54m) was noted when number 12 AWG wire was used instead of number 14 AWG wire.

When the loop turns are spaced to use the maximum practical installation space in the pavement, the height sensitivity is approximately independent of the number of turns provided the loop inductance is approximately ten times larger than the inductance of the "lead in" cable. For example, the self inductance of a 6 ft.(1.83m) by 6 ft.(1.83m), 3 turn loop of number 14 AWG wire with a turn spacing of 1 in.(25.4mm) is 60.15 micro Henries. If the maximum inductance of the lead in cable is 6 micro Henries, the maximum lead in cable length is 27 ft.(8.23m) for a lead in cable inductance of 0.22 micro Henries per ft. (0.30m). The self inductance of a 6 ft.(1.83m) by 6 ft. (1.83m), 6 turn loop of number 14 AWG wire with a turn spacing of .4 in.(102mm) is 227 micro Henries which would allow a lead in cable length of 103 ft.(31.4m).

If a vehicle height detection of 4.4 ft.(1.34m) is acceptable, then the 3 turn loop with a loop turn spacing of 1 in.(25.4mm) can be used with 250 ft.(76.2m) of lead in cable as shown in Table IV. The presence of reinforcing steel 3 in.(72.6mm) from the top loop turn reduces the vehicle height detection to 3.6 ft.(1.10m) for the 3 turn loop.

A 5 turn loop spaced 0.5 in.(12.7mm) between turns with a detector sensitivity of 0.098% has adequate vehicle height detection sensitivity for most applications. One possible method to obtain the 0.5 inch (12.7mm) spacing is to obtain loop wire centered in a flexible, water blocked, 0.5 inch (12.7mm), high density polyethylene tube. Lead in cables longer than 250 ft.(76.2m) will require increasing the sensitivity of the vehicle detector electronics to a value greater than 0.098%.

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6. DeLaski, A.B., Parsonson, P.S., Traffic Detection Handbook, Report No. FHWA-IP-81-1, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., p. 113, April 1985.

APPENDIX F.

DIGITAL FREQUENCY SHIFT VEHICLE DETECTOR ANALYSIS

A simplified block diagram of a single channel, digital frequency shift vehicle detector is presented in Figure F-1. The number of multiplied detector oscillator cycles counted by the frequency counter is:

$$N_{fc} = m\, f_D\, T_{ft} = \left(\frac{mf_D}{f_{nc}}\right) \qquad \text{(F-1)}$$

Where T_{ft} is the frame time of the frequency counter. The frame time is assumed constant at each sensitivity setting. The responce time of this type of detector is equal to the frame time, T_{ft}, which is the inverse of the divided clock frequence, f_{nc}.

For example, with a frame time of one second, the number of counts, N_{fc}, of the frequency counter is the multiplied detector oscillator frequency in Hertz.

For no vehicle present:

$$N_{fc}^{\,nv} = \left(\frac{mf_D^{\,nv}}{f_{nc}}\right) \qquad \text{(F-2)}$$

For a vehicle present:

$$N_{fc}^{\,v} = \left(\frac{mf_D^{\,v}}{f_{nc}}\right) \qquad \text{(F-3)}$$

The output for the first comparator is:

$$\Delta N_{fc} = N_{fc}^{\,v} - N_{fc}^{\,nv}$$

$$= \left(\frac{m}{f_{nc}}\right)\left(f_D^{\,v} - f_D^{\,nv}\right)$$

$$= \left(\frac{m\Delta f_D}{f_{nc}}\right) \qquad \text{(F-4)}$$

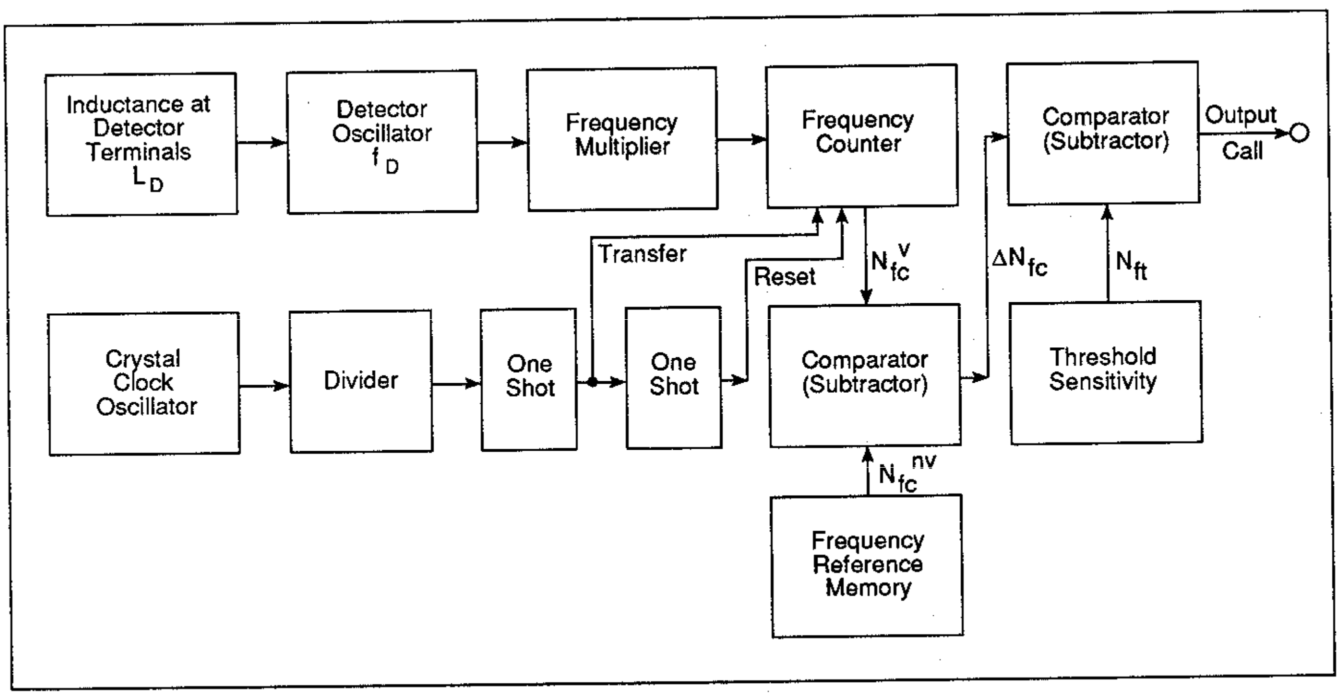

Figure F-1. Simplified block diagram of a digital frequency shift vehicle detector.

When the difference count, ΔN_{fc}, equals the threshold count, N_{fc}, a vehicle call is output.

Since:

$$\Delta N_{fc} = N_{fc} \tag{F-5}$$

$$N_{fc} = \left(\frac{m\Delta f_D}{f_{nc}}\right) \tag{F-6}$$

Using:

$$S_D^{\ f} = -2\left(\frac{\Delta f_D}{f_D}\right) \tag{F-7}$$

and dropping the minus sign which indicates directional change:

$$S_D^{\ f} = \left(\frac{2\,N_{fc}\,f_{nc}}{m\,f_D}\right) \tag{F-8}$$

Since:

$$f_D = \left(\frac{1}{2\,\pi\,\sqrt{L_D\,C_D}}\right) \tag{F-9}$$

$$S_D^{\ f} = \left(\frac{4\,\pi\,N_{fc}\,f_{nc}\,\sqrt{L_D\,C_D}}{m}\right) \tag{F-10}$$

The sensitivity of the digital frequency shift detector is proportional to the threshold frequency count, N_{fc}, the counter frame frequency, f_{nc}, the inductance and capacitance across the detector terminals, and inversely proportional to the detector oscillator multiplier factor, m.

Letting:

$$K_f = \left(\frac{4\,\pi\,N_{fc}\,f_{nc}}{m}\right) \tag{F-11}$$

$$S_D^{\ f} = K_f\,\sqrt{L_D\,C_D} \tag{F-12}$$

Since:

$$N_{fc} = \left(\frac{m f_D}{f_{nc}}\right) \tag{F-13}$$

Then from Equation E-8:

$$S_D^{\ f} = \left(\frac{2\,N_{fc}}{N_{fc}}\right) \tag{F-14}$$

The frequency shift detector sensitivity is proportional to the freqency threshold count, N_{fc}, divided by the total number of counts, N_{fc}, in the frequency counter.

APPENDIX G.
DIGITAL RATIOED FREQUENCY SHIFT VEHICLE DETECTOR ANALYSIS

A simplified block diagram of a single channel, digital frequency shift vehicle detector is presented in Figure G-1. The sensitivity of a digital ratioed shift vehicle detector is given by:

$$S_D{}^f = \left(\frac{2\,N_{fc}\,f_{nc}}{m\,f_D}\right) \qquad \text{(G-1)}$$

If:

$$\left(\frac{f_{nc}}{mf_D}\right) = \text{constant} = \left(\frac{1}{Nf_c}\right) \qquad \text{(G-2)}$$

the sensitivity is independent of detector operating frequency. The frame time is automatically adjusted so that the no call frequency count is constant. The sensitivity is changed by adjusting the frame time for a different number of frequency counts.

The detector response time is primarily dependent on the time required to fill the frequency counter and is:

$$t^f = \left(\frac{f_{nc}}{mf_D}\right) = \left(\frac{2\,N_{ft}}{m\,f_D\;S_D{}^f}\right) \qquad \text{(G-3)}$$

Since N_{ft} and $S_D{}^f$ are constant, the response time changes as the detector oscillator frequency changes.

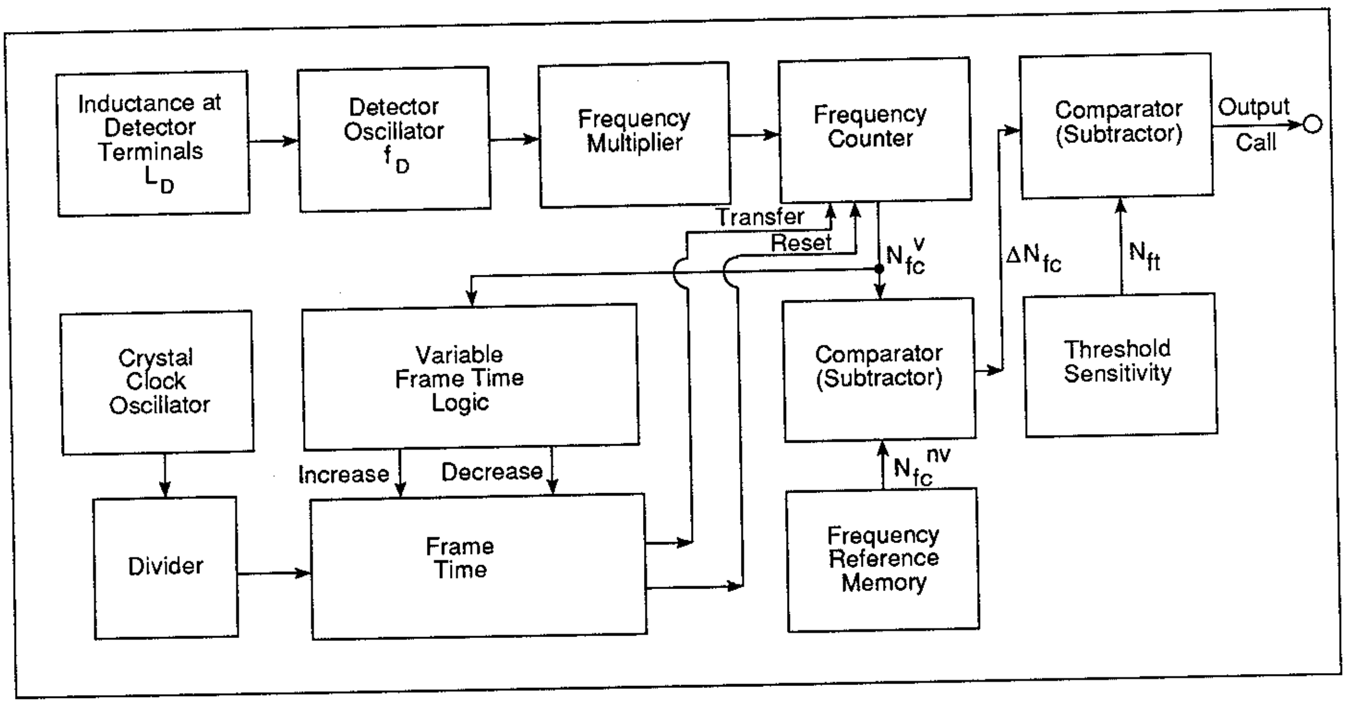

Figure G-1. Simplified block diagram of a digital ratioed frequency shift vehicle detector.

APPENDIX H.

DIGITAL PERIOD SHIFT VEHICLE DETECTOR ANALYSIS

A simplified block diagram of a single channel, digital period shift vehicle detector is presented in Figure H-1. The loop oscillator operates at a frequency, f_L , which is determined by the loop, the transmission line (lead-in cable), and the detector tuning network. The number, m, of loop cycles from the oscillator counter determines the "length" of the gating pulse applied to the AND gate. When the "gating pulse" is m times as long as the loop is occupied, more clock pulses are gated to the period countermaking the detector more sensative.

The period, T_{DC}, of the detector oscillator counter is:

$$T_{DC} = m\,T_D \qquad \text{(H-1)}$$

Where T_D is the period of the loop oscillator,

The length of the gating pulse is:

$$T_g = \left(\frac{T_{LC}}{2}\right) = \left(\frac{m\,T_D}{2}\right) \qquad \text{(H-2)}$$

The number, N_{PC}, of clock pulses counted by the period counter is:

$$N_{PC} = \left(\frac{T_g}{T_C}\right) = \left(\frac{m\,T_D}{2\,T_C}\right) \qquad \text{(H-3)}$$

Where T_C is the period of the clock oscillator.

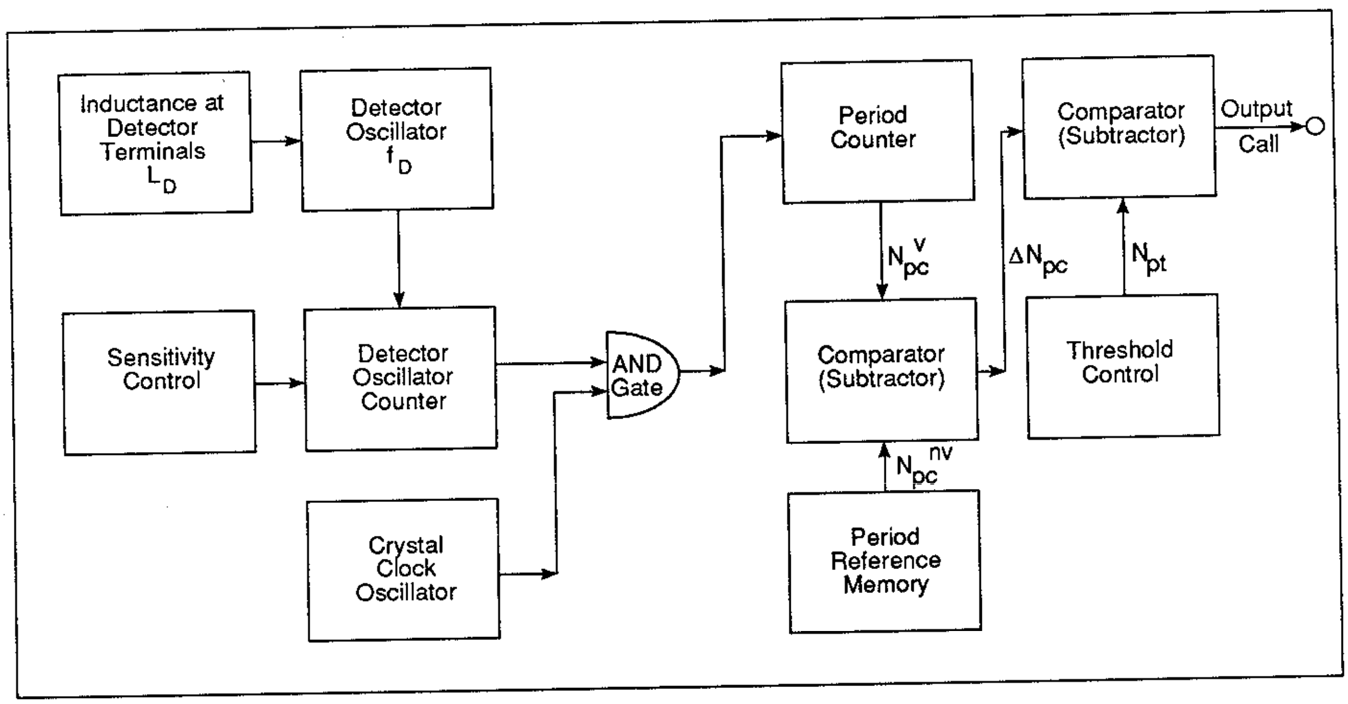

Figure H-1. Simplified block diagram of a digital period shift vehicle detector.

NOTE: The count of the period counter is proportional to the detector oscillator period, T_D.

The number of clock pulses stored in the reference memory when no vehicle is present is:

$$N_{PC}^{nv} = \left(\frac{m\, T_D^{nv}}{2\, T_C}\right) \quad \text{(H-4)}$$

The number of clock pulses counted when a vehicle is present is:

$$N_{PC}^{v} = \left(\frac{m\, T_D^{v}}{2\, T_C}\right) \quad \text{(H-5)}$$

Since the loop inductance decreases when a vehicle is sensed, the detector oscillator frequency, f_D, increases and the detector oscillator period, T_D, decreases. Then:

$$f_D^{v} > f_D^{nv} \longrightarrow N_c^{nv} > N_c^{v} \quad \text{(H-6)}$$

The output of the first comparator is:

$$\Delta N_{PC} = N_{pc}^{nv} - N_{pc}^{v}$$

$$= \left(\frac{m}{2\, T_C}\right)\left(T_D^{nv} - T_D^{v}\right) \quad \text{(H-7)}$$

Since:

$$\Delta T_D = T_D^{nv} - T_D^{v} \quad \text{(H-8)}$$

$$\Delta N_{PC} = \left(\frac{m}{2\, T_C}\right) \Delta T_D \quad \text{(H-9)}$$

NOTE: The output count of the first comparator is proportional to the change, T_D, in the detector oscillator period.

When the output count, N_{PC}, of the first comparator equals the threshold count, N_{pt}, in the second comparator, a vehicle call results.

Then

$$\Delta N_{PC} = N_{pt} \quad \text{(H-10)}$$

Thus

$$N_{pt} = \left(\frac{m}{2\, T_C}\right) \Delta T_D \quad \text{(H-11)}$$

For a high quality factor, tuned circuit, the normalized period shift is approximately:

$$\left(\frac{\Delta T_D}{T_D}\right) = \left(\frac{1}{2}\right)\left(\frac{\Delta L_D}{L_D}\right)$$

$$= \left(\frac{1}{2}\right) S_D^{p} \quad \text{(H-12)}$$

Then

$$S_D^{p} = \left(\frac{2\, \Delta T_D}{T_D}\right) \quad \text{(H-13)}$$

$$S_D^{p} = \left(\frac{4\, N_{pt}\, T_c}{m\, T_D}\right) \quad \text{(H-14)}$$

Since

$$T_c = \left(\frac{1}{f_c}\right) \qquad \text{(H-15)}$$

and

$$T_D = \left(\frac{1}{f_D}\right) \qquad \text{(H-16)}$$

$$S_D{}^p = \left(\frac{4\,N_{pt}\,f_D}{m\,f_c}\right) \qquad \text{(H-17)}$$

For

$$f_D = \left(\frac{1}{2\,\pi\sqrt{L_D\,C_D}}\right) \qquad \text{(H-18)}$$

$$S_D{}^p = \left(\frac{2\,N_{pt}}{\pi\,m\,f_c\sqrt{L_D\,C_D}}\right) \qquad \text{(H-19)}$$

Letting

$$K_p = \left(\frac{2\,N_{pt}}{\pi\,m\,f_c}\right) \qquad \text{(H-20)}$$

$$S_D{}^p = \left(\frac{K_p}{\sqrt{L_D\,C_D}}\right) \qquad \text{(H-21)}$$

Since

$$N_{PC} = \left(\frac{m\,T_D}{2\,T_C}\right) = \left(\frac{m\,f_c}{2\,f_D}\right) \qquad \text{(H-22)}$$

$$S_D{}^p = \left(\frac{2\,N_{pt}}{N_{pc}}\right) \qquad \text{(H-23)}$$

NOTE: The sensitivity of the detector is twice the threshold count divided by the maximum number of counts on the period counter.

The response time of this detector is principally the time required to fill the period counter with clock pulses.

Thus

$$t^p = N_{pc}\,T_c = \left(\frac{N_{pc}}{f_c}\right) \qquad \text{(H-24)}$$

$$t^p = \left(\frac{2\,N_{pt}}{f_c\,S_D{}^p\,f_c}\right) \qquad \text{(H-25)}$$

APPENDIX I.

DIGITAL RATIOED PERIOD SHIFT VEHICLE DETECTOR ANALYSIS

A simplified block diagram of a single channel, digital ratioed shift vehicle detector is presented in Figure I-1. The detector is similar to the digital period shift vehicle detector. The principal difference is the variable threshold count which causes the detector sensitivity to be independent of detector oscillator frequency.

The period shift detector sensitivity, $S_D{}^P$, is given by this equation:

$$S_D{}^P = \left(\frac{2\,N_{pt}}{N_{pc}}\right) \tag{I-1}$$

The threshold count, N_{pt}, is a constant and the period counter count, N_{pc}, is inversely proportional to the detector oscillator frequency which varies with different loop inductance.

A variable threshold, N_{pt}, is selected by multiplying some preset sensitivity factor times the period counter count.

$$N_{pt} = S_t N_{pc} \tag{I-2}$$

$$N_{pt} = \left(\frac{2\,S_t N_{pc}}{N_{pc}}\right) = 2\,S_t \tag{I-3}$$

The detector sensitivity is independent of the detector operating frequency. The response time is identical to the response time of the digital period shift detector.

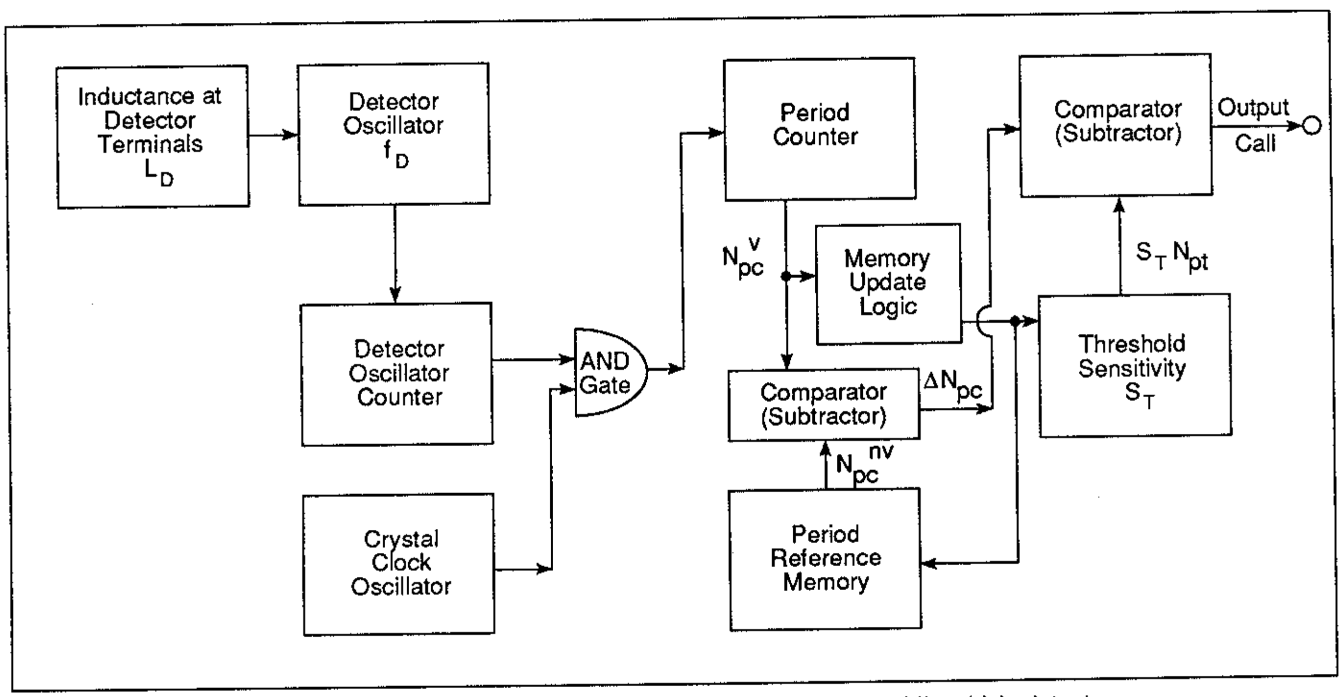

Figure I-1. Simplified block diagram of a digital ratioed period shift vehicle detector.

APPENDIX J

NEMA Standards

Section 15

INDUCTIVE LOOP DETECTORS

Section 15 responds to the need for a series of vehicle loop detectors which provide inputs for traffic-actuated or traffic-response control, surveillance, or data collection systems. The inductive loop detector responds to the presence of vehicles on the roadway by relying upon the effect of the conductive mass of the vehicle on the alternating magnetic field of a loop. When a vehicle passes over the loop of wire embedded in the surface of the roadway, it reacts with the alternating magnetic field which is associated with that loop.

These standards cover the performance and design requirements of interchangeable inductive loop detector units. A detector unit used with a sensor loop embedded in the surface of a roadway detects vehicles moving or standing in the detection zone of the sensor loop. The output of the loop detector unit may be used directly to provide an input to a vehicle-actuated traffic controller unit or provide inputs to traffic-responsive control and surveillance systems. Loop detectors generate outputs indicative of vehicles passing through the sensor loop zone of detection. This output may be used for counting (volume) or for detecting presence time representative of the time that vehicles are in the sensor loop zone of detection (occupancy), or both.

Authorized Engineering Information 8-20-1986.

15.1 LOOP DETECTOR DEFINITIONS

15.1.1 Vehicle Detector System

A system for indicating the presence or passage of vehicles.

NEMA Standard 8-20-1986.

15.1.2 Loop Detector System

A vehicle detector system that senses a decrease in inductance of its sensor loop(s) during the passage or presence of a vehicle in the zone of detection of the sensor loop(s).

NEMA Standard 8-20-1986.

15.1.3 Sensor Loop

An electrical conductor arranged to encompass a portion of roadway to provide a zone of detection and designed such that the passage or presence of a vehicle in the zone causes a decrease in the inductance of the loop that can be sensed for detection purposes.

NEMA Standard 8-20-1986.

15.1.4 Zone of Detection

That area of the roadway within which a vehicle is detected by a vehicle detector system.

NEMA Standard 8-20-1986.

15.1.5 Loop Detector Unit

An electronic device which is capable of energizing the sensor loop(s), of monitoring the sensor loop(s) inductance and of responding to a predetermined decrease in inductance with an output which indicates the passage or presence of vehicles in the zone of detection.

NEMA Standard 8-20-1986.

15.1.6 Channel

Electronic circuitry which functions as a loop detector unit.

NEMA Standard 8-20-1986.

15.1.7 Lead-In Cable

The electrical cable which serves to connect the sensor loop(s) to the input of the loop detector unit.

NEMA Standard 8-20-1986.

15.1.8 Detector Mode

A term used to describe the duration and conditions of the occurrence of a detector output.

NEMA Standard 8-20-1986.

15.1.9 Crosstalk

The adverse interaction of any channel of a detector unit with any other detector channel.

NEMA Standard 8-20-1986.

15.2 FUNCTIONAL STANDARDS

15.2.1 Operation

The inductive loop vehicle detector unit defined and described in this standard shall respond to changes in the inductance of the sensor loop/lead-in combination(s) connected to its loop input terminals. It shall develop a detection output when there is a sufficiently large decrease in the magnitude of the connected inductance.

The sensor loop(s) connected to the detector unit input terminals shall be located at the intended zone(s) of detection. The sensor loop(s) shall be connected to the detector unit by means of lead-in cable.

The sensor loop(s) shall be so configured that the presence of a vehicle in each zone of detection causes a sufficient decrease in inductance to cause an output response from the detector unit.

NEMA Standard 8-20-1986.

15.2.2 Configurations and Dimensions

15.2.2.1 CONFIGURATIONS

This standard covers detector unit configurations shown in Table 15-1.

NEMA Standard 8-20-1986.

Table 15-1
DETECTOR UNIT TYPES

	Without Delay/Extension		With Delay/Extension	
Dectector Type	Relay Output	Solid State Output	Relay Output	Solid State Output
Shelf Mounted 10 Pin MS Connector(s)				
1 Channel	Type 1	Type 2	Type 1T	Type 2T
2 Channel	Type 3	Type 4	Type 3T	Type 4T
(Reserved)				
Card Rack				
2 Channel		Type 7		Type 7T
4 Channel		Type 8		Type 8T
Shelf Mounted 19 Pin MS Connector				
4 Channel	Type 9			

Each channel shall be provided with independent loop input terminals and shall deliver detection information on independent output terminals.

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15.2.2.2 DIMENSIONS

1. Shelf mounted one-channel units shall be a maximum of 2.5" W × 7" H × 9" D, including projections, but excluding the mating connector.
2. Shelf mounted two or four-channel units shall be a maximum of 3.5" W × 7" H × 9" D, including projections, but excluding the mating connector.
3. Two-channel card rack units shall be 1.14" max. W × 4.5" H × 7.00" D, excluding the handle as shown in Figure 15-1.
4. Four-channel card rack units shall be 2.31" max. W × 4.5" H × 7.00" D, excluding the handle as shown in Figure 15-2.

NEMA Standard 8-20-1986.

15.2.3 Connectors

On shelf mounted units, all inputs and outputs, including power, shall enter the unit through a front panel connector. The connectors of shelf mounted units shall mate with the connectors specified in these standards.

NEMA Standard 8-20-1986.

15.2.4 Accessibility

The detector unit shall be easily disassembled to gain access for maintenance. When thus disassembled, the detector unit shall be operational for trouble shooting.

NEMA Standard 8-20-1986.

15.2.5 Material and Construction of Rigid Printed Circuit Assemblies

15.2.5.1 MATERIALS

All printed circuit boards shall be made from NEMA flame resistant Grade FR-4 laminates (glass-epoxy), or equivalent (see NEMA LI 1, *Industrial Laminated Thermosetting Products*). Circuit boards exceeding two inches in any dimension shall be at least $^{1}/_{16}$ inch nominal thickness. Circuit boards not exceeding two inches in any dimenssion shall be at least $^{1}/_{32}$ inch nominal thickness.

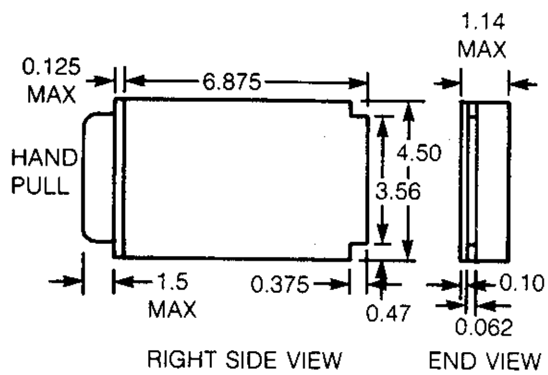
15.2.5.2 CONDUCTORS

The walls of all plated-through holes shall have a minimum copper, or equivalent plating thickness of 0.001 inch. All circuit tracks shall have a conductivity equivalent to at least one ounce per square foot of copper. All electrical mating surfaces shall be made of noncorroding material.

15.2.5.3 COMPONENT IDENTIFICATION

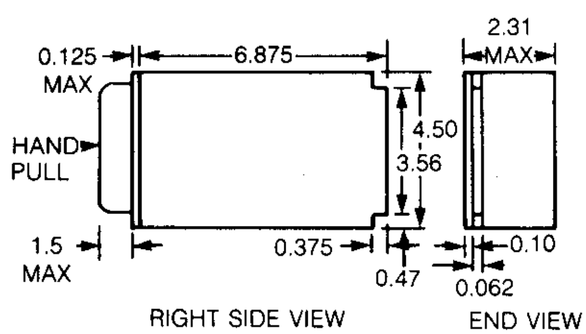
The unit shall be designed so that each component is identified by a circuit reference symbol. This identification shall be affixed to the printed circuit board(s), the cover of the unit, or in an assembly drawing provided with the unit.

NEMA Standard 8-20-1986.



Not to scale
All dimensions in inches
± 0.020 Tolerance (where applicable)

Figure 15-1
TWO-CHANNEL CARD RACK UNIT



Not to Scale
All dimensions in inches
± 0.020 Tolerance (where applicable)

Figure 15-2
FOUR-CHANNEL CARD RACK UNIT

15.2.6 Environmental Requirements

Loop detector units shall operate in accordance with requirements listed herein under the following environmental conditions. The words "loop detector unit" shall be substituted for "controller assembly" where they appear for the purpose of this section.

15.2.6.1 VOLTAGE, AC POWERED UNITS

1. *Voltage Range*—The voltage range shall be in accordance with 2.1.2.
2. *Frequency Range*—The frequency range shall be in accordance with 2.1.3.

15.2.6.2 VOLTAGE, DC POWERED UNITS

1. *Voltage Range*—The voltage range shall be 24 VDC $\pm$ 2.5 VDC.
2. *Ripple*—The maximum supply ripple shall be 500 millivolts peak to peak.

15.2.6.3 AC POWER INTERRUPTION

Two or more power interruptions which are separated by power restorations of 1500 milliseconds or more shall be considered as separate interruptions. The loop detector unit shall react to the power interruptions as follows:

1. Three interruptions of 20 milliseconds or less which are separated by power restorations of 300 milliseconds or more shall not cause the loop detector unit to revert to its start-up sequence.
2. The loop detector unit shall be permitted to revert to its start-up sequence following power interruptions longer than 20 milliseconds.

15.2.6.4 TEMPERATURE AND HUMIDITY

Temperature and humidity shall be in accordance with 2.1.5.

15.2.6.5 TRANSIENTS, AC POWERED UNITS

Loop detector units using 120 VAC 60 Hz input power shall meet the following requirements:

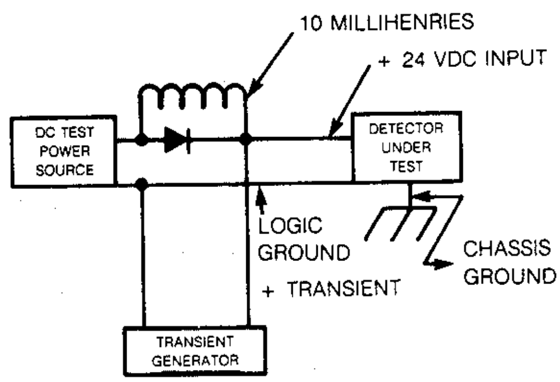
1. The detector unit shall withstand the high-repetition noise transients as described in 2.1.6.1.
2. The detector unit shall withstand the low-repetition, high-energy transients as described in 2.1.6.2.
3. The detector unit shall withstand the nondestructive transient as described in 2.1.8.

15.2.6.6 TRANSIENTS, DC POWERED UNITS

Loop detector units using 24 VDC input power shall operate normally when the test impulse described in 2.1.7 is applied as follows:

1. Between LOGIC GROUND and the +24 VDC power input. The test set-up shown in Figure 15-3 shall be used for this test.
2. Across the output terminals of each channel while in both the detect and non-detect condition.
3. Between LOGIC GROUND and the control inputs.

Detector loop inputs are specifically excluded from this test.



TEST CONDITIONS:

1. Transient generator is described in 2.1.7.
2. The input voltage shall be 24 $\pm$ 2.5 volts dc measured at the input terminal to the loop detector under test.
3. The dc power source must be capable of supplying at least 100 milliamperes per channel.
4. When testing for the reverse polarity transient, the diode shown shall be reversed.

Figure 15-3
TEST CONFIGURATION

15.2.6.7 TRANSIENTS, LOOP DETECTOR INPUT TERMINALS

The detector shall be capable of withstanding the following two nondestructive transient tests:

1. The detector loop input terminals, with loop not connected, shall be subjected to the nondestruct transient immunity test described in 2.1.8, except that the amplitude shall be 200 volts $\pm$ 5 percent.
2. Each detector loop input terminal shall be subjected to one transient pulse of each polarity between the loop terminal and chassis ground with the other loop terminal ungrounded and repeated with the other terminal connected to chassis ground as shown in Figure 15-4.

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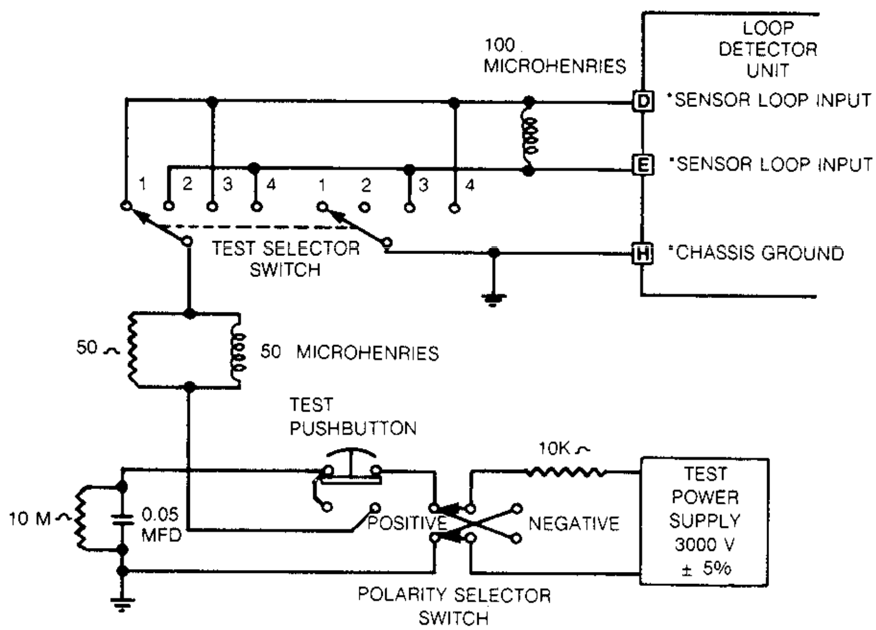


TRANSIENT TEST CONFIGURATIONS

TEST NUMBER	TEST SELECTOR POSITION	POLARITY SELECTOR	TESTED INPUTS*
1	1	POSITIVE	D TO H
2	2	POSITIVE	E TO H
3	3	POSITIVE	D TO E
4	4	POSITIVE	E TO D
5	1	NEGATIVE	D TO H
6	2	NEGATIVE	E TO H
7	3	NEGATIVE	D TO E
8	4	NEGATIVE	E TO D

*The pin designations shown are for a single channel detector. Similar tests shall be performed on all channels of a multichannel detector.

Figure 15-4
LOOP INPUT TERMINAL TRANSIENT TESTS

The eight conditions of the test shall be performed with the detector operating from its normal power source and with a 100 uH ± 10 percent coil connected across the loop terminals of each channel.

The energy source shall be a capacitor of .05 uF ± 5 percent connected in accordance with Figure 15-4.

The voltage on the capacitor shall be adjusted to 3000 volts, ± 5 percent.

The push button shall be activated for at least one second for each of the eight conditions.

15.2.6.8 Vibration

The loop detector unit shall maintain both its physical integrity and operating characteristics when subjected to the vibration test in 2.2.5. This test shall be run at nominal voltage and room environmental conditions.

15.2.6.9 Shock

The loop detector unit shall suffer neither permanent mechanical deformation nor any damage which renders it permanently inoperable when subjected to the shock test described in 2.2.6.

This test shall be run at room environmental conditions without power applied to the unit.

NEMA Standard 8-20-1986.

15.2.7 Power Inputs

15.2.7.1 AC+ (Line Side)

The AC+ (line side) is the protected side of the 120 VAC 60 Hz power source. The steady state input current per channel shall not exceed 100 milliamperes rms.

15.2.7.2 AC− (Common)

The AC− (common) is the unfused and unswitched return side, neutral of the 120 VAC 60 Hz power source. This input shall not be connected to LOGIC GROUND or CHASSIS GROUND within the unit nor to the loop input terminals.

15.2.7.3 Plus 24 VDC

This input supplies power for DC units and is the source of power for DC control inputs in AC powered units. The current consumption of DC powered units shall not exceed 100 milliamperes per channel. The +24 VDC current consumption of AC powered units shall not exceed 10 milliamperes per control input. The return for this input in DC powered units is LOGIC GROUND as described in 15.2.8 The only return for this input in AC powered units is the control input(s) as described in 15.2.10.1. This input shall not be connected within the unit to any loop input.

NEMA Standard 8-20-1986.

15.2.8 Logic Ground

This input is the return for the +24 VDC input on DC powered units. This point shall not be connected within the unit to AC− (common), or to CHASSIS GROUND, or to any loop input terminal.

NEMA Standard 8-20-1986.

15.2.9 Chassis Ground

The loop detector unit shall have a terminal for connection to the chassis of the unit. This input shall not be connected to LOGIC GROUND, AC− (common), or to any other point within the unit, except that it shall be permissible to use this input as a return for transient protection devices.

If the unit has a metallic case, the case shall be connected to a CHASSIS GROUND.

NEMA Standard 8-20-1986.

15.2.10 Control Inputs

15.2.10.1 DC Control Inputs

Control inputs shall have the following characteristics as measured from the negative side of the +24 VDC input supply:

NEMA Standard 8-20-1986.

The negative side of the +24 VDC input supply will normally be returned to LOGIC GROUND within the controller assembly. When the negative side of the +24 VDC input supply is returned to LOGIC GROUND, LOGIC GROUND is the reference point for the control inputs.

Authorized Engineering Information 8-20-1986.

15.2.10.1.1 "Low" or Active State

A voltage between 0 and 8 volts shall be considered the "low" or active state.

15.2.10.1.2 "High" or Inactive State

A voltage greater than 16 volts shall be considered the "high" or inactive state.

15.2.10.1.3 Transition Voltage Zone of Input Circuitry

Transition zone of input circuitry from "low" state to "high" state and vice versa shall occur between 8 and 16 volts.

15.2.10.1.4 External Transition Time

External transition from "Low" state to "high" state and vice versa shall be accomplished within 0.1 millisecond.

15.2.10.1.5 Maximum Current

Over the voltage range 0 to 26 volts DC, maximum current "in" or "out" of any input control terminal shall be less than 10 milliamperes. The input circuitry shall be returned to +24 volt DC supply in such a manner that the removal of all connections to the input shall allow the voltage at the input terminal to rise to the +24 supply voltage.

15.2.10.1.6 Signal Recognition

Any input signal dwelling in a defined logic state for less than 1.0 millisecond shall not be recognized. Any input signal dwelling in a defined logic state for more than 30 milliseconds shall be recognized. Successive similar logic state transitions shall not be recognized when occurring less than 10 milliseconds apart, and shall be recognized when occurring more than 135 milliseconds apart.

15.2.10.1.7 Activation of Delay/Extension Feature

The application of a "low" state voltage to a DELAY/EXTENSION ENABLE input shall activate the delay/extension feature on the channel.

15.2.10.2 AC Control Inputs

Control inputs shall have the following characteristics as measured from the AC−(common) input of the unit:

15.2.10.2.1 "On" or Active Voltage Range

Any voltage from 70 to 135 volts AC shall be considered the "on" or active state.

15.2.10.2.2 "Off" or Inactive Voltage

Any voltage less than 15 volts AC shall be considered the "off" or inactive state.

15.2.10.2.3 Input Current

The input current shall not exceed 50 milliamperes.

15.2.10.2.4 Signal Recognition

Any input signal dwelling in a defined logic state for less than 8.3 milliseconds shall not be recognized. Any input signal dwelling in a defined logic state for more than 333 milliseconds shall be recognized. Successive similar logic state transitions shall not be recognized when occurring less than 16.6 milliseconds apart, and shall be recognized when occurring more than 1 second apart.

15.2.10.2.5 Application of an "On" State Voltage to a DELAY/EXTENSION INHIBIT Input

The application of an "on" state voltage to a DELAY/EXTENSION INHIBIT input shall deactivate the delay/extension feature on that unit or channel in the case of multiple channel units.

NEMA Standard 8-20-1986.

15.2.11 Loop/Lead-In Electrical Properties

Each channel of the detector unit shall function in accordance with the specific requirements of this standard and in addition shall operate without significant degradation with any sensor loop/lead-in combination which exhibits the following electrical properties as measured at the detector unit terminals of the lead-in:

1. Inductance at 50 KHz—50 to 700 microhenries.
2. Q at 50 KHz—greater than 5.
3. Resistance to earth ground—greater than 1 megohm.
4. Field installation practices or detector unit design may require grounding the shield of the loop lead-in cable. Such grounding should be in accordance with the detector manufacturer's recommendation. (The last two sentences have been approved as Authorized Engineering Information.)

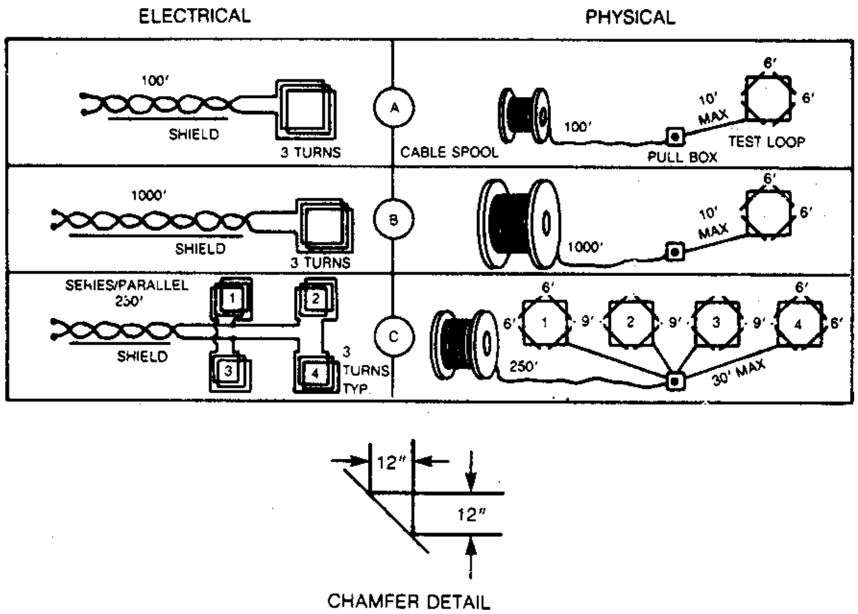
NEMA Standard 8-20-1986.

15.2.12 Test Loop Configurations

Sensor loop and lead-in combinations used to verify the performance requirements of this standard shall consist of the following combinations of 6 ft. × 6 ft. (1.928m × 1.928m) three turn loops and shielded lead-in cable as illustrated in Figure 15-5.

1. Single-loop 6 ft. by 6 ft., three turns, with 100 ft. of lead-in (80-105 microhenries).
2. Single-loop 6 ft. by 6 ft., three turns, with 1,000 ft. of lead-in (260-320 microhenries).
3. Four loops 6 ft. by 6 ft., three turns, in a row in the direction of travel and separated by 9 feet, series/parallel connected with 250 ft. of lead-in (100-140 microhenries).

NEMA Standard 8-20-1986.



CONSTRUCTION—Loop dimension tolerances shall be ± 2 inches. Connections shall be soldered and waterproofed. Loops shall be installed in a nonreinforced pavement and located at least 3 feet (.914m) from any conductive material. Lead-in cable shall be spooled. Loop leads shall exit at one corner of the loop structures. All loop corners shall be chamfered 12 inches.

LOOP WIRE—Each loop shall be three turns of AWG #14 cross,linked polyethelene insulated, stranded copper wire, such as IMSA (International Municipal Signal Association) Specification 51-3, 1984, or equivalent. Loop inductance shall be between 60-80 microhenries.

LEAD-IN WIRE—The lead-in wire shall be AWG #14 twisted pair, aluminum polyester shield, polyethylene insulation, polyethylene jacket, inductance between 20 uH and 24 uH per 100 feet, such as IMSA Specification 50-2, 1984, or equivalent. For standardized test purposes, the shield shall be insulated from ground.

Field installation practices or detector unit design may require grounding the shield of the loop lead-in cable. Such grounding should be in accordance with the detector manufacturer's recommendation. (This paragraph has been approved as Authorized Engineering Information.)

SAWSLOT—The conductors shall be placed at the bottom of a 1-½ ± ¼-inch deep by ¼-inch wide sawslot. Pavement sawslot shall be filled with a suitable epoxy or equivalent sealant.

FIGURE 15-5
TEST LOOP CONFIGURATIONS

15.2.13 Test Vehicle Definition

Detector units shall detect all vehicles which ordinarily traverse the public streets and highways and which are comprised of sufficient conductive material suitably located to permit recognition and response by the detector system.

Vehicles are classified by this standard in accordance with the reduction in inductance resulting when they are centered in the single 6 ft. by 6 ft., three turn-test loop with 100 feet of lead-in.

These minimum reductions are as follows:

Class 1: 0.13 percent $\left(\frac{\Delta L}{L}\right)$ or 0.12 microhenries (ΔL) inductance change with a single 6 ft $\times$ 6 ft, three turn loop, with 100 ft lead-in (small motorcycle);

Class 2: 0.32 percent $\left(\frac{\Delta L}{L}\right)$ or 0.3 microhenries (ΔL) inductance change with a single 6 ft $\times$ 6 ft, three turn loop with 100 ft lead-in (large motorcycle);

Class 3: 3.2 percent $\left(\frac{\Delta L}{L}\right)$ or 3.0 microhenries (ΔL) inductance change with a single 6 ft $\times$ 6 ft, three turn loop, with 100 ft lead-in (automobile).

The maximum reduction caused by any test vehicle shall be 5.4 percent $\left(\frac{\Delta L}{L}\right)$ or 5 microhenries (ΔL) inductance change with a single 6 ft $\times$ 6 ft, three turn loop with 100 ft lead-in.

NEMA Standard 8-20-1986.

15.2.14 Sensitivity

The detector unit shall be capable of detecting any of the vehicles defined in 15.2.13 on any of the test loops defined in 15.2.12.

NEMA Standard 8-20-1986.

15.2.15 Sensitivity Control

When detecting test vehicles as described in 15.2.13 and operating on any of the test loop configurations described in 15.2.12, each channel of the detector unit shall include means to adjust the sensitivity such that it shall not produce an output when the nearest point of any test vehicle of 15.2.13 is 36 inches or more outside the loop(s) perimeter. A minimum of three sensitivity selections shall be provided for each detection channel.

NEMA Standard 8-20-1986.

15.2.16 Approach Speed

The detector unit shall detect any vehicle described in 15.2.13 over any of the single loops described in 15.2.12 traveling within the speed range of 5 to 80 miles per hour.

The detector unit shall detect any vehicle described in 15.2.13 over all of the loops of the four loop configurations described in 15.2.12 traveling within the speed range of 5 to 20 miles per hour.

All channels of a multichannel detector shall be operating at the same sensitivity and connected to equivalent inductances for the purpose of these tests.

NEMA Standard 8-20-1986.

15.2.17 Modes of Operation

Each detector channel shall be capable of functioning in the following two front panel selectable modes:

15.2.17.1 PRESENCE

When a Class 2 vehicle defined in 15.2.13, or larger vehicle occupies the center of any test loops described in 15.2.12, the detector unit shall be capable of maintaining a detection output for a minimum of 3 minutes.

15.2.17.2 PULSE

A detection output between 100 and 150 milliseconds shall be initiated when a vehicle enters the sensor loop zone of detection.

If this vehicle remains in the zone of detection, the detector unit shall become responsive within a maximum of 3 seconds to additional test vehicles entering the zone of detection.

The detector unit shall produce one and only one output pulse for a test vehicle traveling at 10 miles per hour across the zone of detection of the single sensor loops defined in 15.2.12.

NEMA Standard 8-20-1986.

15.2.18 Recovery from Sustained Occupancy

When operating in the presence mode, and following a sustained occupancy of 5 minutes, the detector unit shall recover to normal operation with at least 90 percent of its selected sensitivity within one second after the zone of detection is vacated.

NEMA Standard 8-20-1986.

15.2.19 Response Time

When operating in the presence mode, the detector unit shall be capable of being set to produce an output in response to a step decrease in inductance equivalent to the minimum decrease from a Class 1 vehicle defined in 15.2.13 within not more than 125 milliseconds when tested on either of the single loop test configurations described in 15.2.12. In response to step return to the original inductance, the detector unit shall terminate its output within no more than 125 milliseconds.

When operating in the presence mode, the detector unit shall be capable of being set to produce an output in response to a step decrease in inductance equivalent to the minimum decrease from a Class 3 vehicle defined in 15.2.13 within not more than 50 milliseconds when tested on either of the single loop test configurations described in 15.2.12. In response to a step return to the original inductance, the detector unit shall terminate its output within not more than 50 milliseconds.

All channels of a multi-channel detector unit shall be operating at the same sensitivity and connected to equivalent inductances for the purpose of these tests.

NEMA Standard 8-20-1986.

For certain specific surveillance applications involving vehicle speeds in excess of 45 m.p.h., more precise response times might be required.

Authorized Engineering Information 8-20-1986.

15.2.20 Tuning

Each detector channel shall include one of the following means for accommodating the range of sensor loop/lead-in inductance.

15.2.20.1 Manual Tuning

The unit shall be capable of being tuned by an operator using one or more tuning controls. All necessary tuning controls shall be located on the front panel of the unit. It shall be possible to complete tuning within 3 minutes after the application of power. The unit shall achieve normal operation and at least 90 percent of its selected sensitivity within 3 minutes following tuning.

15.2.20.2 Self-Tuning

The unit shall tune automatically upon the application of power. It shall achieve normal operation and at least 90 percent of its selected sensitivity within 30 seconds after application of power.

NEMA Standard 8-20-1986.

15.2.21 Self-Tracking

The detector unit shall automatically accommodate those after-tuning changes in the loop/lead-in electrical characteristics as might reasonably be expected to occur in undamaged loops, properly installed in sound pavement and exhibiting the electrical properties outlined in 15.2.11, without producing a false output or change in sensitivity.

NEMA Standard 8-20-1986.

15.2.22 Recovery from Power Interruption

After a power interruption longer than 20 milliseconds, the detector unit shall resume normal operation, with at least 90 percent of its selected sensitivity, within 30 seconds after the main supply voltage recovers to a voltage within the specified limits.

NEMA Standard 8-20-1986.

15.2.23 Crosstalk Avoidance

Each detector channel shall include means to prevent that channel from adversely interacting with any other channel. The means to prevent such interaction shall be either inherent, automatic, or manual.

NEMA Standard 8-20-1986.

15.2.24 Delay/Extension

Each channel of a unit with delay/extension shall have three modes of operation—delay, extension, and normal (i.e., neither delay nor extension). Channels 1 and 2 of four channel detector units shall be the ones to include the delay/extension feature.

15.2.24.1 Delay

When selected, the output is delayed for the time set. If the vehicle departs before the time set, an output does not occur and the timer is reset. This delay timing is controlled by the DELAY/EXTENSION ENABLE input defined in 15.2.10.1.7 or DELAY/EXTENSION INHIBIT input defined in 15.2.10.2.5. See Figure 15-6.

The delay time shall be adjustable in the range from 0 to 30 seconds. The setability shall be within one second in the 0-15 second range and within two seconds in the 16-30 second range. The accuracy shall be ± ½ second or ± 5 percent of the setting, whichever is greater. When the DELAY/EXTENSION ENABLE input is inactive, the delay shall be zero (0 to 0.1 seconds). When the DELAY/EXTENSION INHIBIT input is active, the delay shall be zero (0 to 0.1 seconds).

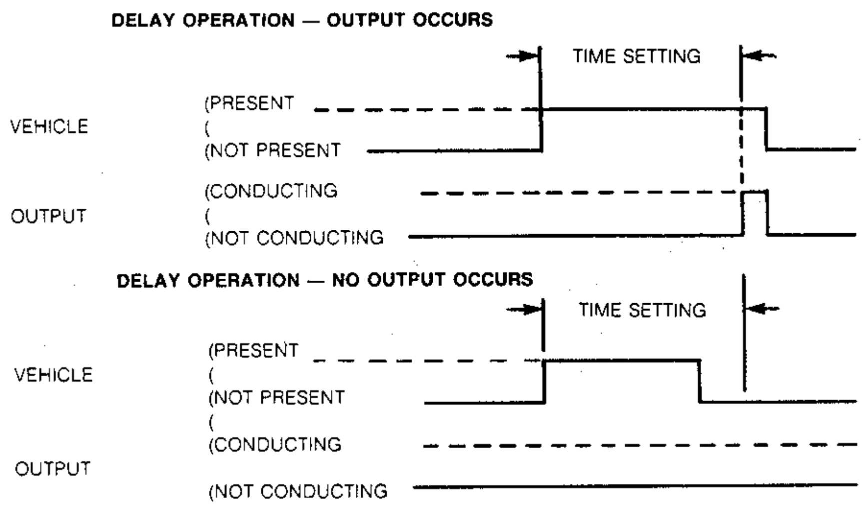


Figure 15-6
DELAY OPERATION

Care should be taken when installing a detector unit which employs DELAY/EXTENSION INHIBIT operation in place of a detector unit which does not have this feature as delay operation may be initiated which would cause improper intersection operation unless the delay/extension timing is set to zero. (This paragraph has been approved as Authorized Engineering Information.)

15.2.24.2 EXTENSION

When selected, the output is extended after the vehicle departs the zone of detection for the time set. If a new vehicle arrives before the extension timer times out, the timer is reset, the output is maintained, and the timer resumes timing when the vehicle departs. See Figure 15-7. This extension timing is controlled by the DELAY/EXTENSION ENABLE input defined in 15.2.10.1.7 or DELAY/EXTENSION INHIBIT input defined in 15.2.10.2.5.

The extension time shall be adjustable in the range from 0 to 7½ seconds. The setability shall be within ½ second. The accuracy shall be ± ½ second. When the DELAY/EXTENSION ENABLE input is inactive, the extension shall be zero (0 to 0.1 seconds). When the DELAY/EXTENSION INHIBIT input is active, the extension shall be zero (0 to 0.1 seconds).

NEMA Standard 8-20-1986.

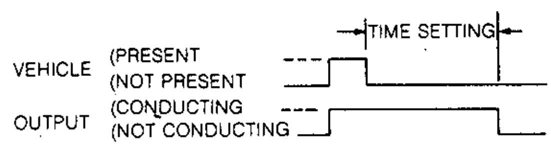


Figure 15-7
EXTENSION OPERATION

15.2.25 Controls and Indicators

All controls and indicators necessary for the operation of the detector unit shall be located on the front panel of the unit except as noted below. Multiple functions combined in a single control shall be permitted. The controls and indicators shall include, but are not limited to:

1. *Output Indicator*—Means to visually indicate the output state of each channel. Each channel shall have a separate indicator.
2. *Sensitivity Control*—Means to permit selection of the sensitivity of each channel as described in 15.2.15.
3. *Overcurrent Protection Device*—Required for ac powered units. If the overcurrent protection device on an ac powered unit is a fuse or circuit breaker, it shall be accessible from the front panel. Internal mounting of any other overcurrent protection device shall be permitted.
4. *Manual Tuning Control*—When required, it shall permit accommodation of the range of loop/lead-in inductances.
5. *Reset*—A control which unconditionally causes the detector or detection channel to retune to a non-vehicle present condition.
6. *Mode Selector*—Shall provide for selection of pulse or presence mode operation of each channel. Card mounting of this control shall be permitted on card rack units.
7. *Crosstalk Control*—As required, shall provide means to prevent interaction of channels as described in 15.2.23. Card mounting of this control shall be permitted on card rack units.
8. *Delay/Extension Selection Control*—The unit shall have either a control or combination of controls to allow for the selection of one of three operating modes—delay, extension, and normal (i.e., neither delay nor extension). It shall be permissible to have the normal mode selected by either setting a three position selector switch to the normal position or setting the delay/extension timing control to zero. Card mounting of the control(s) shall be permitted on card rack units.
9. *Delay/Extension Timing Control*—Shall provide means to permit setting of the time duration of the delay/extension period for each channel as described in 15.2.24. When a unit employing DELAY/EXTENSION INHIBIT operation is used to replace a unit without delay/extension operation, the timing controls shall be set to zero. Internal mounting of this control shall be permitted.

NEMA Standard 8-20-1986.

15.2.26 Marking

All units with Delay/Extension and with relay output(s) shall have a permanently attached notification on either the top, front, or side surface which reads as follows, or the equivalent:

NOTICE: The delay timing on this unit shall be set to zero if Pin J is not connected to a 120 VAC timing inhibit signal.

NEMA Standard 8-20-1986.

15.2.27 Output

This standard defines two devices for output interfacing. Detector units shall be configured to have one of the following devices as defined in 15.2.2. The output device shall have the following characteristics:

5.2.27.1 Relay

1. *Contacts Closed*—Indicate detection output.
2. *Power Outage or Overcurrent Failure Condition*—Contacts closed indicate detection output.
3. *Output Circuit Isolation*—The isolation between the output terminals and other terminals shall exceed:
   a. Resistance 10^6 ohms
   b. Breakdown 1000 V rms
4. *Contact Rating* (resistive load)
   a. 2 milliamperes through 1 ampere @ 18 to 28 volts.
   b. 0.5 amp @ 120 VAC
   c. Maximum closed contact resistance—1 ohm.
5. *Mounting*—Plug-in with socket or direct solder mounting.
6. *Minimum Operations*
   a. 10^6 with contacts at rated load
   b. 10^7 total mechanical
7. Contacts shall be closed if the loop circuit is open.

15.2.27.2 Solid State (Isolated)

1. *Output Solid State Device*—Conducting indicates detection output.
2. *Power Outage or Fuse Failure Condition*—Output device is nonconductive, indicating a no detection output condition.
3. *Output Circuit Isolation*—The isolation between each output device terminal pair and all other terminals shall exceed:
   a. Resistance 10^6 ohms
   b. Breakdown 1000 V rms
4. *Output Rating*—The output shall conduct a minimum of 20 milliamperes with a maximum 1.4 volt drop across the output terminals in the conducting state. The output shall conduct a maximum of 50 microamperes with any voltage between 0 and 26 VDC applied across the output terminals in the nonconductive state.

5. *Transition Time*—When switching to or from a steady state current in the range of 2.4 to 20 milliamperes, the transition time from 8 to 16 volts and vice versa shall be 0.1 milliseconds or less. The circuit(s) to which the output is connected is defined in 13.2.3.
6. *Maximum Voltage*—Hold off 30 VDC minimum under non-detect conditions.
7. Solid state devices shall be conducting if the loop circuit is open.

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15.2.28 Electrical Connections Without Delay/Extension Timings

Detector units without Delay/Extension Timing shall have connector and connector pin terminations as defined in the following:

"Reserved" connector pin terminations are exclusively for assignment by this NEMA Standards Publication of additional specific input-output functions and/or reasons of interchangeability with units already in use not in conformance to this standard. These connector pins shall not be internally connected, except as specifically defined by this NEMA Standards Publication.

15.2.28.1 Single-Channel, Shelf-Mounted Detector

Type 1. Relay Output—Shall mate with cable connector MS3106A-18-1S, or equivalent. Input-output connector pin termination shall be as follows:

Pin A	AC− (common)
Pin B	Relay Common
Pin C	AC+ (line side)
Pin D	Loop Input
Pin E	Loop Input
Pin F	Output Normally Open (continuity to relay common during detect)
Pin G	Reserved*
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Reserved

*May be connected to the normally closed output of the relay—for special function use only. During normal operation, standard detector functions, as defined in this standard, will not require a connection to this pin. Detector unit harnesses will not normally contain a wire connected to pin G. (This note has been approved as Authorized Engineering Information.)

Type 2. Solid State Output (Isolated)—Shall mate with cable connector MS3106A-18-1SW, or equivalent. Input-output connector pin terminations shall be as follows:

Pin A	AC− (common)
Pin B	Output (−)
Pin C	AC+ (line side)
Pin D	Loop Input
Pin E	Loop Input
Pin F	Output (+)
Pin G	Spare
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Reserved

A Type 2 unit is not physically or electrically interchangeable with a single channel detector with a relay output. (This sentence has been approved as Authorized Engineering Information)

15.2.28.2 Two-Channel, Shelf-Mounted Detectors

Type 3. Relay Output, 2-Channel—Shall have two connectors each of which shall mate with cable connector MS3106A-18-1S, or equivalent.

A Type 3 unit is not physically or electrically interchangeable with a 2 channel detector unit with a solid-state output. (This sentence has been approved as Authorized Engineering Information.)

Input-output connector pin terminations shall be as follows:

Channel 1, Connector

Pin A	AC− (common)
Pin B	Relay Common, Ch 1
Pin C	AC+ (line side)
Pin D	Loop Input, Ch 1
Pin E	Loop Input, Ch 1
Pin F	Output Normally Open, Ch 1 (Continuity to relay common Ch 1 during detect)
Pin G	Reserved**
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Reserved

Channel 2, Connector

Pin A	Reserved
Pin B	Relay Common, Ch 2
Pin C	Reserved*

Pin D	Loop Input, Ch 2
Pin E	Loop Input, Ch 2
Pin F	Output Normally Open, Ch 2 (continuity to relay common Ch 2 during detect)
Pin G	Reserved**
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Reserved

*Shall not be internally connected.

**May be connected to the normally closed output of the relay—for special function use only. During normal operation, standard detector functions, as defined in this standard, will not require a connection to this pin. Detector unit harnesses will not normally contain a wire connected to pin G. (This note has been approved as Authorized Engineering Information.)

Type 4. Solid-State Output (Isolated) 2-Channel—Shall have two connectors, each of which shall mate with cable connector MS3106A,-18-1SW, or equivalent. A relay output unit is not physically or electrically interchangeable with a solid-state output unit due to rotation of the connector insert. Input-output connector pin terminations shall be as follows:

Channel 1, Connector

Pin A	AC− (common)
Pin B	Output Ch 1 (−)
Pin C	AC+ (line side)
Pin D	Loop Input, Ch 1
Pin E	Loop Input, Ch 1
Pin F	Output, Ch 1 (+)
Pin G	Spare
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Reserved

Channel 2, Connector

Pin A	Reserved
Pin B	Output, Ch 2 (−)
Pin C	Reserved*
Pin D	Loop Input, Ch 2
Pin E	Loop Input, Ch 2
Pin F	Output Ch 2 (+)
Pin G	Spare
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Reserved

*Shall not be internally connected.

15.2.28.3 Types 7 & 8 Card Rack—Two and Four-Channel

Two and four-channel card racks shall mate with a 44-terminal, double-row, 0.156-inch contact spacing, Cinch Jones card edge connection 50-44A-30M, or equivalent. Input-output connector pin terminations shall be as follows:

Pin A	Logic Ground	1. Reserved
Pin B	+24 VDC Supply	2. Reserved
Pin C	Reserved for Reset	3. Spare
Pin D	Loop Input, Ch 1	4. Redundant Loop Input, Ch 1 (optional)
Pin E	Loop Input, Ch 1	5. Redundant Loop Input, Ch 1 (optional)
Pin F	Output, Ch 1 (+)	6. Spare
Pin H	Output, Ch 1 (−)	7. Spare
Pin J	Loop Input, Ch 2	8. Redundant Loop Input, Ch 2 (optional)
Pin K	Loop Input, Ch 2	9. Redundant Loop Input, Ch 2 (optional)
Pin L	Chassis Ground	10. Spare
Pin M	Reserved	11. Reserved
Pin N	Reserved	12. Reserved
Pin P	Loop Input, Ch 3	13. Redundant Loop Input, Ch 3 (optional)
Pin R	Loop Input, Ch 3	14. Redundant Loop Input, Ch 3 (optional)
Pin S	Output, Ch 3 (+)	15. Spare
Pin T	Output, Ch 3 (−)	16. Spare
Pin U	Loop Input, Ch 4	17. Redundant Loop Input, Ch 4 (optional)
Pin V	Loop Input, Ch 4	18. Redundant Loop Input, Ch 4 (optional)
Pin W	Output, Ch 2 (+)	19. Spare
Pin X	Output, Ch 2 (−)	20. Spare
Pin Y	Output, Ch 4 (+)	21. Spare
Pin Z	Output, Ch 4 (−)	22. Spare

Polarization keys shall be located at three positions:

1. Between B/2 and C/3
2. Between M/11 and N/12
3. Between E/5 and F/6

Two-channel units shall have no connection to pins P, R, S, T, U, V, Y, Z, 13, 14, 17, and 18.

15.2.28.4 TYPE 9 RELAY OUTPUT FOUR CHANNEL MS CONNECTOR

Shall mate with 19 pin cable connector MS 3106A-2-14S, or equivalent.

Input-output connector pin terminations shall be as follows:

Pin A	AC− (common)
Pin B	Relay Common, Ch 4 Pin C AC+ (line side)
Pin D	Loop Input, Ch 1
Pin E	Loop Input, Ch 1
Pin F	Loop Input, Ch 2
Pin G	Loop Input, Ch 2
Pin H	Chassis Ground
Pin J	Loop Input, Ch 3
Pin K	Loop Input, Ch 3
Pin L	Loop Input, Ch 4
Pin M	Loop Input, Ch 4
Pin N	Output Normally Open, Ch 1 (continuity to relay common Ch 1 during detect)
Pin P	Relay Common, Ch 1
Pin R	Relay Common, Ch 2
Pin S	Output Normally Open, Ch 2 (continuity to relay common Ch 2 during detect)
Pin T	Relay Common, Ch 3
Pin U	Output Normally Open, Ch 3 (continuity to relay common Ch 3 during detect)
Pin V	Output Normally Open, Ch 4 (continuity to relay common Ch 4 during detect)

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15.2.29 Electrical Connections With Delay/Extension Timings

Detector units with Delay/Extension Timing shall have connector and connector pin terminations as defined as follows:

''Reserved'' connector pin terminations are exclusively for assignment by this NEMA Standards Publication of additional functions and for reasons of interchangeability with units in use, but not already in conformance to this standard. These connector pins shall not be internally connected, except as specifically defined by this NEMA Standards Publication.

15.2.29.1 SINGLE-CHANNEL, SHELF-MOUNTED DETECTOR

Type 1T Relay Output—Shall mate with cable connector MS3106A-18-1S, or equivalent. When this unit is used to replace a Type 1 unit of the same keying, the delay/extension timing shall be set to zero.

Failure to set the delay/extension timing to zero when replacing a detector unit without delay/extension operation may initiate delay operation which will cause improper intersection op·ration. A relay output unit is not physically or electrically interchangeable with a solid state unit due to rotation of the connector. (This paragraph has been approved as Authorized Engineering Information.)

Input-output connector pin terminations shall be as follows:

Pin A	AC− (common)
Pin B	Relay Common
Pin C	AC+ (line side)
Pin D	Loop input
Pin E	Loop Input
Pin F	Output Normally Open (continuity to relay common during detect)
Pin G	Reserved*
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Delay/Extension Inhibit Input (AC)

*May be connected to the normally closed output of the relay—for special function use only. During normal operation standard detection functions as defined in this standard will not require a connection to this pin. Detector unit harnesses will not normally contain a wire connected to pin G. (This note has been approved as Authorized Engineering Information.)

Type 2T Solid-State Output (isolated)—Shall mate with cable connector MS3106A-18-1SW, or equivalent.

A Type 2T unit is not physically or electrically interchangeable with a single channel detector with a relay output. (This sentence has been approved as Authorized Engineering Information.)

Input-output connector pin terminations shall be as follows:

Pin A	AC− (common)
Pin B	Output (−)
Pin C	AC+ (line side)
Pin D	Loop Input
Pin E	Loop Input
Pin F	Output (+)
Pin G	Spare
Pin H	Chassis Ground
Pin I	+24 VDC Supply Input
Pin J	Delay/Extension Enable Input (DC)

15.2.29.2 TWO-CHANNEL, SHELF-MOUNTED DETECTORS

Type 3T Relay Output, 2-Channel—Shall have two connectors each of which shall mate with cable connector MS3106A,18-1S, or equivalent.

When this unit is used to replace one Type 3 or two Type 1 units of the same keying, the delay/extension timing shall be set to zero. Failure to set the delay/extension timing to zero when replacing a detector unit without delay/extension operation may initiate delay operation which will cause improper intersection operation. A relay output unit is not electrically or physically interchangeable with a solid-state output unit due to the rotation of the connector insert. (Last two sentences have been approved as Authorized Engineering Information.)

Input-output connector pin terminations shall be as follows:

Channel 1, Connector

Pin A	AC− (common)
Pin B	Relay Common, Ch 1
Pin C	AC+ (line side)
Pin D	Loop input, Ch 1
Pin E	Loop Input, Ch 1
Pin F	Output Normally Open Ch 1 (continuity to relay common Ch 1 during detect)
Pin G	Reserved**
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Delay/Extension Inhibit Input (AC), Ch 1

Channel 2, Connector

Pin A	Reserved
Pin B	Relay Common, Ch 2
Pin C	Reserved*
Pin D	Loop Input, Ch 2
Pin E	Loop Input, Ch 2
Pin F	Output Normally Open Ch 2 (continuity to relay common Ch 2 during detect)
Pin G	Reserved**
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Delay/Extension Inhibit Input (AC), Ch 2

*Shall not be internally connected.

**May be connected to the normally closed output of the relay—for special function use only. During normal operation, standard detector functions, as defined in this standard, will not require a connection to this pin. Detector unit harness will not normally contain a wire connected to pin G. (This note has been approved as Authorized Engineering Information.)

Type 4T Solid-State Output (Isolated) 2-channel—Shall have two connectors, each of which shall mate with cable connector MS3106A-18-1SW, or equivalent.

A Type 4T unit is not physically or electrically interchangeable with a 2 channel detector with relay output. (This sentence has been approved as Authorized Engineering Information.)

Input-output connector pin terminations shall be as follows:

Channel 1, Connector

Pin A	AC− (common)
Pin B	Output, Ch 1 (−)
Pin C	AC+ (line side)
Pin D	Loop Input, Ch 1
Pin E	Loop Input, Ch 1
Pin F	Output, Ch 1 (+)
Pin G	Spare
Pin H	Chassis Ground
Pin I	+24 VDC Supply Input
Pin J	Delay/Extension Enable Input (DC), Ch 1

Channel 2, Connector

Pin A	Reserved
Pin B	Output, Ch 2 (−)
Pin C	Reserved*
Pin D	Loop Input, Ch 2
Pin E	Loop Input, Ch 2
Pin F	Output, Ch 2 (+)
Pin G	Spare
Pin H	Chassis Ground
Pin I	Reserved
Pin J	Delay/Extension Enable Input (DC), Ch 2

*Shall not be internally connected.

15.2.29.3 CARD RACK—TWO AND FOUR CHANNEL

Type 7T and 8T—Shall mate with a 44 terminal, double-row, 0.156-inch contact spacing, Cinch Jones card edge connector 50-44A-30M, or equivalent. Input-output connector pin terminations shall be as follows:

Pin A	Logic Ground	1. Delay/Extension Enable Input (DC), Ch 1
Pin B	+24 VDC Supply	2. Delay/Extension Enable Input (DC), Ch 2
Pin C	Reserved for Reset	3. Spare
Pin D	Loop Input, Ch 1	4. Redundant Loop Input, Ch 1 (optional)
Pin E	Loop Input, Ch 1	5. Redundant Loop Input, Ch 1 (optional)
Pin F	Output, Ch 1 (+)	6. Spare
Pin H	Output, Ch 1 (−)	7. Spare
Pin J	Loop Input, Ch 2	8. Redundant Loop Input, Ch 2 (optional)
Pin K	Loop Input, Ch 2	9. Redundant Loop Input, Ch 2 (optional)
Pin L	Chassis Ground	10. Spare
Pin M	Reserved	11. Reserved

Pin N	Reserved	12.	Reserved
Pin P	Loop Input, Ch 3	13.	Redundant Loop Input, Ch 3 (optional)
Pin R	Loop Input, Ch 3	14.	Redundant Loop Input, Ch 3 (optional)
Pin S	Output, Ch 3 (+)	15.	Spare
Pin T	Output, Ch 3 (−)	16.	Spare
Pin U	Loop Input, Ch 4	17.	Redundant Loop Input, Ch 4 (optional)
Pin V	Loop Input, Ch 4	18.	Redundant Loop Input, Ch 4 (optional)
Pin W	Output, Ch 2 (+)	19.	Spare
Pin X	Output, Ch 2 (−)	20.	Spare
Pin Y	Output, Ch 4 (+)	21.	Spare
Pin Z	Output, Ch 4 (−)	22.	Spare

Polarization keys shall be located at three positions:

1. Between B/2 and C/3
2. Between M/11 and N/12
3. Between E/5 and F/6

Two channel units shall have no connection to pins P, R, S, T, U, V, Y, Z, 13, 14, 17, and 18.

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APPENDIX K.

TYPE 170 DETECTOR SPECIFICATION

The following pages contain extracts dealing with detectors from the publication entitled *Type 170 Traffic Signal Control System - HARDWARE SPECIFICATION*. This document is a copy of the New York / California Type 170 Traffic Signal Control System Hardware Specification. This specification was issued by the Offices of Research, Development, and Technology of the Federal Highway Administration of the U. S. Department of Transportation as Implementation Package FHWA–IP–78–16 (July 1985 Revision).

Three chapters are extracted dealing with the three types of detectors discussed in this Handbook, namely, loop detectors, magnetic detectors, and magnetometer detectors. The specific chapters are listed below:

Chapter 4 Specifications for Two Channel Loop Detector Sensor Unit, Model 222. Specifications for Four Channel Loop Detector Sensor Unit, Model 224

- Section I – General Description
- Section II – Functional Requirements
- Section III – Electrical Requirements

Chapter 5 Specifications for Magnetic Detector Sensing Element, Model 231. Specifications for Two Channel Magnetic Detector Amplifier, Model 232. Specifications for Four Channel Magnetic Detector Amplifier, Model 234.

- Section I – General Description
- Section II – Functional Requirements
- Section III – Connector Requirements

Chapter 6 Specifications for Magnetometer Sensing Element, Model 227. Specifications for Two Channel Magnetometer Detector Control Unit, Model 228.

- Section I – General Description
- Section II – Functional Requirements
- Section III – Connector Requirements
- Section IV – Sensing Element Requirements

CHAPTER 4

SPECIFICATIONS FOR TWO–CHANNEL LOOP DETECTOR SENSOR UNIT, MODEL 222

SPECIFICATIONS FOR FOUR CHANNEL LOOP DETECTOR SENSOR UNIT, MODEL 224

This Chapter defines the specifications applicable to the Model 222 Two–Channel Loop Detector Sensor Unit and the Model 224 Four–Channel Loop Detector Unit. These specifications shall supplement the General Specifications for Traffic Control Equipment and in case of conflict the specifications of this Chapter shall govern.

SECTION I

GENERAL DESCRIPTION

1. The two-channel and four- channel loop detector sensor units contain two and four detector channels, respectively. The modules shall be compatible with and intermate to the standard input files. The detector channels working independently, will produce output signals when vehicles pass over of remain within wire loops embedded in the road way.

   The detector units shall be solid state design. The method of detection shall be based upon a design that shall render detection when a conductive metallic mass entering a loop causes a change of 0.01 percent in the detector input inductance

SECTION II

FUNCTIONAL REQUIREMENTS

1. Operational Specifications

   1.1 Each detector channel shall be capable of detecting all types of licensed motor vehicles at a distance of up to 800 feet (244 m) from the loop to the sensor unit.

   1.2 The detector sensor unit shall be mounted on an edge-connected, printed circuit board.

   1.2.1 The 4-channel detector unit shall occupy the space of two 2-channel detector units.

   1.3 Each detector channel shall not draw more than 100 milliamperes from the +24 volt DC cabinet power supply for its operating power.

   1.4 The detector module front panel shall be provided with a hand pull to facilitate insertion and removal from the input file.

   1.5 Each detector channel shall have a front panel-mounted indicator to provide visual indication of each vehicle detection.

1.6 Detector tuning shall be automatic or manual. Only front panel controls shall be used in the manual tuning operation.

1.7 The detectors shall comply with all performance requirements herein specified when connected to an inductance (loop plus lead-in) of from 50 to 500 microhenries with a Q-parameter as low as 5 at the detector operating frequency.

1.8 Each detector channel output shall be an opto-isolated NPN open collector capable of sinking 50 milliamperes at 30 volts. This output shall be compatible with the controller unit inputs.

1.9 Each sensor unit shall intermate with and operate in a Standard Input File.

1.10 A switch position shall be provided to disable the output of each channel on an individual basis.

1.11 Loop inputs to each channel shall be transformer isolated.

2. Tuning

The vehicle detector circuits shall be designed so that drift which occurs with regard to the environment and applied power shall not cause an actuation.

3. Mode Selection Requirements

3.1 Each detector channel shall have two selectable modes of detection — Pulse and Presence.

3.2 Pulse Mode

3.2.1 In the pulse mode, each new vehicle presence within the output pulse of 125 ± 25 milliseconds in duration.

3.2.2 Should a vehicle remain in a portion of the zone of detection for a period in excess of two seconds, the detector channel shall automatically "tune out" the presence of said vehicle. The channel shall the be capable of detecting another vehicle entering the same zone of detection. The recovery time between the first vehicle pulse and the channel capability to detect another vehicle shall be three seconds maximum.

3.3 Presence Mode

3.3.1 In the presence mode, the detector channel shall recover to normal sensitivity with in one second after termination of vehicle presence in the zone of detection regardless of the duration of the presence.

3.3.2 With the detector channel in its most sensitive setting, the presence of a vehicle in the zone of detection shall be detected a minimum of 3 minutes for a vehicle causing 0.01 percent inductance change and a minimum of 10 minutes for a vehicle causing 0.60 percent inductance change.

3.3.3 The lowest sensitivity setting in the presence mode is designated as the "occupancy" (OCC) setting. With the detector channel in the OCC setting, the presence of a vehicle causing a one percent, or greater, change of inductance shall be detected for a minimum of 4 minutes.

4. Sensitivity

4.1 Each detector channel shall be equipped with panel selectable sensitivity setting(s) in both presence and pulse modes to accomplish the following under operational and environmental requirements of this specification:

4.1.1 Each detector channel shall respond to an inductance change of 0.02 percent while connected to the following three turn loop configurations.

(1) Single 6 by 6 foot (1.8 by 1.8 m) loop with a 50 foot (15 m) lead-in cable.

(2) Single 6 by 6 foot (1.8 by 1.8 m) loop with a 800 foot (244 m) lead-in cable.

(3) Four 6 by 6 foot (1.8 by 1.8 m) loops connected in series/parallel with a 250 foot (76 m) lead-in cable.

(4) Four 6 by 6 foot (1.8 by 1.8 m) loops connected in series/parallel with a 800 foot (244 m) lead-in cable.

4.1.2 Each detector channel shall respond to Occupancy (OCC) setting(s) to a nominal change in inductance between 0.15 percent to 0.4 percent while connected to the above loop configurations. This setting shall not respond to an inductance change of less than 0.1 percent.

4.2 The detector channel shall not detect vehicles, moving or stopped, at distances of 3 feet (0.9 m) or more from any loop perimeter.

4.3 All sensitivity settings shall not differ more than ± 40 percent from the nominal value chosen.

5. Response Timing

5.1 Response time of the detector channel for the OCC setting shall be less than 20 milliseconds. That is, for any negative inductance change which exceeds its sensitivity threshold, the output shall a ground true logic level within 20 milliseconds. When such change is removed, the output shall become an open circuit within 20 milliseconds. For test purposes, the negative change of inductance will be maintained for a minimum of 100 milliseconds and a maximum of 600 milliseconds after it is applied. When the difference between the length of time the inductance change is applied, and the corresponding ground true output time are averaged over ten trials, the value that average difference shall not exceed 10 milliseconds.

5.2 The response time of the detector channel for the most sensitive setting shall be less than 250 milliseconds for a 1.0 percent inductance change.

SECTION III

ELECTRICAL REQUIREMENTS

1. Application of Power

    1.1 The detector channels shall begin normal operation within thirty seconds after the application of power or the reset signal.

2. Interference

    2.1 The separate channels contained within a given unit shall include means to prevent cross-talk with one another.

    2.2 Each unit shall include means to prevent cross-talk with other modules. If the prevention means is manual, the control for it shall be located on the front panel of the unit. No additional external wiring shall be required to implement the prevention means.

4. Lightning Protection

    4.1 Lightning protection shall be installed within the detector unit.

        4.1.1 The protection shall enable the detector to withstand the discharge of a 10 microfared capacitor charged to ± 1000 volts directly across the detector input pins with no loop load present.

        4.1.2 The protection shall enable the detector to withstand the discharge of a 10 microfared capacitor charged to ± 2000 volts directly across either the detector inductance pins or from either side of the detector input inductance pins to earth ground. The detector chassis shall be grounded and the detector input pins shall have a dummy resistive load attached equal to 5.0 ohms.

5. Tracking Rate

    5.1 The detector shall be capable of compensating or tracking for an environmental change up to 0.001 percent change in inductance per second. This requirement shall be met within two hours after initial application of operating power.

6. Tracking Range

    6.1 The detector shall be capable of normal operation as the input inductance is changed plus or minus (±) 5.0 percent from the quiescent tuning point regardless of internal circuit drift.

    6.2 The detector shall be capable of normal operation as the input inductance is changed plus or minus (±) 0.5 percent from the quiescent tuning point regardless of internal circuit drift.

7. Temperature Change

7.1 The operation of the detector unit shall not be affected by changes in the inductance of the loop cause by environmental changes with the rate of temperature change not exceeding 1 ° C per three minutes. The opening or closing of the controller cabinet door with a differential temperature of 18 ° C between the inside and outside shall not affect the proper operation of the detector.

8. Board Edge Connector Pin Assignment

Pin	Function	Pin	Function	Pin	Function
A	DC Ground	J	Loop # 2 Input	S	Loop # 3 Output (C)
B.	+ 24 volts DC	K	Loop # 2 Input	T	Loop # 3 Output (E)
C	Detector Reset	L	Chassis Ground	U	Loop # 4 Input
D	Loop # 1 Input	M.	AC –	V	Loop # 4 Input
E	Loop # 1 Input	N	AC +	W	Loop # 2 Output (C)
F	Loop # 1 Output (C)	P	Loop # 3 Input	X	Loop # 2 Output (E)
H	Loop # 1 Output (E)	R	Loop # 3 Input	Y	Loop # 4 Output (C)
				Z	Loop # 4 Output (E)
B.	Slotted for keying	(C)	Collector	(E)	Emitter

9. Reset

9.1 The detector unit shall respond to a ground reset signal of 15 microseconds and begin normal operation within 30 seconds after the reset command.

CHAPTER 5

SPECIFICATIONS FOR MAGNETIC DETECTOR SENSING ELEMENT, MODEL231

SPECIFICATIONS FOR TWO–CHANNEL MAGNETIC DETECTOR AMPLIFIER, MODEL 232

SPECIFICATIONS FOR FOUR–CHANNEL MAGNETIC DETECTOR AMPLIFIER, MODEL 234

This Chapter defines the specifications applicable to the Model 231 magnetic detector sensor element, the Model 232 two-channel magnetic detector amplifier, and the Model 234 four-channel magnetic detector amplifier. These specifications shall supplement the General Specifications for Traffic Control Equipment and in case of conflict the specifications of this Chapter shall govern.

SECTION I

GENERAL DESCRIPTION

1. The two and four channel magnetic detector amplifiers are units containing two or four magnetic detector channels, respectively. Each independent detector channel working with its associated magnetic detector sensing element shall produce an output signal when vehicles pass over the magnetic detector sensing element embedded in the roadway.

   The magnetic detector amplifier shall be of solid state design. The method of detection shall be based upon a design that shall render reliable detection when a voltage is induced in the sensing element by a passing vehicle.

SECTION II

FUNCTIONAL REQUIREMENTS

1. Magnetic detector amplifier requirements (Models 232 and 234).

   1.1 The magnetic detector amplifier shall be mounted on an edge-connected printed circuit board.

      1.1.1 The four channel magnetic detector amplifier shall occupy the front panel space of two 2-channel magnetic detector amplifiers.

   1.2 Each magnetic detector channel shall not draw more than 60 milliamperes from the + 24 volt DC cabinet power supply for its operating power.

   1.3 The detector amplifier front panel shall be provided with a hand pull to facilitate insertion and removal from the Input File.

1.4 Each detector channel shall have a front panel mounted indicator to provide visual indication of each vehicle detection.

1.5 All controls required for tuning, including sensitivity shall be readily adjustable without use of tools and shall be mounted on the front panel.

1.6 When connected to a Model 231 magnetic detector sensing element with 1000 feet (305 m) of lead-in cable the amplifier shall detect a Honda 100 motorcycle passing within 18 inches (46 cm) of the sensing element installed 12 inches (30 cm) below the top of the pavement at all speeds between 3 and 80 miles per hour (5 and 130 kpm).

1.7 Each detector channel output shall be an opto-isolated NPN open collector capable of sinking 50 milliamperes at 30 volts. The output shall be compatible with the inputs for the Model 170 Controller Unit. The output shall indicate the passage of a vehicle by saturating the NPN transistor or optical isolator, with no more than 0.6 volt DC across the output circuit. Detector channel output shall be 100 milliseconds minimum in duration.

1.8 A switch or switch position shall be provided to disable the output of each channel on an individual basis.

1.9 A momentary switch or switch position shall be provided to place a call on each channel on an individual basis.

1.10 Each Amplifier shall intermate with and operate in a Standard Input File.

2. Magnetic Detector Sensing Element (Model 231)

2.2 The case of the sensing element shall be constructed of nonferrous material suitable for use in the environment in which it will operate and shall be sealed to prevent the entrance of moisture. No moving parts or active components shall be contained in the element.

2.3 Each sensing element shall be designed for ease of installation, repositioning, and removal. It shall be no larger than 2-1/4 inches (57 mm) in diameter and shall have no sharp edges along its length. The overall length shall not exceed 21 inches (53 cm).

2.4 Each sensing element shall be provided with a minimum of 75 feet (23 m) of lead-in cable.

2.5 The passage of a Honda 100 motorcycle within 18 inches (46 cm) of the sensing element, at speeds from 3 to 80 miles per hour (5 to 130 kpm), shall provide sufficient signal to operate a Model 232 amplifier with 1000 feet (305 m) of lead-in cable between the amplifier and the sensing element.

SECTION III

CONNECTOR REQUIREMENTS

1. The Printed Circuit Board Edge Connector shall intermate with the Cabinet Input Files.

2. Connector Pin Assignments are as follows:

Pin	Function	Pin	Function	Pin	Function
A	DC Ground	J	Detector # 2 Element	S	Detector # 3 Output (C)
B.	+ 24 volts DC	K	Detector # 2 Element	T	Detector # 3 Output (E)
C	Not Connected	L	Chassis Ground	U	Detector # 4 Element
D	Detector # 1 Element	M.	AC –	V	Detector # 4 Element
E	Detector # 1 Element	N	AC +	W	Detector # 2 Output (C)
F	Detector # 1 Output (C)	P	Detector # 3 Element	X	Detector # 2 Output (E)
H	Detector # 1 Output (E)	R	Detector # 3 Element	Y	Detector # 4 Output (C)
				Z	Detector # 4 Output (E)
B.	Slotted for keying	(C)	Collector	(E)	Emitter

CHAPTER 6

SPECIFICATIONS FOR TWO–CHANNEL MAGNETOMETER DETECTOR CONTROL UNIT, MODEL 228

SPECIFICATIONS FOR MAGNETOMETER SENSING ELEMENT, MODEL 227

This Chapter defines the specifications applicable to the Model 228 two-channel magnetometer detector control unit and the Model 227 magnetometer sensing element. These specifications shall supplement the General Specifications for Traffic Control Equipment and in the event of conflict the specifications of this Chapter shall govern.

SECTION I

GENERAL DESCRIPTION

1.1 The two-channel magnetometer detector control units are units which plug into the cabinet Input File. Each independent detector channel shall produce an output signal when vehicles pass over the magnetometer sensing element embedded in the roadway.

1.2 The detector control units shall be of solid-state design. The method of detection shall be based upon sensing a change in the vertical component of the earth's magnetic field caused by the passage or presence of a vehicle over the detector sensing element.

1.3 A minimum of two modes of operation shall be available as follows:

1.3.1 Pulse Mode. The pulse mode of operation shall provide an output closure of 125 ± 25 milliseconds duration for each vehicle entering the area of detection.

1.3.2 Presence Mode. The presence mode of operation shall indicate continually the presence of a vehicle until the vehicle leaves the area of detection, whereupon the indication shall cease within 100 milliseconds.

SECTION II

FUNCTIONAL REQUIREMENTS

1.1 The magnetometer detector control unit shall be mounted on an edge-connected printed circuit board.

1.2 Each control unit shall house two complete, fully independent detection channels. Each channel shall operate with one to six sensing elements connected to it, and shall provide a separate output closure.

1.3 Each channel shall detect and provide an output closure to indicate the presence or passage of vehicles in lanes equipped with sensing elements at any speed from 0 to 80 miles per hour (0 to 130 kph).

1.4 Parked or stalled vehicles over probes of one channel shall have no effect on the operation of any other channel.

1.5 Each detector channel output shall be an opto-isolated NPN open collector capable of sinking 50 milliamperes at 30 volts. This output shall be compatible with the controller unit inputs.

1.6 Damage to sensing elements or cables of one channel shall not affect operation of any other channel.

1.7 The detector shall operate at any distance up to 3000 feet (914 m) between the control unit and the sensing elements.

1.8 Following a power interruption, the control unit shall return to normal operation within three minutes.

1.9 The front panel of the control unit shall contain:

(a) the light or meter to indicate detection of a vehicle,

(b) the overcurrent protection,

(c) switch for selecting the mode of operation,

(d) controls for calibrating the detector,

(e) a hand pull to facilitate insertion and removal from the Input File,

(f) a switch or control shall be provided to disable the output of each channel on an individual basis. A switch or switch position shall be provided to place a call on each channel on an individual basis.

1.10 All switches and controls shall be clearly and permanently identified and shall be operable without the use of tools or external meters.

1.11 Each control unit shall intermate with and operate in a Standard Input File.

1.12 Each control channel shall not draw more than 120 milliamperes from the + 24 volt DC supply.

1.13 The printed circuit board shall be 4.5 inches by 6.5 inches (11.4 cm by 16.5 cm). The width of the front panel shall be 2.3 inches (5.84 cm).

1.14 The magnetometer detector module shall detect vehicles as required in this section when connected to the magnetometer sensing element, Model 227.

1.15 Each detector channel output shall be an opto-isolated NPN open collector capable of sinking 50 milliamperes at 30 volts. The output shall be compatible with the inputs for the Model 170 Controller Unit.

SECTION III

CONNECTOR REQUIREMENTS

1. The printed circuit board edge connector shall intermate with the 22-pin double-sided connector in the standard Input File.

2. Connector Pin Assignments are as follows:

Pin	Function	Pin	Function	Pin	Function
A	DC Ground	J	Sensing Element # 1 Excitation	S	Control Unit Output # 2 (C)
B.	+ 24 volts DC	K	Sensing Element # 1 Excitation	T	Control Unit Output # 2 (E)
C	Reset	L	Equipment Ground	U	Sensing Element # 2 Excitation
D	Sensing Element # 1 Input	M.	AC –	V	Sensing Element # 2 Excitation
E	Sensing Element # 1 Input	N	AC +	W	NA
F	Control Unit Output # 1 (C)	P	Sensing Element # 2 Input	X	NA
H	Control Unit Output # 1 (E)	R	Sensing Element # 2 Input	Y	NA
				Z	NA
B.	Slotted for keying	(C)	Collector	(E)	Emitter

SECTION IV

MAGNETOMETER DETECTOR SENSING ELEMENTS (MODEL 227)

1. Each magnetometer detector sensing element shall be designed to be compatible with the Magnetometer Detector Module, Model 228.

2. The sensing element shall be cylindrical in shape, shall be no larger than 2 inches (5 cm) in diameter or more than 4.25 inches (10.8 cm) in length and shall contain no moving parts.

3. The sensing element shall have a non-ferrous, moisture-proof housing, shall not be affected by extremes of temperature or humidity, shall be capable of withstanding all types of soil conditions, and shall be sealed to prevent the entrance of moisture.

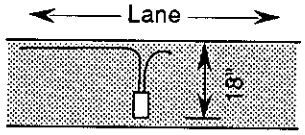
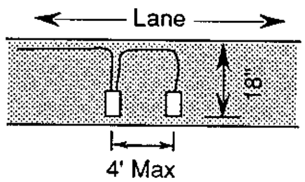
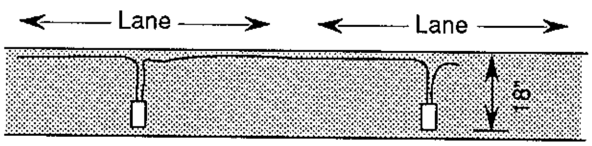
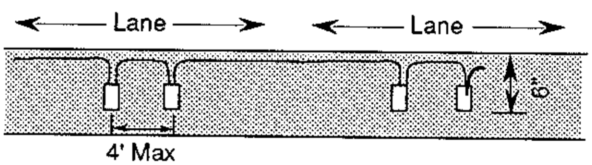
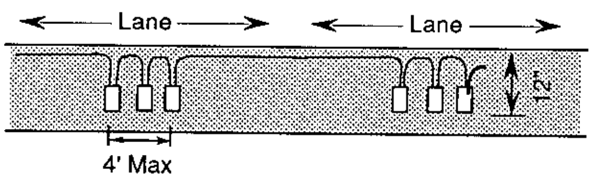
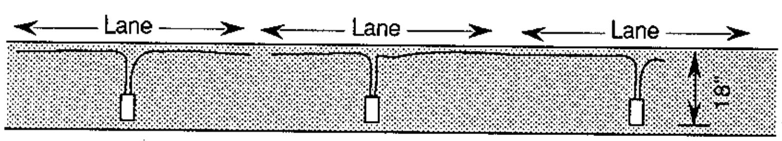
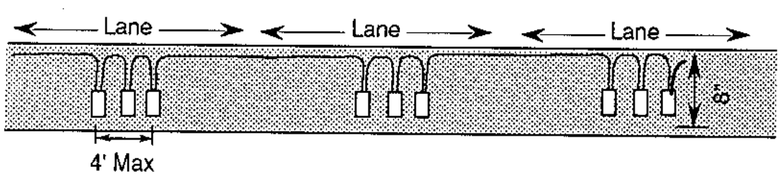
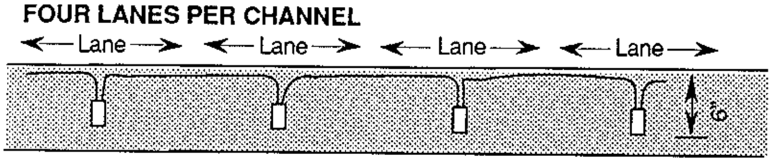
4. The connecting cable attached to each sensing element shall be suitable for both direct burial in earth and installation in conduit, and shall be 50 feet (15 m) in length, minimum.

APPENDIX L

Recommended Magnetometer Configurations

The following material was adapted from the earlier *Traffic Detector Handbook*, 1985. The material originally came from a manufacturer's Application Notes.

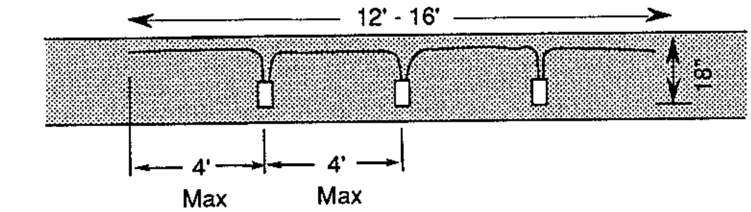
WITHIN LANE DETECTION

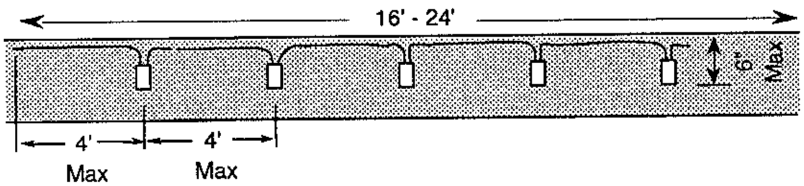
	Application			Lane Width	
	Passage	Presence	Count	$\leq$ 10	10 -12
ONE LANE PER CHANNEL					
	Good	Good	Good	V all	Most
	Best	Best	Best	V all	V all
TWO LANES PER CHANNEL					
	Good	Good	Good	V all	Most
	Good	—	Good (HS)	V all	V all
	Good	Good	Good	V all	V all
THREE LANES PER CHANNEL					
	Good	Good	Good	V all	Most
	Good	Good	Good	V all	V all
FOUR LANES PER CHANNEL					
	Good	—	Good (HS)	V all	Most

HS -High Speed V all -Detects virtually all autos, trucks, buses, etc. Most -Detects most autos, trucks, buses, etc.

WIDE LANE DETECTION

WIDE LANES

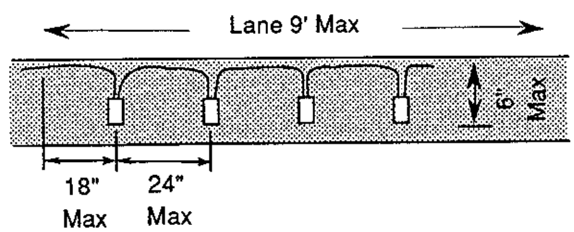


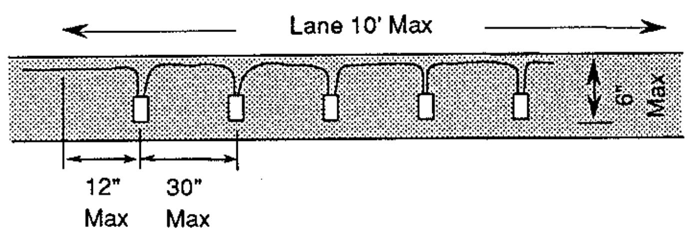


Application			Lane Width	
Passage	Presence	Count	≤ 16	16-24
Good	Good	Good	V all	
Good	Good	Good		V all

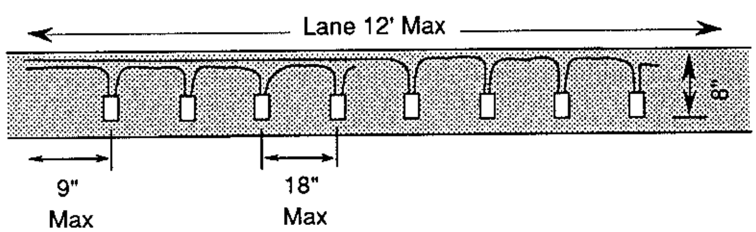
TWO WHEEL VEHICLE DETECTION

ONE CHANNEL PER LANE





TWO CHANNELS PER LANE

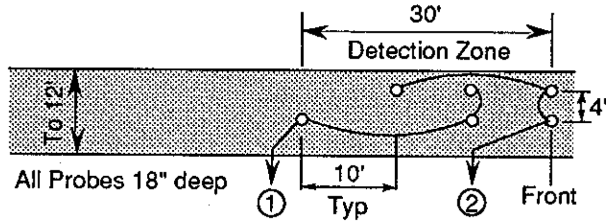


Application			Vehicles	
Passage	Presence	Count	Bikes	MC and Larger
Good	—	Good	Most	V all
Good	—	Good (HS)	Some	V all
Best	Best	Best	V all	Most

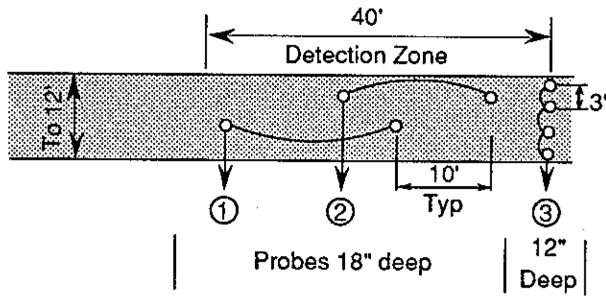
HS -High Speed V all -Detects virtually all autos, trucks, buses, etc. Most -Detects most autos, trucks, buses, etc.

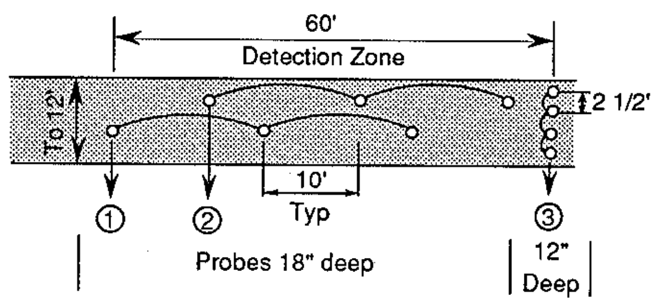
LEFT-TURN LANE DETECTION

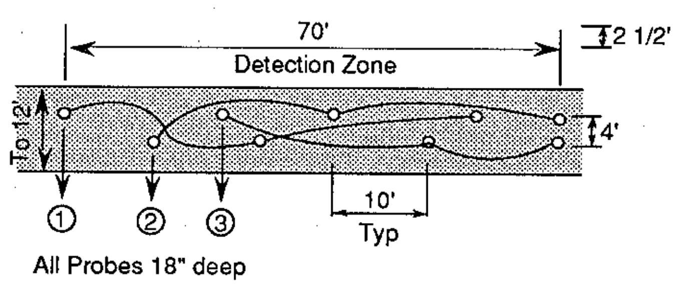
TWO CHANNELS PER LANE



THREE CHANNELS PER LANE







Application		
Number of Probes	Front	Detection Zone
6	V all	Most
8	Most MC & V all	Most
10	Most MC & V all	Most
9	V all	Most

HS -High Speed V all -Detects virtually all autos, trucks, buses, etc. Most -Detects most autos, trucks, buses, etc.

APPENDIX M.
CHARACTERISTICS OF LOOP FAILURES

During the 1980's, a number of studies were conducted to determine the frequency and cause of loop detector failure and to define the factors that contributed to such failures. The underlying purpose of these studies was to identify possible solutions that would increase reliability and life expectancy of loop detector installations. A number of these studies involved testing of various loop configurations and selected materials in agency facilities. None of these particular studies, however, tested all possible configurations or all available materials or products.

SURVEYS EVALUATED

Four studies were particularly significant in that they contained the results of surveys, consisting of questionnaires and interviews, covering the experience of numerous agencies. These studies, identified below, are summarized in this appendix:

- ***Improving Materials and Methods for Insatalling Loop Detectors.*** FHWA-OR-RD 86-03. Oregon Department of Transportation, 1986 (Oregon Study).
- ***Evaluation of Inductor Loop Installation Procedures in Flexible Pavements,*** WA-RD 76.1, University of Washington, 1985 (Washington Study).
- ***Study of Traffic Loop Failures,*** FHWA-MN-RC-84-04. Minnesota Department of Transportation, 1984 (Minnesota Study).
- ***Evaluation and Improvement of Inductive Loop Detectors,*** FHWA Research Report No. 119, New York State Department of Transportation, 1985 (New York Study).

OREGON STUDY

This study was designed to: identify causes of loop system failures and methods used to remedy problem areas through a survey of selected state and local agencies; assess the accumlated data; and test those materials and procedures that appear most likely to be effective in the Oregon state system. To obtain the necessary information, a lengthy questionnaire was distributed to the following state DOT's:

- Alaska
- California
- Idaho
- Montana
- Nevada
- Oregon
- Utah
- Washington

SURVEY RESULTS

Although different materials and installation methods were used by the various agencies surveyed, two major problems associated with loop failure were consistently reported: loop sealant failure (loss of adhesion), and poor installation techniques (e.g. inadequately cleaned or dried sawslots). Another major problem common to many agencies was wire breakage due to asphalt pavement deterioration. The City of Albany, Oregon cited pavement flexing and shoving which caused the epoxy sealant to pop out of the saw slot necessitating resealing. The Portland Metro Region had many problems in loop failure due to road wear down to the loop wire primarily in wheel rut locations. Many agencies also experienced loop loss due to trenching for the installation or maintenance of underground utility lines.

Of particular interest is Alaska's exclusive use of the preformed loop for all of their roadway installed vehicle detection. Their preformed loop is composed of # 12 AWG cross-linked polyethalene wire encased in one-inch, schedule 80 PVC conduit. The loop wire is placed in the conduit, which is then assembled to the specified loop dimensions. Alaska reports no loop failure using this system of preformed loops. Other States also reported the selected use of preformed loops. Oregon uses preformed loops mostly in signalized gravel or dirt detour areas around bridge construction sites. California and Utah have experimented with preformed loops and have achieved satisfactory performance with no loop failures reported.

Table M-1 presents a summary of the survey results. It should be noted that with the exception of the State of Utah, most of the loop installations are performed by contractors.

CONCLUSIONS AND RECOMMENDATIONS

Previous to this study, the Oregon vehicle detection system consisted of a 3- x 3-ft (0.9- x 0.9-m) diamond loop, constructed with four turns of THWN wire. The loop was installed in a 1/4-in (6.5-mm) wide saw cut and encapsulated in a preapproved sealant. The splice between the loop wires and the lead-in cable was made as close as possible to the loop and was soldered, covered with heat shrinkable tubing, and encapsulated with sealant. The lead-in cable (Belden No. 8720) was installed in the sawcut from the loop to the curb or edge of pavement, and then in a conduit underground to the controller.

Based on the research study results, Oregon has amended many of their specifications and practices. They continue to specify a 3- x 3-ft (0.9- x 0.9-m) diamond configuration when the loops are in series in the field. However, any single loops are now required to be 4 x 4 ft (1.2 x 1.2 m). Backer rod to hold down the loop wires is now specified on all state projects. A significant change is that the splice between the loop wires and the lead-in cable is now made exclusively at pullbox locations.

Presence loop configuration evolved to its present specification in order to accommodate the occurrence of smaller vehicles in the traffic stream. Two 3- x 3-ft (0.9- x 0.9-m) diamond loops are connected in series. A single 4- x 4-ft (1.2- x 1.2-m) diamond is placed upstream to provide a long loop effect. Information from this detector is input into a separate detector channel so that the Model 170 controller "carry-over" feature may be used.

Presence type operation is used on left turn lanes and most side streets. Loop spacing is now 4 ft, 12 ft, and 60 ft (1.2, 3.6, and 18 m) from the stop line as shown in Figure M-1.

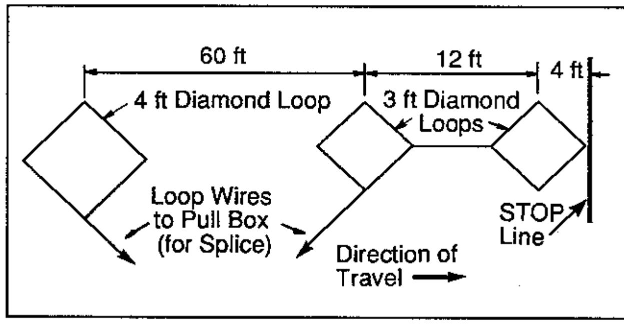


Figure M-1. Presence loop configuration.

Because of the incidents of sealant failure, 16 sealant products were tested on both asphalt and cement pavements. Sealant installation was made in July 1983 and was continually observed until the spring of 1984.

The sealant was subjected to a cross-section of weather. July, August and September were very warm and in December, snow and freezing condition were present. Cold and wet conditions continued though the winter months. Ten of the sealants tested were approved and added to the approved product list. It was recommended that testing of various epoxy sealants be continued.

Oregon State maintenance personnel expressed interest in enclosing the loop wire in a 1/4-inch vinyl tube prior to placement of the wire in the saw slot. While it was determined that this item was worthy of consideration, the State expressed concern about the need for a wider saw slot and extra sealant and the requirement to twist the loop wire 4 to 6 turns per foot from the loop to the pullbox.

Table M-1. Oregon survey results.

State	Percent Installed by		Major Failures	Remarks
	State	Contractor		
Alaska	10	90	No loop failures reported	Exclusive use of preformed loops
California	5	95	Improper sealing and foriegn material in saw slot	Uses preformed loops in poor pavement and dirt detours
Idaho	10	90	Improper sealing	No failure for loops made of # 20002 cable
Montana	10	90	Improper sealing	—
Nevada	5	95	Improper sealing and pavement deterioration	—
Oregon	10	90	Improper sealing	—
Utah	70	30	Improper sealing and pavement deterioration	Used some preformed loops with no failures
Washington	10	90	Improper sealing and foriegn material in saw slot	Need better inspection to improve loop performance

It was evident, from the State experience and from the gathered data, that complete cleanout and drying of the loop saw slot is vital to long lasting, effective loop performance. The State became interested in the saw cut cleanout nozzle developed by the State of New York. This nozzle uses the "venturi" principle to supply pressurized water for cleaning out the slot after sawing. A nozzle was fabricated by the State based on the New York design. Valves were added to control both air and water feed lines so that the option was available to use air only, water only, or an air/water mixture. This nozzle is being used in loop installations by three of Oregon's five regions. They report a better bonding of sealant to the saw slot due to the more efficient cleaning of the saw slot by the nozzle.

WASHINGTON STUDY

This study was conducted by the University of Washington Civil Engineering Department and was sponsored by the Washington State Department of Transportation (WSDOT) in cooperation with FHWA. The purpose of this research was to identify the types and frequency of loop detector failure and to identify possible solutions. Specifically, the study focussed on the reasons for loops becoming dislodged from the saw slot, the frequency of failure, the optimum products and installation techniques.

The information base for the study consisted of a literature search and a State and national telephone survey of traffic engineers. A questionnaire was developed for the survey that could accommodate either verbal or written responses. The survey participants represented 23 cities and 7 counties within Washington State, 6 districts of the WSDOT, and 9 other State agencies representing a geographic cross section of the country. It was noted that many of the State and local agencies did not maintain precise documented records related to detectors; accordingly, respondents were asked to provide estimates as necessary. As a result, much of the information obtained must be considered qualitative.

SURVEY RESULTS

The number of loops within the responding jursidictions and the corresponding failure rates are given the Table M-2. The cities and counties within the State of Washington had the same median number of loops, while the WSDOT districts had a much greater mean, median, and range for the number of loops. County officials reported the lowest incident of loop failures. The WSDOT districts and cities seemed to have relatively comparable failure rates. Out-of-State respondents reported much higher failure rates than those reported in the State of Washington.

Table M-2. Washington State survey results.

	Number of Loops	Failure Rate % per year
Cities (23):		
Mean	477	4.1
Median	300	2.4
Range	1724	11.7
Counties (7):		
Mean	646	3.4
Median	300	1.7
Range	2090	9.5
WSDOT Districts (6):		
Mean	1255	3.8
Median	525	3.0
Range	4070	9.0
Out-of-State (9*):		
Mean	N/A	11.3
Median	N/A	9.0
Range	N/A	34.5
* AZ, FL, GA, IL, MS, NE, NC, PA, & TX		

The majority of the responding agencies felt that their loop failures were not excessive. Those indicating excessive failures complained that repair procedures were very costly and that loop performance needs to be improved.

When asked how failures were detected, the survey showed that for Washington cities, notification of loop failure was primarily from individuals outside the traffic department (i.e., the general public, police, other agencies, etc.). For the WSDOT districts and county agencies, most failures were discovered by their own personnel.

In the case of WSDOT, this is a result of their 12 inspections per year of each installation. Out-of-State agencies reported that failures were most frequently identified by sources outside their responsible department.

Pavement failure was frequently identified as the cause of loop failure. Cracking was listed as the primary mode of pavement distress, while permanent pavement deformation (rutting and shoving), or a combination of this with cracking was also reported as a primary reason for loop failure.

Amplifier failure as defined by respondents ranged from lightning damage to the need for constantly retuning older models to adjust for temperature changes. Other respondents stated that, although retuning was occasionally necessary, it was not considered to be a "failure."

The questionnaire asked what methods were used to monitor detector loops. The answers were categorized as follows: Periodic inspection, wait for complaint about a traffic signal, continuous monitoring, or a combination of the above. Periodic inspections were the predominant method with periods ranging from 1 to 25 times per year per installation. Continuous monitoring was used by some agencies particularly in areas of high congestion in order to optimize traffic flow.

When asked who installed the loops, approximately 90 percent of the installations were performed by contractors. Only one State DOT indicated that 98 percents of its loop installations were accomplished by in-house personnel.

Most of the cities and counties within Washington State cited WSDOT specifications for loop detectors. The loop shape of preference was the square loop or quadrupole. Very few agencies specified rectangular or diamond loops.

Out-of-State agencies specified a variety of loop shapes including the chevron. The quadrupole was given the highest ratings for sensitivity and reliability. Square and rectangular loops scored high on reliability but somewhat less on sensitivity. Most sensitivity problems were associated with vehicles having a high ground clearance such as logging trucks. Most agencies expressed some concern for the detection of light vehicles such as bicycles and small motorcycles.

The preponderance of agencies used only pressurized air to clean out saw cuts. The use of high pressure water followed by pressurized air is seldom used. The reasoning cited for this was the need for the cuts to be dry prior to the placement and sealing of the loop wire.

The choice of loop wire was fairly consistent among the agencies surveyed. Although the State specifies # 14 gauge wire with RHH-RHW insulation, many of the city agencies preferred #12 THHN or TWN wire. Out-of-State agencies were about equally divided between #12 and #14 gauge wire.

The methods and products used for sealing the saw cuts and splices varied considerably. Many of the agencies within the State used the WSDOT specifications for sealants. Some of the city agencies used either polypropelene rope or cotton rope on the top and bottom of the wire to prevent the wire from floating to the surface. (Cotton rope was substituted for the polypropelene rope as the polypropelene rope tends to be deformed when covered with hot asphalt forcing the rope out of the slot. Most of the WSDOT Districts use roofing asphalt as a sealant, while out-of-State agencies tended to use commercial sealants that had been tested and approved prior to their use. For splicing, more out-of-state agencies used sealant kits and/or heat shrink tubing with silicone sealer for their splices than agencies within the State.

CONCLUSIONS AND RECOMMENDATIONS

The failure rates reported by Washington agencies were much lower than reported by out-of-State DOT's and in the literature. The largest single factor contributing to loop failure appears to be pavement cracking. The next most important factor was breaking of loop wires due to utility repair or construction. Other significant factors include poor inspection procedures, pavement rutting, and sealant failure.

Problems associated with the electronic unit can be attributed to the inability of these units to adjust to temperature changes and to moisture or other changes within the loop wire or lead-in cable. This can be resolved by purchaing self-tuning amplifiers and by complete encapsulation of the loop wires. The study recommended that rope to hold down wire be eliminated.

Much concern about the poor quality of inspection of loop installations was expressed by WSDOT districts. It was pointed out that the best remedy for poor inspection is training and experience. Training may be accomplished on-the-job by assinging new inspectors to more experienced personnel or through formal classes. Inspectors must remain in their jobs long enought to be effective in the enforcement of specifications.

It was also suggested that forms and procedures should be developed to track loop performance. Such records would provide valuable information on the expected life of loops, failure rates, failure modes, quality and reliability of products, etc.

Finally, it was recommended that self-sealing heat shrink tubing should be considered for splicing wires. It is used quite successfully in the marine industry in deep underwater applications and adds extra strenth and abrasion resistance to the area of the splice. Heat guns with fixed temperature heads should be used with the temperature selected to avoid damage to the wire coating.

MINNESOTA STUDY

The Minnesota Department of Transportation's Office of Traffic Engineering had determined that 14 percent of their signal maintenance time was spent repairing loop detectors because of poor installation procedures, pavement deterioration, or the environment. Consequently, the State Office of Research and Development as asked to conduct a study to identify the reasons for loop detector failure and where within the installation the failure usually occurs.

A literature search revealed that Minnesota's problems are not unique—loops installed by other States in the snowbelt area are also affected by moisture, loop sealant failure, and pavement cracks and joints. A survey questionnaire form was developed and distributed to all the snowbelt States (all States above 36 degrees latitude were considered in the snow belt region). The District of Columbia and Provinces of Canada were also included as were the major City and County agencies within the Minnesota.

Completed survey forms were received from 26 States, two Counties, two Cities, and three Provinces. The questionnaire covered two critical areas of interest: reasons why the loop detector fails, and the materials and procedures used by each agency when installing loop detectors. In addition to the literature search and the survey, Mn/DOT's personnel were observed making loop repairs.

SURVEY RESULTS

From an initial review of the completed questionnaire it was clear that most states, including Minnesota, did not keep good records concerning reasons for failure. Characteristically, if it was determined that a short or open circuit had occured in the loop wire, no investigation was made as to where or why the short was there. The loop wire was simply replaced.

It was learned that many failures occurred because of broken wires or deteriorated insulation at concrete pavement joints, pavement cracks running through the loop, or at the pavement interface with a curb or shoulder. In addition, failures frequently occured in pull boxes were the loop wires are spliced with the lead-in cables. Only one agency indicated that they did not make their splices in a pull box.

Splice failures occur because of corrosion, moisture, or poor connecting methods. A number of problems occurred with the "V" formed between wires held side by side as their ends were twisted together. Soldering was favored over crimping while some agencies crimp and then solder. Many of the agencies sealed their connections with a waterproofing agent and then wrapped with tape. Other agencies encapsulate the connections in an epoxy or other slot sealant using drug store pill boxes or paper bags to serve as inexpensive molds. Commercial sealing kits were also used.

Another problem frequently mentioned was detector failure caused when older models of amplifiers become de-tuned. Deteriorated wire insulation, poor splices, temperature changes, moisture, vibration, electrical storms, and wire movement all contribute to this type of failure. Many agencies have alleviated this problem by using digital self-tuning amplifiers.

As for wire type, 25 agencies used #14 AWG wire for their loops. Stranded wire is always used, and Type THHN and THWN is favored for insulation. Eleven agencies enclose the insulated wire in a thin vinyl tubing which creates a conduit effect and provides added protection, and three agencies are experimenting with this concept. This tube encased wire is commercially available or can be made up in-house.

For sealing the saw slots, 12 commercial brands of sealant were mentioned as well as many types of epoxy and polyester resins and unspecified asphalt compounds. Experience and price seem to be the criteria used in making a selection.

The question of most concern in this study involved the way the various agencies installed their traffic loops. The response indicated three particular procedures were most important in installing loops: laying and sealing the loop wires, addressing the loop corners, and crossing expansion joints or pavement-shoulder joints.

The evolution of Mn/DOT procedures used to lay and seal the loops wires proceeded from merely inserting the turns of insulated wire in the slot and sealing with any type of inexpensive sealant. It was soon learned that these inexpensive, untested sealants were unsuitable for preventing water and foreign materials from entering the slot. The sealant would either loose its bond with the sides of the slot or would deteriorate to the point where it would just disintegrate. Foreign materials entering the slot could pierce the wire insulation and allow moisture to come into contact with the loop wire thus causing detuning or possibly a short.

This led to the testing of various sealants to find a sealant that will maintain adhesion to the side of the slot during expansion, withstand compression when joints are contracting, and yet be of the right viscosity to be poured into the slot but not run out if the slot is on an incline. It also became apparent sharp edges along the slot edges and at the loop corners could also create breaks in the wire insulation. Therefore, it was determined that the sharp edges should be smoothed and the debris flushed from the slots with pressurized water and then blown dry with compressed air.

Sharp bends at the loop corners were reduced by cutting 45 degree diagonal slots. However, this method created triangles at each corner that could eventually break down from the wheels of vehicles passing over the area. Several agencies covered this problem by drilling 1- or 2-in (2.5- or 5.1-cm) holes at each corner instead of cutting the diagonals. The corners of the hole are then chiseled out to remove the sharp edges. Other agencies did not drill holes at the corners; rather, they chisel out the inside of the corner to create small open triangular areas. Whether they drill holes or chisel, to accommodate any movement of the pavement it was stressed that slack in the wire should be left at each corner.

Many ideas have been presented on how to fill the slots and corners with sealant. Some agencies simply lay the wire in the bottom of the slot and fill with sealant, hoping that most of the wire will be encased. In an effort to better encapsulate the wire, others partially fill the bottom of the slot with sealant, lay the loop wire, and then add more sealant until it is almost flush with the top of the slot. Still other agencies go to the trouble to put sealant in the bottom of the cut and between each turn of the loop wire before final sealing to achieve total encapsulation.

To create a conduit effect without the need for wide saw cuts, some agencies choose to cut a standard slot, lay the wires, and then wedge a form of rope in the slot over the wire before adding sealant. This procedure also reduces the amount of sealant needed. One agency suggested that this method creates problems in that the rope is not as resilient as the sealant and that voids occur between the wires and rope and/or the slot. A conduit effect can be achieved during asphalt pavement construction by cutting the slots and inserting the wire before adding the final layer of bituminous asphalt.

Rigid plastic tubing (PVC) is used as conduit for preformed loops by a number of agencies. This 1/2- to 1-in (13- to 25-mm) tubing is often installed during construction before the final courses are laid. However, if it is used in an existing installation, much wider cuts must be made to accommodate the tubing, thus weaking the pavement structure. Experience has demonstrated that preformed loops are particularly effective where the pavement is broken or in poor condition.

CONCLUSIONS AND RECOMMENDATIONS

Mn/DOT contracts out the installation of new traffic signals, ramp meters, and automatic traffic counters, all of which use loop detectors to activate these traffic control devices. Inspection of new installations is preformed by Mn/DOT inspection personnel. Repairs or replacement of failed loops are primarily accomplished by Mn/DOT maintenance staff.

It should be noted that previously, Mn/Dot did not require its in-house crews to follow the same procedures and State specifications as those required of a contractor. For example, the contractor is required to place a layer of sealant in the bottom of the slot before installing the loop wire, while Mn/DOT crews simply lay in the wire and cover with sealant. In addition, in-house crews use # 14 AWG wire instead of the specified # 12 AWG. However, Mn/DOT forces use insulated wire encased in a thin vinyl tubing, which is not required of the contractor.

It was found that there were occasions where the Mn/DOT crew created their own problems by choosing poor locations for the new loops or routing the lead-in wires through areas already showing distress. Moreover, they do not follow specifications regarding expansion joints, cracks, or pavement edges.

Based on this study project, their primary recommendation was to ensure that the procedures used by Mn/DOT's repair crews be consistent with those required of the contractor in installing a new loop. It was also recommended that effort be directed toward achieving consistency between each crew making repairs. Using Mn/DOT's standard plates as guidelines, it was suggested that the repairmen meet and decide how future repairs would be made. The major points to be covered include:

- Depth of loop saw slots and steps to be taken to ensure that a consistent depth is maintained.
- How loop corners are to be treated.
- Size and type of conductor used for loop wire.
- Treatment of pavement joints or crack passing though the loop.
- Procedures for inserting and sealing loop wire.
- Procedures for splicing and waterproofing splice.

A significant portion of the loop failures experienced in the State was attributed to poor installation procedures by the contractor. Poor inspection procedures contribute to these failures. It was recommended that the Mn/DOT inspectors become more knowledgeable in the proper installation of traffic loops and conduct more aggressive inspections *during* installation.

A major conclusion evolving from this study was consistent with other survey findings: records and documentation of loop failures throughout the country are wholly inadequate. It is common practice to simply replace a failed loop installation without investigating the cause of failure or the precise mechanism of failure. It was concluded that detailed information on loop failures is critical to determine the most appropriate procedure or product that would enhance reliability and loop life expectancy.

To resolve this inadequacy, Mn/DOT has recommended that all new loop installations be documented and stored in a computer program. Initial input would include type and size of wire, model of electronic detector unit, sealant used, identity of installer (contractor or in-house crew), etc. This installation would then be tracked throughout its lifetime with all repairs fully documented.

A new repair sheet would be developed that would include a check-off list for use during trouble shooting and details on reasons for failures and on repairs made. All replaced equipment would be identified and input into the computer for future reference.

NEW YORK STUDY

This study included an indepth survey of nine New York State DOT regions responsible for over 15,000 loop installations. Although this study did not include a survey of out-of-State agencies, several State DOT's were contacted relative to the types of sealants used. The study was initiated after a 1980 study determined that up to 25 percent of New York State's 15,000 loop detectors were not operational at any given time. It was further determined that loop detectors were maintenance-free for an average of only 2 years. Consequently, this study was designed to find the major causes of loop failures and to identify steps to reduce the frequency of failure.

SURVEY RESULTS

All current loop failures in the State were listed and a number of installations were inspected to determine if actual causes of failure were readily discernible. In most instances, failures were attributed to one or more of the following factors:

- Design and installation oversights.
- Sealant failure.
- Wire failure.
- Various types of pavement failure.
- Utility construction activities.

An evaluation sheet was designed to record failure types during the full-scale investigation. A total of 340 failed loops were fully documented and sorted into various categories of major failure type. In all cases, final failure was due to a broken or grounded wire resulting from installation error, material problems, or other difficulties.

Of the surveyed loops, 40 percent had exposed wires, and 20 percent had broken wires. Broken or exposed wires were attributed to three major causes: sealant failure, pavement failure (cracking, potholes, and shoving), and wire float. About 50 percent of the failed loops that were examined had partial or complete sealant failure.

It was determined that when the sealant did not achieve a good bond to the sidewalls of the slot, debris and water could infiltrate the slot. The sealant can then be forced out of the slot, exposing the wire to traffic and inducing loop failure. Moisture could also enter the slot and create an electrical ground. Once moisture entered, expansion and contraction of the water during freeze-thaw cycles would further disrupt the loop and abrade the insulation, exposing the wire to an electrical ground.

The most frequent pavement failure affecting the loop wire is cracking. In general, pavement failure causes the loop wire to be strained resulting in wire breakage, wire insulation wear, or the infiltration of foreign materials. Of the failed loops, 50 percent of the AC and asphalt-overlaid PCC surfaces displayed some cracking.

Loops in PCC without overlays represented only 20 percent of the cracking failures. However, this type of pavement presents other problems: gross slab movements that strain the wire at the pavement-shoulder interface, or where loop wires cross joints. Table M-3 presents a summary of the survey results by types of failures for each type of pavement.

Table M-3. New York survey results.

Failures	Failed Loops, percent			
	Total	Type of Pavement *		
	Loops	AC	Comp	PCC
Number	340	275	20	45
Percent	100	81	6	13
Surface Cracking				
Major	18	20	20	2
Minor	29	30	40	20
None Visible	53	50	40	78
Pavement Heaving				
Visible	10	12	0	0
None Visible	90	88	100	100
Pavement Patching				
Patched	14	14	20	9
No Patching	86	86	80	91
Sealant Loss				
Partial	35	40	10	11
Total	23	20	30	38
None	42	40	60	51
Loop Wire Visible				
Visible	39	39	35	38
Not Visible	61	61	65	62
Broken Loop Wire				
Broken	22	21	25	29
None Evident	78	79	75	71

* AC = Asphalt pavement
Comp = Asphalt overlay on concrete pavement
PCC = Concrete pavement

CONCLUSIONS AND RECOMMENDATIONS

This extensive examination of failed loops revealed two major areas for further study—sealant reliability and reduction of wire breakage due to pavement failure. This survey also led to the conclusion that problems existed in the installation process.

Some failed wires were found very close the surface even when the sealant had adequate adhesion to the sidewalls of the slot. It was concluded that the wire had floated to the surface either before the sealant could cure, or because the sealant remained plastic.

On inspection of various splicing methods and materials used in the pullbox, it was found that different techniques were applied depending on the individual doing the splice. To guarantee waterproofing integrity and longevity of the splice, better techniques should be evaluated and the best methods incorporated into a statewide standard.

After a thorough investigation of various installation elements and procedures, the following changes were recommended:

- Use encased loop wire (requires a 3/8-in (9.5-mm) slot instead of 1/4-in (6.4-mm).
- Chip or core corners of loop sawcut rather than diagonal cuts.
- Use cold-applied sealant. Hot-asphalt sealants have proved less effective and can cause severe damage to wire insulation.
- Use a higher horsepower saw for the sawcut (18 hp or higher) and use water with sawing operation.

- Assure saw slot is properly cleaned and dried before application of sealant.
- Assure that appropariate holddown materials are used and properly applied.
- Use proper splicing techniques.
- Standardize installation techniques, make sure that the work force is fully aware of these standards, and that specifications are rigidly enforced on both the contractor and the agency.
- Continue evaluation to determine best currently available methods and materials.

Ministry of Transportation Ontario

VOLUME 1 - ELECTRICAL DESIGN MANUAL PART 2 - COMPONENT DESIGN

Chapter 9

Grounding

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Reasons for Grounding — Section I

1. Safety Grounding

(1) Grounding of all metallic electrical enclosures is required for safety. If a live conductor touches the metal, a large 'short circuit current' flows to ground thus tripping the circuit breaker. If the metal were not grounded, it would assume the same voltage as the touching conductor and remain so until discharged to ground. When touched the discharge could be through the person's body to ground depending on the resistance of gloves, boots and the material the person is standing on.

2. System Grounding

(1) A low voltage system is grounded throughout to ensure that any line-to-ground fault is cleared by the circuit breakers prior to doing any permanent power system damage such as melting of cables etc. The systems ground is usually tied to the safety ground. If the two grounds are separate the following disadvantages occur:

(a) 'Resistance to ground' of both system and safety grounds is greater than would be the case if the two were connected together.

(b) High currents could still flow in the safety ground in the event of cable insulation failures in the enclosure.

(c) A high degree of coupling, through the earth, is difficult to avoid if the ground rods are in the same local area.

(d) Where decoupling is possible, voltages (often dangerous) can be possible between the nearby 'grounded points'.

3. Lightning Discharge

(1) Lightning induced currents on cables must be given a fast and easy path to ground through protective devices such as lightning arresters, varistors and gas-tube arresters. If the path to ground is not provided properly the voltage surge 'spikes' and resultant current and energy will damage components. Electronic components are particularly susceptable to damage since they operate at very low voltages and high speeds and are not designed to physically absorb any significant energy.

Calculation of Resistance to Ground

Section II

1. General

(1) A minimal resistance to ground is desirable. Older versions of the Code called for 10 Ω maximum to ground. This requirement is now replaced with a description of the physical grounding materials, or, in the case of a substation, limiting the voltage rise, due to a fault, to 5000V. The requirement for 10 Ω was difficult to design and perhaps even more difficult to obtain during installation.

(2) The resistance to ground depends on several non-exclusive factors:

- (a) The number and length of ground rods
- (b) The number and length of connecting ground wires in the ground grid
- (c) The quality of wiring connections
- (d) The resistivity of the earth
- (e) The temperature of the earth
- (f) The water content of the earth

(3) The last three factors are somewhat weather dependent and are therefore beyond precise design.

2. Soil Resistivity

(1) The resistivity of the soil, at the site under consideration, is a measure of the resistance to conducting electrical current and is measured in Ωm (ohm-metres). Representative values are given in Table 1:

Soil Type	Resistivity 'ρ' (Ωm)
Clay, Saturated Silt	100
Sandy or Silty Clay	250
Clayey Sand or Saturated Sand	500
Sand	1500
Gravel	5000
Dry Sand, Rock	>5000

Table 1. Representative values of Soil Resistivity

(2) The soil classification and ρ values in Table1 are left purposely vague since environmental effects can drastically change the resistivity of the soil. Table 2 shows the typical variation of a nominal resistivity with different soil temperatures:

Ground Temperature, 0° C.	Resistivity (% of Nominal)
20	73
10	100
0+	139
0- (freeze)	303
-5	798
-10	3333

Table 2. Variance of Resistivity with Ground Temperature

(3) As well as temperature, resistivity varies widely with moisture content, ranging by a factor of 350% higher for soil in the 'dry' state as opposed to a 'wet' state.

(4) In order to custom design a grounding system, the designer would need to know not only the type of soil and its resistivity but also the condition of future measurements. For this reason, a resistivity of $\rho = 100\ \Omega m$ is selected as the basis of design for grounding systems. (The system is field measured upon installation and any deficiencies can be made up by installing supplementary facilities). It should also be noted that Ontario has little or no lightning activity during months when the ground temperature is below the freezing point.

3. Ground Electrode Resistance to Ground

3.1 Ground Rods

General

(1) Resistance to ground for a single ground rod may be calculated from:

$$R_G = R_R = \frac{\rho}{2\pi L_R}\left[\ln\left(\frac{4L_R}{a_R}\right) - 1\right]$$

where:

R_G = Resistance to ground in ohms

ρ = Soil resistivity in Ω m

L_R = Rod length in metres

a_R = Rod radius in metres

R_R = Resistance to ground of one rod in ohms

Example 1: for 20 mm × 3 m Rod

Given $\rho = 100\Omega m$, $L_R = 3$ m, $a_R = 0.01$ m

$$R_G = \frac{100}{2\pi \times 3}\left[\ln\left(\frac{4\times 3}{0.01}\right) - 1\right] = \boxed{32.2\Omega}$$

If the soil is wet and ρ decreases to $\rho = 50\ \Omega m$

$$R_G = \frac{50}{2\pi \times 3}\left[\ln\left(\frac{4\times 3}{0.01}\right) - 1\right] = \boxed{16.1\ \Omega}$$

If the soil is dry and ρ increases to $\rho = 300\Omega m$:

$$R_G = \frac{300}{2\pi \times 3}\left[\ln\left(\frac{4\times 3}{0.01}\right) - 1\right] = \boxed{96.9\Omega}$$

It may be seen that the nominal resistance to ground of 50 Ω usually quoted for a single ground may vary substantially depending on soil type or conditions.

Example 2: for 20 mm × 6 m Rod

Given $\rho = 100\ \Omega m$, $L_R = 6$ m, $a_R = 0.01$ m

$$R_G = \frac{100}{2\pi \times 6}\left[\ln\left(\frac{4\times 6}{0.01}\right) - 1\right] = \boxed{18.0\Omega}$$

or for a 100% rod depth increase (over example 1), the resistance to ground is decreased by 44%.

Example 3: for 25 mm × 3 m Rod

Given $\rho = 100\ \Omega m$, $L_R = 3$ m, $a_R = 0.0125$ m

$$R_G = \frac{100}{2\pi \times 3}\left[\ln\left(\frac{4\times 3}{0.0125}\right) - 1\right] = \boxed{31.1\Omega}$$

or for a 25% increase in rod diameter (over that of Example 1), the resistance to ground is decrease by 3%.

3.2 Pedestals

(1) Using the same formula as for a single ground rod,

$$\boxed{R_G = R_R = \frac{\rho}{2\pi L_R}\left[\ln\left(\frac{4L_R}{a_R}\right) - 1\right]}$$

we have the following examples:

Example 4: for Steel Footing (220 mm dia. x 2300 mm)

Given $\rho = 100\ \Omega m$, $L_R = 2.30$ m, $a_R = 0.110$ m

$$R_G = \frac{100}{2\pi \times 2.30}\left[\ln\left(\frac{4\times 2.30}{0.110}\right) - 1\right] = \boxed{23.7\Omega}$$

or 26 % "better" than a single rod.

Example 5: for Steel Footing (85 mm dia. x 1830 mm)

Given $\rho = 100\ \Omega m$, $L_R = 1.830$ m, $a_R = 0.043$ m

$$R_G = \frac{100}{2\pi \times 1.830}\left[\ln\left(\frac{4\times 1.830}{0.043}\right) - 1\right] = \boxed{36.0\Omega}$$

or 12 % "worse" than a single ground rod.

3.3 Plate Electrodes

General

(1) For a single plate:

$$\boxed{R_G = R_P = \frac{\rho}{2\pi L_P}\left[\ln\left(\frac{8W_P}{0.5W_P + T_P}\right) - 1\right]}$$

where:

R_P = Resistance of plate to ground in ohms

L_P = Length in metres

W_P = Width in metres

T_P = Thickness in metres

Example 6: for 610 × 610 × 6 mm Plate

Given ρ = 100 Ωm, L_P= 0.61 m, W_P =0.61 m, T_P = 0.006m

$$R_G = \frac{100}{2\pi \times 0.61}\left[\ln\left(\frac{8 \times 0.61}{0.305 + 0.006}\right) - 1\right] = \boxed{45.8\Omega}$$

3.4 Wire Grids

General

(1) For the case of a grounding system consisting of a wire grid only, the wire shape forms a ground plane (similar to antenna design) which, if buried deep enough, can constitute the most effective part of grounding system. (Ground rods are normally driven in any event in order to penetrate below the frost line).

The resistance to ground for a grid system is approximated by:

$$\boxed{R_G = R_W = \frac{\rho}{\pi L_W}\left[\ln\left(\frac{2L_W}{\sqrt{d_W Z_W}}\right) + \frac{1.4L_W}{\sqrt{A_W}} - 5.6\right]}$$

where:

R_W = Resistance of wire grid in ohms

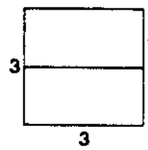
L_W = Total Length of grid wires in metres

d_W = Diameter of wire in metres

Z_W = Burial depth of grid in meters

A_W = Plan area covered by grid in square metres

Example 7: Using 3 × 3 m grid with cross-tie

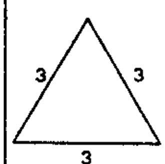


Given: $\rho = 100\,\Omega m$, $L_W = 5 \times 3 = 15\text{m}$, $Z_W = 0.3$ m

$A_W = 3 \times 3 = 9$ sq. m., $d_W = 0.0105$ m (#2/0)

$$R_G = R_W = \frac{100}{\pi \times 15}\left[\ln\left(\frac{2\times 15}{\sqrt{0.0105\times 0.3}}\right) + \frac{1.4\times 15}{\sqrt{9}} - 5.6\right] = \boxed{16.4\Omega}$$

Example 8: Using 3 × 3 × 3 m Triangular Grid



Given: $\rho = 100\,\Omega m$, $L_W = 3 + 3 + 3 = \text{m.}$, $Z_W = 0.3$ m

$d_W = 0.0105$ m (#2/0), $A_W = 0.5 \times 3 \times 3 \sin 60^o$

$= 3.90$ sq. m.

$$R_G = R_W = \frac{100}{\pi \times 9}\left[\ln\left(\frac{2\times 9}{\sqrt{0.0105\times 0.3}}\right) + \frac{1.4\times 9}{\sqrt{3.9}} - 5.6\right] = \boxed{23.2\Omega}$$

3.5 Multiple Rods

General

(1) The combined effect of several rods is similar to the rod resistance acting in parallel and is given by:

$$R_G = R_{MR} = \frac{\rho}{2\pi n L_R}\left[\ln\left(\frac{4L_R}{a_R}\right) - 1 + \frac{2.8L_R(\sqrt{n}-1)^2}{\sqrt{A_R}}\right]$$

where:

R_{MR} = combined resistance of multiple rods to ground in ohms

n = number of rods

A_R = Area covered by the n rods

for 20 mm x 3 m rods:

$$R_{MR} = \frac{\rho}{\pi n}\left[1 + \frac{(1.4)(\sqrt{n}-1)^2}{\sqrt{A_R}}\right]$$

Example 9: Using Four Rods on 3 m Square

Given $\rho = 100\ \Omega m,\ a_R = 0.01$ m, $L_R = 3$ m, $n = 4$

$A_R = 3 \times 3 = 9$ sq. m.

$$R_G = R_{MR} = \frac{100}{\pi \times 4}\left[1 + \frac{1.4(\sqrt{4} - 1)^2}{\sqrt{9}}\right] = \boxed{11.7\Omega}$$

(note: rods not connected by wire)

3.6 Combination Rod & Wire Grids

General

(1) It is maybe necessary to include both rod and wire grids forservice grounds, substations, etc.

The resistance to ground of the combined system is given by:

$$R_G = \frac{R_W R_{MR} - R_{WR}^2}{R_W + R_{MR} - 2R_{WR}}$$

where:

R_G = Total system resistance to ground in ohms

R_W = Resistance of wire grid in ohms (section .4)

R_{MR} = Resistance of multiple rods in ohms (section .5)

R_{WR} = Mutual resistance factor of the wires to the rods

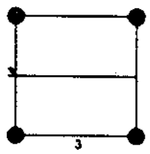
and

$$R_{WR} = \frac{\rho}{\pi L_W}\left[\ln\left(\frac{2L_W}{L_R}\right) + \frac{1.4L_W}{\sqrt{A_W}} - 4.6\right]$$

for 20 mm × 3 m rods:

$$R_{WR} = \frac{\rho}{\pi L_W}\left[\ln(0.67L_W) + \frac{1.4L_W}{\sqrt{A_W}} - 4.6\right]$$

Example 10: Using 3 × 3 m Grid with Cross-tie & Rods



3

Given: $\rho = 100\,\Omega m,\ L_R = 3\text{ m},\ a_R = 0.01\text{ m},$

$A_W = A_R = 3 \times 3 = 9$ sq. m, $n = 4$, $Z_W = 0.3$ m

$d_W = 0.0105$ m (#2/0), $L_W = 5 \times 3 = 15$ m

$$R_{WR} = \frac{\rho}{\pi L_W}\left[\ln\left(\frac{2L_W}{L_R}\right) + \frac{1.4L_W}{\sqrt{A_W}} - 4.6\right]$$

Substituting the given data in the formula, we have:

$$R_{WR} = \frac{100}{\pi \times 15}\left[\ln(0.67 \times 15) + \frac{1.4 \times 15}{\sqrt{9}} - 4.6\right] = \boxed{10.0\Omega}$$

$$R_{MR} = \frac{100}{\pi \times 4}\left[1 + \frac{1.4(\sqrt{4} - 1)^2}{\sqrt{9}}\right] = 11.7\Omega \quad \text{(Example 9)}$$

$$R_W = \frac{100}{\pi \times 15}\left[\ln\left(\frac{2 \times 15}{\sqrt{0.0105 \times 0.3}}\right) + \frac{1.4 \times 15}{\sqrt{9}} - 5.6\right] = 16.4\Omega \quad \text{(Example 7)}$$

$$R_G = \frac{R_W R_{MR} - R_{WR}^2}{R_W + R_{MR} - 2R_{WR}}$$

Substituting the above results in the formula, we have:

$$R_G = \frac{16.4 \times 11.7 - 100}{16.4 + 11.7 - 20} = \boxed{11.3\Omega}$$

If the site soil was clayey sand instead of clay, ρ would be 500 Ωm instead of 100 Ωm (Table 1) and the resistance to ground would be $R_G = 11.3 \times \frac{500}{100} = 56.5\Omega$.

3.7 Single Wire

General

(1) A single wire or counterpoise directly buried in earth has a resistance to ground of :

$$R_G = R_C = \frac{\rho}{2\pi L_W}\left[\ln\left(\frac{L_W}{a_W}\right) + \ln\left(\frac{L_W}{Z_W}\right) - 2 + \frac{2Z_W}{L_W} - \frac{Z_W^2}{L_W^2}\right]$$

where R_C = Resistance to ground of buried conductor in ohms.

Example 11: using #6 AWG Wire

Given: $\rho = 100\ \Omega m$, $Z_W = 0.6$ m, $L_W = 50$ m, $a_W = 0.00252$ m

$$R_C = \frac{100}{2\pi \times 50}\left[\ln\left(\frac{50}{0.00252}\right) + \ln\left(\frac{50}{0.6}\right) - 2 + \frac{2\times 0.6}{50} - \frac{0.6^2}{50^2}\right] = \boxed{3.93\Omega}$$

3.8 Summary of Calculation:

General Formulae

Single Rod Only: $R_G = R_R = \frac{\rho}{2\pi L_R}\left[\ln\left(\frac{4L_R}{a_R}\right) - 1\right]$

Single Plate Only: $R_G = R_P = \frac{\rho}{2\pi L_P}\left[\ln\left(\frac{8W_P}{0.5W_P + T_P}\right) - 1\right]$

Wire Grid Only: $R_G = R_W = \frac{\rho}{\pi L_W}\left[\ln\left(\frac{2L_W}{\sqrt{d_W Z_W}}\right) + \frac{1.4L_W}{\sqrt{A_W}} - 5.6\right]$

Multiple Rods Only:

$R_G = R_{MR} = \frac{\rho}{2\pi n L_R}\left[\ln\left(\frac{4L_R}{a_R}\right) - 1 + \frac{2.8L_R(\sqrt{n} - 1)^2}{\sqrt{A_R}}\right]$

Multiple Rods & Wire Grid: $R_G = \frac{R_W R_{MR} - R_{WR}^2}{R_W + R_{MR} - 2R_{WR}}$

where: $R_{WR} = \frac{\rho}{\pi L_W}\left[\ln\left(\frac{2L_W}{L_R}\right) + \frac{1.4L_W}{\sqrt{A_W}} - 4.6\right]$

Single Wire Only: $R_G = R_C = \frac{\rho}{2\pi L_W}\left[\ln\left(\frac{L_W}{a_W}\right) + \ln\left(\frac{L_W}{Z_W}\right) - 2 + \frac{2Z_W}{L_W} - \frac{Z_W^2}{L_W^2}\right]$

Where:

R_G = Total resistance to ground of the system in ohms

R_R = Resistance to ground of a single ground rod in ohms

R_P = Resistance to ground of a single ground plate in ohms

R_W = Resistance to ground of a single ground wire in ohms

R_{MR} = Resistance to ground of multiple ground rods in ohms

R_{WR} = Mutual resistance factor of wires to rods in ohms

R_C = Resistance to ground of a single buried wire in ohms

L_R = Length of ground rod in metres

L_W = Length of wire in metres

L_P = Width of plate in metres

T_P = Thickness of plate in metres

A_W = Area of wire grid in square metres

A_R = Area covered by several ground rods in square metres

a_R = Radius of ground rod in metres

a_W = Radius of wire in metres

d_W = Diameter of wire in metres

Z_W = Burial depth of wire in metres

n = Number of ground rods

ρ = Soil resistivity in ohm-metres

Useful Formulae

(1) Since the Ministry's grounding system uses common components of,

- 20 mm dia. × 3.0 m long ground rod
- #2/0 and #6 AWG ground wire

then, the general formulae can be reduced to reflect the physical parameters of the common items as follows:

- Single Rod Only: $R_R = 0.32\rho$

- Single 220 x 2300 mm Steel Footing: $R_R = 0.24\rho$
- Single 85 x 1830 mm Steel Footing: $R_R = 0.36\rho$
- Single 610 × 610 × 6 mm Plate: $R_P = 0.46\rho$
- Single #6 wire, 3 m length, (Z_W = 0.30): $R_W = 0.40\rho$
- Single #2/0 wire, 3 m length, (Z_W = 0.30): $R_W = 0.36\rho$
- 3 × 3 m grid c/w cross-tie, (#2/0 wire & 4 rods): $R_G = 0.11\rho$
- 2 Rods @ 3 m space, with #6 tie: $R_G = 0.19\rho$
- 2 Rods @ 3 m space, with #2/0 tie: $R_G = 0.19\rho$

The foregoing formulae are approximate and may be used where special conditions apply.

3.9 Application

(1) The Ministry's designs for grounding systems are based on the following premises:

(a) A resistance to ground of 10 Ω should be obtained in accordance with good practice.

(b) In cases where 10 Ω to ground is impossible to obtain using practical methods, 25 Ω to ground is the minimum requirement provided that adequate steps are taken to ensure that step and touch voltages do not present a safety problem to workers or the public.

(c) Every effort is to be made to meet the 10 Ω to ground requirement, where practical, by addition of ground electrodes and wire in the field.

(d) Since soils and their resistivity vary widely with location and environment respectively, the Ministry's standard criteria for design is $\rho = 100\ \Omega m$. The resistance to ground of the designed system is field checked and any required alterations are made at that time. Where it is obvious to the designer that increased grounding facilities will be required (sand, gravel, rock, etc.) the required facilities can be estimated from Table 3 and included in the design.

(e) Table 3 is derived from the general formulae of sub-section 3.8.

(f) The following notes apply to Table 3:

(i) Configuration No. 9 may be used with the continuous #6 ground wire commonly used for lighting. Grounding at every 5th pole applies.

(ii) Configurations No. 11 or 12 may be used for grounding in clay or areas which remain damp. Configuration No. 13 should be used as the 'standard' design.

(iii) Configurations No. 15 to 18 indicate the results of adding increasing by more wire and rods to the grid. If dry sand, gravel or rocky areas are unavoidable, the principles illustrated may be extended by manual calculation using the formulae given.

(iv) Values shown in brackets are for information as a simpler grid would normally be required.

(v) Values shown are 'stand alone' values (isolated ground). An approximation of resistance to ground for any number of the systems, which are tied together with ground wire, may be made by considering the values to be in parallel.

Ground System Configuration	Description	Normal Use	Resistance (Ω) to Ground According to Type of Soil				
			Clay	Sandy Clay	Clayey Sand	Sand	Sand, Gravel
			ρ = 100 Ωm	ρ = 200 Ωm	ρ = 500 Ωm	ρ = 1500 Ωm	ρ = 5000 Ωm
	1. Single 20 mm x 3 m rod	Addition to System	32	80	160	480	1610
	2. Single 220 x 2300 Steel Footing	Poles (requires additional system)	28	70	140	420	1400
	3. Single 85 x 1830 Steel Footing	Poles, Cabinets (requires additional system)	40	100	200	600	2000
	4. 610 x 610 x 6 mm Plate	Rock overburden 0.6 to 2.0 m	46	115	230	690	2300
3	5. Single #6 wire, bare, 3 m long	Addition to system	41	103	205	615	2050
3	6. Single #2/0 wire, bare, 3 m long	Addition to system	38	95	190	570	1900
3	7. Single #6 wire, 2 rods	Service	19	38	95	290	950
3	8. Single #2/0 wire, 2 Plates	Service in overburden	27	54	140	410	1400
1	9. 220 x 2300, Steel Footing, #6 wire, 1 rod	Poles	19	38	95	285	950
1	10. 85 x 1830, Steel Footing, #6 wire, 1rod	Poles	16	34	80	240	800

Table 3. Resistance to Ground for Various System Components

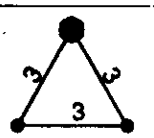
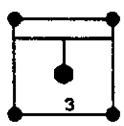
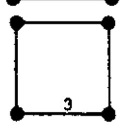
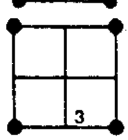
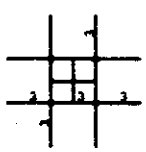
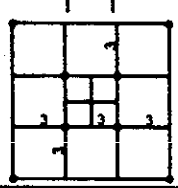
Ground System Configuration	Description	Normal Use	Resistance (Ω) to Ground According to Type of Soil				
			Clay	Sandy Clay	Clayey Sand	Sand	Sand, Gravel
			$\rho =$ 100 Ωm	$\rho =$ 200 Ωm	$\rho =$ 500 Ωm	$\rho =$ 1500 Ωm	$\rho =$ 5000 Ωm
	**11.** 85 x 1830 Steel Footing, #2/0 wire, 2 rods	Cabinets	14	28	70	210	700
	**12.** 85 x 1830 Steel Footing, #2/0 wire, 3 rods	Cabinets	13	26	65	195	650
	**13.** 85 x 1830 Steel Footing, #2/0 wire, 4 rods	Cabinets	10	20	50	150	250
	**14.** #2/0 wire, 4 rods	Service Any for $\rho < 125$	11	22	55	165	550
	**15.** #2/0 wire, 4 rods, 2 ties	Any for $\rho < 125$	11	22	55	165	550
	**16.** #2/0 wire, 4 rods, 2 ties, 4tails	Any for $125 < \rho < 150$	(9)	18	45	135	450
	**17.** #2/0 wire, 4 rods, 2 ties, 8 tails	Any for $150 < \rho < 200$	(6)	12	30	90	300
	**18.** #2/0 wire, 8 rods, 6 ties	Any for $200 < \rho < 350$	(5)	10	25	75	250

Table 3. Continued

3.10 Problem Areas

Problem areas are identified as:

(1) Bedrock or shallow overburden of less than 1 m depth over bedrock:

(a) It will be necessary to drill 150 mm (min.) holes in the bedrock and backfill these with a cementous iron slag slurry mixture (trade name: 'Embico'). Note that previously used methods used rock salt as the chief conductor and that this method is no longer recommended due to corrosion. Difficulty in obtaining (and measuring) proper resistance to ground will be encountered as the ground depends, to some extent, on the number of seams between rock layers that are encountered. In this situation, the first design choice would be to locate the object to be grounded away from the rock area. If this is unavoidable, configuration No. 18, Table 3 should be used for design and added to, if necessary, during construction.

(2) Soil overburden of 1 m to 2 m depth over bedrock:

(a) Plates may be used as ground electrodes, to the same configurations shown in Table 3 for rods (depending on type of soil overburden). A minimum of 300 mm of soil should be left between the rock and plate and the #2/0 wire grid.

(3) Rock Fill

(a) Areas of rock fill can be assumed to have a resistivity in excess of 10,000 Ω m. A previously used method was to run two parallel runs of #2/0 wire through the voids in the rock fill to a location suitable for use of normal grounding methods. The method causes large voltages to appear at the cabinet due to the high inductance of the leads to ground and should be avoided by placing at least 2.0 m of earth fill over the rock fill.

3.11 Application Guidelines

(1) From the examples of the foregoing sections, it is immediately obvious that obtaining a 10 Ω resistance to ground is difficult in soils with high resistivity.

(2) The effect of ground rod diameter is small. About 8% less resistance to ground is obtained by using a 25 mm diameter rod instead of a 20 mm rod. Much better results are obtained by making ground rods longer rather than thicker.

(3) The effect of electrode material (copper or steel) has negligible effect on results since the resistivity of all metals is much less than that of all soils.

(4) Ground rod spacing should be kept within one rod length spacing of each other.

(5) The effect of the size and type of wire interconnecting the ground rods has little effect on results. The #2/0 AWG cable usually used is sized to withstand a 50,000 ampere lightning discharge without complete melting.

(6) The upper 1.0 m of ground rod does not have much effect, even in wet soil. A minimum depth of 2.0 m gives about 25% more resistance to ground than the 3.0 m standard depth rod.

(7) In order to design proper grounding, a soils classification at the intended location should be obtained from the Regional Geotechnical Office (if not on the 'Soils Profile' or indicated on borehole logs included with contract drawings) and District personnel should be consulted.

(8) If the equipment to be grounded will be in a new fill location, the fill should not be composed of sand, gravel, rock and the like (if practical). A note on the grading drawings should be added where necessary: 'Fill in the area of (equipment) to be cohessive material only' or similar.

(9) Table 3 gives the number of ground rods (20 mm x 3.0 m) and grid configurations required for various classes of soil. Where there is not apparent site problem, ground designs corresponding to $\rho = 100\ \Omega m$ should be used by the designer. Where necessary after testing, the design may be adjusted during construction. Where it is not practically possible to obtain 10 Ω to ground, an absolute minimum of 25 Ω may be used.

Effects of Lightning

Section III

1. General

The effects of lightning upon outdoor electrical and electronic equipment can be costly. Damage from lightning may result from:

- Direct strokes
- Power surges
- Inducted transient voltage spikes
- Capacitive voltages

Since it is not practical to protect outdoor equipment against direct strokes, protective systems apply to the prevention or handling of surges and transients. The protective systems consist of the application of proper ground, suppression and shunting devices.

Since weather is somewhat unpredictable, protection design is based on probability:

- the probability of a storm
- the probability of a strike
- the probable potential energy and R.F. energy
- the probable rise time of the voltage (open circuit) wave or current (short circuit) wave
- the probable duration or repetition of a strike.

2. Design Criteria

The design criteria adopted for protection of the Ministry's electronic equipment is:

- Peak Voltage = 15,000 V
- Peak Current = 5,000 A
- Max Current Flow Duration = 500 μs
- Current Waveform = 8 x 20 μs
- Voltage Waveform = 1.2 x 50 μs

Figure 1 indicates waveforms and timing of devices.

Note that the times involved are much too fast to allow power circuit protection devices such as breakers, fuse, lightning arresters etc. to operate, but that devices such as gas tubes and metal oxide varistors (MOV's) will conduct at about 0.15 μs and 0.007 μs respectively.

3. Power Surges

Surges in any equipment including cables, poles etc. can be induced by lightning strikes as much as 6 km away. Surges on overhead high voltage lines are grounded through lightning arresters at transformer locations. Figure 2 shows the voltage and current distribution through the earth near the bottom of the utility pole. Note that for the design value of resistivity $\rho = 100\Omega m$, a voltage of 15,000 volts would be transferred through the earth for a distance of 5.3 m. It is therefore necessary to keep the service ground at a minimum distance from the distribution system ground as indicated in Figure 3. Note that a large voltage will appear at the service 'SN' due to the Ldi/dt voltage on the grounding cable.

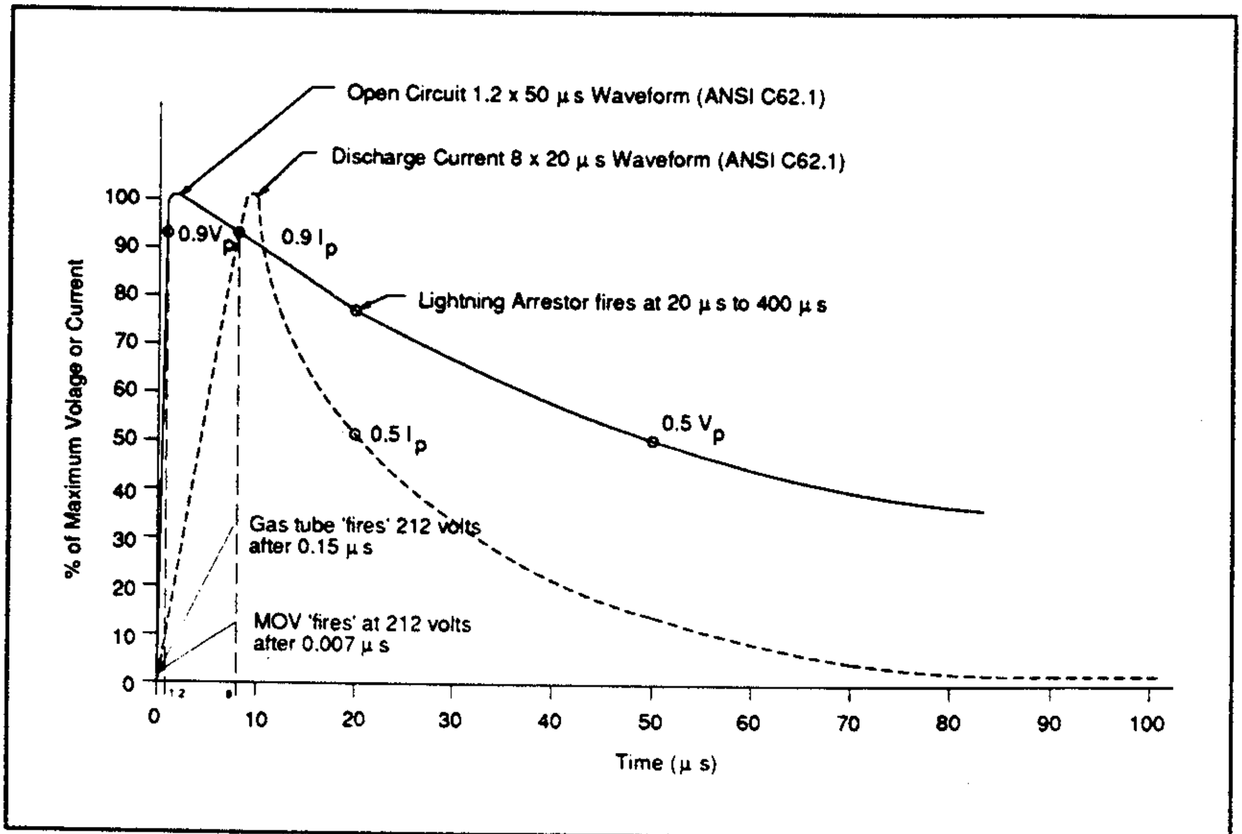


Figure 1. Voltage and current waveforms.

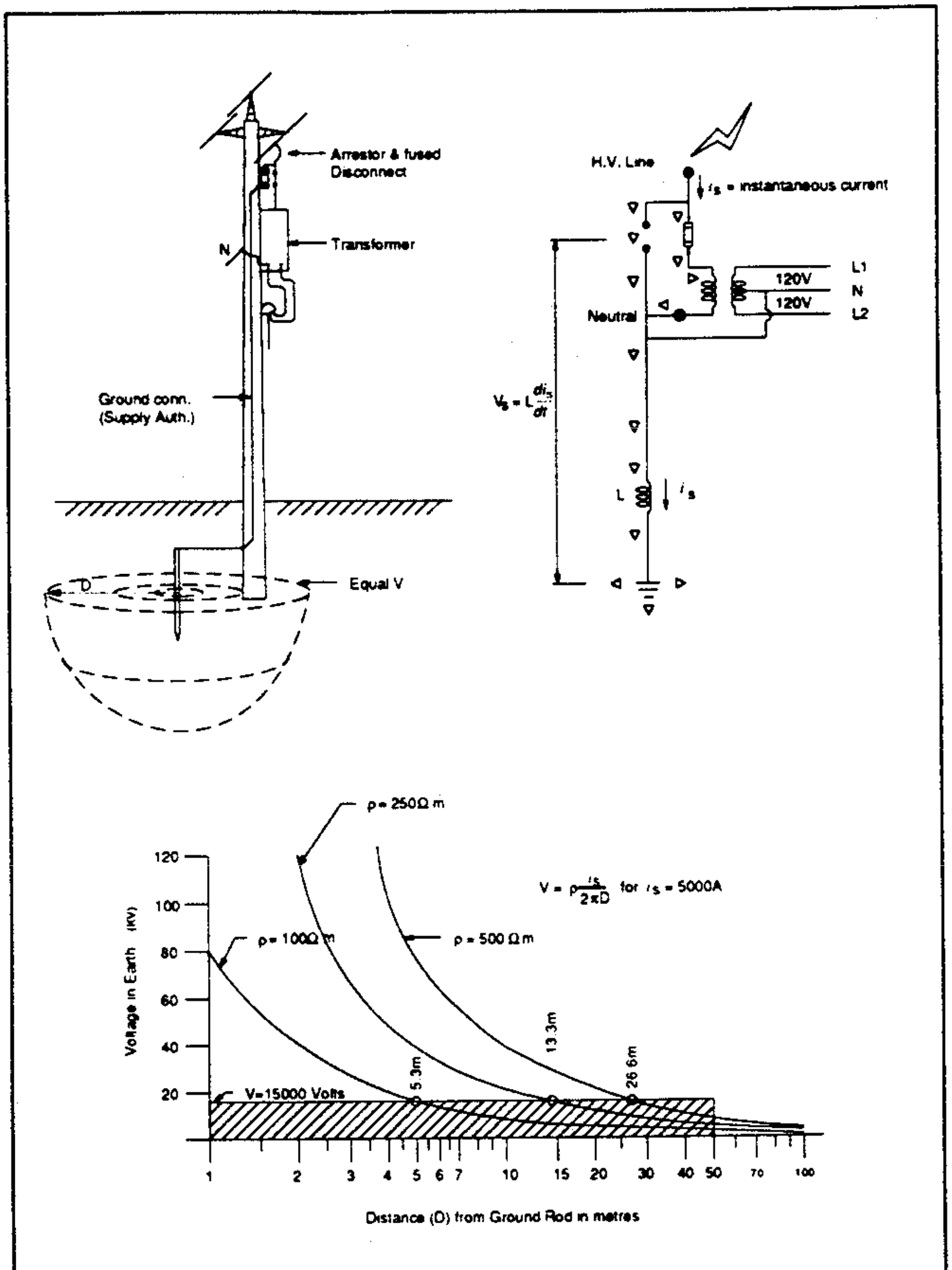


Figure 2. Voltage in earth due to discharging lightning current at service pole.

4. Other Sources of Possible Damage

For traffic signal systems, there are many other sources of transient voltages and currents appearing within the controller cabinet. These sources are not considered as severe as the energy surge through the service neutral and all have protection devices installed within the cabinet. Some sources are:

(a) Detector Loops - detector sensor units (amplifiers) are protected internally with their own lightning arrester and are also provided with external MOV's at the input file. Failure rate due to lightning damage is very low as the voltage impressed on a loop is caused by capacitive effects.

(b) Detector Cable - the possiblity of induced currents caused by transient voltages in the earth is minimized by grounding the cable shield as close to the loop as practical (splice point) and leaving the end of the shield cut off and unconnected in the cabinet.

(c) Signal Cable - signal cable is shielded by metal poles (above ground) but is subject to induced currents caused by transient voltages in the earth. The load switches and the AC-terminals of the cabinet are protected by MOV's and the failure rate is low.

(d) Direct Hits on Cabinet - although nothing can be done to ensure a complete lack of damage, the controller cabinet may be considered to be protected by an umbrella cone of 30^o from an overhead line and somewhat protected by a 45^o cone. It is not desirable however to install the cabinet directly under the lines due to possible electromagnetic interference. The cabinet location should be:

- 13 m minimum from a distribution ground (Figure 4)
- 3 m minimum (horizontally) clear of overhead lines
- Within the 30^o to 45^o cone of protection (within 15 m for normal height lines) of the overhead lines (Figure 4).

(e) Direct Hits on Poles or Equipment - this condition would cause severe damage. The method of mitigating possible damage effects consists of installing a #6 AWG RWU 90 (green) system ground wire connecting all poles and intersection equipment and installing a ground rod on each corner. Connection of the system ground around the intersection should be made at one point only (the cabinet ground bus) as indicated in Figure 5.

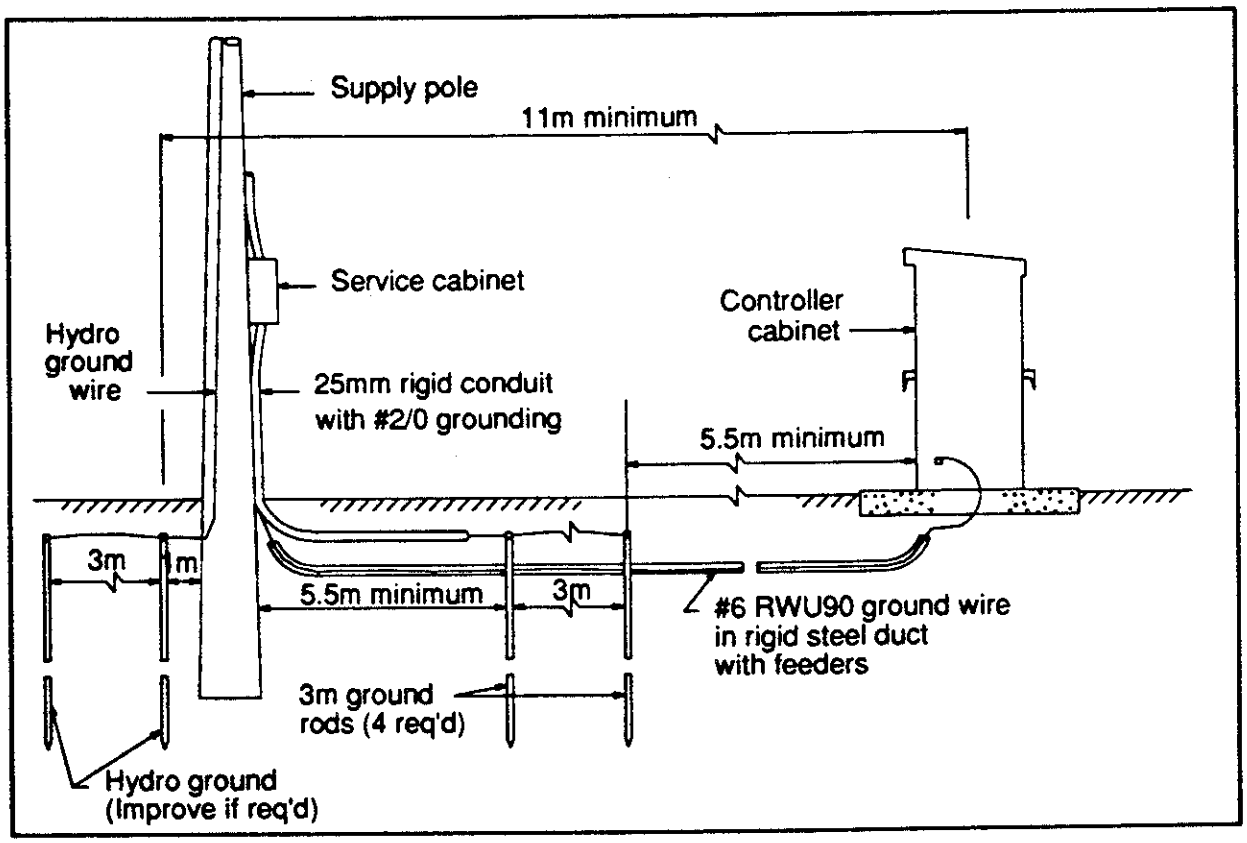


Figure 3. Recommended improvement to system ground connections.

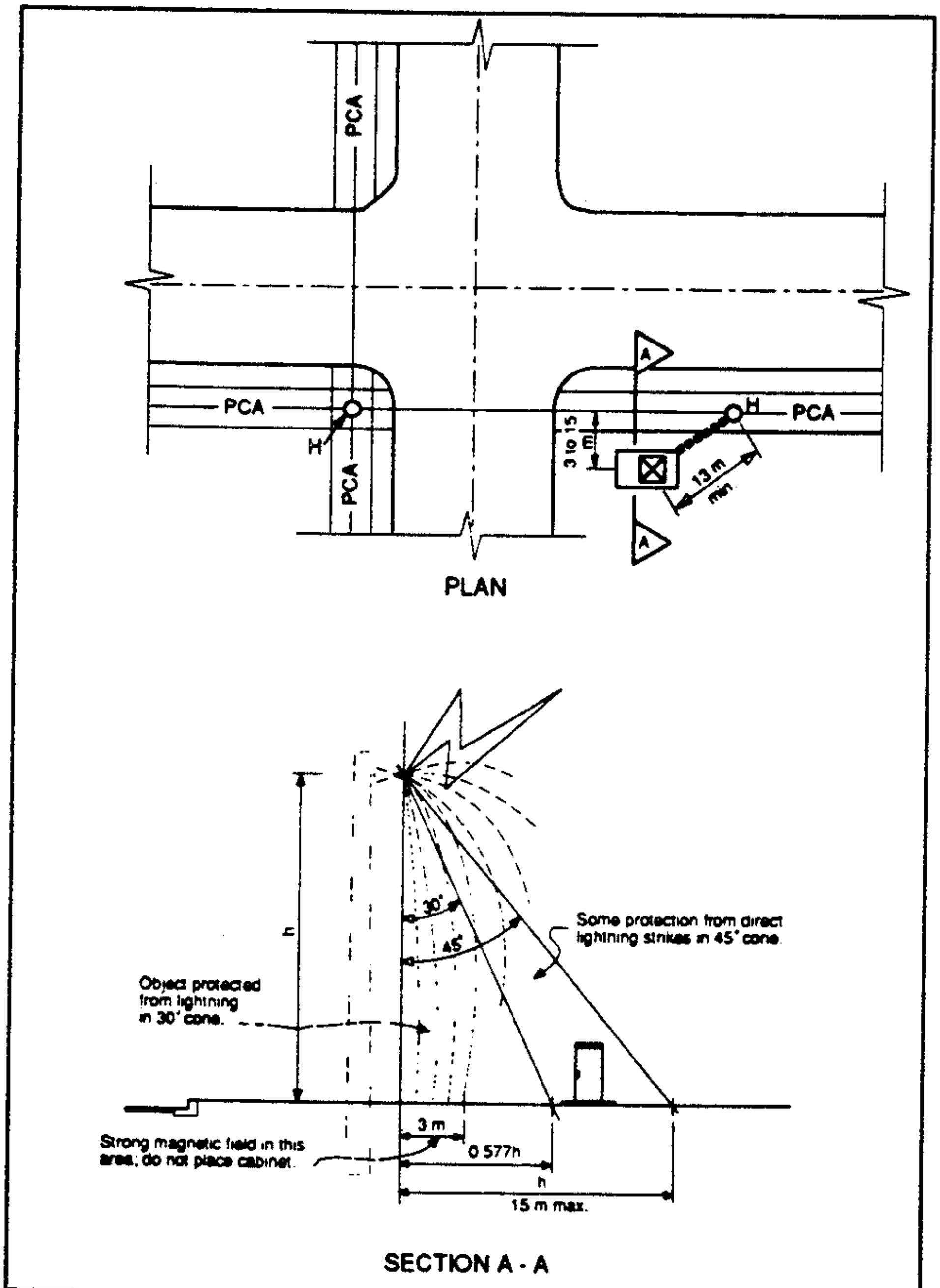


Figure 4. Controller cabinet location for best lightning protection.

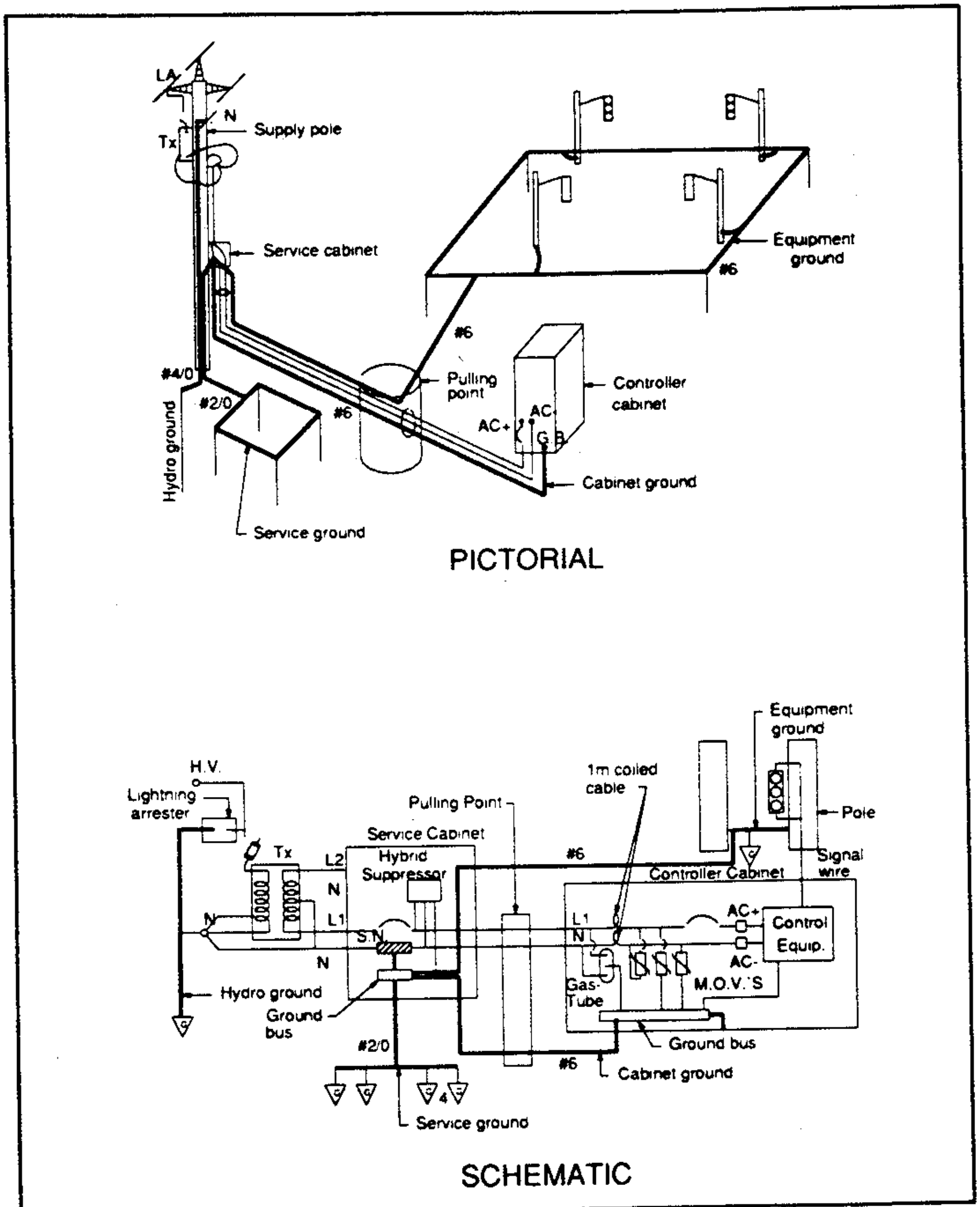


Figure 5. Signal Grounding System (with or without lighting). No ground electrodes at cabinet.

Summary of Design guidelines

Section IV

1. Traffic Signal Systems

(1) Design standard grounding system under normal circumstances:

- Service ground - 4 rods & #2/0 bare ground wire as per Figure 3.
- Cabinet ground - System ground wire connected to cabinet ground bus as per Figure 3.
- System ground - 1 rod or steel footing per intersection corner. #6 insulated wire connected to service ground from cabinet ground bus and from equipment ground as per Figure 5.

(2) Use improved design as per Table 3 for grounds in sand, gravel or rock. Consult Geotechnical information and District Maintenance.

(3) Ground detector cable shield at splice point and cut off in cabinet. (See note)

(4) Locate controller at least 11 m from a hydro pole and at least 3 m horizontally from overhead lines. Locate controller 1.5 m clear minimum from metal objects such as poles, fence and guiderail.

Note:
In 1990, this was changed to : Ground shield in cabinet and insulate shield at pull box.

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Ministry of Transportation Ontario

VOLUME 2 - ELECTRICAL MAINTENACE MANUAL PART 2 - COMPONENT MAINTENANCE

Chapter 9

Grounding

Chapter 9 Table of Contents

Traffic Signal Grounding — Section I

1. Hydro Grounds

(1) Inadequate hydro grounds at service pole will allow energy from lightning discharge into controller. Inspect Hydro grounds visually and arrange for Supply Authority to repair faulty grounds.

(2) At controller sites where lightning problems have occurred, Hydro ground should be reinforced to two 20x3000 mm copperclad rods at 3 m spacing at the service pole and at one hydro pole each way. Arrange purchase order for this work if necessary.

(3) Do not use Hydro ground as Service ground.

2. Service Grounds

(1) To reduce voltages transferred from the Hydro ground (under lightning discharge) to the Service ground, the Service ground should be located as far from the Hydro ground as possible. See Figure 1.

(2) The service ground should consist of a minimum of four 20 x 3000 mm copperclad ground rods on #2/0 bare copper wire grid as per Figure 1.

3. Cabinet Grounds

(1) Proper ground bus bar should be installed in controller cabinet and all ground leads from equipment should connect to this one point.

(2) Controller cabinet ground bus should be connected to the service solid neutral by a #6AWG RWU90 insulated system ground wire.

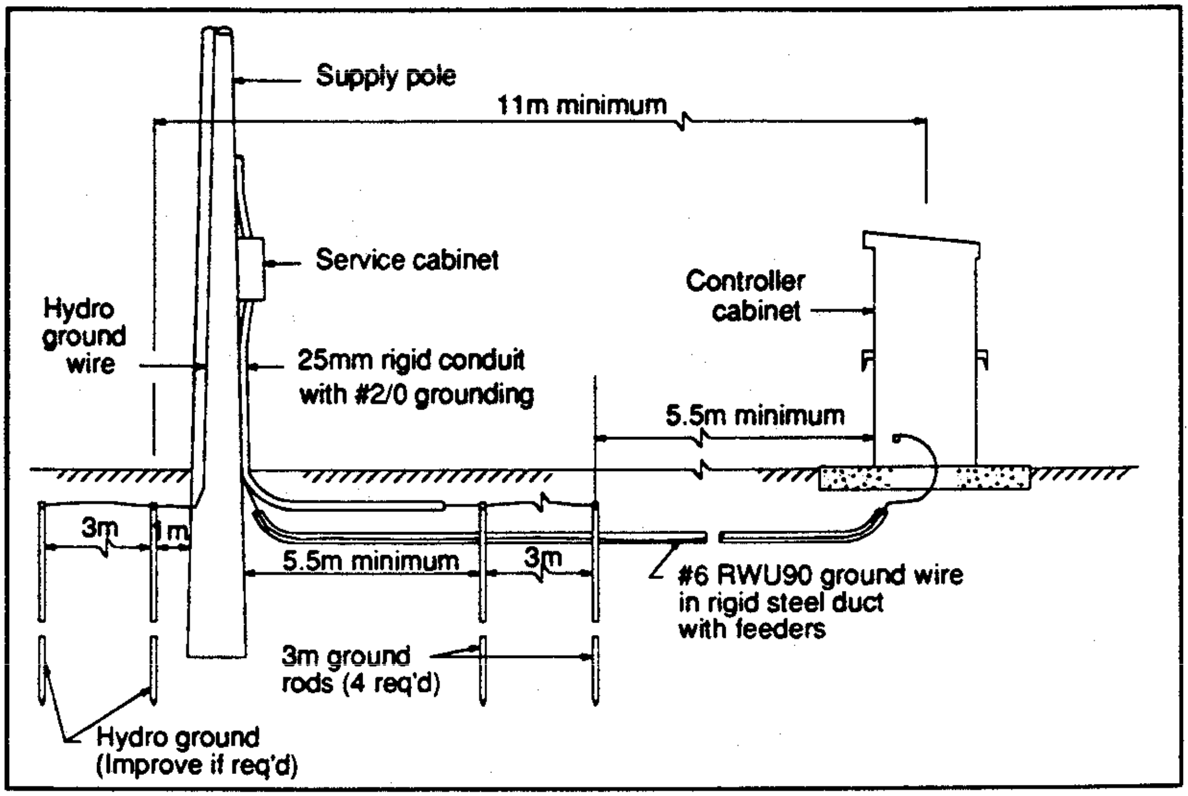


Figure 1. Recommended improvement to system ground connection

4. Special Soil Conditions

(1) Grounding system in areas of sand, gravel or rock may require reinforcement due to poor soil conductivity. Refer to Electrical Design Manual - Volume 1. Request design aid from Electrical Engineering Section if necessary.

5. System Ground

(1) System ground wire for signals to be #6 RWU90-40° C green.

(2) Install connections of the three systems (Service ground, cabinet ground and equipment ground) as indicated in Figure 2.

(3) Ensure that all metal enclosures are bonded to the proper section of the system ground.

(4) All connections to be thermit weld, impact or compression type (no split bolts, etc.).

6. Routine Inspection

(1) Yearly inspection frequency for:

(a) tight connections of accessible ground wires (controller cabinet and service); corrosion

(b) hydro and service grounds; visual for obvious damage from vehicles, etc.

(c) testing of resistance to ground and soil conductivity (service ground) as per sub-section 8.

7. Emergency Inspection

(1) For controllers damaged by lightning:

(a) Inspection Hydro ground as per sub-section 1.

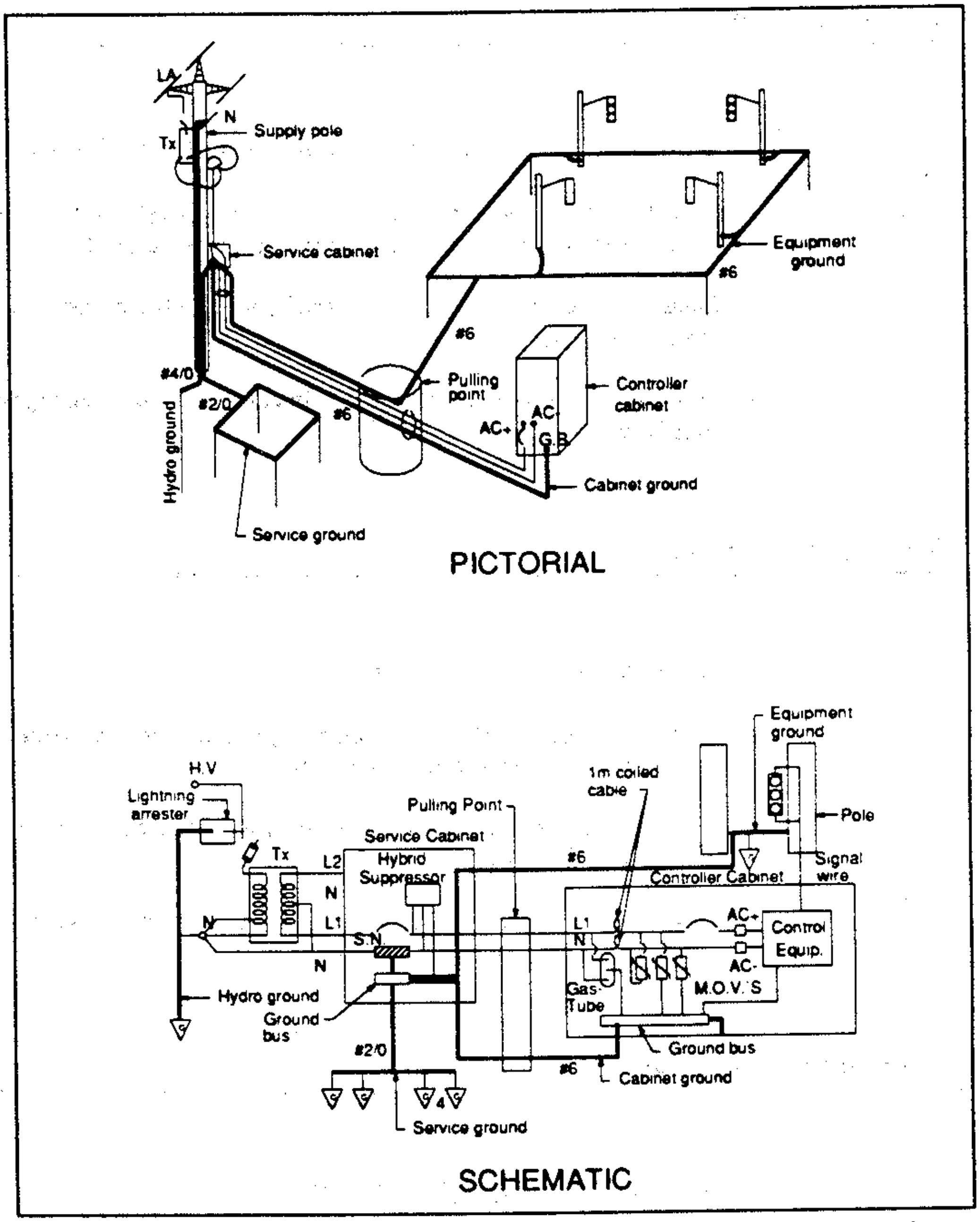


Figure 2. Signal Grounding System (with or without lighting). No ground electrodes at cabinet.

(b) Have Supply Authority check distribution arrestor and upgrade ground and arrestor if required

(c) Inspect for proper installation of grounds as per sub-sections 1 to 5.

8. Measurements

(1) Resistance to ground and soil conductivity should be measured at an 'average' time of year. Measurements taken when soil is wet or frozen are not meaningful.

(2) Use the Megger ground resistance meter and the two small ground rods supplied with the unit. Follow instructions exactly for distances or results will be meaningless. For information regarding the instrument, contact the Electrical Operations Unit.

(3) Measurements to ground to be taken at the SN of the service and the controller cabinet ground bus.

(4) Resistance to ground and soil resistivity are related mathematically. See Electrical Design Manual - Volume 1 Section II.

(5) Resistance to ground should be 10 Ω or less but can vary up to 25 Ω in high resistivity soils. Readings over 25 Ω indicate that further inspection and repairs or replacement should be done or that additional rods and wire should be added (new installations). Add additional elements as per Table 1.

9. Steel Footings

(1) Steel footings may be considered equivalent of a ground rod for resistance to ground purposes.

Ground System Config-uration	Description	Normal Use	Resistance (Ω) to Ground According to Type of Soil				
			Clay	Sandy Clay	Clayey Sand	Sand	Sand, Gravel
			ρ = 100 Ωm	ρ = 200 Ωm	ρ = 500 Ωm	ρ = 1500 Ωm	ρ = 5000 Ωm
	1. Single 20 mm x 3 m rod	Addition to System	32	80	160	480	1610
	2. Single 220 x 2300 Steel Footing	Poles (requires additional system)	28	70	140	420	1400
	3. Single 85 x 1830 Steel Footing	Poles, Cabinets (requires additional system)	40	100	200	600	2000
	4. 610 x 610 x 6 mm Plate	Rock overburden 0.6 to 2.0 m	46	115	230	690	2300
3	5. Single #6 wire, bare, 3 m long	Addition to system	41	103	205	615	2050
3	6. Single #2/0 wire, bare, 3 m long	Addition to system	38	95	190	570	1900
3	7. Single #6 wire, 2 rods	Service	19	38	95	290	950
3	8. Single #2/0 wire, 2 Plates	Service in overburden	27	54	140	410	1400
1	9. 220 x 2300, Steel Footing, #6 wire, 1 rod	Poles	19	38	95	285	950
1	10. 85 x 1830, Steel Footing, #6 wire, 1rod	Poles	16	34	80	240	800

Table 1. Resistance to Ground for Various System Components

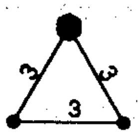
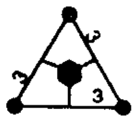
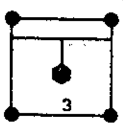
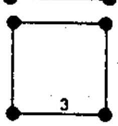
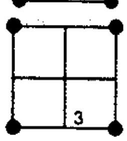
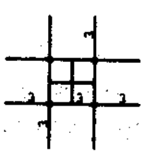
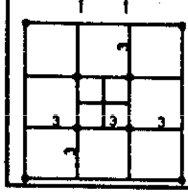
Ground System Configuration	Description	Normal Use	Resistance (Ω) to Ground According to Type of Soil				
			Clay	Sandy Clay	Clayey Sand	Sand	Sand, Gravel
			$\rho =$ 100 Ωm	$\rho =$ 200 Ωm	$\rho =$ 500 Ωm	$\rho =$ 1500 Ωm	$\rho =$ 5000 Ωm
	**11.** 85 x 1830 Steel Footing, #2/0 wire, 2 rods	Cabinets	14	28	70	210	700
	**12.** 85 x 1830 Steel Footing, #2/0 wire, 3 rods	Cabinets	13	26	65	195	650
	**13.** 85 x 1830 Steel Footing, #2/0 wire, 4 rods	Cabinets	10	20	50	150	250
	**14.** #2/0 wire, 4 rods	Service Any for $\rho < 125$	11	22	55	165	550
	**15.** #2/0 wire, 4 rods, 2 ties	Any for $\rho < 125$	11	22	55	165	550
	**16.** #2/0 wire, 4 rods, 2 ties, 4tails	Any for $125 < \rho < 150$	(9)	18	45	135	450
	**17.** #2/0 wire, 4 rods, 2 ties, 8 tails	Any for $150 < \rho < 200$	(6)	12	30	90	300
	**18.** #2/0 wire, 8 rods, 6 ties	Any for $200 < \rho < 350$	(5)	10	25	75	250

Table 1. Continued

10. Ground Rods

(1) One rod length spacing to be obtained between rods.

(2) Connecting wire is more effective if buried to 1/2 the normal frost depth (assuming snow cover).

(3) Do not install rods at more than 45^o angle. Driving jaws for use with a hydraulic drive head are available.

(4) Use 20 x 3000 mm copperclad rods only, with thermit weld or impact connectors.

11. Good Practice

(1) Grounding is a safety device and many members of the Electrical industry are somewhat lax about proper grounding practices as the only times they are required are under abnormal conditions such as short circuits and lightning surges. Poor workmanship or practices are not apparent until such an abnormal problem occurs.

(2) The Ministry's grounding system practices should meet or exceed the requirements of the Code. (The Code is a minimum requirement). If doubt exists as to practice, the regulations contained in the Code should overrule other opinions.

(3) Workers should endeavour to follow the Ministry's practices faithfully so as not to endanger themselves or the Ministry to the possibility of legal prosecution due to mishap through poor practice or application.

References **Section II**

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GLOSSARY

ACTUATED CONTROLLER: A traffic signal controller that receives information from vehicle and/or pedestrian detectors and provides signal timing accordingly.

ACTUATION: The operation of any type of detector (NEMA). The word operation means an output from the detector system to the controller unit.

ADVISORY DETECTOR: The detection of vehicles on one or more intersection approaches solely for the purpose of modifying the phase sequence and/or length for other approaches to the intersection (NEMA).

ALTERNATING CURRENT (AC): A current which reverses direction at regular intervals. The rate of reversal is expressed in hertz (cycles per second).

AMPERE: The unit expressing the rate of flow of an electrical current. One ampere is the current flowing through one ohm resistance with one volt pressure.

AMPLIFIER: See Detector Amplifier.

ANALOG: An electronic design that uses continuously varying voltages, rather than digital numbers.

ANSI: American National Standards Institute.

ANTENNA: The radiating or receiving elements utilized in transmitting or receiving electromagnetic waves (NEMA).

AREA DETECTION: The continuous detection of vehicles over a length of roadway wherein the call of a vehicle in the detection area is intended to be held for as long as the vehicle remains in the area of detection. (Most detectors cannot hold the call indefinitely.) Frequently referred to as large-area detectors, long-loop detectors, or presence detectors.

AREA OF DETECTION: See Zone of Detection.

AREA DETECTOR: See Large Area Detector.

ARTERIAL: A major urban roadway usually with coordinated signals along its length.

ASTM: The American Society for Testing and Materials.

AUXILIARY EQUIPMENT: Separate devices used to add supplementary features to a controller assembly (NEMA).

AWG: American Wire Gauge. The standard measurement of wire size. It is based on the circular mil system. 1 Mil equals .001.

CABLE: A group of separately insulated conductors wrapped together and covered with an outer jacket.

CALL: A registration of a demand for right-of-way by traffic at a controller unit (NEMA). The call comes to the controller from a detector that is outputting an actuation.

CALLING DETECTOR: A detector that is installed in a selected location to detect vehicles which may not otherwise be detected, and whose output may be modified by the controller unit (NEMA). This traditionally has meant a small area detector near the Stop Line, to detect vehicles entering the roadway from a driveway during the red or yellow signal. The detector is disconnected when the green signal is displayed so that extensions of the green can only come from the appropriate Extension Detector.

CAPACITANCE: That property of a system of conductors and dielectrics which permits the storage of electricity separated charges when potential differences exist between the conductors. Its value is expressed as the ratio of an electric charge to a potential difference.

CARD-RACK MOUNTED DETECTORS: See Rack Mounted Detectors.

CARRYOVER OUTPUT: The ability of a detector to continue its output for a predetermined length of time following an actuation (NEMA). See Extended Call Detector.

CHAMFER: Diagonal saw slots at the corners of square or rectangular loops to reduce the angle of bend of the loop wires at the intersecting saw slots.

CHANGE INTERVAL: The yellow interval following the green signal indicating the change to a conflicting phase.

CHANNEL: Electronic circuitry which functions as a loop detector unit (NEMA).

CIRCUIT: A closed path followed by an electric current.

CLEARANCE INTERVAL: A red interval that may be shown following the yellow change interval before allowing a conflicting green signal to be displayed.

COIL: A coiled conductor, wound on a form or core which uses electro magnetic induction to cause changes in a current.

CONDUCTANCE: The measure of ability to conduct electricity.

CONDUCTOR: A medium for transmitting electrical current. A conductor usually consists of copper or other materials.

CONDUIT: A tube for protecting electrical wires or cables.

CONFLICTING CALL: See Serviceable Conflicting Call.

CONFLICTING PHASES: Two or more traffic phases which will cause interfering (i.e., conflicting) traffic movements if operated concurrently.

CONTINUOUS PRESENCE MODE: Detector output continues if any vehicle (first or last remaining) remains in the field of influence (NEMA). This definition does not imply that the use of this mode guarantees that the output will continue indefinitely, as most detectors are incapable of holding a call beyond a finite interval. See Detector Mode.

CONTROLLED OUTPUT: The ability of a detector to produce a pulse that has a predetermined duration regardless of the length of time a vehicle is in the field of influence (NEMA). See Detector Mode.

CONTROLLER ASSEMBLY: A complete electrical mechanism mounted in a cabinet for controlling the operation of a traffic control signal (NEMA).

A. **Traffic-Actuated Controller Assembly:** A controller assembly for supervising the operation of traffic control signals in accordance with the varying demands of traffic as registered with the controller by detectors (NEMA).

B. **Semi-Traffic-Actuated Controller Assembly:** A type of traffic actuated controller assembly in which means are provided for traffic actuation on one or more but not all approaches to the intersection (NEMA).

C. **Full-Traffic-Actuated Controller Assem-bly:** A type of traffic actuated controller assembly in which means are provided for traffic actuation on all approaches to the intersection (NEMA).

D. **Pedestrian-Actuated Controller Assembly:** A controller assembly in which intervals, such as pedestrian WALK and clearance intervals, can be added to or included in the controller cycle by the actuation of a pedestrian detector (NEMA). Pedestrian actuation may be part of an intersection controller or be used to control a midblock crosswalk.

CONTROLLER UNIT: A controller unit is that potion of a controller assembly that is devoted to the selection and timing of signal displays (NEMA). Also referred to as the Dispatcher or Timer.

CRITICAL INTERSECTION CONTROL (CIC): An algorithm employed in traffic systems to dynamically control the split at signalized locations where the traffic patterns are such that special control, responsive to changing conditions, is needed.

CRITICAL LANE DETECTION: A system of hardware and software designed to provide data on traffic flow for a selected lane, usually the heaviest volume lane on an approach to a signalized intersection.

CROSSTALK: The adverse interaction of any channel of a detector unit with any other detector channel (NEMA). It is the mutual coupling of magnetic fields that produces interaction between two or more detector units in the same cabinet when the units are operating at similar frequencies. Crosstalk results in a detector outputting an actuation in the absence of a vehicle.

CYCLE: A complete sequence of all signal indications at an intersection. In an actuated controller, a complete cycle is dependent on the presence of detector calls on all phases.

CYCLE LENGTH: The time period in seconds required for a complete cycle. Cycle length is normally variable for actuated intersections unless they are part of a coordinated system.

DELAYED CALL DETECTOR: A detector that does not issue an output until the detection zone has been occupied for a period of time that exceeds the time preset on an adjustable timer incorporated into the detector unit.

DELAYED OUTPUT: The ability of a detector to delay its output for a predetermined length of time during an extended actuation (NEMA).

DELTA L (L): The change in inductance.

DEMAND: The request for service, e.g., one or more vehicles desiring to use a given segment of roadway during a specified unit of time.

DEMAND CONTROL: See Loop Occupancy Control.

DEMAND OPERATION: A mode of operation whereby the service provided at an intersection reflects the presence of demand for that service without regard to background cycles.

DENSITY: A measure of the concentration of vehicles, stated as the number of vehicles per mile per lane.

DENSITY CONTROLLER: Actuated controller that has timing adjustments for the selection of the allowable gap independent of the passage time. A volume-density controller and a modified density controller are each a type of density controller.

DESIGN SPEED: the speed used as typical by the designer of the detector/controller system in the kinematic analysis of the scheme under free traffic flow conditions.

DETECTION ZONE; That area of the roadway within which a vehicle will be detected by a vehicle detector (NEMA). Also called "zone of detection" or "sensing zone."

DETECTOR: A device for indicating the presence or passage of vehicles or pedestrians (NEMA). This general term is usually supplemented with a modifier indicating type (e.g., loop detector, magnetic detector, etc.); operation (e.g., point detector, presence detector, etc.); or function (e.g., calling detector, extension detector, etc.).

DETECTOR AMPLIFIER: A device that is capable of intensifying the electrical energy produced by a sensor (NEMA). An example is a magnetic detector amplifier. A loop detector unit is commonly called an amplifier, although its electronic function actually is different.

DETECTOR FAILURES: The occurrence of detector malfunctions including non-operation, chattering, or other intermittently erroneous detections.

DETECTOR MEMORY: The retention of an actuation for future utilization by the controller assembly. The phrase might better be detection memory to make it clearer that the memory is within the controller, not the detector.

DETECTOR MODE: A term used to describe the operation of a detector channel output when a presence detection occurs (NEMA). See Pulse Mode, Controlled Output, Continuous Presence Mode, and Limited Presence Mode.

DETECTOR SETBACK: Longitudinal distance between stop line and detector.

DETECTOR SYSTEM: The complete sensing and indicating group consisting of the detector unit in the controller, the lead-in cable, the lead-in wires, and the sensor.

DETECTOR UNIT: The portion of a detector system other than the sensor and lead-in cable, consisting of an electronic assembly.

DIELECTRIC: Any insulating material that is a nonconductor of electricity.

DILEMMA ZONE: A distance or time interval related to the onset of the yellow interval. Originally the term was used to describe that portion of the roadway in advance of the intersection within which a driver can neither stop prior to the stop line nor clear the intersection before conflicting traffic is released. That usage pertained to insufficient length of timing of the yellow and/or all-red intervals. More recently the term has been used to describe that portion of the roadway in advance of the intersection within which a driver is indecisive regarding stopping prior to the stop line or proceeding into or through the intersection. May also be expressed as the increment of time corresponding to the dilemma zone distance.

DILEMMA-ZONE PROTECTION: Any method or procedure that attempts to control the end of the green interval so that no vehicle will be caught in the dilemma zone when the signal turns yellow.

DIRECT CURRENT (DC): an electrical current which travels uniformly in one direction.

DRIFT: Change in the electrical properties of the detector system or a portion of it due to environmental changes particularly temperature variations and rain water.

EDDY CURRENT: An electric current induced within the body of a conductor when that conductor moves through a nonuniform magnetic field.

EFFECTIVE LOOP AREA: See Zone of Detection.

ENCAPSULATION: The process of filling the saw slot with sealant to surround the wires in the slot and protect them from traffic, weather, etc.

ENCASEMENT: The loop wire is encased in a polyvinyl or polyethylene tube to provide protection for the wire. Often referred to as Detect-a-duct or other similar commercial names.

EPOXY: A resin used in bonding.

EXTENDED CALL DETECTOR: When selected, this detector extends the output (See Carryover Output) after the vehicle departs the zone of detection for a preset time.

EXTENDED CALL TIMING: A detector with carryover output. It holds or stretches the call of a vehicle for a period of seconds that has been set on an adjustable timer incorporated into the detector. It can be designed to begin the timing of that period when the vehicle enters the detection area, or when it leaves. The latter is specified by NEMA. Also referred to as a "Stretch Detector."

EXTENSION DETECTOR: A detector that is arranged to register actuations at the controller only during the green interval for a given approach so as to extend the green time for that approach to accommodate the actuating vehicles. It is not active during the red or yellow intervals for that approach.

EXTENSION LIMIT: The maximum length of time that the actuations on any traffic phase may retain the right-of-way after an actuation on an opposing traffic phase. Also known as maximum green.

FAILSAFE (as in output relay design): A type of output-relay design that produces a constant call, thereby keeping traffic moving, in the event that the detector unit fails.

FARAD: A unit of capacitance, usually expressed in microfarads (µF), one millionth of a farad.

FEEDER CABLE: See Lead-In Cable.

FIELD OF INFLUENCE: See Zone of Detection.

FREEWAY SURVEILLANCE: Process or method of monitoring freeway traffic performance and control system operation.

FREQUENCY: The number of times an alternating current repeats its cycle in 1 second.

FULL-TRAFFIC-ACTUATED CONTROLLER ASSEMBLY: A type of traffic-actuated controller assembly in which means are provided for traffic actuation on all approaches to the intersection.

GAP: The time interval between the end of one vehicle detector actuation and the beginning of the next actuation.

GAP OUT: Terminating of a green phase due to an excessive time interval between the actuations of vehicles arriving on the green, so green may be served to a competing phase.

GAP REDUCTION: Å feature whereby the unit extension or allowed time spacing between successive vehicle actuations on the phase displaying the green in the extensible portion of the interval is reduced (NEMA).

GREEN EXTENSION SYSTEM: Hardware assembly of extended call detectors and auxiliary logic. Êhe logic can monitor the signal display, enable or disable the selected extended call detectors, and hold the controller in artery green.

GROUND: The earth and all parts conduc-tively connected to the earth.

HAND HOLE: See Pull Box.

HENRY (h): The measure of inductance, defined as the inductance of a circuit in which a counter electromotive force of one volt is generated when the current is changing at the rate of one ampere per second.

HERTZ (Hz): A term replacing cycles-per-second as an indication of frequency.

HOLD: A command that retains the existing right-of-way. A command to the controller which causes it to retain the existing right-of-way. A momentary release of the hold command allows the controller to yield to other conflicting phases requesting service (often referred to as the yield command or yield point).

HOLD ON LINE: A connection that modifies a controller from full-actuated, isolated operation to semi-actuated, system controlled operation. It is used as the basic tie from the local intersection to the system master.

HOME-RUN CABLE: See Lead-In Cable.

HONDA 100: A small motorcycle commonly considered to be the smallest registered motor vehicle. It is used as the baseline for motorized vehicle detection.

Hz (HERTZ): A measure of frequency in cycles per second.

µh (MICRO HENRY): A measure of inductance. See Inductance.

IMSA: The International Municipal Signal Association.

INDUCTANCE: That property of an electric circuit or of two neighboring circuits whereby an electromotive force is generated in one circuit by a change of current in itself or in the other. The ratio of the electromotive force to the rate of change of the current. Measured in micro henries (µh).

INDUCTIVE REACTANCE: The reactance (ohms) of an ideal (lossless) inductor is the product of the voltage across the inductor and the sine of the phase angle (90 degrees) between inductor voltage and current divided by the inductor current assuming sinusoidal operation.

INFRARED DETECTOR: A detector that senses radiation in the infrared spectrum (NEMA). A detector installed over the roadway capable of being actuated by the passage of a vehicle through its field of emitted electromagnetic waves.

INITIAL PORTION: The first timed portion actuated controller Unit:

A. **Fixed Initial Portion:** A preset initial portion that does not change.

B. **Computed Initial Portion:** An initial portion which is traffic adjusted.

C. **Maximum Initial Portion:** The limit of the computed initial portion.

D. **Minimum Initial Portion:** (see "Fixed initial Portion").

E. **Added Initial Portion:** An increment of time added to the minimum initial portion in response to vehicle actuations.

INTERVAL: The part of parts of the signal cycle during which signal indications do not change (NEMA).

ISOLATED INTERSECTION CONTROL: Form of signal control for a single signalized intersection through which the flow of traffic is controlled without consideration of the operation of adjacent signalized intersections.

ITE: The Institute of Transportation Engineers.

JUNCTION WELL: See Pull Box.

JUNCTION BOX: See Pull Box.

KILOHERTZ (kHz): Thousands of hertz. A measure of frequency.

L: The symbol used for inductance.

L: The change in inductance.

LARGE AREA DETECTOR: A detector or series of detectors wired together in series, parallel, or series/parallel covering an area in the approach to an intersection. Detection area varies from 6 x 40 ft (1.8 x 12 m) to 6 x 100 ft (1.8 x 30 m) or larger. One of the more common configurations is four 6- x 6-ft (1.8- x 1.8-m) loops spaced 10 ft (3 m) apart for a length of 54 ft (16.5 m).

LAST CAR PASSAGE: A selected feature of a density controller which, upon gap-out, will cause the green to complete the timing of the passage time. The last vehicle to have been detected, known as the Last Car, will therefore retain the green until it reaches the stop line. Thus, it is assured of avoiding the dilemma zone problem and of clearing the intersection. This feature is not defined by NEMA, however, a number of manufacturers provide it.

LEAD-IN CABLE: The electrical cable which serves to connect the lead-in wire in the pull box to the input of the loop detector unit in the controller cabinet (NEMA). Sometimes called "home-run" cable or transmission line.

LEAD-IN WIRE: That portion of the loop wire that is between the physical edge of the loop and the pull box which should be twisted a specified number of turns per foot. For a magnetic detector or a magnetometer, it is the wire which runs from the sensor (probe) to the pull box.

LIGHT-SENSITIVE VEHICLE DETECTOR: A detector consisting of a light source and photoelectric cell or cells, capable of being operated by the passage of a vehicle interrupting the beam or beams of light. When properly equipped, directional characteristics are present.

LIMITED PRESENCE MODE: Detector output continues for a limited period of time if vehicles remain in the field of influence. See Detector Mode.

LINK: The length of roadway between two signalized locations.

LIP: See Local Intersection Program.

LOCAL CONTROLLER: A controller supervising the operating of traffic signals at a single intersection. Also see Controller Assembly and Controller Unit.

LOCAL INTERSECTION PROGRAM (LIP): A Type 170 software program developed by Caltrans which incorporated detector timing features within the program.

LOCKING DETECTION MEMORY: A selectable feature of the circuit design for a controller phase whereby the call of a vehicle arriving on the red (or yellow) is remembered or held by the controller after the vehicle leaves the detection area until it has been satisfied by the display of a green interval to that phase.

LOOP DETECTOR: A detector that senses a change in inductance of its inductive loop sensor caused by the passage or presence of a vehicle near the sensor (NEMA). See Also Loop Detector System.

A. Motion Loop Detector, Nondirectional: An induction loop detector which is capable of being actuated by the passage of a vehicle over any portion of the loop.

B. Motion Loop Detector, Directional: An induction loop detector consisting of two separate loops either closely spaced or partially overlapping which is not affected by the passage of a vehicle except in the desired direction.

C. Presence Loop Detector: An induction loop detector which is capable of detecting the presence of a standing or moving vehicle in any portion of the effective loop area.

LOOP DETECTOR SYSTEM: A vehicle detector system that senses a decrease in inductance of its sensor loop(s) during the passage or presence of a vehicle in the zone of detection of the sensor loop(s) (NEMA). Means the same as loop detector but is clearer in its inclusion of the wire as well as the electronics package.

LOOP DETECTOR UNIT: An electronic device which is capable of energizing the sensor loop(s), of monitoring the sensor loop(s) inductance,, and of responding to a predetermined decrease in inductance with an output which indicates the passage or presence of vehicles in the zone of detection (NEMA). It is the electronics package, exclusive of the loop(s) and lead-in cable.

LOOP OCCUPANCY CONTROL: A detector/controller design using long detection loop(s) (normally 30 ft (9 m) or longer), and a controller unit operated in the non-locking mode. A loop occupancy controller may, but need not necessarily, be designed to rest in all red in the absence of any traffic demand. Loop occupancy control can utilize magnetometer detectors as well as loop detectors.

LOOP SYSTEM; A combination of loop of wire connected through lead-in cable to the detector in-put terminals.

LOOP LEAD-IN WIRE: The portion of the loop wire that is not a part of the loop but is in the sawslot connecting the loop to the edge of the roadway, where it is carried in conduit to the controller or else to a pull box, where it is connected to the lead-in cable.

LSI CHIP: An electrical component with more than 1,000 logic elements. This is "large scale integration" of miniature elements and is used in some loop detector units of digital design.

MAGNETIC DETECTOR: A detector that senses changes in the Earth's magnetic field caused by the movement of a vehicle near its sensor (NEMA). A vehicle detector placed under the roadway which makes use of both the Earth's magnetic field and the energy change created by the passage of a vehicle over the detector to produce an output. Not to be confused with a magnetometer detector.

A. Compensated Magnetic Vehicle Detector: Any magnetic detector which is so designed and structured as not to be affected by changing electromagnetic influence other than those resulting from the passage of a vehicle. When properly equipped, a compensated magnetic detector has substantial directional characteristics.

B. Noncompensated Magnetic Detector: Any magnetic detector other than a compensated magnetic detector.

MAGNETIC SHADOW: The distortion of the flux lines of the Earth's magnetic field as they pass through a ferrous vehicle, due to the fact that the vehicle is more permeable to these flux lines than is air.

MAGNETOMETER DETECTOR: A detector that measures the difference in the level of the Earth's magnetic forces caused by the passage or presence of a vehicle near its sensor (NEMA). A device capable of being activated by the magnetic disturbance caused by the passage or presence of a vehicle. A magnetic flux generator/sensor is installed in the roadway and connected to sensor amplifier electronics. Not to be confused with a magnetic detector.

MAXIMUM GREEN LIMIT: The maximum green time after an opposing actuation, which may start in the initial portion.

MEGGER: A device used by power companies to measure very high resistance to earth ground.

MEGOHM: One million ohms, which is the unit of electrical resistance.

MEMORY OFF: A selectable feature of an actuated controller, synonymous with non-locking detection memory.

MICROHENRY: One millionth of a henry, from the unit of measurement of inductance. Symbolized μh.

MINIMUM GREEN INTERVAL: The shortest green time of a phase. If a time setting control is designated as "minimum green," the green time shall not be less than that setting.

MINIMUM VEHICLE STANDARD: A test unit that produces the minimum change in input for which the detector system must sense and indicate passage or presence. NEMA specifies a Class 1 vehicle (a small motorcycle).

MOTION DETECTOR: A detector that detects the motion of a vehicle passing through the zone of detection of the detector at some minimum speed usually 2 to 3 mph (3.2 to 4.8 kph). Vehicles traveling slower than the minimum speed or stopped in the zone of detection are not detected.

NANOHENRY: One billionth of a henry, from the unit of measurement of inductance.

NEMA: The National Electrical Manufacturers Association.

NETWORK: A series of intersecting arterials or streets that are a part of a coordinated signal system.

A. Open Network: A network where the arterials do not intersect more than once (i.e., there are no closed loops in the system).

B. Closed Network: A network that contains closed loops.

NOMINAL INDUCTANCE: A design value of inductance where the actual value can vary from the nomial within a range that permits satisfactory equipment operation.

NON-CONFLICTING PHASES: Two or more traffic phases which will not cause interfacing traffic movements if they are operated concurrently.

NON-DIRECTIONAL DETECTOR; A detector capable of being actuated by vehicles proceeding in any direction.

NON-LOCKING MEMORY: A mode of actuated-controller unit operation which does not require memory (NEMA). In this mode of operation the call of a vehicle arriving on the red (or yellow) is forgotten or dropped by the controller as soon as the vehicle leaves the detection area.

OCCUPANCY: The proportion of time a detector is occupied. Occupancy is a pseudo measure of density on a roadway.

OHM: The unit of electrical resistance equal to the resistance through which a current of one ampere will flow when there is a potential difference of 1 volt across it.

PASSAGE DETECTION: The ability of a vehicle detector to detect the passage of a vehicle moving through the detection zone and to ignore the presence of a vehicle stopped within the detection zone (NEMA).

PASSAGE DETECTOR: The ability of a vehicle detector to detect the passage of a vehicle moving through the detection zone and to ignore the presence of a vehicle stopped within the detection zone (NEMA).

PASSAGE PERIOD: The time allowed for a vehicle to travel at a selected speed from the detector to the nearest point of conflicting traffic (NEMA).

PASSAGE TIME: The timing interval during the extensible portion which is resetable by each detector actuation. The green right-of-way of the phase may terminate on expiration of the unit extension time. Also known as Vehicle Interval or Preset Lap.

PEDESTRIAN ACTUATED CONTROLLER ASSEMBLY: A controller assembly in which intervals, such as pedestrian WALK and clearance intervals, can be added to or included in the controller cycle by the actuation of a pedestrian detector.

PEDESTRIAN CLEARANCE INTERVAL: The first clearance interval following the pedestrian WALK indication, normally flashing DON'T WALK. A detector that is responsive to operation by or the presence of a pedestrian (NEMA).

PEDESTRIAN DETECTOR: A detector that is responsive to operation by or the presence of a pedestrian (NEMA). This traditionally has been of the push-button type, installed near the roadway and operated by hand. Preferably it should have some form of pilot light to indicate upon actuation that the unit is operating, but this is rarely provided because of susceptibility to vandalism. Also, NEMA does not provide an output to illuminate this indicator.

PEDESTRIAN PHASE: A traffic phase allocated to pedestrian traffic which may provide a right-of-way indication either concurrently with one or more vehicular phases, or to the exclusion of all vehicular phases.

PEDESTRIAN-ACTUATED CONTROLLER: See Controller Assembly.

PHASE: A traffic signal phase has two different meanings in traffic signal terminology, as follows:

A. **NEMA:** A vehicular phase is a phase which is allocated to one specific vehicular traffic movement (e.g., east bound through traffic as timed by a dual ring controller unit). See Conflicting Phases and Non-Conflicting Phases.

B. **TRADITIONAL:** A part of the cycle allocated to any specific traffic movement receiving the right-of-way or to any combination of traffic movements receiving the right-of-way simultaneously during one or more intervals.

PHASE SEQUENCE: A predetermined order in which the phases of a cycle occur.

POINT DETECTION: The detection of vehicles as they pass a specific point on the roadway. Frequently referred to as small area detection.

POINT DETECTOR: A detector that measures the passage of vehicles past a point (i.e., a small area usually not exceeding 6 x 6 ft (1.8 x 1.8 m)). Also referred to as a Small Area Detector.

POLYCHLOROPRENE: Chemical name for Neoprene. Used for jacketing wire and cable that will be subject to rough usage, moisture, oil, greases, solvents, and/or chemicals. May also be used as a low voltage insulating material.

POLYETHYLENE: A family of insulating materials derived from the polymerization of ethylene gas. All members of the family are excellent dielectrics. Electrically they are far superior to any other extruded dielectric in use today. It has high insulation resistance, high dielectric strength, and good abrasion resistance Polyethylene is being widely used for insulation on signal and detector wire and cable. They are suitable for direct burial.

POLYOLEFINS: A family of plastics including cross-linked polyethylene and various ethylene copolymers which shrinks when heat is applied. Commonly used in splicing.

POLYPROPYLENE: A thermoplastic with good electrical characteristics, high tensile strength, and resistance to heat.

POLYSULFONE: A polymer highly resistant to mineral acid, alkali, and salt solutions.

POLYURETHANE: Enamel that has excellent moisture resistance, easily soldered, and excellent winding properties.

POLYVINYL CHLORIDE (PVC): A family of insulating compounds whose basic ingredient is either polyvinyl chloride or its copolymer with vinyl acetate. Can be either rigid as used in conduit for preformed detector loops or flexible as used in duct tubing to encase detector wire. It is also widely used as insulation material on wire known as types T and TW used in detector applications. Known as PVC or Vinyl.

POWERHEAD: A small 3- x 6-ft (0.9- x 1.9-m) loop installed at the stop line end of a long loop in order to improve the detection of small vehicles. It usually has multiple turns of wire and may have an angled configuration.

PRESENCE DETECTION: The ability of a vehicle detector to sense that a vehicle, whether moving or stopped, has appeared in its field (NEMA).

PRESENCE DETECTOR: The ability of a vehicle detector to sense that a vehicle, whether moving or stopped, has appeared in its field (NEMA). The sensor may cover a large area or be a series of small sensors wired together in series, parallel, or series/parallel.

PRESENCE DETECTOR: Traffic detector which is able to detect the presence or absence of a vehicle within its field of detection.

PRESENCE HOLDING TIME: The time that a detector system will continue to indicate the presence of a vehicle over one of its loops without adjusting to consider the vehicle a new environment. Upon making this adjustment the actuation is terminated. NEMA requires that a Class 2 vehicle (large motor cycle) be detected for a minimum of 3 minutes.

PRESENCE LOOP DETECTOR: An inductance loop detector which is capable of detecting the presence of a standing or moving vehicle in any portion of the effective loop area (ITE).

PRESET GAP: See Passage Time.

PRESSURE DETECTOR: A detector used for well over 40 years that consisted of two metal plates separated by spacers. When a vehicle tire passed over the detector, it compressed the spacers and allowed the two plates to make contact, thereby closing an electrical circuit. This type of detector normally produced two or more pulses per vehicle because each axle would cause a contact.

PROBE: The sensor form that is commonly used with a magnetometer-type detector (NEMA). A magnetic detection sensor is also referred to as a probe.

PROGRESSIVE FLOW: Coordinated movement along an arterial at a given speed is termed progressive flow.

PULL BOX: A container usually at least 1 cubic foot in size that is placed underground with a removable cover flush with the ground surface. Splices between the loop lead-in wires (or magnetometer or magnetic detector cables) and the lead-in cable to the controller cabinet are located in the pull box..

PULSE MODE: The detector produces a short output pulse (between 100 and 150 ms) when a vehicle enters the sensor loop zone of detection. This occurs even though the vehicle remains in the detection zone for a longer time. See Detector Mode.

Q: See Quality Factor.

QUADRUPOLE: A loop configuration that adds a longitudinal sawslot along the center of the rectangle, so that the wire can be installed in a figure-eight pattern, thereby producing four electromagnetic poles instead of the normal two. The design improves the sensitivity to small vehicles and also minimizes splashover. Also spelled Quadrapole and Quadripole in various documents.

QUALITY FACTOR: A numerical index for rating the quality of a resonant circuit. A higher number indicates less losses and increased detection sensitivity in a resonant type detector system.

QUEUE DETECTOR: Component of a traffic control system which senses the presence (or number) of vehicles waiting in a queue at an intersection or on a freeway ramp.

QUEUE LENGTH: Number of vehicles that are stopped or slowly moving in a line where the movement of each vehicle is constrained by that of the lead vehicle.

RACK MOUNTED DETECTORS: Detector units that have no enclosing case and, therefore, must be placed in the controller cabinet by inserting its printed circuit board into a wired receptacle or "rack" made for the purpose. Compare Shelf Mounted Detectors.

RADAR DETECTOR: A vehicle detector installed above or adjacent (side mounted) to the roadway capable of being activated by the passage of a vehicle through its field of emitted microwave energy.

RADIO-FREQUENCY DETECTOR: A vehicle detector consisting of a loop of wire embedded in the roadway that is tuned to receive a preselected radio frequency from a transmitter located on a vehicle.

REACTANCE: The reactance (ohms) of a circuit component is the product of the voltage across the component and the sine of the phase angle between the voltage and the current divided by the current through the component assuming sinusoidal operation.

RED CLEARANCE INTERVAL: A clearance interval which may follow the yellow interval during which both the terminating phase and the next right-of-way phase display red (NEMA).

REJECTION (Adjacent Lane): The ability of a detector not to output an unwanted actuation caused by a vehicle in a land adjacent to that in which the detector is located.

RELUCTANCE: The opposition which a magnetic material or magnetic circuit offers to the passage of magnetic lines of force. Reluctance is the reciprocal of permeability (the ability of a metal to conduct lines of force) and permeance (the measure of that conductivity). Therefore, reluctance is related to permeability and permeance in much the same way as resistance is related to conductance in electic circuits.

REPHASE: The process of resetting, after a pulse actuation, to enable another pulse actuation should another vehicle enter the detection area. Can also be used as a verb: "The detector shall rephase 2 seconds after initiating an output pulse."

RESIN: An organic substance that is a non-conductor of electricity. Resins are widely used for insulation and encapsulation.

RESISTANCE: The opposition that a device or material offers to the flow of direct current, equal to the voltage drop across the element divided by the current through the element.

RESONANT FREQUENCY: The natural vibration frequency of a loop and its lead-in wire, to which the detector unit must tune.

RESPONSE TIME: The time a detector takes to respond to the initiation of a detection by a vehicle.

REST-IN-RED: A controller operational mode intended to display red to all movements, in the absence of any traffic demand.

SAMPLING DETECTOR: Any type of vehicle detector used to obtain representative traffic flow information (NEMA).

SCANNING DETECTOR: A multi-channel detector in which the loop(s) of each channel are energized in sequence, one at a time, in quick succession.

SEALANT: The material used in a saw slot of a loop detector to seal the wires in the slot.

SELF-POWERED VEHICLE DETECTOR (SPVD): A detector buried in the pavement that uses a self contained battery for power and transmits the detector information to the controller without the need for direct connection (lead-in cable).

SELF-TRACKING DETECTOR: A loop detector unit, not necessarily self-tuning, that includes electronics that compensate for environmental drift.

SELF-TUNING LOOP DETECTOR UNIT: One that is capable of adapting its operation to the resonant frequency of the loop and lead-in wire without any manual adjustment required. The term applies particularly to the start-up of the detector's operation, upon turn-on. Compare Selftracking Detector.

SEMI-TRAFFIC-ACTUATED CONTROLLER ASSEMBLY: A type of traffic-actuated controller assembly in which means are provided for traffic actuation on one or more but not all approaches to the intersection.

SENSING ZONE: See Zone of Detection.

SENSITIVITY: As it relates to a loop system the change in total inductance of a system caused by a minimum vehicle at one loop, expressed as a percentage of the total inductance. As it relates to a detector, is the minimum inductance change in percent required at the input terminals to cause the detector to actuate.

SENSOR (SYSTEM AND LOCAL): Traffic detection devices (detectors) that permit the system master or a local controller to obtain information as to the traffic flow characteristics in the area of the sensor. (see Detector.) NEMA limits the meaning of "sensor" to the sensing element of a detector.

SENSOR LOOP: An electrical conductor arranged to encompass a portion of the roadway to provide a zone of detection and designed in such a way that the passage or presence of a vehicle in the zone causes a decrease in the inductance of the loop that can be sensed for detection purposes (NEMA).

SERIES-PARALLEL: Type of electrical interconnection of four 6- x 6-ft (1.8- x 1.8-m) loops, usually 9 ft (2.7 m) apart and installed in a line in one lane to give a 51 ft (15.3 m) length of detection area. This interconnection scheme gives a combined inductance close to optimum.

SERVICEABLE CONFLICTING CALL: A call which:

A. Occurs on a conflicting phase not having the right-of-way at the time the call is placed.

B. Occurs on a conflicting phase which is capable of responding to the call.

C. When occurring on a conflicting phase operating in an occupancy mode, remains present until given its right-of-way (NEMA).

SHEATH: The outer covering or jacket over the insulated conductors to provide mechanical protection for the conductors.

SHELF MOUNTED DETECTORS: Units that have an enclosing case and, therefore, can be located in the cabinet by placing them on a shelf. They can stand alone. Compare Rack Mounted Detectors.

SHIELD: A conductive material surrounding the twisted pair(s) of wires in the lead-in cable of a loop detector installation, so that outside electrical interferences will not induce noise onto the twisted pair(s).

SHORTED TURN MODEL: A shorted turn model is a lossless shorted, single turn loop with a size and shape equal to the perimeter of the vehicle located above the loop at the average vehicle undercarriage height.

SIDE-FIRE DETECTOR: A vehicle detector with its sensor located to one side of the roadway (NEMA), such as on a pole, rather than directly over the roadway.

SMALL AREA DETECTOR: A detector intended to detect vehicles at a spot location upstream of the stopline. They may detect more than one lane. The 6- x 6-ft (1.8- x 1.8-m) loop detector is a prominent example. Also, included are ultrasonic and radar units, whose detection areas may be as long as 20 to 30 ft (6 to 9 m), because the length of time the moving vehicle is in the detection zone is not used in the intersection control logic. This detector is also referred to as a Point Detector.

SONIC DETECTOR: A vehicle detector which emits sound energy from a transducer at a high frequency (one that is in the upper range of human hearing) and that senses the reflection of its energy from a vehicle in its field.

SOUND-SENSITIVE VEHICLE DETECTOR: A detector that responds to sound waves generated by the passage of a vehicle over the surface of the sensor (NEMA).

SPEED ANALYSIS SYSTEM: A type of hardware assembly composed of two loop detectors and auxiliary logic. The two loops are in the same lane, a precise distance apart. A vehicle passing over the loops produces two actuations. The time interval between the first and the second is measured, and a speed is computed.

SPLASHOVER: An unwanted actuation caused by a vehicle in a lane adjacent to the lane in which the detector is located. Often occurs where long loops are used.

SPLICE BOX: See Pull Box.

SPLIT: A division of the cycle length allocated to each of the various phases (normally expressed in percent).

SPVD: See Self-Powered Vehicle Detector.

STRETCH DETECTOR: See Extended Call Detector.

SYSTEM DETECTOR: Detectors located to provide information to central control computers selecting appropriate control programs to meet the traffic demands.

TAPESWITCH: A temporary detector consisting of two strips of metal encased in a flat ribbon that is temporarily affixed to the roadway. When a vehicles tire crosses the tapeswitch, the two metal strips make contact closing an electrical circuit.

TERMINAL: Any fitting used for making a convenient electrical connection.

TF: The UL designation for fixture wire, solid soft copper conductor, insulated with thermoplastic.

TFF: Same as TF, except has stranded copper conductor.

THHN: Building wire, plastic insulated, 90 °C, 600 volt, nylon jacketed.

THRESHOLD: A minimum level of percent change in inductance which occurs to produce an actuation.

THW: Building wire, plastic insulated, heat, flame, and moisture resistant,75 °C.

THWN: Same as THW with overall nylon jacket.

TIME HEADWAY: The time separation between vehicles approaching an intersection, measured from the front of the lead vehicle to the front of the trailing vehicle.

TRAFFIC DETECTOR: A device by which vehicles, streetcars, buses, or pedestrians are enabled to register their presence with a traffic-actuated controller.

TRAFFIC PHASE: Those right-of-way and clearance intervals in a cycle assigned to any independent movement(s) of traffic.

TRAFFIC-ACTUATED CONTROLLER ASSEMBLY: A controller assembly for supervising the operation of traffic control signals in accordance with the varying demands of traffic as registered with the controller by detectors.

TRAFFIC-ACTUATED CONTROLLER: See Controller Assembly.

TRAILING CAR: The vehicle behind the last car upon gap-out a density controller. Gap-out occurs because the time headway between the last car and trailing car exceeds the allowable gap imposed by the controller.

TRANSDUCER: A sensor that transmits energy to the detection zone and interprets the signal received from the detection zone (NEMA). A device that is actuated by power from one system and supplies power usually in another form to a second system.

TRANSMISSION LINE: See Lead-In Cable.

TW: The UL designation for thermoplastic insulated wire for use in conduit and underground and wet locations. It is a common building wire having a soft copper conductor, which may be either solid or stranded.

TWISTED PAIR: Two insulated conductors twisted together and coded.

TWO-COIL MAGNETIC DETECTOR: This describes a magnetic detector with two coils. This detector is capable of serving as a directional detector.

TYPE 170 (179) CONTROLLER: One of the two major types of traffic signal controllers. Hardware is standardized with the actual control being provided by specialized software. which uses input from either loop detectors, magnetic detectors, or magnetometers.

UL: Underwriter's Laboratories, Inc., is chartered as a non-profit organization to maintain and operate laboratories for the examination and testing of devices, systems, and materials relative to life, fire and casualty, hazards, and crime preven-tion.

UL APPROVED: A product that has been tested and approved to Underwriter's Laboratories standards.

ULTRASONIC DETECTOR: A detector that is capable of sensing the passage or presence of a vehicle through its field of omitted ultrasonic energy (NEMA).

VARIABLE INITIAL INTERVAL: A controller design feature which adjusts the duration of initial interval for the number of vehicles in the queue.

VEHICLE DETECTOR SYSTEM: A system for indicating the presence or passage of vehicles (NEMA). See Detector System.

VEHICLE STANDARD: A test unit that produces a change in the loop inductance equivalent to a conventional American Sedan.

VEHICULAR PHASE: A traffic phase allocated to vehicular traffic.

VIDEO IMAGING DETECTOR SYSTEM (VIDS): A detection system under development that analyzes a video image of an approach and by pattern matching identifies and classifies (perhaps) vehicles in that approach. See also Wide Area Detection System.

VOLUME DENSITY CONTROLLER: An actuated controller which has a gap-reduction factor based on opposing phase vehicle time waiting.

VOLUME EXTENSION MODE: A manner of operation of a multiple detector design in which the green is extended by heavy traffic operating at a speed below the Design Speed. The speed is so low that the extension is attributable to the heavy volume. Compare with above.

WEIGH IN MOTION (WIM): A system of detectors and weighing devices that weigh vehicles while they are in motion over the detectors.

WIDE AREA DETECTOR SYSTEM (WADS): A developmental system using video interpretation to provide detection over a wide area of an approach. A micro-processor evaluates a video image of the approach to determine the presence of vehicles. Later developments are referred to as VIDS.

WIM: See Weigh in Motion.

WIRE GAUGE: See AWG.

WATERBLOCKED: Impervious to water entrance and migrations as a waterblocked lead-in cable or waterblocked splices.

XHHW: Cross-linked polyethylene insulated wire, rated at 90 °C in dry, and 75 °C in wet locations.

YELLOW CHANGE INTERVAL: The first interval following the green right-of-way interval in which the signal indication for that phase is yellow (NEMA) indicating the imminent change of right-of-way.

YIELD COMMAND: See Hold.

ZONE OF DETECTION: That area of the roadway within which a vehicle is be detected by a vehicle detector system (NEMA).

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