Traffic Detector Handbook:

Third Edition—Volume II

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U.S. Department of Transportation
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Research, Development, and Technology
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FOREWORD

The objective of the third edition of the *Traffic Detector Handbook* is to provide a comprehensive reference document to aid the practicing traffic engineer, planner, or technician in selecting, designing, installing, and maintaining traffic sensors for signalized intersections and freeways. Judicious application of the concepts and procedures set forth in the Handbook should result in improved installations and operations of traffic sensors and a long-term savings of public funds.

Sensor types include both in-roadway and over-roadway sensors. Topics covered include sensor technology, sensor applications, in-roadway sensor design, sensor installation techniques and sensor maintenance. The sensor technology chapter discusses the operation and uses of inductive loop detectors, magnetic sensors and detectors, video image processors, microwave radar sensors, laser radars, passive infrared and passive acoustic array sensors, and ultrasonic sensors, plus combinations of sensor technologies. Sensor application topics include safety, operation, multimodal issues, and physical and economic factors that affect installation and performance. The appendixes include a variety of research, background papers, and implementation guidance. The information contained in this Handbook is based on the latest research on available treatments and best practices in use by jurisdictions across the United States and elsewhere. References are provided for the student, practitioner, researcher, or decisionmaker who wishes to learn more about a particular subject.

The third edition is published in two volumes, of which this is the second, Volume II (FHWA-HRT-06-139), containing Chapters 5 and 6 and all Appendixes. Volume I (FHWA-HRT-06-108) contains Chapters 1 through 4.

Antoinette Wilbur, Director
Office of Operations
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David R.P. Gibson (David.Gibson@fhwa.dot.gov) at the Turner-Fairbank Highway Research Center (http://www.tfhrc.gov) was the Technical Representative for the Federal Highway Administration (FHWA). Milton K. Mills, Advanced Research Team FHWA, contributed many technical papers. Traffic sensor researchers and practitioners contributed significantly to document organization, content, and exhibits. The peer review panel, consisting of Darcy Bullock of Purdue University, Dan Middleton of Texas Transportation Institute, and Tom Urbanik of the University of Tennessee, provided peer review and advice based on their use and testing of sensors. Tom Potter of Reno A&E gave technical advice on the electrical functioning of loop detectors. Sensor vendors provided technical information and exhibits on their technologies. In addition, many FHWA staff members participated as sensor group members and/or provided comments throughout the project, including Pamela Crenshaw, Ralph Gillman, Peter Huang, David Jones, and Raj Ghaman.

16. Abstract

The objective of this Handbook is to provide a comprehensive resource for selecting, designing, installing, and maintaining traffic sensors for signalized intersections and freeways. It is intended for use by traffic engineers and technicians having responsibility for traffic sensors, whether in-roadway or over-roadway sensors. These two families of sensors have different characteristics and thus corresponding advantages and disadvantages that are discussed throughout the Handbook. Topics covered include sensor technology, applications, in-roadway sensor design, installation techniques, and maintenance. The sensor technology chapter discusses the operation and uses of inductive loop detectors, magnetic sensors and detectors, video image processors, microwave radar sensors, laser radars, passive infrared and passive acoustic array sensors, and ultrasonic sensors, plus combinations of sensor technologies. The sensor application topics addresses safety, operational performance, multimodal issues, and physical and economic factors that the practitioner should consider. Appendixes include research, background papers, and implementation guidance. The information contained in this Handbook is based on the latest research available on treatments and best practices in use by the surveyed jurisdictions. References are provided for the student, practitioner, researcher, or decisionmaker who wishes to learn more about a particular subject.

The third edition is published in two volumes, of which this is the second, Volume II (FHWA-HRT-06-139), containing Chapters 5 and 6 and all Appendixes. Volume I (FHWA-HRT-06-108) contains Chapters 1 through 4.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 5. SENSOR-INSTALLATION TECHNIQUES

Sensor installation may appear to be a relatively easy task once the operation of candidate sensor technologies is understood, the suitability of a particular technology to an application is reviewed, and the design, specifications, and plans are developed. However, the mechanical operations associated with sensor installation often present challenges. For example, inductive-loop detector installation requires approved procedures for cutting a slot in the pavement, laying turns of wire in the slot, covering them with sealant, removing excess sealant, splicing the wire to the cable, and connecting the cable to the electronics unit in the controller cabinet. For over-roadway sensors, analogous tasks and related issues appear, such as installation of mounting structures, power and data cables, sensor alignment, and calibration verification.

In reality, the seemingly uncomplicated activity of sensor installation is composed of several critical processes. Improper or sloppy installation causes many of the sensor failures and signal malfunctions that are observed. 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, dependence on properly functioning sensors increases as traffic congestion and delay become a more urgent problem and traffic-control equipment becomes more sophisticated.

This chapter addresses the needs of project engineers, contractors, inspectors, field crew supervisors, and traffic technicians by reviewing the proper techniques for installing traffic-flow sensors; and it discusses preinstallation activities that apply to all types of sensors. To underscore the criticality of the installation process, the magnitude and causes of inductive-loop detector failures are addressed next. Inductive-loop detector installation procedures for existing roadways are then described, followed by a discussion of loop-installation procedures for new and repaved roadways. Installation of magnetometers, magnetic detectors, and over-roadway sensors (e.g., video image processors, microwave and laser radars, passive infrared sensors, ultrasonic sensors, passive acoustic sensors, and sensor combinations) are discussed in sequence in the latter sections of the chapter.

TYPICAL PREINSTALLATION ACTIVITIES

The design of the sensor system involves a number of decisions that are made previous to installation. Examples of these decisions for in-roadway sensors utilized for signal control were discussed in Chapter 4. Included there are specifications for the type and configuration of the sensor hardware necessary to meet previously identified operational and data requirements, and a preliminary plan showing the sensor layout at the selected location.

Preinstallation 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 and effective manner. The implication of these activities is discussed further in the following paragraphs.

SCALE DRAWING OF SENSOR INSTALLATION SITE

A scale drawing of the location showing the geometry of the roadway and the location of the in-roadway or over-roadway sensor components in relation to the pavement markings or mounting structure is needed. The drawing should depict the location and content of conduit, manholes, power sources, pavement materials, and electrical equipment that interface with the installation. Because it provides fundamental guidance for the installation crew and becomes part of the procurement package needed for a contractor installation, the accuracy of this drawing directly affects sensor installation.

The completed drawing should be reviewed with the design engineer to insure that the sensors are located as specified in the configuration design and in areas free of underground or under pavement hardware or overhead obstructions (in the case of over-roadway sensors) that could interfere with proper operation.

FIELD VISITS

Field visits to the installation site are required before and after the scale drawing is made. The field visit made prior to drawing preparation is for inventorying the existing conditions and identifying potential problem areas. These include pavement joints, which may affect the design of an inductive-loop detector system, and lines of sight and identification or lack of support structures, which affect installation of over-roadway sensors. Other factors to be noted during the site visit are listed in the “Video Image Processors” section under “Site Surveys.”

As a result of this visit, the project engineer should determine the method for burying cables, installing in-roadway and over-roadway sensors, and the types of equipment needed for the installation strategy. Methods for 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 is made to verify their accuracy.

INSTALLATION CREW ESTIMATES

The size and skills required of the installation crew should be estimated prior to installation. Plan drawings should provide sufficient information to determine the scope of the installation tasks, the amount of time required, and the size of the crew necessary for the installation. Depending upon the size of the crew, many of the tasks may be performed simultaneously, thereby reducing the time traffic is disrupted.

EQUIPMENT REQUIREMENTS

The sensor types and layout dictate the equipment required for the installation. Table 5-1 lists equipment commonly needed for a typical inductive-loop detector installation. Barricades, signs, cones, safety vests, and other devices are also necessary to control traffic safely during the installation process.

In addition, magnetometer installation requires a drill and bit to bore the vertical hole in the roadway for the sensor probe. Magnetic detector installation usually requires a backhoe, a horizontal boring machine, a level, and a tamping machine.

Over-roadway sensor installation usually requires a bucket truck.

Table 5-1. Equipment for typical inductive-loop detector installation.

Item	Description and use
Power saw	Self-propelled 18–65 horsepower (hp) saw equipped with 1 / 4 to 3 / 8 inch (6.4 to 9.5 mm) thick blade (abrasive or diamond), water valve, depth gauge, and horizontal guide
Water supply	Used with diamond blade for cooling and cleaning out of sawcuts
Jackhammer	Bores holes through concrete curb
Air compressor	Used with jackhammer to clean and dry sawed cuts
Chisel and hammer	Removes sharp edges at corners of sawcuts
Blunt tool	For example, a wooden stirring stick for seating wire in saw slot
Twister	Provides uniform twists of the lead-in wires
Template or straight edge	Marks outlines of loops on pavement
Trenching machine	Used to bury cable in dirt
Megohmmeter and volt/ohm meter	Used to inspect and test wire continuity and resistance
Loop analyzer	Tests continuity and inductance of the wire loop
Soldering iron	Either a butane torch with a soldering tip or an electric soldering iron for making solder connections at the splice
Measuring tape	100 ft (30 m) minimum-length tape for making exact measurements for loop placement

MATERIAL REQUIREMENTS

As with manpower and equipment, the type and amount of installation materials should be determined. Material quantities should be ample to avoid any interruptions of work. A typical material list for inductive-loop detector installations is provided in Table 5-2. Other types of power and data cables and suitable mounting brackets are required when installing over-roadway sensors.

Table 5-2. List of materials for typical inductive-loop detector installation.

Material	Function
Detector wire	Forms the loop and lead-in wires
Lead-in cable	Spliced to the loop lead-in wire in the pull box, it connects the lead-in wires to the electronics unit in the controller cabinet
Pull box	Contains the connection (splice) between the lead-in wire and lead-in cable and provides access for maintenance
Sealant	Seals the loop wire in the sawcut and protects the loop from environmental damage
Cement, sand, or talc	Dusted on sawcut after sealant is applied to prevent tracking
Concrete	Holds the pull box in place
Surge voltage protector	Provides protection for the electronics in the controller cabinet
Solder	Needed to make splices
Splice kits (or equivalent)	Environmentally seals the splices
Spray paint or chalk and line	Outlines loop dimensions prior to sawcutting

INDUCTIVE-LOOP DETECTOR INSTALLATION

The inductive-loop detector system is composed of one or more wire loops embedded in the pavement (the sensing element), a splice between the lead-in wire and the lead-in cable in the pull box, lead-in cable (usually in a conduit) connecting to the terminal strip in the controller cabinet, cable from the terminal strip to the inductive-loop electronics unit, and finally, the electronics unit, itself. The interconnections among these various components are illustrated in Figure 5-1.

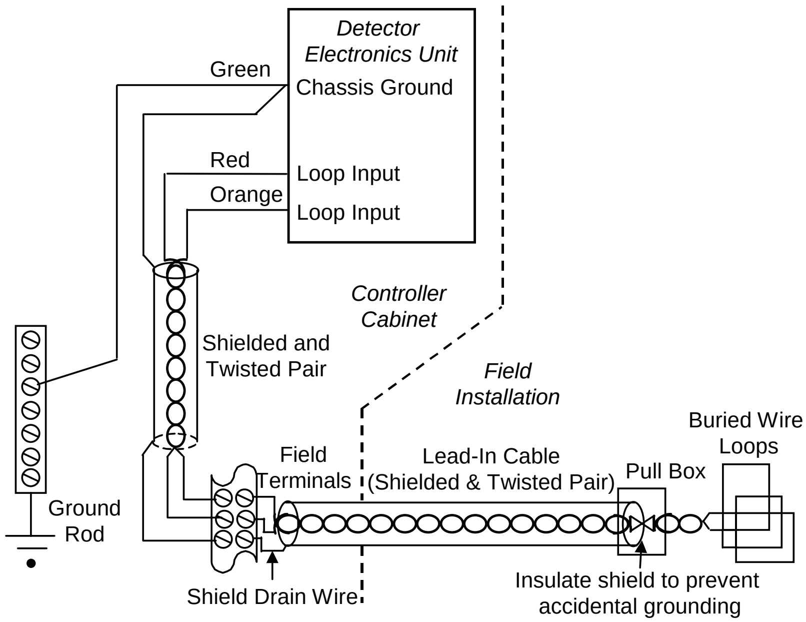


Figure 5-1. Inductive-loop detector system configuration.

The paragraphs below describe the installation of inductive-loop detectors, beginning with an overview and followed by detailed discussions of failure mechanisms associated with poor installation, common installation techniques and materials, and alternative installation techniques.

INSTALLATION TECHNIQUES

Inductive-loop detectors are installed in asphalt or portland cement concrete pavements using the process illustrated in Figures 5-2 through 5-7 and described by the steps below:

- Cutting a slot.
- Cleaning and drying the slot.
- Laying in the inductive-loop detector wire.
- Sealing the sawcut.
- Connecting the wire to the lead-in cable.
- Connecting the cable to the terminal strip in the cabinet.
- Ensuring the harness connects the terminal strip to the electronics unit.

Installation techniques differ in the treatment of the corners where two saw cuts intersect, splicing techniques, sealant types, and sealant application. Guidelines and recommendations to assist highway maintenance agencies and other related organizations in planning and installing inductive-loop detectors are found in this chapter and other FHWA reports.(1)

Figure 5-2. Loop sawcut process.

Figure 5-3. Pavement washing.

Figure 5-4. Pavement blow drying.

Figure 5-5. Pressing in wire and backer rod.

Figure 5-6. Inserting loop sealant.

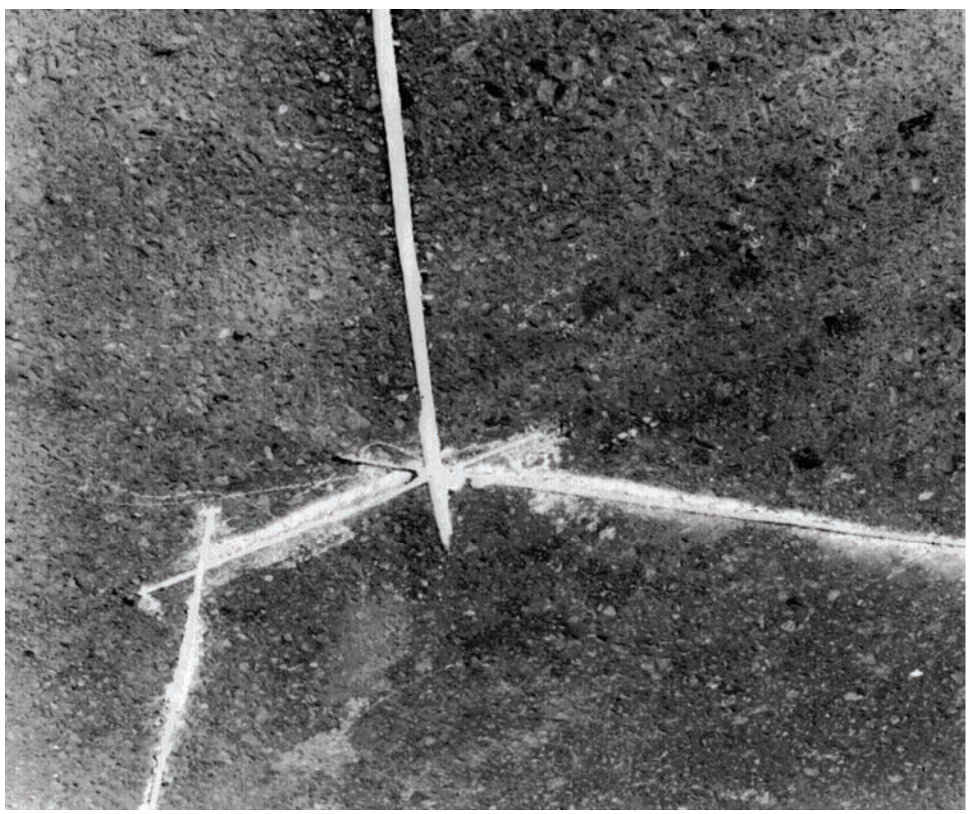


Figure 5-7. Detail of final inductive-loop installation.

Installation techniques and theories vary widely among traffic agencies as shown, for example, in the survey of western State practices exhibited in Table 5-3.[2,3] Procedures developed over time frequently become outdated or are no longer effective; yet there is often great resistance to change. In many cases, contractors perform sensor installation using proprietary shortcuts (and shortcomings). The importance of appropriate installation procedures for long-term operational effectiveness of sensors cannot be overstressed. Since contractors primarily install inductive-loop detectors, it follows that construction supervision and inspection by the responsible agency is critical to their proper operation and reduced maintenance.

Table 5-3. Installation practices in western States.

State	Loop type	Sawcut dimensions	Cleaning method	Loop wire	Lead-in cable	Electronics unit 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 and drain	Shelf
California	6 x 6 ft square or diamond (3 turns) 6 x 6–50ft quadrupole (2-4-2 or 1-2-1)	W = 1 / 4 to 1 / 2 inches (6.4-12.7 mm); D = 1-3/4 inches (44.5 mm)	Flush with water and blow out and dry with air	#12 RHW Use neoprene or x-link polyethylene 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 (9.5 mm); D = 1-1/2 inches (38.1 mm) min.	Blow out with air	Model 20002 vehicle homerun cable (4 #18 conductors)	Belden 8227	Rack
Montana	6 x 6 ft square 6 x 20 ft quadrupole (various numbers of turns)	Asphalt: W = 1/4 inch (6.4 mm); D = 2 inches (50.8 mm); Concrete: W = 1/4 inch (6.4 mm); D = 11/4 inches (31.8 mm)	Blow out with 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 (6.4 mm); D = 2 inches (50.8 mm)	Blow out with air	#12 RHW and XHHW N. Nevada solid S. Nevada stranded	IMSA 19-2 (pair communication cable with shield)	Mostly shelf
Oregon	Single loop – 4 x 4ft diamond Series of loops – 3 x 3ft diamonds (both 4 turns)	W = 1/4 inch (6.4 mm); D = 2 inches (50.8 mm)	Flush with water and blow out with 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 rectangle (2 turns)	W = 1/4 inch (6.4 mm); D = 2 inches (50.8 mm)	Blow out with 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 (6.4 mm); D = 2 1/2 to 3 inches (38.1 to 63.5 mm) inches	Blow out with air	#14 XLP, RHH, or RHW or #12 XLP stranded	AIW 7311 or Belden 8718	Shelf and rack

1 ft = 0.3 m; W = width; D = depth

Newer inductive-loop detector installations are 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 a 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 reduce street installation time. Other agencies preform the loops (i.e., the loop consists of 1/2- or 3/4-inch (12- or 19-mm) polyvinyl chloride (PVC) pipe with the wire enclosed). These loops require at least a 1-inch (25-mm) wide slot in the pavement rather than the narrow sawcut used for conventional loops. Another technique utilizes wider slots of up to 4 inches (100 mm) to facilitate placement of the preformed loop.

Because of harsh weather, Alaska enhances loop protection with their preformed loop. The loop is enclosed in 1-inch (25-mm) Schedule 40 PVC pipe (instead of Schedule 80). The loop wire is #12 AWG crosslinked polyethylene with backer rod fill to prevent damage caused by water encroachment and eventual freezing.

In addition, many inductive-loop detectors are now built into the pavement during construction of a new roadway or during repaving. In Puerto Rico, concrete slabs with the inductive-loop detectors in place are being installed (see later discussion under “Inductive-Loop Detector Installation Alternatives”). This technique replaces the sawcut that usually contains the loop wires with a slab that includes a built-in loop. The slab, which replaces a section of roadway, can also be installed in new road construction.

INDUCTIVE-LOOP DETECTOR FAILURES

The relatively large number of inductive-loop detector failures nationwide in the 1980s resulted in an aggressive effort to determine their major causes and seek ways to eliminate or minimize them. FHWA, in cooperation with various State agencies, funded a number of studies to quantify the extent of inductive-loop detector failures, identify the causes, and evaluate the various installation procedures (e.g., sawcutting and cleaning slots) and materials (e.g., sealants, conduits, wires, and cables). The results of these studies are summarized below and are presented in more detail in Appendix M.

Causes of Inductive-Loop Detector Failures

Inductive-loop detector system failures are frequently traced to the in-road loop wire or to the splice between the loop wire lead-in and the lead-in cable. Since the introduction of the digital self-tuning electronics units, failure attributed to the amplifier/oscillator unit has all but disappeared. Failures continue to plague agencies using older electronics units that do not adjust to changes in temperature, moisture, and number of turns or type of loop wire and lead-in cable type and length. 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 a “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 caused by “deteriorated pavement.”

No matter how failures are categorized, the inescapable conclusion is that the predominant causes for failures in the inductive-loop detector system can be ameliorated by improved installation techniques and vigilant supervision and inspection.

Failure Frequency

Inductive-loop detector failure rates differ from agency to agency because of the large number of variables that contribute to the failures. In addition, until recently, very few agencies maintained comprehensive records. If a loop in a traffic-signal control system 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.[4,5] It was found that, of the 15,000 existing inductive-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.[4,5] This high failure rate encouraged New York State to develop the improved installation methods described later in the chapter.

The failure rate reported by New York is consistent with other failure rate literature. For example, one district in Minnesota reported an annual failure rate of 24 percent and Cincinnati, OH, reported 29 percent failures per year. Although these areas experience cold weather climates, failure rates in the sun-belt States are about the same, but the causal factors differ.

Failure Mechanisms

Although most failures originate in the loop wire, the wire itself is not necessarily the precipitating cause of the failure. The failure is usually caused by one of several breakdown mechanisms, such as poor pavement condition or improper installation of sealant, which allows the wire to float to the top and become vulnerable to deterioration caused by traffic.

Table 5-4 summarizes the results of an inductive-loop detector failure survey of eight western States.[2,3] Further discussion of loop failures is found in Appendix M.

Table 5-4. Summary of inductive-loop detector failures.

State	Percent installed by State	Percent installed by Contractor	Major failures	Remarks
Alaska	10	90	No loop failures reported	Preformed loops used exclusively
California	5	95	Improper sealing and foreign material in saw slot	Preformed loops used 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	Some preformed loops used with no failures reported
Washington	10	90	Improper sealing and foreign material in saw slot	Need better inspection to improve loop performance

LOOP LAYOUT AND SAWCUTS

After securing the work zone with appropriate barricades, cones, etc., to divert traffic from the work area, carefully mark the pavement to depict the size and shape of the loop to be installed. A lumber crayon, chalk, or spray paint is typically used for this purpose. If available, a template of the proper size and shape is recommended. 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 that shown in Figure 5-8 is made to ease the stress on the wire that would otherwise occur from a sharp 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 the corners.

A diagonal cut of approximately 12 inches (30 cm) or more is recommended. Some agencies use a hexagonal, octagonal, or round loop design in order to eliminate the sharp turn and reduce splashover. Another technique for installing round loops is presented later in this chapter under “Loop Installation Alternatives.”

Many agencies find that diagonal cuts across the corners of the sawcut cause the triangular portion of the pavement to break up. Instead, 1.25-inch (3.1-cm) holes are drilled at the loop corners before the slots are sawcut. 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 5-9.

The State of New York uses an alternative to core-drilled corners.[4] Their technique overlaps straight sawcuts at the corners (i.e., no diagonal sawcuts) and then chips out the inside corner 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

Sawing 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 ensuring it is in good operating condition.

Overview of Saw-Cutting Equipment

Many saw types and sizes are available for cutting slots. In the past, equipment for saw-cutting specified at least an 8- or 9-hp gasoline engine-powered saw with a 1/4- or 3/8-inch (6- or 9-mm) abrasive or diamond blade. Because it was perceived to be more economical, the abrasive blade was favored by some agencies. 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 with an abrasive blade is irritating and dangerous to workers, motorists, and pedestrians. Furthermore, 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.

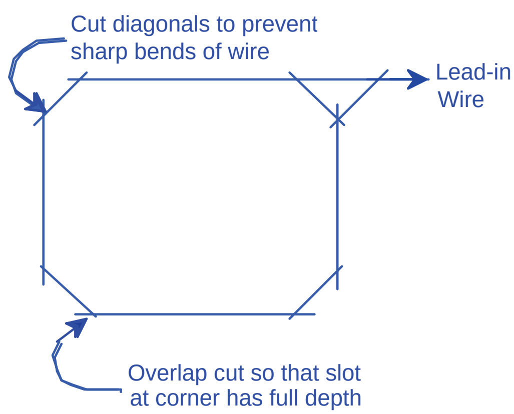
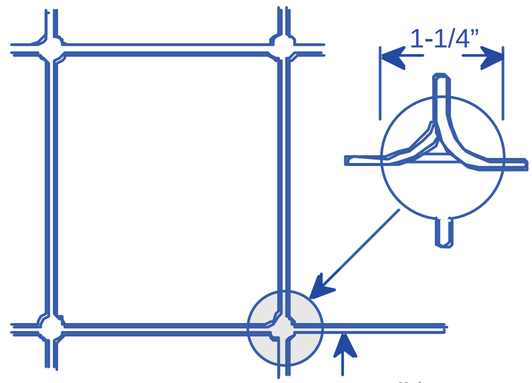


Figure 5-8. Chamfer-cut corner treatment.



1 inch = 2.5 cm

Figure 5-9. Core-drilled corner treatment.

Although abrasive blades are less expensive than diamond blades on a per-blade basis, the service life of abrasive blades 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, they concluded that a higher horsepower saw using a water-cooled diamond blade reduced cutting time 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 diamond blades is a specialized area of expertise. A number of manufacturers have their own proprietary designs. Generalization about the best design is difficult because of the differences 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 maximizing blade life and exposing new diamond cutting edges only after the surface chips are rounded to the point where the blade no longer cuts efficiently.

The diamond chips are set in a matrix, which is laser-welded to the blade blank. Faster cutting implies exposing new diamond chips more quickly. This, in turn, means a reduction in the blade life. 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 requires a change to a blade suited for the particular saw and the speed at which it operates.

Saw-Blade Troubleshooting

Table 5-5 lists several problems encountered when using saw blades to cut pavements for loops and magnetometers.[6] The probable cause of the problem and potential solutions are also shown.

Table 5-5. Saw-blade issue resolution.

Problem	Possible cause	Solution
Loss of one or more cutting elements	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 hairline cracks appear in cutting elements	Blade matrix metal too hard for application or saw RPM too high	Purchase new blade to match job requirements and saw being used
Vertical hairline cracks appear in core below air gap	Cutting element bond too hard or improper blade tension for RPMs being used	Purchase blade with softer bond or drill a hole at base of crack to stop its growth
Horizontal hairline 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 and/or reblank blade
Arbor hole out of round	Saw mandrel scored or too small for blade	Replace or reblank blade; for minor damage, ream and insert a reducer bushing
Undercutting of core below the cutting element	Material being cut is excessively abrasive	Remove blade before cutting elements are lost; replace or reblank blade if cutting is to continue; a wear guard may be added during reblanking
Core dished—blade tension lost	Bond may be too hard for RPMs 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 or blade not suited for application	Insure proper blade for job requirements
Short blade life	Improper RPM selection, inadequate water, blade not suited to job, or excessive friction	Insure adequate water supply that strikes blade near each side of arbor; check saw RPM against blade requirements

Saw Horsepower

Saw horsepower is a critical factor affecting the cost of the sawcut. Cutting speed is directly proportional to saw horsepower and is influenced by the hardness of the surface to be cut. Accordingly, 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, higher cutting speeds result in a decrease in the time a lane must be closed to traffic.

The saw must be large enough to provide the power needed to keep the blade from bogging down.(6) Other indications of an underpowered saw or the improper match of the blade to the saw are described below:

- 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 this condition results in excessive diamond chip loss and short blade life.

- Breakup of part or complete loss of the cutting edge indicates excessive pressure on the blade during cutting. Reduction in cutting speed or selection of a better-suited blade is required to avoid this difficulty.

On the basis of its l983 study, the State of New York revised its recommendation for its saw from 9 hp to l8 hp.[4] However, most contractors and a number of State agencies favor a more powerful saw. Wet-cut tests conducted in Texas with a 65-hp saw with a diamond blade reached cutting speeds ranging from 37- to 82-inch-ft (28- to 62-cm-m) per minute in 1-inch-(2.5-cm) deep cut in asphalt concrete. The average speeds are given in Table 5-6. Ten tests were run on asphalt concrete (AC) surfaces and four on portland cement concrete (PCC). All tests cut to a 1-inch (2.5-cm) depth. The table also lists the average projected cutting speeds for other slot depths.

During the 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 0.5 inch (1.3 cm) was common. Adding a 50-pound (lb) (23-kilogram (kg)) dead weight directly over the blade driveshaft reduced this problem when the cutting speed was between 25 and 30 inch-ft (19 to 23 cm-m) per minute.

Table 5-6. Average saw-cutting speeds (inch-ft) as a function of surface type and slot depth.

Type of surface	Number of test cuts	Actual slot depth	Projected slot depth		
		1.0 inch	1.5 inches	2 inches	2.5 inches
AC	10	55.7 inch-ft	37.1 inch-ft	27.9 inch-ft	22.3 inch-ft
PCC	4	9.0 inch-ft	6.1 inch-ft	4.5 inch-ft	3.5 inch-ft

1 inch = 2.54 cm; 1 inch-ft * 0.77 = 1 cm-meter

Wet Versus Dry Cutting

The preponderance of experience supports the need for wet cutting in portland cement concrete and its desirability in asphalt surfaces, particularly with higher-speed saws. While asphalt concrete can be successfully dry cut at high speed, such speeds reduce blade life. For example, 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 to arrive at the cutting edge of the blade just as the edge point goes down into the pavement surface. This maximizes cooling and lubrication.

Sawcut Depth

Saws should be equipped with a depth gage to assist in maintaining proper depth and a horizontal guide to assure alignment. The appropriate depth is dependent on the type of pavement and the number of turns of wire. Table 5-7 contains a general guide for slot depth, which suggests a minimum of 1-1/8 inches (29 mm) when one turn of wire is used and a maximum of 2 inches (51 mm) when 5 or 6 turns of wire are used.[6] However, some agencies such as the Virginia DOT use 3- and 4-inch (76- and 102-mm) slot depths for multiple wire-turn loops to prevent overlays from destroying the loop. The depth of the sawcut should be verified frequently during cutting to assure a constant value. Several agencies specify additional depth to allow for a 0.5-inch (13-mm) sealant cover over the wires, while some manufacturers recommend planning for at least 1-inch (25-mm) of sealant cover.

Table 5-7. Sawcut slot depth guide.

Turns of wire	Saw slot depth	
	Inches	Millimeters
1	1-1/8	29
2	1-3/8	35
3	1-9/16	40
4	1-3/4	44
5	2	51
6	2	51

Finishing the Sawcut

Sawcuts should be clean and well defined. All jagged edges and protrusions should be removed with a small chisel and hammer. It is crucial that the sawcut be clean and dry. Cleaning should take place immediately after the cutting is complete. Cutting dust, grit, oil, and contaminants must be kept out of the cut, which should be flushed clean with pressurized water and then dried with compressed air.

Many agencies only require that the sawcut be cleaned with compressed air. If an inordinate rate of wire failure occurs, however, these agencies should consider flushing the cut with pressurized water as well as with compressed air. Cleaning procedures should be designed to avoid blowing the debris in the direction of passing pedestrians or vehicles.

Only one sawcut along the marking should be made. If the sawcut is out of alignment, *another cut should not be made near the first cut* as this significantly weakens the pavement. If another cut is necessary, at least 4 to 6 inches (10 to 15 cm) should be allowed between the old and new cuts.

INSTALLING LOOP WIRE

The loop wire can be installed after the slot is cut and cleaned. The following discussion describes common practices utilized by a number of loop installers. Many contractors specializing in installing inductive-loop detectors have developed individual methods and short cuts, some of which are highly effective. Others are merely expedient and, in the long run, prove costly to the agency. This underlies the need for careful inspection procedures during the installation process.

Field crew personnel are not always as vigilant or careful in handling loop wire as would be desired. Accordingly, the installation supervisor and/or inspector should ensure that the wire is not damaged during the installation process as damage could cause malfunction of the inductive loop and its eventual replacement. Should any damage occur to the wire during handling, it should be pulled up immediately and replaced.

Wire Type

Wire gauge designation is based on cross sectional area, where gauge numbers are separated by 20.6 percent in wire cross sectional area.

Wire sizes are classified in accordance with the American Wire Gauge (AWG), originally called Brown & Sharpe™ Gauge. AWG numerically represents wire size, where the lowest AWG numbers correspond to the largest wire cross sections. The gauge designations differ by 20.6 percent in cross-sectional area. Thus, #12 AWG is 20.6 percent larger than #14 AWG, etc.

Wire is further defined by insulation type. Designations for some of the more commonly used wire for inductive-loop detector applications are shown in Table 5-8. The most common wire sizes range from #12 AWG to #16 AWG. Agencies that use the larger wire are about equally divided between #12 AWG and #14 AWG.

Table 5-8. Wire standard designations.

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 wet locations; it is a common building wire having a bare, soft-copper solid or stranded conductor[a]
XHHN	Cross-linked, polyethylene-insulated wire rated at 90 °C in dry locations and at 75 °C in wet locations

[a] Building wire is defined as a commercial wire used to supply energy to light sources and power outlets in permanent installations utilizing 600 volts or less. Typically used in an enclosure not exposed to outdoor environments.

However, some manufacturers recommend #16 AWG, claiming 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 inductive-loop detector manufacturers. The insulation must withstand wear and abrasion from shifting streets, moisture, attack by solvents and oils, and the heat of high-temperature sealants. Stranded-loop wire is preferred over solid wire because stranded wire is more likely to survive bending and stretching due to its mechanical characteristics.

Ducted Wire

A growing tendency in inductive-loop design is to use insulated loop wire encased in continuous cross-linked polyethylene tubing. A number of manufacturers make these loop materials. Brand names include Detecta-Duct, Power Loop, Signal Duct, and Electroloop.

A typical product is composed of flexible ducting encasing THHN type #14 AWG stranded wire conductors. Ducted-loop wire has the following advantages:

- 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 duct maintains its integrity when in contact with high-temperature (400 °F (149 °C) or more) sealing compounds.
- Ducted-loop wire retains its flexibility over a wide range of temperatures.

Prewound Loops

Some agencies prewind and bind loop wire (or ducted wire) in their shops to meet length and size specifications, thus making a prefabricated loop for transport to the site. This is accomplished by winding the loop wire around pegs mounted on a wall or table. The spacing between pegs is measured to accurately reflect the required loop dimensions. Prewinding 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 along with the required length of lead-in to the pull box. 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 5-10.

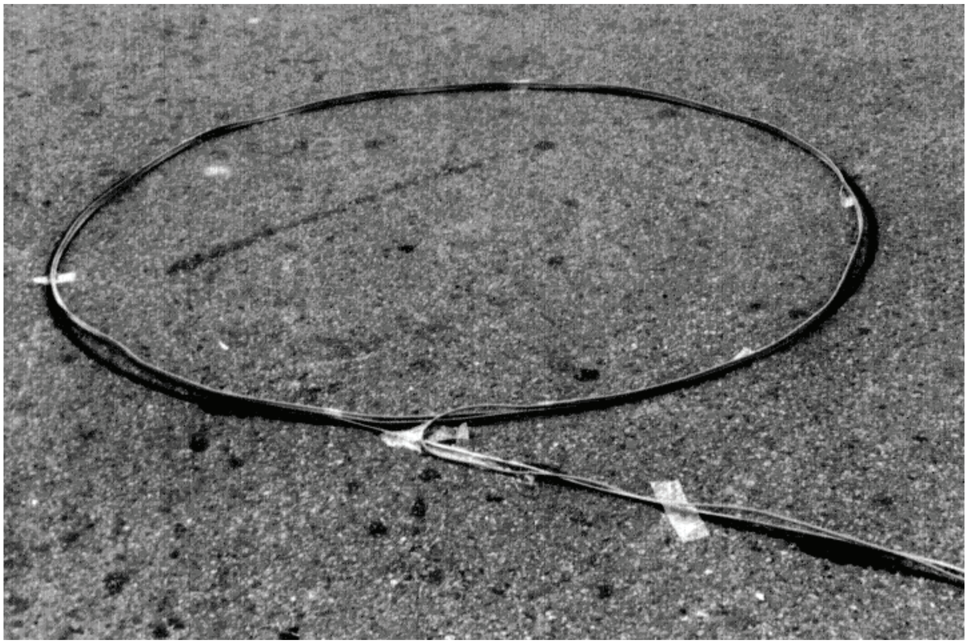


Figure 5-10. Prewound loop installation.

Preformed Loops

A preformed inductive loop is an inductive coil that is manufactured before installation in the road surface. Preformed loops are usually encased in a protective jacket or conduit to mechanically and electrically isolate the coil and lead-in wires. Preformed loops are installed using two different methods: paveover and sawcut. Primarily, they are paved over during the construction of new road surfaces. Secondarily, they are installed in sawcut grooves similar to field-wound sawcut loops. Preformed loops are an important alternative to field-wound sawcut loops, which suffer frequent failure as a result of the factors below:

- Wire damage during installation or from sharp debris left in the sawcut groove.
- Incorrectly formed sensors resulting from an incorrect number of turns or incorrect sawcut shape.
- Eventual exposure of the loop wires to vehicle-caused abrasion from sealant or road material failure.

Preformed loops address these problems by mechanically protecting the wires from damage and by fixing the number of turns and perimeter of the loop. Paveover preformed loops avoid the problems associated with sealant because there is no sawcut to compromise road surface integrity. However, the low profile of some sawcut preformed loops means they are less likely to migrate out of the sawcut. Preformed loops have demonstrated improved reliability, stable electrical isolation from ground, and a long physical life.

Preformed loops are available in two different designs: conduit-type preformed loops and the InstaLoop™ sensor. Conduit-type loops are constructed of a continuous length of insulated wire encased in a heavy wall plastic pipe or conduit. The InstaLoop™ is manufactured from heavy-duty multiconductor cable.

Figure 5-11 illustrates a conduit-type preformed loop commercially manufactured by several companies. In addition to the square shape, preformed loops are also available in rectangular and round configurations. Local signal maintenance shops frequently construct these loops from readily available materials for installation in their own municipalities. Homemade preformed loops can easily be customized to suit the requirements of the local agency, and are less expensive than the commercially available preformed loops. Commercial preformed loops come in several conduit sizes and materials suitable for different methods of installation. The outside diameters of the conduits range from a minimum of 3/8 inch (9 mm) to greater than 1 inch (25 mm). Typical conduit materials are common PVC irrigation pipe and fiber-reinforced hydraulic hose. Although the narrowest versions of this style of preformed loop are advertised for installation in a sawcut, a perfectly formed 0.5-inch- (12-mm-) wide sawcut is required to accommodate pipe fittings, causing a concomitant lack of adjustability. Therefore, conduit-type preformed loops are limited to paveover installations.

Figure 5-12 shows the InstaLoop™ sensor, which is made of heavy-duty multiconductor cable instead of wire wound inside conduit. This more efficient design enables the use of narrow, 0.25-inch- (6-mm-) wide sawcuts, which minimize road damage. Also, the lower profile InstaLoop™ paveover sensor reduces reflective road surface cracking. Sensitivity, signal quality, and noise rejection are all improved due to optimal geometry and twisted pair lead-in cable. InstaLoops™ are far more flexible than conduit-type loops, simplifying shipment, storage, transportation, and installation at the job site. Most importantly, they are field- and laboratory-tested to be highly resistant to cuts, scrapes, chemicals, and water damage.

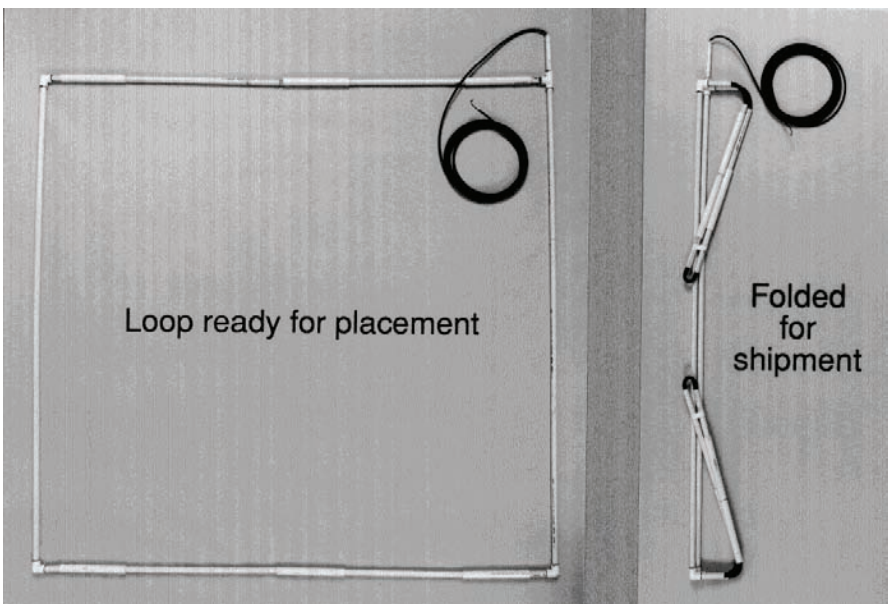


Figure 5-11. Preformed loop assembly.

Other manufacturers of preformed paveover inductive loops for asphalt and concrete are Patriot Technologies, International Road Dynamics, Lead-In Systems and Debron Inc. These products have a maximum outside diameter of 5/8 inch (16 mm).

Figure 5-12. InstaLoop™ Paveover Sensor.

The InstaLoop™ has two unique features that improve performance: installation in a 0.25-inch- (6-mm-) wide sawcut groove and adjustable loop size. Sensor width is minimized and sensitivity maximized through use of multiconductor flat cable that stacks the wires in the slot. A 0.25-inch- (6-mm-) wide linear junction transitions the loop cable into the lead-in cable and thereby allows adjustment of the loop head size through movement of the junction located in the lead-in sawcut. The junction is fully sealed and rated for direct burial.

Preformed Loop Sensor Installation

Preformed loops can be installed in new road surfaces under concrete or asphalt and can be installed in sawcut slots.

Concrete Paveover Installation

To install paveover loop sensors under concrete, the loop must be secured in the desired position while the cement is poured. On bridge decks and roads where reinforcement bar is exposed before the pour, the preformed loops can be tied directly to the bars to hold them in place. Otherwise, they can be laid on the base course in position, and small piles of concrete placed on points along the loop head and lead-in to hold it in place. Once the loops are in place, concrete is poured as usual while making sure not to move the loops after they are covered.

Asphalt Paveover Installation

Installing preformed loops under asphalt is more challenging because of the requirement to ensure that the loops are not damaged or moved during the paving operation. Installation problems may occur due to the following three factors:

1. High-temperature asphalt can melt loop insulation and conduit.
2. Low-riding, hard-wheeled asphalt spreaders can move or destroy loops.
3. Rough, unpaved surfaces and sharp aggregate can cut loop insulation and wires during compression.

Metal-Sheathed Loop Cable

A metal-sheathed loop known as mineral-insulated cable was first included in National Electrical Code (NEC) in 1953. It finds use in hazardous locations or difficult environments. Mineral-insulated 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.

Mineral-insulated installations are found in many industries, including mining, aerospace, marine, petrochemical, and cryogenic, and in blast furnaces. Its application to inductive-loop detector installations is made possible by the observation that loop wires operate efficiently while encased in metal. These installations appear to be best suited to loops installed on the base course, previous to their being covered 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 inherent advantages of this type of loop cable is the excellent shielding system. Shielding starts at the electronics unit and continues through the electronics unit wiring harness to the controller cabinet field terminals. The shielding proceeds 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 inch (1.27–2.54 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 electronics unit end.

IDOT developed a regulated procedure for installation of loop wire to combat haphazard construction procedures that seriously degraded performance. IDOT uses mineral-insulated cable loops primarily in new pavements and for replacing loops that are destroyed by widening and resurfacing projects. Figure 5-13 shows the installation detail suggested by the IDOT. Their specification is reproduced in Figure 5-14 for those agencies interested in using this type of product.[7]

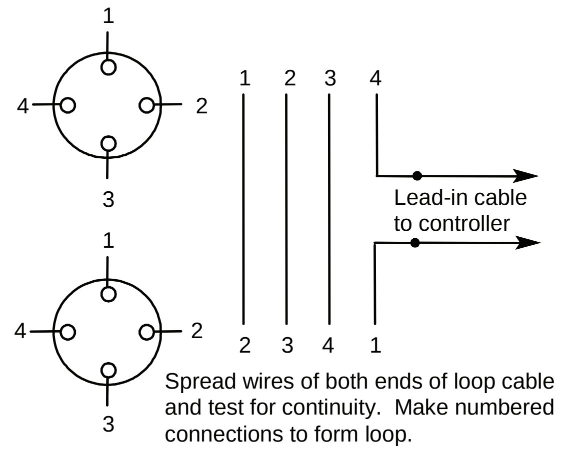


Figure 5-13. Metal-sheathed loop cable installation.

Wire Insertion

One continuous wire must be laid 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.

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., a 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 subject 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 5-15. Many agencies use rigid plastic conduit or flexible tubing. The State of Illinois has used common rubber garden hose in some of their installations. The material should be approximately 0.75 inch (1.9 cm) in diameter and at least 1 ft (30 cm) long. The conduit is placed in a cut, which measures 1.25 inches (31 mm) wide and 16 inches (40 cm) long, as shown in Figure 5-16.

SPECIFICATION FOR METAL SHEATHED LOOP CABLE

The cable shall be #16 AWG with 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 with subassembly kit composed of a pot, cap, sealer, and sleeves.

Installation shall consist of furnishing and installing Mineral-Insulated 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 are present, the hole shall begin where the base course and gutter meet. 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 than 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 mineral-insulated 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 that allows moisture to enter them.

The sleeved conductors shall be spliced together and tested with a loop test meter 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 are then sealed by centering them in a bottle mold and filling 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.

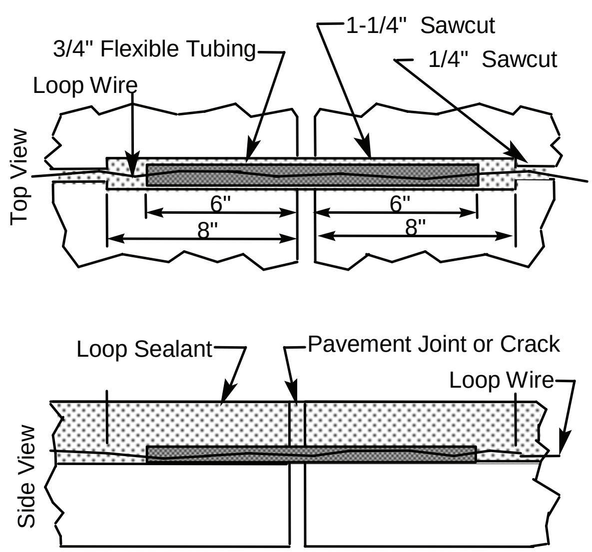
The inductance and resistance of the loop as metered shall be within 10% of the calculated values for that loop as shown on the loop detail sheet.

1 inch = 2.5 cm

Figure 5-14. IDOT specification and installation procedures for metal-sheathed loop cable.

The alternative installation technique provides an excess of wire at the pavement joint. The most common method for securing additional space for the extra wire is to make the cut in the shape of a diamond. The cut should be small, 2 inches (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 5-17. The diamond (and the adjacent joint, if necessary) is filled with an appropriate sealant.

Figure 5-15. Crossing pavement joints using rigid tubing.



1 inch = 2.5 cm

Figure 5-16. Pavement joint crossing details.

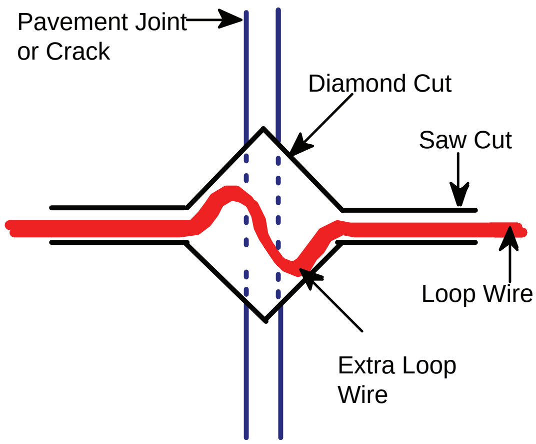


Figure 5-17. Crossing pavement joints using diamond cut.

TWISTING THE LOOP WIRE LEAD-IN

The two lead-in wires from the start and end 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 sawcut. 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 lead-in wires are illustrated in the top portion of Figure 5-18. Although wires may be twisted by hand, more effective methods, shown at the bottom of the figure, employ (1) an anchor clamp and stick and (2) electrical tape and a mechanical twister to 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 applicable wiring alternative is determined by the inductive-loop system designer through consideration of factors such as system configuration, system requirements, and the recommendations of the selected electronics unit manufacturer. The proper connections for each of the wiring alternatives are shown in Figure 5-19.

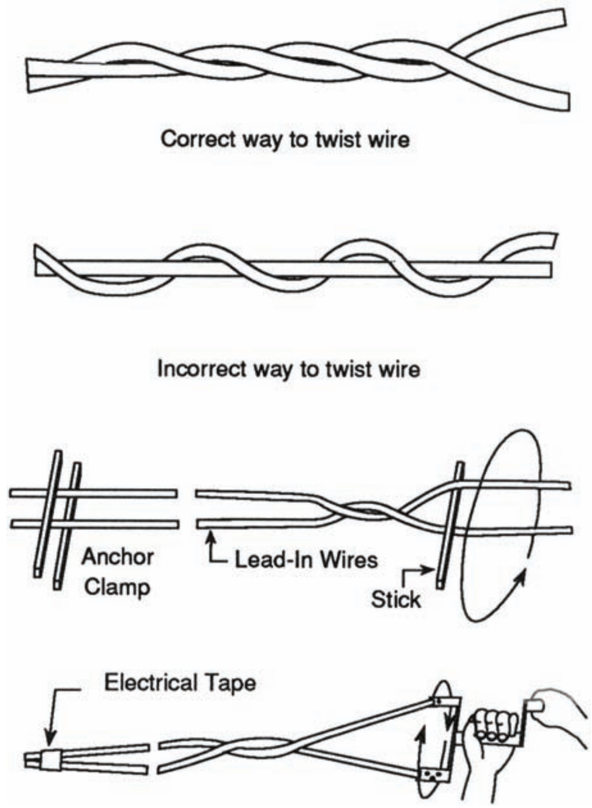


Figure 5-18. Method of twisting lead-in wires.

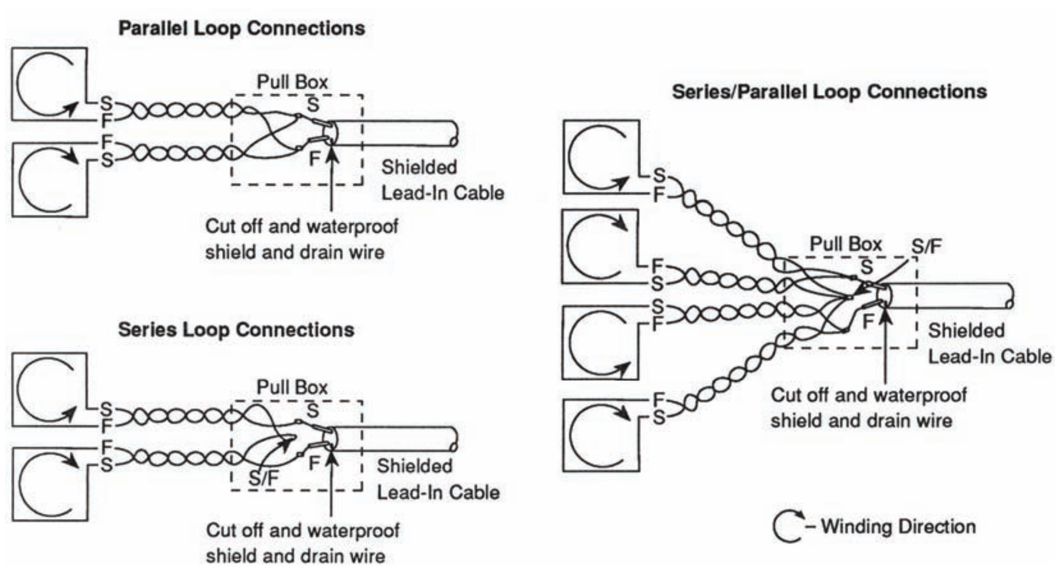
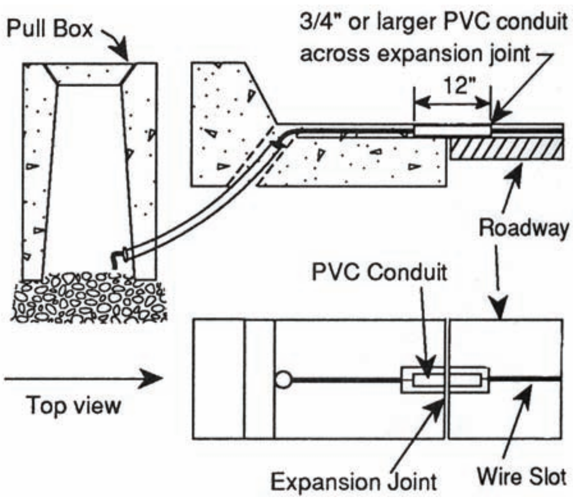


Figure 5-19. Loop wire winding diagrams for multiloop installations.

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 5-20. Liquid-tight flexible conduit is then installed in the hole for insertion of 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 5-21 shows a cross-section view of the conduit through which wire from the sawcut enters the pull box. The conduit should be installed at the same time as the pull box.

Figure 5-20. Entry hole for curb crossing installations.



1 inch = 2.5 cm

Figure 5-21. Loop lead-in wire placement in conduit at roadway-curb interface.

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 shown in Figure 5-22. The roadway end of the conduit is normally 2 inches (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 inches (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.

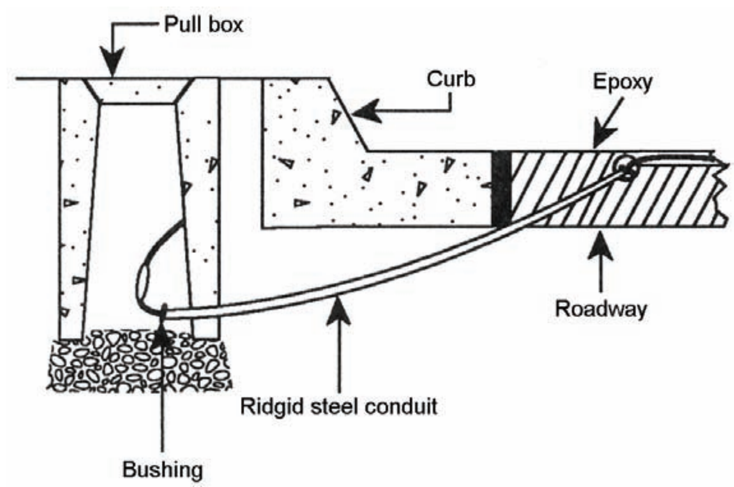
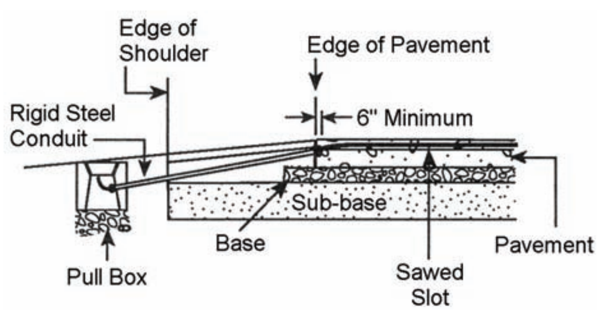


Figure 5-22. Detail of lead-in wire placement for shallow curb section.

Some agencies will drill through pavement before reaching the curb and gutter and will install a conduit beneath the curb section en route to the pull box. These agencies believe this is 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, eliminate problems with the joint between the pavement slab and the curb-gutter section.

When a curb is not present, a hole is drilled through the edge of the pavement to the pull box at a 45-degree angle, as depicted in Figure 5-23. The top of the hole should be at least 6 inches (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.



1 inch = 2.5 cm

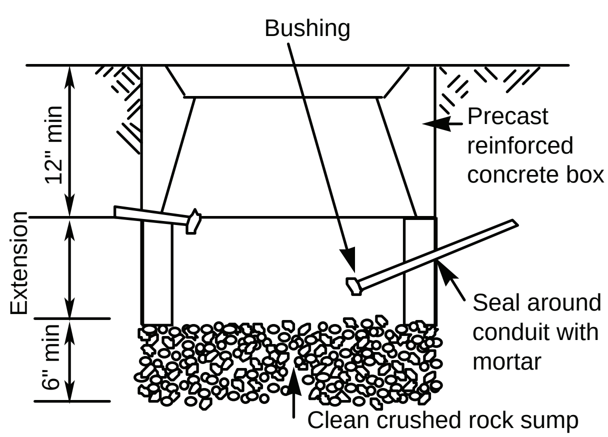
Figure 5-23. Loop lead-in wires at pavement edge when no curb is present.

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 electronics units in the controller housing. Pull boxes can be made of concrete, plastic, metal, or fiberglass.

Figure 5-24 illustrates a standard pull box. Typically, this is a no. 3 or no. 5 pull box in most installations. The box type and 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 5-25.

Figure 5-24. Standard pull box.



1 inch = 2.5 cm

Figure 5-25. Pull box installation detail.

The lead-in wires are protected by conduit inserted into the hole through the curb or pavement and connected to the pull box. Although a 3/4-inch (1.9-cm) conduit is adequate for a single pair of lead-in wires (one loop), it is common to use a 1-inch (2.5-cm) minimum conduit. Table 5-9 gives the size of conduit as a function of the number of loop conductors. Normally, no more than two twisted pairs are installed in one sawcut slot; however, sometimes loop lead-in wires are collected at an in-street pull box (i.e., a pull box located in the travel way) and then routed to the terminal pull box in a conduit under the pavement.

At the roadway end, the conduit should be terminated 2 inches (5 cm) below the pavement surface and a nonmetallic bushing 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. Finally, each loop lead-in wire should be tagged for identification with the loop number and the start ("S") and finish ("F") of each individual loop.

Table 5-9. Conduit size.

Conduit size inches (cm)	Number of pairs of loop conductors
1 (2.5)	1–2
1.5 (3.7)	3–4
2 (5)	5 or more

TESTING THE LOOP

Continuity, inductance, and resistance of the loop and lead-in wire should be verified before the loop wires are sealed in the pavement. Tests should be conducted with one or more loop tester devices capable of measuring the induced ac voltage, inductance in microhenrys (μH), integrity of the wire insulation, and loop wire resistance in ohms. A loop insulation tester, such as the one shown on the left in Figure 5-26, measures loop insulation resistance at 500 volts in the range of 5 megohms to 500 megohms and loop wire resistance in the range of 0 to 10 ohms. The frequency tester, shown on the right, measures loop frequency to determine inductance. An inductive-loop system analyzer, such as the model illustrated in Figure 6-2, may also be used to measure these parameters.

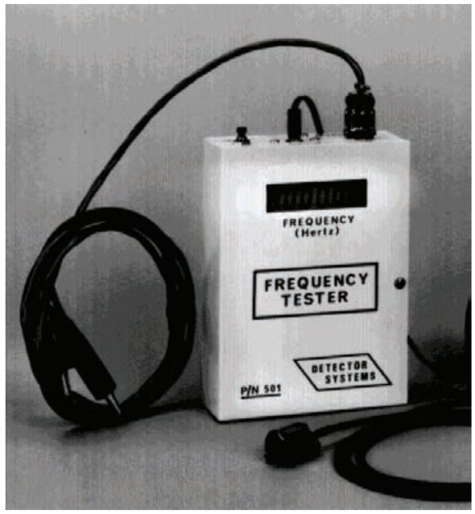


Figure 5-26. Loop test devices.

The integrity of the wire insulation can also be measured with a megohmmeter (popularly called a “megger”). The loop insulation resistance should be in excess of 100 megohms between each end of the lead-in and the nearest reliable electrical ground (e.g., street light or fire hydrant) under any operational condition.

The wiring diagram of the plan set or the inspection report should include a table of calculated values of the inductance in microhenrys 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 on a voltmeter.
- Inductance: The inductance reading on the loop tester is within 10 percent of calculated value.
- Leakage to ground: The resistance to ground of a newly installed loop exceeds 100 megohms as measured with a 500 volt (V) megger.
- Loop resistance: The reading on an ohmmeter is within 10 percent of the calculated value.

The measured 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 is used for future testing and maintenance. Reference 8 describes procedures utilized by Caltrans to verify the operation and measure the sensitivity of a new loop installation. These procedures involve the following steps:

1. Measurement of the resonant frequency of the wire loop and lead-in cable combination.
2. Calculation of the inductance corresponding to the measured resonant frequency. This computation includes the effect of any external capacitance that may have been added to the wire loop terminals.

3. Comparison of the calculated inductance (from step 2) with the nominal value found from curves such as those in Figure 2-6 and data from tables such as Tables 2-6 and 2-7. Caltrans recommends that the calculated and nominal values should not differ by more than approximately 20 percent.
4. Measurement of the change in frequency created when a vehicle model (such as that for a small motorcycle) is placed in the center of the loop under test. The small motorcycle (100 cc Honda) model consists of a 2- x 2-ft (0.6- x 0.6-m), 1/2-inch- (1.3-cm-) thick plywood board, containing one turn of #14 AWG solid wire laid into a 1/8-inch- (4-mm-) wide by 1/4-inch- (7-mm-) deep groove cut into its perimeter. The wire is spliced and soldered to form a shorted turn.
5. Comparison of the measured frequency change (from step 4) with the expected frequency change for the wire loop and lead-in cable combination. The expected frequency change is calculated using equations similar to those described in the "Loop System Sensitivity" and "Single-Loop Example" sections of Chapter 2. Caltrans recommends that the measured frequency change should not be less than the expected value by more than 20 percent.

SEALING THE SAWCUT

One of the major challenges in inductive-loop detector technology is protecting the loop wires from breakage, moisture, and from floating to the top of the sawcut and becoming vulnerable to the ravages of traffic. The critical factors are sealant selection and application technique. Sealant types, application methods, and wire protection within the slots are discussed below.

Types of Sealants

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 inductive-loop detector operation.

During the 1970s, sealant types were about equally divided between asphalt-based and epoxy-based sealants. Early asphalt-based sealants were heated before application. These were soon replaced with gun-grade asphalts marketed as caulking compounds. These, in turn, were superseded 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.

Available sealants possess a variety of desirable characteristics. Hardness allows the sealant to resist the penetration of foreign materials and street debris such as nails or metal fragments, which might pierce or break the wire. Flexibility allows deformation without cracking during thermal expansion and contraction. Corrosive resistance protects against road salts, gasoline, antifreeze, transmission fluids, brake fluid, and engine oils commonly found on roadway surfaces. Other advantageous sealant properties are good adhesion, and contraction and expansion characteristics similar to those of the highway material in which it is installed.

A rapid curing rate and the ability to be applied to damp surfaces are other beneficial sealant traits. A rapid curing rate is desirable because it minimizes lane-closure time 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 apply the sealant directly to damp surfaces rather than first drying them with butane torches, which is time consuming and may damage the asphalt road surface.

Three material families grouped by composition and manufacturing process are recommended for sealing and filling asphalt-surfaced pavements.[1] These are:

- Cold-applied thermoplastic bituminous materials—
  - Liquid asphalt (emulsion).
  - Polymer-modified liquid asphalt.
- Hot-asphalt thermoplastic bituminous materials—
  - Asphalt cement.
  - Fiberized asphalt.
  - Asphalt rubber.
  - Rubberized asphalt.
  - Low-modulus rubberized asphalt.
- Chemically cured thermosetting materials—
  - Self-leveling silicone.

A summary of asphalt concrete crack treatment material types, test methods, applications, and cost is given in Table 5-10. Table 5-11 describes the properties of recommended asphalt concrete sealant materials. Sealants recommended for use with portland cement concrete are shown in Table 5-12.[9] A synthesis of the state of the technology in overlays for hot-mix asphalt and portland cement concrete can be found in Reference 10.

Table 5-10. Asphalt concrete crack treatment materials.[1]

Material	Applicable specification	Recommended application	Cost range based on 1998 costs ($/kg)
Asphalt emulsion	ASTM D 977, ASTM D 2397, AASHTO M 140, AASHTO M 208	Filling	0.15 to 0.30
Asphalt cement	ASTM D 3381, AASHTO M 20, AASHTO M 226	Filling	0.15 to 0.30
Fiberized asphalt	Manufacturer's recommended specifications	Filling	0.35 to 0.60
Polymer-modified emulsion	ASTM D 977, ASTM D 2397, AASHTO M 140, AASHTO M 208	Filling (possibly sealing)	0.80 to 1.20
Asphalt rubber	State specifications, ASTM 5078	Sealing (possibly filling)	0.45 to 0.65
Rubberized asphalt	ASTM D 1190, AASHTO M 173, Fed SS-S-164	Sealing	0.55 to 0.85
	ASTM D 3405, AASHTO M 301, Fed SS-S-1401	Sealing	0.65 to 1.10
Low-modulus rubberized asphalt	State-modified ASTM D 3405 specifications	Sealing	0.75 to 1.40
Self-leveling silicone	ASTM D 5893	Sealing	5.75 to 6.75

$1 /kg = $2.17 /lb

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 cold- and hot-pour sealants must not revert to their liquid state during hot weather as this would 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. The sealant must always be applied in strict adherence with the manufacturer's instructions.

Table 5-11. Properties of asphalt concrete filler and sealant materials.(1)

Property	Material type							
	Emul-Sion	Asphalt cement	Fiber-ized asphalt	Polymer-modified emulsion	Asphalt rubber	Rubber-ized asphalt	Low-modulus rubberized asphalt	Self-leveling silicone
Short preparation	●			●				●●
Quick and easy to place	●	●●	●●	●	●●	●●	●●	
Short cure time		●●	●●		●●	●●	●●	●
Adhesive-ness	●●	●●	●	●	●	●	●	●
Cohesive-ness					●	●	●●	●
Resistance to softening and flow in cured state				●	●	●	●●	●●
Flexibility				●	●	●	●●	●●
Elasticity				●	●	●	●	●●
Resistance to aging and weathering						●	●	●●
Resistance to abrasion					●	●●	●	

● = applicable, ●● = very applicable.

Table 5-12. Portland cement concrete sealant materials.(9)

Material	Applicable specification	Design extension* (%)	Cost range based on 1998 estimated costs ($/L)
PVC coal tar	ASTM D 3406	10 to 20	1.75 to 2.75
Rubberized asphalt	ASTM D 1190, ASTM D 3405, AASHTO M 173, AASHTO M 301	15 to 30	0.60 to 1.00
Low-modulus rubberized asphalt	Modified ASTM D 3405	30 to 50	0.70 to 1.20
Polysulfide (1 and 2 part)	Fed SS-S-200E	10 to 20	Not available
Polyurethane	Fed SS-S-200E	10 to 20	5.20 to 7.20
Silicone (nonsag)	ASTM D 5893	30 to 50	6.50 to 9.00
Silicone (self-leveling)	ASTM D 5893	30 to 50	6.50 to 9.50

* Consult manufacturers' specifications for specific design extensions.

$1 /G = $3.8 /L

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 process 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. Its use requires the specified loop wire to have insulation that can withstand the 400 °F (205 °C) application temperature of the rubberized asphalt sealant. Modern epoxy formulations 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 various, commercially available sealants prior to listing the acceptable sealant products in their specifications.(11) In reviewing the documentation of these State tests, a product that scored highest in one State was sometimes considered unacceptable in another State. The disparities in test results are 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.

Sealant Application Techniques

Common practices for sealing the loop wire are depicted in Figure 5-27. One procedure (shown on the left of Figure 5-27) consists of applying a layer of sealant to the floor of the sawcut 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 sawcut, 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 illustrated in the middle of Figure 5-27, 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 on the right of Figure 5-27 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 of approximately 1 inch (2.5 cm) in length every foot or two (30 cm to 61 cm) to anchor the wire in the slot before applying the sealant.

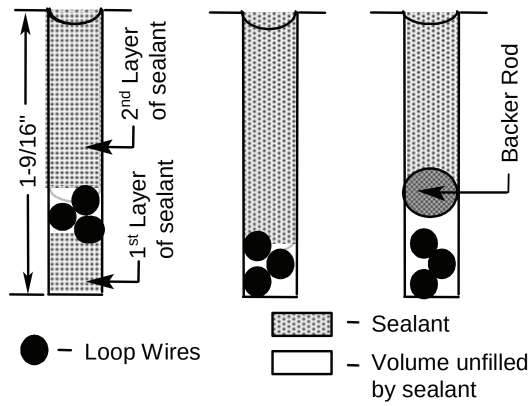


Figure 5-27. Methods of applying sealant.

Table 5-13 lists commonly used backer rod materials, testing method standards, backer rod properties, and compatibility.

Table 5-13. Backer rod materials.[9]

Material	Applicable standard	Properties*	Compatibility
Extruded closed-cell polyethylene	ASTM D 5249, Type 3	NMA, ECI, NS	Most cold-applied sealants
Cross-linked extruded closed-cell polyethylene	ASTM D 5249, Type 1	HR, NMA, ECI, NS	Most hot- and cold-applied sealants
Extruded polyolefin	ASTM D 5249, Type 3	NMA, NS, NG, CI, IJ	Most cold-applied sealants

* CI = chemically inert, ECI = essentially chemically inert, HR = heat resistant, IJ = fills irregular joint well, NG = nongassing, NMA = nonmoisture-absorbing, NS = nonstaining.

No published evidence of the superiority of one sealant application method over another has appeared. Most inductive-loop 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 (as depicted on the left in Figure 5-27) 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 placing sealant on the bottom of the sawcut report that the extra protection afforded by the sealant bed 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. Alternatively, some agencies specify the placement of a layer of sand rather than sealant at the bottom of the sawcut. This provides a smooth bed 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 sawcut, but not overfill. A trowel or other tool should be used to ensure that the sealant is slightly below the pavement surface and to remove any excess sealant. Figure 5-28 shows the result of poor installation procedures. It shows overfilling, underfilling, and air bubbles in the sealant. All three conditions can lead to inductive-loop detector failure and should have been corrected during the installation process.

Sealant may be applied with a special applicator as shown earlier in Figure 5-6 or by hand directly from a container as depicted in Figure 5-29. In this illustration, one member of the crew is placing the lead-in wires in the slot while another is pouring the sealant into the sawcut. A paint stirrer has been inserted into the slot to hold the wire down while the sealant is being applied. Other techniques can be used (e.g., backer rod strips, and nylon rope) to hold the wire securely in place while sealant is added. Figure 5-30 shows the crew properly completing the sealant application procedure by removing any excess material from the pavement and dusting talc on the fresh sealant.

A number of agencies and loop installers coat the newly applied sealant with sand or talc after the sealant has been applied and before opening the lane to traffic. 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 by tamping it into the slot after the wire is placed in the sawcut. However, the sand is easily tracked out of the slot and the wires may become dislodged. Therefore, this practice is not recommended.

Figure 5-28. Poor sealant application.

Figure 5-29. Crew applying sealant by hand.

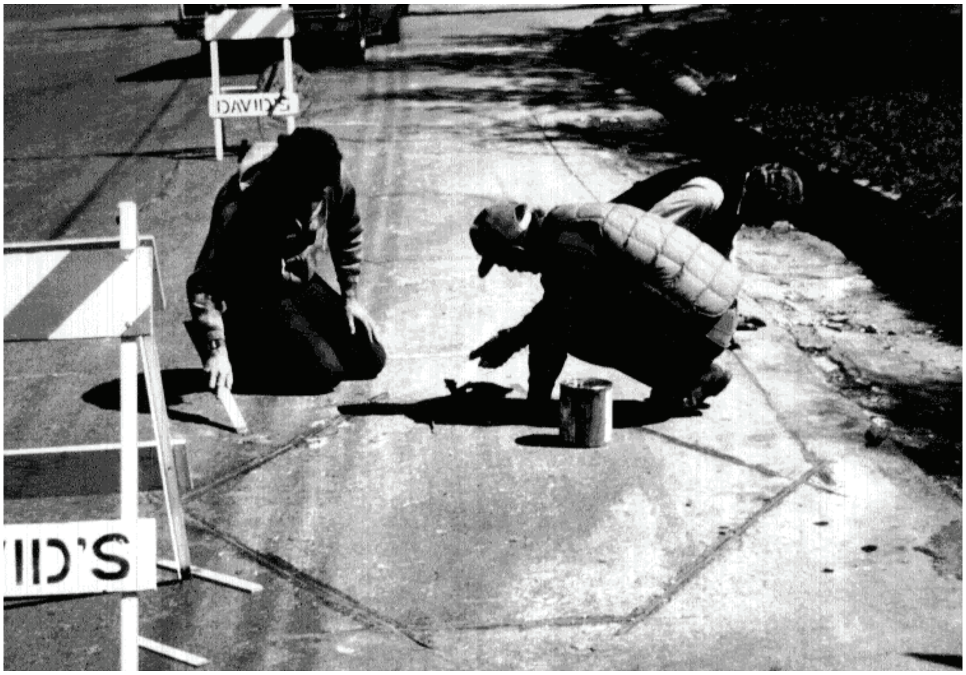


Figure 5-30. Finishing sealant application.

SPLICING THE WIRE

Another critical step in the loop installation process is splicing the loop lead-in wire to the lead-in cable that connects to the electronics unit in the controller cabinet. This splice, located in the pull box, should be the only splice in the loop system. The splice is frequently the cause of inductive-loop detector system failure; however, if proper splicing procedures are used, the splice should not pose a problem. There are two steps to creating a splice: the physical connection of the wires and the environmental sealing of the connection.

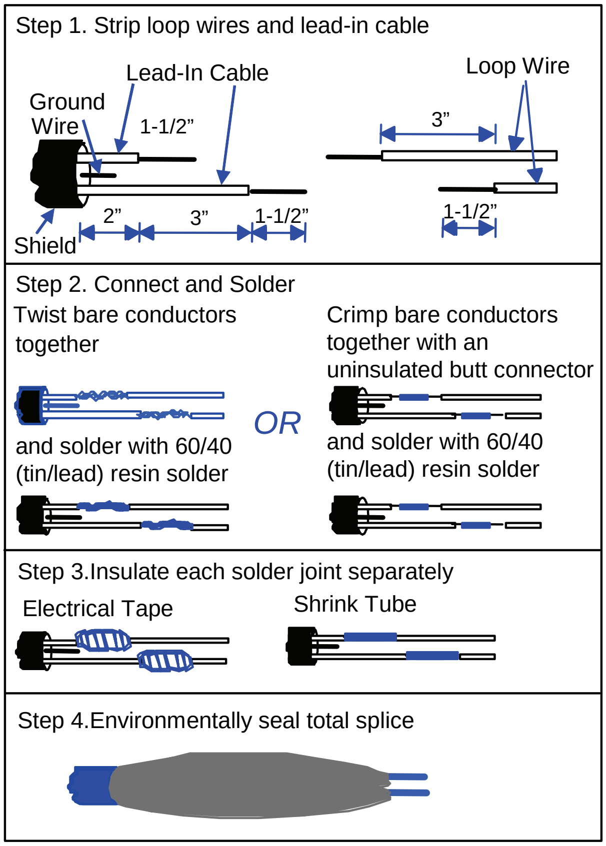
Connecting the Wires

Methods for physically connecting 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 electronics unit 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 assemblies now makes soldered connections preferable. These assemblies operate at 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.

The procedures for making a twisting and soldering or crimping and soldering connection begin in the same manner as shown in Figure 5-31. First, 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 1.5 inch (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 noninsulated butt connector. Care must be exercised to assure that the correct wires are connected.

High-quality crimp connections can be made using a pressure crimping tool that provides a uniform 360-degree crimp. Only bare wire, and not the adjacent insulation, should be inserted into the crimp connector. The individual wire splices should be staggered so that the entire cable spice does not become too bulky. Soldered connections should be made with 60/40 (tin/lead) resin core solder. The Ontario Ministry of Transport specifies the use of 60/40 (lead/zinc) resin core solder as an alternative.[6]



1 inch = 2.5 cm

Figure 5-31. Splicing loop wire at pull box.

Sealing the Splice from the Operating Environment

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 reliable 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, taking care 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 apply. 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 alternative process places a form around the splice area. A liquid sealant is poured into the form; care must be taken to totally fill it with sealant and ensure that no voids appear within the splice area.

A simple encapsulation process consists of using a common drug store pill bottle as shown in Figures 5-32 and 5-33. 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.

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.

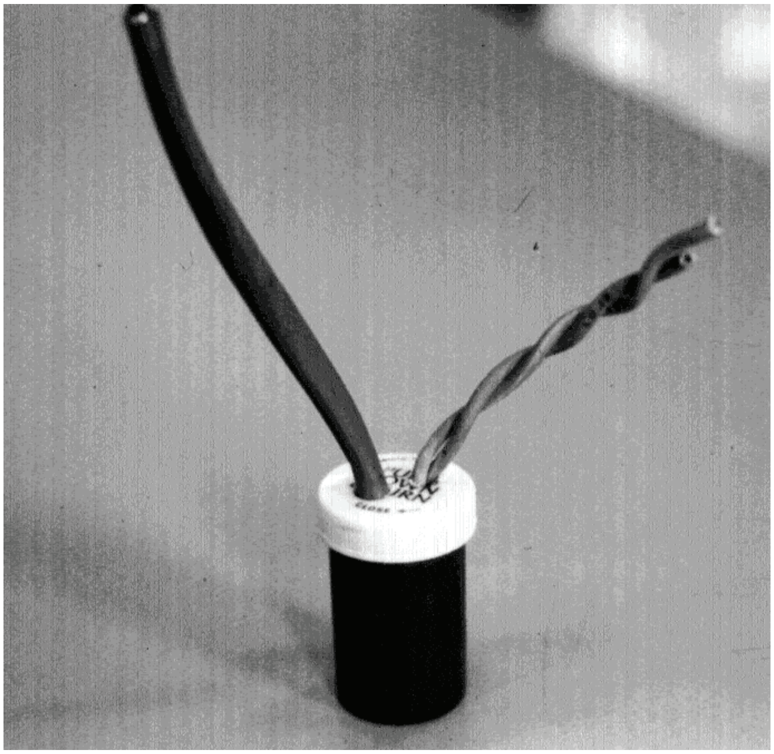
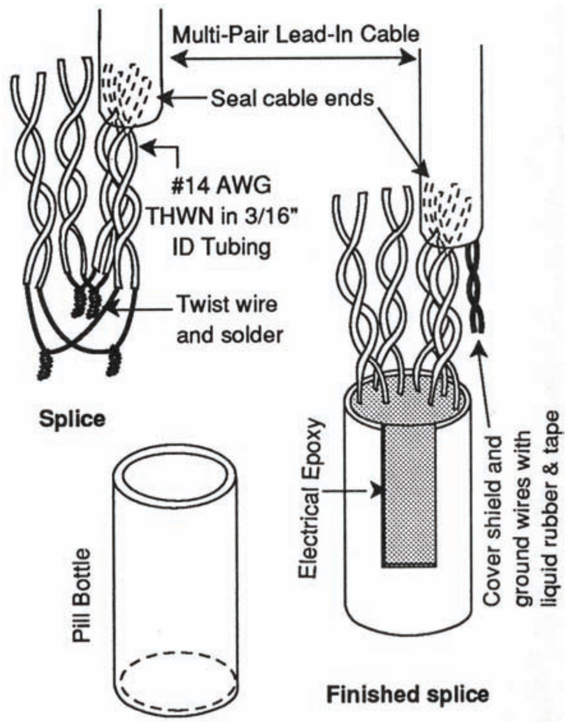


Figure 5-32. Pill bottle splice.



1 inch = 2.5 cm

Figure 5-33. Pill bottle splice details.

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 18 inches (45 cm) below the surface. If conduit is used, it should be waterproofed.

Trenching is the most common method for installing underground cable. The construction plans should specify the depth of the trench. The trench is backfilled in layers not to exceed 6 inches (15 cm) after the cable is placed in the trench. It is recommended that each layer of backfill be compacted with mechanical tampers to the approximate density of the surrounding ground. No extra material should remain when the backfill procedure is complete.

The lead-in cable terminates inside the controller cabinet at the field terminal strip as illustrated in Figure 5-34. An excess of 18 inches (45 cm) of cable should be provided in the cabinet housing.

Some equipment manufacturers and agencies recommend that the shield of the cable not be connected to the third or ground terminal. One manufacturer describes this technique by stating that the cable shield should be insulated from ground and float at both ends (namely at the cabinet and in the pull box). This recommendation is the same as that from the Ontario Ministry of Transportation, which does not recommend grounding the lead-in cable shield at either end. (See Appendix N, Section IV, bullet 3.) The justification given for this procedure is that the detection system operates at extra-low voltage (e.g., typically, output voltage for an inductive-loop electronics card is 5 V, with a current draw measured in milliamperes) and the cabinet and card rack are firmly connected to ground.

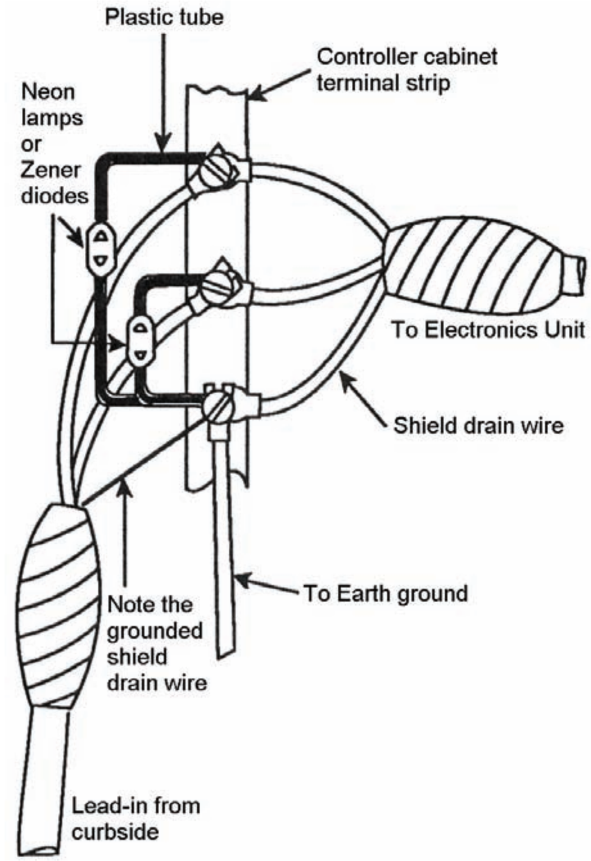


Figure 5-34. Lead-in cable grounding at the field terminal strip.

Other manufacturers recommend grounding at the cabinet (i.e., connecting the shield to the terminal as in Figure 5-34) 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.

NEMA avoids the issue by stating that "Field installation practices or inductive-loop detector electronics unit design may require grounding the shield of the loop lead-in cable. Such grounding should be in accordance with the electronics unit 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 electronics units. Back-to-back zener diodes or neon lamps usually provide adequate protection.

Most modern electronics units have built-in lightning protection features. Even so, some agencies in lightning prone areas (specifically Ontario, Canada[(6)] 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 5-34. Other grounding and lightning protection approaches are described in Appendixes N and O.

FINAL TESTS AND RECORD KEEPING

Final tests are recommended after all loops and cables are installed. The final tests repeat the initial tests, described previously in this section, to ensure the inductive-loop detector installation is performing as expected and is fully operational after all cables have been buried.

The test results should be recorded on an installation data sheet such as the one depicted in Figure 5-35. Any modifications made to the original plan drawings should be noted, dated, and retained as “As Built” plans.

The inspector should verify that the correct readings from the tests are recorded and that the modified plans reflect the as-built conditions. These records comprise the history of the particular inductive-loop detector system and serve as the baseline 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 5-35. Representative inductive-loop installation data sheet.

GENERAL INSTALLATION GUIDELINES

General guidelines for installing inductive-loop detectors at signalized intersections are presented in Table 5-14.[12,13] These general guidelines apply under a wide variety of circumstances. The design engineer is cautioned that installations at specific locations may require that other design, installation procedures, testing, etc., be followed.

Table 5-14. General installation guidelines for installing inductive-loop detectors.

Design
• The width of the loop should be tailored to the width of the lane • Loops should not be over 6 ft (1.8 m) wide in a 12 ft (3.7 m) lane. • Loops should not be less than 5 ft (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. • Sawcut should be cleaned out with high-pressure water after cutting and then dried with compressed air. • If 1/4-inch (0.64 cm) sawcut is 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 polypropylene. • Wire should be laid in sawcuts using the same rotation (clockwise or counter-clockwise) in each 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 5-14. General installation guidelines for installing inductive-loop detectors—*Continued*

Testing

- Prior to filling sawcuts with sealant, loops should be tested with an ohm-meter for continuity, and loop and lead-ins in pull boxes should be tested with a 500 V DC megger to confirm insulation resistance >100 megohms.
- Loops should be tested with a direct reading inductance meter at the pull box to confirm the number of turns of wire in any loop. The following formula provides 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, where *K* is found from the table below:

No. of Turns	*K* (µH/ft)
1	0.5
2	1.5
3	3.0
4	5.0
5	7.5

- The electrical splice configuration of multiple loops should be confirmed with the inductance meter to assist in the selection of the correct sensitivity setting on the electronics unit.

Sealant

- Loop sealant should be applied to insulate and protect wires.
- Loop sealant should encapsulate loop wires to the fullest extent possible.
- At least 1 inch (25 mm) of sealant should cover the loop wires (i.e., do not allow wires to float).
- Sealant 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 (3 mm) of surface. For installation prior to overlay, the sawcut should be filled completely with sealant before paving.

Connections

- All spade lug connections in the loop circuit should be soldered.
- Multiple loops connected to the same channel of an electronics unit should be connected in series or series/parallel. (Some manufacturers dispute the use of series/parallel.)
- Series splice should be verified with inductance measurement prior to connecting to lead-in cable.
- Multiple loops connected to the same channel of an electronics unit 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 electronics unit.

INDUCTIVE-LOOP DETECTOR INSTALLATION ALTERNATIVES

Agencies and vendors continue to search for better ways to manufacture and install inductive-loop detectors. The following sections describe two alternatives to conventional loops that have been developed, tested, and are currently operational. The conventional loop installation processes such as splicing, testing, etc., described earlier also apply to these alternative designs.

SLAB LOOPS

In the early 1980s, the Puerto Rico Highway Authority and the Department of Transportation and Public Works began to experiment with placing inductive-loop detectors in heavily reinforced precast concrete slabs for installation in bituminous pavements.(14) 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. These slabs could not be precast because of their size and weight.

Puerto Rico selected smaller unitized slabs as an effective sensor design. They are 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 inch (20.3 cm) deep. A circular slot 40 inches (102 cm) in diameter, 3 inches (7.6 cm) deep, and 0.5–0.75 inches (13–19 mm) wide is impressed in the concrete to house the conductors forming the loop.

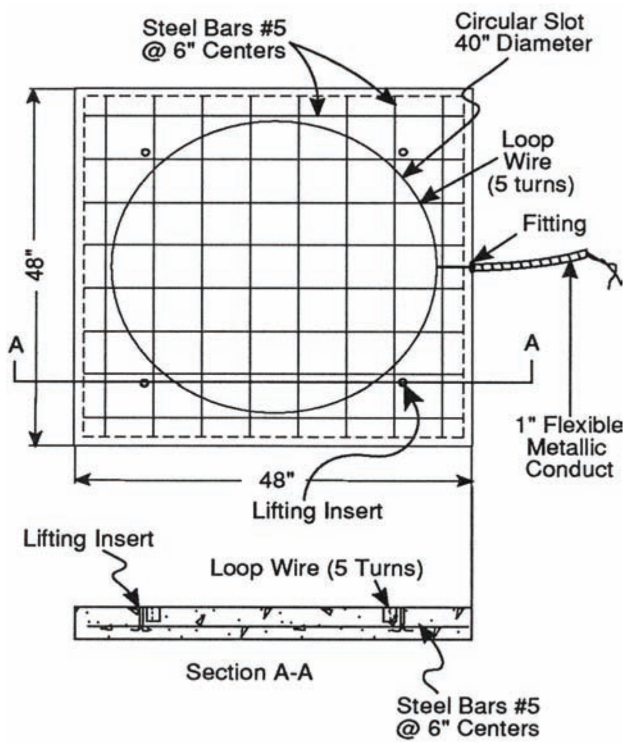
Five turns of wire are standard in these installations, with three turns considered to be the minimum acceptable. Adequate vehicle detection has been obtained with up to 1,000 ft (300 m) of lead-in cable between the pull box and the electronics unit. After the wire is wound in the slot, a 5/8- to 7/8-inch (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-inch (25-mm) flexible metallic conduct encloses the lead-in wires leading to the pull box.

As shown in the plan details in Figure 5-36, the slabs are provided with four lift point devices for handling during the original installation and for resetting in the case of overlays.(14) These slabs can be easily handled by two men and a small loader-backhoe combination.

Hot-poured asphaltic sealant and silicone sealant have been used successfully. An emulsified asphalt sealant is also being tested because it is less expensive and does not need to be heated. Epoxy sealant has not been used for this purpose because it may make reentry into the slot for repairs more difficult.

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 oversized square is cut out of the pavement and the precast slab is installed with concrete backfill.

Puerto Rico uses nonreinforced 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.



1 inch = 2.5 cm

Figure 5-36. Plan details of slab-loop installation.

Precast loop slabs have been used successfully in four basic configurations, as shown in Figure 5-37: 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 electronics units.

Precast loop slabs have been installed at isolated intersections and 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 1,800 slab-loop detectors installed in Puerto Rico. Over a 5-year period there had been no traffic- or pavement-induced failures. On three occasions, excavations in the sidewalk or adjacent pavement areas had damaged the lead-in wires. In addition, 13 incidences of failure in the wire insulation resulted from a manufacturing error.

Although Puerto Rico experiences heavy rainfall, the annual temperature falls 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. Freeze-thaw could possibly affect the use of these slabs in colder climates.

Those failures provided opportunities 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.

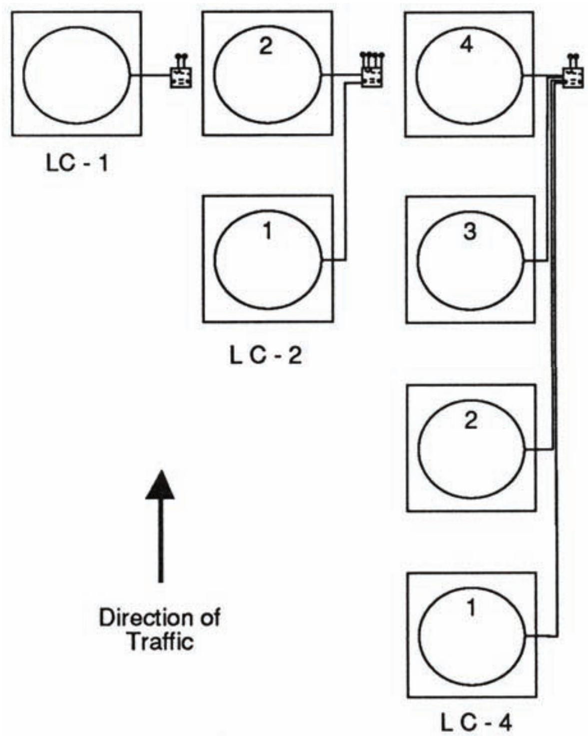


Figure 5-37. Precast loop slab configurations.

Loop slabs have been very successful in Puerto Rico. Typical installations on an off-ramp and in a left-turn lane are shown in Figure 5-38. In the mid-1980s, 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 has not been conducted between the precast and the sawed loop detectors, 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.

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. Modern cutting techniques appear to have eliminated the difficulty associated with cutting the circular shape in the pavement.

Figure 5-38. Slab-loop installations.

Round-Loop Installation in Roadways

One installer has addressed the cutting issue by developing a patented vehicle designed to saw a circular slot 6 ft (1.8 m) in diameter, 0.5 inch (1.25 cm) wide, and 3 inches (7.6 cm) deep for circular loop installation in either asphalt or concrete road surfaces.[15] The self-contained vehicle, shown in Figure 5-39, is equipped with a 6-ft (1.8-m) diameter bit to cut the circle, a 500-gallon (1.9-kiloliters) 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 roadway installation process is illustrated in Figures 5-39 through 5-41. The truck arrives at the site and the two-man crew sets out cones to divert traffic. The lift gate 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 holding 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-inch (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 out 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-inch (7.6-cm) core to reduce bending stress. The installation is now ready to be sealed. The sealant is pumped into the slot after it reaches its melting point. The installation is complete when the sealant is applied, and the lane may be opened to traffic immediately as the sealant hardens as soon as it is exposed to air.

The circular loop installer 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 minimal disruption to traffic flow in the area.

Figure 5-39. Roadway installation of round loops—cutting loop circle.

Figure 5-40. Roadway installation of round loops—retraction of saw.

Figure 5-41. Roadway installation of round loops—completed installation.

Round-Loop Installation on Sidewalks

Other cutting equipment is used to cut round loops in more confined areas such as sidewalks. The series of photographs showing the installation procedure using this equipment is found in Figures 5-42 through 5-52 and was provided by the Traffic Signal Laboratory at Purdue University.

There is debate regarding placing backer rod material over the entire wire or simply using short pieces of material every foot or so. The first method supports easier installation from the contractor's perspective; the second provides better encapsulation by the sealant and less wire movement.

Figure 5-42. Round loop saw at beginning of installation process.

Figure 5-43. Round sawcut in process.

Figure 5-44. Completed round sawcut.

Figure 5-45. Blowing out debris from sawcut.

Figure 5-46. Firmly seating loop wire in sawcut with rolling-blade tool.

Figure 5-47. Inserting backer rod material over loop wire.

Figure 5-48. Firmly seating backer rod material over loop wire.

Figure 5-49. Tape placed around both sides of sawcut to prevent sealant from adhering to concrete.

Figure 5-50. Placing sealant in sawcut.

Figure 5-51. Removing excess sealant.

Figure 5-52. Isolation of affected area to allow sealant to dry.

INSTALLATION OF TWO-AXIS FLUXGATE MAGNETOMETERS

Representative fluxgate magnetometer installations for various lane configurations are illustrated in Figure 5-53. The probes are buried 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 and Appendix L) and the size of the probes.

After the preinstallation activities (described earlier in this chapter) have been completed, installation usually follows the step-by-step procedures discussed below.

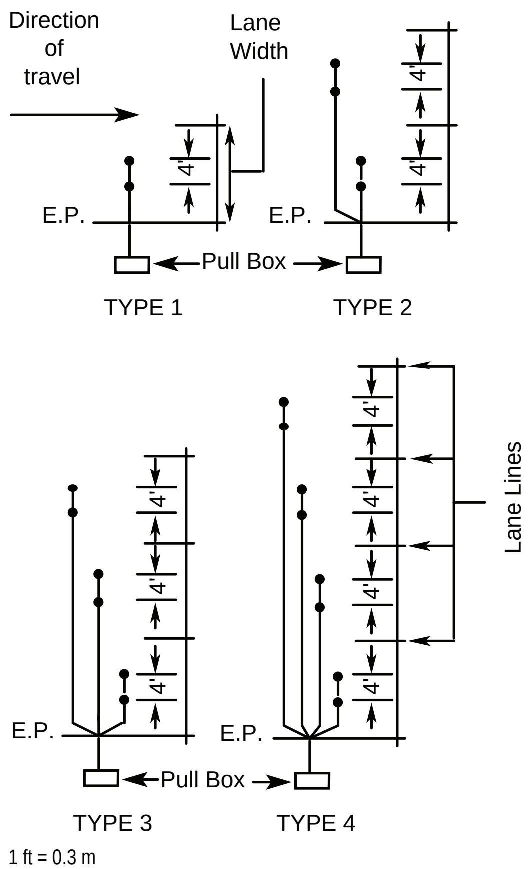


Figure 5-53. Fluxgate magnetometer installations for various lane configurations.

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 layout 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 ferrous metal objects that would degrade performance as discussed in Chapter 4.

Holes for the probes are subsequently 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-inch (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 previously 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 sand or using sealant around it. A representative standard plan for magnetometer installation is shown in Figure 5-54.

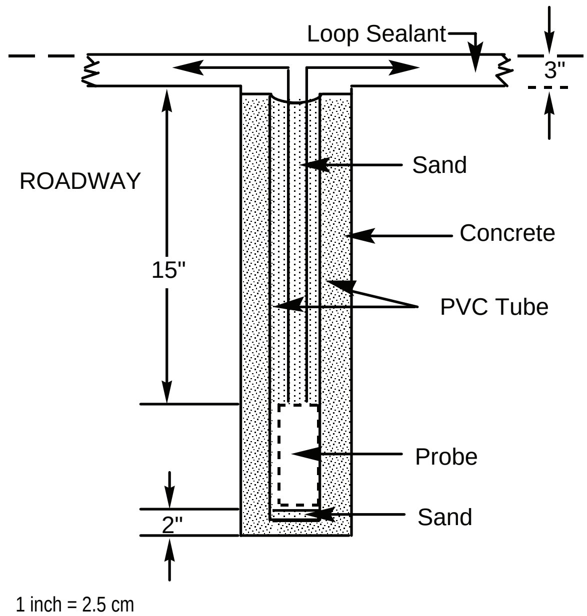


Figure 5-54. Standard plan for fluxgate magnetometer installation.

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) length of extra cable should be left at the pull box. The cables should be identified by lane or by probe designation.

A volt–ohmmeter should be used to verify the series resistance (continuity) of the probe and cable. 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 large value of 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 inductive-loop detectors. The lead-in cable should not be spliced between the pull box and the controller cabinet.

The same precautions identified for loop detectors should be addressed when installing magnetometers. Two types of heat-shrinkable polyolefin tubing are used for splicing probe cables to the lead-in (home-run) cable—small diameter tubes insulate the individual conductors and a single large tube seals and protects the splice. An electric heat gun and butane hand torch or electric soldering iron are required to complete the splice. The procedure recommended for splicing probe cables to the lead-in (home-run) cable consists of the steps below:

- Strip both cable jackets back 8 inches (27 cm).
- Clip 3 inches (7.6 cm) from one colored wire of one cable and clip 3 inches (7.6 cm) from the other colored wire of the second cable.
- Strip individual conductors back 1-1/2 inches (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 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 for inductive loop installation should be made using a low range ohmmeter. In this test, the series resistance will be higher because of the added resistance of the lead-in cable.

An operational check should also be conducted at the controller cabinet. Connecting the probe cables to an electronics unit and applying power may accomplish this. The electronics unit should then be calibrated following the manufacturer's guidelines. Check each probe using a bar magnet oriented in a direction which aids the horizontal or vertical components of the Earth's magnetic field intensity. Dual-axis fluxgate magnetometers are responsive to horizontal and vertical components of the Earth's magnetic field. 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-inch (1.6-mm) increment marks 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 electronics unit turns on. If the system fails at a later time, the same measurement procedure can be repeated. If the magnet must be closer to the probe to light the indicator, this indicates that the probe has rotated.

SEALING THE HOLES AND CUTS

Once the system tests are competed, the probe holes and the sawcuts containing the cables can be sealed in the same manner used for inductive-loop detectors. This completes the installation of the magnetometer detector system.

INSTALLATION OF MAGNETIC DETECTORS

The preinstallation activities for magnetic detectors are much the same as those described for inductive loops. When the magnetic detector probe is installed 12 to 30 inches (30 to 76 cm) under the roadway, the long axis is generally horizontal and is perpendicular 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 5-55. For installation in a four-lane, divided roadway with a median, many agencies have found it desirable to install from the median. The median is preferable as these areas have fewer sign posts, guard rails, and utility activities.

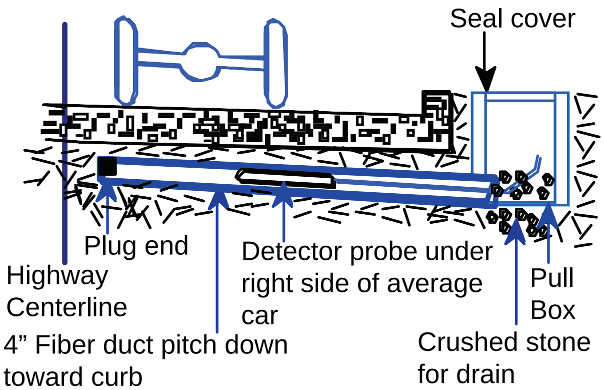


Figure 5-55. Magnetic detector probe installation from the side or median of a road.

After locating and marking the desired area for the placement of the probe, measure the distance from the pull box to a point on the road where the conduit ends. Using a backhoe, dig a pit 3 ft (0.9 m) deep, 2 ft (0.6 m) wide, and 10 ft (3 m) long. A horizontal boring machine is then placed in the pit, leveled, squared, and secured. The hole is 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-inch (76- or 102-mm) schedule 40 PVC is capped and placed in the hole, section by section. Each section of pipe must be fitted squarely and glued. Before the final section of PVC is fitted, place the pull box in the trench and set it 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

Trenching is an alternative to the boring method of installing a conduit to hold the magnetic detector. 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-inch (76- to 102-mm) 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 inches (15 cm) of concrete. When dirt or stone covers the conduit, as with 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. The mark helps to locate the sensor in the correct position when the wire reaches the edge of the pull box. The sensor is inserted into the conduit and pushed into position using a steel 3/8-inch (9-mm) span wire.

After the probe is placed in the conduit, the next step is to install the pull box in the same way as 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. Because the magnetic detector generates an extremely small current, splices should be soldered. Procedures were discussed previously in this chapter for splicing and environmentally sealing splices used with loop-detector and fluxgate magnetometer installations.

Two conductors are required for each magnetic detector. 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 traffic signal currents. Leakage between the traffic signal wires and detector wires will cause erratic operation of the detectors. Electromagnetic or electrostatic induction between traffic 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 3,800 ohms, plus or minus 10 percent. If there are two probes, the reading should be approximately 7,600 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 electronics unit amplifier, it should be at the lowest value possible to insure proper operation. This is done 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.

OVER-ROADWAY SENSOR INSTALLATION

Over-roadway sensors require structures such as sign bridges, mast arms, and poles for mounting. If these are not already in place, then appropriate overhead structures must be installed to support the sensors. The field of view or footprint of a sensor, i.e., the area of the roadway within which a vehicle is detected and data are collected by a sensor system, is a function of mounting height, offset of the mounting location from the lanes to be monitored, aperture size, elevation changes, curves, and objects that may block the view. The footprint for many sensor technologies is calculated in a similar manner, with only the aperture, i.e., the active transmitting and receiving area of the sensor, varying. In a microwave sensor, for example, the antenna beamwidth definition utilized to calculate the footprint is the angle in degrees or radians at which the radiated power is reduced by one half (i.e., 3 dB). Ultrasonic sensors use the same beamwidth definition. By contrast, infrared sensors and other optical devices express the beamwidth as the angle at which the first null in the diffraction pattern occurs. In any case, the geometrical relations for the footprint are the same for all these sensor technologies.[16]

The following sections describe representative installation and calibration procedures for video image processor, microwave radar, and laser radar sensors. Sensor manufacturers should be contacted to obtain detailed installation and operating instructions for their products.

INITIAL SENSOR EVALUATIONS

Before embarking on an initial large-scale deployment of over-roadway sensors, it is wise to evaluate the performance of the candidate sensors under real-time operating conditions where differences in flow rate, road configuration, obstructions, lighting, and weather can be experienced. Such evaluations have been performed for many of the sensors currently available, but the introduction of new models and the unique features of each deployment location make this requirement a recurring one. Guidelines for conducting such tests are found in the reports issued by several sensor evaluation projects. (See references 17–23.)

VIDEO IMAGE PROCESSORS

Since each site has unique features, distributors of the Autoscope VIP recommend that potential users evaluate candidate sites to determine their suitability for video detection.[24] This site survey assists in developing requirements for lens selection, camera mounting, power and signal transmission, and image processor location.

SITE SURVEYS

Site surveys assist in determining whether geometric factors and lack of obstructions near each sensor station allow for the installation of overhead sensors and, if so, what additional mounting structures are required. When wireless transmission of data and video are part of the design, the site survey also determines whether the transmission path between the sensor and data reception locations permits unimpeded transmission.

Questions posed during a site survey include:

- What traffic flow parameters are needed?

- Where are the locations of the detection areas? Are there obstructions such as power lines, signs, billboards, or trees?
- Is occlusion of the detection area by moving vehicles a concern?
- Besides utilizing video imagery to obtain traffic flow parameters, is the video imagery required for surveillance and will it be shared with other agencies?
- Where will the video image processor be located, e.g., nearby controller cabinet, more distant controller cabinet, or traffic management center? What are video transmission options from the camera to the image processor?
- Is remote retrieval of data required?
- Where will cameras be mounted? Are special mounting facilities planned? If mounting structures are already present, are they stiff enough to prevent unwanted camera movement? Can a better view of traffic, and hence more accurate data, be obtained by mounting the camera over the center of the lanes of interest? Is lighting available to enhance nighttime performance at signalized intersections?
- Can a camera be mounted temporarily in the same location as the permanent camera to obtain imagery that can be played through the image processor to determine performance?
- Is power available at the site?
- Have provisions for grounding and terminating the power, data, and video cables been made? Are other lightning protection protocols needed?
- Are the video image processor outputs compatible with the controller that will be used?
- Are special protection measures required to protect equipment from vandalism or theft?

Rules of thumb are also available to assist in camera location, mounting, and setup. These are based on the following:

- Optimal performance is obtained by maximizing camera height and centering the camera over the traffic flow as much as possible. Recommended minimum camera mounting height has been increased to 40 ft (12 m) above the detection area if the camera is centered over the roadway. Higher mounting heights (on the order of 50 ft (15 m) or greater) are generally required if the camera is located at the side of a roadway. The camera mounting height should increase as the camera is moved further from the road edge to achieve optimal performance.

- Effective camera viewing distance is related to camera height. For each foot (0.3 m) of camera mounting height, viewing distance upstream and downstream of the camera location is estimated as about 10 ft (3 m) by some VIP manufacturers. Across traffic lanes, the camera can view about 2.5 ft (0.8 m) for every foot (0.3 m) of mounting height. However, conservative freeway design procedures reduce the upstream and downstream viewing distance estimate because of factors such as road configuration (e.g., elevation changes, curvature, and overhead or underpass structures), congestion level, vehicle mix, and inclement weather. Occlusion will probably generate volume errors at the furthest observation points at traffic levels of service D and E. Although a calibration factor or some other logic may assist in reducing the volume error, reduction of presence and occupancy errors may be more difficult.
- Select the camera location to minimize occlusion of down-lane and cross-lane vehicles. Down-lane occlusion refers to vehicle blocked from view by a tall vehicle in front of it. Cross-lane occlusion refers to a vehicle blocked from view by a tall vehicle in a lane closer to the camera.
- Select camera locations that minimize vibration and motion.
- Camera mounting should prevent the horizon from being visible in the horizontal or vertical fields of view. This may require a downward tilt to the camera or the installation of a sunshield.
- Minimize reflections from the pavement, for example by viewing traffic approaching the camera from uphill. However, uphill traffic detection will increase the probability that headlights will shine directly into the lens at night.
- Approaching nighttime traffic will produce headlight reflections from the road surface that may cause false detections. This is more likely with low camera mounting heights, under bridges, in tunnels, and on curved roadway sections.
- A longer focal length lens will minimize glare entering the camera. On shorter poles, the longer focal length assists in minimizing the horizon in the field of view. For example, an 8-mm lens (as contrasted with a 6-mm lens) allows greater adjustment of the sunshield to minimize glare and the horizon. With shorter poles, aiming the camera at the lower half of trucks minimizes the horizon. A longer focal length lens also improves performance by increasing the relative size of the detection zones that are placed on the pavement.

Reports of poor VIP nighttime performance at unlighted intersections at several locations in Indiana led to an investigation into the probable causes of these events.[25,26] The following recommendations were developed by the Indiana DOT (INDOT) with the concurrence of several VIP manufacturers to address these issues:[27]

- Height of camera shall be 40 to 41 ft (12.2 to 12.5 m) above the pavement surface directly under the camera.

- Maximum detection distance for full detection functionality of the VIP is 200 ft (61 m) from the spot on the pavement surface directly below camera (based on 5:1 aspect ratio at 40 ft (12.2 m) camera height).
- Lateral camera placement:
  - Cameras mounted on the far side: Camera shall be laterally aligned on an extension of the lane-line separating the left and through lanes of the inbound approach.
  - Cameras mounted on the near side (over lanes to be detected): Camera shall be laterally aligned over the center of the approach.
  - Field inspection will occur with the inspector 150 ft (45.7 m) back from the stop bar and sighting the camera with a transit/plumb bob. Tolerance on camera placement is ± 1 ft (0.3 m).
- Highway lighting shall be provided.
- Highway lighting shall be 40 to 41 ft (12.2 to 12.5 m) above the pavement surface. Consider specifying an airport-type lighting head.
- Design shall provide cross section within 5 ft (1.5 m) of pole location. This ensures that poles are not located in ditches below the roadway grade, which would adversely affect proper camera mounting height.
- All utilities and facilities affecting pole locations and camera views, both overhead and underground, must be accurately located on plans and their height noted.
- Camera sight triangles (elevation view) shall be included in the plans to show:
  - Location of detection zones.
  - Any occlusions such as, but not limited to, signal heads, mast arms, span catenary, tether, and overhead utilities.

TXDOT has also developed a manual for deploying video detection at signalized intersections.[28]

LENS SELECTION

The focal length of the lens is dependent on the mounting height of the camera, the local topography, distance to the nearest detection area, and the width of the detection area.[24,29] Some vendors supply a program that calculates the horizontal and vertical fields of view and corresponding focal length of the lens from these input data. If the required focal length does not correspond to a standard lens, then the mounting height or one of the detection area parameters is varied in order to specify a standard lens having a horizontal focal length above or below that of the initial calculation. Table 5-15 shows the horizontal and vertical fields of view for several standard lenses. Some VIP vendors supply variable focal length lenses with their cameras so that a specific lens does not have to be selected in advance. Another advantage of this approach is that the number of different focal length lenses required for maintenance operations is reduced.

Table 5-15. Horizontal and vertical fields of view (FOV) of standard lenses.

Lens (mm)	4.8	6.0	8.0	12.5	16.0	25.0
Horizontal FOV (deg)	67.4	56.1	43.6	28.7	22.6	14.6
Vertical FOV (deg)	53.1	43.6	33.4	21.7	17.1	11.0

Table 5-16 illustrates how the dimensions of the image area are calculated once the focal length is chosen. A camera mounting height of 40 ft (12.2 m) is assumed.

Table 5-16. Calculation of image area dimensions for an 8-mm focal length lens.[a]

Dimension	Symbol	How determined	Value
Camera height above detection area	h	Input parameter	40 ft (12.2 m)
Half the vertical angular FOV of the lens	α_V	Lens specification (e.g., from Table 5-11) based on required FOV	16.7 deg
Half the horizontal angular FOV of the lens	α_H	Lens specification (e.g., from Table 5-11) based on required FOV	21.8 deg
Angle between camera line-of-sight and mounting structure	θ	$\theta = (90-5) - \alpha_V$, where 5 is the number of degrees the FOV is below the horizon	68.3 deg
Distance to bottom of image	d_1	$d_1 = h \tan(\theta - \alpha_V)$	50.5 ft (15.4 m)
Width of bottom of image	w_1	$w_1 = 2h \tan \alpha_H / \cos(\theta - \alpha_V)$	51.5 ft (15.7 m)
Distance to top of image	d_2	$d_2 = h \tan(\theta + \alpha_V)$	457.2 ft (139.4m)
Width of top of image	w_2	$w_2 = 2h \tan \alpha_H / \cos(\theta + \alpha_V)$	367.1 ft (111.9 m)

[a] Camera mounting height of 40 ft (12.2 m) and level topography are assumed (from: *Autoscope Consultant's Designers Guide.* Econolite Control Products, Anaheim, CA. 1998).

Figure 5-56 defines the angular field of view of the camera lens, which is used in the image area calculations. The other dimensions are illustrated in Figure 5-57. The angle α, which the extreme rays make with the axis, is the half field of view angle or more simply the half-field angle of the lens. It limits the dimensions of the object seen by the lens. The chief rays *SET* and *REU* incident at the periphery of the lens that pass through the entrance pupil *E* are refracted through the conjugate plane *E*', in this case the location of the charge-coupled device (CCD) camera array. The focal length of the lens is the distance *CF* or *CF*'. The shaded cones *ETU* and *ERS* indicate the boundaries within which any object must lie in order to be observed in the image field.[30]

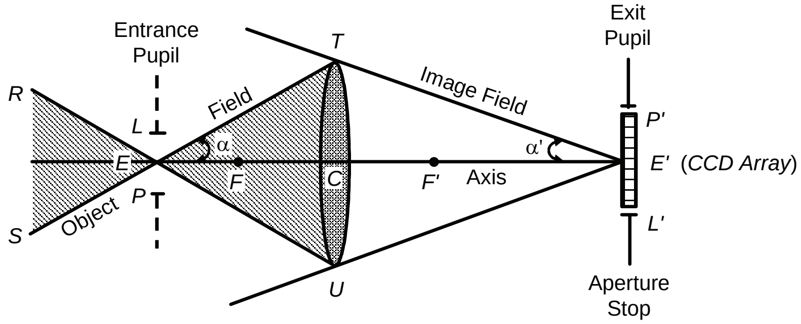


Figure 5-56. Field of view of a converging lens.

Tables 5-17 and 5-18 display the image area dimensions for 30-, 40-, and 50-ft (9.1-, 12.2-, and 15.2-m) camera mounting heights. These dimensions are plotted in Figure 5-57, which shows the increased sensitivity of the top image area dimensions to variations in camera height.

Table 5-17. Image area dimensions for 30-, 40-, and 50-ft (9.1- 12.2-, and 15.2-m) camera mounting heights, using an 8-mm focal length lens.

Camera mounting height	30 ft (9.1 m)	40 ft (12.2 m)	50 ft (15.2 m)
Distance to top of image	343 ft (104.5 m)	457 ft (139.3 m)	572 ft (174.3 m)
Width of top of image	275 ft (83.8 m)	367 ft (111.9 m)	459 ft (139.9 m)
Distance to bottom of image	38 ft (11.6 m)	50 ft (15.2 m)	63 ft (19.2 m)
Width of bottom of image	39 ft (11.9 m)	52 ft (15.8 m)	64 ft (19.5 m)

Table 5-18. Image area dimensions for 60- and 70-ft (18.3- and 21.3-m) camera mounting heights, using an 8-mm focal length lens.

Camera mounting height	60 ft (18.3 m)	70 ft (21.3 m)
Distance to top of image	686 ft (209.1 m)	800 ft (243.8 m)
Width of top of image	551 ft (167.9 m)	642 ft (195.7 m)
Distance to bottom of image	76 ft (23.2 m)	88 ft (26.8 m)
Width of bottom of image	77 ft (23.5 m)	90 ft (27.4 m)

Camera specifications vary with the VIP manufacturer. Most VIP manufacturers will recommend one or more cameras that are compatible with the software and capabilities in the image processor. The specifications in Table 5-19 are typical of those required.[21,24,31] Camera horizontal resolution (pixel size) must be adequate to calibrate the system, especially at longer distances from the camera mounting location. Resolution also affects the accuracy of vehicle size measurement and the tracking of vehicles through the camera's field of view. Vertical resolution is controlled by the Electronic Industry Association (EIA) or International Radio Consultative Committee (CCIR) specifications. Dynamic range indicates the range of light levels that are distinguished by the camera, while sensitivity describes the ability of the camera to detect objects under low illumination conditions. Tests at California Polytechnic Institute at San Luis Obispo suggest that the dynamic range specification is more critical than sensitivity in most traffic surveillance applications.[32]

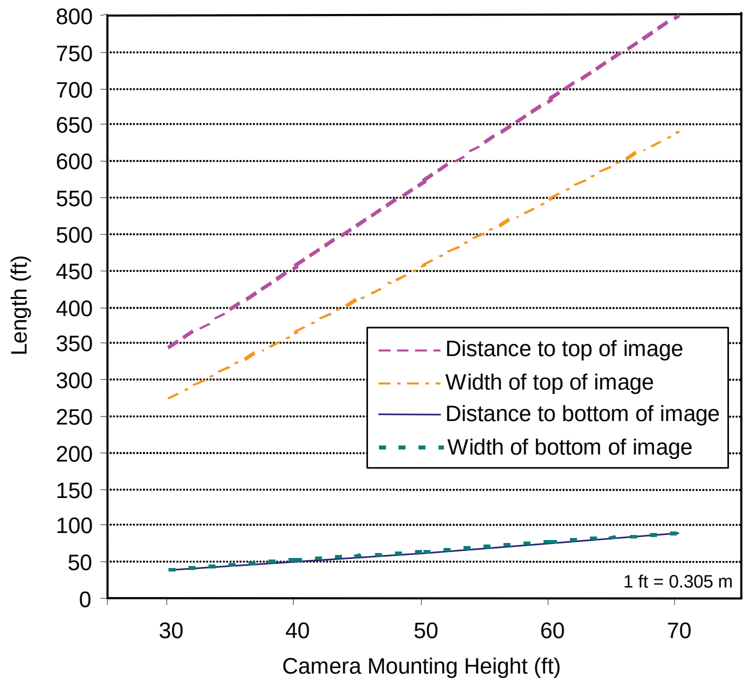


Figure 5-57. Image area dimensions for 30- to 70-ft (9.1- to 21.3-m) camera mounting heights, assuming an 8-mm focal length lens.

After power, control, and data cables are in place and the camera mounted and transmitting video imagery to the image processor, the VIP operating parameters can be set up, the image area calibrated, and detection zones placed on the roadway. Most VIPs contain software for this purpose; some require separate purchase of the setup and calibration software. The software operates on a personal computer that connects to the VIP through an RS-232 interface.

Calibration menu items used by one manufacturer include set lanes; set external communication rate; set video reference level to correspond to camera output voltage; set alarm parameters based on flow rate, lane occupancy, speed, headway, or vehicle length; and set clock. The detection zones typically gather vehicle presence, count, speed, lane occupancy, and vehicle length classification data. Some processors provide Boolean operators, such as AND and OR, for connecting detection zone outputs. These may be useful in obtaining more accurate counts and presence calls. The detection zones are drawn with a mouse or keyboard commands on the computer monitor screen displaying the field of view of the camera. Zones can be created for multiple lanes that are contained within the field of view of the camera.

Table 5-19. Typical camera specifications for VIP applications.(19,22,28)

Parameter	Value
Minimum light level for usable video	0.1 lux for intersections, 0.04 lux for freeways[a]
Maximum light level for usable video	10,000 lux
Dynamic range	56 decibels (dB) minimum from minimum to maximum usable video signal
Automatic gain control (AGC) range	20 dB minimum with 1 s damping
Minimum vertical resolution[b]	350 to 383 lines
Minimum horizontal resolution[b]	550 to 580 lines
Lens format	.25- to 1-inch interline or frame transfer CCD
Active pixel elements	768 horizontal, 494 vertical minimum
Iris	Automatic with damping controlled by a time constant of 0.25 s or greater
Wavelength filter	600 nm to 1400 nm wavelengths attenuated to 10%
Operating temperature range	-40 °C to +60 °C
Sunshield	Required
Internal heater	Required
Maximum weight	Compatible with pan and tilt camera mount
Video signal interface[c]	RS 170, NTSC, CCIR, or PAL[d]

[a] Sensitivity is also specified with respect to video, AGC, and signal-to-noise ratio (S/N) levels. Thus, a minimum sensitivity specification may appear as 0.1 lux at 100 percent video with no AGC and S/N = 55 dB.

[b] Distant vehicles at the upper edge of the field of view often span only two video resolution lines, making them barely detectable. A lower resolution camera will reduce the usable field of view to the lower half of the video image or less.

[c] Not all VIP models support all video signal interfaces.

[d] NTSC = National Television Standards Committee. PAL = Phase alternate lines.

CALIBRATION ISSUES

VIP models require several pieces of information to calibrate the image area dimensions and hence the data acquired by the sensor. Most calibration methods utilize combinations of along-lane and cross-lane dimensions, camera mounting height and angle (measured from the vertical or horizontal), lens focal length, and CCD array format (size). The image area calibration information required by one VIP system is given in Tables 5-20 and 5-21.(33)

Lane dimensions can be measured and marked with traffic cones or paint stripes before beginning the calibration process, as shown in Figures 5-58 and 5-59. These dimensions are usually needed at the near and far edges or at the corners that mark the viewing area boundaries. Image area markers can be positioned using two people, one to view a monitor containing the field of view and another to move the markers into place according to instructions received from the image viewer. Lane widths can be measured in advance to provide cross-lane calibration information. Existing roadway and lane markers can be used for image area calibration, but only if distances are measured and confirmed before the calibration procedure begins. Nominal values of marker separation and location should not be used, as discrepancies in their assumed placement cause VIP system calibration errors and poor data quality.

Table 5-20. Image area and data calibration information.

Parameter	Interpretation
Focal length	The focal length of the camera lens.
CCD array size	Size of CCD array used in the camera.
Image area	Camera image area as defined by a rectangle drawn on the road surface shown on the monitor. The dimension of one side (either length or width) of the rectangle. An alternate dimension is the distance between dashed lines that separate lanes.
Number of lanes	Number of lanes in which data are collected.
Detection zone location	Positions of markers that define two detection zones in each lane. Length and width dimensions between markers.
Traffic flow direction	For each lane, define flow as toward top or bottom of video image or in both directions.
Edit detection zones	Modify location or size of detection zones.

Table 5-21. Alternate image area and data calibration information.

Parameter	Interpretation
Camera vertical angle	Vertical angle between axis in plane of road surface and camera viewing direction.
Camera horizontal angle	Horizontal angle between camera viewing direction and traffic flow direction.
Camera height	Height of camera above road surface.
Camera offset	Ground distance between the camera and a calibration axis parallel to the traffic flow direction.
Detection zone location	Ground distance between camera and near and far detection zone markers in each lane.
Detection zone length	Ground distance between markers that define the near and far detection zones in each lane.

Camera mounting height and angle can be measured, while focal length and CCD format are determined from lens and camera specifications. Some VIPs may require the camera offset angle with respect to the traffic flow direction and camera offset distance with respect to a calibration axis parallel to the traffic flow.[31] The effect of improper lens selection, unsuitable camera mounting location, poor image area calibration, and low camera sensitivity on VIP data quality were discussed with respect to the VIP performance shown in Figure 2-54.[19]

Figure 5-58. Up-lane distance measure aided by traffic cones placed at 25-ft (7.6-m) intervals (temporary markings).

Figure 5-59. Down-lane road surface dimensions marked with paint as used for sensor evaluation and performance comparison.

SERIAL DATA INTERPRETATION SOFTWARE

Some VIPs transmit data to the controller through a serial interface and make the data protocol available to the user. Others require interface or driver software to be purchased or written by the user agency so that their central computer system or controller can interpret the serial data. VIPs also provide data that emulate inductive loop outputs, i.e., optically isolated transitions, so that the VIP data appear to the controller as if they originated from inductive loops. Hence, the controller treats these VIP data in the same manner as inductive-loop data and the same traffic management software can be utilized.

AUTOSCOPE 2004 VIDEO IMAGE PROCESSOR DETECTION ZONES

Figures 5-60 and 5-61 contain examples of detection zones drawn for the Autoscope 2004 VIP on the I-5 Freeway in Orange County, CA, as part of the evaluation of a mobile surveillance and wireless communications system.[34] On the mainline (Figure 5-60), vehicle count sensors were connected by AND logical operators to reduce false counts caused by image projection from vehicles into more than one lane. This problem was caused by the relatively low 30-ft (9-m) camera height and side-viewing geometry. Speed sensors (the long rectangular detection zones), presence sensors, and demand sensors were created to demonstrate the different options available for vehicle detection.

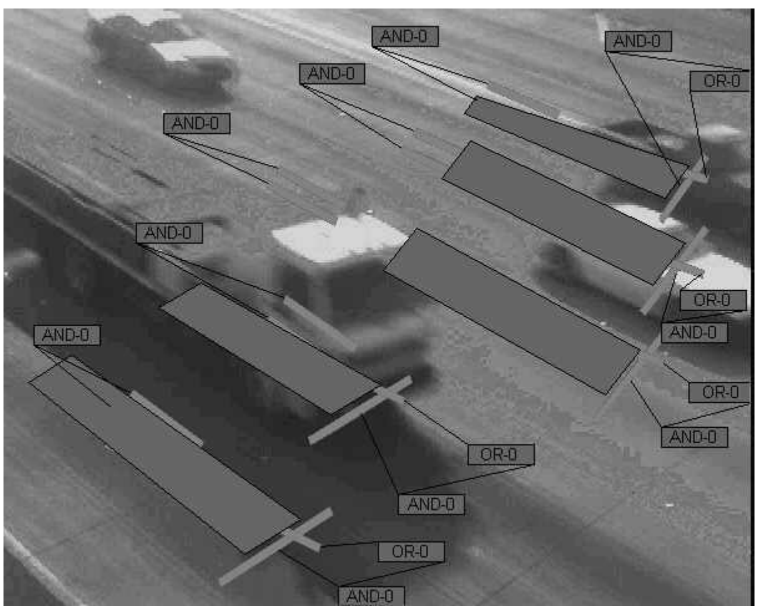


Figure 5-60. Mainline count and speed detection zones for an Autoscope 2004 VIP using a side-mounted camera. Count sensors are represented by the lines perpendicular to traffic flow; speed sensors by the long, rectangular box.

The detection zones on the ramp (Figure 5-61) consisted of demand and count sensors. Sometimes detection zones were placed parallel to the traffic flow direction, and other times sensors were configured in the shape of an × to increase vehicle detection probability. Depending on whether projection of tall vehicle images from one lane into another or occlusion was the more severe problem at a particular site, the × sensors were connected with AND or OR logical operators respectively. OR logic was also applied to increase the probability of vehicle detection by the VIP and the consequent change of signal from red to green. In this application, the primary goal was to prevent vehicles from being trapped at a red signal, rather than concern about a potential increase in false calls.[34]

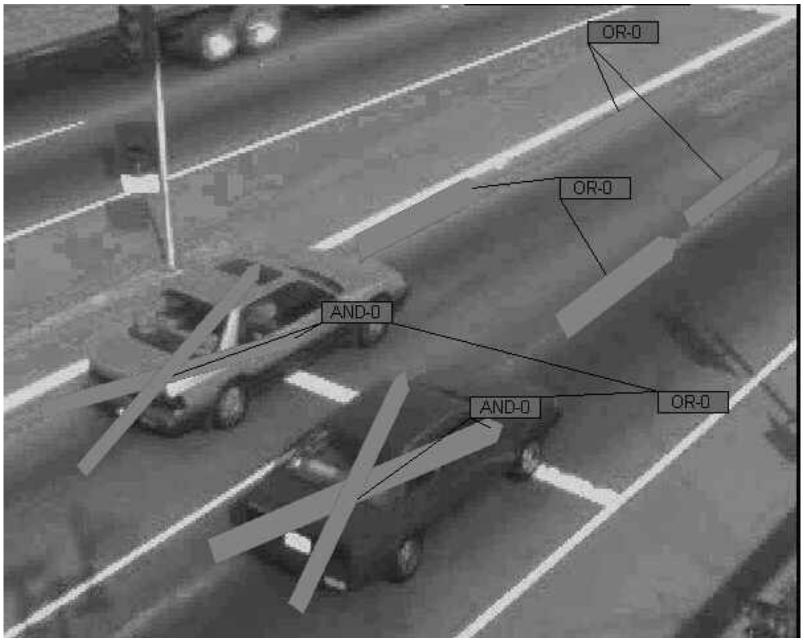


Figure 5-61. Ramp demand zones (× configuration) for an Autoscope 2004 VIP with a side-mounted camera. The zones beyond the stop line record vehicle passage.

Figure 5-62 illustrates the viewing perspective in detection zones created on roadway surfaces, far from low-mounted cameras. The detection zones now enclose a smaller percentage of the pixels in the field of view, decreasing the probability of a detection. In addition, occlusion and projection of tall vehicle images from one lane into another are more prevalent because of the relative size of the detection zone.[34]

TRAFICON VIP2 VIDEO IMAGE PROCESSOR DETECTION ZONES

Figure 5-63 displays the image and data provided by the Traficon VIP2 traffic data detector, designed for collection of traffic flow data on freeways and arterials.[35] The configuration and data acquisition software operate in a personal computer architecture using RS-232 or RS-485 serial interfaces to the VIP. Data are output to a controller through eight optically isolated semiconductors. The data provided for each lane and the three selectable length-based vehicle classes are volume, speed, gap times, and headway. In addition, the VIP gives the occupancy and density for each lane.

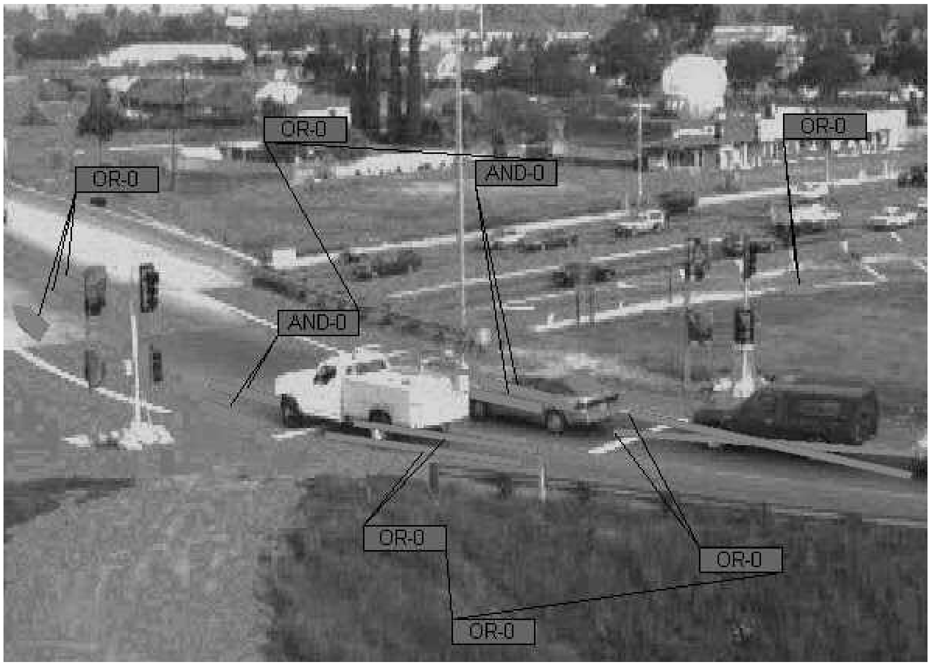


Figure 5-62. Ramp detection zone placement for an Autoscope 2004 VIP when the camera is neither close to the monitored roadway nor at a sufficient height.

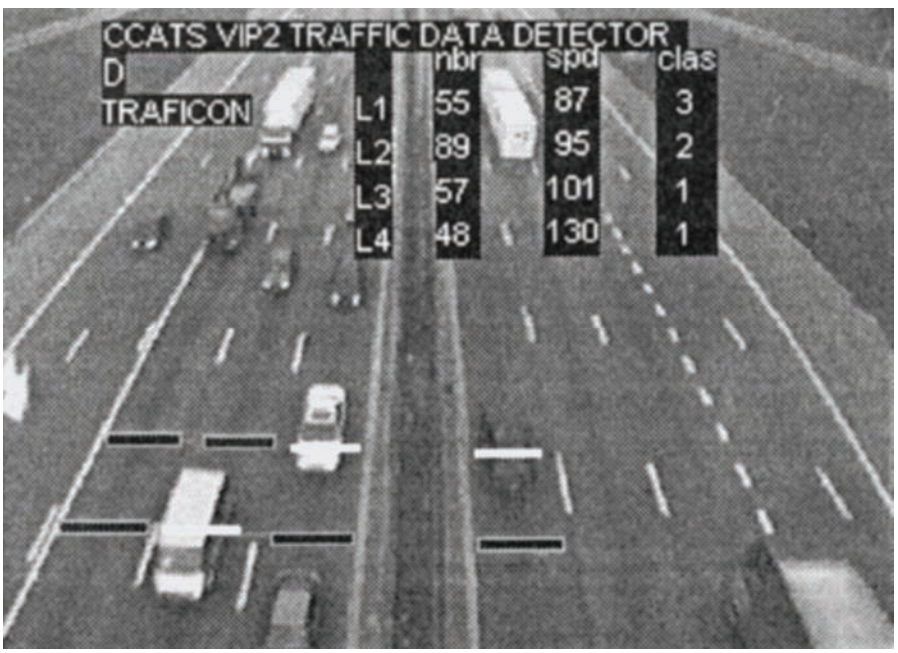


Figure 5-63. Image and data displays for Traficon VIP2 traffic data detector (Source: *CCATS® VIP2 Specification.* VDS, Inc., San Diego, CA. 1997).

MICROWAVE RADAR SENSORS

The two types of microwave radars exploited for traffic management are CW Doppler and FMCW presence-detecting sensors. CW Doppler radar sensors detect vehicles traveling at speeds greater than 3 to 5 mi/h (4.8 to 8.0 km/h), but cannot detect stopped vehicles. CW Doppler sensors do not require programming to operate. Most do have jumpers or switches, however, that convey the direction of traffic flow, i.e., approaching or departing, to the sensor. This feature enables some models to detect traffic moving in the wrong direction, such as wrong-way traffic on an entry or exit ramp or on a reversible lane. Presence and passage of moving vehicles are provided from optically isolated semiconductor or relay outputs. Speed is supplied through a serial interface, which usually requires a software driver to be written by the user agency. Some CW Doppler radars allow the detection pattern to be expanded or contracted to cover the area of interest. The antenna design provides the proper beamwidth for measuring traffic parameters over single or multiple lanes, depending on the sensor application, when the sensor is mounted at the recommended height.

Forward- and side-looking radar sensors form elliptical footprints on the road surface. Figure 5-64 defines the footprint and the parameters for a forward-looking sensor. When the 3-dB antenna beamwidths are available from the manufacturer, the along-lane and cross-lane footprint dimensions can be estimated as[16]

$$d_a = h[\tan(\theta + \theta_a/2) - \tan(\theta - \theta_a/2)] \qquad (5\text{-}1)$$

$$d_c = 2R \sin\theta \tan(\theta_c/2) = 2h \tan\theta \tan(\theta_c/2) \qquad (5\text{-}2)$$

where

d_a, d_c = along-lane and cross-lane sensor footprint diameter, respectively

$h = R\cos\theta$ = sensor mounting height

R = slant range from sensor aperture to center of ground footprint

$R\sin\theta$ = distance along roadway measured from projection of sensor aperture onto the roadway directly under the aperture to the center of the ground footprint

θ_a = along-lane two-way 3-dB antenna beamwidth

θ_c = cross-lane two-way 3-dB antenna beamwidth

θ = angle of incidence of the sensor measured from nadir (downward-looking direction).

The footprint dimension equations assume that range binning is not used to increase the resolution of the footprint along the major axis. The range bin concept is depicted in Figure 2-59.

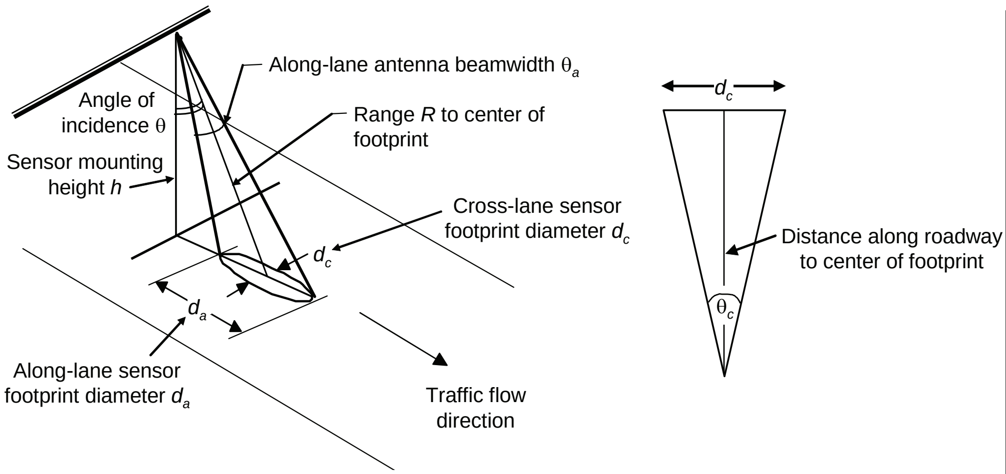


Figure 5-64. Microwave sensor detection area for upstream and downstream viewing.

WHELEN TDN-30 CW DOPPLER SENSOR

The Whelen TDN-30 narrow beam CW Doppler microwave sensor is mounted centered over the lane of interest (within ± 1.5 ft (0.5 m)) with its bottom surface parallel to the roadway (within ± 5 degrees). With this orientation, the angle of incidence of the antenna with respect to the road surface is 45 deg. The antenna is located inside the sensor housing. The along-lane and cross-lane dimensions of the detection zone are established by the mounting height, as shown in Table 5-22.[36]

Table 5-22. Detection zone of Whelen TDN-30 CW Doppler microwave sensor.

Mounting height		Along-lane beam diameter[a]		Cross-lane beam diameter[a]	
(ft)	(m)	(ft)	(m)	(ft)	(m)
15	4.6	4.2	1.3	2.9	0.9
20	6.1	5.6	1.7	3.9	1.2
25	7.6	7.0	2.1	4.9	1.5
30	9.1	8.4	2.6	5.9	1.8

[a] Calculated using Equations 5-1 and 5-2 and approximate antenna 3-dB beamwidths of 8 deg for each direction.

In addition to a jumper for selecting travel direction, the TDN-30 has jumpers that specify the RS-232 data transmission rate (1200 or 2400 baud), transmission mode (modem or free running serial data), operating mode (freeway management, incident detection, or speed and direction detection), dwell count utilized with the incident detection mode, and optically isolated closure time used in the speed and direction detection mode. The freeway management mode permits vehicle speed and count data to be collected. The incident detection mode allows selection of an incident speed threshold and dwell count threshold. If the speed is below the speed threshold, the dwell count is increased by one. If consecutive vehicles, equal in number to the dwell count threshold, are detected below the speed threshold, then a normally open contact is pulsed to indicate the detection of an incident. However, if a vehicle is detected with a speed greater than the speed threshold, the dwell counter is reset.

Once an incident is detected, the sensor begins to measure vehicle speeds to determine if the incident has cleared. An automatic incident cleared speed threshold is calculated equal to the speed threshold plus 25 percent. As before, the dwell counter must increase on consecutive vehicles before a second normally open contact is pulsed, indicating that the incident has cleared. In the speed and direction detection mode, a speed threshold between 5 and 80 mi/h (8 and 129 km/h) is set on thumbwheel switches. As a vehicle is detected, its speed is compared to the threshold. If the speed exceeds the threshold, an optically isolated contact is activated for a user-selectable time of 2, 4, 8, or 16 s.[36]

MICROWAVE SENSORS TC-20 CW DOPPLER SENSOR

Some CW Doppler radar manufacturers provide plots of the detection pattern. One such plot is given in Figure 5-65 for the Microwave Sensors TC-20. The coverage is adjustable by turning a potentiometer clockwise to maximize the pattern size and counterclockwise to minimize it.[37]

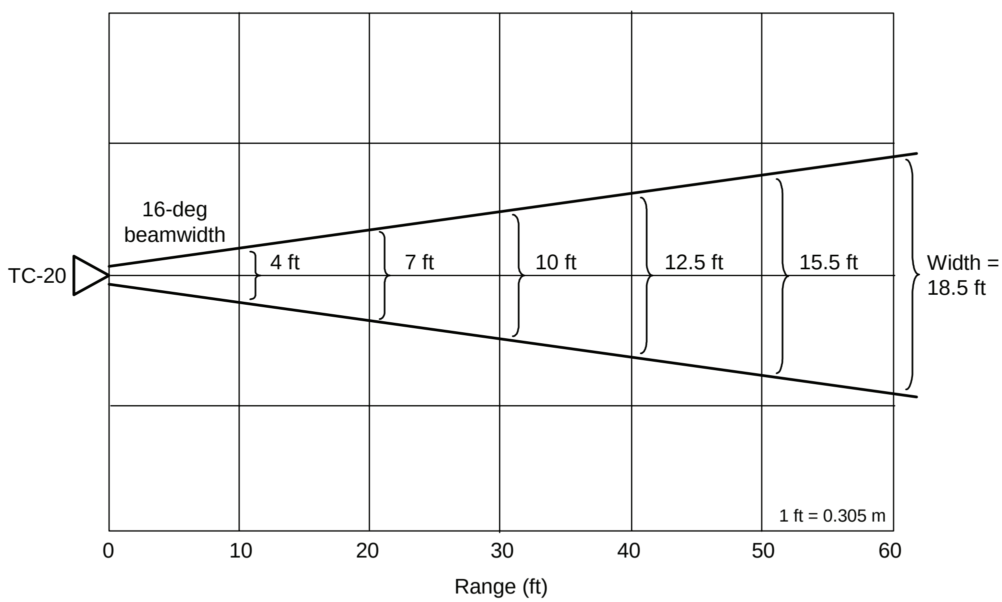


Figure 5-65. Approximate detection pattern for Microwave Sensors TC-20 Doppler radar (Source: *TC-20 installation instructions.* Microwave Sensors, Ann Arbor, MI).

EIS RTMS FMCW RADAR

The RTMS presence-detecting microwave sensor combines FMCW and Doppler operation. In its side-fired configuration, it is a multilane sensor capable of detecting stopped or moving vehicles in up to eight lanes. The traffic flow parameters provided per lane are volume, occupancy, speed, and classification based on user-specified vehicle length. In its forward-looking mode, the sensor's detection zones form a speed trap and measure speed and length of vehicles in a single lane. The speed and length measurements can each be placed in up to seven bins when the sensor is operated in the forward-looking mode. The sensor adds a Doppler speed measurement (maximum error = 2 percent) for speeds exceeding 10 mi/h (16 km/h) in forward-looking operation.

Optically isolated contacts in the RTMS provide presence indication in each detection zone similarly to that of inductive-loop detectors. Thus, the sensor is compatible with controllers that are configured to accept inductive-loop data. Flow rate, occupancy, speed, and classification are available through RS-232 and RS-485 serial interfaces at rates up to 115,200 Baud or through a TCP/IP interface option. Real-time vehicle speed and length are also available for specialized applications, e.g., speed and red light enforcement or excessive speed warning systems.

RTMS setup and calibration are performed using a personal computer and manufacturer-supplied software through an RS-232, RS-485, or TCP/IP interface located on the sensor.[38] The setup wizard can automatically determine the optimum calibration of the RTMS, including operating mode, required number of detection zones and locations, and verify correct operation of the sensor as shown on the setup utility image in Figure 5-66.

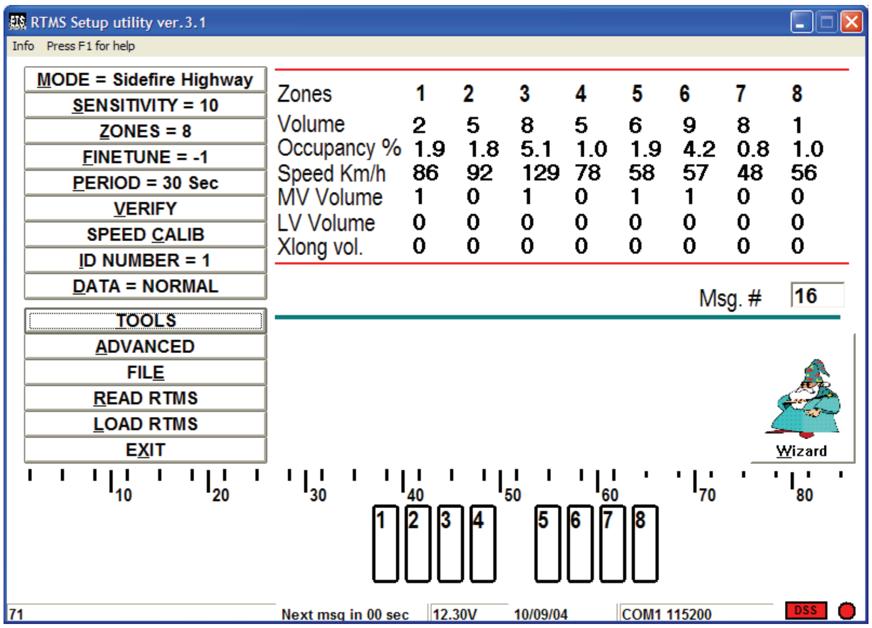


Figure 5-66. RTMS microwave sensor detection zone setup and calibration screen (Image courtesy of EIS Electronic Integrated Systems Inc., Toronto, Canada).

During setup, the lower portion of the figure displays every vehicle within the radar's field-of-view at that moment as a dark rectangular blip at its corresponding range. A detection zone location is defined by surrounding the blip with a rectangular outline box, which is moved with the arrow keys on the keyboard. A detection zone can include one or more lanes. After a zone is defined, its corresponding optically isolated output contact pair closes every time a vehicle is detected. Once all zones are defined, a manual vehicle count is made and compared with the RTMS count to calculate the accuracy of the setup configuration. If the accuracy is not adequate, the detection zones are adjusted and the manual and RTMS count comparison is repeated.

Early users of the RTMS have remarked about the time needed to accurately aim the radar and calibrate the multiple detection zones when the sensor is in a side-looking configuration to view five or more lanes of traffic. Others have not voiced this concern. Newer versions of the setup software claim to alleviate this issue. Nevertheless, once the viewing angle has been set, sensor performance generally falls within the manufacturer's specifications.

ACCUWAVE 150LX FMCW RADAR

The single detection zone Accuwave 150LX presence-detecting microwave radar by Naztec also is software programmable from a personal computer using the RS-232 interface on the sensor. Figure 5-67 displays the basic and advanced parameters that can be adjusted.

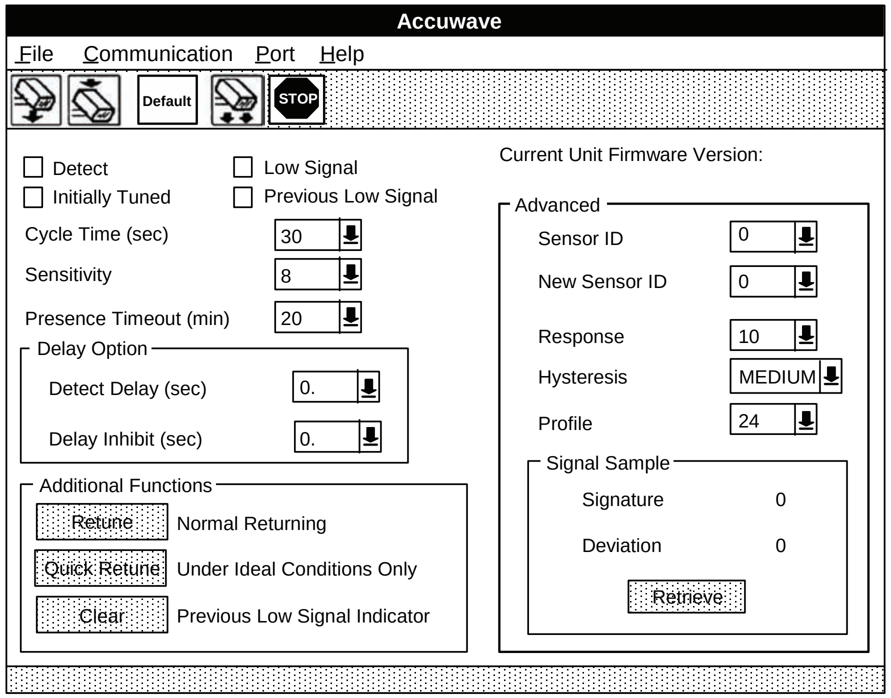
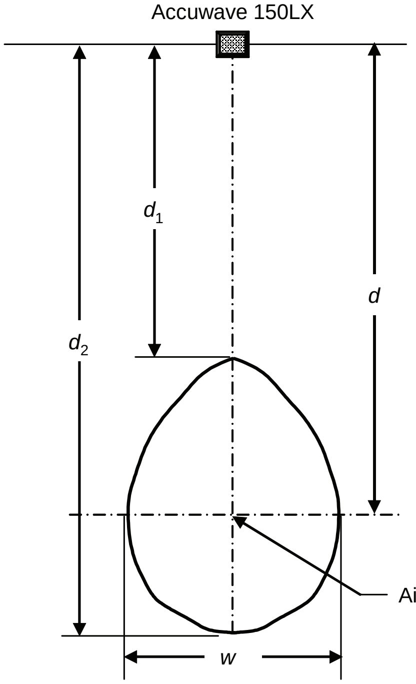


Figure 5-67. Accuwave 150LX microwave sensor interface and setup options screen (Source: *Accuwave 150LX Instruction Manual.* Naztec, Inc., Sugar Land, TX).

Basic parameters are cycle time (longest expected intersection cycle time), sensitivity (smaller numbers require a larger signal for a detection), presence timeout (elapsed number of minutes while in a continuous detect state before sensor recycles), detect delay time (elapsed time after sensor detects a vehicle until the sensor becomes active again), and delay inhibit (elapsed time after a vehicle detection before the detect delay time is used again). Advance parameters are sensor identification (address to differentiate a sensor from others on the same communications line), response time (application dependent—intersection applications with slow moving and stationary vehicles require longer response times, hysteresis (low, medium, high), and a fine tuning parameter called profile.[39]

After all entries are made, the download button on the toolbar is pressed to write the parameters into nonvolatile memory in the sensor. The 150LX provides vehicle presence through an optically isolated semiconductor output. The detection area of the 150LX along the road is shown in Figure 5-68.



For Mounting Height = 20 ft:

Aimpoint *d* (ft)	d_1 (ft)	d_2 (ft)	*w* (ft)
30	20	44	14
45	30	65	24
50	35	75	25
80	40	90	30

1 ft = 0.305 m

Figure 5-68. Accuwave 150LX microwave sensor road surface detection area (Source: *Accuwave 150LX Instruction Manual.* Naztec, Inc., Sugar Land, TX).

LASER RADAR SENSORS

Laser radar sensors operate in the near infrared spectrum by transmitting beams that fully scan one or two lanes to provide presence, count, speed, and classification data. Figure 5-69 illustrates the mounting configuration and beam geometry for the Autosense II sensor.[40] The first beam normally has an incidence angle of 10 deg and the second beam an incidence angle of 0 deg. The specified incidence angles are obtained by mounting the sensor with a 5-deg forward tilt, although other mounting configurations can be accommodated. The operating temperature range is from –40 °F to +158 °F (–40 °C to +70 °C) plus sun loading. A 30-minute warmup time is needed at –40 °F (–40 °C).

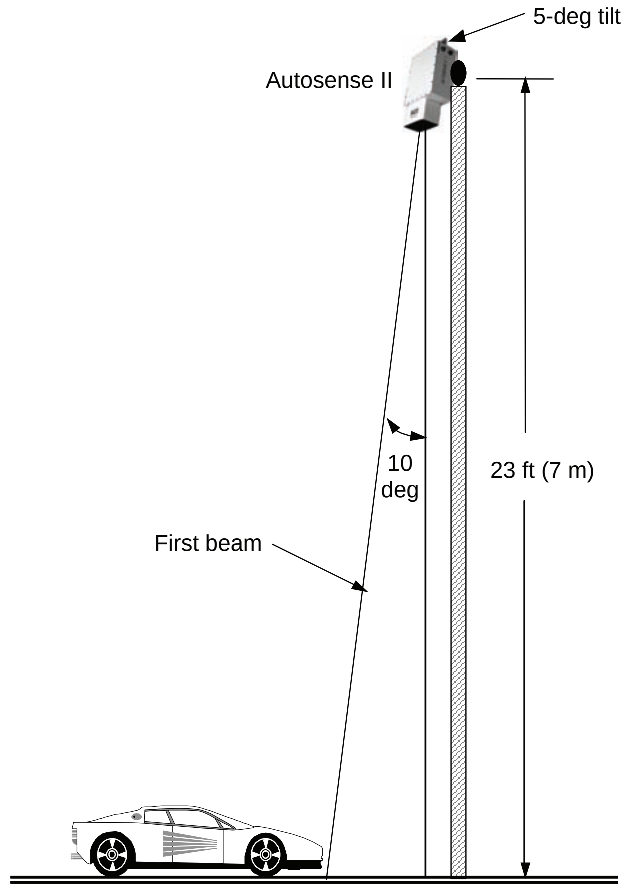


Figure 5-69. Autosense II laser radar mounting (Source: *Autosense II User's Manual and System Specification.* Schwartz Electro-Optics, Inc, Orlando, FL, now OSI Laserscan, 1998).

Autosense II communicates over the factory default RS-422 interface at 57.6 kbaud, 8 data bits, 1 stop bit, and no parity. An optional RS-232 full-duplex serial interface is available. Other outputs include a logic-level vehicle detect line and a solid-state relay (optional). The manufacturer recommends that the data cable be made of low-capacitance polyethylene (such as Belden 9807) as the cable capacitance, which should not exceed 2500 pF, limits the maximum cable length for reliable RS-232 operation.

The Autosense configuration software is executed on a 486 or Pentium personal computer. The data frame format provides frame synchronization, frame start, message, and checksum information. The software menu provides the option of saving all of the data to an ASCII text file. The file name field permits the data to be redirected to another drive. After the software is configured, a power-on message can be accessed to show self-test results, firmware version number, and the measured range to the road for each sample in both beams. A test data output command is available to verify the range and intensity data for each sample in both beams.

Classification is performed by using software that categorizes the profiles of different vehicles. For each vehicle passing through the Autosense II field of view, the sensor outputs five messages based on the location of the vehicle. These messages are as follows:

- Message 1—First beam vehicle detection message.
- Message 2—Second beam vehicle detection message.
- Message 3—First beam end of vehicle message.
- Message 4—Second beam end of vehicle message.
- Message 5—Vehicle classification message.

As the vehicle passes through the first laser beam, the sensor detects the vehicle, assigns a vehicle identification number and outputs Message 1 to the computer. When the front bumper of the vehicle passes the second laser beam, the sensor outputs left edge position, right edge position, and vehicle speed to the computer as Message 2. This message is used to estimate the position of the vehicle. When the rear bumper clears the first laser beam, the left edge position and right edge positions are transmitted from the sensor to the computer as Message 3. As the vehicle continues forward, its rear bumper passes through the second laser beam. Message 4 is transmitted at this time to indicate the end of the vehicle. The Autosense II compiles data accumulated for the vehicle, generates a classification code, a confidence level for the classification estimate, and transmits these data to the computer as Message 5.

PASSIVE INFRARED SENSORS

Passive infrared sensors contain fixed field of view optics. Some offer a variety of focal length lenses to suit various applications and mounting distances from the detection area of interest. Presence and passage are provided from optically isolated semiconductors or relays. Multiple detection zone passive infrared sensors that measure speed contain a serial interface, which usually requires a software driver to be written by the user agency.

Manufacturers typically provide footprint dimensions for passage infrared sensors as illustrated in Table 5-23.(41) The mounting height h and the range R from the sensor to the center of the ground detection area define the incidence angle θ, as was shown in Figure 5-64. Multiple detection zone passive infrared sensors provide tables that give the dimensions of each zone as a function of mounting height and the distance between the edges of the detection zones and the base of the mounting structure.

ULTRASONIC SENSORS

The field of view of most ultrasonic pulsed sensors illuminates one traffic lane when they are mounted at the recommended height and pointed directly downward. The one exception is the two-lane Lane King model manufactured by Novax.

Figure 5-70 shows the overhead mounting configuration for the Microwave Sensors TC-30C ultrasonic sensor. The range of the TC-30C is adjusted so that it detects objects at least 2 to 3 ft (0.61 to 0.91 m) above the road surface, e.g., tops of vehicles. The detection gate established by this adjustment differentiates between pulses reflected from the road surface and those reflected from vehicles.

Table 5-23. Eltec 842 infrared sensor footprint dimensions.

Mounting height *h*	Range *R*	Incidence angle θ	Ground distance *d*	Footprint width *w*	Footprint length *l*
15 ft	21 ft, 3 in	45 deg	15 ft	2 ft, 8 in	2 ft, 6 in
15 ft	25 ft, 0 in	53 deg	20 ft	3 ft, 1 in	3 ft, 6 in
15 ft	29 ft, 2 in	59 deg	25 ft	3 ft, 8 in	4 ft, 9 in
15 ft	33 ft, 6 in	63 deg	30 ft	4 ft, 3 in	6 ft, 3 in
20 ft	40 ft, 4 in	60 deg	35 ft	5 ft, 1 in	7 ft, 3 in
20 ft	44 ft, 9 in	63 deg	40 ft	5 ft, 7 in	8 ft, 5 in
20 ft	49 ft, 3 in	66 deg	45 ft	6 ft. 2 in	10 ft, 2 in
20 ft	53 ft, 10 in	68 deg	50 ft	6 ft, 9 in	12 ft, 3 in

1 ft = 0.3 m

h = mounting height, *d* = ground distance between center of the detection area and the base of the sensor mounting structure, *R* = range from sensor aperture to center of detection area, *w* = ground footprint width, *l* = ground footprint length. θ is not selected independently, but is determined from the *h* and *R* values through $\cos \theta = h/R$.
(*From*: Eltec Instruments, *Model* 842 *Presence Sensor Data Sheet*, Daytona Beach, FL.)

When mounted horizontally, ultrasonic sensors view the side of any vehicles that pass by. In this configuration, the range is adjusted so that the detection zone extends approximately half way through the lane.(42)

Presence and passage are provided from optically isolated semiconductors or relays. Ultrasonic sensors that measure speed contain a serial interface, which usually requires a software driver to be written by the user agency.

PASSIVE ACOUSTIC SENSORS

The guidelines for installing single-lane and multiple-lane passive acoustic sensor models are described below.

IRD SMARTSONIC SINGLE-LANE ACOUSTIC SENSOR

The SmartSonic sensor receives acoustic energy through one beam pointed at the center of the monitored lane. The sensor is aimed by sighting along the tube that serves as part of the mounting hardware.(43) The installation geometry is illustrated in Figure 5-71. The sensor contains an integrated self-test on startup and online, real-time fault monitoring. Optional solar power and spread spectrum wireless transmission link are available to transmit sensor data to a controller. The line of sight range of the wireless link depends on the transmitted power level and bit error rate. Minimum range is 800 ft (244 m) and maximum range is at least 4,800 ft (1,463 m).

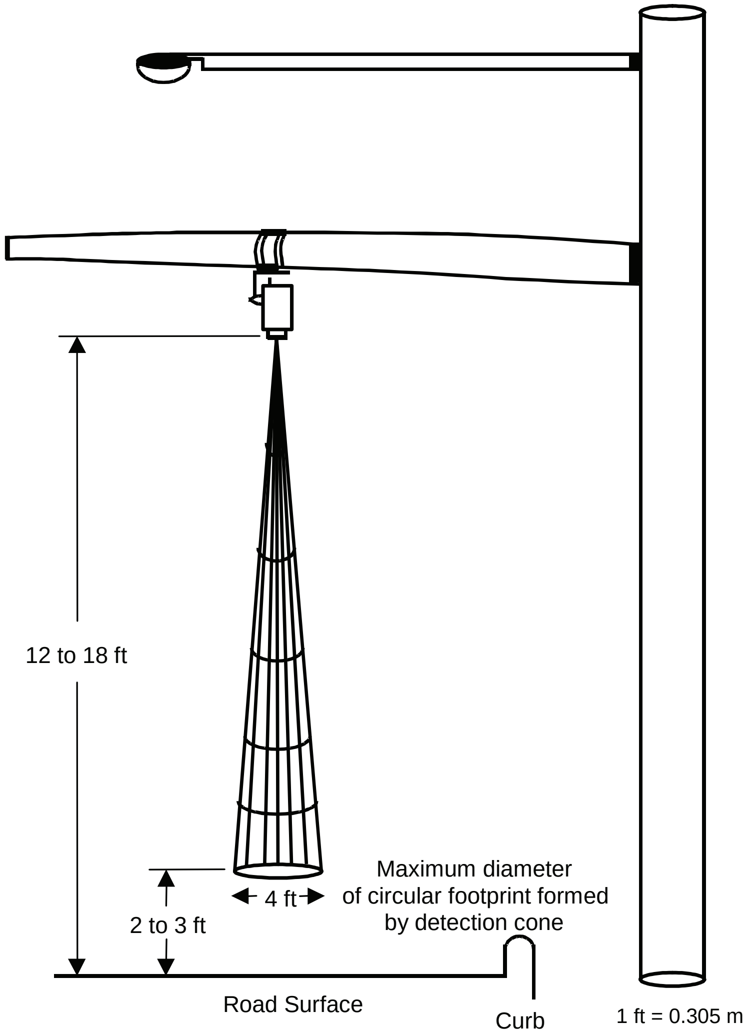


Figure 5-70. TC-30C ultrasonic sensor overhead mounting pattern (Source: Microwave Sensors, *TC-30C installation instructions*, Ann Arbor, MI).

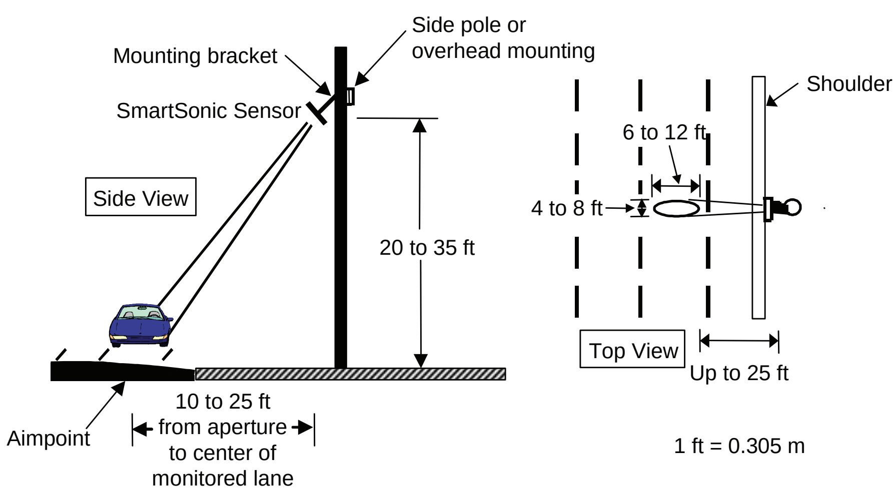


Figure 5-71. SmartSonic acoustic sensor installation geometry (Source: IRD, Inc., *Smartsonic Acoustic Vehicle Detection System Specifications)* Saskatoon, Saskatchewan. 1996.

The SmartSonic detects vehicle presence through an optically isolated semiconductor. A serial interface on the controller card installed with the sensor provides volume, lane occupancy, speed, vehicle classification (cars, light trucks, heavy trucks and buses), and sensor status messages.

SMARTEK SAS-1 MULTIPLE-LANE ACOUSTIC SENSOR

The SAS-1 is designed to monitor up to five lanes when mounted in a side-looking configuration. Detection zones are created with Windows-based software supplied with the sensor.(44) These zones are equivalent in size to a 6-ft (1.8-m) inductive-loop in the direction of traffic flow and are user-selectable in size in the cross-road direction. The software allows monitoring of acoustical signatures and output data as displayed in Figure 5-72. Output data include volume, lane occupancy, and average vehicle speed over a serial interface, which may require interface software to a controller or central computer to be written by the user agency.

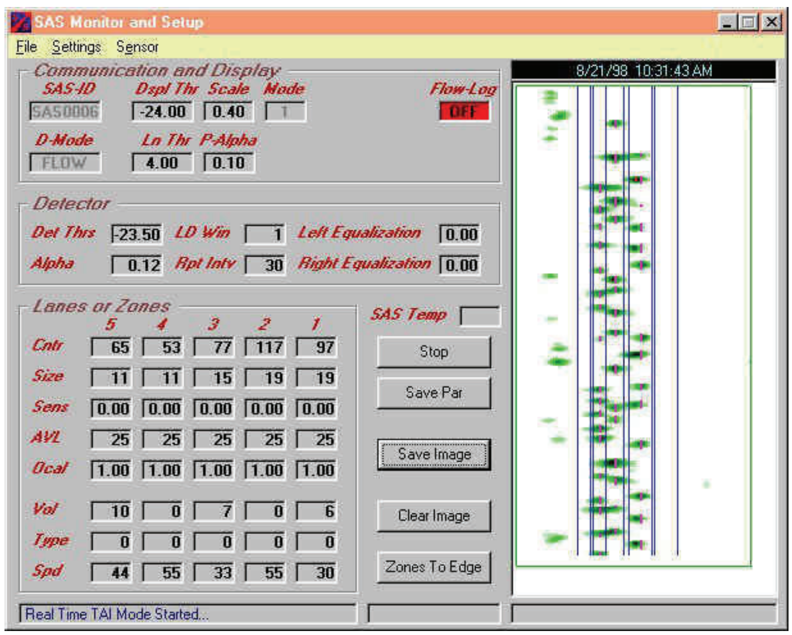


Figure 5-72. SAS-1 acoustic sensor data display (Source: SmarTek Systems, Inc., *SAS-1 Specifications*, Woodbridge, VA).

SENSOR COMBINATIONS

The ground footprint dimensions for sensors that utilize combinations of different technologies, such as passive infrared and CW Doppler microwave radar, are specified for each sensor as shown in Table 5-24 and Figure 5-73. In this example, the manufacturer recommends mounting the sensor above the center of the monitored lane facing approaching traffic with the top surface of the unit horizontal or parallel to the road surface if an incline is present.(45) The infrared presence zone is activated as soon as the front of a vehicle enters this portion of the footprint and remains activated until the vehicle leaves. The switching output of the dynamic infrared zone remains activated as long as there is movement detected in this area. The radar measures high to medium speed vehicles and is used by the infrared sensor for speed calibration. Data are output through a serial interface that usually requires driver software to be written by the user agency.

Table 5-24. ASIM DT 281 dual-technology passive infrared and CW Doppler radar sensor footprint dimensions.

Mounting height (m)	5	6	7	8
Doppler radar footprint length (m)	9.0	10.5	12.5	14.0
Doppler radar footprint width (m)	2.2	2.6	3.0	3.5
Passive infrared footprint length (m)	4.0	4.5	5.2	6.0
Passive infrared footprint width (m)	0.8	1.0	1.2	1.5

1 m = 3.28 ft

(*From*: ASIM Technologies, Ltd., *DT 281 data sheet*, Uznach, Switzerland.)

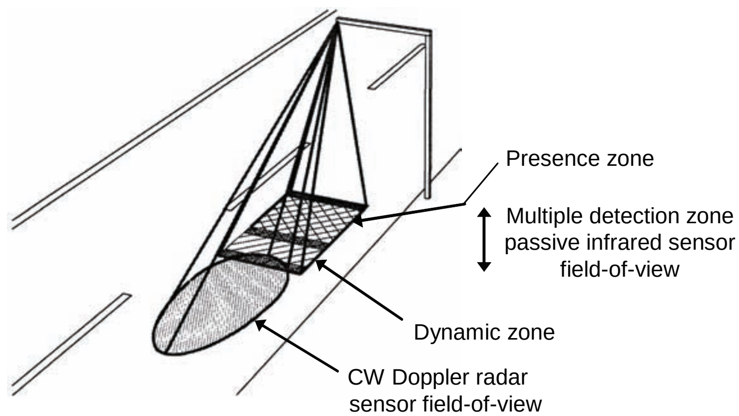


Figure 5-73. ASIM DT 281 dual technology passive infrared and CW Doppler microwave sensor ground footprints. (*Source*: ASIM Technologies, Ltd., *DT 281 data sheet*, Uznach, Switzerland.)

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CHAPTER 6. SENSOR MAINTENANCE

Maintenance is essential for successful traffic signal and freeway surveillance and management systems operation over time.

Use of appropriate sensor installation techniques and specification of suitable materials and products will minimize maintenance and other life cycle costs. However, even with superior design and installation, systems do not operate as intended for extended periods if maintenance is not provided. Therefore, proper and regularly scheduled sensor maintenance is critical to effective and prolonged operation of traffic signal control systems and freeway surveillance and management systems.

Many factors can contribute to lack of maintenance. 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 a cost consciousness that frequently focuses only on initial cost, rather than on lifetime cost. Consequently, less expensive products, materials, and processes are used in the original installation because of their lower initial cost. However, this is not always a cost effective life-cycle solution.

While funding problems might not be easily resolved, they may be ameliorated by increased attention to cost effectiveness in all phases of design, installation, operation, and maintenance. Staffing concerns related to numbers and skill levels of maintenance personnel may be reduced somewhat by selecting only equipment that can be realistically maintained by available agency personnel or local contractors.

This chapter is designed to assist maintenance operations managers, supervisors, and technicians in identifying and resolving maintenance-related issues. Design engineers and those responsible for installation and operations should be fully aware of the cause-and-effect relationship between their activities and maintenance issues.

A number of excellent reference sources address the maintenance process. These include the ITE *Traffic Signal Installation and Maintenance Manual,*[(1)] the TRB publication, *Maintenance Management of Traffic Signal Equipment and Systems,*[(2)] and the FHWA *Traffic Control Devices Handbook*.[(3)]

NATURE OF THE PROBLEM

Sensor maintenance issues associated with inductive-loop detectors have changed considerably over the years. For example, the inductive-loop detector electronics unit, which formerly accounted for a considerable portion of sensor malfunctions, has matured to the point where many currently available digital models seldom experience failure. As stressed continually throughout this handbook, proper installation using appropriate materials and processes is the key to longer sensor system life, lower failure rates, and reduced required maintenance.

There is little question that sensor malfunctions and associated signal failures increase motorists' time and delay, maintenance costs, accidents, and liability. For example, a simple failure of an inductive-loop detector can cause 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 inductive-loop detector fails without a call, the most common temporary response 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.

FAILURE MODES IN INDUCTIVE-LOOP DETECTOR SYSTEMS

When an inductive-loop 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 cause.

FAILURE MECHANISMS

A failure mechanism may be defined as the malfunction that is observed in the operation of an inductive-loop detector system. The following are common failure mechanisms.

Omitted Phase

An omitted phase occurs when the signal does not service one phase because of the lack of a call from the electronics unit. This is usually caused by a loop failure. Some early electronics units with solid-state outputs would fail in the open position, resulting in no call to the controller. Newer models have circuitry that provides a continuous call if the loop circuit is incomplete. (See "Phase Extending to Maximum.")

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 sensor system, but by a controller failure. On occasion, a vehicle not being properly detected may cause a stuck signal. Another cause of a stuck signal is an inductive-loop electronics unit, operating with the delay feature, not retaining the call for a sufficient 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 inductive-loop electronics unit and can generate extra delays of up to one-half the normal daily delay. The continuous call may be the result of a faulty electronics unit or an open loop circuit.

Intermittent Problems

Low sensitivity of the loop or the electronics unit (or a combination of both) can result in intermittent problems. Unstable oscillators in the electronics unit may also cause intermittent problems during periods of rapid temperature shifts. However, many current electronics unit models are capable of retuning. When the problem persists for no apparent reason (called ghost problems), the electronics 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 the process of elimination has determined that the only remaining cause could be a broken wire.

External devices that have been 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 wires. Crosstalk may produce false detections when there are no vehicles in the detection zone. It may also result in lockup 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-induced signal.

Crosstalk occurs when the normal operating frequency of one loop installation is influenced by the frequency of another. This normally arises 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 to each other and electronic coupling exists between the two oscillators. There are numerous sources of electronic coupling. Some of the more common 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 electronics unit.

Splashover

The false detection of vehicles outside the detection zone is called splashover. This problem often occurs when long loops are operated at a sensitivity level required to detect small vehicles (i.e., motorcycles). With this high 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 Appendix M, surveys of traffic agencies indicate that there are eight major causes of loop failure. These are:

- Pavement cracking and moving.
- Breakdown of wire insulation.
- Poor sealants or inadequate sealant application.
- Inadequate splices or electrical connections.
- Damage caused by construction activities.
- Improper electronics unit tuning.
- Electronics unit failure.
- Lightning/electrical surges.

FACTORS AFFECTING REQUIRED MAINTENANCE

Many agencies report that most of their maintenance problems involving inductive-loop detectors can be directly attributed 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 personnel to install inductive-loop detector systems. In these cases, the contract to install the systems is usually awarded to the lowest bidder. The lowest-bidder concept has been successful in encouraging competitive bidding and generally lowering costs. To be effective, however, a procuring agency must apply stringent prequalification guidelines to avoid awarding the contract to an electrical contractor with inadequate experience or knowledge.

If inspection is inadequate, the potential for contractor expediency and error is enormous. The consequences of improper shortcuts or errors may not surface until the contractor’s responsibility has elapsed and, therefore, the loop must 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, IL, IDOT maintains more than 18,000 inductive-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.[4]

TROUBLESHOOTING PROCEDURES FOR INDUCTIVE-LOOP DETECTORS

The analysis of a malfunctioning inductive-loop detector can be a difficult task. The root cause of the failure may be associated with environmental conditions or other factors attributed to installation. The technician analyzing a faulty inductive-loop system should consider all the causes of failures listed above. Initially, of course, it is necessary to isolate the problem to one associated with the sensor system.

An experienced technician is frequently able to pinpoint the troubled area or faulty part by visual examination. Figure 6-1 shows a readily apparent pavement failure along the saw slot, which has exposed loop wires. When visual inspection does not immediately disclose the problem, systematic troubleshooting is required. Such procedures for identifying and correcting malfunctioning inductive-loop detector systems are discussed below.

Figure 6-1. Pavement failure near an inductive-loop installation.

SAWCUT MAINTENANCE

The hostile street environment makes the loop wire the most vulnerable component of an inductive-loop detector system. Therefore, a scheduled visual inspection of the roadway at and around the sawcut should be conducted every 6 months 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. Loops with exposed or shallow-buried wires should be replaced. The early detection and correction of saw slot problems can prevent many future inductive-loop detector system malfunctions.

Unstable, cracked or deteriorating sealant should be removed with a blunt instrument. The slot should be blown clean with compressed air and new sealant poured over the old. This is especially important in areas where snow removal equipment is used and salt applications are prevalent.

Potholes within the loop area should also be repaired. The two major factors influencing quality pothole patching are material selection and repair procedures. Thus, these factors control the cost effectiveness of the overall patching operation through associated material, labor, and equipment costs. The combinations of materials and procedures that produce optimum cost effectiveness vary from agency to agency.[5]

Materials available for pothole repair in asphalt concrete include stockpiled cold mix materials, spray-injection heated emulsions, and hot mix asphalt concrete. FHWA reports provide detailed instructions for repairing potholes and spalls in asphalt surfaced pavements and portland cement concrete. (See references 5–10.)

REARRANGEMENT OF LOOP CONNECTIONS

A low value of inductance is the usual cause for inadequate loop sensitivity to detect a vehicle. Low inductance can 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 any of these factors are present in a multiple-loop configuration, the condition can be temporarily corrected by removing the defective loop from operation.

Multiple loops can be connected in series or series/parallel to maintain an equivalent inductance within the range needed by the electronics unit. Quantitative measurements are made to determine if the inductance of a malfunctioning system has dropped below the acceptable value. Several test meters are commercially available to measure inductance. Some of these perform direct measurements, while others measure frequency, which is inversely related to the inductance value. In the latter case, accompanying charts or graphs are used to determine inductance.

ELIMINATING CROSSTALK

Crosstalk may occur when any of the following conditions are present:

- Two loop lead-in cables share a common conduit.
- Operations occur at close to the same frequencies.
- Cable shields are not properly connected.
- Two loops are installed within a few feet of each other.
- Two sets of lead-in wires occupy the same saw slot.
- 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 using high-quality soldered joints, soldering of all crimp connections, minimizing the number of joints, using high-quality connectors and replacement if worn, using safeguards against corrosion, tightening terminal block screws, and twisting and 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 electronics unit 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 electronics units, 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 electronics units; and frequency separation.
- **Grounding the lead-in cable shield at controller cabinet field terminals:** A potential solution is to use the three-terminal connection illustrated in Figure 5-35. The first step in the procedure consists of stripping the insulation on the individual lead-in cables back a maximum of 2 to 3 inches (5 to 8 cm) and then grounding each lead-in cable independently.
- **Coupling between closely spaced harness wires from the field terminals to the electronics unit:** The solution is to use either shielded twisted cable with proper grounding of the shield or twisted wire pair.

Caltrans uses a modified loop tester and the following four-step procedure for identifying and correcting crosstalk:(11)

1. Using the auxiliary input to the tester, measure the operating frequency of the inductive-loop detector suspected of crosstalk.
2. If the operating frequencies of two or more inductive-loop 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 electronics units have a range switch or other means of selecting frequencies, adjust the frequencies so that at least 2 kHz separates operating frequencies.
4. If adjustments cannot be made, adding parallel capacitors to the field terminals may shift the operating frequencies. A quality capacitor such as one made of polycarbonate or ceramic should be used to assure good temperature stability. The capacitance value should be adequate to shift the resonant frequency by about 2 kHz. This procedure cannot be used with electronics units where the operating frequency is independent of loop inductance. Some manufacturers do not approve of adding capacitance external to the electronics unit because temperature-stable capacitors are difficult to procure and are still prone to value change with rapid temperature shifts.

If wire loops are causing the crosstalk, they can be reassigned to different channels or the lead-in wires in the pull box can be retwisted and respliced, thus eliminating one cause for potential crosstalk.

To identify which electronics unit is cross talking, one general procedure is to disconnect all units except those that have the most frequent false calls. If no new false calls or lockups occur, then crosstalk from another unit is indicated. By selectively reconnecting the other electronics units, the unit causing the crosstalk between wire loops can be identified.

Specific multichannel electronics units have a scanning feature that reduces potential crosstalk. In these units, the sequential scanning system activates one loop channel at a time, while the remaining loops, connected to other channels, are deenergized and thus unable to provide coupling to the active channel. This does not, however, eliminate crosstalk between channels on different electronics units. Frequency separation will reduce crosstalk between adjacent loops as well as other wire loop detectors.

SUBSTITUTION OF ELECTRONICS UNITS

Experience indicates that older electronics units cannot be freely substituted for each other. Tests in Los Angeles, CA, revealed that "…there are some brands of electronics units 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."[(12)] 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. Newer electronics units having the same characteristics and quality can generally be interchanged without problem, since different manufactured units operate on different frequencies; however, any unit that passes the NEMA tests can usually be interchanged.

Each unit within an agency's inventory should be checked for sensitivity to ensure that all electronics units achieve minimum sensitivity. After this check has been made, the substitution process can be used to determine if the electronics unit at the malfunctioning installation is the cause of the failure. Thus, if the electronics unit is replaced and the system functions normally, this may indicate a failure in the electronics unit. Conversely, if loop system operation does not improve with the substituted unit, then the original unit is reinserted and another problem source determined.

Since many malfunctions are crosstalk-related, any change that affects the loop frequency will improve the situation, at least temporarily. Therefore, substitution of another unit, even of the same model and frequency setting, will often return the loop to normal operation due to small differences in the values of the input capacitors in the electronics unit. Substitution of a different model (especially from a different manufacturer) is often successful due to differences in front-end electronics design. The best solution is to eliminate, to the maximum practical extent, those elements that contribute to crosstalk.

OPERATIONAL CHECK OF MALFUNCTIONING INDUCTIVE-LOOP DETECTOR

Several operational checks can be conducted to expedite analysis of a malfunctioning inductive-loop detector system. These checks can be performed utilizing a maintenance vehicle and a vehicle simulator that 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 electronics unit. The sensitivity is then adjusted so that the maintenance vehicle does not cause an output. However, the sensitivity must not be set too low to prevent the electronics unit from detecting a small vehicle in the detection zone.

It should be noted that this procedure does not test the worst case. The worst case occurs when several vehicles are stopped in the adjacent lane and occupy the entire length of the long loop.

Several loop configurations avoid or minimize adjacent lane detection, e.g., a series of small loops, quadrupole loops, adjustable diamond loops, and others that are described in Chapter 4. When it is not possible to change loop configurations, delay timing can be utilized to detect a vehicle only if it is in the detection zone for a specified amount of time (say, 5 seconds). With this approach, passing vehicles in an adjacent lane are not detected, although stopped vehicles may present a signal large enough to hold the call in the empty lane.

Intermittent Operation

The beginning of loop failure is often associated with intermittent operation. As stated 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 electronics unit to lock up when a motor vehicle passes over the point of the fault.

To identify this problem, the operation of the inductive loop 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 them with a 500-volt megger and a low-ohm midscale ohmmeter.

System Sensitivity

A simulated vehicle that represents the smallest detectable vehicle can be used to determine if the inductive-loop system sensitivity is in balance and to determine the minimum sensitivity required of the system. The same procedure can also be used to test new installations. Caltrans uses a shorted-turn vehicle model to simulate a 100 cc Honda motorcycle. The simulator is placed in the detection zone, and the electronics unit is observed to determine if the vehicle is detected. Reference 11 provides the construction details and procedures for using this model.

The simulated vehicle is utilized 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 taken.

The difference between the two frequencies provides a measure of the change in inductance due to the presence of the vehicle according to:

$$\Delta f/f = 0.5\ \Delta L/L. \qquad (6\text{-}1)$$

This is an approximate relationship valid for changes in inductance up to 10 percent and for loop quality factor Q greater than 5. This equation shows that the percent change in inductance is twice the percent change in frequency as was discussed in Chapter 2.

ELECTRICAL TESTING OF AN INDUCTIVE-LOOP DETECTOR SYSTEM

Table 6-1 identifies several malfunctions that occur in inductive-loop detector operation and their causes. Potential causal factors for each listed malfunction are identified by an "X" in the appropriate table cell. Maintaining the correct resistance values and knowledge of the inductance values required for proper operation of the electronics units will eliminate many of the problems associated with loop performance.

Table 6-1. Inductive-loop detector malfunctions and potential causes.

Malfunction / Potential cause	No call	Constant call	False call	Drifting	Crosstalk	Will not tune	Unbalanced sensitivity
Low quality factor		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
Electronics unit malfunction	X	X	X	X		X	

Four devices are needed to analyze loop systems:

- High voltage resistance tester (megger) to measure insulation resistance.
- Frequency tester, inductive-loop analyzer (such as the model illustrated in Figure 6-2) or inductance meter to measure inductance.
- Digital VOM to measure series resistance.
- Low-ohm (measurement range ≈ 2 to 3 ohms) midscale ohmmeter to measure the dynamic change in the series resistance.

Low resistance-to-ground and high series resistance are major contributors to 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 can be avoided if, during installation, the materials are handled properly and appropriate splice sealing methods are followed. Low resistance-to-ground can also occur when wires are exposed as a result of pavement cracking, sealant cracking, frost action, and wear to pavement from studded tires. 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.

Poor splices, corroded or loose screw terminals, poor crimping, or inadequate wire size can cause high series resistance. High series resistance is a problem exacerbated by humidity, temperature, and vibration, which cause drifting and false calls. These are the same problems that occur when the system has low resistance-to-ground.

Figure 6-2. Model ILA-550 inductive-loop system analyzer. Measures the leakage resistance of a loop to ground at 500 V dc; frequency and relative signal strength of a loop network; loop inductance, resistance, and *Q*; and change in inductance caused by vehicle driving over a loop (Photo courtesy of US Traffic Corp., Santa Fe Springs, CA).

TEST PROCEDURES

The following equipment is required to isolate the causes of erratic operation or malfunction of an inductive-loop detector system using the procedures discussed below:[(12)]

- Ohmmeter, battery operated.
- Voltmeter (ac), high-impedance input to 100 kHz.
- Digital frequency counter, input impedance > 50 Kohms to 200 Kohms.
- Quality factor test meter.

- Loop test meter.
- Data recording forms for quality factor Q and sensitivity S, samples of which are illustrated in Figures 6-3 and 6-4, respectively.
- Vehicle simulator, sensitivity standard.

QUALITY FACTOR (*Q*)

Location: ______________________________ Date: _______________________

Description: ____________________________ By: _________________________

Loop 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, respectively; BW = bandwidth = $f_h - f_l$; Q calculated = f_r/BW; R_P = resistance to ground.

Figure 6-3. Quality factor *Q* data form.

SENSITIVITY (*S*)

Location: ______________________________ Date: _______________________

Description: ____________________________ By: _________________________

Loop Position	Sensitivity Standard	f_r (kHz)	f_2 (kHz)	$f_2^2 - f_r^2$ (kHz)	Sensitivity *S* (%)	Presence (minutes)	Remarks

Analysis:

f_r = resonant or tuning frequency; f_2 = loop frequency with test standard or vehicle;
S = $[(f_2^2 - f_r^2)/f_2^2]$ x 100 = change in inductance in percent.

Figure 6-4. Sensitivity *S* data form.

Figure 6-5 shows a loop finder, which can be used to locate a loop when pavement overlays cover the loop installation.

Figure 6-5. Loop finder.

Sequential Test Procedure

The six steps described below assist in isolating the causes of inductive- loop detector system malfunction or erratic operation.

Step 1. Conduct Visual Inspection

Check for indication of broken or cut loop or lead-in wires. Check for open leads within the controller and for the connection of the power source to the electronics unit.

Step 2. Check Operation of Inductive-Loop Electronics Unit

To eliminate the electronics unit as the source of the problem, replace the existing 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. As discussed above, substitution of an electronics unit, even of the same model and frequency switch settings, will frequently be successful in eliminating the problem due to subtle differences in the values of electronics unit input capacitors. Therefore, substitution of electronics units may solve the problem temporarily without addressing the real problem. If the problem is crosstalk-related, the most effective solution is to identify and eliminate the causes of the crosstalk.

Step 3. Measure Parameters Needed To Determine Quality Factor Q

Measure and record the following data on the quality factor data form.

- With the electronics unit disconnected and power removed from the loop, measure the resistance from either loop terminal to the bus or conduit ground. Record as R_P on the quality factor data form. Check for series continuity between the terminals.
- With the loop test meter attached to the controller tie points and the electronics unit 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 of the loop system, follow the procedure described below and record the results on the quality factor data form:

- 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}.
- Successively increase and decrease the frequency 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 Q, where $BW = f_h - f_l$ and $Q = f_r/BW$.

Step 5. Measure Sensitivity of Inductive-Loop System

Record the frequencies obtained from either of the following methods on the sensitivity data form.

Method 1

- 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 electronics unit to the new resonant point and record as f_2.
- Calculate the sensitivity as shown on the data form.

Method 2

- Set the function switch to "INTERNAL" and the mode switch to "*S*" on the *Q* test unit.
- Allow the electronics unit 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 on the data form.

Step 6. Analysis

Perform the analysis by comparing the measured values for each of the items with the values shown in the "Indicated Conditions" column in Table 6-2. Determine the required maintenance from the suggested "Corrective Actions" listed in the table.

MAGNETOMETER SYSTEM MAINTENANCE

Conventional magnetometer systems are composed of the sensor probe, probe cable, lead-in cable, and the electronics unit. The same precautions should be observed for the probe cable and lead-in (home run) cable as with an inductive-loop detector lead-in wire and lead-in cable. Magnetometers that transmit data via RF transmission to the electronics unit do not require a probe cable, but do need a lead-in cable that connects the antenna (that receives the transmitted data) to the electronics unit in the controller cabinet. A magnetometer probe cable, when required, is placed in a slot in the road surface and should be sealed with the same care and procedures as used for inductive-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

Four key areas can affect the operation of a magnetometer system. These are proper burial depth of the sensor 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

Vertical placement of the probe is critical to system performance. Deep placement of approximately 24 inches (60 cm) will provide good single-count detection, but will result in lower signal levels. Shallow placement of about 6 inches (15 cm) will provide a stronger signal, but will also increase the potential for double counting. Therefore, the burial depth must be appropriate for the intended application, as described in Chapters 4 and 5.

Probe Movement

Probes must be firmly supported in their holes. Any displacement of the vertical alignment of the probes may result in performance instability. A recommended installation approach is to utilize PVC conduit as a shell, with sand tamped around the probe to prevent lateral displacement.

Probe Cable

Water-blocked cable must be used to prevent moisture penetration. Any moisture can cause excessive capacitance or leakage between wires or to ground. In addition, moisture across the connections to a magnetometer may induce drift. Wherever possible, it is recommended that the probe cable run directly to the electronics unit, thus eliminating splices. If this is not possible, splices must be electrically sound and environmentally protected.

Table 6-2. Inductive-loop detector troubleshooting guide.[a]

Item	Indicated conditions	Corrective actions
Loop wires	Broken, cut, or exposed insulation worn away	Install new loops shifted by 6 inches (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 Patch street surface if loop wire is not exposed
Resistance to ground	100 MΩ (megohms) 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
Quality factor	>5 if R_P >100 MΩ <5 for any other value of R_P	Acceptable with modern electronics units Replace electronics unit
Sensitivity of loop system	Measures lower than design value for the configuration	Consider Q, shunt R_P, and series R_S as possible causes and correct as indicted Determine loop interconnection and rework to accepted design values
Sensitivity of electronics unit	Remains actuated Does not actuate Insufficient sensitivity	Substitute known serviceable electronics unit Substitute known serviceable electronics unit Substitute and return unit removed to shop

[a] The limiting values in the table are nominal values determined from the original investigation. They may require modification to incorporate additional experience.

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 inductive-loop sawcut, any cracking or deteriorating sealant should be chipped away, blown clean, and replaced with new sealant.

TROUBLESHOOTING PROCEDURES

The initial step for troubleshooting problems with magnetometer systems is to visually inspect all system components, 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 components should be examined for loose connections, poor sealant, exposed wires, bad splices, or evidence of recent construction.

If none of these elements show evidence of problems, the next step is to examine the probe for tilting. Without retuning the electronics unit, use a bar magnet oriented in a direction which adds to 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 electronics 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 with 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, MD.[13] This device has automatic compensating circuitry, which is incorporated into the electronics unit. It works similarly to an inductive-loop detector in tracking environmental changes. One of these devices is required for each channel in the electronics unit.

If detection does not occur during the test for tilting, the problem could be in the cable, wire, probe, splice, or electronics unit. Series resistance and resistance-to-ground measurements should then be made at the controller cabinet with a VOM. 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 VOM read. This should be repeated with the bottom two wires. If these values are high, the lead-in cable should be replaced. If not, the problem originates in the splice and a proper reconnection of the splice is needed to 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 consist of cable encased in underground conduit, the opportunity for failure is relatively small. User surveys indicate that these sensors 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 electronics unit. When false responses occur (the electronics unit 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 unit was at fault. If the system still does not work, a series resistance test followed by a resistance-to-ground test is required. This should identify any leakage in the system.

The total circuit resistance-to-ground of the detector 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. Proper cable layout and good splicing can avoid this condition. Occasionally, one probe circuit will pick up more extraneous signal than another probe circuit on the same phase. If this occurs, interchange probes at the terminal strip so that the probe circuit picking up the largest extraneous signal is at the “Magnetic Detector Minus” side of the system.

If the voltmeter needle moves erratically when there are no vehicles passing the probes, it generally indicates surges in nearby power wires. If the probe can be located closer to traffic, the sensitivity of the electronics unit can be decreased to reduce the effect of power lines. Changing the orientation of the detector axis can eliminate or minimize the effect of a particular power line. For minimum disturbance, the detector axis should be parallel to the power lines.

Relay units are designed to be immune to all line voltage changes except extreme ones. If line voltage changes are suspected of causing the voltmeter needle to behave in an erratic manner, disconnect the “Magnetic Detector Plus” and the “Magnetic Detector Minus” leads, and short them together. If the voltmeter needle is still erratic, the trouble is due to line voltage changes. In this case, examine the power service connections to make sure they are properly soldered and insulated. If there are no obvious problems, request that the power company check the regulation of the power being supplied and make any necessary modifications to their equipment.

If the voltmeter needle tends to behave erratically 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 is steady when the electronics unit operates with the detector leads shorted and tends to be erratic when the signal lights change with the detectors reconnected, then 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 capacitors are in place across the terminals to which the magnetic detectors are connected, as these capacitors are designed to absorb such surges.

Fluctuations on the neutral power wire with respect to ground might also cause intermittent response. A connection to a conducting rod driven into the ground (required in most modern installations) can stabilize this condition. If the connections are stable, check for leakage in the detector circuit by making the same tests that were described above with a VOM.

Other problems could involve induced voltage response, which can occur when the detector leads are placed in the conduit with the power supply leads. Induced voltage can cause false responses. Consequently, the lead-in cable should not be inserted into conduit with other signal wiring. Another cause of false response is setting the gain too high. Reducing the gain on the electronics unit will generally solve this problem.

OVER-ROADWAY SENSOR MAINTENANCE

Maintenance and life cycle costs may be determined, in part, by published values of the mean time between failures. Some over-roadway sensors are designed with mean time between failures of 64,000 to 90,000 hours. The effects of lightning strikes and other natural or human-induced failure modes are not included in this number. Thus, maintenance and replacement costs for these devices may be significantly less than for inductive loops over a 10-year period, especially if commercial vehicle loads, poor subsoil, inclement weather, and utility improvements frequently require road resurfacing and loop replacement.

Some agencies require lane closures at night and traffic diversion for installing or repairing in-roadway sensors on freeways. Such requirements create significant differences between the cost of freeway and arterial sensor maintenance. Other maintenance items, such as electronics unit retuning, are generally not needed with over-roadway sensors. However, new maintenance requirements, such as camera lens cleaning, can arise.

VIDEO IMAGE PROCESSORS

The most pervasive maintenance operation for video image processors is the periodic cleaning of the camera lens. The cleaning frequency varies from six months to one year, depending on the camera mounting height, the truck traffic volume, and precipitation and dust characteristics of the monitored area. Cleaning may be performed by the agency responsible for traffic management or may be contracted out. Cameras mounted on the tallest poles (e.g., 70 feet (21 m)) may require more specialized boom trucks for cleaning.

MICROWAVE RADAR SENSORS

Radar sensors do not appear to require much maintenance. EIS Electronic Integrated Systems Inc., the manufacturer of the RTMS, reports that of 624 units shipped to one North American client, 10 (or 1.6%) were returned for repair from April 1994 through June 2002.

MAINTENANCE COST COMPARISONS AMONG SENSOR TECHNOLOGIES

A 10-year study of inductive-loop maintenance costs in Houston, TX, found as few as 42 failures and as many as 341 failures per year in the 600 to 1000 intersections maintained during the 1989–1998 study period. The calculated loop replacement costs per intersection varied from $107 to $628 (U.S.).[14] Actual costs per intersection are probably higher because the calculation assumes all intersections had loops (some were not actuated and hence did not use loops), 100 percent of loop failures were discovered (some were not), and no maintenance besides replacement was performed.

In a summary of maintenance costs of four Autoscope VIP systems used by the Road Commission of Oakland County, MI, TTI found that monthly camera maintenance averaged $5.05 and monthly processor maintenance averaged $26.71 from 1995 through 1998. A total of 692 cameras and 194 controllers were included in the study. Costs included labor, fringe benefits, and truck, lift, and radio equipment. Because the VIPs were under warranty for at least part of the time, the manufacturer or distributor paid for some repair parts and new replacement units. Therefore, older units whose warranty period has expired may experience higher maintenance costs.[14]

Table 6-3 compares the annualized per-lane cost for inductive-loop detectors, VIPs, multiple detection zone presence-detecting microwave radar, and acoustic array sensors for a six-lane freeway sensor station.[14] Motorist delay and excess fuel consumption incurred during installation further add to the annualized cost of the inductive loops.

Table 6-3. Annualized per-lane sensor cost comparison to instrument a six-lane freeway sensor station.[14]

Sensor	Number required for 6 lanes	Expected life	Annualized cost
ILD	12	10	$746
VIP	2 cameras, 1 processor	10	$580
Multidetection zone microwave presence-detecting radar	1	7[a]	$314
Acoustic array	6	5	$486

[a] Manufacturer's mean time between failures suggests a 10-year expected life.

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APPENDIX A. INDUCTIVE-LOOP SYSTEM EQUIVALENT CIRCUIT MODEL

ABSTRACT

Appendix A describes the derivation and application of an equivalent circuit model and computer program that calculates the apparent self-inductance and quality factor versus frequency of square, rectangular, quadrupole, and circular loops of round wire buried in a roadway. The effects of transmission lines and matching transformers between the loop in the roadway and roadside electronics units are 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.

The equivalent electrical circuit model for an inductive-loop system allows the loop's inductance and quality factor to be calculated.

Inductive-loop detectors are commonly used in actuated and computer-controlled traffic surveillance systems. The size, shape, and number of turns of wire in the loop should be designed to provide adequate vehicle detection sensitivity and prevent the lead-in wire and lead-in cable from reducing sensitivity. The inductance value at the input to the electronics unit must be within the range specified by the unit's manufacturer. The computer program described in this appendix allows engineers to calculate the apparent loop inductance and quality factor versus operating frequency (20–60 kHz) for selected loop size, shape, wire diameter, number of turns, turn spacing, slot width, pavement loss tangent, and slot sealant dielectric constant.

INTRODUCTION

An inductive-loop detector system is composed of a buried loop of wire in the roadway pavement, which is connected with a transmission line (i.e., lead-in wire and lead-in cable) to a roadside electronics unit. When a vehicle is sensed by the loop, a small decrease in loop inductance is detected by the electronics unit. Furthermore, since the series inductance of the transmission line decreases the magnitude of the inductance change at the input to the electronics unit, the loop inductance should be larger than the transmission line series inductance. The loop inductance can be increased by winding additional turns into the loop and adding a transformer between the loop and transmission line.

The frequency range of typical electronics units is 20–60 kHz, although newer units that provide vehicle classification can operate at hundreds of kilohertz. Loop capacitance can cause the inductance sensed by the electronics unit to change significantly with frequency if too many turns are used in the roadway loop. To better predict inductive-loop system performance, an equivalent circuit model of the loop system was developed and programmed on a computer. The computer program allows inductive-loop system designers and maintenance technicians to calculate the detection system inductance and quality factor as a function of frequency, wire gauge size, wire spacing, etc.

The equivalent loop system model contains 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 elsewhere.[1,2] King describes the calculation of the self-inductance of circular loops.[3] This appendix expands the model to include the internal and external capacitance of such loops so that the high-frequency performance of the loop system can be calculated. A wideband transformer model is used. The transmission line model incorporates a complex characteristic impedance. All equations used in the loop computer program are included in this appendix.

LOOP CAPACITANCE THEORY

INTERNAL-LOOP CAPACITANCE

The stray capacitance between turns of wire in an inductive loop is calculated using a multilayer transformer model.

The capacitance between loop turns is calculated using a low-frequency, multilayer, transformer model.[4] The model assumes uniform flux coupling through the loop turns with minimum leakage flux. Figure A-1 illustrates the capacitance between two adjacent isolated loop turns.

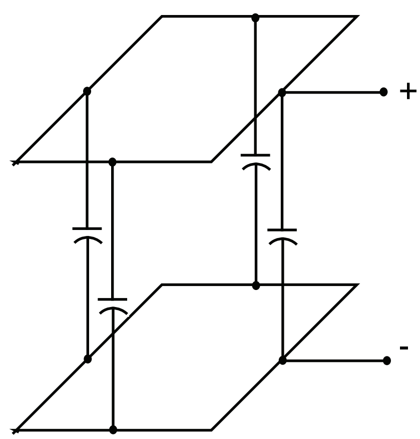

Figure A-1. Capacitance between adjacent isolated loop turns.

The loop wires are modeled as parallel transmission lines that have a capacitance per unit length C' of[5]

$$C' = \frac{(\varepsilon/\varepsilon_0) \times 10^{-9}}{36 \cosh^{-1}(D/2a)} \text{ F/m} \quad \text{(A-1)}$$

where

D = spacing between conductor centers (m)

a = conductor radius (m)

$\varepsilon/\varepsilon_0$ = relative dielectric constant of the material that surrounds the turns of wire (equal to 1 for air)

ε_0 = permittivity of free space = 8.854 x 10^{-12} F/m.

The total capacitance between adjacent but isolated loop turns is given by

$$C^i = C' P, \quad \text{(A-2)}$$

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 A-2.

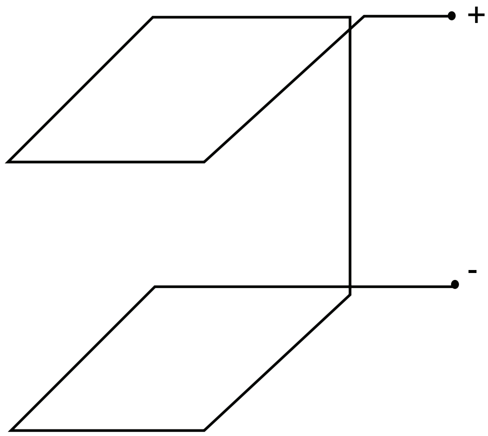

Figure A-2. Connection of adjacent loop turns.

The parallel transmission line is shorted at the end. The input capacitance of the shorted transmission line is given by

$$C_T^i = \int_0^P \left(\frac{X}{P}\right)^2 C'\,dx = \frac{1}{3} C' P \,. \tag{A-3}$$

Figure A-3 shows the circuit model for a multiturn loop, where L_L represents the low-frequency inductance of the loop and $C_L{}^i$ the lumped internal capacitance across the loop terminals.

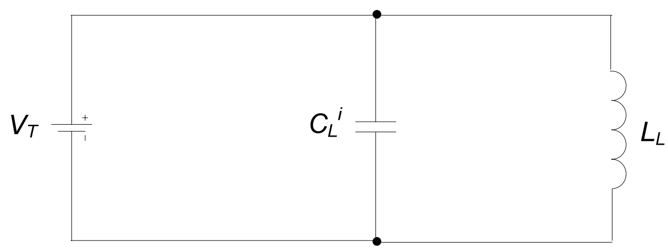

Figure A-3. Multiturn loop equivalent circuit model.

The total internal energy stored in the capacitor is

$$E_T = \frac{1}{2} C_L^i V_T^2 = \frac{1}{2}\left(\sum_{j=2}^{n} C_j^i V_j^2\right) . \tag{A-4}$$

When the voltage drop is linear, the voltage across each turn is directly proportional to the total voltage drop and inversely proportional to the number of turns. Accordingly,

$$V_j = \frac{2}{n} V_T \tag{A-5}$$

and

$$C_L^i = \sum_{j=2}^{n} \left[\frac{C' P}{3} \left(\frac{2}{n} \right)^2 \right] \tag{A-6}$$

where n is equal to the number of loop turns.

The lumped internal capacitance across the loop terminals is given by

$$C_L^i = \frac{4}{3}\frac{(n-1)}{n^2}C'P \quad . \tag{A-7}$$

This equation is identical to the equation for the capacitance between transformer winding layers with the exception of C'.[7]

EXTERNAL-LOOP CAPACITANCE

External capacitance is created when a conductor is located in the vicinity of a dielectric material. This does not occur when a conductor is placed near another conducting surface such as a metal. Figure A-4 illustrates capacitive coupling between turns of loop wire (i.e., the conductor) and the edge boundaries of a sawcut or sealant (i.e., the dielectric). The dielectric constant of the material surrounding the wire is denoted by ε and its conductivity by σ. Since loop wires are typically closer to the top of the slot (i.e., sealant in the bottom of the slot supports the loop wire), the capacitive coupling between the wire and bottom of the slot was neglected.

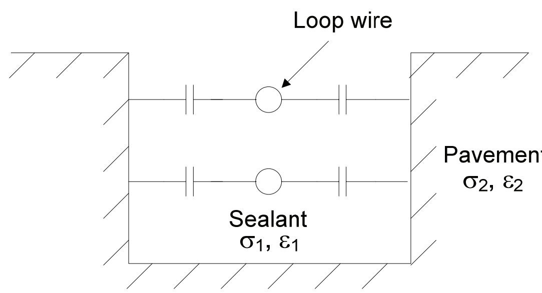

Figure A-4. Capacitance between loop conductors and slot.

Galejs determines the impedance of a buried insulated wire.[8] The capacitance is calculated assuming the region surrounding the slot or cavity is finitely conducting. If region one is composed of low-loss dielectric, we can write[9]

$$\left|j\omega\varepsilon_1\right| > \sigma_1 \quad . \tag{A-8}$$

Stratton also shows that a perfectly conducting outer conductor, as found in a coaxial line, provides a good approximation to a finitely conducting one when calculating shunt admittance.[10] The slot walls are approximated by infinitely conducting ground planes, as illustrated in Figure A-5. These observations allow the combination of a coaxial conductor and TEM transmission line for use in modeling the capacitance of loop wires embedded in a slot.

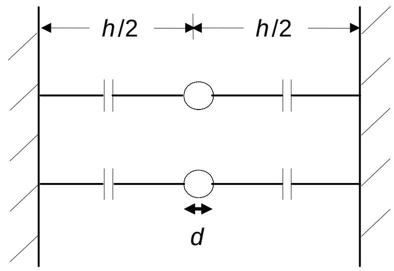

Figure A-5. Capacitance between loop conductors and infinitely conducting planes.

The characteristic impedance Z_0 of a coaxial conductor is given by[11]

$$Z_0 = \frac{138}{\sqrt{e_r}} \log_{10}\left(\frac{4h}{\pi d}\right) \quad \text{(A-9)}$$

where

h = sawcut slot width

d = diameter of loop wire.

The capacitance per unit length of a TEM transmission line is expressed as

$$C' = \frac{120\pi \varepsilon_0 \sqrt{\varepsilon_r}}{Z_0} \quad . \quad \text{(A-10)}$$

Thus

$$C' = \frac{2\pi \varepsilon_0 \varepsilon_r}{\ln\left(\frac{4h}{\pi d}\right)} \quad \text{(A-11)}$$

or

$$C' = \frac{1}{18} \frac{\varepsilon_r \times 10^{-9}}{\ln\left(\frac{4h}{\pi d}\right)} \text{ F/m} \quad \text{(A-12)}$$

where $\ln(x) = (2.303)[\log_{10}(x)]$.

The total external capacitance for the loop conductor is

$$C = C'P \quad . \quad \text{(A-13)}$$

Inductive loops are typically balanced, as shown in Figure A-6.

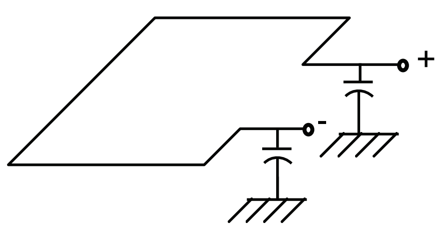

Figure A-6. Balanced inductive loop.

Because of the balanced configuration and zero potential point at the conductor perimeter center,

$$C_1 = C_2 = \left(\frac{C'}{3}\right)\left(\frac{P}{2}\right) = \frac{C'P}{6} \quad . \qquad \text{(A-14)}$$

Thus

$$C_L^e = C_1 \| C_2 = \frac{C'P}{12} \qquad \text{(A-15)}$$

where $C_1 \| C_2$ denotes the parallel connection of C_1 and C_2.

If only one side of the loop is grounded, then

$$C_L^e = \frac{C'P}{3} \quad . \qquad \text{(A-16)}$$

LOOP RESISTANCE THEORY

LOOP RESISTANCE

The series loop resistance R_L is composed of the direct-current wire resistance R, the high-frequency skin-effect resistance R_{ac}, and the ground resistance R_g. The dominant 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 large moisture content. Ground resistance is calculated by assuming that the pavement and subgrade materials cause a magnetic loss similar to that of a ferrite or iron core in an inductor. The permeability μ_g of the pavement and subgrade material is assumed to be one. Appendix A-1, of this Appendix A, contains a derivation of the ground resistance.

The series loop resistance R_L is expressed as

$$R_L = R + R_{ac} + R_g \qquad \text{(A-17)}$$

where

R = direct-current loop resistance (Ω)

R_{ac} = skin-effect resistance (Ω)

R_g = ground resistance (Ω)

$$R_g = \omega L_L \tan \delta_g \qquad \text{(A-18)}$$

$\tan\delta_g$ = loss tangent of pavement material

L_L = loop self-inductance (H)

ω = operating radian frequency = $2\pi f$ (radians)

f = operating frequency (Hz).

INTERNAL INDUCTANCE AND RESISTANCE PER UNIT LENGTH FOR A CYLINDRICAL CONDUCTOR

Johnson shows that the ratio of actual internal inductance to low-frequency internal inductance and the ratio of internal resistance to low-frequency internal resistance are given by[12]

$$\frac{L_i}{L_{i0}} = \frac{4}{q}\left[\frac{bei(q) \times bei'(q) + ber(q) \times ber'(q)}{(bei'(q))^2 + (ber'(q))^2}\right] \quad \text{(A-19)}$$

ber(q) is the real part of the complex Bessel function of the first kind. ber'(q) is the first derivative of the real part of the complex Bessel function of the first kind. bei(q) is the imaginary part of the complex Bessel function of the first kind. bei'(q) is first derivative of the imaginary part of the complex Bessel function of the first kind.

and

$$\frac{R}{R_{i0}} = \frac{q}{2}\left[\frac{ber(q) \times bei'(q) - bei(q) \times ber'(q)}{(bei'(q))^2 + (ber'(q))^2}\right] \quad \text{(A-20)}$$

respectively, where

$$q = \frac{a\left(\sqrt{2}\right)}{\delta} \quad \text{(A-21)}$$

L_i = internal inductance (H/m)

a = radius of wire (m)

δ = skin depth (m),

$$\delta = \frac{1}{\sqrt{\mu_r \mu_0 \, \pi \, f \, \sigma}} \quad \text{(A-22)}$$

μ_0 = permeability of free space = $4\pi \times 10^{-7}$ H/m

μ_r = relative permeability of copper wire = 1

f = operating frequency (Hz)

σ = conductivity of copper wire = 0.58×10^{8} mhos/m

L_{i0} = low-frequency internal inductance (H/m),

$$L_{i0} = \frac{\mu_0 \mu_r}{8\pi} \ \text{(H/m)} \quad \text{(A-23)}$$

= 0.5×10^{-7} H/m for copper wire

R_{i0} = low-frequency internal resistance (Ω),

$$R_{i0} = \frac{\rho_r}{\pi \, a^2} \ (\Omega) \quad \text{(A-24)}$$

ρ_r = resistivity (ohm-meter = Ωm)

= 1.74×10^{-8} Ωm for copper wire.

LOOP-INDUCTANCE THEORY

SELF-INDUCTANCE OF SINGLE-TURN CIRCULAR LOOP

The self-inductance L_0 of a single-turn circular loop is given by[14]

$$L_0 = \mu_r \mu_0 (2r - a)\left[\left(1 - \frac{k^2}{2}\right)K(k) - E(k)\right] \quad \text{(A-25)}$$

where

$$k^2 = \frac{4r(r-a)}{(2r-a)^2} \tag{A-26}$$

$E(k)$ = complete elliptic integral of first kind

$K(k)$ = complete elliptic integral of second kind

r = radius of the loop coil relative to an axis normal to the plane of the loop that passes through the center of the loop (m)

a = radius of the loop wire (m).

Therefore, the radius from the axis to the inside edge of the loop wire is $r - a$.

The formula for $E(k)$ is found in Appendix A-3 of this Appendix A.[15]

SELF-INDUCTANCE OF MULTITURN CIRCULAR LOOP

Following King[17], the inductance for a circular coil with N equally spaced identical turns is given by

$$L_T = NL_0 + 2(N-1)M_{12} + 2(N-2)M_{13} + \ldots \tag{A-27}$$

or

$$L_T = NL_0 + 2\sum_{i=1}^{N}(N-i)M_{1,(i+1)} \tag{A-28}$$

where $M_{1,(i+1)}$ is the mutual inductance between turn 1 and turn i+1.

According to Ramo,[18]

$$M = \mu_r \mu_0 \sqrt{r_1 r_2}\left[\left(\frac{2}{k} - k\right)K(k) - \frac{2}{k}E(k)\right] \tag{A-29}$$

$$k^2 = \frac{4r_1 r_2}{d^2 + (r_1 + r_2)^2} \tag{A-30}$$

where

M = mutual inductance (H)

r_1 = radius of turn one (m)

r_2 = 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. Thus

$$L_0^e = L_{pl}^e + L_{p2}^e \, . \tag{A-31}$$

The external inductance of a single turn rectangular loop is[1]

$$L_0^e = \frac{\mu_0}{\pi}\left\{\ell_1 \ln\left[\frac{\ell_1}{a}+\sqrt{1+\left(\frac{\ell_1}{a}\right)^2}\right]-\ell_1 \ln\left[\frac{\ell_1}{\ell_2}+\sqrt{1+\left(\frac{\ell_1}{\ell_2}\right)^2}\right]+\ell_2 \ln\left[\frac{\ell_2}{a}+\sqrt{1+\left(\frac{\ell_2}{a}\right)^2}\right]\right.$$

$$-\ell_2 \ln\left[\frac{\ell_2}{\ell_1}+\sqrt{1+\left(\frac{\ell_2}{\ell_1}\right)^2}\right]-\sqrt{\ell_1^2+a^2}-\sqrt{\ell_2^2+a^2}+2\sqrt{\ell_1^2+\ell_2^2}$$

$$\left.-(\ell_1+\ell_2)+2a\right\} \qquad \text{(A-32)}$$

where

ℓ_1 = width of loop (m)

ℓ_2 = length of loop (m)

a = radius of the conductor (m).

This equation can be written in more compact form by combining the logarithmic terms.

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 inductances as

$$L_0 = L_0^i + L_0^e \qquad \text{(A-33)}$$

$$L_0^i = 2(\ell_1 + \ell_2)L^i \qquad \text{(A-34)}$$

where L^i is given by Equation A-19 and L_0^e is given by Equation A-32.

SELF-INDUCTANCE OF MULTITURN RECTANGULAR LOOP

The self-inductance of a coil with N equally spaced identical turns is given by

$$L_T = NL_0 + 2(N-1)M_{12} + 2(N-2)M_{13} + \ldots \qquad \text{(A-35)}$$

MUTUAL INDUCTANCE OF PARALLEL FILAMENTARY CIRCUITS

The mutual inductance between a pair of filamentary circuits located in free space and illustrated in Figure A-7 is given by[(19)]

$$M(\ell, d) = \pm\frac{\mu_0 \ell}{2\pi}\left\{\ln\left[\frac{\ell}{d}+\sqrt{1+\left(\frac{\ell}{d}\right)^2}\right]-1+\sqrt{\left(\frac{d}{\ell}\right)^2}+\frac{d}{\ell}\right\} \qquad \text{(A-36)}$$

where

μ_0 = permeability of free space = $4\pi \times 10^{-7}$ H/m

ℓ = filamentary length (m)

d = filamentary spacing (m)

$M(\ell,d) =$ mutual inductance (H).

The mutual inductance is positive when the current flow in the filaments is in the same direction and negative when the current flow is in opposite directions.

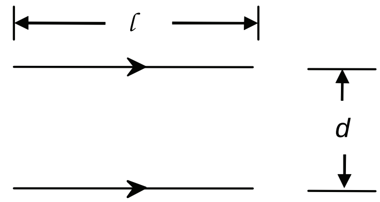

Figure A-7. Pair of parallel current elements.

MUTUAL INDUCTANCE OF TWO COAXIAL AND PARALLEL RECTANGULAR LOOPS

Equation A-36 can be used to calculate the total mutual inductance of the coaxial and parallel rectangular loops displayed in Figure A-8.

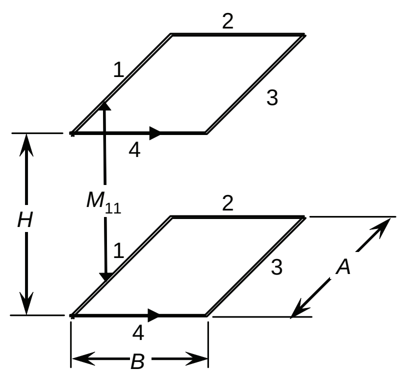

Figure A-8. Geometry for calculating mutual inductance of coaxial and parallel rectangular loops.

Accordingly, the total mutual inductance is given by the sum of the mutual inductances between the parallel sides as

$$M = -2\left[M_{13}\left(A, \sqrt{H^2 + B^2}\right) - M_{11}(A, H) + M_{24}\left(B, \sqrt{H^2 + B_2}\right) - M_{22}(B, H)\right] \quad \text{(A-37)}$$

where M_{11} is the mutual inductance between side 1 of the bottom loop turn and side 1 of the top loop turn. All mutual inductances are symmetrical, e.g., $M_{13} = M_{31}$ and $M_{24} = M_{42}$.

SELF-INDUCTANCE OF MULTITURN QUADRUPOLE LOOP

Figure A-9 illustrates a two-turn quadrupole loop[20] and Figure A-10 a multiturn quadrupole loop.

The external inductance of an N-turn quadrupole loop is

$$L_T = 2NL_0 + 2NM_{12} + 4(N-1)M_{13} + 4(N-1)M_{14} + 4(N-2)M_{15} + 4(N-2)M_{16}\ldots \quad \text{(A-38)}$$

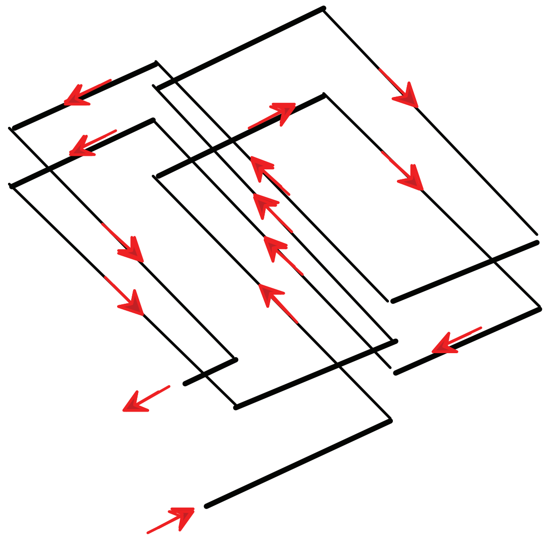

Figure A-9. Two-turn quadrupole loop.

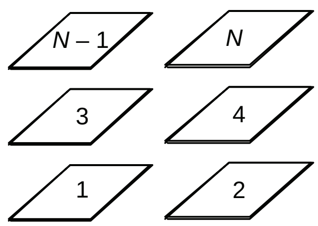

Figure A-10. Multiturn quadrupole loop.

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. In Figure A-11, these filaments are labeled Segment i and Segment k.

Following Jefimenko[(21)], the mutual inductance between the two parallel current filaments illustrated in Figure A-11 is given by

$$M_{ik} = \pm \frac{\mu_0}{4\pi}\left[\ln\left(\frac{(a+A)^a (b+B)^b}{(c+C)^c (d+D)^d}\right) + (D+C) - (B+A)\right]_{ik} \qquad \text{(A-39)}$$

where the positive sign is used for filaments with current flow in the same direction.

This expression assumes that the filament lengths are much less than the wavelength divided by 2π and the conductor radius is much less than the filament length. Grover[(22)] shows that this type of general formula can also be derived by applying the laws of summation of mutual inductance to Equation A-36.

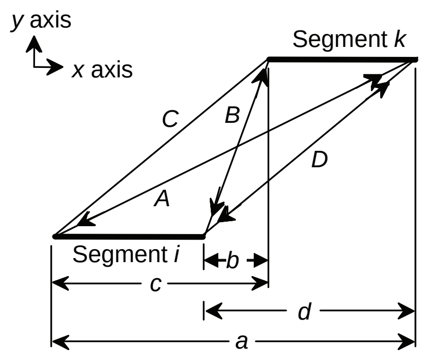

Figure A-11. Mutual inductance of two parallel segments *i* and *k*.

INDUCTIVE-LOOP CIRCUIT MODEL

Figure A-12 illustrates an inductive-loop system electrical circuit model that contains resistive, capacitive, and inductive components.

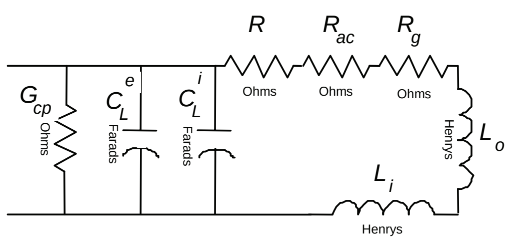

Figure A-12. Inductive-loop system circuit model.

Let

$$L_S = L_0 + L_i \tag{A-40}$$

$$R_S = R + R_g \tag{A-41}$$

$$C_P = C_L^i + C_L^e . \tag{A-42}$$

Following Johnson,[23] the slot dielectric loss conductance is

$$G_P = \omega C_P \tan \delta_c \tag{A-43}$$

where $\tan\delta_c$ is the loss tangent of the slot sealer material.

Appendix A-4, of this Appendix A, shows that the inductive-loop system circuit model of Figure A-12 reduces to the circuit model of Figure A-13, where

$$R_{in}^L = \frac{G_P}{G_P^2 + \left(\omega C_P - \frac{1}{\omega L_P}\right)^2} \tag{A-44}$$

and

$$X_{in}^L = \frac{\frac{1}{\omega L_P} - \omega C_P}{G_P^2 + \left(\omega C_P - \frac{1}{\omega L_P}\right)^2} . \tag{A-45}$$

The loop quality factor is given by

$$Q_{in}^{L} = \frac{X_{in}^{L}}{R_{in}^{L}} = \frac{\frac{1}{\omega L_P} - \omega C_P}{G_P} . \qquad \text{(A-46)}$$

The self-resonant frequency of the loop is given by

$$f_0 = \frac{1}{2\pi}\sqrt{L_P C_P} . \qquad \text{(A-47)}$$

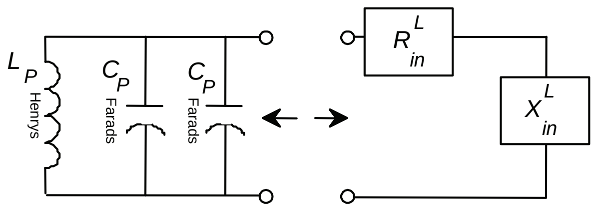

Figure A-13. Equivalent loop circuit model.

LOOP TRANSMISSION LINE THEORY

LOOP TRANSMISSION LINE MODEL

A transmission line connects the roadway loop with the roadside electronics unit. The complex impedance Z_L of the loop is transformed to a complex impedance Z_{in} by the transmission line cable according to[24]

$$Z_{in}^{c} = Z_0 \frac{Z_L + Z_0 \tanh \gamma \ell}{Z_0 + Z_L \tanh \gamma \ell} \qquad \text{(A-48)}$$

where

$$Z_L = R_L + j\,\omega L_L \qquad \text{(A-49)}$$

$$Z_0 = \sqrt{\frac{R + j\,\omega L}{G + j\,\omega C}} \qquad \text{(A-50)}$$

$$\gamma = \sqrt{(R + j\,\omega L)(G + j\,\omega C)} \qquad \text{(A-51)}$$

The ratio of current to voltage is defined as conductance G = i / v. The unit of conductance is the mho (for inverse ohms) and is denoted by an inverted capital omega.

and where

R = transmission line per unit resistance (Ω/m)

G = transmission line per unit conductance (mhos/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 (radians)

ℓ = length of transmission line

γ = complex propagation constant.

A useful equation for computing Z_{in} is given by[25]

$$\tanh(x \pm ky) = \frac{\sinh 2x \pm j \sin 2y}{\cosh 2x + \cos 2y}\ . \quad \text{(A-52)}$$

FREQUENCY SHIFT ELECTRONICS UNIT SENSITIVITY

The frequency shift Δf_D at the terminals of the electronics unit is required to compute the sensitivity of the inductive-loop system as a function of loop and cable inductance.

Let

$$f_V - f_{NV} = -\Delta f_D \quad \text{(A-53)}$$

and

$$f_{NV} = f_D \quad \text{(A-54)}$$

where f_V, f_{NV} are the frequencies measured by the electronics unit with and without a vehicle present.

The sensitivity S_D of the frequency shift electronics unit is defined as

$$\frac{\Delta f_D}{f_D} = -\frac{1}{2} S_D\ . \quad \text{(A-55)}$$

The total inductance L_D at the electronics unit is the sum of the loop and cable inductances given by

$$L_D = L_L + L_C\ . \quad \text{(A-56)}$$

Therefore, the change in inductance created by a vehicle passing over the loop is

$$\Delta L_D = \Delta L_L \quad \text{(A-57)}$$

since it is only the loop inductance that varies in the presence of a vehicle.

To convert the expression for sensitivity in terms of $\Delta f_D/f_D$ to one in terms of $\Delta L_L/L_L$, note that

$$f_D = 1/[2\pi(L_D C_D)^{1/2}]. \quad \text{(A-58)}$$

Thus,

$$\frac{\Delta f_D}{f_D} = -\frac{1}{2}\frac{\Delta L_L}{L_L + L_C}\ . \quad \text{(A-59)}$$

By inspection,

$$S_D = \frac{\Delta L_L}{L_L + L_C}\ . \quad \text{(A-60)}$$

Therefore,

$$S_D = \frac{\Delta L_L}{L_L}\left(\frac{1}{\frac{L_L + L_C}{L_L}}\right) = \frac{\Delta L_L}{L_L}\left(\frac{1}{1 + \frac{L_C}{L_L}}\right) = S_L\left(\frac{1}{1 + \frac{L_C}{L_L}}\right) \quad \text{(A-61)}$$

and Equation A-55 becomes

$$\frac{\Delta f_D}{f_D} = -\frac{1}{2} S_L \left(\frac{1}{1 + \frac{L_C}{L_L}} \right) \quad \text{(A-62)}$$

where

$$S_L = \frac{\Delta L}{L} . \quad \text{(A-63)}$$

Equation A-62 shows that the cable inductance L_C strongly affects the sensitivity of the frequency shift electronics unit. If the cable inductance is one-tenth or less of the loop inductance, the cable has a negligible effect on inductive-loop system sensitivity, provided the quality factor Q_D is five or greater. The frequency shift electronics unit sensitivity results also apply to period shift electronics units.

LOOP TRANSFORMER THEORY

INDUCTIVE-LOOP TRANSFORMER MODEL

A transformer with low leakage inductance (e.g., 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.[26] The transformer will remove the reduction in sensitivity caused by the transmission line.

The transformer model is shown in Figure A-14.[27]

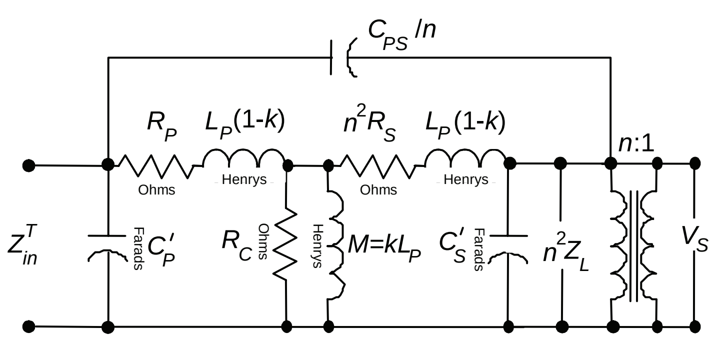

Figure A-14. Loop transformer model.

The definitions of the parameters that appear in Figure A-14 are referred to the primary of the transformer. Thus,

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,

$$C_S' = \frac{C_S}{n^2} + \frac{C_{PS}}{n}\left(\frac{1}{n} - 1\right) \tag{A-64}$$

C_{PS}/n = referred primary to secondary capacitance

C_P' = modified primary capacitance,

$$C_P' = C_P + C_{PS}\left(1 - \frac{1}{n}\right) \tag{A-65}$$

n = ratio of primary to secondary turns,

$$n = \frac{\sqrt{L_P}}{\sqrt{L_S}} \tag{A-66}$$

L_P = open circuit primary inductance at low frequency

$L_P(1–K)$ = one-half total leakage inductance

K = coupling coefficient,

$$K = \frac{M}{\sqrt{L_P L_S}} \tag{A-67}$$

M = mutual inductance.

The equivalent transformer model of Figure A-15 was used to derive an expression for the transformed load impedance Z_{in}^T.

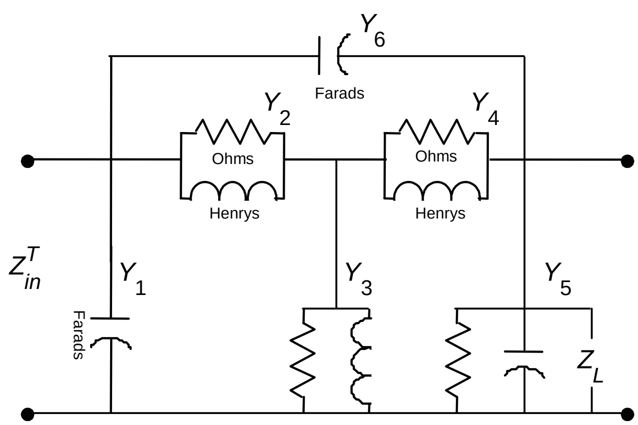

Figure A-15. Equivalent transformer model.

Appendix A-5, of this Appendix A, shows that the transformed load impedance is given by

$$Z_{in}^T = \frac{\left[(Y_2+Y_3+Y_4)(Y_4+Y_5+Y_6)-Y_4^2\right]}{(Y_1+Y_2+Y_3)\left[(Y_2+Y_3+Y_4)(Y_4+Y_5+Y_6)-Y_4^2\right]-2Y_2Y_4Y_6-Y_6^2(Y_2+Y_3+Y_4)-Y_2^2(Y_4+Y_5+Y_6)}. \tag{A-68}$$

LOOP-DETECTOR ANALYSIS SYSTEM PROGRAM

The loop-detector analysis system (LDAS) computer program calculates loop inductance and quality factor for rectangular, quadrupole, and circular loops. The loop inductance and quality factor are transformed by the transmission line (nonshielded, twisted-loop wire) to the roadside junction box and transmission line (shielded, twisted pair) between the junction box and electronics unit in the controller box. The program also models 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 QuickBasic. All mathematical functions are computed using double precision calculations.

COMPARISON OF CALCULATED AND MEASURED LOOP SELF-INDUCTANCE AND QUALITY FACTOR

Table A-1 contains measured self-inductance and quality factor data for a 6- x 6-ft (1.8- x 1.8-m) three-turn inductive loop. The measured and LDAS computed data compare favorably as shown in Table A-2. Measured loop inductance and quality factor data versus frequency were unavailable for quadrupole and circular loops.

Table A-1. Measured inductive-loop parameters of 3-turn 6- x 6-ft (1.8- x 1.8-m) loop with no vehicle present.

f_0 (kHz)	f_2 3dB (kHz)	f_1 3dB (kHz)	$Q = \frac{f_0}{f_2 - f_1}$	C (μF)	$L = \frac{1}{(2\pi f_0)^2 C}$ (μH)	$R = \frac{2\pi f_0 L}{Q}$ (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
60	60.704	59.342	44.1	0.093450	75.3	0.64

Loop size: 6 ft x 6 ft (1.83 m x 1.83 m)
Loop number of turns: 3
Loop wire size: #14 AWG
Loop lead-in length: 60 in (1.5 m)
Loop self-resonant frequency: 697.06 kHz
50 pF residual capacitance in decade box neglected in *C* value

Table A-2. Comparison of measured and computed inductive-loop parameters of 3-turn 6- x 6-ft (1.8- x 1.8-m) loop with no vehicle present.

f_0 (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 are based on:

- Loop size: 6 ft x 6 ft (1.83 m x 1.83 m)
- Pavement loop slot width: 375 mils (0.95 cm)
- Loop slot sealant dielectric constant: 6
- Pavement material loss tangent: 0.01
- Loop wire insulation dielectric constant: 2.5
- Effective loop wire insulation loss tangent: 0.001
- Loop conductor spacing: 200 mils (0.51 cm)
- Wire gauge: #14 AWG

Tables A-3 through A-5 list 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-ft (73.2-m) length approximately halves the quality factor. Inductive-loop detector applications requiring transmission lines over 200 ft (61 m) in length should use number #12 AWG wire for the loop and nonshielded 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.

Table A-3. 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	189.39	22.95

* Transmission line
** Transformer loop

Notes: 1. 20 kHz; loop size:6 ft x 6 ft (1.83 m x 1.83 m); other parameters are the same as those given for Table A-2.
2. All inductance and quality factors in Table A-3 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 (millihenrys)	= 5
Secondary resistance (ohms)	= 1

Secondary capacitance (picofarads) = 10
Primary to secondary turns ratio = 5
Core loss resistance (ohms) = 1,000,000
Coupling coefficient = 0.99
Primary to secondary capacitance (picofarads) = 10

4. Transmission line parameters
   Length = 240 ft (73.2 m)
   Resistance (milliohms/ft) = 2.5 (6.25 milliohms/m)
   Inductance (microhenrys/ft) = 0.22 (0,72 microhenrys/m)
   Conductance (microohms/ft) = 0.000076 (0.000249 microohms/m)
   Capacitance (picofarads/ft) = 26 (85.3 picofarads/m)

Table A-4. Quadrupole-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	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

Notes: 1. 20 kHz; loop size:6 ft x 6 ft (1.83 m x 1.83 m); lateral conductor spacing: 200 mils (0.51 cm), other parameters are the same as those given for Table A-2.
2. All inductance and quality factor values in Table A-4 are apparent values (i.e., the effect of loop capacitance and resistance is included).

Table A-5. Circular-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	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

Notes: 1. 20 kHz; loop diameter: 7 feet (2.1 m); other parameters are the same as those given for Table A-2.
2. All inductance and quality factor values in Table A-5 are apparent values (i.e., the effect of loop capacitance and resistance is included).

CONCLUSIONS

Loop inductance should be measured at 1 kHz to remove effects of capacitance when determining the number of turns in a buried loop. All loop measurements at frequencies of 20 kHz or greater should be made with a balanced instrument since the loop electronics unit is balanced. An unbalanced measurement produces incorrect results because of the different capacitance-to-ground values. Since the external capacitance is determined by the dielectric constant of the slot sealing material, the loop wire should be completely sealed to prevent water from entering the loop slot. The large dielectric constant of water produces a significant change in the external capacitance and causes the apparent loop inductance to change. Thus, unstable loop operation can result from incomplete sealing of the loop sawcut.

APPENDIX A-1

LOOP GROUND-RESISTANCE DERIVATION

The complex impedance Z_L of the loop results from a complex permeability μ_g, where μ_g represents a complex number. The complex impedance is given by

$$Z_L = j\omega\mu_g L_L \quad \text{(A-69)}$$

$$= j\omega(\mu'_g - j\mu''_g)L_L . \quad \text{(A-70)}$$

The material loss tangent, denoted as $\tan\delta_g$, is given by

$$\tan\delta_g = \frac{\mu''_g}{\mu'_g} . \quad \text{(A-71)}$$

Letting $\mu'_g = 1$, the loss tangent becomes

$$\tan\delta_g = \mu''_g . \quad \text{(A-72)}$$

Then

$$Z_L = j\omega(1 - j\tan\delta_g)L_L \quad \text{(A-73)}$$

$$Z_L = \omega\tan\delta_g L_L + j\omega L_L . \quad \text{(A-74)}$$

When the complex impedance is written in the form

$$Z_L = R_g + jX_L , \quad \text{(A-75)}$$

the real and imaginary parts of Z_L become

$$R_g = \omega L_L \tan\delta_g \quad \text{(A-76a)}$$

and

$$X_L = \omega L_L \quad \text{(A-76b)}$$

where R_g is the material ground loss and X_L is the inductive reactance.

APPENDIX A-2

REAL PART OF COMPLEX BESSEL FUNCTION OF FIRST KIND

$$ber\ x = 1 - \frac{\left(\frac{1}{2}x\right)^4}{(2!)^2} + \frac{\left(\frac{1}{2}x\right)^8}{(4!)^2} - \ldots \quad \text{(A-77)}$$

or

$$ber\ x = 1 + \sum_{n=1}^{\infty} (-1)^n \frac{\left(\frac{1}{2}x\right)^{4n}}{(2n!)^2} \quad \text{(A-78)}$$

DERIVATIVE OF REAL PART

$$ber' x = -\frac{\left(\frac{1}{2}x\right)^3}{1!2!} + \frac{\left(\frac{1}{2}x\right)^7}{3!4!} - \frac{\left(\frac{1}{2}x\right)^{11}}{5!6!} + \ldots \qquad \text{(A-79)}$$

or

$$ber' x = \sum_{n=1}^{\infty} (-1)^n \frac{\left(\frac{1}{2}x\right)^{(4n-1)}}{(2n-1)!\,2n!} \qquad \text{(A-80)}$$

IMAGINARY PART OF COMPLEX BESSEL FUNCTION OF FIRST KIND

$$bei\, x = \frac{\left(\frac{1}{2}x\right)^2}{(1!)^2} - \frac{\left(\frac{1}{2}x\right)^6}{(3!)^2} + \frac{\left(\frac{1}{2}x\right)^{10}}{(5!)^2} - \ldots \qquad \text{(A-81)}$$

or

$$bei\, x = \sum_{n=1}^{\infty} -(-1)^n \frac{\left(\frac{1}{2}x\right)^{(4n-2)}}{[(2n-1)!]^2} \qquad \text{(A-82)}$$

DERIVATIVE OF IMAGINARY PART

$$bei' x = \frac{1}{2}x - \frac{\left(\frac{1}{2}x\right)^5}{2!3!} + \frac{\left(\frac{1}{2}x\right)^9}{4!5!} - \ldots \qquad \text{(A-83)}$$

or

$$bei' x = \sum_{n=1}^{\infty} -(-1)^n \frac{\left(\frac{1}{2}x\right)^{(4n-3)}}{(2n-2)!\,(2n-1)!} \qquad \text{(A-84)}$$

APPENDIX A-3

COMPLETE ELLIPTIC INTEGRAL OF FIRST KIND

$$K(k) = \frac{\pi}{2} \prod_{m=0}^{\infty} (1 + k_{m+1}) \qquad \text{(A-85)}$$

$$k_{m+1} = (1 - k_{m'})/(1 + k_{m'}) \qquad \text{(A-86)}$$

$$k_{m'} = \sqrt{1 - k_m^2} \qquad \text{(A-87)}$$

$$k_0 \equiv k \qquad \text{(A-88)}$$

COMPLETE ELLIPTIC INTEGRAL OF SECOND KIND

$$E(k) = \frac{\pi}{2(1-k)}\left[1 + \frac{k^2}{2^2} + \frac{1^2}{2^2 \times 4^2}k^4 + \frac{1^2 \times 3^2}{2^2 \times 4^2 \times 6^2}k^6 + \ldots\right] \qquad \text{(A-89)}$$

or

$$E(k) = \frac{\pi}{2(1-k)}\left[1 + \sum_{N=1}^{\infty}\left[\frac{(2N-3)!!}{(2N)!!}\right]^2 k^{2N}\right] \quad \text{(A-90)}$$

$$k = (1-k')/(1+k') \quad \text{(A-91)}$$

$$k' = \sqrt{1-m} \quad \text{(A-92)}$$

$$M = k^2 \quad \text{(A-93)}$$

where $2N!! \equiv 2^N N!$.

APPENDIX A-4

SERIES TO PARALLEL CIRCUIT TRANSFORMATION

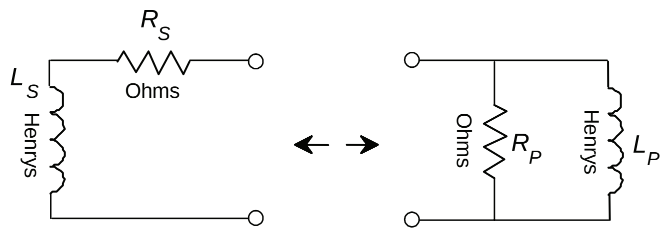

Figure A-16. Series-circuit to parallel-circuit equivalency (general).

From Figure A-16,

$$Z_{in} = R_S + j\,\omega L_S \text{ and } Y_{in} = \frac{1}{R_P} - j\frac{1}{\omega L_P} \quad \text{(A-94)}$$

setting

$$\frac{1}{Z_{in}} = Y_{in}, \quad \text{(A-95)}$$

we find

$$R_P = \frac{R_S^2 + \omega^2 L_S^2}{R_S} \quad \text{(A-96)}$$

and

$$L_P = \frac{R_S^2 + \omega^2 L_S^2}{\omega^2 L_S}. \quad \text{(A-97)}$$

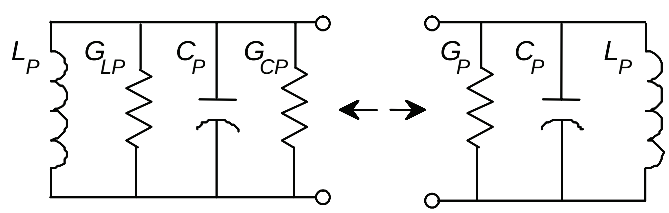

Figure A-17. Loop-series to parallel-circuit equivalency.

From Figure A-17,

$$G_P = G_{LP} + G_{CP} \quad \text{(A-98)}$$

$$Y_{in}^{L} = G_P + j\left(\omega C_P - \frac{1}{\omega L_P}\right) \quad \text{(A-99)}$$

$$Z_{in}^{L} = \frac{1}{Y_{in}} \; . \quad \text{(A-100)}$$

APPENDIX A-5

TRANSFORMER MODEL INPUT IMPEDANCE

The transformed load impedance shown in equation A-68 is derived from nodal analysis of the transformer model. The transfer function is defined as the ratio of the output of a system to the input. It is thus used to find the output of a system or module for a given input.

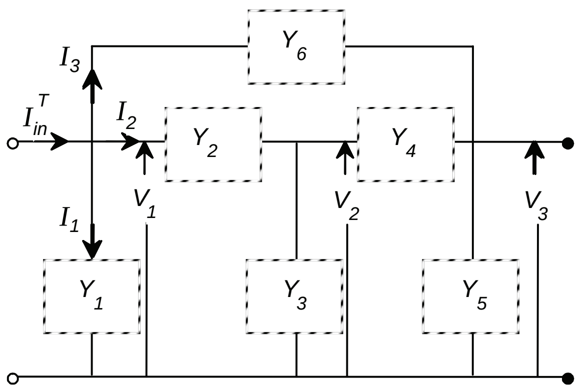

Figure A-18. Transformer nodal analysis diagram.

From Figure A-18, we find

$$\begin{bmatrix}1\\0\\0\end{bmatrix} = \left[\begin{pmatrix}Y_1+Y_2+Y_6\\ -Y_2\\ -Y_6\end{pmatrix}\begin{pmatrix}-Y_2\\ Y_2+Y_3+Y_4\\ -Y_4\end{pmatrix}\begin{pmatrix}-Y_6\\ -Y_4\\ Y_4+Y_5+Y_6\end{pmatrix}\right]\begin{bmatrix}V_1\\V_2\\V_3\end{bmatrix} \quad \text{(A-101)}$$

$$I_{in}^{T} = I_1 + I_2 + I_3 \quad \text{(A-102)}$$

$$I_{in}^{T} = Y_1V_1 + Y_6(V_1 - V_3) + Y_2\,(V_1 - V_2) \quad \text{(A-103)}$$

$$Z_{in}^{T} = \frac{V_1}{I_{in}} = \frac{1}{Y_1 + Y_6\left(1 - \frac{V_3}{V_1}\right) + Y_2\left(1 - \frac{V_2}{V_1}\right)} \quad \text{(A-104)}$$

$$\begin{bmatrix}V_1\\V_2\\V_3\end{bmatrix} = \begin{bmatrix}Y_{11} & Y_{12} & Y_{13}\\ Y_{21} & Y_{22} & Y_{23}\\ Y_{31} & Y_{32} & Y_{33}\end{bmatrix}^{-1}\begin{bmatrix}1\\0\\0\end{bmatrix} = \begin{bmatrix}Y_{11}' & Y_{12}' & Y_{13}'\\ Y_{21}' & Y_{22}' & Y_{23}'\\ Y_{31}' & Y_{32}' & Y_{33}'\end{bmatrix} = \begin{bmatrix}1\\0\\0\end{bmatrix} \quad \text{(A-105)}$$

$$V_1 = Y_{11}{'} = \frac{V_{22}Y_{33} - Y_{23}Y_{32}}{|Y|} \quad \text{(A-106)}$$

$$V_2 = Y_{21}' = \frac{-(V_{21}Y_{33} - Y_{23}Y_{31})}{|Y|} \qquad \text{(A-107)}$$

$$V_3 = Y_{31}' = \frac{V_{21}Y_{32} - Y_{22}Y_{31}}{|Y|} \qquad \text{(A-108)}$$

where

$$Y_{21} = -Y_2 \qquad \text{(A-109)}$$

$$Y_{22} = Y_2 + Y_3 + Y_4 \qquad \text{(A-110)}$$

$$Y_{23} = -Y_4 \qquad \text{(A-111)}$$

$$Y_{31} = -Y_6 \qquad \text{(A-112)}$$

$$Y_{32} = -Y_4 \qquad \text{(A-113)}$$

$$Y_{33} = Y_4 + Y_5 + Y_6 \,. \qquad \text{(A-114)}$$

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APPENDIX B. CURRENT SHEET FORMULA FOR CALCULATION OF LOOP INDUCTANCE

A formula for calculating the inductance produced by a rectangular current sheet is given by[(1)]

$$L = 0.004\pi N^2 \left(\frac{a\ a_1}{b} \right) F' \ \mu\text{H} \qquad \text{(B-1)}$$

where

$$F' = \beta_1\ \gamma + \beta_1'\ \gamma\ \ln\left(\frac{1}{\gamma}\right) + \beta_2\ \gamma^2 + \beta_3\ \gamma^3 - \beta_5\ \gamma^5 + \ldots \qquad \text{(B-2)}$$

$$\gamma = \left(\frac{b}{a}\right) = \left(\frac{\text{length} \cdot \text{of} \cdot \text{current} \cdot \text{sheet}}{\text{longer} \cdot \text{side} \cdot \text{of} \cdot \text{rectangle}}\right) \qquad \text{(B-3)}$$

N = number of turns and

a_1 = length of shorter side of loop.

The term, "length of current sheet," is defined as the axial length of a coil or solenoid. For an inductive loop, the length of the current sheet is equivalent to the height of the wires in the slot, as described in the sample calculation that follows. Since the length of the current sheet is very small compared to the longer side of the rectangle, γ is also very small. The factor F' adjusts for the fact that inductive loops perform as very short solenoids (i.e., the loop area is much greater than the turn spacing).

Inductive loops are modeled as very short solenoids.

The values of β are obtained from Table B-1. The factor K that appears in the table is given by

$$K = \left(\frac{a_1}{a}\right) \qquad \text{(B-4)}$$

Table B-1. Values of β coefficients for short rectangular solenoids.[(2)]

K	β_1	β_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	

Table B-1. Values of β coefficients for short rectangular solenoids (continued).

K	β_1	β_1'	β_2	β_3	β_5	β_7
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	22.5480	497.36	14280.00

SAMPLE INDUCTANCE CALCULATION

An example from reference 1 is used to demonstrate the calculation of the self inductance for a short, three-turn, 6- by 6-foot (1.8- by 1.8-m) loop, using the current sheet model described above.

The following parameters are used:

$a_1 = 6 \text{ ft} = 182.88 \text{ cm}$

$a = 6 \text{ ft} = 182.88 \text{ cm}$

$N = 3 \text{ turns}$

$P = \text{turn spacing} = 150 \text{ mils} = 0.381 \text{ cm}$

$b = N\,P = (3)(0.381) = 1.143 \text{ cm}$

$$\gamma = \left(\frac{b}{a}\right) = 1.143/182.88 = 0.00625 \text{ cm}$$

$$K = \left(\frac{a_1}{a}\right) = 1.$$

From Table B-1,

$\beta_1 = 0.4622$

$\beta_1' = 0.6366$

$\beta_2 = 0.2122$

$\beta_3 = -0.0046$

$\beta_5 = 0.0046$

$\beta_7 = -0.0382.$

Solving Equation B-2 for F' yields

$$F' = \beta_1\,\gamma + \beta_1'\,\gamma\,\ln\left(\frac{1}{\gamma}\right) + \beta_2\,\gamma^2 + \beta_3\,\gamma^3 - \beta_5\,\gamma^5 + \ldots \qquad \text{(B-5)}$$

$$F' = 0.0029 + 0.0200 + 8.16 \times 10^{-6} = 0.0229 \qquad \text{(B-6)}$$

where

$$\ln\left(\frac{1}{\gamma}\right) = 5.0754\,. \qquad \text{(B-7)}$$

Using Equation B-1, the inductance of the loop is found as

$$L = 0.004\,\pi\,N^2\left(\frac{a\;a_1}{b}\right)F'\;\;\mu\text{H} \qquad \text{(B-8)}$$

or

$$L = 0.004\pi(3^2)(182.88*182.88/1.143)(0.0229) = 75.8\;\mu\text{H}. \qquad \text{(B-9)}$$

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APPENDIX C. LOOP INDUCTANCE AND QUALITY FACTOR TABLES

ABSTRACT

Loop inductance and quality factor values calculated for rectangular, quadrupole, and circular loops at excitation frequencies of 1, 20, 40, and 60 kHz are given in these tables. The frequency *f* at which the values apply is shown as part of the table title. The appropriate length or diameter of the loop is given in the first column, while the number of turns is stated in the first row.

Detector loops are in fact very short solenoids.

Rectangular and quadrupole loop inductance and quality factor values for 6-ft (1.8-m) wide loops are displayed for 6–20-ft (1.8–6.1-m) loop lengths in 1-ft (0.3-m) increments and for 20–50-ft (6.1–15.2-m) loop lengths in 5-ft (1.5-m) increments. Circular loop inductance and quality factor values are listed for loop diameters of 4, 5, 6, 7, and 8 feet (1.2, 1.5, 1.8, 2.1, and 2.4 m, respectively). All tables show inductance and quality factor values for 1 through 7 turns of wire.

The loop inductance shown in these tables is the *apparent loop inductance value* expressed in μH that includes loop resistance and capacitance effects. It thus represents the value which the user will actually measure when an appropriate measuring instrument is used.

Inductance values shown in the tables are apparent or measured values that include loop resistance and capacitance effects.

Table C-1. Rectangular-loop inductance in μH at f = 1 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	10.53	36.02	74.46	124.67	185.81	257.24	338.44
7 (2.1)	11.52	39.49	81.72	136.94	204.23	282.91	372.40
8 (2.4)	12.51	42.94	88.94	149.12	222.52	308.38	406.08
9 (2.7)	13.50	46.38	96.12	161.25	240.71	333.71	439.58
10 (3.0)	14.48	49.80	103.28	173.32	258.83	358.94	472.94
11 (3.3)	15.46	53.22	110.42	185.37	276.90	384.09	506.20
12 (3.7)	16.44	56.63	117.54	197.39	294.93	409.19	539.38
13 (3.9)	17.42	60.04	124.65	209.39	312.93	434.25	572.51
14 (4.3)	18.40	63.44	131.76	221.38	330.91	459.27	605.59
15 (4.6)	19.37	66.84	138.85	233.35	348.87	484.27	638.63
16 (4.9)	20.35	70.23	145.95	245.32	366.81	509.24	671.64
17 (5.2)	21.32	73.63	153.03	257.27	384.74	534.09	704.63
18 (5.5)	22.30	77.02	160.12	269.22	402.66	559.13	737.59
19 (5.8)	23.27	80.41	167.20	281.16	420.57	584.06	770.54
20 (6.1)	24.25	83.80	174.27	293.10	438.47	608.97	803.47
25 (7.6)	29.12	100.74	209.63	352.73	527.89	733.42	967.96
30 (9.1)	33.98	117.66	244.95	412.31	617.22	857.75	1132.29
35 (10.7)	38.84	134.57	280.25	471.85	706.51	982.00	1296.52
40 (12.2)	43.71	151.48	315.55	531.38	795.76	1106.21	1460.70
45 (13.7)	48.57	168.38	350.83	590.89	885.00	1230.40	1624.85
50 (15.2)	53.43	185.28	386.11	650.39	974.22	1354.56	1788.98

Table C-2. Rectangular-loop quality factor at *f* = 1 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	1.07	1.81	2.48	3.09	3.67	4.21	4.72
7 (2.1)	1.08	1.83	2.51	3.14	3.72	4.27	4.79
8 (2.4)	1.09	1.85	2.54	3.17	3.76	4.32	4.85
9 (2.7)	1.09	1.87	2.56	3.20	3.80	4.36	4.90
10 (3.0)	1.10	1.88	2.58	3.22	3.83	4.40	4.94
11 (3.3)	1.11	1.89	2.59	3.24	3.85	4.43	4.97
12 (3.7)	1.11	1.90	2.61	3.26	3.87	4.45	5.00
13 (3.9)	1.11	1.91	2.62	3.28	3.89	4.47	5.03
14 (4.3)	1.12	1.91	2.63	3.29	3.91	4.49	5.05
15 (4.6)	1.12	1.92	2.64	3.30	3.92	4.51	5.07
16 (4.9)	1.12	1.92	2.65	3.31	3.94	4.53	5.09
17 (5.2)	1.13	1.93	2.65	3.32	3.95	4.54	5.11
18 (5.5)	1.13	1.93	2.66	3.33	3.96	4.56	5.12
19 (5.8)	1.13	1.94	2.67	3.34	3.97	4.57	5.14
20 (6.1)	1.13	1.94	2.67	3.35	3.98	4.58	5.15
25 (7.6)	1.14	1.96	2.70	3.38	4.02	4.62	5.20
30 (9.1)	1.15	1.97	2.71	3.40	4.05	4.66	5.23
35 (10.7)	1.15	1.98	2.73	3.42	4.07	4.68	5.26
40 (12.2)	1.15	1.98	2.73	3.43	4.08	4.70	5.28
45 (13.7)	1.16	1.99	2.74	3.44	4.09	4.71	5.30
50 (15.2)	*1.16*	1.99	2.75	3.45	4.10	4.72	5.31

Table C-3. Rectangular-loop inductance in μH at f = 20 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	10.50	35.96	74.39	124.62	185.85	257.48	339.07
7 (2.1)	11.49	39.43	81.65	136.90	204.32	283.27	373.23
8 (2.4)	12.48	42.88	88.87	149.10	222.66	308.88	407.26
9 (2.7)	13.46	46.31	96.05	161.24	240.92	334.37	441.10
10 (3.0)	14.44	49.73	103.21	173.34	259.12	359.80	474.86
11 (3.3)	15.42	53.15	110.35	185.42	277.28	385.17	508.58
12 (3.7)	16.40	56.56	117.48	197.47	295.41	410.53	542.29
13 (3.9)	17.37	59.96	124.60	209.51	313.54	435.87	576.01
14 (4.3)	18.35	63.36	131.71	221.54	331.65	461.22	609.76
15 (4.6)	19.32	66.75	138.82	233.57	349.76	486.58	643.54
16 (4.9)	20.30	70.15	145.92	245.59	367.87	511.95	677.38
17 (5.2)	21.27	73.54	153.02	257.61	385.99	537.35	711.28
18 (5.5)	22.24	76.93	160.12	269.62	404.11	562.78	745.24
19 (5.8)	23.21	80.32	167.21	281.65	422.25	588.24	779.28
20 (6.1)	24.19	83.71	174.31	293.67	440.40	613.73	813.41
25 (7.6)	29.04	100.65	209.79	353.85	531.41	741.89	985.51
30 (9.1)	33.90	117.58	245.31	414.22	622.99	871.46	1160.59
35 (10.7)	38.75	134.52	280.89	474.83	715.29	1002.77	1339.33
40 (12.2)	43.60	151.47	316.54	535.75	808.46	1136.14	1522.43
45 (13.7)	48.45	168.43	352.28	597.01	902.63	1271.89	1710.61
50 (15.2)	53.30	185.41	388.13	658.67	997.93	1410.37	1904.64

Table C-4. Rectangular-loop quality factor at *f* = 20 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	15.61	24.06	30.40	35.41	39.51	42.95	45.87
7 (2.1)	15.75	24.28	30.67	35.73	39.85	43.30	46.24
8 (2.4)	15.86	24.46	30.90	35.98	40.12	43.59	46.52
9 (2.7)	15.95	24.61	31.08	36.18	40.35	43.81	46.75
10 (3.0)	16.03	24.73	31.23	36.36	40.53	44.00	46.93
11 (3.3)	16.10	24.84	31.36	36.50	40.68	44.16	47.08
12 (3.7)	16.15	24.93	31.48	36.63	40.82	44.29	47.21
13 (3.9)	16.20	25.01	31.58	36.74	40.93	44.40	47.31
14 (4.3)	16.25	25.08	31.66	36.83	41.03	44.49	47.39
15 (4.6)	16.29	25.14	31.74	36.92	41.11	44.57	47.46
16 (4.9)	16.32	25.20	31.81	36.99	41.18	44.64	47.51
17 (5.2)	16.36	25.25	31.87	37.06	41.25	44.69	47.55
18 (5.5)	16.39	25.30	31.93	37.12	41.30	44.74	47.59
19 (5.8)	16.41	25.34	31.98	37.17	41.35	44.78	47.61
20 (6.1)	16.44	25.38	32.02	37.22	41.39	44.81	47.62
25 (7.6)	16.54	25.53	32.20	37.39	41.53	44.88	47.59
30 (9.1)	16.60	25.63	32.31	37.48	41.58	44.85	47.44
35 (10.7)	16.65	25.71	32.38	37.53	41.57	44.74	47.18
40 (12.2)	16.69	25.76	32.43	37.54	41.51	44.57	46.84
45 (13.7)	16.72	25.80	32.46	37.53	41.42	44.34	46.43
50 (15.2)	16.75	25.83	32.47	37.49	41.29	44.07	45.95

Table C-5. Rectangular-loop inductance in μH at f = 40 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	10.44	35.86	74.28	124.61	186.13	258.43	341.24
7 (2.1)	11.43	39.33	81.55	136.94	204.76	284.58	376.22
8 (2.4)	12.41	42.77	88.78	149.19	223.28	310.63	411.12
9 (2.7)	13.39	46.20	95.97	161.40	241.75	336.65	446.04
10 (3.0)	14.37	49.62	103.14	173.59	260.21	362.21	481.07
11 (3.3)	15.34	53.03	110.30	185.76	278.66	388.76	516.24
12 (3.7)	16.32	56.43	117.45	197.92	297.14	414.92	551.61
13 (3.9)	17.29	59.83	124.60	210.09	315.64	441.17	587.21
14 (4.3)	18.26	63.23	131.74	222.27	334.18	467.54	623.08
15 (4.6)	19.23	66.62	138.88	234.46	352.77	494.04	659.24
16 (4.9)	20.20	70.02	146.03	246.66	371.42	520.68	695.72
17 (5.2)	21.17	73.41	153.18	258.89	390.13	547.49	732.56
18 (5.5)	22.14	76.81	160.33	271.13	408.91	574.47	769.77
19 (5.8)	23.11	80.20	167.48	283.40	427.76	601.63	807.38
20 (6.1)	24.07	83.59	174.64	295.69	446.70	628.99	845.42
25 (7.6)	28.91	100.57	210.56	357.63	542.74	769.19	1043.04
30 (9.1)	33.75	117.57	246.71	420.50	641.54	916.19	1255.80
35 (10.7)	38.58	134.62	283.16	484.52	743.73	1071.72	1488.10
40 (12.2)	43.42	151.72	319.96	549.90	849.98	1237.75	1745.46
45 (13.7)	48.25	168.88	357.16	616.85	961.04	1416.63	2035.03
50 (15.2)	53.09	186.12	394.82	685.62	1077.75	1611.21	2366.36

Table C-6. Rectangular-loop quality factor at *f* = 40 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	22.45	33.19	40.64	46.18	50.48	53.89	56.63
7 (2.1)	22.63	33.46	40.95	46.51	50.80	54.19	56.89
8 (2.4)	22.78	33.67	41.19	46.76	51.05	54.41	57.07
9 (2.7)	22.90	33.85	41.39	46.97	51.24	54.57	57.18
10 (3.0)	23.01	33.99	41.56	47.13	51.38	54.68	57.24
11 (3.3)	23.09	34.12	41.70	47.27	51.50	53.76	57.26
12 (3.7)	23.17	34.23	41.82	47.38	51.59	54.80	57.24
13 (3.9)	23.24	34.32	41.92	47.47	51.65	54.82	57.19
14 (4.3)	23.30	34.41	42.01	47.55	51.70	54.82	57.12
15 (4.6)	23.35	34.48	42.08	47.61	51.73	54.80	57.02
16 (4.9)	23.39	34.54	42.15	47.66	51.75	54.76	56.90
17 (5.2)	23.44	34.60	42.21	47.70	51.75	54.71	56.77
18 (5.5)	23.48	34.65	42.25	47.73	51.74	54.64	56.61
19 (5.8)	23.51	34.70	42.30	47.75	51.72	54.56	56.44
20 (6.1)	23.54	34.74	42.33	47.76	51.69	54.46	56.25
25 (7.6)	23.67	34.90	42.45	47.75	51.44	53.83	55.08
30 (9.1)	23.76	35.00	42.48	47.61	51.01	52.96	53.59
35 (10.7)	23.82	35.05	42.45	47.39	50.46	51.89	51.80
40 (12.2)	23.87	35.09	42.28	47.10	49.78	50.64	49.74
45 (13.7)	23.91	35.10	42.27	46.74	49.00	49.21	47.41
50 (15.2)	23.94	35.09	42.14	46.33	48.11	47.61	44.82

Table C-7. Rectangular-loop inductance in μH at f = 60 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	10.40	35.79	74.25	124.77	186.85	260.30	345.26
7 (2.1)	11.38	39.25	81.53	137.19	205.75	287.11	381.59
8 (2.4)	12.36	42.69	88.78	149.56	224.60	313.94	418.12
9 (2.7)	13.34	46.12	96.00	161.90	243.46	340.88	454.97
10 (3.0)	14.31	49.54	103.21	174.24	262.36	367.98	492.24
11 (3.3)	15.28	52.95	110.41	186.59	281.34	395.31	530.03
12 (3.7)	16.25	56.36	117.61	198.96	300.41	422.89	568.41
13 (3.9)	17.22	59.76	124.81	211.37	319.59	450.76	607.46
14 (4.3)	18.19	63.16	132.02	223.81	338.89	478.96	647.24
15 (4.6)	19.16	66.57	139.24	236.29	358.34	507.52	687.83
16 (4.9)	20.12	69.97	146.47	248.83	377.94	536.47	729.31
17 (5.2)	21.09	73.37	153.70	261.41	397.71	565.85	771.74
18 (5.5)	22.05	76.78	160.96	274.06	417.66	595.69	815.22
19 (5.8)	23.02	80.18	168.23	286.77	437.80	626.02	859.83
20 (6.1)	23.98	83.59	175.51	299.55	458.15	656.87	905.65
25 (7.6)	28.81	100.67	212.62	364.62	563.43	820.32	1156.67
30 (9.1)	33.63	117.83	249.52	432.01	675.89	1003.04	1456.51
35 (10.7)	38.45	135.10	287.53	502.29	797.51	1211.88	1828.33
40 (12.2)	43.28	152.49	326.39	576.05	930.74	1456.41	2312.27
45 (13.7)	48.11	170.04	366.24	653.98	1078.66	1750.56	2979.87
50 (15.2)	52.95	187.75	407.21	736.88	1245.26	2115.67	3977.12

Table C-8. Rectangular-loop quality factor at f = 60 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	26.56	38.32	46.10	51.65	55.77	58.86	61.17
7 (2.1)	26.77	38.60	46.40	51.94	56.02	59.04	61.24
8 (2.4)	26.93	38.82	46.64	52.16	56.19	59.13	61.21
9 (2.7)	27.07	39.01	46.83	52.33	56.30	59.15	61.10
10 (3.0)	27.18	39.16	46.98	52.46	56.37	59.12	60.93
11 (3.3)	27.28	39.29	47.11	52.55	56.39	59.04	60.71
12 (3.7)	27.37	39.40	47.21	52.61	56.39	58.93	60.44
13 (3.9)	27.44	39.49	47.30	52.66	56.36	58.78	60.12
14 (4.3)	27.51	39.58	47.37	52.68	56.30	58.60	59.77
15 (4.6)	27.56	39.65	47.42	52.69	56.22	58.39	59.37
16 (4.9)	27.62	39.71	47.46	52.68	56.12	58.15	58.94
17 (5.2)	27.66	39.76	47.50	52.66	56.01	57.89	58.48
18 (5.5)	27.71	39.81	47.52	52.63	55.88	57.61	57.99
19 (5.8)	27.74	39.85	47.54	52.59	55.73	57.30	57.46
20 (6.1)	27.78	39.89	47.55	52.53	55.57	56.98	56.91
25 (7.6)	27.92	40.01	47.51	52.14	54.56	55.05	53.70
30 (9.1)	28.01	40.06	47.36	51.56	53.26	52.67	49.83
35 (10.7)	28.08	40.07	47.12	50.82	51.69	49.87	45.34
40 (12.2)	28.13	40.03	46.81	49.95	49.88	46.68	40.25
45 (13.7)	28.16	39.97	46.43	48.94	47.84	43.10	34.59
50 (15.2)	28.19	39.87	45.99	47.81	45.56	39.15	28.35

Table C-9. Quadrupole-loop inductance in μH at f = 1 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	17.73	61.33	127.13	212.86	316.90	438.00	575.12
7 (2.1)	20.06	69.53	144.29	241.80	360.23	498.17	654.45
8 (2.4)	22.38	77.72	161.44	270.73	403.55	558.32	733.75
9 (2.7)	24.70	85.91	178.59	299.65	446.85	618.46	813.03
10 (3.0)	27.02	94.09	195.74	328.57	490.15	678.59	892.31
11 (3.3)	29.34	102.28	212.88	357.49	533.45	738.71	971.58
12 (3.7)	31.67	110.47	230.03	386.41	576.75	798.84	1050.85
13 (3.9)	33.99	118.65	247.18	415.33	620.05	858.96	1130.11
14 (4.3)	36.31	126.84	264.32	444.24	663.34	919.08	1209.38
15 (4.6)	38.63	135.03	281.47	473.16	706.64	979.20	1288.65
16 (4.9)	40.95	143.21	298.61	502.08	749.93	1039.33	1367.91
17 (5.2)	43.27	151.40	315.76	530.99	793.23	1099.45	1447.18
18 (5.5)	45.60	159.59	332.91	559.91	836.52	1159.57	1526.45
19 (5.8)	47.92	167.77	350.05	588.83	879.82	1219.70	1605.73
20 (6.1)	50.24	175.96	367.20	617.74	923.12	1279.82	1685.00
25 (7.6)	61.85	216.89	452.92	762.33	1139.61	1580.47	2081.42
30 (9.1)	73.45	257.83	538.65	906.92	1356.11	1881.15	2477.90
35 (10.7)	85.06	298.76	624.38	1051.52	1572.63	2181.88	2874.48
40 (12.2)	96.67	339.69	710.11	1196.12	1789.18	2482.66	3271.16
45 (13.7)	108.28	380.63	795.85	1340.73	2005.75	2783.49	3667.95
50 (15.2)	119.89	421.56	881.59	1485.36	2222.35	3084.39	4064.88

Table C-10. Quadrupole-loop quality factor at f = 1 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	1.20	2.06	2.82	3.52	4.16	4.77	5.33
7 (2.1)	1.22	2.10	2.88	3.59	4.25	4.87	5.45
8 (2.4)	1.24	2.13	2.93	3.66	4.33	4.96	5.55
9 (2.7)	1.25	2.16	2.97	3.71	4.39	5.03	5.63
10 (3.0)	1.26	2.18	3.00	3.75	4.44	5.09	5.70
11 (3.3)	1.28	2.20	3.03	3.79	4.49	5.14	5.76
12 (3.7)	1.28	2.22	3.05	3.82	4.52	5.19	5.81
13 (3.9)	1.29	2.23	3.07	3.84	4.56	5.22	5.85
14 (4.3)	1.30	2.25	3.09	3.87	4.59	5.26	5.89
15 (4.6)	1.30	2.26	3.11	3.89	4.61	5.29	5.93
16 (4.9)	1.31	2.27	3.13	3.91	4.46	5.32	5.96
17 (5.2)	1.31	2.28	3.14	3.93	4.66	5.34	5.98
18 (5.5)	1.32	2.29	3.15	3.94	4.68	5.36	6.01
19 (5.8)	1.32	2.29	3.16	3.96	4.69	5.38	6.03
20 (6.1)	1.33	2.30	3.17	3.97	4.71	5.40	6.05
25 (7.6)	1.34	2.33	3.21	4.02	4.77	5.47	6.13
35 (10.7)	1.35	2.35	3.24	4.06	4.81	5.52	6.19
40 (12.2)	1.36	2.36	3.26	4.08	4.84	5.56	6.23
40 (10.7)	1.36	2.37	3.28	4.10	4.87	5.59	6.26
45 (13.7)	1.37	2.38	3.29	4.12	4.89	5.61	6.29
50 (15.2)	1.37	2.39	3.30	4.13	4.90	5.63	6.31

Table C-11. Quadrupole-loop inductance in μH at f = 20 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	17.69	61.26	127.08	212.98	317.49	439.56	578.46
7 (2.1)	20.01	69.45	144.26	242.03	361.15	500.51	659.37
8 (2.4)	22.32	77.64	161.44	271.10	404.88	561.64	740.66
9 (2.7)	24.64	85.82	178.63	300.21	448.71	622.98	822.40
10 (3.0)	26.96	94.01	195.83	329.35	492.64	684.58	904.66
11 (3.3)	29.28	102.20	213.05	358.53	536.70	746.45	987.48
12 (3.7)	31.59	110.40	230.27	387.77	580.88	808.63	1070.92
13 (3.9)	33.91	118.59	247.51	417.05	625.20	871.14	1155.04
14 (4.3)	36.23	126.79	264.76	446.39	669.68	934.00	1239.90
15 (4.6)	38.55	134.99	282.03	475.79	714.33	997.25	1325.55
16 (4.9)	40.86	143.19	299.32	505.25	759.15	1060.91	1412.05
17 (5.2)	43.18	151.40	316.62	534.78	804.16	1125.01	1499.47
18 (5.5)	45.50	159.61	333.95	564.38	849.37	1189.58	1587.86
19 (5.8)	47.82	167.82	351.29	594.05	894.79	1254.64	1677.30
20 (6.1)	50.14	176.03	368.66	623.81	940.43	1320.24	1767.86
25 (7.6)	61.73	217.17	455.85	773.93	1172.42	1657.20	2239.86
30 (9.1)	73.32	258.42	543.75	926.67	1411.89	2012.31	2751.56
35 (10.7)	84.92	299.81	632.50	1082.59	1660.59	2390.42	3315.54
40 (12.2)	96.53	341.36	722.23	1242.29	1920.49	2797.33	3948.06
45 (13.7)	108.14	383.08	813.10	1406.39	2193.80	3240.10	4670.95
50 (15.2)	119.75	425.01	905.26	1575.59	2483.09	3727.59	5514.46

Table C-12. Quadrupole-loop quality factor at *f* = 20 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	17.26	26.53	33.28	38.48	42.64	46.05	48.87
7 (2.1)	17.51	26.91	33.74	38.98	43.16	46.56	49.37
8 (2.4)	17.71	27.22	34.10	39.38	43.57	46.96	49.73
9 (2.7)	17.88	27.47	34.40	39.70	43.89	47.26	50.00
10 (3.0)	18.02	27.69	34.65	39.97	44.15	47.50	50.20
11 (3.3)	18.14	27.87	34.87	40.18	44.36	47.68	50.33
12 (3.7)	18.25	28.02	35.04	40.37	44.52	47.81	50.42
13 (3.9)	18.34	28.16	35.20	40.52	44.66	47.91	50.46
14 (4.3)	18.42	28.28	35.33	40.65	44.77	47.98	50.47
15 (4.6)	18.49	28.38	35.45	40.76	44.85	48.02	50.44
16 (4.9)	18.55	28.47	35.55	40.85	44.92	48.04	50.39
17 (5.2)	18.61	28.55	35.63	40.93	44.96	48.03	50.31
18 (5.5)	18.66	28.63	35.71	40.99	45.00	48.01	50.21
19 (5.8)	18.71	28.69	35.78	41.04	45.01	47.97	50.08
20 (6.1)	18.75	28.75	35.84	41.09	45.02	47.92	49.94
25 (7.6)	18.91	28.98	36.04	41.18	44.89	47.44	48.95
30 (9.1)	19.03	29.12	36.14	41.12	44.56	46.68	47.58
35 (10.7)	19.11	29.21	36.15	40.96	44.07	45.68	45.88
40 (12.2)	19.17	29.27	36.12	40.71	43.44	44.48	43.86
45 (13.7)	19.22	29.30	36.04	40.38	42.69	43.08	41.56
50 (15.2)	19.26	29.31	35.92	39.99	41.82	41.49	38.97

Table C-13. Quadrupole-loop inductance in μH at f = 40 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	17.61	61.14	127.09	213.56	319.54	444.65	589.12
7 (2.1)	19.92	69.33	144.35	242.97	364.23	508.03	675.03
8 (2.4)	22.23	77.52	161.64	272.50	409.28	572.25	762.72
9 (2.7)	24.54	85.72	178.97	302.18	454.75	637.45	852.47
10 (3.0)	26.85	93.92	196.35	332.02	500.67	703.75	944.54
11 (3.3)	29.16	102.14	213.77	362.04	547.11	771.28	1039.25
12 (3.7)	31.47	110.36	231.25	392.26	594.11	840.17	1136.92
13 (3.9)	33.78	118.59	248.78	422.70	641.74	910.56	1237.90
14 (4.3)	36.09	126.83	266.38	453.37	690.03	982.62	1342.58
15 (4.6)	38.40	135.08	284.04	484.29	739.06	1056.49	1451.40
16 (4.9)	40.71	143.34	301.78	515.49	788.88	1132.37	1564.81
17 (5.2)	43.02	151.61	319.59	546.97	839.56	1210.42	1683.35
18 (5.5)	45.33	159.90	337.48	578.76	891.16	1290.86	1807.62
19 (5.8)	47.64	168.20	355.46	610.89	943.75	1373.91	1938.27
20 (6.1)	49.96	176.51	373.53	643.36	997.41	1459.80	2076.06
25 (7.6)	62.53	218.33	465.40	811.78	1284.60	1942.02	2907.06
30 (9.1)	73.11	260.61	560.30	992.54	1612.56	2548.33	4123.51
35 (10.7)	84.72	303.46	658.95	1189.34	1998.78	3357.78	6162.33
40 (12.2)	96.40	346.97	762.14	1406.81	2466.77	4524.99	10461.3
45 (13.7)	107.99	391.24	870.79	1650.98	3058.41	6402.00	26153.2
50 (15.2)	119.66	436.39	985.93	1929.88	3841.27	10005.70	68070.5

Table C-14. Quadrupole-loop quality factor at *f* = 40 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	24.62	36.14	43.82	49.33	53.42	56.48	58.74
7 (2.1)	24.95	36.58	44.31	49.79	53.81	56.76	58.85
8 (2.4)	25.21	36.94	44.68	50.14	54.08	56.89	58.80
9 (2.7)	25.43	37.23	44.98	50.40	54.24	56.91	58.61
10 (3.0)	25.61	37.47	45.22	50.58	54.33	56.83	58.31
11 (3.3)	25.77	37.67	45.41	50.72	54.34	56.68	57.90
12 (3.7)	25.90	37.84	45.57	50.80	54.31	56.45	57.41
13 (3.9)	26.02	37.99	45.69	50.85	54.22	56.16	56.84
14 (4.3)	26.12	38.11	45.78	50.86	54.09	55.81	56.18
15 (4.6)	26.21	38.22	45.86	50.85	53.93	55.41	55.46
16 (4.9)	26.29	38.31	45.91	50.81	53.72	54.96	54.67
17 (5.2)	26.36	38.39	45.95	50.75	53.49	54.47	53.82
18 (5.5)	26.42	38.46	45.97	50.66	53.22	53.93	52.90
19 (5.8)	26.48	38.52	45.98	50.56	52.92	53.34	51.92
20 (6.1)	26.54	38.57	45.98	50.44	52.60	52.72	50.88
25 (7.6)	26.74	38.72	45.81	49.59	50.61	49.02	44.85
30 (9.1)	26.88	38.75	45.44	48.40	48.04	44.43	37.50
35 (10.7)	26.97	38.70	44.91	46.91	44.96	39.01	28.93
40 (12.2)	27.04	38.59	44.25	45.14	41.38	32.80	19.22
45 (13.7)	27.08	38.43	43.46	43.11	37.11	25.85	8.45
50 (15.2)	27.11	38.22	42.55	40.83	32.83	18.19	-3.31

Table C-15. Quadrupole-loop inductance in μH at f = 60 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	17.55	61.08	127.31	214.81	323.36	453.84	698.32
7 (2.1)	19.85	69.28	144.73	244.86	369.89	521.58	703.48
8 (2.4)	22.15	77.50	162.23	275.21	417.28	591.44	803.28
9 (2.7)	24.46	85.73	179.82	305.90	465.67	663.76	908.57
10 (3.0)	26.76	93.97	197.52	336.98	515.20	738.91	1020.35
11 (3.3)	29.06	102.23	215.32	368.49	566.00	817.32	1139.78
12 (3.7)	31.37	110.52	233.25	400.48	618.23	899.44	1268.22
13 (3.9)	33.68	118.82	251.32	432.99	672.04	985.81	1407.32
14 (4.3)	35.98	127.15	269.53	466.07	727.63	1077.63	1559.08
15 (4.6)	38.29	135.50	287.90	499.78	785.18	1173.78	1725.94
16 (4.9)	40.60	143.88	306.43	534.17	844.91	1276.87	1910.97
17 (5.2)	42.90	152.28	325.15	569.29	907.05	1387.23	2118.05
18 (5.5)	45.21	160.72	344.06	605.20	971.87	1505.96	2352.17
19 (5.8)	47.53	169.18	363.18	641.98	1039.65	1634.37	2619.87
20 (6.1)	49.84	177.68	382.51	679.68	1110.73	1774.02	2929.90
25 (7.6)	61.41	220.74	482.97	884.97	1530.25	2725.24	5781.94
30 (9.1)	73.02	264.88	591.16	1127.49	2116.11	4590.35	24158.9
35 (10.7)	84.67	310.38	709.46	1425.35	3027.21	10214.52	−14095.7
40 (12.2)	96.36	357.47	840.85	1808.24	4699.56	−77203.2	−5948.3
45 (13.7)	108.11	406.48	989.27	2329.10	8926.13	−10112.4	−3900.7
50 (15.2)	119.91	457.72	1160.02	3093.03	40376.3	−5506.1	−2956.9

Table C-16. Quadrupole-loop quality factor at *f* = 60 kHz.

Length ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
6 (1.8)	28.99	41.41	49.24	54.51	58.09	60.40	61.66
7 (2.1)	29.35	41.87	49.68	54.85	58.23	60.25	61.11
8 (2.4)	29.64	42.23	50.00	55.05	58.22	59.91	60.32
9 (2.7)	29.88	42.52	50.24	55.15	58.08	59.41	59.32
10 (3.0)	30.08	42.75	50.42	55.17	57.83	58.77	58.14
11 (3.3)	30.25	42.94	50.53	55.12	57.50	58.01	56.79
12 (3.7)	30.40	43.09	50.61	55.01	57.08	57.13	55.28
13 (3.9)	30.52	43.22	50.64	54.84	56.58	56.14	53.62
14 (4.3)	30.63	43.32	50.65	54.63	56.02	55.05	51.82
15 (4.6)	30.73	43.40	50.62	54.38	55.38	55.39	49.88
16 (4.9)	30.82	43.47	50.57	54.09	54.69	52.59	47.81
17 (5.2)	30.89	43.52	50.49	53.76	53.94	51.22	45.61
18 (5.5)	30.96	43.56	50.40	53.39	53.14	49.77	43.28
19 (5.8)	31.03	43.58	50.28	53.00	52.27	48.23	40.83
20 (6.1)	31.08	43.60	50.15	52.57	51.36	46.61	36.26
25 (7.6)	31.29	43.54	49.24	49.97	46.02	37.30	23.69
30 (9.1)	31.42	43.32	47.99	46.69	39.49	26.15	6.52
35 (10.7)	31.50	42.97	46.42	42.78	31.85	13.30	-12.97
40 (12.2)	31.54	42.51	44.57	38.28	23.18	-1.11	-34.45
45 (13.7)	31.56	41.96	42.46	33.21	13.53	-16.91	-57.64
50 (15.2)	31.56	41.31	40.08	27.59	2.97	-33.96	-82.23

Table C-17. Circular-loop inductance in μH at f = 1 kHz.

Diameter ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
4 (1.2)	5.32	18.10	37.28	62.23	92.52	127.80	167.79
5 (1.5)	6.87	23.49	48.53	81.21	120.99	167.44	220.21
6 (1.8)	8.45	29.02	60.12	100.80	150.42	208.47	274.51
7 (2.1)	10.07	34.68	71.99	120.91	180.66	250.65	330.38
8 (2.4)	11.71	40.46	84.12	141.46	211.58	293.82	387.60

Table C-18. Circular-loop quality factor at f = 1 kHz.

Diameter ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
4 (1.2)	1.03	1.74	2.37	2.95	3.49	4.00	4.48
5 (1.5)	1.06	1.81	2.47	3.08	3.65	4.19	4.69
6 (1.8)	1.09	1.86	2.55	3.18	3.78	4.34	4.87
7 (2.1)	1.11	1.90	2.61	3.27	3.88	4.46	5.01
8 (2.4)	1.13	1.94	2.67	3.34	3.98	4.57	5.14

Table C-19. Circular-loop inductance in μH at f = 20 kHz.

Diameter ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
4 (1.2)	5.31	18.07	37.24	62.18	92.47	127.76	167.79
5 (1.5)	6.85	23.45	48.47	81.15	120.94	167.44	220.30
6 (1.8)	8.43	28.98	60.06	100.75	150.40	208.54	274.78
7 (2.1)	10.04	34.63	71.93	120.86	180.69	250.85	330.93
8 (2.4)	11.68	40.40	84.05	141.43	211.68	294.21	388.55

Table C-20. Circular-loop quality factor at f = 20 kHz.

Diameter ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
4 (1.2)	15.16	23.32	29.46	34.34	38.35	41.72	44.61
5 (1.5)	15.57	23.99	30.31	35.32	39.42	42.86	45.79
6 (1.8)	15.90	24.53	30.99	36.09	40.26	43.75	46.72
7 (2.1)	16.19	24.98	31.55	36.73	40.95	44.47	47.46
8 (2.4)	16.43	25.37	32.03	37.26	41.53	45.07	48.07

Table C-21. Circular-loop inductance in µH at *f* = 40 kHz.

Diameter ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
4 (1.2)	5.28	18.02	37.16	62.09	92.40	127.75	167.92
5 (1.5)	6.81	23.38	48.38	81.07	120.92	167.58	220.76
6 (1.8)	8.39	28.90	59.96	100.68	150.48	208.94	275.80
7 (2.1)	9.99	34.54	71.83	120.84	180.92	251.66	332.81
8 (2.4)	11.62	40.30	83.96	141.48	212.16	295.61	391.66

Table C-22. Circular-loop quality factor at *f* = 40 kHz.

Diameter ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
4 (1.2)	21.85	32.30	39.59	45.08	49.38	52.86	55.74
5 (1.5)	22.40	33.11	40.56	46.13	50.47	53.97	56.83
6 (1.8)	22.84	33.77	41.33	46.95	51.31	54.80	57.63
7 (2.1)	23.21	34.31	41.95	47.61	51.98	55.44	58.23
8 (2.4)	23.53	34.77	42.48	48.16	52.52	55.95	58.66

Table C-23. Circular-loop inductance in µH at *f* = 60 kHz.

Diameter ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
4 (1.2)	5.26	17.98	37.10	62.05	92.40	127.89	168.30
5 (1.5)	6.79	23.33	48.32	81.05	121.04	167.99	221.73
6 (1.8)	8.35	28.84	59.90	100.72	150.79	209.83	277.76
7 (2.1)	9.95	34.48	71.79	120.98	181.53	253.27	336.29
8 (2.4)	11.58	40.23	83.95	141.76	214.20	298.26	397.32

Table C-24. Circular-loop quality factor at *f* = 60 kHz.

Diameter ft (m)	1 Turn	2 Turn	3 Turn	4 Turn	5 Turn	6 Turn	7 Turn
4 (1.2)	25.89	37.38	45.06	50.65	54.92	58.28	60.99
5 (1.5)	26.50	38.25	46.05	51.69	55.95	59.26	61.88
6 (1.8)	27.00	38.94	46.83	52.47	56.70	59.95	62.45
7 (2.1)	27.42	39.51	47.45	53.09	57.27	60.41	62.76
8 (2.4)	27.77	39.99	47.97	53.59	57.70	60.71	62.89

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APPENDIX D. ELECTRICAL CHARACTERISTICS OF WIRE AND CABLE

This appendix describes the calculation of the electrical characteristics of twisted lead-in wire composed of Belden #14 AWG copper conductor wire. The wire size and spacing definitions are shown in Figure D-1. Here, *D* represents the distance between the center of the wire cores in the twisted pair and *d* is the diameter of the wire core.

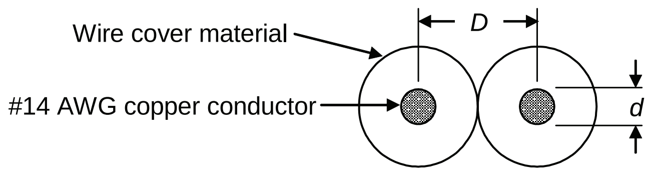

Figure D-1. Wire spacing and size definitions used in wire inductance and capacitance calculations.

CAPACITANCE OF PARALLEL CONDUCTORS

The capacitance *C* of the twisted wire pair is given by

$$C = \frac{\left(\frac{\varepsilon}{\varepsilon_0}\right) \times 10^{-9}}{36 \cosh^{-1}\left(\frac{D}{d}\right)} \text{ F/m} \quad \text{(D-1)}$$

where the factor $\varepsilon/\varepsilon_0$ is the relative dielectric constant of the wire cover material.

#14 AWG Belden 9438 is commonly used to construct inductive loops.

For Belden 9438, the relative dielectric constant of the polyethylene covering of the wire core is 2.3. Therefore,

$$C = \frac{2.3 \times 10^{-9}}{36 \cosh^{-1}\left(\frac{139 \text{ mils}}{64.1 \text{ mils}}\right)}. \quad \text{(D-2)}$$

The capacitance can also be expressed as

$$C = \frac{2.3 \times 10^{-9}}{36 \ln\left(\frac{139 \text{ mils}}{32.05 \text{ mils}}\right)} \quad \text{(D-3)}$$

or

$$C = 4.355 \text{ x } 10^{-11} \text{ F/m} = 43.55 \text{ pF/m} = 13.3 \text{ pF/ft}. \quad \text{(D-4)}$$

Figure D-2 depicts the electromagnetic field lines that surround the dielectric material in a twisted pair of wires.

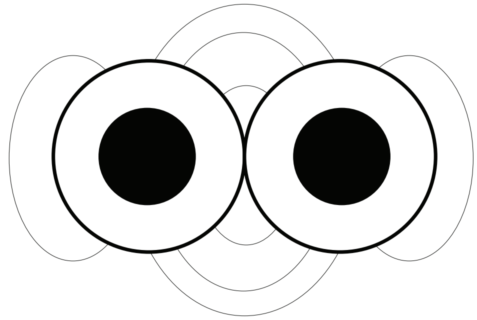

Figure D-2. Dielectric field surrounding a pair of wires.

This geometry is simplified as shown in Figure D-3 by including the region that encompasses most of the electromagnetic field.

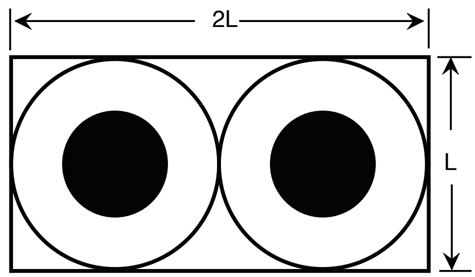

Figure D-3. Simplified geometry that includes most of the electromagnetic field surrounding a twisted pair of wires.

The following heuristic approach modifies the capacitance value given by Equation D-1 for estimating the capacitance of a twisted wire pair based on the geometry of Figure D-3. It assumes that all the electromagnetic field energy is contained in a box surrounding the two wires and their insulation. It gives a reasonable approximation to the capacitance in a closed form equation. An exact closed form solution for the capacitance is not known.

The area of the cable is given by

$$A_{cable} = \frac{\pi\, L^2}{4} + \frac{\pi\, L^2}{4} = \frac{\pi\, L^2}{2}\ , \tag{D-5}$$

where L is the diameter of the wire, including the polyethylene insulation.

The area of the box surrounding the twisted wire pair is given as

$$A_{\text{rectangle}} = (2L)\,(L) = 2L^2\ . \tag{D-6}$$

The ratio of the cable area to the box area is thus:

$$\text{Ratio of Areas} = \frac{\left(\dfrac{\pi L^2}{2}\right)}{2L^2} = \frac{\pi}{4} = 0.79\ . \tag{D-7}$$

From Equation D-3, the capacitance of the twisted wire pair becomes

$$C = (0.79)\ (13.3\,\text{pF/ft}) = 10.45\,\text{pF/ft}. \tag{D-8}$$

For 100 ft (30 m) of wire,

$$C = 1045 \text{ pF} \quad . \tag{D-9}$$

Table D-1 shows that the actual measured capacitance is in the range of 997 to 1006 pF for 100 ft (30 m) of wire. All units of picofarads per foot may be converted to picofarads per meter by multiplying by 0.305 meters per foot. Thus, the heuristic calculation produces a reasonable value. The heuristic result may be fed into finite element analysis models as a first approximation to a final "exact" answer.

INDUCTANCE OF PARALLEL CONDUCTORS

The inductance L of the twisted wire pair is given by

$$L = 0.4 \ln(\frac{2D}{d}) + 2L_i \quad \mu\text{H/m} \tag{D-10}$$

The internal inductance L_i is calculated using Equation A-23 of Appendix A with μ_r =1 and μ_0 =4π x 10^{-7} H/m.

μH/m can be converted to to μH/ft by dividing by 0.3048.

The internal inductance L_i of copper at 1 kHz is 0.05 μH/m. Thus,

$$L = 0.4 \ln(\frac{2D}{d}) + 0.1 \quad \mu\text{H/m} \quad . \tag{D-11}$$

For Belden 9438 wire,

$$L = 0.4 \ln(\frac{2 \times 139\text{mils}}{64.1\,\text{mils}}) + 0.1 \quad \mu\text{H/m} \tag{D-12}$$

or

$$L = 0.69 \ \mu\text{H/m} = 0.21 \ \mu\text{H/ft} \, . \tag{D-13}$$

For 100 ft (30 m) of wire,

$$L = 21 \ \mu\text{H} \, . \tag{D-14}$$

Table D-1. Measured lead-in cable electrical characteristics of #14 AWG twisted pair.

Frequency (kHz)	Open circuit measurement of capacitance (pF)	Open circuit measurement of conductance (μmhos)	Short circuit measurement of inductance (μH)	Short circuit measurement of resistance (Ω)
0.1	997	−0.0005	22.87	0.57
1.0	999	−0.0082	22.95	0.57
5.0	1000	−0.056	22.97	0.58
10.0	1001	−0.14	22.91	0.60
15.0	1002	−0.24	22.83	0.63
20.0	1002	−0.36	22.72	0.67
25.0	1002	−0.51	22.60	0.72
30.0	1002	−0.67	22.47	0.77
35.2941	1003	−0.85	22.33	0.82
40.0	1003	−1.02	22.21	0.87
45.4545	1003	−1.21	22.09	0.92
50.0	1003	−1.40	21.99	0.97
54.5454	1003	−1.58	21.90	1.01
60.0	1003	−1.77	21.8	1.06
66.6666	1003	−2.03	21.69	1.12
71.4286	1003	−2.26	21.62	1.16
75.0	1004	−2.43	21.57	1.19
80.0	1004	−2.67	21.51	1.24
85.714	1004	−2.95	21.44	1.28
96.0	1004	−3.46	21.33	1.37
100.0	1005	−3.79	21.29	1.4
120.0	1005	−4.74	21.12	1.56
125.0	1006	−5.02	21.09	1.59
150.0	1006	−6.52	20.93	1.78

Type: Twisted pair of Belden 9438 wire (not shielded)

Gauge: #14 AWG

Twists per foot: 5.5 (18.1 twists per meter)

Pair length: 100 ft (30 m)

Wire location: Laboratory floor, Turner-Fairbank Highway Research Center

Measuring Instrument: HP 4284A

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	3.711	16.07	4.04
150	13.52	4.29	15.27	4.67

Type: Shielded cable

Gauge: #12 or #14 AWG

Length: 100 ft (30 m)

Wire location: Laboratory floor, Turner-Fairbank Highway Research Center

Measuring Instrument: HP 4284A

Note: Balun unavailable; instrument unbalanced during measurements

Table D-3. Measured inductive-loop electrical characteristics: Belden 8718 shielded lead-in.

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 ft (1.8 x 1.8 m)

Number of turns: 3 (closely wound)

Gauge: #14 AWG

Loop location: 3 ft (0.9 m) above electronics laboratory floor, Turner-Fairbank Highway Research Center

Lead-in cable: Belden 8718 (# 12 AWG)

Lead-In cable length: 100 ft (30 m)

Measuring Instrument: HP 4284A

Note: Balun unavailable; instrument unbalanced during measurements

Table D-4. Measured inductive-loop electrical characteristics: Belden 8720 shielded lead-in.

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 ft (1.8 x 1.8 m)

Number of turns: 3 (closely wound)

Gauge: #14 AWG

Loop location: 3 feet (0.9 m) above electronics laboratory floor, Turner-Fairbank Highway Research Center

Lead-in cable: Belden 8720 (# 14 AWG)

Lead-in cable length: 100 ft (30 m)

Measuring instrument: HP 4284A

Note: Balun unavailable; instrument unbalanced during measurements

Table D-5. Measured inductive-loop electrical characteristics: Belden 9438 twisted pair lead-in.

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	2.7	35

Loop size: 6 x 6 ft (1.8 x 1.8 m)

Number of turns: 3 (closely wound)

Gauge: #14 AWG

Loop location: 3 ft (0.9 m) above electronics laboratory floor, Turner-Fairbank Highway Research Center

Lead-in cable: Belden 9438 twisted-pair (5.5 twists/ft) (15/m)

Lead-in cable length: 100 ft (30 m)

Measuring instrument: HP 4284A

Note: Balun unavailable; instrument unbalanced during measurements

Table D-6. Measured inductive-loop electrical characteristics: Loop without 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 ft (1.8 x 1.8 m)

Number of turns: 3 (closely wound)

Gauge: #14 AWG

Loop location: 3 ft (0.9 m) above electronics laboratory floor, Turner-Fairbank Highway Research Center

Lead-in cable: None

Lead-in Length: 0 ft (0 m)

Measuring instrument: HP 4284A

Note: Balun unavailable; instrument unbalanced during measurements

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APPENDIX E. VEHICLE DETECTION SENSITIVITY FORMULAS FOR RECTANGULAR LOOPS

ABSTRACT

This appendix describes the derivation and application of formulas to calculate the vehicle detection sensitivity of single-turn and multiturn rectangular loops of coaxial wire. The effect on detection sensitivity of reinforcing steel mesh in the pavement and lead-in cable inductance is accounted for in the models. The loop is installed in the roadway pavement and connected to a roadside electronics unit by lead-in cable, which is modeled as a transmission line. 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 electronics unit.

The multiturn rectangular loop is modeled as a number of series connected, single-turn, rectangular loops that exhibit mutual coupling between each turn of wire. The multiturn loop is represented by the primary of an air core transformer, which contains two secondary windings composed of shorted turns that simulate the vehicle undercarriage and reinforcing steel mesh. The derived equations are used to calculate tables of vehicle detection sensitivity, expressed as vehicle undercarriage detection height, as a function of number of loop turns, loop size, and loop spacing.

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 3-turn, 6- x 6-ft (1.83- x 1.83-m) loop of #14 AWG wire embedded in the pavement, a lead-in cable to roadside, and roadside electronics unit. The vehicle-detection sensitivity is the normalized inductance change at the terminals of the electronics unit 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 nondetection of part of the vehicle. Increasing the sensitivity of the electronics unit to sense such small inductance changes usually increases the response time of the electronics unit, which causes errors in ILD applications for measuring vehicle speed.

The vehicle-detection sensitivity of an inductive-loop detection system is maximized when the spacing between loop turns is correctly selected. The increased sensitivity should improve detection of high-ground-clearance trucks.

This appendix is based on a previous paper that developed a detection-sensitivity formula for a single-turn rectangular loop.(1) 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 multiturn, rectangular loop are tightly coupled, the sensitivity is independent of the number of loop turns, provided the loop inductance is approximately ten times larger than the inductance of the lead-in cable. A formula for the self-inductance of a multiturn 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 calculations of loop system sensitivity, the wire grid simulating the vehicle is 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 E-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 circuit model. A plus sign indicates current flow in the same direction and a minus sign current flow in opposite directions.

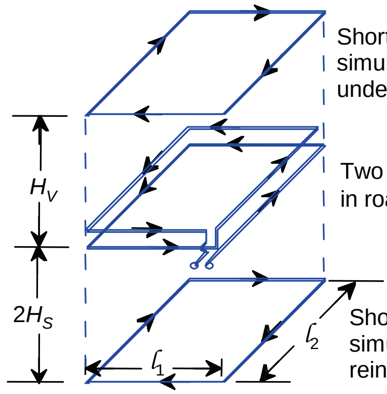

Figure E-1. Two-turn loop in roadway.

CIRCUIT MODEL FOR ONE-TURN LOOP

Figure E-2 shows the air core transformer model of a one-turn inductive loop, vehicle undercarriage, and reinforcing steel mesh. The inductive loop is modeled as the primary winding of the transformer, while the vehicle and reinforcing steel are modeled as shorted turn secondary windings. The secondary winding simulating the vehicle is movable to simulate changes in vehicle undercarriage height H_V. The secondary winding modeling the shorted turn reinforcing steel mesh is located at a distance of twice the steel mesh to inductive loop spacing H_S.

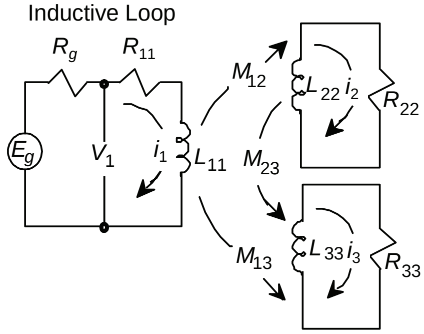

Figure E-2. Single-turn inductive-loop circuit model.

Circuit Equations for One-Turn Loop

The circuit equations corresponding to Figure E-2 are:

Z is impedance in ohms. I is current in amperes. Equations E-2 and E-3 are set equal to 0 since there is no external driving voltage in the two secondary windings in Figure E-2 that contain L_{22} and L_{33}.

$$V_1 = Z_{11}I_1 + Z_{12}I_2 + Z_{12}I_3 \quad \text{(E-1)}$$

$$0 = Z_{21}I_1 + Z_{22}I_2 + Z_{23}I_3 \quad \text{(E-2)}$$

$$0 = Z_{31}I_1 + Z_{32}I_2 + Z_{33}I_3 \quad \text{(E-3)}$$

where

R is resistance in ohms. j represents the square root of -1 in the imaginary term. ω is frequency in radians. L is inductance in henries.

$$Z_{11} = R_{11} + j\omega L_{11} \quad \text{(E-4)}$$

$$Z_{22} = R_{22} + j\omega L_{22} \quad \text{(E-5)}$$

$$Z_{33} = R_{33} + j\omega L_{33} \quad \text{(E-6)}$$

$$Z_{12} = j\omega M_{12} \quad \text{(E-7)}$$

$$Z_{13} = j\omega M_{13}\,. \quad \text{(E-8)}$$

All mutual impedances are symmetrical (i.e., $Z_{12} = Z_{21}$, $Z_{13} = Z_{31}$, $Z_{23} = Z_{32}$).

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 gives

$$Z_{11} = j\omega L_{11} \quad \text{(E-9)}$$

$$Z_{22} = j\omega L_{22} \quad \text{(E-10)}$$

$$Z_{33} = j\omega L_{33}\,. \quad \text{(E-11)}$$

Inductive-Loop Driving-Point Impedance

The loop driving-point impedance Z_1 from Equations E-1, E-2, and E-3 is

$$Z_1 = \frac{V_1}{I_1} = \frac{Z_{11}Z_{22}Z_{33} - (Z_{31})^2 Z_{22} - (Z_{32})^2 Z_{11} - (Z_{21})^2 Z_{33} + 2 \times Z_{21}Z_{31}Z_{32}}{Z_{22}Z_{33} - (Z_{32})^2}\,. \quad \text{(E-12)}$$

If the reinforcing mesh is spaced a great distance from the inductive loop,

$$Z_{13} = Z_{23} = 0 \quad .$$

Then

$$Z_1 = \frac{Z_{11}Z_{22} - (Z_{21})^2}{Z_{22}}\,. \quad \text{(E-13)}$$

In this case, the loop driving-point impedance Z_1 depends only on the effect of the vehicle.

Inductive-Loop Sensitivity

NV represents the value of the variable when no vehicle is present.
V represents the value of the variable when a vehicle is present.

The sensitivity S_L of an inductive loop is defined as

$$S_L = \frac{\Delta Z_1}{Z_1^{NV}}\,. \quad \text{(E-14)}$$

The change in loop driving-point impedance ΔZ_1 is given by

$$\Delta Z_1 = Z_1^{NV} - Z_1^{V} \quad \text{(E-15)}$$

where ΔZ_1^{NV} is the loop driving-point impedance with no vehicle present and ΔZ_1^{V} is the loop driving-point impedance when sensing a vehicle.

The loop driving-point impedance Z_1 can also be expressed as

$$Z_1 = Z_{11} - \frac{(Z_{13})^2 Z_{22} + (Z_{12})^2 Z_{33} - 2Z_{12}Z_{13}Z_{23}}{Z_{22}Z_{33} - (Z_{23})^2}\,. \quad \text{(E-16)}$$

Then, if no vehicle is present,

$$Z_{12} = Z_{23} = 0$$

$$Z_1^{NV} = Z_{11} - \frac{(Z_{13})^2}{Z_{33}} = \frac{Z_{11}Z_{33} - (Z_{13})^2}{Z_{33}} \tag{E-17}$$

$$Z_1^{V} = Z_{11} - \frac{(Z_{13})^2 Z_{22} + (Z_{12})^2 Z_{33} - 2Z_{12}Z_{13}Z_{33}Z_{23}}{Z_{22}Z_{33} - (Z_{23})^2} \tag{E-18}$$

$$\Delta Z_1 = \frac{(Z_{13})^2(Z_{23})^2 + (Z_{12})^2(Z_{33})^2 - 2Z_{12}Z_{13}Z_{33}Z_{23}}{Z_{33}(Z_{22}Z_{33} - (Z_{23})^2)} . \tag{E-19}$$

The loop sensitivity S_L is given by

$$S_L = \frac{\Delta Z_1}{Z_1^{NV}} = \frac{(Z_{13})^2(Z_{23})^2 + (Z_{12})^2(Z_{33})^2 - 2Z_{12}Z_{13}Z_{33}Z_{23}}{(Z_{11}Z_{33} - (Z_{13})^2)(Z_{22}Z_{33} - (Z_{23})^2)} \tag{E-20}$$

if

$$Z_{13} = Z_{23} = 0$$

$$S_L = \frac{(Z_{12})^2}{Z_{11}Z_{22}} . \tag{E-21}$$

Applying Equations E-9, E-10, and E-11 to Equation E-20 yields the loop sensitivity S_L in percent as

$$S_L = 100\frac{M_{12}^2 L_{33}^2 + M_{13}^2 M_{23}^2 - 2M_{12}M_{13}M_{23}L_{33}}{(L_{11}L_{33} - M_{13}^2 - M_{13}^2)(L_{22}L_{33} - M_{23}^2)} \tag{E-22}$$

where

S_L = inductive loop sensitivity (percent)

M_{12} = mutual inductance between inductive loop and loop-simulating vehicle (H)

M_{13} = mutual inductance between inductive loop and loop-simulating reinforcing mesh (H)

M_{23} = mutual inductance between loop-simulating vehicle and loop-simulating reinforcing mesh (H)

L_{11} = self-inductance of inductive loop (H)

L_{22} = self-inductance of loop-simulating vehicle (H)

L_{33} = self-inductance of loop-simulating reinforcing steel mesh (H).

When reinforcing steel mesh is not present,

$$S_L = 100\frac{(M_{12})^2}{L_{11}L_{22}} . \tag{E-23}$$

CIRCUIT MODEL FOR TWO-TURN LOOP

Figure E-3 shows the air core transformer model of a two-turn inductive loop, vehicle undercarriage, and reinforcing steel mesh. Mutual inductance terms that model the effects of the multiple-turn loop have been added to the model.

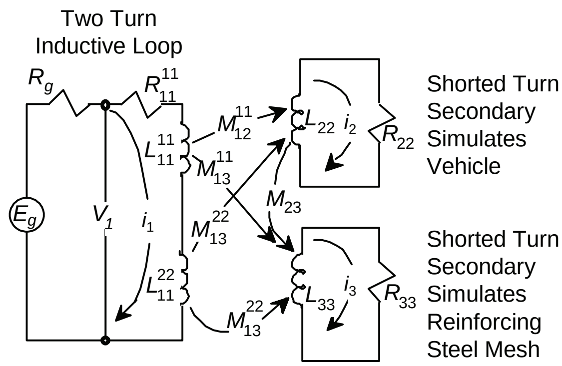

Figure E-3. Two-turn inductive-loop circuit model.

Circuit Equations for Two-Turn Loop

From Figure E-3, the circuit equations for the two-turn loop are given by

$$V_1 = (Z_{11}^{11} + Z_{11}^{22} + Z_{11}^{12} + Z_{11}^{21})I_1 + (Z_{12}^{11} + Z_{12}^{22})I_2 + (Z_{13}^{11} + Z_{13}^{22})I_3 \quad \text{(E-24)}$$

$$0 = (Z_{21}^{11} + Z_{21}^{22})I_1 + Z_{22}^{22} I_2 + Z_{23}^{22} I_3 \quad \text{(E-25)}$$

$$0 = (Z_{31}^{11} + Z_{31}^{22})I_1 + Z_{32}^{22} I_2 + Z_{33}^{33} I_3 \quad \text{(E-26)}$$

where

Z_{12}^{11} = mutual impedance between primary turn 1 of the transformer and secondary shorted turn 2, which models the vehicle,

Z_{12}^{22} = mutual impedance between primary turn 2 of the transformer and secondary shorted turn 2, which models the vehicle,

Z_{11}^{12} = mutual impedance between primary turn 1 and primary turn 2.

Then

$$Z_{11} = Z_{11}^{11} + Z_{11}^{22} + Z_{11}^{12} + Z_{11}^{21} \quad \text{(E-27)}$$

$$Z_{12} = Z_{12}^{11} + Z_{12}^{22} \quad \text{(E-28)}$$

$$Z_{13} = Z_{13}^{11} + Z_{13}^{22} \quad \text{(E-29)}$$

$$Z_{21} = Z_{21}^{11} + Z_{21}^{22} \quad \text{(E-30)}$$

$$Z_{22} = Z_{22}^{22} \quad \text{(E-31)}$$

$$Z_{23} = Z_{23}^{22} \quad \text{(E-32)}$$

$$Z_{31} = Z_{31}^{11} + Z_{31}^{22} \quad \text{(E-33)}$$

$$Z_{32} = Z_{32}^{22} \quad \text{(E-34)}$$

$$Z_{33} = Z_{33}^{33}. \quad \text{(E-35)}$$

As compared to the one-turn loop model, 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 MULTITURN LOOP

Circuit equations for a multiturn loop are given by

$$V_1 = ZI_1 + \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{12}^{ij} I_2 + \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{13}^{ij} I_3 \qquad \text{(E-36)}$$

$$0 = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{21}^{ij} I_1 + Z_{22} I_2 + Z_{23} I_3 \qquad \text{(E-37)}$$

$$0 = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{31}^{ij} I_1 + Z_{32} I_2 + Z_{33} I_3 \qquad \text{(E-38)}$$

where δ_{ij} is the Kronecker Delta function (i.e., $\delta_{ij} = 1$ for $i = j$ and $\delta_{ij} = 0$ for i not equal to j). Then

$$Z_{11} = Z_N = \text{multiturn loop self impedance} \qquad \text{(E-39)}$$

$$Z_{12} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{12}^{ij} \qquad \text{(E-40)}$$

$$Z_{13} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{13}^{ij} \qquad \text{(E-41)}$$

$$Z_{21} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{21}^{ij} \qquad \text{(E-42)}$$

$$Z_{31} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} Z_{31}^{ij} \; . \qquad \text{(E-43)}$$

Equations E-39–E-43 are generalized for the multiturn case by letting

$$L_{11} = L_N^* \qquad \text{(E-44)}$$

$$M_{12} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{12}^{ij} \qquad \text{(E-45)}$$

$$M_{13} = \delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{13}^{ij} \qquad \text{(E-46)}$$

where L^*_N is the total self-inductance of the loop.

VEHICLE-DETECTION SENSITIVITY FOR A MULTITURN LOOP

Detection sensitivity is expressed as

$$S_L(\%) = 100 \left[\frac{\left(\delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{12}^{ij}\right)^2 L_{33} + \left(\delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{13}^{ij}\right)^2 M_{23}}{\left[L_N^* L_{33} - \left(\delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{13}^{ij}\right)^2\right]\left[L_{22}L_{33} - (M_{23})^2\right]} \right.$$
$$\left. \frac{-2\left(\delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{12}^{ij}\right)\left(\delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{13}^{ij}\right) M_{23} L_{33}}{\left[L_N^* L_{33} - \left(\delta_{ij} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{13}^{ij}\right)^2\right]\left[L_{22}L_{33} - (M_{23})^2\right]} \right] \; . \qquad \text{(E-47)}$$

For a two-turn ($N = 2$) loop,

$$S_L(\%) = 100 \frac{\left(M_{12}^{11} + M_{12}^{22}\right)^2 L_{33} + \left(M_{13}^{11} + M_{13}^{22}\right)^2 M_{23} - 2\left(M_{12}^{11} + M_{12}^{22}\right)\left(M_{13}^{11} + M_{13}^{22}\right) M_{23} L_{33}}{\left[L_N^* L_{33} - \left(M_{13}^{11} + M_{13}^{22}\right)^2\right]\left[L_{22}L_{33} - (M_{23})^2\right]} \; . \qquad \text{(E-48)}$$

The formula for multiturn 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, the sensitivity of the electronics unit to a change in loop-system inductance caused by vehicle passage or presence is given by

$$S_L(\%) = 100\frac{\left(\delta_{ij}\sum_{i=1}^{N}\sum_{j=1}^{N}M_{12}^{ij}\right)^2}{L_N^* L_{22}} . \qquad \text{(E-49)}$$

Equation E-47 can be applied to a multiturn rectangular loop with N coaxial, equal-spaced, identical turns. The low-frequency inductance L_N for such a loop is given by[3]

$$L_N = NL_{11} + 2(N-1)M_{12} + 2(N-2)M_{13} + \ldots \qquad \text{(E-50)}$$

or

$$L_N = NL_{11} + 2\sum_{i=1}^{N}(N-i)M_{1,i+1} \qquad \text{(E-51)}$$

where L_{11} is the self-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,

$$L_N = 2L_{11} + 2M_{12} . \qquad \text{(E-52)}$$

The total self-inductance L^*_N of the loop is equal to the sum of the low-frequency inductance L_N and the high-frequency, skin-effect inductance L_H and is expressed as

$$L_N^* = L_N + L_H \qquad \text{(E-53)}$$

where

$$L_H = 2(\ell_1 + \ell_2)L^i . \qquad \text{(E-54)}$$

ℓ_1 and ℓ_2 are turn width (m) and turn length (m), respectively, and the internal inductance L^i is 0.036 µH/m (0.111 µH/ft) at 47 kHz.

INDUCTIVE-LOOP DETECTOR SENSITIVITY

The series inductance L_C of the transmission line connecting the loop in the roadway to the electronics unit reduces the inductive-loop system sensitivity S_L at the electronics unit to

$$S_P = S_L\left[\frac{1}{1+\frac{L_C}{L_N^*}}\right] . \qquad \text{(E-55)}$$

LOOP-DETECTOR SENSITIVITY MEASURED DATA AND CALCULATED RESULTS

LOOP-DETECTOR SENSITIVITY COMPUTER PROGRAM

Equations E-47, E-51, E-53, and E-55 were programmed in BASIC and run on an IBM 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, multiturn, 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 number of loop conductor turns are presented in Table E-1. These data were obtained by driving a compact automobile over a 6- x 6-ft (1.83- x 1.83-m) loop with 10 ft (3.05 m) of #14 underground feeder (UF) cable connected between the loop and the laboratory equipment. Loop sensitivity as a function of the number of loop turns was calculated from the change in loop inductance recorded with and without the vehicle. The sensitivity magnitude increased approximately 5 percent when the operating frequency changed from 15 to 100 kHz for four or more loop turns.

COMPARISON BETWEEN MEASURED AND CALCULATED SENSITIVITY DATA

Since the average undercarriage height of the compact automobile used was unknown, the automobile was modeled with a 6- x 6-ft (1.83- x 1.83-m) shorted turn coaxially located 0.71 ft (216 mm) over the loop of #14 AWG wire. A loop-wire spacing of 150 mils (38 mm) and lead-in cable inductance of 0.22 μH/ft (0.72 μH/m) were assumed.

Table E-1 shows that the agreement between measured and calculated loop-detector sensitivity is good. Therefore, values calculated from the computer program model can be used to infer the effects of inductive-loop design parameters on loop sensitivity as described below.

Table E-1. Comparison of measured and calculated loop detector sensitivity data.

Loop turns	Measured loop detector sensitivity** (%)	Calculated loop detector sensitivity (%)	Difference (%)
1	3.25	3.72	14.47
2	4.75	4.75	0
3*	5.20	5.20	0
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 ft (0.22 m) was selected so that the difference equaled zero.

** Data measured at f = 50 kHz.

EFFECT OF LOOP TURNS ON SENSITIVITY

Vehicle-detection height is approximately proportional to volume enclosed by the loop windings and is approximately independent of the number of loop turns for a given volume when effects of lead-in cable length and steel mesh are noncontributory.

A survey by Dorsey[(5)] found that 15 of 21 States cut loop slots greater than 2 inches (50.8 mm) in the pavement. 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 (50.8 mm) for analysis. In practice, a much closer top-to-bottom turn spacing is used. A loop slot depth of 1-3/8 inches (35 mm) is recommended in the *Traffic Detector Handbook* for a two-turn loop. A nominal sensitivity of 0.098 percent was assumed for the 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 ft (304.8 m) from the loop. Results from the loop-detector system sensitivity computer program are presented in Table E-2 for 1 to 8 loop turns. The vehicle undercarriage detection height is approximately proportional to the volume enclosed by the loop conductors and is approximately independent of the number of loop turns for a given volume. For example, the volume of the 6- x 6-ft (1.83- x 1.83-m) by 2000-mils (50.8-mm) loop is 6 ft^3 (0.171 m^3), as illustrated by the results in Table E-2.

EFFECT OF LOOP VOLUME ON SENSITIVITY

Vehicle-detection height slowly increases when the turn spacing exceeds 1 inch (25 mm).

Since Table E-2 demonstrates that the undercarriage detection height is approximately independent of the number of loop turns for three or more turns, the effect on loop sensitivity and hence detection height of increasing the spacing between turns in a three-turn loop was calculated as shown in Table E-3. The vehicle undercarriage detection height slowly increases when the turn spacing exceeds 1 inch (25 mm). The volume of the 6- x 6-ft (1.83- x 1.83-m) by 300-mils (7.6-mm) loop is 0.90 ft^3 (0.25 mm^3) with a detection height of 4.7 ft (1.43 m). Increasing the loop volume by a factor of 10 results in a 0.3-ft (9.1-cm) increase in vehicle detection height.

Table E-2. Vehicle undercarriage detection height versus number of loop turns and spacing (calculated results).

Loop turns	Loop turn spacing (mils)	Loop turn spacing (mm)	Vehicle detection height for 5- x 5-ft (1.52- x 1.52-m) loop (ft)	Vehicle detection height for 5- x 5-ft (1.52- x 1.52-m) loop (m)	Loop inductance for 6- x 6-ft (1.83- x 1.83-m) loop (μh)	Vehicle detection height for 6- x 6-ft (1.83- x 1.83-m) loop (ft)	Vehicle detection height for 6- x 6-ft (1.83- x 1.83-m) loop (m)
1	NA	NA	3.8	1.16	10.42	4.5	1.37
2	2,000	50.8	4.1	1.25	29.15	4.8	1.46
3	1,000	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 cable length: 0 ft
Mesh spacing: 1,000 ft (305 m)
Detection sensitivity threshold: 0.098 percent

Table E-3. Vehicle undercarriage detection height versus loop-turn spacing for 3-turn loop in inch-pound and metric units (calculated results).

Loop turn spacing (mils)	Vehicle detection height for 6- x 6-ft loop (ft)	Loop turn spacing (mm)	Vehicle detection height for 1.83- x 1.83-m loop (m)
150	4.7	3.8	1.43
300	4.8	7.6	1.46
450	4.8	11.4	1.46
600	4.9	15.2	1.49
750	4.9	19.1	1.49
900	4.9	22.9	1.49
1,050	5.0	26.7	1.52
1,200	5.0	30.5	1.52
1,350	5.0	34.3	1.52
1,500	5.0	38.1	1.52

Conductor type: #14 AWG cable
Lead-in cable length: 0
Mesh spacing: 1,000 ft (305m)
Detection sensitivity threshold: 0.098 percent

EFFECT OF LEAD-IN CABLE INDUCTANCE ON SENSITIVITY

Lead-in cable inductance reduces loop sensitivity to vehicles and hence vehicle undercarriage detection height. Additional loop turns increase the loop inductance, which reduces the detrimental effect of the lead-in cable inductance. Tables E-4 and E-5 illustrate this effect.

Lead-in cable inductance reduces loop sensitivity and hence vehicle detection height.

Reinforcing steel mesh reduces loop sensitivity and hence vehicle detection height.

EFFECT OF MESH ON SENSITIVITY

Reinforcing steel mesh also reduces loop sensitivity to vehicles and hence vehicle undercarriage detection height. Adding loop turns has little effect on negating the reduced sensitivity caused by the mesh, as shown in Tables E-4 and E-5.

Combined effects of lead-in cable inductance and steel mesh accentuate the reduction of loop sensitivity and hence vehicle detection height.

EFFECT OF LEAD-IN CABLE AND MESH ON SENSITIVITY

The combined effects of lead-in cable inductance and steel mesh accentuate the reduction of loop sensitivity and hence vehicle undercarriage detection height. Tables E-4 and E-5 show that the number of loop turns should be five or more for detection of 4-ft-high (1.22-m-high) ground-clearance trucks when lead-in cable and steel mesh are present.

Table E-4. Vehicle undercarriage detection height versus number of loop turns and spacing with lead-in cable and reinforcing steel mesh for 5- x 5-ft loop (calculated results) (see Table E-5 for metric units version).

Loop turns	Loop turn spacing (mils)	Vehicle detection height with lead-in cable (ft)	Vehicle detection height with mesh (ft)	Vehicle detection height with lead-in cable and mesh (ft)
1	NA	2.3	3.9	1.9
2	2,000	3.5	4.3	3.0
3	1,000	4.1	4.4	3.6
4	660	4.4	4.4	3.9
5	500	4.6	4.5	4.1
6	400	4.7	4.5	4.2
7	330	4.8	4.5	4.3
8	286	4.9	4.5	4.3

Conductor type: #14 AWG Cable
Lead-in cable length: 250 ft
Mesh spacing: 3,000 mils
Detection sensitivity threshold: 0.098 percent

Table E-5. Vehicle undercarriage detection height versus number of loop turns and spacing with lead-in cable and reinforcing steel mesh for 1.52- x 1.52-m loop (calculated results) (see Table E-4 for inch-pound units version)

Loop turns	Loop turn spacing (mm)	Vehicle detection height with lead-in cable (m)	Vehicle detection height with mesh (m)	Vehicle detection height with lead-in cable and mesh (m)
1	NA	0.70	1.19	0.58
2	50.8	0.94	1.31	0.91
3	25.4	1.25	1.34	1.10
4	16.8	1.34	1.34	1.19
5	12.7	1.40	1.37	1.25
6	10.2	1.43	1.37	1.28
7	8.4	1.46	1.37	1.31
8	7.3	1.49	1.37	1.31

Conductor type: #14 AWG Cable
Lead-in cable length: 76.2 m
Mesh spacing: 72.6 mm
Detection sensitivity threshold: 0.098 percent

RESULTS AND CONCLUSIONS

A formula for calculating the vehicle detection sensitivity for a multiturn loop was presented. Results from this formula indicate that the vehicle detection sensitivity for a 6- x 6-ft (1.83- x 1.83-m), 3-turn loop of #14 AWG wire increases as the spacing between turns increases. Although a maximum detection height of 5.05 ft (1.54 m) occurs with a turn spacing of 2 inches (50.8 mm), a detection height of 4.99 ft (1.52 m) occurs at the more practical turn spacing of 1 inch (2.54 cm). A very small increase in detection height to 5.06 ft (1.54 cm) was noted when #12 AWG wire was used instead of #14 AWG wire.

When the loop turns are spaced to use the maximum practical installation space in the pavement, the undercarriage detection height is approximately independent of the number of turns, provided that the loop inductance is approximately ten times larger than the inductance of the lead-in cable. For example, the self-inductance of a 6- x 6-ft (1.83- x 1.83-m), 3-turn loop of #14 AWG wire with a turn spacing of 1 inch (25.4 mm) is 60.15 μH. If the maximum inductance of the lead-in cable is 6 μH and the maximum lead-in cable length is 27 ft (8.23 m), then the lead-in cable inductance is 0.22 μH/ft (0.72 μH/m). The self-inductance of a 6- x 6-ft (1.83- x 1.83-m), 6-turn loop of #14 AWG wire with a turn spacing of 0.4 inches (10.2 mm) is 226 μH, which allows a lead-in cable length of 104 ft (31.7 m) when constrained by the requirement to limit the lead-in cable inductance to no more than 23 μH (i.e., 1/10 the value of the loop inductance).

If a vehicle undercarriage detection height of 4.1 ft (1.25 m) is acceptable, then the 3-turn loop with a loop-turn spacing of 1 inch (25.4 mm) can be used with 250 ft (76.2 m) of lead-in cable, as shown in Table E-4. The presence of reinforcing steel 3 inches (76.2 mm) from the top loop turn reduces the vehicle detection height to 3.6 ft (1.10 m) for the 3-turn loop.

A 5-turn loop spaced 0.5 inches (12.7 mm) between turns with a detector sensitivity of 0.098 percent has adequate vehicle detection height sensitivity for most applications. One possible method to obtain the 0.5-inch (12.7-mm) spacing is to use loop wire centered in a flexible, water-blocked, 0.5-inch (12.7-mm) height density polyethylene tube. Lead-in cables longer than 250 ft (76.2 m) require increasing the sensitivity of the electronics unit to a value greater than 0.098 percent.

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5. Dorsey, W.F. *Status Report on Vehicle Detectors*, Report No. FHWA-RD-77-137. U.S. Department of Transportation, Federal Highway Administration, Washington, DC. November 1976.
6. DeLaski, A.B., and P.S. Parsonson. *Traffic Detector Handbook*, Report No. FHWA-IP-81-1. U.S. Department of Transportation, Federal Highway Administration, Washington, DC. 1985. p. 113.

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APPENDIX F. DIGITAL FREQUENCY-SHIFT ELECTRONICS UNIT ANALYSIS

ABSTRACT

Appendix F describes the operation of the digital frequency-shift electronics unit, which measures the difference in oscillator frequency f_D that occurs with and without a vehicle present. A frequency counter computes the frequency difference by determining a count difference that is proportional to the frequency difference. The frequency-shift electronics unit sensitivity is shown to be proportional to the threshold count N_{ft} divided by the total number of counts N_{fc} in the frequency counter.

Using a frequency counter, the frequency-shift electronics unit uses the change in inductance caused by a vehicle passing over a loop to measure the altered electronics unit oscillator frequency.

ANALYSIS

A simplified block diagram of a single-channel, digital frequency-shift electronics unit is illustrated in Figure F-1. The change in inductance at the electronics unit terminals causes a change in the oscillator frequency. The frequency is multiplied by the frequency multiplier. The resultant frequency is transformed into a frequency count by the frequency counter.

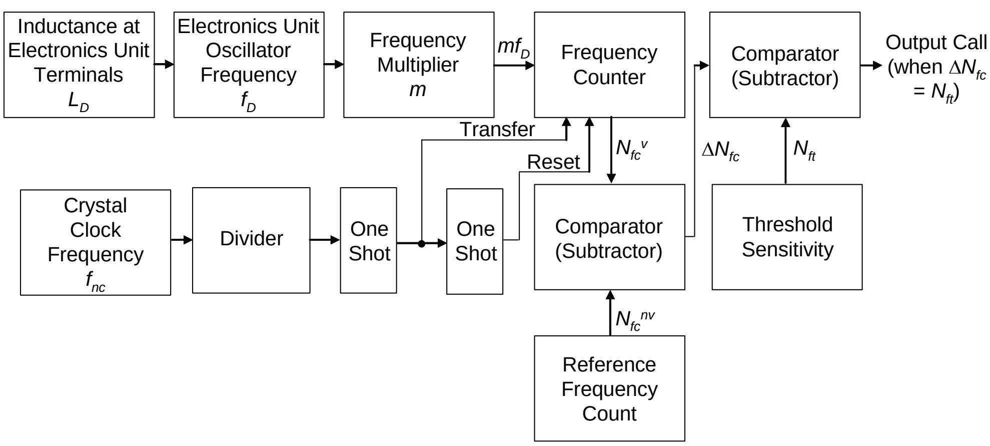

Figure F-1. Digital frequency-shift electronics unit block diagram.

The frequency counter is first initialized to zero. Frequency count data are then collected for a preset time frame. The first one-shot module then causes the frequency count to be transferred to the frequency counter and first comparator at the end of the time frame. The second one-shot module resets the frequency counter to zero so that it can collect data for the next time frame. The cycle then repeats.

The first comparator subtracts the reference frequency count stored in memory, which corresponds to the count when no vehicle is present, from the frequency count just transferred, which may or may not correspond to the presence of a vehicle. The count difference is next sent to the second comparator. If the second comparator finds that the count difference is greater than the threshold sensitivity count, then a vehicle is presumed present and a call is output.

The reference frequency count in memory updates at a specified time interval whenever no change has occurred in the call status over that interval.

The number of oscillator cycles counted by the frequency counter is

$$N_{fc} = m\, f_D\, T_{ft} = \left(\frac{m\, f_D}{f_{nc}} \right) \qquad \text{(F-1)}$$

where

T_{ft} = frame time of the frequency counter in s

m = frequency multiplier

f_D = frequency of electronics unit oscillator in Hz

f_{nc} = crystal clock frequency in Hz.

The frame time is assumed to be constant at each sensitivity setting. The response time of the digital frequency-shift electronics unit is equal to the frame time T_{ft}, which in turn is equal to the inverse of the divided crystal clock frequency.

For example, with a frame time of one second, the number of counts N_{fc} made by the frequency counter is the electronics unit oscillator frequency multiplied by m.

Since the frequency of the electronics unit oscillator changes when a vehicle is present, the count given by the frequency counter will also change. Thus, the presence of a vehicle is ascertained by noting when the change in the output of the frequency counter is above some threshold.

The reference count is measured with no vehicle present and is equal to

$$N_{fc}^{nv} = \frac{m f_D^{nv}}{f_{nc}} \; . \qquad \text{(F-2)}$$

With a vehicle present, the count becomes

$$N_{fc}^{v} = \frac{m f_D^{v}}{f_{nc}} \, . \qquad \text{(F-3)}$$

The electronics unit computes the difference in count ΔN_{fc} with and without a vehicle present at the output of the first comparator as

$$\Delta N_{fc} = N_{fc}^{v} - N_{fc}^{nv} \, . \qquad \text{(F-4)}$$

Substituting Equations F-2 and F-3 into the above equation yields

$$\Delta N_{fc} = \frac{m\, f_D^{v}}{f_{nc}} - \frac{m\, f_D^{nv}}{f_{nc}} \; . \qquad \text{(F-5)}$$

Factoring out m and f_{nc} yields

$$\Delta N_{fc} = \left(\frac{m}{f_{nc}} \right) \left(f_D^{v} - f_D^{nv} \right) . \qquad \text{(F-6)}$$

Denoting $\left(f_D{}^{v} - f_D{}^{nv}\right)$ by Δf_D, we get

$$\Delta N_{fc} = \left(\frac{m\,\Delta f_D}{f_{nc}}\right) \tag{F-7}$$

as the difference in count that occurs when a vehicle is present and not present.

A vehicle call is output when the difference count ΔN_{fc} equals the threshold count N_{ft}.

Accordingly when a call is made, one can write

$$\Delta N_{fc} = N_{ft} \tag{F-8}$$

or

$$N_{ft} = \left(\frac{m\,\Delta f_D}{f_{nc}}\right). \tag{F-9}$$

From Equation 2-51 in Chapter 2, the sensitivity of the digital frequency shift electronics unit is given by

$$S_D^f = -2\left(\frac{\Delta f_D}{f_D}\right). \tag{F-10}$$

Upon substituting Δf_D from Equation F-9 into Equation F-10, we obtain

$$S_D^f = \frac{-2N_{ft}\,f_{nc}}{mf_D} \tag{F-11}$$

Since

$$f_D = \left(\frac{1}{2\pi\sqrt{L_D C_D}}\right), \tag{F-12}$$

the sensitivity becomes

$$S_D^f = \left(\frac{-4\pi\,N_{ft}\,f_{nc}\sqrt{L_D C_D}}{m}\right). \tag{F-13}$$

Thus, the sensitivity of the digital frequency-shift electronics unit is directly proportional to the threshold frequency count N_{ft}, the crystal clock frequency f_{nc}, and the square root of the product of the total inductance L_D across the electronics unit terminals and total capacitance C_D across the electronics unit terminals (C_D includes internal tuning capacitance). Sensitivity is inversely proportional to the oscillator multiplier factor m.

An equivalent electrical circuit showing the inductive and capacitive elements that contribute to L_D and C_D is shown in Figure F-2.

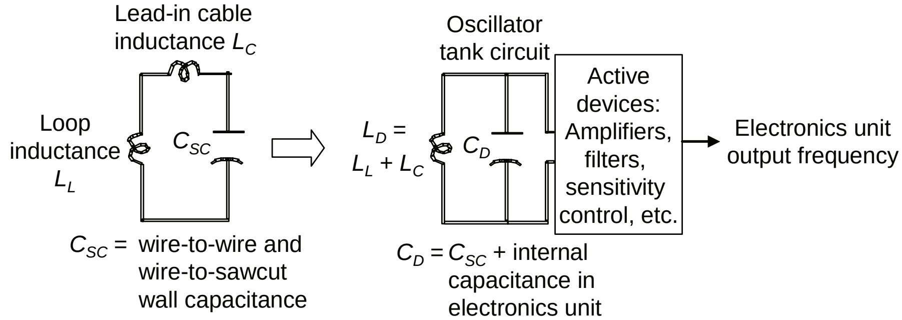

Figure F-2. Loop-inductive and capacitive elements at electronics unit terminals.

If we define

$$K_f = \left(\frac{-4\pi N_{ft} f_{nc}}{m} \right) , \tag{F-14}$$

then

$$S_D^f = K_f \sqrt{L_D C_D} \ . \tag{F-15}$$

Another form for the sensitivity equation is obtained by substituting

$$N_{fc} = \left(\frac{m f_D}{f_{nc}} \right) \tag{F-16}$$

from Equations F-2 or F-3 into Equation F-11 as

$$S_D^f = -\frac{2N_{ft} f_{nc}}{m f_D} = -\frac{2N_{ft} f_{nc}}{mN_{fc} f_{nc} / m}$$

or

$$S_D^f = -\frac{2N_{ft}}{N_{fc}} \ . \tag{F-17}$$

Thus, the frequency shift electronics unit sensitivity is proportional to the frequency threshold count N_{ft} divided by the total number of counts N_{fc} in the frequency counter.

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APPENDIX G. DIGITAL RATIOED FREQUENCY-SHIFT ELECTRONICS UNIT ANALYSIS

ABSTRACT

Appendix G describes the derivation of the digital ratioed frequency-shift electronics unit sensitivity, which is shown to be independent of the electronics unit operating frequency. The response time is proportional to the electronics unit oscillator frequency.

ANALYSIS

A simplified block diagram of a single-channel, digital ratioed frequency-shift electronics unit is illustrated in Figure G-1.

The ratioed frequency-shift electronics unit utilizes the change in inductance caused by a vehicle passing over a loop to measure the altered electronics unit oscillator frequency by using a frequency counter with a selected crystal clock frequency and frequency multiplier that make the sensitivity independent of the oscillator frequency.

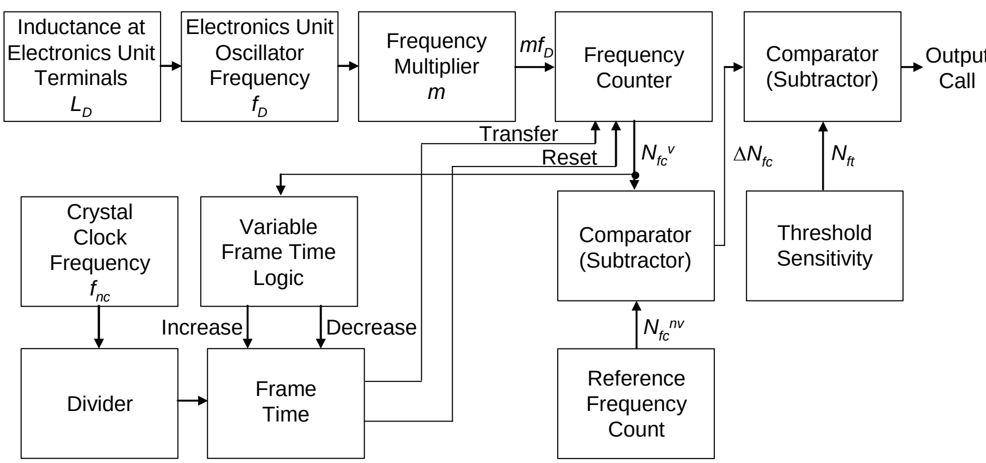

Figure G-1. Digital ratioed frequency-shift electronics unit block diagram.

The sensitivity S_D^f of a digital ratioed frequency-shift electronics unit is given by

$$S_D^f = \left(\frac{-2 N_{fc} \, f_{nc}}{m \, f_D} \right) \qquad \text{(G-1)}$$

where the parameters in equation G-1 are defined in Figure G-1.

If

$$\frac{f_{nc}}{m \, f_D} = \text{constant proportional to } \frac{1}{N_{fc}}, \qquad \text{(G-2)}$$

the sensitivity is independent of the electronics unit oscillator frequency f_D.

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 response time of the electronics unit is primarily dependent on the time required to fill the frequency counter and is equal to

$$t^{f} = \frac{f_{nc}}{m\, f_D} = \frac{2\, N_{ft}}{m\, f_D\, S_D^{f}}\,. \tag{G-3}$$

Since N_{ft} and S_D^{f} are constant, the response time changes in proportion to the electronics unit oscillator frequency.

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APPENDIX H. DIGITAL PERIOD-SHIFT ELECTRONICS UNIT ANALYSIS

ABSTRACT

Appendix H describes the derivation of the digital period-shift electronics unit sensitivity, which is shown to be proportional to the threshold count N_{pt} divided by the total number of counts N_{pc} in the frequency counter. The response time is proportional to the threshold count, divided by the product of the sensitivity and the frequency of the crystal clock.

The period-shift electronics unit utilizes the change in inductance caused by a vehicle passing over a loop to measure the altered electronics unit oscillator frequency using a counter to count the number of pulses that occur during the electronics unit oscillator period.

ANALYSIS

The oscillator in a digital period-shift electronics unit operates at a frequency f_D, which is determined by the loop, lead-in cable, and the electronics unit tuning network. The number m of oscillator cycles from the period scaler 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 sent to the period counter, making the electronics unit more sensitive.

A simplified block diagram of a single channel, digital period-shift vehicle electronics unit is illustrated in Figure H-1. The change in inductance at the electronics unit terminals caused by a vehicle produces a change in the oscillator frequency. The sine wave oscillator frequency is converted by a period scaler into a square wave. The square wave is input to an AND gate, which compares the signal level (i.e., high or low) to that of the crystal clock frequency pulse.

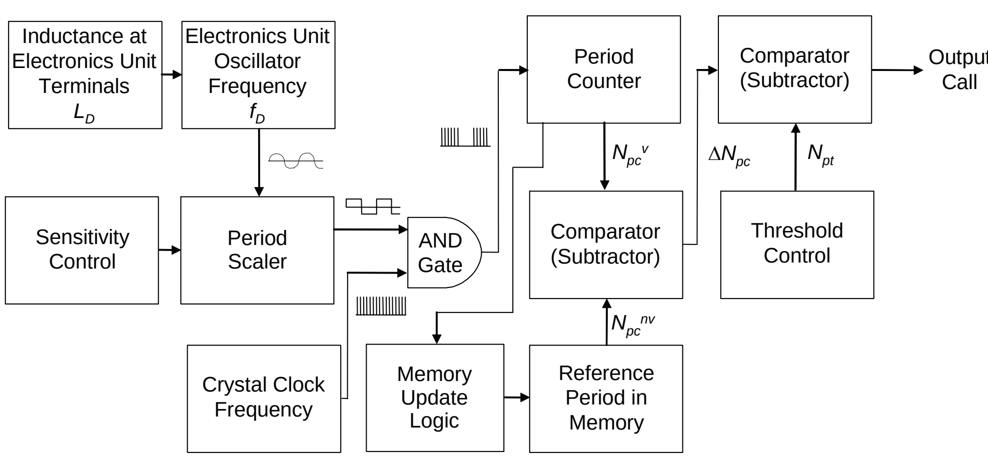

Figure H-1. Digital period-shift electronics unit block diagram.

If both the square wave and the crystal clock pulse are high, a count is sent to the period counter. The count is equal to the number of clock pulses that occur in a period.

At the end of the period, the count is sent to the first comparator. The comparator subtracts the reference period count stored in memory, which represents the count when no vehicle is present, from the current period count. The difference enters the second comparator. If the second comparator finds that the difference is in excess of the threshold sensitivity, then a vehicle is presumed present and a call is output.

The period T_{DC} of the electronics unit oscillator is

$$T_{DC} = mT_D \tag{H-1}$$

where

T_D = $1/f_D$ = period of electronics unit oscillator in s

f_D = electronics unit oscillator frequency in Hz

m = number of oscillator cycles from the period scaler.

The length of the gating pulse is

$$T_g = \left(\frac{T_{DC}}{2}\right) = \left(\frac{mT_D}{2}\right) . \tag{H-2}$$

The number N_{pc} of clock pulses counted by the period counter is

The count of the period counter is proportional to the electronics unit oscillator period T_D.

$$N_{pc} = \left(\frac{T_g}{T_C}\right) = \left(\frac{mT_D}{2T_C}\right) , \tag{H-3}$$

where T_C is the period of the crystal clock equal to the inverse of the clock frequency.

The number of clock pulses stored in the reference memory when no vehicle is present is

$$N_{pc}^{nv} = \left(\frac{m{T_D}^{nv}}{2T_C}\right) . \tag{H-4}$$

The number of clock pulses counted when a vehicle is present is

$$N_{pc}^{v} = \left(\frac{m{T_D}^{v}}{2T_C}\right) . \tag{H-5}$$

Since the loop inductance decreases when a vehicle is sensed, the electronics unit oscillator frequency f_D increases and the oscillator period T_D decreases. Then

$$f_D^v > f_D^{nv} \text{ implies } N_c^{nv} > N_c^v . \tag{H-6}$$

The output of the first comparator is

$$\Delta N_{pc} = N_{pc}^{nv} - N_c^v = \left(\frac{m}{2T_C}\right)\left(T_D^{nv} - T_D^v\right) . \tag{H-7}$$

Since

$$\Delta T_D = \left(T_D^{nv} - T_D^{v}\right) , \qquad \text{(H-8)}$$

the output of the first comparator can be written as

$$\Delta N_{pc} = \left(\frac{m}{2T_C}\right)\Delta T_D . \qquad \text{(H-9)}$$

The output count of the first comparator is proportional to the change ΔT_D in the oscillator period.

When the output count ΔN_{pc} of the first comparator equals the threshold count N_{pt} in the second comparator, a vehicle call results.

Then,

$$\Delta N_{pc} = N_{pt} . \qquad \text{(H-10)}$$

Thus,

$$N_{pt} = \left(\frac{m}{2T_C}\right)\Delta T_D . \qquad \text{(H-11)}$$

For a high quality factor tuned circuit, the normalized period shift is approximated by

$$\left(\frac{\Delta T_D}{T_D}\right) = \left(\frac{1}{2}\right)\frac{\Delta L_D}{L_D} = \left(\frac{1}{2}S_D^p\right) . \qquad \text{(H-12)}$$

Solving for sensitivity, we get

$$S_D^p = \left(\frac{2\Delta T_D}{T_D}\right) \qquad \text{(H-13)}$$

$$= \left(\frac{4N_{pt}T_C}{mT_D}\right) . \qquad \text{(H-14)}$$

Since

$$T_C = \left(\frac{1}{f_C}\right) \qquad \text{(H-15)}$$

and

$$T_D = \left(\frac{1}{f_D}\right) \qquad \text{(H-16)}$$

$$S_D^p = \left(\frac{4N_{pt}\,f_D}{m\,f_C}\right) \qquad \text{(H-17)}$$

when

$$f_D = \left(\frac{1}{2\pi\sqrt{L_D C_D}}\right) \qquad \text{(H-18)}$$

$$S_D^p = \left(\frac{2N_{pt}}{\pi m \, f_C \sqrt{L_D C_D}} \right) . \tag{H-19}$$

Letting

$$K_p = \left(\frac{2N_{pt}}{\pi m f_C} \right), \tag{H-20}$$

the sensitivity becomes

$$S_D^p = \left(\frac{K_p}{\sqrt{L_D C_D}} \right) \tag{H-21}$$

since

$$N_{pc} = \left(\frac{mT_D}{2T_C} \right) = \left(\frac{m \, f_C}{2 \, f_D} \right) \tag{H-22}$$

from Equation H-3,

The sensitivity of the digital period-shift electronics unit is twice the threshold count divided by the maximum number of counts on the period counter.

$$S_D^p = \left(\frac{2N_{pt}}{N_{pc}} \right) . \tag{H-23}$$

The response time of the digital period-shift electronics unit is primarily due to the time required to fill the period counter with clock pulses. Thus,

$$t^p = N_{pc} T_C = \left(\frac{N_{pc}}{f_C} \right) . \tag{H-24}$$

Rewriting equation H-23 to solve for N_{pc}, we get

$$N_{pc} = \left(\frac{2N_{pt}}{S_D^p} \right) . \tag{H-25}$$

Upon substituting this result into equation H-24, the response time becomes

$$t^p = \left(\frac{2N_{pt}}{S_D^p \, f_C} \right) . \tag{H-26}$$

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APPENDIX I. DIGITAL RATIOED PERIOD-SHIFT ELECTRONICS UNIT ANALYSIS

ABSTRACT

Appendix I describes the derivation of the digital ratioed period-shift electronics unit sensitivity, which is shown to be equal to the threshold count N_{pt} divided by 2. The response time is identical to the response time of the digital period-shift electronics unit. Thus, the response time is proportional to the threshold count divided by the product of the sensitivity and the frequency of the crystal clock oscillator.

ANALYSIS

The ratioed period- shift electronics unit utilizes the change in inductance caused by a vehicle passing over a loop to measure the altered electronics unit oscillator frequency using a counter to count the number of pulses that occur during the electronics unit oscillator period and a variable threshold count to make the sensitivity independent of the oscillator frequency.

A simplified block diagram of a single channel, digital ratioed period-shift electronics unit is illustrated in Figure I-1. This electronics unit is similar to the digital period shift electronics unit except for the variable threshold count, which allows the sensitivity to be independent of the electronics unit oscillator frequency.

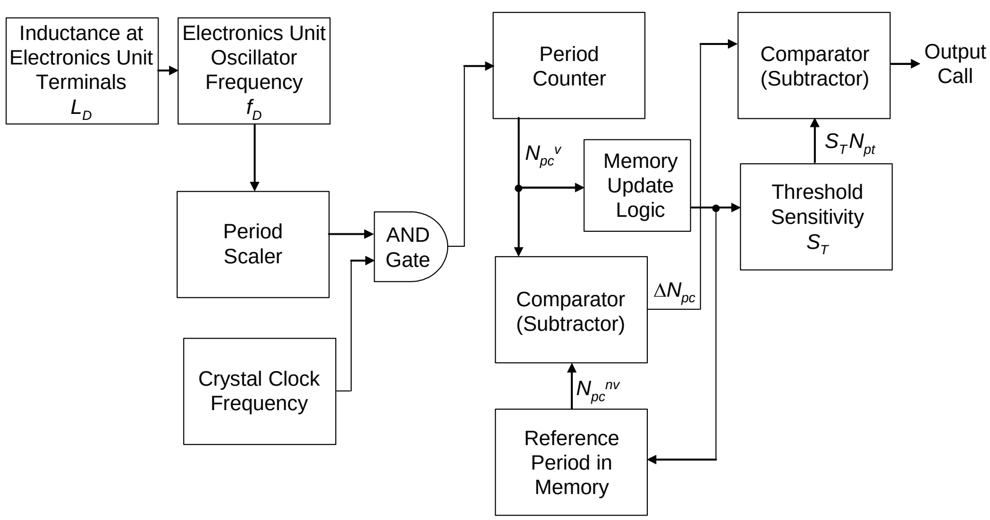

Figure I-1. Digital ratioed period-shift electronics unit block diagram.

The ratioed period-shift electronics unit sensitivity S_D^p is given by

$$S_D^p = \frac{-2\,N_{pt}}{N_{pc}} \qquad \text{(I-1)}$$

where the threshold count N_{pt} is a constant and the count established by the period counter N_{pc} is inversely proportional to the electronics unit oscillator frequency. The oscillator frequency is a function of loop inductance.

A variable threshold N_{pt} is selected by multiplying the count established by the period counter by a preset sensitivity factor. Thus,

$$N_{pt} = S_t\,N_{pc} \qquad \text{(I-2)}$$

or

$$N_{pt} = \frac{-2\,S_t\;N_{pc}}{N_{pc}} = -2\,S_t\,. \tag{I-3}$$

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Numbered headings correspond to the numbering of sections in the NEMA standard. Unnumbered sections are narrative explaining the context of the document.

LIST OF FIGURES: APPENDIX J.

Numbers for figures and tables correspond to the numbering in the NEMA standard. Therefore, figure and table numbering are NOT sequential in this appendix.

NEMA captions are in all capital letters.

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APPENDIX J. NEMA DETECTOR STANDARDS EXCERPTS

INTRODUCTION

The following excerpts are provided from NEMA Standards Publication TS 2-2003 v02.06, *Traffic Controller Assemblies with NTCIP* [National Transportation Communications for Intelligent Transportation Systems (ITS) Protocol] *Requirements*. TS 2-2003 v02.06 is a revised and reballoted version of TS 2-1998. Version v02.06 includes the revisions from TS 2 amendment 1 v01 and also includes minor revisions to sections 3, 5, and 6. TS 2-2003 v02.06 was balloted in January 2003 and approved by NEMA in May 2003.

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NEMA TS 2-2003 is published by the National Electrical Manufacturers Association, 1300 North 17th Street, Suite 1847, Rosslyn, VA 22209. For further information and to order a complete copy of the standard, visit www.nema.org. NEMA TS 2 was developed and is maintained by the member companies in the NEMA Transportation Management Systems and Associated Control Devices Product Group.

 For clarity, text in [square brackets] has been revised from the original.

NOTES:

1. NEMA standards have headers and text set in Arial, normal, 10-point type. Heading, figure and table numbers and font type in this appendix correspond to those in the actual NEMA standard rather than those found in rest of the *Traffic Detector Handbook*.
2. The term *detector* as used by NEMA is replaced by the terms *sensor* or *electronics unit*, depending on context, in the other chapters and sections of this *Handbook*.
3. In case of conflict with *Detector Terms and Definitions* beginning on page J-2, those listed in Chapter 1 and Appendix P are recommended for the applications described in this *Handbook*.

NEMA TS 1 AND TS 2 TRAFFIC CONTROL SYSTEMS

The NEMA TS 2 standard expands on the older NEMA TS 1 Traffic Control Systems standard. The TS1 standard was based on the philosophy that controllers would provide a basic set of features and standard connectors. Manufacturers would compete based on the hardware and software they provided inside the controllers. The NEMA TS1 standard was successful for isolated actuated intersection control, but it lacked sufficient detail for implementing more advanced features, such as coordinated-actuated operation and preemption. Type 1 systems include the controller unit, conflict monitor, and the included features of each. Individual vendors supplemented the TS 1 standard by providing the complement of features necessary for deploying coordinated-actuated traffic signal systems. This introduced incompatibility and procurement issues, particularly when government agencies needed to upgrade existing signal systems at a later date and had to solicit competitive bids. Nevertheless, the competitive market forces continued to rapidly advance the state of the practice and created a following that led many States to adopt the NEMA standard. In the late 1980s and early 1990s, the NEMA TS1 specification was updated with NEMA TS2 to provide coordinated-actuated operation, preemption, and an optional serial bus to simplify wiring.(1)

The detectors, referred to as electronics units in other chapters of this *Handbook*, are described in the TS 2 standard by the following attributes:

- Rack mounted, 16 detector channels per rack, up to four racks.
- Port 1 connector: pluggable, interchangeable Bus Interface unit to convert Port 1 high speed serial data to format required by individual detectors.
- Communications with controller unit, as described above.
- Per channel diagnostic data: open loop; shorted loop; excessive inductance change; watchdog failure.
- Detector reset capability.
- Operation from either 12 volt or 24 volt DC power supply.

DETECTOR TERMS AND DEFINITIONS

These definitions reflect the consensus of the traffic control equipment industry as represented by NEMA and are intended to be in harmony with terminology in current usage, such as is published in the *Manual on Uniform Traffic Control Devices* and various technical reports of the Institute of Transportation Engineers.

1.2.4 Detection

1.2.4.1 Advisory Detection

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.

1.2.4.2 Passage Detection

The ability of a vehicle detector to detect the passage of a vehicle moving through the zone of detection and to ignore the presence of a vehicle stopped within the zone of detection.

1.2.4.3 Presence Detection

The ability of a vehicle detector to sense that a vehicle, whether moving or stopped, has appeared in its zone of detection.

1.2.5 Detector

A device for indicating the presence or passage of vehicles or pedestrians.

1.2.5.1 Bidirectional Detector

A detector that is capable of being actuated by vehicles proceeding in either of two directions and of indicating in which of the directions the vehicles were moving.

1.2.5.2 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.

1.2.5.3 Classification Detector

A detector that has the capability of differentiating among types of vehicles.

1.2.5.4 Directional Detector

A detector that is capable of being actuated only by vehicles proceeding in one specified direction.

1.2.5.5 Extension Detector

A detector that is arranged to register actuations at the controller unit only during the green interval for that approach so as to extend the green time of the actuating vehicles.

1.2.5.6 Infrared Detector

A detector that senses radiation in the infrared spectrum.

1.2.5.7 Light-Sensitive Detector

A detector that utilizes a light-sensitive device for sensing the passage of an object interrupting a beam of light directed at the sensor.

1.2.5.8 Loop Detector

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

1.2.5.9 Magnetic Detector

A detector that senses changes in the earth's magnetic field caused by the movement of a vehicle near its sensor.

1.2.5.10 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.

1.2.5.11 Nondirectional Detector

A detector that is capable of being actuated by vehicles proceeding in any direction.

1.2.5.12 Pedestrian Detector

A detector that is responsive to operation by or the presence of a pedestrian.

1.2.5.13 Pneumatic Detector

A pressure-sensitive detector that uses a pneumatic tube as a sensor.

1.2.5.14 Pressure-Sensitive Detector

A detector that is capable of sensing the pressure of a vehicle passing over the surface of its sensor.

1.2.5.15 Radar Detector

A detector that is capable of sensing the passage of a vehicle through its field of emitted microwave energy.

1.2.5.16 System Detector

Any type of vehicle detector used to obtain representative traffic flow information.

1.2.5.17 Side-Fire Detector

A vehicle detector with its sensor located to one side of the roadway.

1.2.5.18 Sound-Sensitive Vehicle Detector

A detector that responds to sound waves generated by the passage of a vehicle near the surface of the sensor.

1.2.5.19 Ultrasonic Detector

A detector that is capable of sensing the passage or presence of a vehicle through its field of emitted ultrasonic energy.

1.2.6 Detector Mode

A term used to describe the operation of a detector channel output when a presence detection occurs.

1. Pulse Mode: Detector produces a short output pulse when detection occurs.
2. 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 zone of detection.
3. Continuous-Presence Mode: Detector output continues if any vehicle (first or last remaining) remains in the zone of detection.
4. Limited-Presence Mode: Detector output continues for a limited period of time if vehicles remain in zone of detection.

1.2.7 Inductive Loop Detector System

See 1.6.56.5.1.5.

1.2.8 Inductive Loop Detector Unit

See 6.5.1.6.

1.2.9 Lead-in Cable

See 1.6.56.5.1.4

1.2.10 Output

1.2.10.1 Extension Output

The ability of a detector to continue its output for a predetermined length of time after the vehicle has left its zone of detection.

1.2.10.2 Delayed Output

The ability of a detector to delay its output for a predetermined length of time after a vehicle has entered its zone of detection.

1.2.11 Probe

The sensor form that is commonly used with a magnetometer type detector.

1.2.12 Sensor

The sensing element of a detector.

1.2.13 Vehicle Detector System

See 6.5.1.10.

1.2.14 Zone of Detection (Sensing Zone)

That area of the roadway within which a vehicle will be detected by a vehicle detector system.

ENVIRONMENTAL TESTING OF DETECTORS

[NEMA TS 2-2003] Section 2 relates to environmental standards and operating conditions for intersection traffic control equipment. This section establishes the limits of the environmental and operation conditions in which the Controller Assembly will perform. This section defines the minimum test procedures which may be used to demonstrate conformance of a device type with the provisions of the standard. These test procedures do not verify equipment performance under every possible combination of environmental requirements covered by this standard.

2.8 LOOP DETECTOR UNIT TESTS

The Loop Detector Unit shall perform its specified functions under the conditions set forth in this Section. This Clause defines the test procedures required to demonstrate the conformance of a Loop Detector Unit with the provisions of the standards.

2.8.1 Environmental Requirements

Loop detector units shall operate in accordance with requirements listed herein under the following environmental conditions.

2.8.1.1 Voltage, DC Supply

1. Voltage Range—The voltage range shall be 10.8 VDC minimum to 26.5 VDC maximum.

2. Ripple—The maximum supply ripple shall be 500 millivolts peak to peak.

2.8.1.2 Temperature and Humidity

Temperature and humidity shall be in accordance with 2.1.5.

2.8.1.3 Transients, DC Powered Units

Loop detector units shall operate normally when the test impulse described in 2.1.7 is applied as follows:

1. Between **Logic Ground** and the DC Supply power input. The test setup shown in Figure 2-4 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.

In the NEMA standard, tables and figures are delineated by a double ruled bar at the top and bottom of the table or figure. When the figure or table has notes at the bottom, the double rule is below the notes. This delineation is kept in this appendix for consistency with the standard.

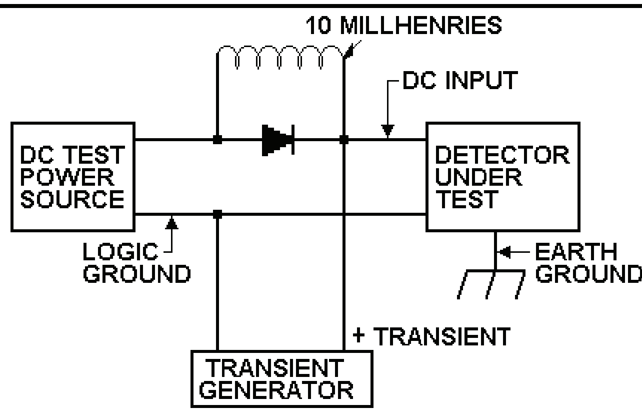

Figure 2-4
TEST CONFIGURATIONS

TEST CONDITIONS:

The transient generator is described in 2.1.7.

The input voltage shall be 10.8 to 26.5 volts DC measured at the input terminal to the loop detector unit under test.

The DC power source must be capable of supplying at least 50 milliamperes per channel.

When testing for the reverse polarity transient, the diode shown shall be reversed.

2.8.1.4 Transients, Loop Detector Input Terminals

The loop detector unit shall be capable of withstanding the eight nondestructive transient tests described in Figure 2-5. Each test shall be repeated 10 times with the loop detector unit operating from its normal power source. The time between repetitions shall not exceed 10 seconds.

The energy source shall be a capacitor, oil filled, 10 microfarads ± 5 percent, internal surge impedance less than 1 ohm connected in accordance with Figure 2-5. The voltage on the capacitor shall be adjusted as described herein. The test push button shall be activated for at least one second for each of the 80 test repetitions.

After the foregoing tests, the loop detector unit shall operate normally.

1. Test Numbers 1 and 5. The Loop detector unit shall withstand the discharge of a 10 microfarad capacitor charged to ± 1000 volts applied directly across the loop detector unit sensor loop input pins with no sensor loop load present.
2. Test Numbers 2, 3, 4, 6, 7, and 8. The loop detector unit shall withstand the discharge of a 10 microfarad capacitor charged to ± 2000 volts applied directly across either the loop detector unit sensor loop input pins or from either side of the sensor loop input pins to equipment ground. The loop detector unit sensor loop input pins shall have a dummy resistive load attached equal to 5.0 ohms ± 10 percent.

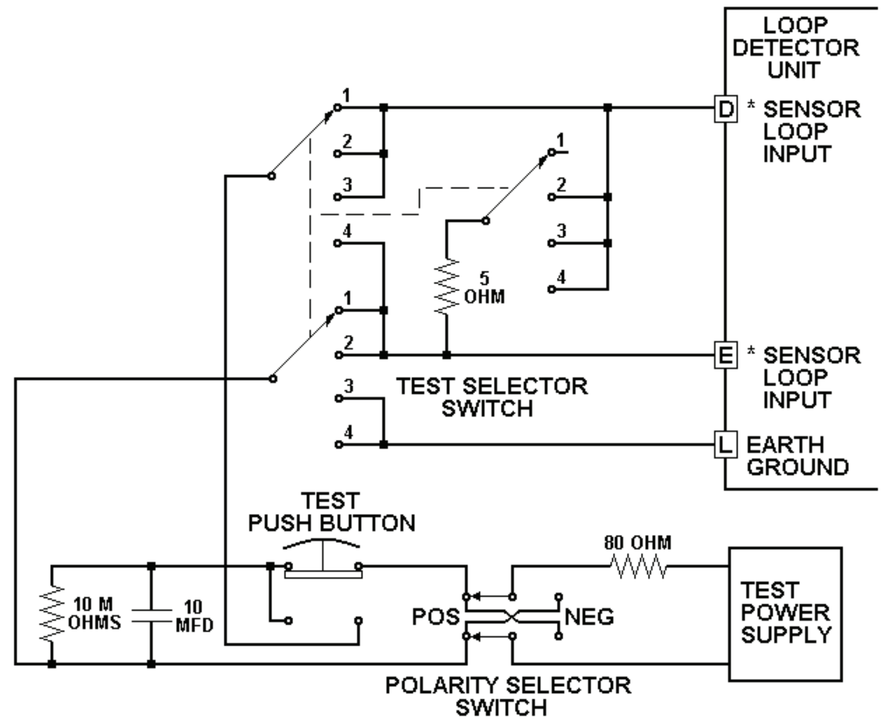

Figure 2-5
LOOP INPUT TERMINAL TRANSIENT TESTS

The Transient Test Configurations data are not listed as a table in the NEMA specifications. Therefore, for consistency they are not listed as a table in this appendix.

Transient Test Configurations

Test Number	Test Selector Position	Power Supply Setting +5%	Polarity Selector	Load Across Detector Input	Tested Inputs
1	1	1000	Positive	None	D to E
2	2	2000	Positive	5 ohms	D to E
3	3	2000	Positive	5 ohms	D to L
4	4	2000	Positive	5 ohms	E to L
5	1	1000	Negative	None	D to E
6	2	2000	Negative	5 ohms	D to E
7	3	2000	Negative	5 ohms	D to L
8	4	2000	Negative	5 ohms	E to L

*The pin designations shown are for Channel 1. Similar tests shall be performed on all channels (i.e., pin pairs J and K, P and R, and U and V, respectively and as applicable) of the loop detector unit.

2.8.1.5 Vibration

The loop detector unit shall maintain both its physical integrity and operating characteristics after being subjected to the vibration test in 2.2.8. This test shall be run at nominal voltage and room environmental conditions.

2.8.1.6 Shock

The loop detector unit shall suffer neither permanent mechanical deformation nor any damage which renders it permanently inoperable after being subjected to the shock test described in 2.2.9.

This test shall be run at room environmental conditions without power applied to the unit.

MINIMUM REQUIREMENTS FOR DETECTORS

[NEMA TS 2-2003 Section 6] defines the minimum requirements for auxiliary devices within the cabinet, consisting of solid state load switches, solid state flashers, flash transfer relays, and inductive loop detector units.

[In the] TS 2-1998 update of TS 2-1992, the SECTION 6 [was revised to include these changes in detector specifications:]

Detector Configurations has been modified to add four new types (AC, BC, CC, & DC) with communications port TX & RX capability.

Detection Outputs & Status Outputs condition has been added for the Disable and Reset states.

Detector Connector Terminations has been modified to add Detector Address Bit #3.

6.5 INDUCTIVE LOOP DETECTOR UNITS

Clause 0 responds to the need for a series of Inductive Loop Detector Units which provide inputs for traffic-actuated or traffic-responsive control, surveillance, or data collection systems. The Inductive Loop Detector Unit 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. On standard loops this reaction is a reduction in loop inductance.

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 Detector Unit may be used directly to provide an input to a vehicle-actuated traffic CU or provide inputs to traffic-responsive control and surveillance systems. Detector Units 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. When two loops are placed in a lane, one downstream from the other, the time between the sequential responses of detectors attached to these loops may be used to measure speed.

6.5.1 Loop Detector Unit Definitions

6.5.1.1 Channel

Electronic circuitry which functions as a Loop Detector System.

6.5.1.2 Crosstalk

The adverse interaction of any channel of a Detector Unit with any other channel.

6.5.1.3 Detector Mode

A term used to describe the duration and conditions of the occurrence of a detector output.

6.5.1.4 Lead-In Cable

The electrical cable which serves to connect the sensor loop(s) to the input of the Detector Unit.

6.5.1.5 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).

6.5.1.6 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 output(s) which indicates the passage or presence of vehicles in the zone(s) of detection.

6.5.1.7 Reset Channel

A command for the Detector Unit to calculate a new reference frequency (the frequency that the loop oscillates at when no vehicle is influencing the loop) for the channel being reset and to appropriately adjust other channel related parameters.

6.5.1.8 Reset Unit

A command for the Detector Unit to set all parameters to the states they would be set at if power had been applied at the moment the RESET command is received or released.

6.5.1.9 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.

6.5.1.9 Vehicle Detector System

A system for indicating the presence or passage of vehicles.

6.5.1.9 Zone of Detection

That area of the roadway within which a vehicle is detected by a vehicle detector system.

6.5.2 Functional Standards

6.5.2.1 Operation

The 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.

6.5.2.2 Configurations and Dimensions

6.5.2.2.1 Configurations

This standard covers Detector Unit configurations shown in Table 6-1.

Table 6-1 DETECTOR UNIT TYPES

Rack Mount Detector Unit Type	NEMA Detector Unit Designations	Delay/Extension Timing	Communication Port RX & TX
2 Channel	Type A	None	No
4 Channel	Type B	None	No
2 Channel	Type C	Included	No
4 Channel	Type D	Included	No
2 Channel	Type AC	None	Yes
4 Channel	Type BC	None	Yes
2 Channel	Type CC	Included	Yes
4 Channel	Type DC	Included	Yes

Each channel shall be provided with independent loop input terminals and shall deliver detection information on independent output terminals.

6.5.2.2.2 Dimensions

1. Two-channel card rack units shall be 28.96 mm (1.14 in.) max. W x 114.3 mm (4.5 in.) H x 177.8 mm (7.00 in.) D, excluding the handle as shown in Figure 6-4.

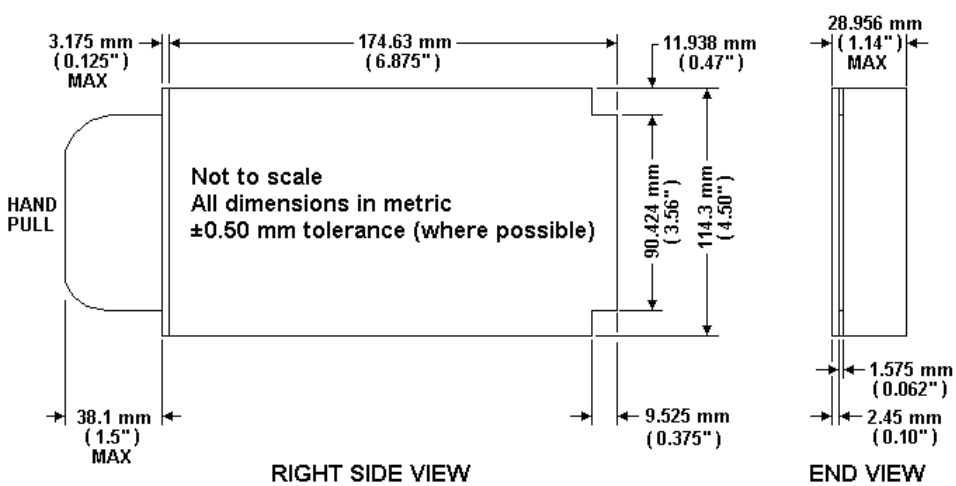

Figure 6-4
TWO CHANNEL CARD RACK UNIT

2. Four-channel card rack units shall be 59.44 mm (2.34 in.) max. W x 114.3 mm (4.5 in.) H x 177.8 mm (7.00 in.) D, excluding the handle as shown in Figure 6-5.

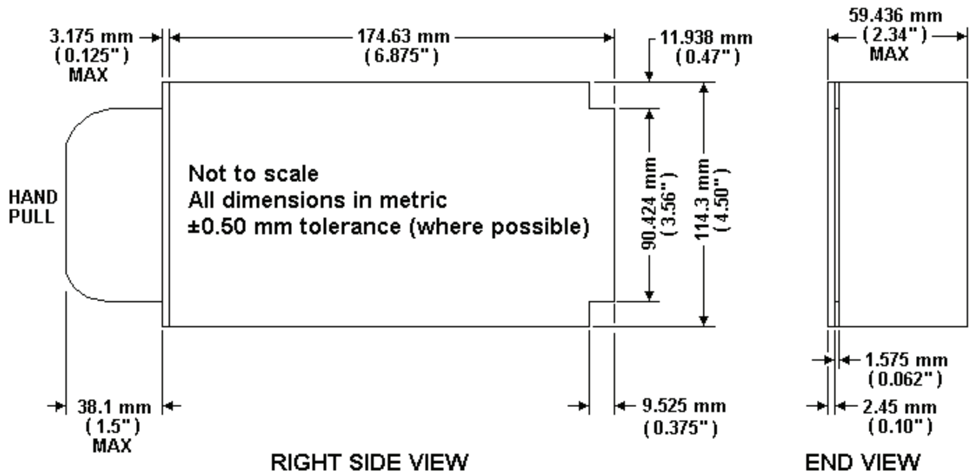

Figure 6-5
FOUR CHANNEL CARD RACK UNIT

6.5.2.3 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.

6.5.2.4 Material and Construction of Rigid Printed Circuit Assemblies

6.5.2.4.1 Materials

All printed circuit boards shall be per 3.2.3.1.

6.5.2.4.2 Component Identification

All components shall be identified per 3.2.3.3.

6.5.2.5 Power Inputs

Detector Unit DC Supply Voltage

1. Voltage Range–The voltage range shall be 10.8 VDC minimum to 26.5 VDC maximum.

2. Ripple–The maximum supply ripple shall be 500 millivolts peak to peak.

This input supplies power. The current consumption shall not exceed 50 milliamperes per channel. The return for this input is **Logic Ground** as described in 6.5.2.6. This input shall not be connected within the unit to any loop input. The input shall draw a surge current not to exceed 5 amperes at the time of power application to the input. The Detector Unit shall not be damaged by insertion to or removal from a powered Detector Rack.

6.5.2.5.2 Low Supply Voltage Automatic Reset

A **Reset Unit** condition shall be activated anytime the input DC supply voltage falls below that which is required for operation, as defined in this standard.

A **Reset Unit** condition shall not be activated when the DC Supply Input falls below 10 volts for less than 0.25 milliseconds.

6.5.2.6 Logic Ground

This input is the return for the Detector Unit DC Supply input. This point shall not be connected within the unit to AC Neutral, Earth Ground, or to any loop input terminal.

6.5.2.7 Earth 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 Neutral**, 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 or front panel, the case and/or front panel shall be connected to **Earth Ground**.

6.5.2.8 DC Control Inputs

Control inputs shall have the following characteristics as measured from **Logic Ground**.

6.5.2.8.1 Low or Active State

A voltage between 0 and 8 volts shall be considered the **Low** or active state.

6.5.2.8.2 High or Inactive State

A voltage greater than 16 volts shall be considered the **High** or inactive state.

6.5.2.8.3 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.

6.5.2.8.4 External Transition Time

External transition from **Low** state to **High** state and vice versa shall be accomplished within 0.1 milliseconds.

6.5.2.8.5 Maximum Current

Over the voltage range 0 to 26 volts DC, the maximum current **In** or **Out** of any input control terminal shall be less than 10 milliamperes. The input circuitry shall be returned to the Detector Unit 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 **High** or inactive state. Rising to Detector Unit DC supply voltage is permitted.

6.5.2.8.6 Signal Recognition

Any input signal (including External Reset, Pin C) shall respond as defined in 3.3.5.1.3.

All channels shall remain in a RESET UNIT or RESET CHANNEL condition, see 6.5.1.7 and 6.5.1.8, while Pin C is held in an Active State (**Low**) voltage.

6.5.2.8.7 Activation of Delay/Extension Feature

The application of a **Low** state voltage to a **Delay/Extension** input shall function to inhibit the delay timing function and/or enable the extend timing function.

This input is provided for downward compatibility. (Authorized Engineering Information.)

6.5.2.8.8 Activation of Detector Unit Address Feature

The application of a **Low** state voltage to a **Detector Unit Address** input shall activate the input, e.g. it is a logic **1**. Four address input pins shall provide for a maximum of 15 hard wired addresses. Address FF(hex) shall be a broadcast address.

6.5.2.9 Data Receive (RX) Input

The Data Receive input, RX, must have an input impedance 45 kohm to 105 kohm and an input capacitance less than 250 picofarads. This input impedance shall terminate to DC common. The input open circuit voltage shall be less than 0.9 VDC. The input shall be functional when voltages over the range of ±25 VDC are applied to it. The Transition Region is any voltage between a Mark and a Space.

6.5.2.9.1 Mark State (Binary 1)

During Mark, the RX input shall recognize as a Mark voltages less than 0.9 VDC.

6.5.2.9.2 Space State (Binary 0)

During Space, the RX input shall recognize as a Space voltages greater than 3.0 VDC.

6.5.2.9.3 Other States

The RX input shall not be damaged when connected to any voltage up to 26 VDC and:

1. Shall rise to >8.5 VDC when connected to +12 VDC through 30 kohm.
2. Shall rise to >16 VDC when connected to +22 VDC through 11 kohm.

6.5.2.9.4 Transient Withstand

The RX input shall not be damaged by application of the transients described in 2.1.7.1 through 2.1.7.5.

6.5.2.10 Loop Inputs

Two loop input terminals shall be provided for each sensor channel. These inputs shall be isolated (resistance > 10^6 and breakdown voltage >1000 V rms) from **Logic Ground**, **AC Neutral**, and the control input and output circuits.

6.5.2.11 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 1000 microhenrys.
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 Unit manufacturer's recommendation.

6.5.2.12 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 1.828 m x 1.828 m (6 ft. x 6 ft) three-turn loops and shielded lead-in cable as illustrated in Figure 6-6.

1. Single-loop 1.828 m x 1.828 m (6 ft by 6 ft), three turns, with 30.48 m (100 ft) of lead-in (80–105 microhenrys).
2. Single-loop 1.828 m x 1.828 m (6 ft by 6 ft), three turns, with 304.8 m (1,000 ft) of lead-in (260–320 microhenrys).
3. Four loops 1.828 m x 1.828 m (6 ft by 6 ft), three turns, in a row in the direction of travel and separated by 2.743 m (9 ft), series/parallel connected with 76.0 m (250 ft) of lead-in (100–140 microhenrys).

6.5.2.13 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 1.828 m x 1.828 m (6 ft x 6 ft), three-turn-test loop with 30.48 m (100 ft) of lead-in.

These minimum reductions are as follows:

1. Class 1: 0.13 percent ($\Delta L/L$) or 0.12 microhenrys (ΔL) inductance change with a single 1.83 m x 1.83 m (6 ft x 6 ft), three turn loop, with 30.48 m (100 ft) lead-in (small motorcycle).
2. Class 2: 0.32 percent ($\Delta L/L$) or 0.3 microhenrys (ΔL) inductance change with a single 1.83 m x 1.83 m (6 ft x 6 ft), three turn loop, with 30.48 m (100 ft) lead-in (large motorcycle).
3. Class 3: 3.2 percent ($\Delta L/L$) or 3 microhenrys (ΔL) inductance change with a single 1.83 m x 1.83 m (6 ft x 6 ft), three turn loop, with 30.48 m (100 ft) lead-in (automobile).

   The maximum reduction caused by a class three vehicle shall be 5.4 percent ($\Delta L/L$) or 5 microhenrys (ΔL) inductance change with a single 1.83 m x 1.83 m (6 ft x 6 ft), three-turn loop with 30.48 m (100 ft) lead-in.

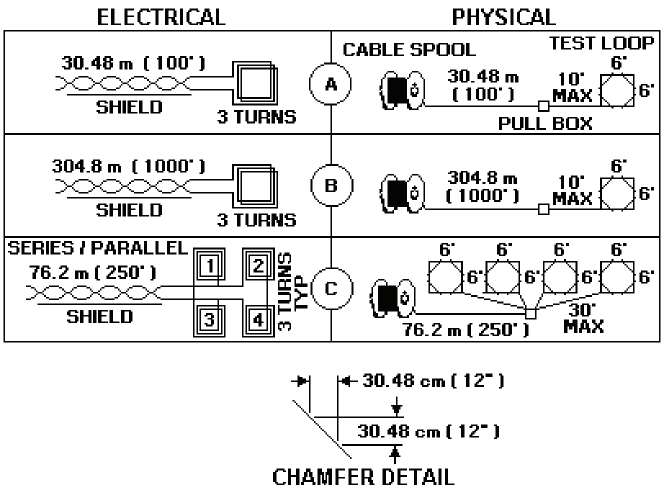

Figure 6-6
TEST LOOP CONFIGURATIONS

Construction–Loop dimension tolerances shall be +50.8 mm (2 in.). Connections shall be soldered and waterproofed. Loops shall be installed in a non-reinforced pavement and located at least 0.914 m (3 feet) 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 0.305 m (12 in.).

Loop Wire–Each loop shall be three turns of AWG #14 cross-linked polyethylene insulated, stranded copper wire, such as IMSA (International Municipal Signal Association) Specification 51-3, 1984, or equivalent. Loop inductance shall be between 60–80 microhenrys.

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 30.48 m (100 ft), 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 Unit manufacturer's recommendation. (Authorized Engineering Information).

Sawslot–The conductors shall be placed at the bottom of a 38.1 mm + 6.35 mm (1-1/2" +1/4 in.) deep by 6.35 mm (1/4 in.) wide sawslot. Pavement sawslot shall be filled with a suitable polyurethane or equivalent sealant.

6.5.2.14 Sensitivity

The Detector Unit shall be capable of detecting any of the vehicles defined in 6.5.2.14 on any of the test loops defined in 6.5.2.13.

6.5.2.15 Sensitivity Control

When detecting test vehicles as described in 6.5.2.13 and operating on any of the test loop configurations described in 6.5.2.12, 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 6.5.2.13 is 0.914 m (36 in.) or more outside the loop(s) perimeter. A minimum of three sensitivity selections shall be provided for each detection channel.

6.5.2.16 Approach Speed

The Detector Unit shall detect any vehicle described in 6.5.2.13 over any of the single loops described in 6.5.2.12 traveling within the speed range of 8.045 km to 128.72 km (5 to 80 miles) per hour.

The Detector Unit shall detect any vehicle described in 6.5.2.13 over all of the loops of the four loop configurations described in 6.5.2.12 traveling within the speed range of 8.045 km to 64.36 km (5 to 40 miles) per hour.

All channels of a multichannel Detector Unit shall be operating at the same sensitivity and connected to equivalent inductances for the purpose of these tests.

6.5.2.17 Modes of Operation

Each Detector Unit channel shall be capable of functioning in the following two front panel selectable modes:

6.5.2.17.1 Presence

When a Class 2 vehicle defined in 6.5.2.13, or larger vehicle occupies the center of any test loops described in 6.5.2.12, the Detector Unit shall be capable of maintaining a detection output for a minimum of 3 minutes.

6.5.2.17.2 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 16.09 km (10 miles) per hour across the zone of detection of the single sensor loops defined in 6.5.2.12.

6.5.2.18 Recovery from Sustained Occupancy

When operating in the presence mode, and following an occupancy of any duration, the Detector Unit shall recover to normal operation with at least 90 percent of its selected sensitivity within five seconds after the zone of detection is vacated.

6.5.2.19 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 one vehicle as defined in 6.5.2.13 within not more than 100 milliseconds when tested on either of the single loop test configurations described in 6.5.2.12. In response to step return to the original inductance, the Detector Unit shall terminate its output within no more than 100 milliseconds.

6.5.2.19.1 Variation in Response Time

The difference between the minimum measured response time and the maximum measured response time for input changes in either direction, over any number of tests, to an input change equivalent to a Class 1 vehicle shall not exceed 10 milliseconds per channel multiplied by the number of active channels. The Detector Unit must be set to the proper sensitivity to detect a Class 1 vehicle.

The difference between the minimum measured response time and the maximum measured response time for input changes in either direction, over any number of tests, to an input change equivalent to a Class 3 vehicle shall not exceed 5 milliseconds per channel multiplied by the number of active channels. The Detector Unit must be set to the proper sensitivity to detect a Class 3 vehicle.

All channels of a multichannel Detector Unit which are ON shall be operating at the same sensitivity and connected to equivalent inductances for the purpose of these tests.

For certain specific surveillance applications involving vehicle speeds in excess of 72.405 km (45 miles) per hour, a more precise response time will be required. (Authorized Engineering Information.)

6.5.2.20 Tuning

Each Detector Unit channel shall include means for accommodating the range of sensor loop/lead-in inductance.

The unit shall tune automatically upon the application of power. It shall operate with at least its minimum sensitivity within 2 seconds after application of power, and at 90 percent of its selected sensitivity within 5 seconds after application of power.

6.5.2.21 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 6.5.2.11, without producing a false output or change in sensitivity.

6.5.2.22 Recovery From Reset

After any reset, Reset Unit or Reset Channel, the Detector Unit shall operate with at least its minimum sensitivity within 2 seconds after the removal of the reset condition, and at 90 percent of its selected sensitivity within 5 seconds after the removal of the reset condition.

6.5.2.23 Crosstalk Avoidance

Each Detector Unit 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 switch.

6.5.2.24 Delay/Extension

Each channel of a unit with delay/extension shall have at least three modes of operation–delay, extension, and normal (neither delay nor extension). Channels 1 and 2 of four-channel Detector Units shall be the channels to include the delay/extension feature. Delay and extension timing shall be setable on a per channel basis with the timing programmed independently.

6.5.2.24.1 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. If a vehicle is present and the delay timer is active, when the delay inhibit is applied, the output shall become active. See Figure 6-7. This delay timing is controlled by the **Delay/Extension** input defined in 6.5.2.8.7.

The delay time shall be adjustable over the range from 0 to 30 seconds. The setability shall be within one second in the 0 to 15 second range and within two seconds in the 16 to 30 second range. The accuracy shall be ± 1/2 second or ± 5 percent of the setting, whichever is greater. When the **Delay/Extension** input is active, the delay shall be zero (0 to 0.1 second).

6.5.2.24.2 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 6-8. This extension timing is controlled by the **Delay/Extension** input defined in 6.5.2.8.7.

The extension time shall be adjustable in the range from 0 to 7-1/2 seconds. The setability shall be within 1/2 second. The accuracy shall be ± 1/2 second. When the **Delay/Extension** input is inactive, the extension shall be zero (0 to 0.1 second).

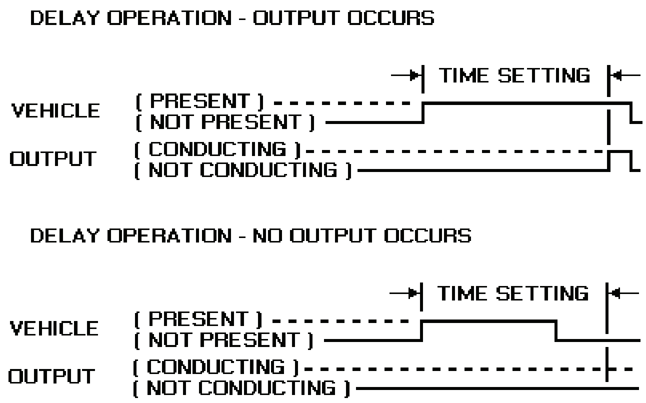

Figure 6-7
DELAY OPERATION

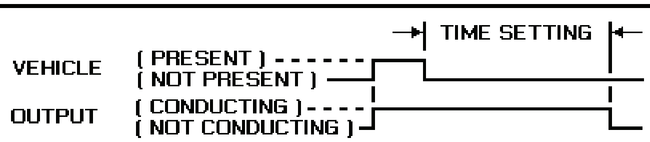

Figure 6-8
EXTENSION OPERATION

6.5.2.25 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 6.5.2.15.
3. Reset—(Reset Unit or Reset Channel or both) A control which unconditionally causes the Detector Unit or detection channel to retune to a non-vehicle present condition.

4. Mode Selector—Shall provide for selection of pulse or presence mode operation of each channel. Card mounting of this control shall be permitted where actuation does not require disassembly.
5. Crosstalk Control—As required, shall provide means to prevent interaction of channels as described in 6.5.2.23.
6. Delay/Extension Selection Control—The type C, D, CC, and DC Detector Units shall have either a control or combination of controls to allow for the selection of one of at least three operating modes–delay, extension, and normal (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 where actuation does not require disassembly.
7. Delay/Extension Timing Control—The type C, D, CC, and DC Detector Units shall provide a means to permit setting of the time duration of the delay/extension period for each channel as described in 6.5.2.24. Card mounting of this control shall be permitted where actuation does not require disassembly.
8. Enable/disable—Means to turn ON (enable) or OFF (disable) a channel or number of channels on a Detector Unit.

6.5.2.26 Outputs

6.5.2.26.1 Solid State Channel Detection Outputs

The output interface of each channel shall be an independent, isolated, solid-state output. Each output device shall have the following characteristics:

1. Output Solid-State Device—The output shall be conducting when a vehicle is detected or when the loop circuit is in a failed state (i.e., open loop or shorted loop). The channel Disabled (OFF) condition shall have the output in the non-conducting state. During a Reset (Reset Unit or Reset Channel) condition the output shall be in the conducting state.
2. DC Supply Voltage Failure Condition—The output shall be conducting when it is terminated to a NEMA defined input, indicating a 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 3.5 volt drop across the output terminals in the conducting state. The output shall conduct a maximum of 500 microamperes with any voltage between 0 and 26 VDC applied across the output terminals in the non-conductive 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 3.3.5.1.3.
6. Maximum Voltage—When in the non-conducting state, the output shall tolerate a voltage as high as 30 VDC without damage.

6.5.2.26.2 Channel Status Outputs

Each Detector Unit channel shall provide a channel status output. The channel status output shall be a solid state device with the following characteristics:

1. Output Solid State Device—The output shall be conducting when the channel is operating properly. The channel Disabled (OFF) condition shall have the output in the non-conductive state. During a Reset (Reset Unit or Reset Channel) condition the output shall be in the non-conducting state.
2. DC Supply Voltage Failure Condition—Output device is nonconductive, indicating a fault condition.
3. Status Outputs shall be referenced to logic ground.
4. Output Rating—The output shall conduct a minimum of 20 milliamperes with a maximum 3.5 volt drop across the output terminals in the conducting state. The output shall conduct a maximum of 100 microamperes with any voltage between 0 and 26 VDC applied across the output terminals in the non-conductive 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 3.3.5.1.3.
6. Maximum Voltage—When in the non-conducting state, the output shall tolerate a voltage as high as 30 VDC without damage.

6.5.2.26.3 Channel Status Reporting

The Channel Status Output shall provide for the communication of eight distinct status states as defined below:

1. Normal operation (Detector Unit and loop OK).
2. Detector Unit failure (watch dog time-out, channel currently in RESET, or channel disabled).
3. Open loop (An open loop may be reported when the terminal inductance is >1000 microhenrys and <2500 microhenrys. The open loop shall be reported when the terminal inductance is >2500 microhenrys).
4. Shorted loop (A shorted loop may be reported when the terminal inductance is <50 microhenrys and >20 microhenrys. A shorted loop shall be reported when the terminal inductance is <20 microhenrys).
5. Excessive inductance change (±25%).
6. Reserved.
7. Reserved.
8. Reserved.

Pulse width modulation shall be utilized to encode the eight possible states as described below:

1. Continuous **Low** or **On** state.
2. Continuous **High** or **Off** state.
3. 50 milliseconds **Off** time.
4. 100 milliseconds **Off** time.
5. 150 milliseconds **Off** time.
6. 200 milliseconds **Off** time.
7. 250 milliseconds **Off** time.
8. 300 milliseconds **Off** time.

The tolerance for all times listed above shall be ± 10 milliseconds; the **On** time between pulses shall be 50 milliseconds ± 10 milliseconds.

The Channel Status Output shall reflect the current fault status of the channel (i.e., the fault status shall be self clearing in the event that a fault condition clears).

The Channel Status Output shall maintain an output state, other than a condition generated during a Reset, for a minimum of 5 seconds. The Channel Detection Output shall maintain the conducting state during a fault condition only while the fault condition exists.

The Channel Status Output shall be in State 2 during RESET. Once the RESET is complete and the Detector Unit resumes normal operation, the channel status output shall return to State 1.

The Channel Status Output shall be in State 2 for channels that are disabled (OFF). The Channel Detection Output shall maintain the non-conductive state (State 2) for channels that are disabled.

The last channel failure status shall be stored in memory for future reference. Enunciation of the last failure status shall be accomplished through the use of the front panel indicators. If power is removed or the Reset is activated, the last channel status information shall be cleared.

The particular method employed to enunciate past failure status is not specified and will be manufacturer specific. (Authorized Engineering Information.)

6.5.2.26.4 Data Transmit Output (TX)

This output shall have 3 states: Mark, Space, and High Impedance. The output shall be in the High Impedance state except when transmitting to the BIU. The transmitter output shall go from the High Impedance state to the Mark state until the first Start Bit is sent. The Transition Region shall be defined as any voltage between a Mark and a Space.

6.5.2.26.4.1 Mark State (Binary 1)

During Mark, the TX output shall be less than 0.5 VDC when sinking 4 milliamperes current.

6.5.2.26.4.2 Space State (Binary 0)

During Space, the TX output shall be greater than 3.5 VDC when sourcing 4 milliamperes current.

6.5.2.26.4.3 High Impedance State

The TX output shall have an impedance greater that 1 Megohm in the High Impedance state. When connected to the following loads, the TX output in the High Impedance state:

1. Shall be >8.5 VDC when connected to +12 VDC through 30 kohm.
2. Shall be >16 VDC when connected to +22 VDC through 11 kohm.

6.5.2.26.4.4 Output Impedance During Power Off

When power is OFF, the output impedance shall be greater that 300 ohms when measured with an applied voltage not greater than 2 volts in magnitude to circuit common.

6.5.2.26.4.5 TX Output Shorts

The TX output shall not be damaged under these situations:

1. The TX output shall be capable of withstanding a continuous short to DC common.
2. The TX output shall be capable of withstanding a continuous short to +26 VDC through 600 ohms.

6.5.2.26.4.6 Rise/Fall Time

The transition time from the Space to the Mark voltage or from the Mark to the Space voltage shall be less than 2.5 microseconds or 4% of a bit time, whichever is less. This shall apply with 3750 picofarads attached to the TX output. There shall be no reversal of the direction of voltage change while the signal is in the Transition Region. The Transition Region shall not be reentered until the next change of signal condition.

6.5.2.26.4.7 Transient Withstand

The TX output shall not be damaged by application of the transients described in 2.1.7.1 through 2.1.7.5.

6.5.2.27 Communication Port Functional Requirements

The protocol for this port is under definition.

Inductive Loop Detector Unit types AC, BC, CC, and DC have this communication port.

6.5.2.27.1 Communication Port Electrical Requirements

This port, RX and TX and DC Common, is an unbalanced, +5 volt nominal, standard NRZ (Mark/Space) format, asynchronous serial communication port. For compatibility with systems currently in use, when TX is shorted to the Ch 2(+) Output and when RX is shorted to the Ch 4(+) Output, TX and RX must not interfere with Ch 2(+) or Ch 4(+) operation. See 6.5.2.9 for RX specification details and 6.5.2.26.4 for TX specification details.

6.5.2.27.2 Baud Rate

The port shall be capable of operation at a baud rate of 9600 bps ±1%. The width of 1 bit shall be the reciprocal of the baud rate.

6.5.2.27.3 Communication Parameters

The standard NRZ (Mark/Space) format shall be used. Further specifications are under definition.

6.5.2.27.4 Slot Addresses

The address of a Detector Unit slot is "hard-wired" at each Detector Rack connector. A logic 1 shall be created by wiring an address pin to DC Common. Open or +24VDC shall be a logic 0. Slot 1 shall be Address 0 and Slot 15 shall be Address 14.

6.5.2.28 Electrical Connections

6.5.2.28.1 Connector Description

Two and four channel card rack units shall mate with a 44 terminal, double row, 3.2 mm (0.156 in.) contact spacing, Cinch Jones card edge connection 50-44A-30M, or equivalent.

6.5.2.28.2 Connector Terminations

Input / Output connector pin terminations shall be as shown in Table 6-2.

Table 6-2
CONNECTOR TERMINATIONS

Pin	Function	Pin	Function
A	Logic Ground	1	Channel 1 Delay/Extension Input
B	Detector Unit DC Supply	2	Channel 2 Delay/Extension Input
C	External Reset	3	Detector Unit Address Bit #3
D	Channel 1 Loop Input	4	Channel 1 Redundant Loop Input (Optional)
E	Channel 1 Loop Input	5	Channel 1 Redundant Loop Input (Optional)
F	Channel 1 Output (+)	6	Detector Unit Address Bit #0
H	Channel 1 Output (-)	7	Channel 1 Status Output
J	Channel 2 Loop Input	8	Channel 2 Redundant Loop Input (Optional)
K	Channel 2 Loop Input	9	Channel 2 Redundant Loop Input (Optional)
L	Chassis Ground	10	Detector Unit Address Bit #1
M	Reserved (AC Neutral)	11	Reserved (AC Neutral)
N	Reserved (AC Line)	12	Reserved (AC Line)
P	Channel 3 Loop Input	13	Channel 3 Redundant Loop Input (Optional)
R	Channel 3 Loop Input	14	Channel 3 Redundant Loop Input (Optional)
S	Channel 3 Output (+)	15	Detector Unit Address Bit #2
T	Channel 3 Output (-)	16	Channel 3 Status Output
U	Channel 4 Loop Input	17	Channel 4 Redundant Loop Input (Optional)
V	Channel 4 Loop Input	18	Channel 4 Redundant Loop Input (Optional)
W	Channel 2 Output (+)	19	Data Transmit Output (TX)
X	Channel 2 Output (-)	20	Channel 2 Status Output
Y	Channel 4 Output (+)	21	Data Receive Input (RX)
Z	Channel 4 Output (-)	22	Channel 4 Status Output

6.5.2.28.3 Type A Two Channel Without Delay / Extension Timing

The following pins shall be inactive: P, R, S, T, U, V, Y, Z, 1, 2, 13, 14, 16, 17, 18, and 22.

6.5.2.28.4 Type B Four Channel Without Delay / Extension Timing

The following pins shall be inactive: 1 and 2.

6.5.2.28.4 Type C Two Channel With Delay / Extension Timing

The following pins shall be inactive: P, R, S, T, U, V, Y, Z, 13, 14, 16, 17, 18, and 22.

Pin 1 through 22 is on the top (component) side and pin A through Z is on the back (solder side). Polarization keys shall be located at three positions:

Between B/2 and C/3

Between M/11 and N/12

Between E/5 and F/6

Pins 3, 6, 10, and 15 are address pins for Type AC, BC, CC and DC Inductive Loop Detector Units. When one of these Detector Unit types are installed, it will be assigned an address associated with the Detector Unit position in the Detector Rack.

Pins 19 and 21 are the TX output and RX input for communication with the Detector Unit. The communication protocol is under definition. (Authorized Engineering Information.)

REFERENCES

1. Bullock, D., and T. Urbanik. “Traffic Signal Systems: Addressing Diverse Technologies and Complex User Needs,” TRB A3A18 Committee on Traffic Signal Systems. http://gulliver.trb.org/publications/millennium/00116.pdf/, accessed Feb. 23, 2005.

TABLE OF CONTENTS: APPENDIX K.

LIST OF TABLES: APPENDIX K.

Numbered headings correspond to the numbering of sections in the Chapter 5 of the Caltrans Transportation Electrical Equipment Specifications, *August 16, 2002 Edition. Unnumbered sections are narrative explaining the context of the document.*

APPENDIX K. CALTRANS TRANSPORTATION ELECTRICAL EQUIPMENT SPECIFICATIONS (TEES) FOR ELECTRONICS UNITS AND MAGNETIC DETECTORS

This appendix contains specifications for the following loop detectors (i.e., electronics units) and magnetic detectors (i.e., electronics units), as described in Chapter 5 of the Caltrans *Transportation Electrical Equipment Specifications* (TEES), August 16, 2002 Edition.(1)

- MODEL 222E TWO-CHANNEL LOOP DETECTOR SENSOR UNIT
- MODEL 224E FOUR-CHANNEL LOOP DETECTOR SENSOR UNIT
- MODEL 231E MAGNETIC DETECTOR SENSING ELEMENT
- MODEL 232E MAGNETIC DETECTOR SENSOR UNIT

As in Appendix J, the numbering system used in this appendix corresponds to that used in the cited specification, in this case—TEES, rather than this Handbook. The exception is that Tables K-1 and K-2 have been numbered and titled so that they can be added to the table of contents. TEES places Metric units first with the English units in parenthesis while the style of the Handbook is to place English units first with Metric units in parenthesis. Where definitions for advanced transportation controller (ATC)- and 2070-related terms are not provided, they may be found in the glossary.

SECTION 1. GENERAL REQUIREMENTS

5.1.1 – Channel Independence and Power Requirements

The sensor and isolator channels shall be operationally independent from each other. Each sensor or isolator channel shall draw no more than 50 mA from the +24 VDC [voltage direct current] cabinet power supply and shall be insensitive to 700 mV RMS [root-mean-square] ripple on the incoming +24 VDC line.

5.1.2 – Sensor Unit Features

The sensor unit or isolator front panel shall be provided with the following:

- Hand pull to facilitate insertion and removal from the input.
- Control switches.
- Channel visual indication of detection or incoming signal.

5.1.3 – Output Device Type

Each sensor or isolator channel output shall be an opto-isolated NPN open collector capable of sinking 50 mA at 30 VDC. The output shall be compatible with the controller unit inputs.

5.1.4 – Output Signal Characteristics

A valid channel input shall cause a channel Ground True Output to the controller unit of a minimum 100 ms in duration. An onboard two-post shunt jumper shall be provided to disallow this requirement when the jumper is in an OPEN position.

5.1.5 – Interface Requirements

The sensor unit or sensing element shall operate and interface successfully with an associated Caltrans Standard Sensing Unit or Element.

5.1.6 – Output Device Switching Time

The output transistor shall switch from OFF to ON state or ON to OFF state in 20 µs or less.

5.1.7 – Serial Output Definition

Each Enhanced (E) Sensor Unit shall provide a Tri-State EIA [Electronic Industries Association] 423 Serial Port for interface with through pins 19 and 21 of the unit connector to the assembly SIU [serial interface unit] Connector C03. Each sensor unit shall read in the Slot Address pins located at unit connector for unit slot Identification. Four onboard switches shall match the upper 5th to 8th bits associated Assembly name. Slot Pin 22 shall turn on the SIU Drivers allowing RXD to the ATC [advanced transportation controller]. Status and report messages shall meet SDLC [synchronous data link control] Protocol transmitting at 19,200 bps. Said Messages shall be as called out by the user.

5.1.8 – Electrical Surge Protection

Onboard protection shall be provided to enable the sensor unit or isolator to withstand the discharge of a 10 µF capacitor charged to ±1000 Volts directly across the input pins with no load present. With a dummy load of 5 Ohms, protection shall enable the sensor unit or isolator to withstand the discharge of a 10 µF capacitor charged to ±2000 Volts directly across either the input pins or from either side to equipment ground.

SECTION 2. MODEL 222E AND 224E LOOP DETECTOR SENSOR UNIT REQUIREMENTS

5.2.1 – Output Signal Definition

The sensor unit channel shall produce an output signal when a vehicle passes or remains over loop wires embedded in the roadway. The method of detection shall be based upon a design that renders the output signal when a metallic mass (vehicle) enters the detection zone causing a change of 0.02% minimum decrease in inductance of the circuit measured at the input terminals of the sensor unit.

5.2.2 – Malfunctioning Loop Signal Definition

An open, shorted, or otherwise malfunctioning loop shall cause the sensor unit channel to a constant signal state. A two-post shunt jumper or approved switch shall be provided to dictate output state upon malfunction. The jumper in closed position (Ground True) shall cause a Ground True Output to the controller unit. An open position (Ground False) shall cause a Ground False Output to the controller unit. An indicator labeled “EOS” (Event Output Status) shall be provided on the front panel. When in closed position, the indicator shall be ON. A second indicator per channel labeled “EVENT” shall be provided indicating a malfunctioning loop or tracking condition. The indicators shall be reset by the Unit RESET Switch.

5.2.3 – Supported Loop Configurations

Each sensor unit channel shall be capable of detecting all types of AGENCY licensed motor vehicles when connected to the loop configuration/lead-in requirements of Section 5.2.9.1.

5.2.4 – Inductance and Q Range of Supported Loop and Lead-in Cable Assemblies

The sensor unit shall comply with all performance requirements when connected to an inductance (loop plus lead-in) from 50 to 700 μH with a Q-parameter as low as 5 at the sensor unit operating frequency.

5.2.5 – Transformer Isolation of Loop Inputs

Loop inputs to each channel shall be transformer isolated.

5.2.6 – Number of Supported Operating Frequencies

Each individual channel shall have a minimum of 4 switch selectable operating frequencies.

5.2.7 – Drift Compensation of Tuning Circuits

The sensor unit channel tuning circuits shall be automatic and shall be so designed that drift caused by environmental changes or changes in applied power shall not cause an actuation.

5.2.8 – Pulse and Presence Mode Support

Each sensor unit channel shall have PULSE and PRESENCE selectable modes.

5.2.8.1: Pulse Mode Description

In the PULSE MODE, each new vehicle presence within the detection zone shall initiate a sensor unit channel output pulse of 125 (±25) ms in duration. Should a vehicle remain in a portion of the detection zone for a period in excess of 2 seconds, the sensor unit channel shall automatically “tune out” the presence of said vehicle. The sensor unit channel shall then be capable of detecting another vehicle entering the same detection zone. The recovery time to full sensitivity between the first vehicle pulse and channel capability to detect another vehicle shall be 3 seconds maximum.

5.2.8.2: Presence Mode Description

In the PRESENCE MODE, the sensor unit channel shall recover to normal sensitivity within 1 second after termination of vehicle presence in the detection zone regardless of the duration of the presence. The channel sensitivity settings 2 and 6 shall provide presence detection of a vehicle in the detection zone for a specified time period and inductance change as shown in Table K-1.

Table K-1. Presence detection time for detector sensitivity settings of 2 and 6.

Setting	Minimum time duration (minutes)	Detector Input Inductance change (%)
6	3	0.02 or more
	10	0.06 or more
2	4	1.00 or more

5.2.9 – Sensitivity

5.2.9.1: California Standard Plan ES-5A and B Loop Configurations (California Department of Transportation Standard Plans) are listed below:

5.2.9.1.1 – Single Type A, B, Q, or Round Loop with a 250 foot (76 m) lead-in cable.

5.2.9.1.2 – Single Type A, B, Q, or Round Loop with a 1000 foot (305 m) lead-in cable.

5.2.9.1.3 – Four Type A, B, or Q Loops connected in series/parallel with a 250 foot (76 m) lead-in cable.

5.2.9.1.4 – Four Type A, B, Q, or Round Loops connected in series with a 1000 foot (305 m) lead-in cable.

5.2.9.1.5 – One 50 foot (15 m) Type C Loop with a 250 foot lead-in cable.

5.2.9.2: Sensitivity Settings – Each sensor unit channel shall be equipped with 7 selectable (digitally read) sensitivity settings (shown in Table K-2) in presence and pulse modes to accomplish the following under operational and environmental requirements of this specification.

Table K-2. Sensitivity settings for presence and pulse modes.

Setting	Sensitivity	Setting	Sensitivity
1	0.64% delta L	5	0.04% delta L
2	0.32% delta L	6	0.02% delta L
3	0.16% delta L	7	0.01% delta L
4	0.08% delta L	0	Channel OFF

5.2.9.2.1 – All sensitivity settings shall not differ by ±40% from the nominal value chosen.

5.2.9.3: Each sensor unit channel shall not detect vehicles, moving or stopped, at distances of 3 feet (0.91 m) or more from any loop perimeter, in all configurations listed in paragraph 5.2.9.1.

5.2.10 – Response Time

Response time of the sensor unit channel for Sensitivity Settings 1, 2 and 3 shall be less than 5 ± 1 ms at an approximate loop frequency of 40 kHz. That is, for any decreased inductive change that exceeds its sensitivity threshold, the channel shall output a ground true logic level within 5 ± 1 ms. When such change is removed, the output shall become an open circuit within 5 ± 1 ms.

5.2.11 – Normal Operation Time

The sensor unit channels shall begin normal operation within 2 seconds after the application of power or after a reset signal of 30 µs.

5.2.12 – Tracking Rate

The sensor unit shall be capable of compensating or tracking for an environmental change up to 0.001% change in inductance per second.

5.2.13 – Tracking Range

The sensor unit shall be capable of normal operation as the input inductance is changed from ±5.0% from the quiescent tuning point regardless of internal circuit drift. The sensor unit shall be capable of normal operation as the input resistance is changed from ±0.5% from the quiescent tuning point regardless of internal circuit drift.

5.2.14 – Temperature Change

The operation of the sensor unit shall not be affected by changes in the inductance and/or capacitance of the loop caused by environmental changes with the rate of temperature change not exceeding 1 degree C (1.8 degrees F) per 3 minutes. The opening or closing of the controller cabinet door with a temperature differential of up to 18 degrees C (32.4 degrees F) between the inside and outside air shall not affect the proper operation of the sensor unit.

SECTION 3. MAGNETIC DETECTOR REQUIREMENTS

5.3.1 MODEL 231E MAGNETIC DETECTOR SENSING ELEMENT

5.3.1.1 – Design Requirements

Each sensing element shall be designed for ease of installation, repositioning, and removal. The sensing element shall be 57 mm (2.2 in) maximum in diameter, have no sharp edges, and its length not exceed 450 mm (18 in). The sensing element shall be constructed of nonferrous material and shall be moisture proof. The element shall contain no moving parts or active components. The element shall have a 15.4 m (50 ft) lead-in cable. Leakage resistance shall be a minimum of 10 megohms when tested with 400 VDC between lead wire, including lead wire entrance, and the fluid of a salt water bath after the device has been entirely immersed in the bath for a period of 24 hours at 20 ±3 degrees C (36 ± 5.4 degrees F) . The salt water bath concentrate shall contain one fourth ounce of salt per gallon (2 gm per liter) of water.

5.3.1.2 – DC Resistance

Each sensing element including lead-in shall have a DC resistance of less than 3500 ohms and an inductance of 20 Henry ± 15%.

5.3.2 MODEL 232E TWO CHANNEL MAGNETIC DETECTOR SENSING UNIT

5.3.2.1 – Output Signal Definition

When resident in an active cabinet input assembly and attached to one or more Model 231E Sensing Elements resident in conduit under the travelway, the sensing channel shall output a Ground True Output to the Controller Unit when sensing an induced voltage caused by a California Licensed Vehicle passing within 1.83 m (6 ft) from an element with a 305 m (1000 ft) of lead-in cable at all speeds between 5 and 130 km/h (3 and 80 mi/h). The sensing channel output shall be continuous as long as the vehicle is detected. A digital reading switch with 8 selected step positions for gain (0 to Full) and a momentary test switch providing a voltage test input shall be furnished for each channel on the front panel.

REFERENCES

1. *Transportation Electrical Equipment Specifications* (TEES). California Department of Transportation, Sacramento, CA, August 16, 2002. Available at http://www.dot.ca.gov/hq/traffops/elecsys/2070/reports/TEES.pdf (Accessed March 28, 2004.)

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LIST OF FIGURES: APPENDIX L.

APPENDIX L. CLASSIFICATION OF SENSOR SYSTEMS BY SENSOR DENSITY LEVEL

ABSTRACT

Appendix L describes a series of successively higher sensor density levels and how they relate to traffic control system requirements. Sensor density is described in terms of a web of sensors required for different kinds of arterial and network traffic control and surveillance systems by link and by lane.

TERMINOLOGY

The sensor web density level terminology used in this edition of the *Traffic Detector Handbook* and the 2005 edition of the *Traffic Control Systems Handbook* (TCSH) differs slightly from that used in previous editions of the TCSH.(1) The refinement of the terminology is due to several factors. The first is the need to distinguish between levels of sensor density and sensor characteristics. The second is the need to distinguish how different kinds of interconnected traffic control systems utilize sensor data and thus require different densities and distributions of sensors. A third factor is that traffic adjusted and traffic responsive systems have evolved since control systems were originally introduced to traffic management. The evolution was spurred on by increases in computing power and speed of communications. Similarly, traffic adaptive systems require a sensor density and data transmission rate that were not physically nor fiscally feasible 30 years ago. The control systems terminology is described in more detail in the TCSH and in Table 3-1.

Sensor density levels relate to traffic control levels and their requirements. Categories of control systems are described in more detail in the 2005 Traffic Control Systems Handbook. Their characteristics are described in Table 1 of Chapter 3 of this Handbook.

The first traffic control system to use volume and occupancy to select timing plans was developed by the company Automatic Signal in the 1950s. They named their system a traffic adjusted system—hence the use of the term here to distinguish it from systems using and manipulating flexible timing plans (see definitions on next page,)

For the purposes of this Handbook, control systems are broken down into the following categories:

UNCOORDINATED SIGNALS or UNCOORDINATED CONTROL

This is a form of signal control in which an individual signalized intersection has neither control relationships between intersections nor any data flow between intersections. There are no system sensors. The individual isolated intersection may have local actuated control or Time of Day/Day of Week (TOD/DOW) changes based on historical traffic flows. This category has also been called isolated signal control and totally isolated systems. These systems have neither time-based nor communications-based connections between intersections. They present no system response to variations in traffic demand.

TIME-BASED COORDINATION or TIME-BASED COORDINATED CONTROL

The key difference between categories of traffic control is how rapidly a system makes changes in response to variations in traffic demand.

These are control systems in which basic coordination is provided by a highly accurate real-time clock within the traffic signal controller. This information is used to determine the local signal timing of offset and cycle/split or actuated timing based on the TOD/DOW. There are no system sensors. System response to variations in traffic demand is measured in weeks or months. In a fixed timing plan, cycle, split, offset and actuated settings are not adjusted between switching of timing plans. These are used in uncoordinated signal control, time-based coordinated control, interconnected control, and traffic adjusted control systems.

INTERCONNECTED CONTROL

These are control systems in which basic coordination is provided by wireline or wireless interconnect. There are no system sensors. This information is used to determine the local signal timing of offset and cycle/split or actuated timing based on TOD/DOW. The operator can select timing, download timing plans and changes, and monitor system status. System response to variations in traffic demand is measured in weeks or months.

***Time of Day/Day of Week* (*TOD/DOW*)** are control features which isolated control systems, time-based control systems, and interconnected systems may possess. In systems using these features, timing plan selections are based on the clock and calendar rather than on system traffic information. TOD/DOW systems operate with no system sensors (or at a sensor web density level of 0). These systems do not measure any characteristics of traffic flow. They may use clocks or wireline or wireless communications to provide the timing plan selection. Totally isolated and TOD/DOW may be given some response to traffic through the use of traffic actuated controllers.

TRAFFIC ADJUSTED CONTROL

Traffic adjusted systems are particularly beneficial where traffic is not disrupted by unpredictable incidents and special events and traffic growth is very predictable.

These systems operate with few sensors (or at sensor web density levels of 1.0 and 1.5) and use fixed timing plans, selection of which is adjusted by a minimum number of system sensors at periodic intervals. The sensors in these systems measure systemwide variations in traffic demand using either volume plus weighted occupancy or using predominant direction of flow. They then use pattern matching to choose from among a set of preselected fixed plans. This definition builds on the original definition by Kell and Fullerton in the *Manual of Traffic Signal Design.*[2] This in turn is built on that of Automatic Signal. System response to variations in traffic demand is about 15 minutes.

TRAFFIC RESPONSIVE CONTROL

In a flexible timing plan, cycle, split, offset, and actuated settings are adjusted once per cycle. This occurs between switching of timing plans. These are used in traffic responsive systems.

These systems operate at a moderate sensor density (sensor web density levels of 2.0 and 2.5) and use flexible timing plans in which the offsets, splits, and phase durations can be adjusted in reaction to changes in traffic on a nearly cycle-by-cycle basis and have to have at least one sensor per link up to one sensor per lane per link. Cycle, split, and offset are each optimized in the selection of the flexible timing plan to be implemented. These systems typically use macroscopic measures of traffic flow on individual links such as platoon dispersion and other characteristics. System response to variations in traffic demand ranges from one cycle length to 15 minutes, depending on the extent of the changes.

TRAFFIC ADAPTIVE CONTROL

Traffic responsive and traffic adaptive systems are particularly beneficial where traffic is regularly disrupted by unpredictable incidents and special events and/or traffic growth is strong but erratic.[1]

These systems operate with two sensors per lane per link for optimum efficiency (sensor web density level of 3.0). Adaptive systems do not have cycle, split, or offsets in the classic sense. They forecast traffic into the near future and proactively change signal timing, including selection and sequence of phasing. These systems need to measure the flow of individual vehicles so that they can predict the future flow of the individual vehicles.

System response to variations in traffic demand ranges from a few seconds to a minute.

The key difference between interconnected, traffic adjusted, traffic responsive and traffic adaptive control strategies is the rapidity of response to variations in traffic flow. As the response time is decreased, the frequency of changes to the control parameters must increase and the selection of timing features must change. More rapid response requires more sensor data and more frequent updates of the sensor data. This in turn leads to changes in requirements for sensor density and data communications rates. These differences are highlighted in Table 3-1. If a jurisdiction cannot afford to operate and maintain the dense sensor and communications networks required for traffic responsive or traffic adaptive systems, then those systems are *not* good choices for that jurisdiction. However, the additional costs required by denser sensor networks introduce increased capabilities to the control systems, and thus justify their introduction in that manner.

Sensor web density levels are described in the next section along with figures illustrating them in a sample networks.

SENSOR WEB DENSITY LEVELS

SENSOR WEB DENSITY LEVEL 0.0

This density level has no vehicle detection or sensors. Therefore, no maintenance of sensors is required. See Figure L-1 for the network layout.

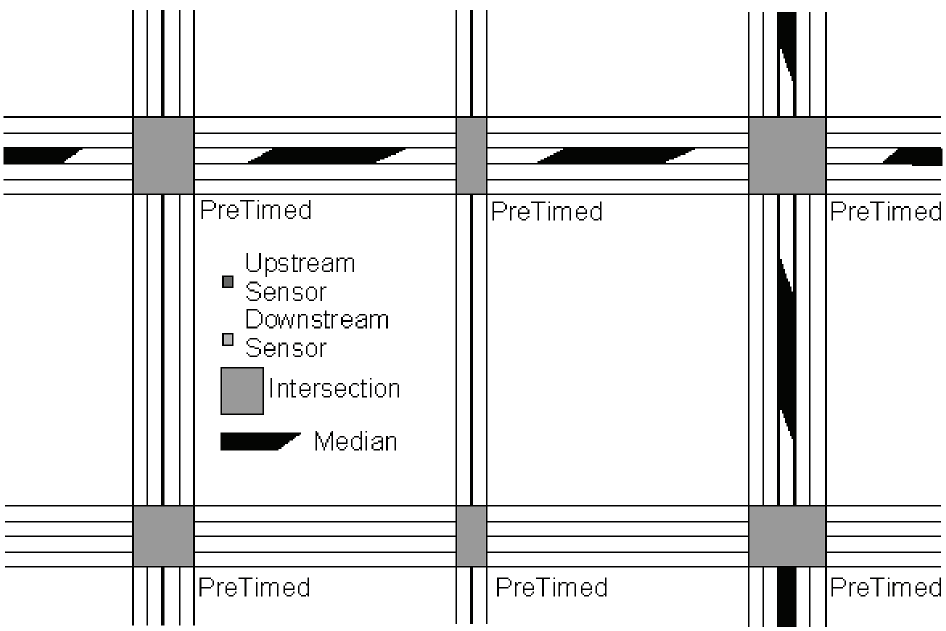

Figure L-1. Network sensor web density level 0.0—no sensors.

Systems may operate on fixed timing plans with no actuated phases. The systems may operate either as totally isolated systems or as TOD/DOW, in which precalculated, fixed timing plans are implemented accordingly.

SENSOR WEB DENSITY LEVEL 0.5

This has a very low level of sensor density. Thus, a very low level of maintenance is needed. See Figure L-2 for a typical network layout.

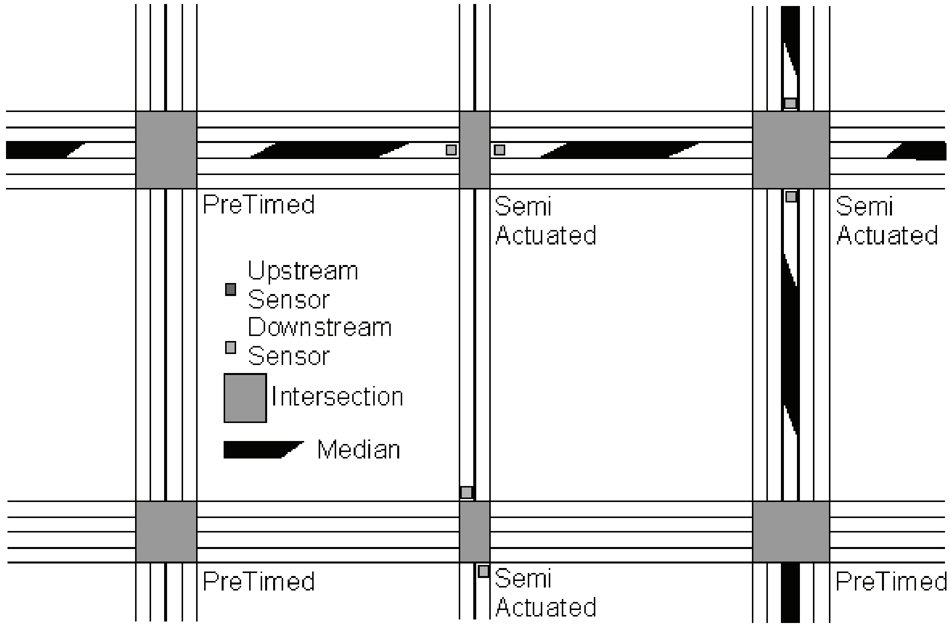

Figure L-2. Network sensor web density level 0.5—occasional minor movement stop bar detection.

These systems are TOD/DOW systems made more responsive to traffic by the incorporation of semiactuated and fully actuated controllers at key locations. The purpose of the semiactuated controllers is generally to minimize the breakup of progressive flow when side-street traffic is not present. The traffic actuated controller's actuated signal settings may be varied by time of day and day of week. Generally only left turns and minor side streets are actuated.

SENSOR WEB DENSITY LEVEL 1.0

How to locate system detectors for traffic adjusted systems is described in "Locating Detectors for Advanced Traffic Control Strategies."[4.5] These reports state that this kind of system "requires instrumentation on the entrance links and approximately every fourth block thereafter on arterials and on every third block within grid networks. Links that carry low volumes (peak hour volumes of less than 100 vph [vehicles per hour]/lane should not be instrumented …"

This density level provides a low level of sensor density with up to one sensor per link. A low level of sensor maintenance is needed. See Figure L-3 for a typical network layout.

This density level is used for traffic adjusted systems. For this Handbook, a traffic adjusted system is defined as one in which a timing plan is selected based on a combination of TOD/DOW and the real demands of traffic. These systems require system sensors for volume plus weighted occupancy (VPLUSKO) or peak direction of flow data to choose timing plans. However, the timing plans are selected from a fixed library of timing plans previously calculated (either on line or off line). Examples of traffic adjusted systems are UTCS (Urban Traffic Control System) 1st Generation traffic responsive, UTCS 1.5 Generation and various closed loop systems. Periodic manual traffic counts are required for calibration of system sensors.

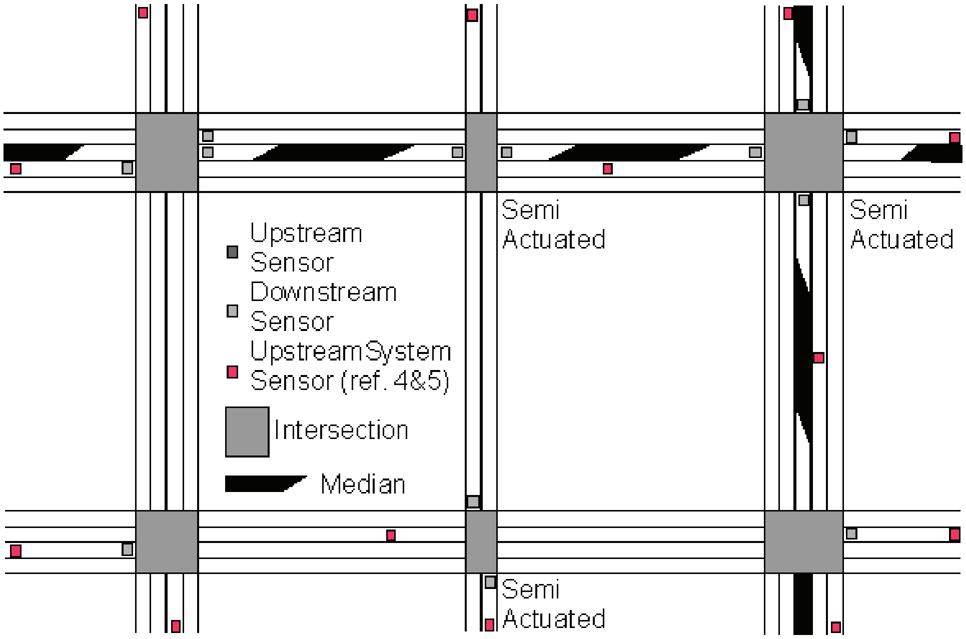

Figure L-3. Network sensor web density level 1.0 (UTCS 1.5, closed-loop systems—several minor movement without detectors).

SENSOR WEB DENSITY LEVEL 1.5

This density level provides a moderate sensor density with up to one sensor per link and additional sensors for actuated controllers. A moderate level of sensor maintenance required due to the greater density of system and traffic actuated sensors.

This level might be used for a traffic adjusted system that has been made more responsive to traffic by the incorporation of traffic actuated controllers. The actuated signal settings may be varied by time of day and day of week. Sensors are placed at key locations along with more intensive sensor placement at actuated locations. Periodic manual traffic counts are required. A moderate degree of sensor maintenance is also required due to the greater density of system and traffic actuated sensors. See Figure L-4 for a typical network layout.

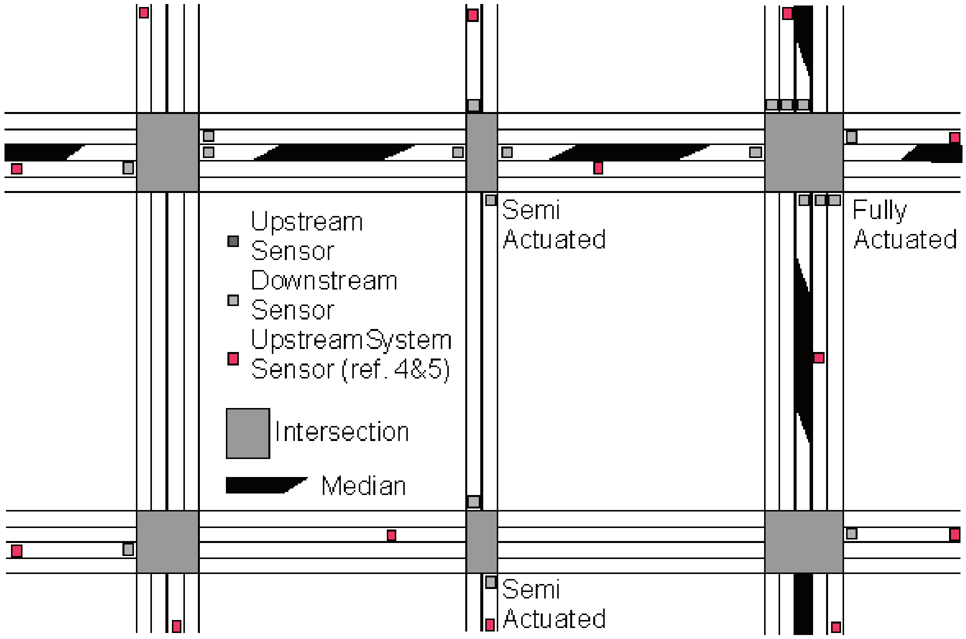

Figure L-4. Network sensor web density level 1.5 (UTCS 1.5, closed-loop systems—with heavily actuated controller & several minor movement without detectors).

SENSOR WEB DENSITY LEVEL 2.0

This density level provides a medium density of at least one system sensor per approach link. A medium level of sensor maintenance is required due to the greater density of system sensors. See Figure L-5 for a typical network layout.

UTCS 2 GC "requires instrumentation on all links between 'major intersections which are defined as those intersections operating within the strategic optimization routine" (p. 84, ref. 5).

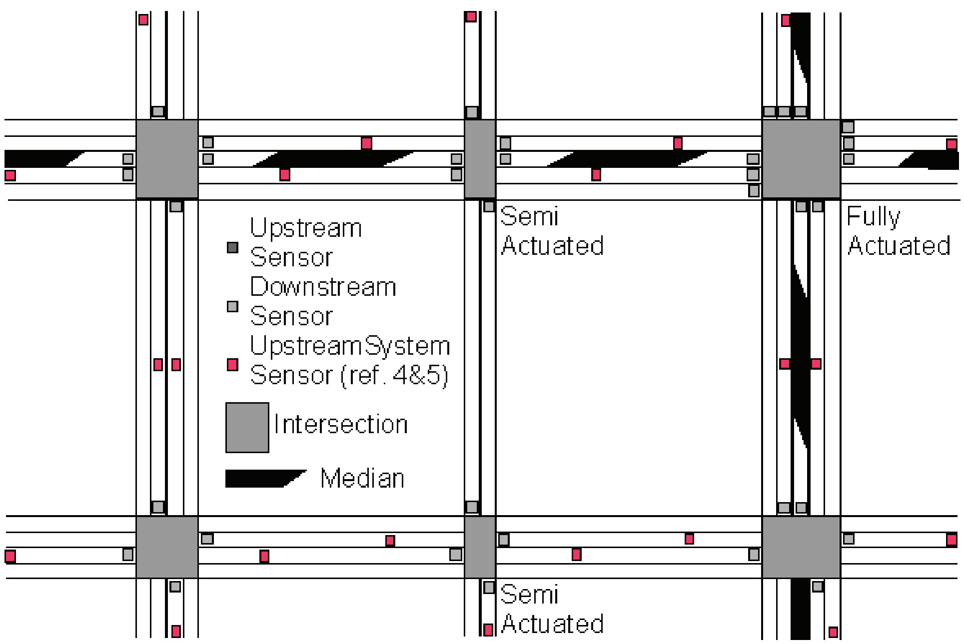

Figure L-5. Network sensor web density level 2.0 (traffic adjusted, UTCS 2 GC).

Sensor Web Density Level 2.0 is applicable to simpler traffic responsive control systems found in arterial and closed loop systems. These systems are characterized by timing plans that are selected or computed based on real-time demands of traffic as detected by vehicle sensors. The plans are implemented at regular intervals of not less than 15 minutes (and rechecked at shorter intervals thereafter). Since traffic responsive systems have fixed offsets, changes of these plans more than once every 15 minutes may result in system degradation. An example of a system using a Level 2 density is UTCS 2nd Generation Traffic Responsive. Systems using Level 2 sensor web density and above are usually able to include some form of traffic prediction. Periodic manual calibration counts are required to obtain an accurate distribution of traffic across lanes for fully utilizing system sensors.

Note that some major phases may need dilemma zone protection. TxDOT has offered several publications describing different kinds of techniques and dilemma zone systems that might be useful.(6,7,8) The sensor network needed for dilemma zone protection is discussed under sensor web density level 3.0.

SENSOR WEB DENSITY LEVEL 2.5

This level provides a high sensor density of at least one sensor per lane per link (as for example, the approach link for SCATS (Sydney Coordinated Adaptive Control System) or the departure leg of SCOOT (The split, cycle and offset optimization technique). Sensor web density level 2.5 requires a large amount of sensor and communications maintenance due to the heavy concentration of system sensors.

This density level might be used for traffic responsive systems. A traffic responsive system is defined as one in which key aspects of the timing plan may be altered between signal timing plan updates and timing plan updates are possible at least every 15 minutes. These would include the distributed intelligence traffic control system (DITCS) that uses timing plans but dynamically adjusts splits. Also, SCATS(9,10) updates intersection cycle length using the sensors at the stop line. SCATS allows for phase skipping. Sensor web density level 2.5 systems might typically include some form of traffic prediction. SCOOT(11,12) may make modest adjustments (<4 s) to the offset, split, and cycle in each cycle. See Figure L-6 for a typical network layout for SCATS and Figure L-7 for a typical network layout for SCOOT.

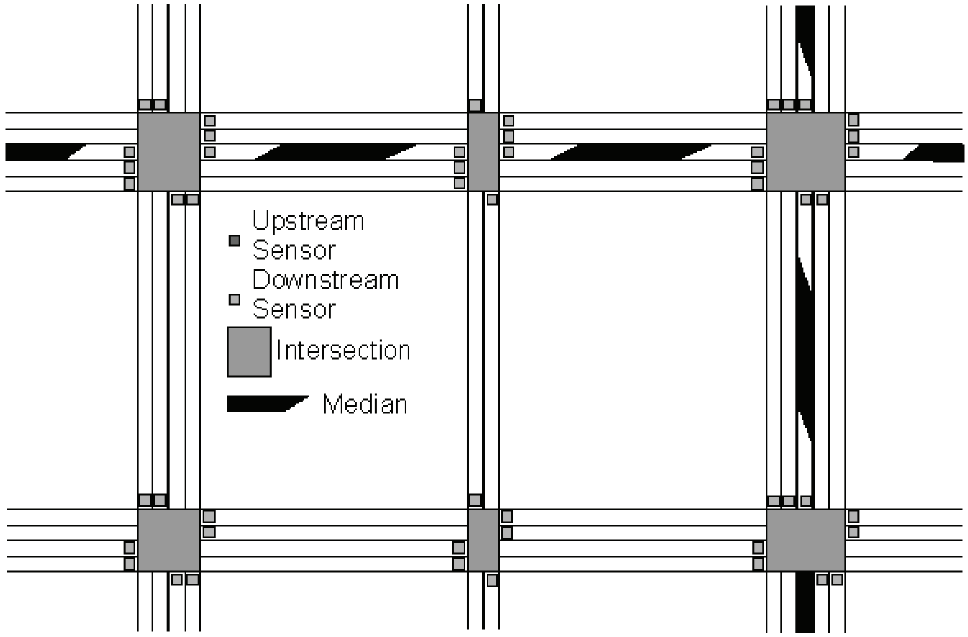

Figure L-6. Network sensor web intensity level 2.5 (SCATS)
(SCATS optimal sensor layout, downstream sensors, 1 per lane link).

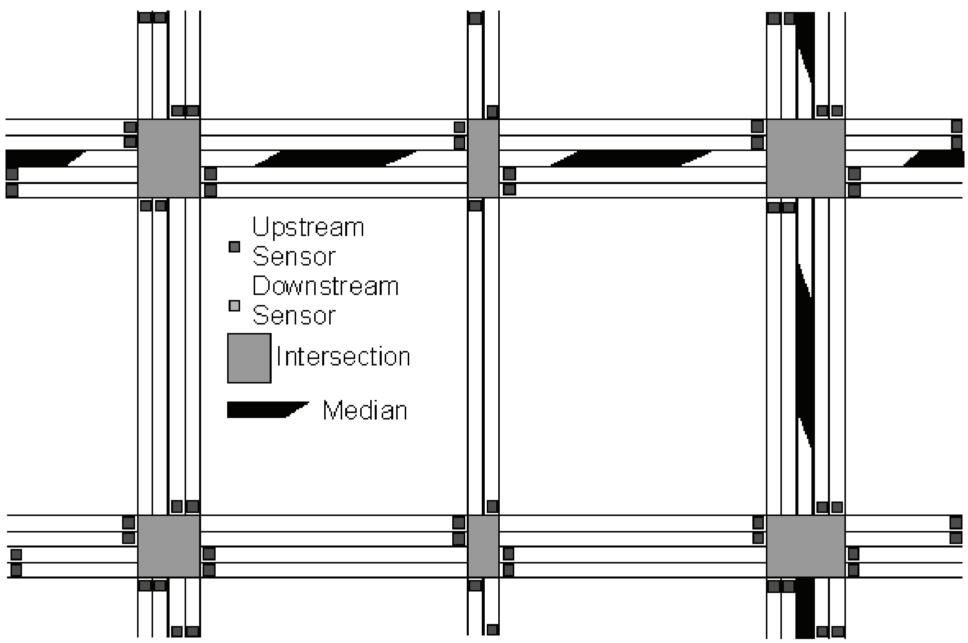

Figure L-7. Network sensor web density level 2.5 (SCOOT)
(SCOOT optimal sensor layout, upstream sensors, 1 per lane link).

SENSOR WEB DENSITY LEVEL 3.0

This density level has two or more sensors per lane per link. This requires a very high level of sensor and communications maintenance. See Figure L-8 for a typical network layout.

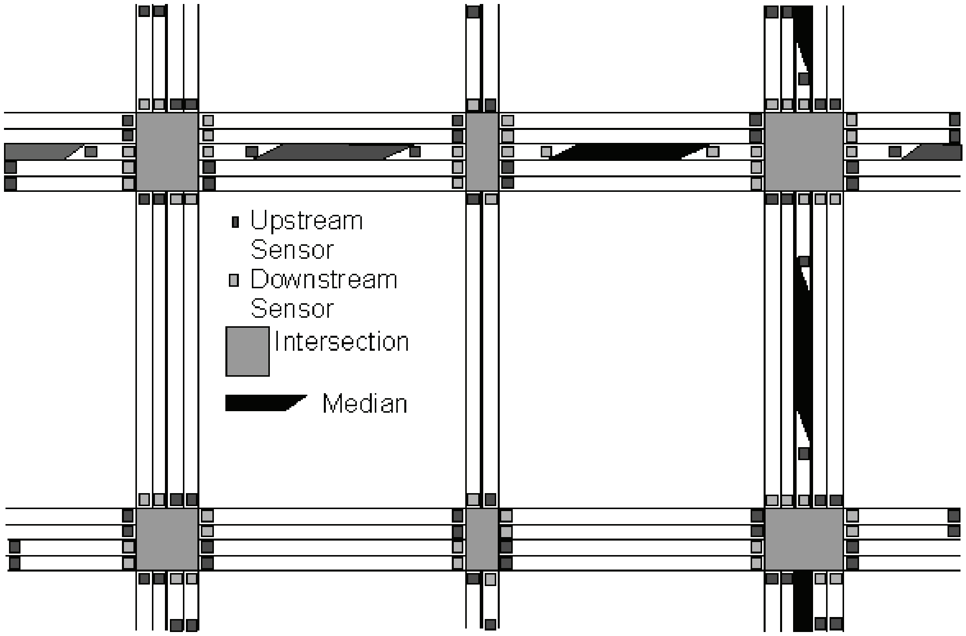

Figure L-8. Network sensor web density level 3.0 (sensor layout for ACS systems such as RHODES, optimal sensor layout of upstream and downstream sensors shown, 2 per lane link).

For ACS systems, the upstream sensors should be placed to provide a rolling 10-second traffic prediction window. This means at 10 seconds travel time distance upstream from the stop bar. This will be approximately 250 feet (76 m) at 25 ft/s (7.6 m/s).[14]

Level 3 is applicable to traffic adaptive systems. A traffic adaptive system for this purpose is defined as one in which all signal timings are evaluated and changed based on forecasts of future traffic flow continuously in real time. A rolling prediction horizon of from 1 to 4 seconds to 20 seconds is a key element of traffic adaptive systems. A traffic adaptive system usually does *not* have offsets in the classical pretimed or traffic responsive sense. This is because the signal settings are in constant adaptation. Traffic adaptive systems are frequently distributed systems with the algorithms running in individual controllers and the controllers negotiating with each other over the settings. For example, RHODES requires an upstream, free-flow sensor and a downstream stop bar sensor and left turn bay sensors to operate at full efficiency. Thus, RHODES[13,15] and other ACS systems operate at a sensor web density level 3.0.

Sensor density level 3.0a is really a higher density version of sensor web density level 2. This level presents advance systems for dilemma zone protection on the major approaches and stop bar sensors for minor movement protection on minor approaches and phases. Density level 3.0a is illustrated in Figure L-9. Network Sensor Web Density Level 3.0a

Density level 3.0a is used by State highway departments on rural, high-speed State highways to help prevent red light running crashes. The upstream detectors on coordinated movements may also be used for volume-density operation. Volume-density, where it is configured correctly, is quite effective.

SENSOR WEB DENSITY LEVEL 3.5

This is an enhancement of level 3.0. This level uses vehicle identification, classification and tracking sensors. It could be used for traffic responsive or traffic adaptive systems. This level uniquely identifies each vehicle entering a leg, know its classification, and know when that vehicle left the leg. The sensors to support this level are in research and development, and the first research networks are being built.

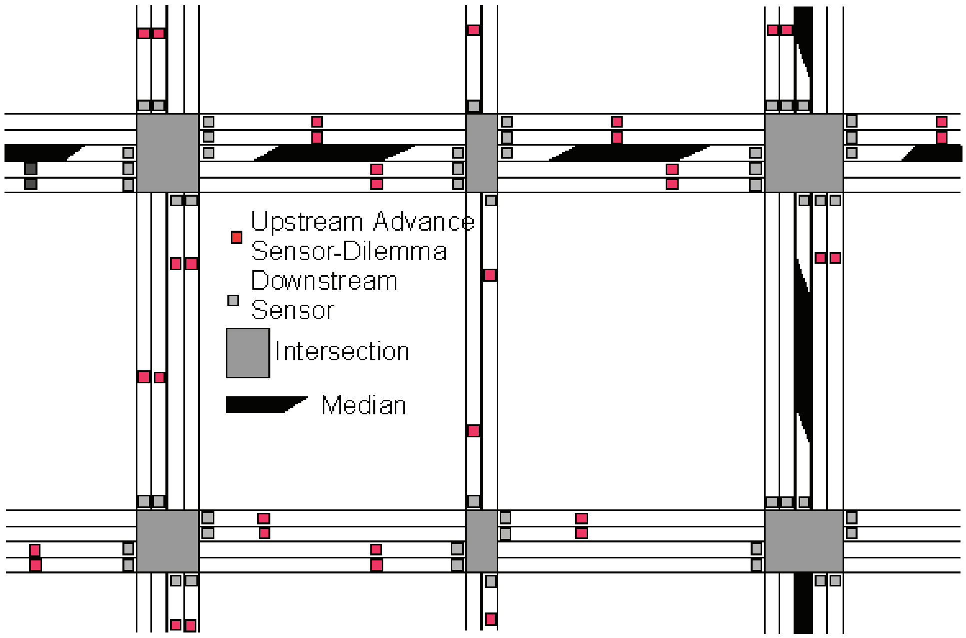

Figure L-9. Network sensor web density level 3.0a (advance dilemma zone sensors and minor movement protection).

SENSOR WEB DENSITY LEVEL 4.0

This is a hypothetical level that will become possible with the widespread adoption of DSRC (Dedicated Short-Range Communications), high-accuracy GPS, (Global Positioning System) and in-vehicle computers and communications. Each vehicle will regularly report its location, and possibly its destination, to the traffic management system. This would allow the creation of a new category of traffic control using long time horizon traffic prediction, which might be called, for example, traffic predictive control.

GENERAL OBSERVATIONS

The higher the sensor density level number, the higher is the need for detectors. Level 0.0 density systems do not support real-time systems and do not need sensors. Level 0.5 systems only have sensors for locally actuated controllers.

The more variable and unpredictable the traffic, the greater is the need for sensors.

Closed-loop systems that use less communications to the central master and microcomputer-based masters can fit into many of the above categories. ACS Lite is a closed-loop subset of ACS and may utilize a sensor web density of level of 1.0 or 1.5.

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APPENDIX M. EXTENT AND CAUSES OF INDUCTIVE-LOOP FAILURES

A number of studies were conducted during the 1980s to determine the extent and causes of inductive-loop detector failures. The underlying purpose of those investigations was to identify potential solutions to increase reliability and life expectancy of inductive-loop installations. Several of the studies involved testing 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.

STUDIES SUMMARIZED IN THIS APPENDIX

Four studies were particularly significant in that they contained the results of questionnaire and interview surveys, which documented the experience of numerous agencies. These studies are listed below and their results are summarized in this appendix:

- *Improving Materials and Methods for Installing 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

The Oregon study was designed to:

1. Identify the causes of loop system failures and the methods used to remedy the identified problems.
2. Assess the accumulated data.
3. Test and evaluate those materials and procedures that appeared most likely to be effective in the Oregon state system.

The required information was obtained by distributing a lengthy questionnaire to the following State departments of transportation:

- Alaska.
- California.
- Idaho.
- Montana.
- Nevada.
- Oregon.
- Utah.
- Washington.

Some local agencies also participated in the survey.

OREGON SURVEY RESULTS

The Oregon study reported two major causes of loop failure: loss of adhesion in the sealant and poor installation techniques.

Although different materials and installation methods were used by the agencies surveyed, two major causes of loop failure were consistently reported: loop sealant failure (loss of adhesion) and poor installation techniques (e.g., inadequately cleaned or dried saw slots). Another key problem common to many agencies was wire breakage due to asphalt pavement deterioration. The City of Albany, OR, cited pavement flexing and shoving, which caused the epoxy sealant to pop out of the saw slot, requiring resealing. The Portland, OR, metropolitan region had many loop failures because of road wear down to the loop wire, primarily in wheel rut locations. Many agencies also experienced loop loss resulting from trenching for the installation or maintenance of underground utility lines.

Alaska reported no failures when using preformed loops.

Of particular interest was 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 polyethylene wire encased in 1-inch (2.54-cm), schedule 80 PVC conduit. The loop wire is placed in the conduit, which is then assembled to the specified loop dimensions. Alaska reported no loop failure using the preformed loops. Other States also reported 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 summarizes the Oregon survey results. With the exception of the State of Utah, most loop installations were performed by contractors.

Table M-1. Oregon inductive-loop failure survey results.

State	Percent installed by State	Percent installed by Contractor	Major failures	Remarks
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

OREGON CONCLUSIONS AND RECOMMENDATIONS

Previous to this study, the Oregon vehicle detection system consisted of a 3- by 3-ft (0.9- by 0.9-m) diamond loop, constructed with four turns of THWN wire. The loop was installed in a 1/4-inch (6.5-mm) wide sawcut and encapsulated in a preapproved sealant. The splice between the loop wires and the lead-in cable was made in proximity 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- by 3-ft (0.9- by 0.9-m) diamond configuration when the loops are in series in the field. However, any single loops are now required to be 4 ft by 4 ft (1.2 m by 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 pull box locations.

Presence loop configuration evolved to its present specification in order to accommodate the detection of smaller vehicles in the traffic stream. Two 3- by 3-ft (0.9- by 0.9-m) diamond loops are connected in series. A single 4- by 4-ft (1.2- by 1.2-m) diamond is placed upstream to provide a long loop effect. Information from this detector is input into a separate electronics unit 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.

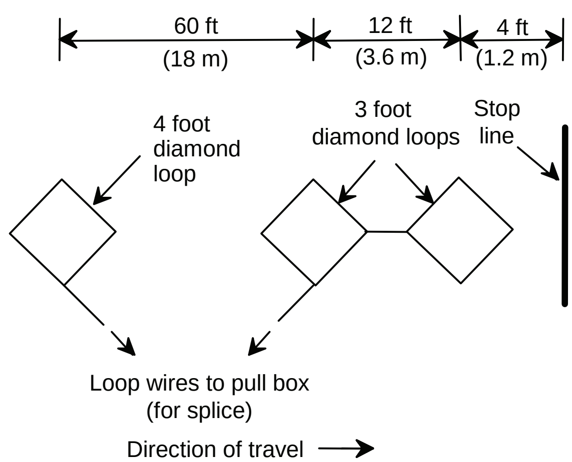

Figure M-1. Oregon presence loop configuration.

Because of sealant failure incidents, 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 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 0.25-inch (6-mm) vinyl tube prior to inserting the wire in the saw slot. While this technique was worthy of consideration, the State expressed concern about the need for a wider saw slot, extra sealant, and the requirement to twist the loop wire 4 to 6 turns per foot (13 to 20 turns per meter) from the loop to the pull box.

It was apparent from the Oregon experience and from the gathered data that complete cleanout and drying of the loop saw slot are vital to long lasting, effective loop performance. Oregon became interested in the sawcut 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 Oregon based on the New York design. Valves were added to control both air and water feed lines so that options existed 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 because of the more efficient cleaning of the saw slot by the nozzle.

WASHINGTON STUDY

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 Washington State Department of Transportation (WSDOT), and 9 other State agencies, representing a geographic cross section of the Nation. Many of the State and local agencies did not maintain precise documented records related to inductive-loop detectors; accordingly, respondents were asked to provide estimates as necessary. As a result, much of the information obtained was qualitative.

WASHINGTON SURVEY RESULTS

This study was conducted by the University of Washington Civil Engineering Department and sponsored by 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. The specific study focus was on the reasons for loops becoming dislodged from the saw slot, the frequency of failure, the optimum products, and installation techniques.

The number of loops within the responding jurisdictions and the corresponding failure rates are given in 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.

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 notification of loop failure by Washington cities 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 WSDOT, failures were reported as a consequence 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.

Table M-2. Washington State inductive-loop failure rate survey results.

Jurisdiction	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, and TX.

The most frequent causes for electronics unit failures, as defined by the respondents, included lightning damage and the need for constantly retuning older models to accommodate 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, waiting 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 where optimizing traffic flow was a concern.

When asked who installed the loops, the response was contractors approximately 90 percent of the time. Only one State DOT indicated that in-house personnel installed 98 percent of its loops.

Most of the cities and counties within Washington State cited WSDOT specifications for loop detectors. The preferred loop shape 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. High-pressure water followed by pressurized air was 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 Washington 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 sawcuts and splices varied considerably. Many of the agencies within the State used the WSDOT specifications for sealants. Some city agencies used either polypropylene 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 polypropylene rope because the polypropylene rope tends to deform when covered with hot asphalt, forcing the rope out of the slot. Most WSDOT districts used roofing asphalt as a sealant, while out-of-State agencies tended to use commercial sealants that were 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 Washington State.

WASHINGTON CONCLUSIONS AND RECOMMENDATIONS

Primary cause of loop failure uncovered by the WSDOT study was pavement cracking. Secondary causes included wire breakage, poor inspection, pavement rutting, and sealant failure.

The failure rates reported by Washington State agencies were much lower than reported by out-of-State DOTs and in the literature. The largest single factor contributing to loop failure appeared to be pavement cracking. The next most important factor was breaking of loop wires due to utility repair or construction. Other significant factors included poor inspection procedures, pavement rutting, and sealant failure.

Problems associated with the electronics unit could 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 could be resolved by the purchase of self-tuning amplifiers and by complete encapsulation of the loop wires. The study recommended the elimination of using rope to hold down wire.

WSDOT districts expressed much concern about the poor quality of inspection of loop installations. It was pointed out that the best remedy for poor inspection is training and experience. Training may be accomplished on the job by assigning new inspectors to more experienced personnel or through formal classes. Inspectors must remain in their jobs long enough to be effective in the enforcement of specifications.

It was also suggested that forms and procedures 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 be considered for splicing wires. It is used quite successfully in the marine industry in deep underwater applications and adds extra strength and abrasion resistance to the area of the splice. Heat guns with fixed temperature heads should be used with the temperature selected ahead of time to avoid damage to the wire coating.

MINNESOTA STUDY

The Minnesota Department of Transportation (MnDOT) Office of Traffic Engineering determined that 14 percent of their signal maintenance time was spent repairing loop detectors because of poor installation procedures, pavement deterioration, or environmental effects. Consequently, the State Office of Research and Development was asked to conduct a study to identify the reasons for loop detector failure and where within the installation the failure usually occurred.

Inductive-loop detector failures reported in the MnDOT study were due to broken wires or deteriorated insulation at pavement joints, pavement cracks running through the loops, poor splice technique, treatment of loop corners, and improper sealant choice or application technique.

A literature search revealed that Minnesota's problems were not unique. Loops installed by other States in the Snowbelt area were also affected by moisture, loop sealant failure, and pavement cracks and joints. A survey questionnaire was developed and distributed to all the Snowbelt States (all States above 36 degrees latitude were considered to be in the Snowbelt region). The District of Columbia and Provinces of Canada were also included, as were the major city and county agencies within Minnesota. The questionnaire covered two critical areas of interest: (1) reasons why the loop detector failed and (2) the materials and procedures used by each agency when installing loop detectors.

Completed surveys were received from 26 States, two counties, two cities, and three Canadian provinces. In addition to the literature search and the survey, MnDOT personnel were observed while making loop repairs.

MINNESOTA SURVEY RESULTS

An initial review of the completed questionnaire revealed that most States, including Minnesota, did not keep good records concerning reasons for loop failures. Characteristically, if it were determined that a short or open circuit had occurred in the loop wire, no investigation was made as to where or why the short occurred. The loop wire was simply replaced.

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 occurred in pull boxes where 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 occurred 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, although some agencies crimp and then solder. Many of the agencies sealed their connections with a waterproofing agent and then wrapped with tape. Other agencies encapsulated 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 frequently mentioned problem was electronics unit failure caused when older models of electronics units become detuned. Deteriorated wire insulation, poor splices, temperature changes, moisture, vibration, electrical storms, and wire movement all contributed to this type of failure. Many agencies have alleviated this problem by using digital self-tuning electronics units.

As for wire type, 25 agencies used #14 AWG wire for their loops. Stranded wire was always used, and type THHN and THWN were favored for insulation. Eleven agencies enclosed the insulated wire in thin vinyl tubing, which creates a conduit effect and provides added protection. Three agencies were reported 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 were many types of epoxy and polyester resins and unspecified asphalt compounds. Experience and price seemed 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: (1) laying and sealing the loop wires, (2) addressing the loop corners, and (3) crossing expansion joints or pavement-shoulder joints.

Initial MnDOT procedures used to lay and seal the loop wires merely specified inserting the turns of insulated wire into 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 one that would maintain adhesion to the side of the slot during expansion, withstand compression when joints were contracting, and yet be of the right viscosity to be poured into the slot but not run out if the slot were on an incline. It also became apparent that sharp edges along the slot edges and at the loop corners could create breaks in the wire insulation. Therefore, procedures were undertaken to smooth sharp edges, flush debris from slots with pressurized water, and blow-dry the slot with compressed air.

Cutting 45-degree diagonal slots reduced sharp bends at the loop corners. However, this method created triangles at each corner that could eventually break down from the wheels of vehicles passing over the area. Several agencies resolved this problem by drilling 1- or 2-inch (2.5- or 5.1-cm) holes at each corner instead of cutting the diagonals. The corners of the hole were chiseled out to remove the sharp edges. Other agencies did not drill holes at the corners; rather, they chiseled out the inside of the corner to create small open triangular areas. Slack in the wire should be left at each corner, whether holes are drilled or chiseled to accommodate any movement of the pavement.

Many ideas were presented on how to fill the slots and corners with sealant. Some agencies simply laid the wire in the bottom of the slot and filled it with sealant, hoping that most of the wire would be encased. To better encapsulate the wire, others partially filled the bottom of the slot with sealant, laid the loop wire, and then added more sealant until it was almost flush with the top of the slot. Still other agencies went 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 sawcuts, some agencies chose 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 reduced the amount of sealant needed. One agency suggested that this method created problems in that the rope was not as resilient as the sealant and that voids could occur between the wires and rope and/or the slot. A conduit effect could be achieved during asphalt pavement construction by cutting the slots and inserting the wire before adding the final layer of bituminous asphalt.

PVC rigid plastic tubing was used as conduit for preformed loops by a number of agencies. This 0.5- to 1-inch (13- to 25-mm) tubing was often installed during construction before the final courses were laid. However, if it were used in an existing installation, much wider cuts would be made to accommodate the tubing, thus weakening the pavement structure. Experience demonstrated that preformed loops were particularly effective where the pavement was broken or in poor condition.

MINNESOTA CONCLUSIONS AND RECOMMENDATIONS

MnDOT contracts out the installation of new traffic signals, ramp meters, and automatic traffic counters, all of which use loop detectors for activation. MnDOT inspection personnel preform inspection of new installations. MnDOT maintenance staff primarily carry out repairs and replacement of failed loops.

Previous to this study, MnDOT did not require its in-house crews to follow the same procedures and State specifications as those required of contractors. For example, a contractor is required to place a layer of sealant in the bottom of the slot before installing the loop wire, while MnDOT 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, MnDOT personnel use insulated wire encased in a thin vinyl tubing, which is not required of the contractor.

It was found that, on occasions, MnDOT crews created problems by choosing poor locations for the new loops or routing the lead-in wires through areas already showing distress. Moreover, they did not follow specifications regarding expansion joints, cracks, or pavement edges.

The primary recommendation of the MnDOT study was that MnDOT repair crews use the same procedures as those required of contractors installing new loops. The study also recommended that consistency be achieved among all crews making repairs. Using MnDOT standard plates as guidelines, it was suggested that the repairmen meet and decide how future repairs would be made. The major points to be addressed included:

- 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 splices.

Poor installation procedures by contractors were the cause of a significant portion of loop failures experienced in the State. Faulty inspection procedures contributed to these failures. It was recommended that the MnDOT inspectors become more knowledgeable in the proper installation of traffic loops and conduct more aggressive inspections during installation.

A major conclusion from this study was consistent with other survey findings: that records and documentation of loop failures throughout the United States 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. The study concluded that detailed information on loop failures remains critical to determining the procedures and products most appropriate to enhanced reliability and loop life expectancy.

To resolve this inadequacy, MnDOT has recommended that all new loop installations be documented and stored in electronic form. Initial input would include type and size of wire, model of inductive-loop detector electronics unit, sealant type, identity of installer (contractor or in-house crew), etc. This installation would then be tracked throughout its lifetime with all repairs being fully documented.

A new repair sheet would be developed that would include a checkoff list for use during troubleshooting 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 was based on an in-depth survey of 9 New York State DOT regions responsible for more than 15,000 loop installations. Although the study did not include a survey of out-of-State agencies, several other State DOTs were contacted to ascertain the types of sealants they used. The survey was initiated after a 1980 study determined that as many as 25 percent of New York State's 15,000 loop detectors were not operational at any given time. The 1980 study further determined that loop detectors were maintenance-free for an average of only 2 years. Consequently, this investigation was designed to discover the major causes of loop failures and to identify steps to reduce the frequency of failure.

NEW YORK SURVEY RESULTS

All current loop failures in New York State were listed and a number of installations were inspected to determine if the actual failure causes 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. Table M-3 lists the number of loops installed in each of three pavement types, AC, composite, or PCC. Table M-4 summarizes the survey results by the types of failures that occurred in each type of pavement.

Table M-3. New York State distribution of inductive loops by pavement type in failure survey.

	Total loops	AC pavement	Composite pavement	PCC pavement
Number	340	275	20	45
Percent	100	81	6	13

Table M-4. Inductive-loop failure percentage by cause of failure and pavement type.

Failure type	Total loops	% Failure AC*	% Failure composite*	% Failure PCC*
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	71	75	71

* AC = asphalt pavement
Composite = asphalt overlay on concrete pavement
PCC = concrete pavement

Of the surveyed loops, approximately 40 percent had exposed wires and approximately 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. Almost 60 percent of the failed loops that were examined had partial or complete sealant failure.

When the sealant did not achieve a good bond to the sidewalls of the slot, debris and water could infiltrate the slot. Sealant could 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 was cracking. In general, pavement failure caused 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 pavement and asphalt-overlaid concrete pavement surfaces displayed some cracking.

Loops in PCC without overlays represented approximately 20 percent of the cracking failures. However, this type of pavement presented other problems, such as gross slab movements that strained the wire at the pavement-shoulder interface or where loop wires cross joints.

NEW YORK CONCLUSIONS AND RECOMMENDATIONS

Major causes of inductive-loop failure uncovered by the New York study were sealant reliability and wire breakage due to pavement failure.

This extensive examination of failed loops revealed two major areas for further study: sealant reliability and reduction of wire breakage due to pavement failure. The survey also concluded that problems existed in the installation process.

Some failed wires were found very close to 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.

Inspection of splicing methods and materials used in the pull box 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 (which requires a 3/8-inch (9.5-mm) slot instead of a 1/4-inch (6.4-mm) slot).
- Chip or core corners of loop sawcut rather than use 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 appropriate hold-down materials are used and properly applied.
- Use proper splicing techniques.
- Standardize installation techniques, and make sure that the work force are 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.

APPENDIX N. GROUNDING (DESIGN GUIDELINES)

The material in this appendix is a reproduction of the information that appears in:

Electrical Design Manual, volume 1
Chapter 9, "Grounding"
Part 2, "Component Design"
Pages 9-1 to 9-39

as published by the Ontario Ministry of Transportation, Ontario, Canada

December 1989 and October 1992 updates to Section III, Subsections 3 and 4, and Section IV.

(Note: The *format* of the material has been modified to conform in appearance to the other parts of the *Traffic Detector Handbook*.)

Ontario

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APPENDIX N. GROUNDING (DESIGN GUIDELINES)

SECTION I—REASONS FOR GROUNDING

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 occur 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 system ground is usually tied to the safety ground. If the two grounds are separated, 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 susceptible to damage since they operate at very low voltages and high speeds and are not designed to physically absorb any significant energy.

SECTION II—CALCULATION OF RESISTANCE TO GROUND

1. GENERAL

(1) A minimal resistance to ground is desirable. Older versions of the Code called for 10 ohm (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 5000 V. 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 Ohm-meters (Ωm). Representative values are given Table N-1.

Table N-1. Representative values of soil resistivity.

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

(2) The soil classification and ρ values in Table N-1 are left purposely vague since environmental effects can drastically change the resistivity of the soil. Table N-2 shows the typical variation of a nominal resistivity with different soil temperatures.

Table N-2. Variation of resistivity with ground temperature.

Ground Temperature (°C)	Resistivity ρ (% of nominal)
20	73
10	100
0+	139
0– (freeze)	303
– 5	798
–10	3333

(3) Resistivity varies widely with moisture content as well as temperature, with values a factor of 350% higher for soil in the 'dry' state than in the '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

(1) Resistance to ground for a single ground rod may be calculated from

$$R_G = R_R = \frac{\rho}{2\pi L_R}[\ln(\frac{4L_R}{a_R}) - 1]$$

where

R_G = Resistance to ground in Ohms (Ω)

ρ = Soil resistivity in Ohm-meters (Ωm)

L_R = Rod length in meters (m)

a_R = Rod radius in meters (m)

R_R = Resistance to ground of one rod in Ohms (Ω).

Example 1: for 20 mm dia. x 3 m Rod

Given $\rho = 100\ \Omega$m, $L_R = 3$ m, $a_R = 0.01$ m

$$R_G = \frac{100}{2\pi \times 3}[\ln(\frac{4 \times 3}{0.01}) - 1] = 32.2\ \Omega.$$

If the soil is wet and ρ decreases to $\rho = 50\ \Omega$m

$$R_G = \frac{50}{2\pi \times 3}[\ln(\frac{4 \times 3}{0.01}) - 1] = 16.1\ \Omega.$$

If the soil is dry and ρ increases to $\rho = 300\ \Omega$m

$$R_G = \frac{300}{2\pi \times 3}[\ln(\frac{4 \times 3}{0.01}) - 1] = 96.6\ \Omega.$$

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 dia. x 6 m Rod

Given $\rho = 100\ \Omega$m, $L_R = 6$ m, $a_R = 0.01$ m

$$R_G = \frac{100}{2\pi \times 6}[\ln(\frac{4 \times 6}{0.01}) - 1] = 18.0\ \Omega$$

or for a 100% rod depth increase (over example 1), the resistance to ground is decreased by 44%.

Example 3: for 25 mm dia. x 3 m Rod

Given $\rho = 100\ \Omega m$, $L_R = 3$ m, $a_R = 0.0125$ m

$$R_G = \frac{100}{2\pi \times 3}[\ln(\frac{4 \times 3}{0.0125}) - 1] = 31.1\ \Omega$$

or for a 25% increase in rod diameter (over that of Example 1), the resistance to ground is decreased by 3%.

3.2 Pedestals

(1) Using the same formula as for a single ground rod,

$$R_G = R_R = \frac{\rho}{2\pi L_R}[\ln(\frac{4L_R}{a_R}) - 1]$$

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

$$R_G = \frac{100}{2\pi \times 2.30}[\ln(\frac{4 \times 2.30}{0.110}) - 1] = 23.7\ \Omega$$

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

$$R_G = \frac{100}{2\pi \times 1.830}[\ln(\frac{4 \times 1.830}{0.043}) - 1] = 36.0\ \Omega$$

or 12 % "worse" than a single ground rod.

3.3 Plate Electrodes

General

(1) For a single plate,

$$R_G = R_P = \frac{\rho}{2\pi L_P}[\ln(\frac{8W_P}{0.5W_P + T_P}) - 1]$$

where

R_P = Resistance of plate to ground in Ohms

L_P = Length in meters

W_P = Width in meters

T_P = Thickness in meters.

Example 6: for 610 x 610 x 6 mm Plate

Given ρ = 100 Ohm, L_P = 0.61 m, W_P = 0.61 m, T_P = 0.006 m

$$R_G = \frac{100}{2\pi \times 0.61}[\ln(\frac{8 \times 0.61}{0.305 + 0.006}) - 1] = 45.8\ \Omega$$

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 the 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

$$R_G = R_W = \frac{\rho}{\pi L_W}[\ln(\frac{2L_W}{\sqrt{d_W Z_W}}) + \frac{1.4L_W}{\sqrt{A_W}} - 5.6]$$

where

R_W = Resistance of wire grid in Ohms

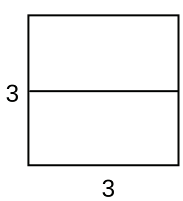
L_W = Total Length of grid wires in meters

d_W = Diameter of wire in meters

Z_W = Burial depth of grid in meters

A_W = Plan area covered by grid in square meters.

Example 7: Using 3 x 3 m grid with cross-tie

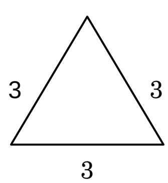


Given ρ = 100 Ωm, L_W = 5 x 3 = 15 m, Z_W = 0.3 m

A_W = 3 x 3 = 9 sq m, d_W = 0.0105 m (#2/0)

$$R_G = R_W = \frac{100}{\pi \times 15}[\ln(\frac{2 \times 15}{\sqrt{0.0105 \times 0.3}}) + \frac{1.4 \times 15}{\sqrt{9}} - 5.6] = 16.4\,\Omega$$

Example 8: Using 3 x 3 m triangular grid



Given ρ = 100 Ωm, L_W = 3 + 3 + 3 = 9 m, Z_W = 0.3 m

A_W = 0.5 x 3 x 3 sin(60°) = 3.90 sq m, d_W = 0.0105 m (#2/0)

$$R_G = R_W = \frac{100}{\pi \times 9}[\ln(\frac{2 \times 9}{\sqrt{0.0105 \times 0.3}}) + \frac{1.4 \times 9}{\sqrt{3.9}} - 5.6] = 23.3\,\Omega$$

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

$$R_G = R_{MR} = \frac{\rho}{2\pi n L_R}[\ln(\frac{4L_R}{a_R}) - 1 + \frac{2.8L_R(\sqrt{n}-1)^2}{\sqrt{A_R}}]$$

where

R_{MR} = Combined resistance of multiple rods to ground in Ohms

L_R = Rod length in meters

n = Number of rods

A_R = Area covered by the n rods in square meters.

For 20 mm x 3 m rods,

$$R_{MR} = \frac{\rho}{\pi n}[1 + \frac{1.4(\sqrt{n}-1)^2}{\sqrt{A_R}}]$$

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

$$R_G = R_{MR} = \frac{100}{\pi \times 4}[1 + \frac{1.4(\sqrt{4}-1)^2}{\sqrt{9}}] = 11.7\,\Omega$$

(Note: rods not connected by wire)

3.6 Combination Rod and Wire Grids

General

(1) It is may be necessary to include both rod and wire grids for service 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 (Subsection 3.4)

R_{MR} = Resistance of multiple rods in Ohms (Subsection 3.5)

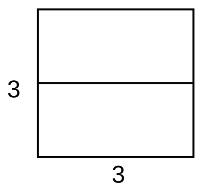
R_{WR} = Mutual resistance factor of the wires to the rods

$$= R_{WR} = \frac{\rho}{\pi L_W}[\ln(\frac{2L_W}{L_R}) + \frac{1.4L_W}{\sqrt{A_W}} - 4.6]$$

For 20 mm x 3 m rods,

$$R_{WR} = \frac{\rho}{\pi L_W}[\ln(0.67) + \frac{1.4L_W}{\sqrt{A_W}} - 4.6]$$

Example 10: Using 3 x 3 m grid with cross-tie and rods



Given $\rho = 100\ \Omega$m, $L_R = 3$ m, $a_R = 0.01$ 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,

$$R_{WR} = \frac{\rho}{\pi L_W}[\ln(\frac{2L_W}{L_R}) + \frac{1.4L_W}{\sqrt{A_W}} - 4.6]$$

Substituting the given data in the formula, we have

$$R_{WR} = \frac{100}{\pi \times 15}[\ln(0.67 \times 15) + \frac{1.4 \times 15}{\sqrt{9}} - 4.6] = 10.0\,\Omega$$

$$R_{MR} = \frac{100}{\pi \times 4}[1 + \frac{1.4(\sqrt{4} - 1)^2}{\sqrt{9}}] = 11.7\,\Omega$$

(from Example 9).

$$R_W = \frac{100}{\pi \times 15}[\ln(\frac{2 \times 15}{\sqrt{0.0105 \times 0.3}}) + \frac{1.4 \times 15}{\sqrt{9}} - 5.6] = 16.4\,\Omega$$

(from 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 for R_G, we have

$$R_G = \frac{16.4 \times 11.7 - 100}{16.4 + 11.7 - 20} = 11.3\,\Omega$$

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

$$R_G = R_C = \frac{\rho}{2\pi L_W}[\ln(\frac{L_W}{a_W}) + \ln(\frac{L_W}{Z_W}) - 2 + \frac{2Z_W}{L_W} - \frac{Z_W^2}{L_W^2}],$$

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,

$$R_C = \frac{100}{2\pi \times 50}[\ln(\frac{50}{0.00252}) + \ln(\frac{50}{0.6}) - 2 + \frac{2 \times 0.6}{50} - \frac{0.6^2}{50^2}] = 3.93\,\Omega$$

3.8 Summary of Calculations

General Formulae

Single Rod Only: $R_G = R_R = \frac{\rho}{2\pi L_R}[\ln(\frac{4L_R}{a_R}) - 1]$

Single Plate Only: $R_G = R_P = \frac{\rho}{2\pi L_P}[\ln(\frac{8W_P}{0.5W_P + T_P}) - 1]$

Wire Grid Only: $R_G = R_W = \frac{\rho}{\pi L_W}[\ln(\frac{2L_W}{\sqrt{d_W Z_W}}) + \frac{1.4L_W}{\sqrt{A_W}} - 5.6]$

Multiple Rods Only:

$$R_G = R_{MR} = \frac{\rho}{2\pi n L_R}[\ln(\frac{4L_R}{a_R}) - 1 + \frac{2.8L_R(\sqrt{n} - 1)^2}{\sqrt{A_R}}]$$

Multiple Rods and Wire Grid: $R_G = \frac{R_W R_{MR} - R_{WR}^2}{R_W + R_{MR} - 2R_{WR}}$

where $R_{WR} = \frac{\rho}{\pi L_W}[\ln(\frac{2L_W}{L_R}) + \frac{1.4L_W}{\sqrt{A_W}} - 4.6]$

Single Wire Only:

$$R_G = R_C = \frac{\rho}{2\pi L_W}[\ln(\frac{L_W}{a_W}) + \ln(\frac{L_W}{Z_W}) - 2 + \frac{2Z_W}{L_W} - \frac{Z_W^2}{L_W^2}]$$

The symbols that appear in the above formulae are defined as:

$R_G =$ 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 meters

$L_W =$ Length of wire in meters

$L_P =$ Width of plate in meters

$T_P =$ Thickness of plate in meters

$A_W =$ Area of wire grid in square meters

$A_R =$ Area covered by several ground rods in square meters

$a_R =$ Radius of ground rod in meters

$a_W =$ Radius of wire in meters

$d_W =$ Diameter of wire in meters

$Z_W =$ Burial depth of wire in meters

$n =$ Number of ground rods

$\rho =$ Soil resistivity in Ohm-meters.

Useful Formulae

(1) Since the Ministry's grounding system uses common components of

- 20 mm dia. x 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 x 610 x 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 x 3 m grid c/w cross-tie (#2/0 wire and 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 N-3 and included in the design.

(e) Table N-3 is derived from the general formulae of Subsection 3.8.

(f) The following notes apply to Table N-3:

(i) Configuration No.9 may be used with continuous #6 ground wire commonly used for lighting. Grounding at every 5^{th} pole applies.

(ii) Configurations No. 11 or 12 may be used for grounding in clay or areas that remain damp. Configuration No. 13 should be used as the 'standard' design.

(iii) Configurations No. 15 to 18 indicate the results of adding 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.

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 in Table N-3 should be used for design and added to during construction if necessary.

(2) Soil overburden of 1 m to 2 m depth over bedrock:

(a) Plates may be used as ground electrodes with the same configurations shown in Table N-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 Ωm. 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.

Table N-3. Resistance to ground for various ground system configurations and soils.

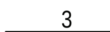
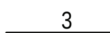
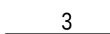
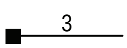
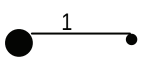
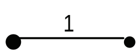
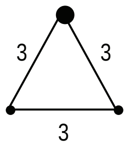
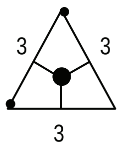
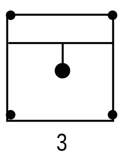
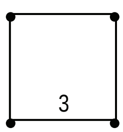
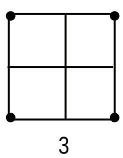
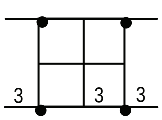
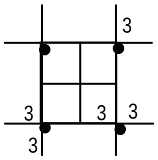
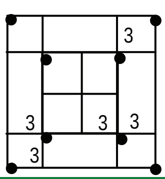
Ground System Configuration	Description	Normal Use	Resistance to Ground (Ω) in Clay (ρ=100Ωm)	Resistance to Ground (Ω) in Sandy Clay (ρ=200Ωm)	Resistance to Ground (Ω) in Clayey Sand (ρ=500Ωm)	Resistance to Ground (Ω) in Sand (ρ=1500Ωm)	Resistance to Ground (Ω) in Sand, Gravel (ρ=5000Ωm)
	1. Single 20 mm x 3 m rod	Addition to system	32	80	160	480	1610
	2. Single 220 mm dia. x 2300 mm steel footing	Poles (requires additional system)	28	70	140	420	1400
	3. Single 85 mm dia. x 1830 mm 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
	5. Single #6 wire, bare, 3 m long	Addition to system	41	103	205	615	2050
	6. Single #2/0 wire, bare, 3 m long	Addition to system	38	95	190	570	1900
	7. Single #6 wire, 2 rods	Service	19	38	95	290	950
	8. Single #2/0 wire, 2 plates	Service in overburden	27	54	140	410	1400
	9. 220 mm dia. x 2300 mm steel footing, #6 wire, 1 rod	Poles	19	38	95	285	950
	10. 85 mm dia. X 1830 mm steel footing, #6 wire, 1 rod	Poles	16	34	80	240	800

Table N-3. Resistance to ground for various ground system configurations and soils (continued).

Ground System Configuration	Description	Normal Use	Resistance to Ground (Ω) in Clay (ρ=100Ωm)	Resistance to Ground (Ω) in Sandy Clay (ρ=200Ωm)	Resistance to Ground (Ω) in Clayey Sand (ρ=500Ωm)	Resistance to Ground (Ω) in Sand (ρ=1500Ωm)	Resistance to Ground (Ω) in Sand, Gravel (ρ=5000Ωm)
	11. 85 mm dia. x 1830 mm steel footing, #2/0 wire, 2 rods	Cabinets	14	28	70	210	700
	12. 85 mm dia. x 1830 mm steel footing, #2/0 wire, 3 rods	Cabinets	13	26	65	195	650
	13. 85 mm dia. x 1830 mm steel footing, #2/0 wire, 4 rods	Cabinets	10	20	50	150	250
	14. #2/0 wire, 4 rods	Service Any for ρ < 125 Ωm	11	22	55	165	550
	15. #2/0 wire, 4 rods, 2 ties	Any for ρ < 125 Ωm	11	22	55	165	550
	16. #2/0 wire, 4 rods, 2 ties, 4 tails	Any for 125 < ρ < 150 Ωm	(9)	18	45	135	450
	17. #2/0 wire, 4 rods, 2 ties, 8 tails	Any for 150 < ρ < 200 Ωm	(6)	12	30	90	300
	18. #2/0 wire, 8 rods, 6 ties	Any for 200 < ρ < 350 Ωm	(5)	10	25	75	250

3.11 Application Guidelines

(1) From the examples in 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 cohesive material only or similar.'

(9) Table N-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 an 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.

SECTION III—EFFECTS OF LIGHTNING

1. GENERAL

The effects of lightning on 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 the following probabilities:

- Probability of a storm
- Probability of a strike
- Probable potential energy and RF energy
- Probable rise time of the voltage (open circuit) wave or current (short circuit) wave
- Probable duration or repetition of a strike.

2. DESIGN CRITERIA

The design criteria adopted for protection of the Ministry's electronic equipment are:

- Peak voltage = 15,000 V
- Peak current = 5,000 A
- Maximum current flow duration = 500 μs
- Current waveform = 8 x 20 μs
- Voltage Waveform = 1.2 x 50 μs.

Figure N-1 indicates waveforms and timing of lightning protection devices.

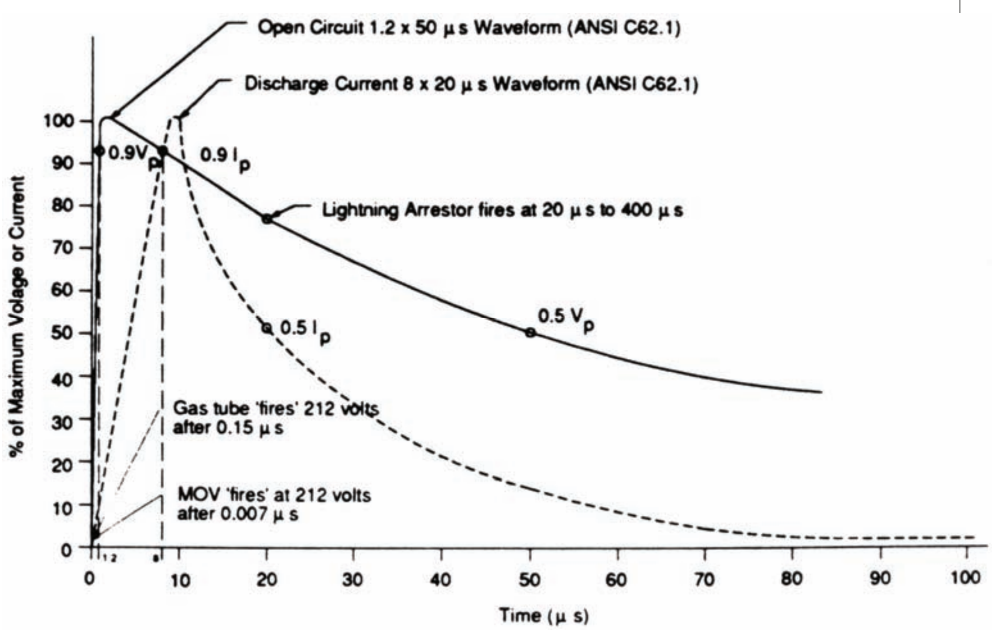


Figure N-1. Voltage and current waveforms.

Note that the times needed for protection are much too fast to allow power circuit protection devices such as breakers, fuse, lightning arresters etc. to operate effectively. However, devices such as gas tubes and metal oxide varistors (MOVs) will initiate protection 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 far as 6 km away. Surges on overhead high voltage lines are grounded through lightning arresters at transformer locations.

Figure N-2 shows the voltage and current distribution through the earth near the bottom of the utility pole. For the design value of resistivity $\rho = 100$ Ωm, 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 a minimum distance from the Hydro ground as indicated in Figure N-3. Since the designer seldom knows where the Hydro ground line is located, the convention of 5.5 m to the center of the pole is used as a design practice. Note that a large voltage will appear at the service 'SN' due to the L*di/dt* voltage on the grounding cable.

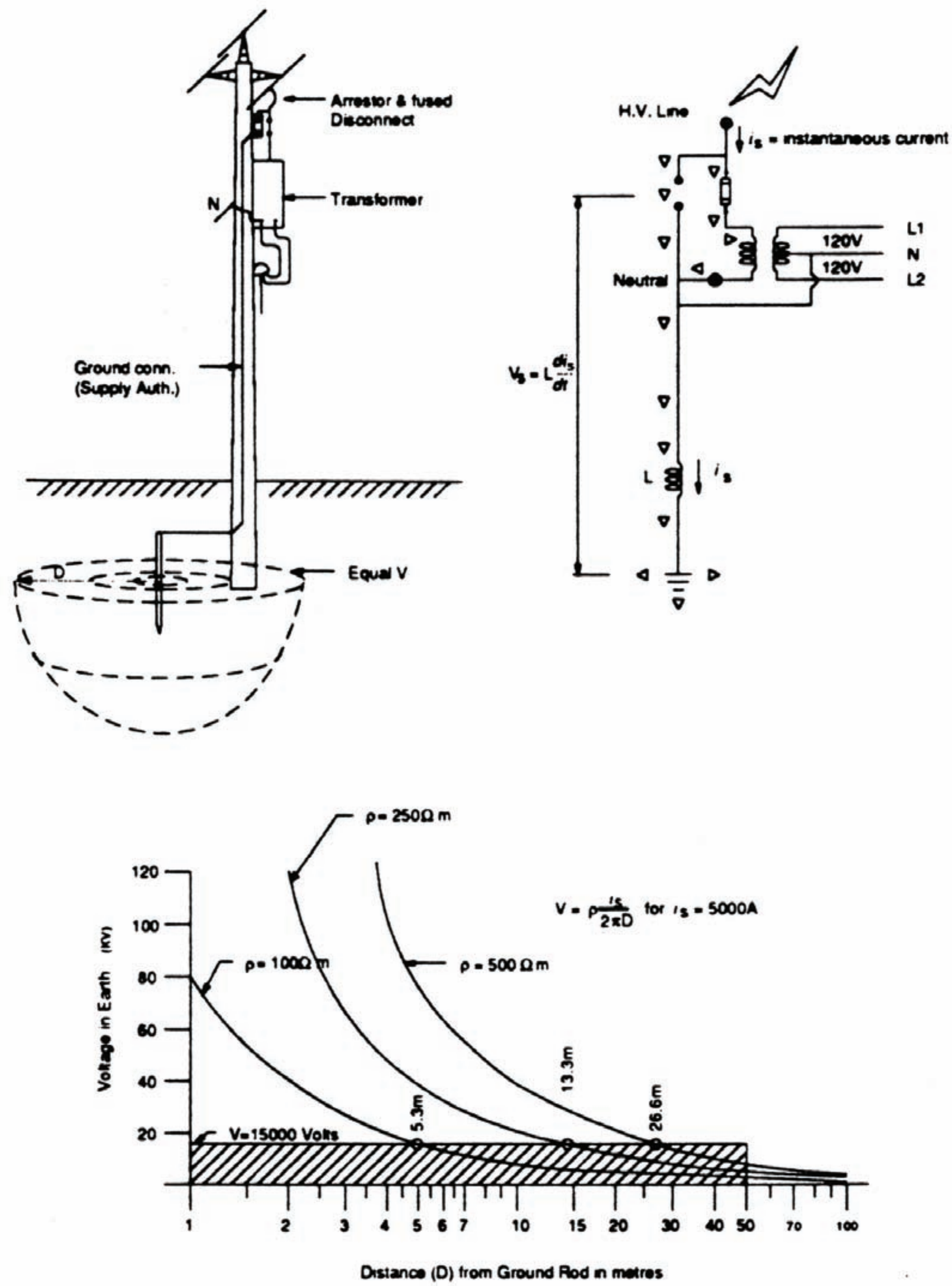


Figure N-2. Voltage in earth due to discharging lightning current at service pole.

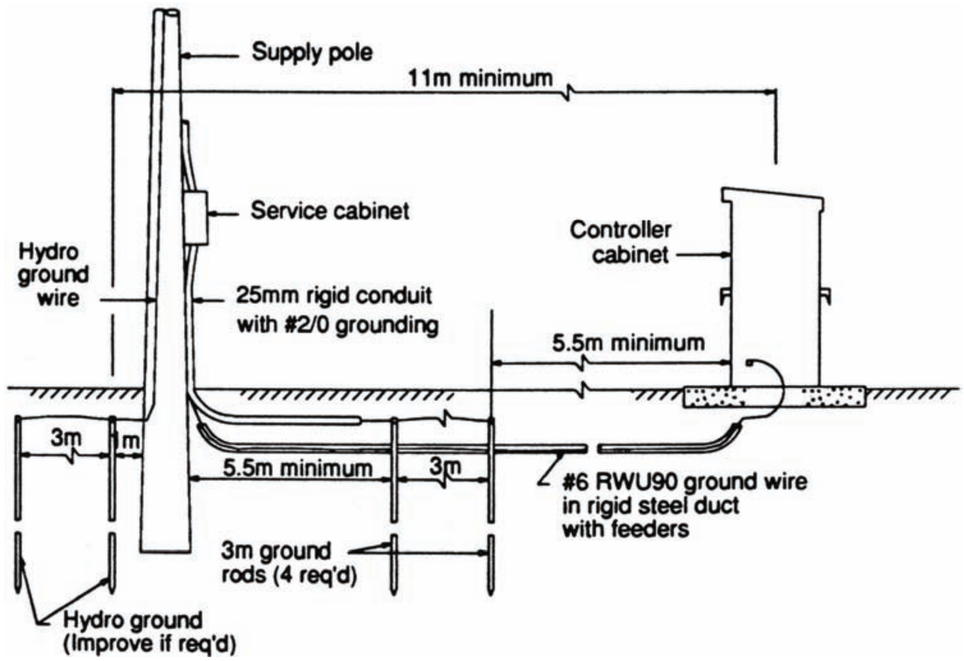


Figure N-3. Recommended improvement to system ground connections.

4. OTHER SOURCES OF POSSIBLE DAMAGE

Traffic signal systems contain many other sources of transient voltages and currents 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—inductive loop detector electronics units are protected internally with their own lightning arrester and are also provided with external MOVs 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 possibility of induced currents caused by transient voltages in the earth is minimized by shielding the detector cable and leaving both ends of the shield cut off.

(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 MOVs 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° from an overhead line and somewhat protected by a 45° cone. It is not desirable, however, to install the cabinet directly under the lines due to possible electromagnetic interference. The cabinet location (Figure N-4) should be:

- 11 m minimum from the supply pole
- 3 m minimum (horizontally) clear of overhead lines

- Within the 30º to 45º cone of protection (within 15 m for normal height lines) of the overhead lines.

If the controller is to be situated across the road from the hydro lines, then the #6 AWG (green) ground wire and the" feeder wires should be run in rigid steel duct, to the nearest electrical chamber. These conductors should then be run to the next chamber across the road via the under-pavement crossing, and from this chamber to the controller in any approved electrical duct, not necessarily of metal.

(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 service ground bus) as indicated in Figure N-5.

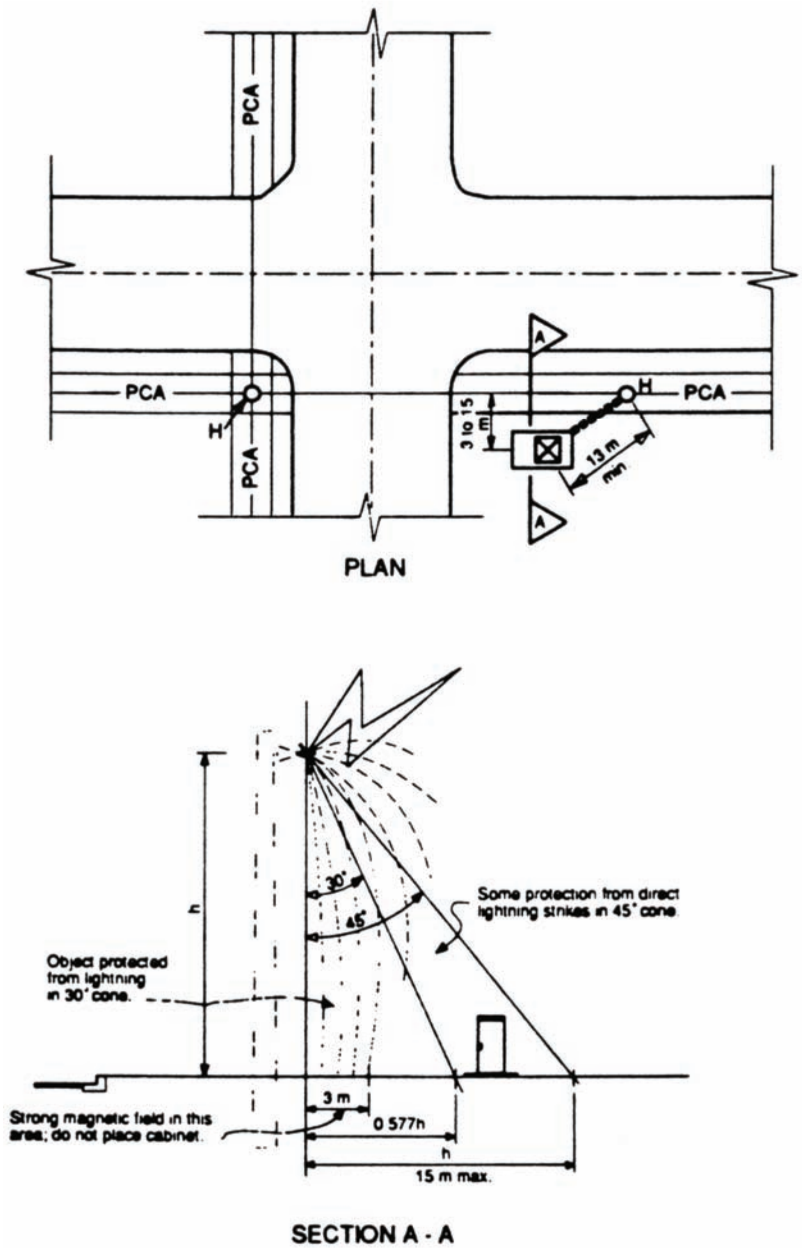


Figure N-4. Controller cabinet location for best lightning protection.

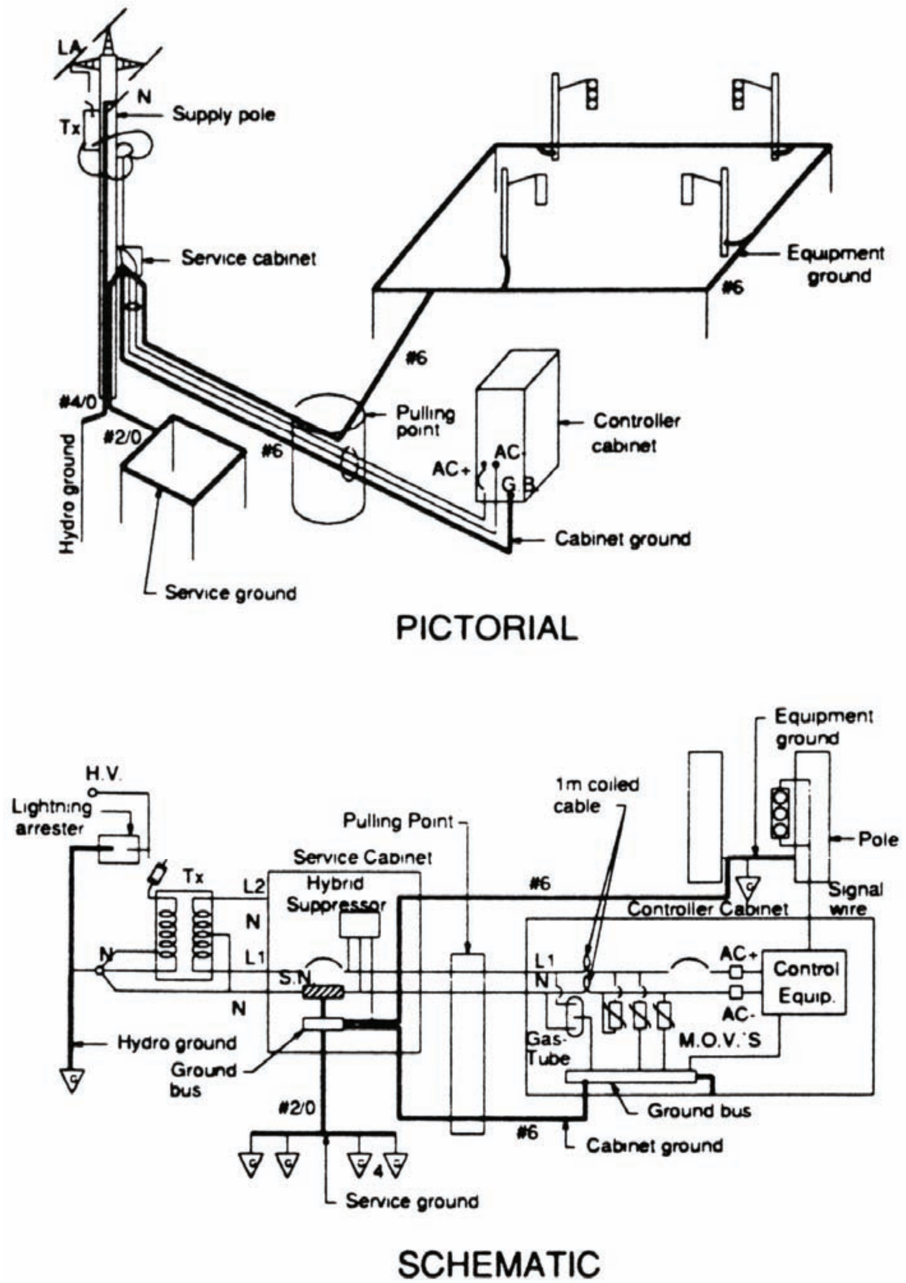


Figure N-5. Signal grounding system (with or without lighting). No ground electrodes at cabinet.

SECTION IV—SUMMARY OF DESIGN GUIDELINES

1. TRAFFIC SIGNAL SYSTEMS

(1) Design standard grounding system under normal circumstances (Figures N-3 and N-5):

- Service ground—4 rods and #2/0 bare ground wire.
- Controller cabinet ground connected to system ground at service ground bus.

- Equipment ground—1 rod or steel footing per intersection corner interconnected with #6 insulated wire.
- System ground—interconnect the controller cabinet ground and the equipment ground to the service ground at service ground bus.

(2) Use improved design as per Table N-3 for grounds in sand, gravel, or rock. Consult Geotechnical Information and District Maintenance.

(3) Both ends of the detector cable shield should be cut off and left unconnected.

(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, fences, and guide rails.

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APPENDIX O. GROUNDING (MAINTENANCE GUIDELINES)

The material in this appendix is a reproduction of the information that appears in:

Electrical Maintenance Manual, volume 2
Chapter 9, "Grounding"
Part 2, "Component Maintenance,"
Pages 9-1 to 9-11

as published by the Ontario Ministry of Transportation, Ontario, Canada

December 1989.

(Note: The format of the material has been modified to conform to the styles used in other parts of the *Traffic Detector Handbook*.)

Ontario

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APPENDIX O. GROUNDING (MAINTENANCE GUIDELINES)

SECTION I—TRAFFIC SIGNAL GROUNDING

1. HYDRO GROUNDS

(1) Inadequate hydro grounds at a service pole will allow energy from lightning discharge into the controller. Inspect Hydro grounds visually and arrange for the Supply Authority to repair faulty grounds.

(2) At controller sites where lightning problems have occurred, the Hydro ground should be reinforced to two 20 x 3000 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 a 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 O-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 O-1.

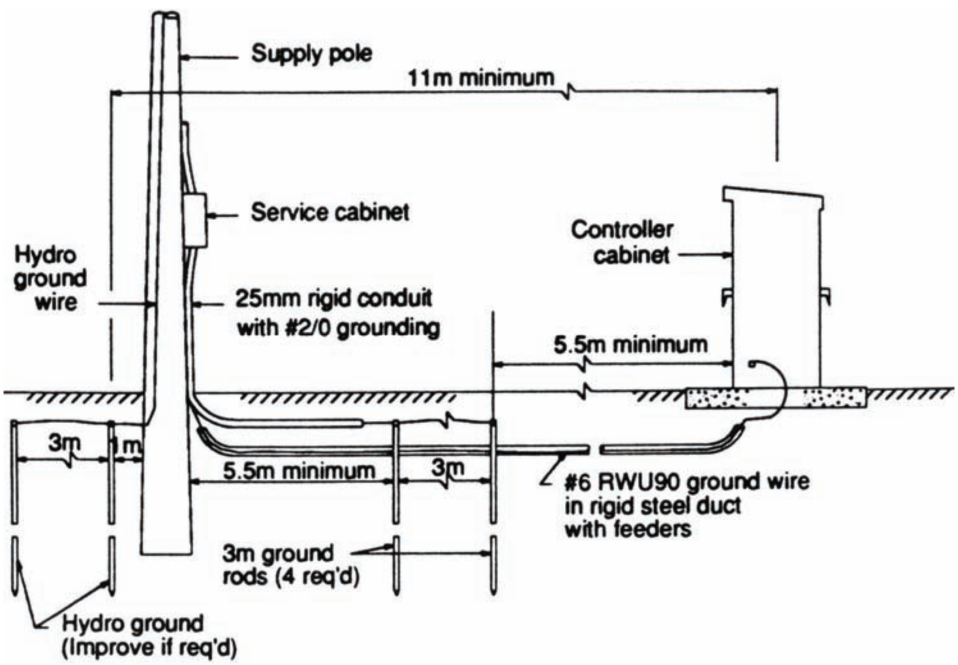


Figure O-1. Recommended improvement to system ground connection.

3. CABINET GROUNDS

(1) Proper ground bus bar should be installed in the controller cabinet and all ground leads from equipment should connect to this one point.

(2) The controller cabinet ground bus should be connected to the service solid neutral by a #6AWG RWU90 insulated system ground wire.

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 #16 AWG RWU90–40°C green.

(2) Insta11 connections of the three systems (Service ground, cabinet ground, and equipment ground) as indicated in Figure O-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 Subsection 8.

7. EMERGENCY INSPECTION

(1) For controllers damaged by lightning:

- (a) Inspection Hydro ground as per Subsection 1.
- (b) Have Supply Authority check distribution arrestor and upgrade ground and arrestor if required.
- (c) Inspect for proper installation of grounds as per Subsections 1 to 5.

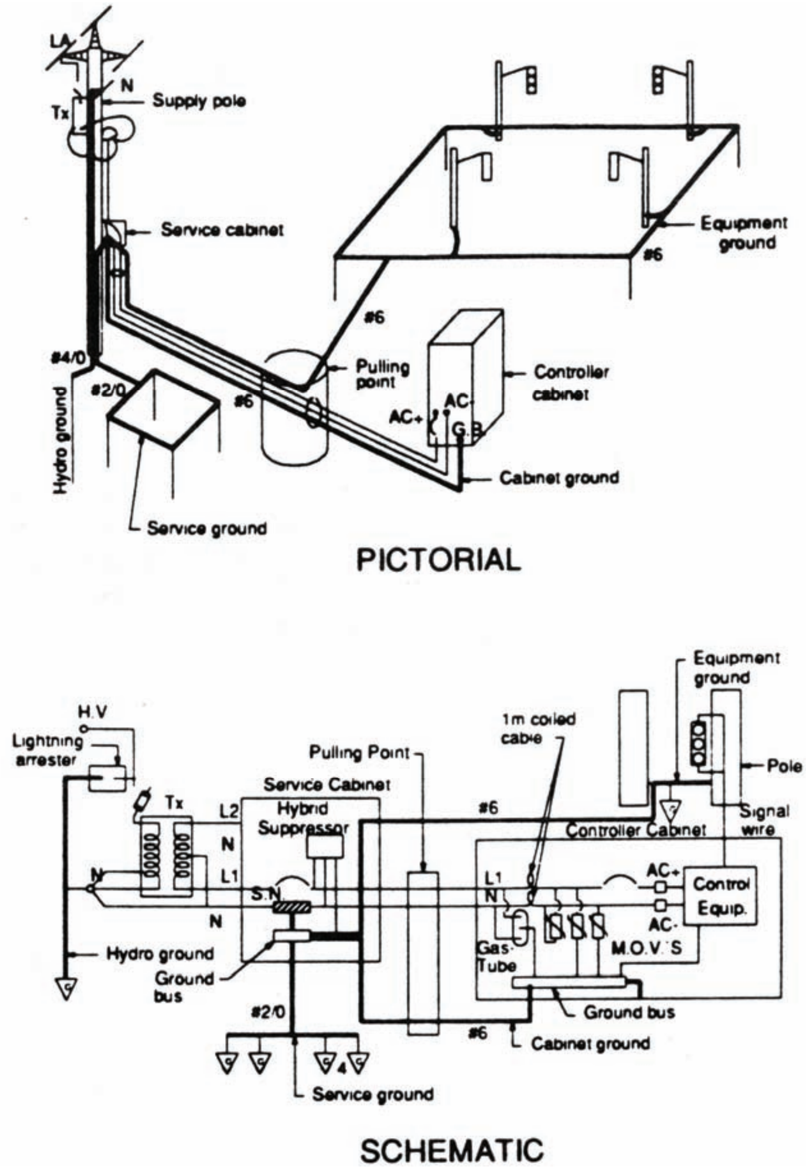


Figure O-2. Signal grounding system (with or without lighting). No ground electrodes at cabinet.

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 O-1.

9. STEEL FOOTINGS

(1) Steel footings may be considered the equivalent of a ground rod for resistance to ground purposes.

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).

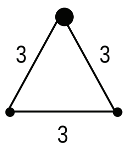
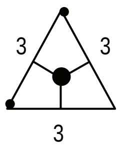
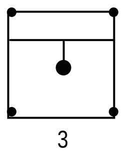
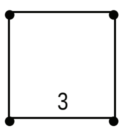
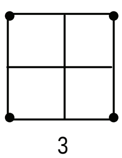
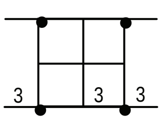
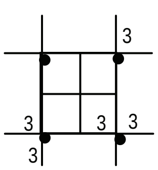
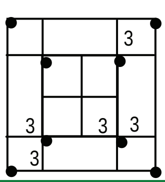
(3) Do not install rods at more than 45° angle. Driving jaws for use with a hydraulic drive head are available.

(4) Use 20 x 3000 mm copperclad rods only, with thermit weld or impact connectors.

Table O-1. Resistance to ground for various ground system configurations and soils.

Ground System Configuration	Description	Normal Use	Resistance to Ground (Ω) in Clay (ρ=100Ωm)	Resistance to Ground (Ω) in Sandy Clay (ρ=200Ωm)	Resistance to Ground (Ω) in Clayey Sand (ρ=500Ωm)	Resistance to Ground (Ω) in Sand (ρ=1500Ωm)	Resistance to Ground (Ω) in Sand, Gravel (ρ=5000Ωm)
•	1. Single 20 mm x 3 m rod	Addition to system	32	80	160	480	1610
●	2. Single 220 mm dia. x 2300 mm steel footing	Poles (requires additional system)	28	70	140	420	1400
●	3. Single 85 mm dia. x 1830 mm 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 mm dia. x 2300 mm steel footing, #6 wire, 1 rod	Poles	19	38	95	285	950
• 1 •	10. 85 mm dia. X 1830 mm steel footing, #6 wire, 1 rod	Poles	16	34	80	240	800

Table O-1. Resistance to ground for various ground system configurations and soils (continued).

Ground System Configuration	Description	Normal Use	Resistance to Ground (Ω) in Clay (ρ=100Ωm)	Resistance to Ground (Ω) in Sandy Clay (ρ=200Ωm)	Resistance to Ground (Ω) in Clayey Sand (ρ=500Ωm)	Resistance to Ground (Ω) in Sand (ρ=1500Ωm)	Resistance to Ground (Ω) in Sand, Gravel (ρ=5000Ωm)
	11. 85 mm dia. x 1830 mm steel footing, #2/0 wire, 2 rods	Cabinets	14	28	70	210	700
	12. 85 mm dia. x 1830 mm steel footing, #2/0 wire, 3 rods	Cabinets	13	26	65	195	650
	13. 85 mm dia. x 1830 mm steel footing, #2/0 wire, 4 rods	Cabinets	10	20	50	150	250
	14. #2/0 wire, 4 rods	Service Any for ρ < 125 Ωm	11	22	55	165	550
	15. #2/0 wire, 4 rods, 2 ties	Any for ρ < 125 Ωm	11	22	55	165	550
	16. #2/0 wire, 4 rods, 2 ties, 4 tails	Any for 125 < ρ < 150 Ωm	(9)	18	45	135	450
	17. #2/0 wire, 4 rods, 2 ties, 8 tails	Any for 150 < ρ < 200 Ωm	(6)	12	30	90	300
	18. #2/0 wire, 8 rods, 6 ties	Any for 200 < ρ < 350 Ωm	(5)	10	25	75	250

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 endeavor 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.

SECTION II—REFERENCES

(1) "Equipment, Manuals and Procedures Evaluation for the Design and Maintenance of Traffic Signal Systems," *Report No. 2, Grounding*. Ministry of Transportation of Ontario, May 1988.

TABLE OF CONTENTS: APPENDIX P.

APPENDIX P. GLOSSARY

AC (also written ac): Alternating Current. See definition of alternating current.

ACTIVE SENSOR: A sensor that transmits energy, a portion of which is reflected or scattered from a vehicle or other objects and surfaces in its detection zone back toward the receiving aperture of the sensor.

ACTUATED CONTROLLER: A traffic signal controller that receives information from vehicle and/or pedestrian sensors and provides appropriate signal timing.

ACTUATION: The operation of any type of sensor (NEMA). The word operation means an output from the sensor system to the controller.

ADVISORY SENSOR: A device that detects 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 that reverses its magnitude and direction of flow at regular intervals. The rate of reversal is expressed in hertz (cycles per second).

AMPERE: The unit expressing the rate of flow of electrons through a conductor. One ampere is the current flowing through a 1-ohm resistance with 1-volt pressure.

AMPLIFIER: See electronics unit.

ANALOG: An electronic design that uses continuously varying voltages, rather than discrete digital values.

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 sensors cannot hold the call indefinitely.) Sensors used for this are frequently referred to as large-area detectors, long-loop detectors, or presence detectors.

AREA OF DETECTION: See Detection Zone.

AREA DETECTOR: See Large Area Detector.

ARTERIAL: A major urban roadway usually having coordinated signals along its length.

ASTM: American Society for Testing and Materials.

ATC: Advanced Transportation Controller.

AUXILIARY EQUIPMENT: Separate devices used to add supplementary features to a controller assembly (NEMA).

AWG: American Wire Gauge. The standard measurement of wire size based on the circular mil system (1 mil equals 0.001 inch).

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 traffic flow sensor that is outputting an actuation.

CALLING DETECTOR (CALLING SENSOR): A detector (sensor) 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 dielectric materials that permits the storage of electrically separated charges when potential differences exist between the surfaces of the dielectric. Capacitance is expressed as the ratio of an electric charge to a potential difference.

CARD-RACK MOUNTED ELECTRONICS UNIT: See Rack Mounted Electronics Unit.

CARRYOVER OUTPUT: The ability of a sensor 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 inductive 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 that processes information from an inductive-loop detector or other sensor.

CIRCUIT: A closed path followed by an electric current.

CLEARANCE INTERVAL: See Red Clearance Interval.

COIL: A coiled conductor, wound on a form or core, which uses electromagnetic induction to cause changes in a current.

CONDUCTANCE: The measure of ability to conduct electricity expressed in units of inverse ohms-meter.

CONDUCTOR: A medium for transmitting electrical current. A conductor usually consists of copper or other electrically conductive 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 (sensor) 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 (sensor) 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 Assembly:** 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. Another controller class (i.e., Type 170, 179, and 2070) standardizes hardware modules and uses specialized software to implement traffic management functions.

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 sensor or sensor electronics unit with any other channel in that or another device. Crosstalk can occur via mutual coupling of magnetic fields in nearby inductive loops. The effect is an interaction between two or more electronics units in the same cabinet when the units operate at the same or nearby frequencies. Crosstalk results in a sensor output 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 sensor 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 (ELECTRONICS UNIT): A detector (electronics unit) 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 electronics unit.

DELAYED OUTPUT: The ability of an electronics unit to delay its output for a predetermined length of time during an extended actuation (NEMA).

DELTA L (ΔL): 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 sensor/-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 sensor (NEMA). Also called zone of detection, sensing zone, area of detection, detection area, effective loop area, field of influence, field of view, or footprint.

DETECTOR or SENSOR: A device for indicating the presence or passage of automotive vehicles, light and heavy rail, buses, or pedestrians. This general term is usually supplemented with a modifier indicating type (e.g., inductive-loop detector, magnetic detector, radar sensor, and video image processor); operation (e.g., point detector or sensor, presence detector or sensor, and large area sensor); or function (e.g., calling detector and extension detector). See also Traffic Detector or Sensor.

DETECTOR AMPLIFIER: See Electronics Unit.

DETECTOR (ELECRONICS UNIT) FAILURES: The occurrence of detector malfunctions including nonoperation, chattering, or other intermittently erroneous detections.

DETECTOR (ELECTRONICS UNIT) 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 sensor.

DETECTOR MODE: See Electronics Unit Mode.

DETECTOR SETBACK: See Sensor Setback.

DETECTOR SYSTEM: See Sensor System.

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 that travels in one direction.

DISPATCHER: Obsolete Name. See Controller Unit

DRIFT: Change in the electrical properties of the sensor 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 time-varying magnetic field.

EFFECTIVE LOOP AREA: See Detection Zone.

EIA: Electronic Industries Association.

ELECTRONICS UNIT: An electronic device that energizes the wire loop(s), monitors the loop(s) inductance by filtering and amplifying the signals it receives, and responds to a predetermined decrease in inductance with an output that indicates the passage or presence of vehicles in the detection zone. It is the electronics element in a loop detector system, i.e., it does not include the loop(s), lead-in wire, or lead-in cable. Sometimes called an amplifier or detector, although it performs other functions as well, e.g., sensitivity adjustment, failure indication, and delayed actuation. Electronics units are also used with magnetic detectors and magnetometers.

ELECTRONICS UNIT MODE: A term used to describe the operation of an electronics unit channel output when a presence (or passage) detection occurs (NEMA). Also referred to as Detector Mode. See pulse mode, controlled output, continuous presence mode, and limited presence mode.

ENCAPSULATION: The process of filling the saw slot with sealant to surround the wires in the slot and protect them from traffic, weather, and debris.

ENCASEMENT: Material used to enclose the loop wire for protection, such as a polyvinyl or polyethylene tube. Often referred to as Detect-a-duct or other similar commercial names.

EPOXY: A resin used in bonding.

EXTENDED CALL DETECTOR (ELECTRONICS UNIT): When selected, this detector extends the output (See Carryover Output) after the vehicle departs the detection zone for a preset time.

EXTENDED CALL TIMING: An electronics unit 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 electronics unit. 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 (ELECTRONICS UNIT): An electronics unit that is configured 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 electronics 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 Detection Zone.

FIXED TIMING PLAN: Timing plan in which the cycle length, split, offset, and actuated settings are not adjusted between switching of timing plans. These are used in TOD/DOW and traffic adjusted systems.

FLEXIBLE TIMING PLAN: A dynamic timing plan in which the cycle length, split, offset, and actuated settings may be adjusted once per cycle between switching of timing plans. These are used in Traffic Responsive Systems such as SCOOT.

FMCW: Frequency modulated, continuous wave. A waveform Capable of detecting presence and measuring the relative speed of vehicles within the range measurement interval.

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 controller assembly for supervising the operation of traffic control signals in which means are provided for traffic actuation on all approaches to the intersection.

GAP: The time interval between the end of one vehicle sensor 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, allowing the green to 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 electronics units and auxiliary logic. The logic can monitor the signal display, enable or disable the selected extended call sensors, and hold the controller in artery green.

GROUND: The earth and all parts conductively 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 the measurement unit for 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 fully actuated, isolated operation to semiactuated, 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 cc MOTORCYCLE: A small motorcycle commonly considered to be the smallest registered motor vehicle. It is used as the baseline for motorized vehicle detection.

μH (MICROHENRY): A measure of inductance. See Henry and Inductance.

IMSA: 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 circuit. The ratio of the electromotive force to the rate of change of the current. Measured in microhenrys (μH).

INDUCTIVE-LOOP DETECTOR: See Loop Detector.

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 (0 to 90 degrees) between inductor voltage and current divided by the inductor current assuming sinusoidal excitation.

INFRARED SENSOR: See passive infrared sensor.

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 that 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.

IN-ROADWAY SENSOR: A sensor that is embedded in the pavement of the roadway, embedded in the subgrade of the roadway, or taped or otherwise attached to the surface of the roadway.

INTERCONNECTED CONTROL: Control systems in which basic coordination is provided by wireline or wireless interconnect. This information is used to determine the local signal timing of offset and cycle/split or actuated timing based on the Time-of-Day/Day-of-Week. The operator can select timing and download timing plans and changes and monitor system status. There are no system detectors in Interconnected Control systems.

INTERVAL: The part of parts of the signal cycle during which signal indications do not change (NEMA).

ISOLATED INTERSECTION CONTROL: The form of signal control for a single signalized intersection that does not have control relationships between intersections nor any data flow between intersections. The ***system*** of intersections is not responsive to traffic in real time. The individual isolated intersection may have local actuated control or Time of Day/Day of Week changes based on historical traffic flows. Also called uncoordinated signal control. See also totally isolated systems.

ITE: Institute of Transportation Engineers.

JUNCTION WELL: See Pull Box.

JUNCTION BOX: See Pull Box.

KILOHERTZ (kHz): Thousands of hertz. A measure of frequency.

***L*:** Symbol for inductance.

ΔL: Symbol for change in inductance.

LARGE AREA SENSOR: One or more sensors or combination of sensors connected together in series, parallel, or series/parallel covering an area in the approach to an intersection or extended freeway segment. Large area sensors that monitor intersection approaches have detection areas that vary from 6 x 40 ft (1.8 x 12 m) to 6 x 100 ft (1.8 x 30 m) or larger. A common configuration 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). Also known as large area detector, area detector, or area sensor.

LASER RADAR: An active sensor that transmits energy usually in the near infrared spectrum for traffic management applications. Single and two-lane models are manufactured.

LAST CAR PASSAGE: A selected feature of a density controller that, 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 that is spliced to the lead-in wire in the pull box and connects to the input of the electronics unit in the controller cabinet (NEMA). Sometimes called home-run cable, transmission line, or feeder cable.

LEAD-IN WIRE: That portion of the inductive-loop wire between the physical edge of the loop and the pull box, which should be twisted a specified number of turns per foot. The lead-in wire is located in the saw slot connecting the loop to the edge of the roadway. From there, it is placed in conduit to the controller or to a pull box, where it is spliced to the lead-in cable. For a magnetic detector and magnetometer, it is the wire that runs from the sensor (probe) to the pull box.

LIGHT-SENSITIVE VEHICLE SENSOR: A sensor consisting of a light source and photoelectric cell or cells, capable of being actuated by the passage of a vehicle interrupting the beam or beams of light. When properly equipped, directional characteristics are present.

LIMITED PRESENCE MODE: Electronics unit output continues for a limited period of time if vehicles remain in the field of influence. See electronics unit 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 that incorporates electronics unit 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: An active sensor composed, in part, of one or more loops of wire whose inductance decreases in response to the passage or presence of a vehicle in the detection zone of the loops. See also Loop Detector System.

A. **Motion loop detector, nondirectional:** An inductive-loop detector that produces a signal when a vehicle passes over any portion of the loop.

B. **Motion loop detector, directional:** An inductive-loop detector consisting of two separate loops either closely spaced or partially overlapping that is not affected by the passage of a vehicle except in the desired direction.

C. **Presence loop detector:** An inductive-loop detector that 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 detection system that senses a decrease in inductance of the wire loop(s) during the passage or presence of a vehicle in the detection zone of the loop(s) (NEMA). Has the same meaning as loop detector, but is clearer in its inclusion of the wire loop(s), lead-in wire, lead-in cable, and the electronics unit.

LOOP ELECTRONICS UNIT: See Electronics Unit.

LOOP OCCUPANCY CONTROL: A detector/controller design using long detection loop(s) [normally 30 ft (9 m) or longer], and a controller operated in the nonlocking 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 and other sensors, as well as inductive-loop detectors.

LOOP SYSTEM: The wire loops and lead-in wire that are connected through lead-in cable to the input terminals of the electronics unit.

LOOP LEAD-IN WIRE: See Lead-In Wire.

LSI CHIP: An electrical component with more than 1,000 logic elements. This large-scale integration of miniature elements is used in some digital loop electronics units.

MAGNETIC DETECTOR: A passive device that senses changes in the Earth's magnetic field caused by the movement of a ferrous-metal vehicle in or near its detection zone. It is placed under or in the roadway to detect the passage of a vehicle over the sensor. These sensors generally detect only moving vehicles. Also known as induction and search coil magnetometers. Their output is connected to an electronics unit.

A. **Compensated magnetic vehicle detector:** Any magnetic detector that is designed and structured to not be affected by changing electromagnetic influence other than that resulting from the passage of a vehicle. When properly equipped, a compensated magnetic detector has strong 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 greater permeability of the vehicle to these flux lines as compared to air.

MAGNETOMETER SENSOR: A passive device that detects the passage or presence of a ferrous metal object through the perturbation (know as a magnetic anomaly or magnetic shadow) it causes in the Earth's magnetic field. Its output is connected to an electronics unit. Not to be confused with a magnetic detector. Also known as a fluxgate magnetometer. Two-axis fluxgate magnetometers respond to changes in the vertical and horizontal components of the Earth's magnetic field.

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 nonlocking detection memory.

MICROHENRY: One millionth of a henry (μH), from the unit of measurement of inductance.

MICROWAVE RADAR SENSOR: An active vehicle sensor installed above or adjacent (side-mounted) to the roadway that transmits and receives energy in the microwave portion of the electromagnetic spectrum. Two types of microwave radar sensors exist. The Doppler or continuous wave radar is a passage sensor and detects only vehicles moving faster than some minimum speed. The FMCW presence radar detects stopped and moving vehicles. Models are manufactured for single and multilane applications.

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 sensor system must detect and indicate passage or presence. NEMA specifies a Class 1 vehicle (a small motorcycle).

MOTION SENSOR: A sensor that detects the motion of a vehicle passing through the detection zone of the sensor at some minimum speed, usually 2 to 3 mi/h (3.2 to 4.8 km/h). Vehicles traveling slower than the minimum speed or stopped in the detection zone are not detected.

NANOHENRY: One billionth of a henry, from the unit of measurement of inductance.

NEMA: 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 specified value within a range that permits satisfactory equipment operation.

NONCONFLICTING PHASES: Two or more traffic phases that will not cause interfacing traffic movements if they are operated concurrently.

NON-DIRECTIONAL SENSOR: A sensor capable of being actuated by vehicles proceeding in any direction.

NON-LOCKING MEMORY: A mode of actuated-controller unit operation that 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 percent of time a sensor's detection zone is occupied. Occupancy is a pseudomeasure 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.

OVER-ROADWAY SENSOR: A sensor that is mounted above the surface of the roadway either above the roadway itself or alongside the roadway, offset from the nearest traffic lane by some distance.

PASSAGE DETECTION: The ability of a vehicle sensor 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 SENSOR: A traffic flow sensor that detects the passage of a vehicle moving through the detection zone and ignores the presence of a vehicle stopped within the detection zone (NEMA). Also known as a motion sensor, dynamic detector or sensor, and movement detector or sensor.

PASSAGE PERIOD: The time allowed for a vehicle to travel at a selected speed from the sensor to the nearest point of conflicting traffic (NEMA).

PASSAGE TIME: The timing interval during the extensible portion that is resetable by each electronics unit 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 gap.

PASSIVE SENSOR: A sensor that transmits no energy of its own, but rather receives energy emitted from objects in its detection zone or energy transmitted from other sources that is reflected from objects in the detection zone.

PASSIVE ACOUSTIC SENSOR: A sensor that detects acoustic energy or audible sounds produced by vehicular traffic from a variety of sources within each vehicle and from the interaction of vehicle's tires with the road. Also known as passive acoustic array sensors because they consist of arrays of small microphones.

PASSIVE INFRARED SENSOR: A sensor utilized in traffic management applications, which operates in the far infrared spectrum. It transmits no energy of its own. Rather it detects energy from two sources: (1) energy emitted from vehicles, road surfaces, and other objects in their field of view and (2) energy emitted by the atmosphere and reflected by vehicles, road surfaces, or other objects into the sensor aperture.

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 sensor.

PEDESTRIAN CLEARANCE INTERVAL: The first clearance interval following the pedestrian WALK indication, normally flashing DON'T WALK.

PEDESTRIAN SENSOR: A sensor 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 that is allocated to one specific vehicular traffic movement (e.g., eastbound 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 SENSOR: A sensor 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 or small area sensor.

POLYCHLOROPRENE: (Chemical name for Neoprene.) Used for jacketing wire and cable that will be subject to rough usage, moisture, oil, greases, solvents, 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 superior to other extruded dielectrics in use today. They have high insulation resistance, high dielectric strength, and good abrasion resistance. Polyethylene is widely used for insulation on signal and loop detector wire and cable. It is suitable for direct burial.

POLYOLEFINS: A family of plastics including cross-linked polyethylene and various ethylene copolymers, one that 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 in detector applications. Known as PVC or Vinyl.

POWERHEAD: A small 3- x 6-ft (0.9- x 1.8-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 sensor to detect a moving or stopped vehicle in its detection zone.

PRESENCE SENSOR: A traffic flow sensor that detects the presence of a vehicle within its detection zone and holds the call for a specified minimum time. The sensor may cover a large area or be a series of small sensors wired together in series, parallel, or series/parallel.

PRESENCE HOLDING TIME: The time that a sensor system will continue to indicate the presence of a vehicle over one of its loops without adjusting to vehicle movement to a new position. When the adjustment occurs, the actuation is terminated. NEMA requires that a Class 2 vehicle (large motorcycle) be detected for a minimum of 3 minutes.

PRESENCE LOOP DETECTOR: An inductive-loop detector that 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 OR SENSOR: A sensor that consists of two metal plates separated by spacers. When a vehicle tire passes over the sensor, it compresses the spacers and allows the two plates to make contact, thereby closing an electrical circuit. This type of sensor normally produces two or more pulses per vehicle because each axle creates a contact.

PROBE: The type of sensor commonly used with a magnetometer sensor. A magnetic detector is also referred to as a probe.

PROGRESSIVE FLOW: Coordinated movement along an arterial at a given speed.

PULL BOX: A container usually at least 1 cubic foot (0.028 cubic meter) 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 electronics unit output that produces a short pulse (between 100 and 150 ms) when a vehicle enters the sensor detection zone. This occurs even though the vehicle remains in the detection zone for a longer time. See Electronics Unit Mode.

Q: See Quality Factor.

QUADRUPOLE: A loop configuration that adds a longitudinal saw slot 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.

QUALITY FACTOR: A numerical index for rating the quality of a resonant circuit. A higher number indicates lower loss and increased detection sensitivity in a resonant type sensor system such as is typical of inductive-loop detectors.

QUEUE DETECTOR OR SENSOR: Component of a traffic control system that senses the presence (or number) of vehicles waiting in a queue at an intersection or on a freeway ramp.

QUEUE LENGTH: Number of vehicles stopped or slowly moving in a line, where the movement of each vehicle is constrained by that of the lead vehicle.

RACK-MOUNTED ELECTRONICS UNITS: Electronics units that have no enclosing case and are connected to the sensor system by inserting its printed circuit board into a wired receptacle or "rack" located in the controller cabinet. Compare with shelf mounted electronics units.

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 that 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 sensor not to output an unwanted actuation caused by a vehicle in a lane adjacent to that in which the sensor is located.

RELUCTANCE: The opposition that 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 electrical circuits.

REPHASE: The process of resetting, after a pulse actuation, to enable another pulse actuation should another vehicle enter the detection zone. Can also be used as a verb: "The sensor shall rephase 2 seconds after initiating an output pulse."

RESIN: An organic substance that is a nonconductor of electricity. Resins are widely used for insulation and encapsulation.

RESISTANCE: The opposition that a device or material offers to the flow of current, equal to the voltage drop across the element divided by the current through the element.

RESONANT FREQUENCY: The oscillation frequency of a loop and its lead-in wire, to which the electronics unit must tune.

RESPONSE TIME: The time a sensor system 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.

RMS: Root-Mean-Square.

SAMPLING SENSOR: Any type of vehicle sensor used to obtain representative traffic flow information (NEMA).

SCANNING ELECTRONICS UNIT: A multichannel electronics unit in which the loop(s) of each channel are energized in sequence, one at a time, in quick succession.

SCATS: The Sydney Coordinated Adaptive Traffic System (SCATS). A real-time system developed by the Roads and Traffic Authority (RTA) of New South Wales, Australia. SCATS uses two levels of control. Strategic control determines timing plans for areas and sub-areas based on average traffic conditions. Tactical control applies at the individual intersection. This system is considered to fall under the Traffic Responsive category of real time traffic signal system control categories.

SCOOT: The Split, Cycle and Offset Optimization Technique (SCOOT) is a real-time system developed by the Transport and Road Research Laboratory (TRRL) in Great Britain. SCOOT computes the cyclic flow profile for every traffic link every four seconds. It projects these profiles downstream using the TRANSYT dispersion model.

SDLC: Synchronous Data Link Control.

SEALANT: The material used in a saw slot of an inductive-loop detector to seal the wires in the slot.

SELF-POWERED VEHICLE DETECTOR (SPVD): One type of magnetometer sensor buried in the pavement, which uses a self-contained battery for power and transmits vehicle flow information to the controller without the need for direct connection (lead-in cable).

SELF-TRACKING ELECTRONICS UNIT (DETECTOR): A loop electronics unit, not necessarily self-tuning, which includes circuits that compensate for environmental drift.

SELF-TUNING LOOP ELECTRONICS UNIT (DETECTOR): 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 startup of the electronic unit's operation, upon turn-on. Compare Self-Tracking Electronics Unit.

SEMI-TRAFFIC-ACTUATED CONTROLLER ASSEMBLY: A controller assembly for supervising the operation of traffic control signals in which means are provided for traffic actuation on one or more but not all approaches to the intersection.

SENSING ZONE: See Detection Zone.

SENSITIVITY: As it relates to an inductive-loop system, the change in total inductance of a system caused by a minimum-sized vehicle at one loop, expressed as a percentage of the total inductance. As it relates to an electronics unit, it is the minimum inductance change in percent required at the input terminals to the electronics unit that cause it to actuate.

SENSOR (SYSTEM AND LOCAL): Traffic detection devices that permit the system master or a local controller to obtain information about the traffic flow characteristics in the detection zone of the sensor. (See Detector.) NEMA limits the meaning of "sensor" to the sensing element of a detection system.

SENSOR LOOP: An electrical conductor arranged in a square, rectangular, circular, or other configuration to encompass a portion of the roadway. It provides a detection zone 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 measured for detection purposes (NEMA). Also known as wire loop or inductive-loop detector.

SENSOR OFFSET: For an over-roadway sensor, the horizontal distance between the sensor mounting location and the edge of the closest portion of the detection zone.

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 (15.5 m) length of detection area. This interconnection scheme gives a combined inductance close to the optimum value.

SENSOR SETBACK: The longitudinal distance between stop line and traffic flow sensor.

SENSOR SYSTEM: The complete sensing and actuation group of components, consisting of the electronics unit in the controller, the lead-in cable, the lead-in wires, and the sensor.

SENSOR WEB DENSITY: The density of the configuration of sensors required for different kinds of arterial and network traffic control and surveillance systems by link and by lane.

SERVICEABLE CONFLICTING CALL: A call that:

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 that 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 ELECTRONICS UNITS: Electronics units that have an enclosing case and, therefore, can be mounted in the cabinet by placing them on a shelf. They can stand alone. Compare Rack-Mounted Electronics Units.

SHIELD: A conductive material surrounding the twisted pair(s) of wires in the lead-in cable of an inductive-loop detector installation, so that outside electrical interference will not induce noise onto the twisted pair(s).

SHORTED-TURN MODEL: 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 SENSOR: A vehicle sensor located to one side of the roadway, such as on a pole, rather than directly over the roadway.

SIU: Serial interface unit which provides communication, interface and message protocol between the ATC and the Input and Output units but does no processing of the data and control messages.

SMALL-AREA SENSOR: A sensor that detects vehicles at a spot location, i.e., a small area usually not exceeding 6 x 6 ft (1.8 x 1.8 m). It may detect vehicles in more than one lane. The 6- x 6-ft (1.8- x 1.8-m) inductive-loop detector is a prominent example. Ultrasonic and radar devices may function as small area sensors with detection areas as long as 20 to 30 ft (6 to 9 m). When used in this manner, the length of time the moving vehicle is in the detection zone is not needed for the intersection control logic. The small area sensor is also referred to as a point sensor or point detector.

SOUND-SENSITIVE VEHICLE SENSOR: A sensor that responds to sound waves produced when a vehicle passes through the detection area of the sensor.

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 known 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 sensor 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 OR SENSOR: Sensors located to provide information to central control computers selecting appropriate control programs to meet the traffic demands.

TAPESWITCH: A temporary sensor consisting of two strips of metal encased in a flat ribbon that is temporarily affixed to the roadway. When a vehicle tire crosses the tapeswitch, the two metal strips make contact, thereby closing an electrical circuit.

TERMINAL: Any fitting used for making a convenient electrical connection.

TF: The Underwriter's Laboratories, Inc. (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 (LOOP): A minimum level of percent change in inductance that 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.

TIME-BASED COORDINATION: Control systems in which basic coordination is provided by a highly accurate real time clock within the traffic signal controller. This information is used to determine the local signal timing of offset and cycle/split or actuated timing based on the Time-of-Day/Day-of-Week. Also called time-based coordinated control.

TIME-OF-DAY/DAY-OF-WEEK (TOD/DOW): Timing plan selections based on the clock and calendar rather than on system traffic information. TOD/DOW systems operate with no system sensors (or at a sensor density Level of 0 or 0.5). These systems measure no characteristics of traffic flow. They may use clocks or wireline or wireless communications to provide the timing plan selection. Two categories of traffic control systems have predominantly TOD/DOW characteristics. These are the time based coordination and the interconnected control categories. In addition, isolated intersection control may sometimes use TOD/DOW considerations.

TIMER: Obsolete name. See Controller Unit.

TOTALLY ISOLATED SYSTEMS: Control systems without either time-based or communications-based connections between intersections. Thus, these systems operate each intersection without consideration of the operation of adjacent signalized intersections.

TRAFFIC DETECTOR OR SENSOR: A device by which automotive vehicles, light and heavy rail, buses, or pedestrians are enabled to register their presence with a traffic-actuated controller.

TRAFFIC PHASE: 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 traffic flow sensors.

TRAFFIC-ACTUATED CONTROLLER: See Controller Assembly.

TRAFFIC ADAPTIVE (CONTROL) SYSTEM: Control systems that operate with 2 sensors per lane per link for optimum efficiency (Sensor web density level of 3.0). Adaptive systems do not have cycle, split, and offsets in the classic sense. They forecast traffic into the near future and proactively reoptimize selection, sequence, and duration of phases every several seconds. These systems need to measure the flow of individual vehicles so that they can predict the future flow of the individual vehicles or small packets of vehicles. System response to traffic changes is proactive.

TRAFFIC ADJUSTED CONTROL SYSTEM: Traffic Adjusted systems operate with few sensors (or at sensor web density levels of 1.0 and 1.5) and use fixed timing plans, the selection of which is adjusted by a minimum number of system sensors at periodic intervals. The sensors in these systems measure system-wide variations in traffic demand using either volume plus weighted occupancy or predominant direction of flow. They then use pattern matching to choose from among a set of preselected plans. This definition builds on the original definition by Kell and Fullerton in the *Manual of Traffic Signal Design*. The first usage of this term was by Automatic Signal in describing one of their control systems in the 1950s. System response to variations in traffic flow is relatively slow.

TRAFFIC RESPONSIVE CONTROL SYSTEM: Control systems that use flexible timing plans in which the offsets, splits, and phase durations can be adjusted in reaction to changes in traffic on a nearly cycle-by-cycle basis. They contain at least one sensor per lane per link and operate at a moderate sensor density (Sensor web density levels of 2.0 and 2.5). Cycle, split, and offset are each optimized in the selection of the flexible timing plan to be implemented. These systems typically use macroscopic measures of traffic flow on individual links such as platoon and other characteristics. System response to traffic changes is prompt.

TRAILING CAR: With a volume density controller, when the time headway between two consecutive cars passing over a sensor exceeds the allowable gap imposed by the controller, an event called Gap-Out occurs. The first of these cars is called the last car and the second is called the trailing car.

TRANSDUCER: That part of a sensor that transmits and receives or simply receives energy from the detection zone and converts the received signal into electrical form.

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 with each end marked for identification.

TWO-COIL MAGNETIC DETECTOR: A magnetic detector with two coils. This sensor is capable of serving as a directional sensor.

TYPE 170 (179) AND 2070 CONTROLLER: One of the two major types of traffic signal controllers, the other being NEMA controllers. The traffic management function is implemented through standardized hardware and specialized software. Inputs from loop detectors, magnetic detectors, magnetometers, and a variety of over-roadway sensors may be used to provide traffic flow information to these controllers.

UL: Underwriter's Laboratories, Inc., a chartered, nonprofit organization that maintains and operates laboratories for the examination and testing of devices, systems, and materials relative to life, fire and casualty, hazards, and crime prevention.

UL APPROVED: A product that has been tested and approved to Underwriter's Laboratories standards.

ULTRASONIC SENSOR: An active vehicle sensor that transmits sound energy from a transducer at a high frequency (one that is above the upper range of human hearing) and that senses the reflection of the energy from a vehicle in its detection zone.

UNCOORDINATED (SIGNAL) CONTROL: Form of signal control for a single signalized intersection that does not have control relationships between intersections nor any data flow between intersections. The ***system*** of intersections is not responsive to traffic in real time. The individual isolated intersection may have local actuated control or Time of Day/Day of Week changes based on historical traffic flows. Also called isolated signal control. See also totally isolated systems.

VAC: Voltage Alternating Current.

VARIABLE INITIAL INTERVAL: A controller design feature that adjusts the duration of initial interval for the number of vehicles in the queue.

VDC: Voltage Direct Current.

VEHICLE DETECTOR (SENSOR) SYSTEM: A system for indicating the presence or passage of vehicles (NEMA). See Sensor 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 IMAGE PROCESSOR (VIP): A type of passive sensor that analyzes a video image of a roadway by digitizing it and subjecting the digitized information to algorithms or neural networks that differentiate moving objects from background patterns.

VOLUME DENSITY CONTROLLER: An actuated controller that has a gap-reduction factor based on opposing phase vehicle time waiting.

VOLUME EXTENSION MODE: Operation of a multiple sensor 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 Volume Density Controller.

WEIGH-IN-MOTION (WIM) SYSTEM: A system that estimates a moving vehicle's gross weight and the portion of that weight carried by each wheel, axle, or axle group, or combination thereof, by measurement and analysis of dynamic vehicle tire forces (ASTM E 867 and E 1318).

WIM: See Weigh-In Motion.

WIRE GAUGE: See AWG.

WATER BLOCKED: Impervious to water entrance and migration as a water blocked lead-in cable or water blocked splices.

XHHW: Cross-linked polyethylene insulated wire, rated at 90 $^{\circ}$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: See Detection Zone.

TABLE OF CONTENTS: APPENDIX Q.

APPENDIX Q. REGISTERED TRADEMARKS

Trademark name	Trademark owner
3M	3M Company, St. Paul, MN 55144
AASHTO	American Association of State Highway and Transportation Officials, Suite 225, 444 N. Capitol St., NW, Washington, DC 20001
Autoscope	Image Sensing Systems, St. Paul, MN 55104
Autoscope Solo	Image Sensing Systems, St. Paul, MN 55104
Autovue	Iteris, Inc., Anaheim, CA 92802
Detector Systems	Intersection Development Corporation, Stanton, CA 90680
Eagle Signal	Gulf & Western Industries, Inc. New York, NY 10023
Econolite	Econolite Control Products, Inc., Anaheim, CA 92806
Groundhog	Nu-Metrics, Uniontown, PA 15401
Iteris	Iteris, Inc., Anaheim, CA, 92802
Motorola	Motorola, Inc., Schaumburg, IL 60196
NEMA	National Electrical Manufacturers Association, Rosslyn, VA 22209
Nestor Traffic Systems	Nestor Traffic Systems, Inc., Providence, RI 02906
Nu-Metrics	Nu-Metrics, Uniontown, PA 15401
Orincon	Lockheed Martin Orincon Defense Corporation, San Diego, CA 92037
Peek	Peek Traffic, Inc., Sarasota, FL 34236
Reno A&E	Reno A&E, Reno, NV 89502
RTMS	EIS Electronic Integrated Systems Inc., North York, ON, Canada M6A 1Z5
Safetran	Safetran Systems Corporation, Minneapolis, MN 55421
SCATS	Roads & Traffic Authority of New South Wales, Sydney, NSW 2000, Australia
Smartsensor	Wavetronix LLC, Lindon, UT 84042
SmarTek Systems	SmarTek Systems, Inc. Woodbridge, VA 22193
Sumitomo	Sumitomo Heavy Industries, Ltd., Tokyo, Japan
Traficon	Traficon N.V., Bissegem Belgium B-8501
Vantage	Iteris, Inc., Anaheim, CA, 92802
VideoTrak	Peek Traffic, Chicago, IL 60601
Whelen	Whelen Engineering, Chester, CT 06412-0684

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