SmartPark Truck Parking Availability System: Magnetometer Technology Field Operational Test Results

U.S. Department of Transportation
Federal Motor Carrier Safety Administration

January 2011

FOREWORD

The purpose of this study was to assess the suitability of existing or near-term technology to implement a truck parking availability system with the code name, SmartPark.

The work performed under the project included:

- Developing the SmartPark Project Plan
- Drafting the SmartPark Concept of Operations.
- Drafting the Performance Requirements.
- Drafting the Field Operations Test Plan.
- Drafting the Evaluation Plan.
- Designing, implementing, and commissioning the SmartPark installations.
- Conducting system tests and continuously improving performance.
- Executing the Field Operations Test Plan.
- Analyzing the test data.
- Drafting a Final Report.

NOTICE

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16. Abstract

The purpose of this project was to conduct field operations tests to determine the feasibility of using magnetometry to determine truck parking availability. The field operations tests were conducted at two locations: a private truck stop, Interstate Travel Plaza, on U.S. 1 in Wrentham, MA and at a public rest stop, Mile Marker 9 on I-95 northbound in Mansfield, MA. The magnetometry technology detects the presence of a truck by a disturbance in the earth's magnetic field. The technology deploys an inexpensive wireless, battery-powered vehicle sensor unit (size of a soda can) embedded in the pavement to measure the disturbance and trigger the event. A base station unit wirelessly collects the event data from a group of four to six vehicle sensor units. A parking area relay wirelessly collects the event data from all the base station units and transmits the aggregated data to a centralized database server where a detection/classification processor uses rules-based algorithms to determine truck parking availability for an entire truck parking area. A ground truth camera was installed to allow for manual verification of (1) the detection of a vehicle (presence or absence) and (2) the classification of a vehicle (car, truck, or other). The magnetometry performed vehicle detection at an accuracy rate of 96.2% at Mile Marker 9 (n=2056 vehicles) and 96.5% at Interstate Travel Plaza (n=1241 vehicles). There were no overcounts, but there were undercounts (false negative detections). Furthermore, the magnetometry achieved only a vehicle classification accuracy of 92.2% at Mile Marker 9 (same sample size as given above) and 78.6% at Interstate Travel Plaza (same sample size as given above). Because the magnetometry technology did not meet performance requirements for vehicle classification accuracy, FMCSA will be repeating the field operations test with another technology to be announced.

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SI* (MODERN METRIC) CONVERSION FACTORS

Table of 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 yards	0.836	square meters	m^2
ac	Acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME	Note: Volumes greater than 1000 L shall be shown in m^3	
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
		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	Temperature is in exact degrees	
°F	Fahrenheit	5 × (F-32) ÷ 9 or (F-32) ÷ 1.8	Celsius	°C
		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

Table of 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	Temperature is in exact degrees	
°C	Celsius	1.8C + 32	Fahrenheit	°F
		ILLUMINATION		
lx	Lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		Force & 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, Section 508-accessible version September 2009)

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LIST OF ACRONYMS

ASOS	Automated Surface Observing System
BSU	base station unit
DCP	detection/classification processor
DSL	digital subscriber line
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
ft	feet
ISM	industrial, scientific, and medical
ITP	Interstate Travel Plaza
m	meter(s)
MHz	Megahertz
mi/h	miles per hour
MM9	mile marker 9
NEMA	National Electrical Manufacturer’s Association
PAR	parking area relay
RV	recreational vehicle
USDOT	United States Department of Transportation
VDU	vehicle detection unit

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EXECUTIVE SUMMARY

PURPOSE

The U.S. Department of Transportation (USDOT) Federal Motor Carrier Safety Administration (FMCSA) commissioned the SmartPark program to evaluate technology and processes that may be used to implement a parking availability information system.

FMCSA's mission is to reduce crashes, injuries, and fatalities involving large trucks and motor coaches. Driver fatigue is a known cause of fatal commercial motor vehicle crashes. Contributing to fatigue is the lack of safe, available truck parking. More information can be found in a previous white paper, "Intelligent Transportation Systems (ITS) and Truck Parking," available at http://www.fmcsa.dot.gov/safetyprogs/research/researchpubs.htm.

Truck drivers typically park either in publicly owned roadside rest areas or at privately owned truck stops. In the absence of a reservation system, a driver must stop at every location along the driver's route to determine parking space availability. If parking spaces are not available at a given location, the driver must travel to the next. Parking areas are not evenly spaced; if a driver finds no parking space at the last area before a long stretch of road, the driver has two choices: park illegally along the roadside or continue driving illegally in violation of hours-of-service rules. A method is needed for a unified communication system to show parking availability.

The overall objective of this study is as follows:

- Demonstrate commercially available or near-term technology for conveying information about parking availability in real-time to truck drivers on the road continuously.

More specifically, such a system must:

- Monitor parking occupancy and availability at truck parking sites, both public and private.
- Distribute parking availability information to interested parties by various means, including variable message signs, highway advisory radio, and Web sites.
- Accommodate parking reservations.
- Operate unattended continuously.
- Be inexpensive to install and operate.
- Be economically self-sustaining.

The project comprises two phases. In Phase I, test sites have been implemented with an occupancy monitoring system and a Web server accessible to project participants and other authorized parties. In Phase II, additional sites are to be implemented and parking availability information is to be disseminated to end users. This report describes the operation and results of Phase I.

TECHNOLOGY

The test systems are built from components and technology developed by the authors and include the following elements:

- Vehicle detection units (VDU) buried in pairs at each entry or exit in a parking area and, optionally, in each parking space. A VDU senses changes caused by vehicles in the Earth's local magnetic field and transmits its data wirelessly to the parking area relay (PAR). VDUs are battery operated with a lifetime of 5–7 years, are easily installed by core drilling, and do not require maintenance.
- PAR that communicates with the VDUs and forwards their data to the database Server. The PAR is located in the parking area and typically operates on 120 volt utility power, although a solar-powered unit is an option.
- Wireless network located in the parking area that connects the VDUs with the PAR. The network operates on a proprietary protocol designed to maximize VDU battery life.
- Database server located at the facility that hosts a detection/classification processor (DCP), an occupancy database, and a Web server. The database server collects the data from the VDUs, determines when a vehicle has transitioned or parked, updates the occupancy database, and formats database contents into Web pages for access by authorized users.
- Internet connection between the PAR and the database server. At the test sites, the Internet connection is provided by a commercial cellular modem service. Any Internet service with adequate bandwidth, including digital subscriber line (DSL) or cable modem, is equally suitable.

TEST METHODOLOGY

Phase I was conducted in three stages: planning and procurement, development and installation, and operation and evaluation. During the earlier stages, requirements and goals were defined and test plans developed. In the last stage, the test plans were executed. Ground truth video systems were used as benchmarks against which to compare the performance of the systems being tested.

The test systems were installed at two sites, a public rest area located at mile marker nine (MM9) on Interstate 95 in Mansfield, MA and a private truck stop, Interstate Travel Plaza (ITP), located on U.S. Route 1 in Wrentham, MA. The sites are about 7 miles apart and close to the intersection of Interstate-95 and Interstate 495 south of Boston, MA.

The public rest area has separate sections for cars and trucks and can accommodate 27 trucks in marked parking spaces plus considerable room to park outside marked parking spaces. There is a single entrance and a single exit to the truck parking section located at opposite ends of the rest area. A visitor center, attended during working hours, provided utility power for the PAR. VDUs were installed in each parking space at the facility. However, an adequate video ground truth system in the parking area proved to be too complex and expensive. Further, the utility of the parking sensors were lessened by unanticipated uncontrolled driving behavior. Accordingly, the parking sensors were decommissioned and resources were focused on optimizing the entry/exit sensors.

The private truck stop has unmarked parking space for approximately 35 trucks. The entry and exit are in parallel lanes, separated by an island, and controlled by automatic gates. The utility power on the island to operate the gates was used to power the PAR. The associated fueling facility is on the other side of a four-lane road.

Once the installation at each site was commissioned, testing began according to the test plans. After each testing sequence, the results were analyzed and compared to the requirements. System modifications were made to address the shortcomings and the process repeated. An early modification was the addition of a second VDU at each entry/exit so that direction and speed of transitioning vehicles could be measured. Most of the subsequent modifications were algorithmic changes to the DCP to improve the detection and classification performance.

After each test sequence, discrepancies were analyzed and the DCP algorithms re-optimized using both heuristic and automatic regression techniques. As a result, performance improved continually. The location of the DCP in the database server was beneficial because the processor was more capable than others in the chain (e.g., the PAR) and had immediate access to the entire database.

The last test sequences were conducted July 20, 2009–August 3, 2009 at MM9 and July 9, 2009–August 8, 2009 at ITP.

TEST RESULTS

The performance results reported related to occupancy are based on the last test sequences. Other performance results were measured for the duration of the test phase, January 2009–August 2009.

- The occupancy performance requirements, based on the last test sequence, were mixed. The results were measured by comparing the system-generated occupancy counts with putative counts accumulated from manual analysis of the ground truth video.
  - There were no false-positive detections (overcounts) at any entry or exit at either installation during the entire test phase.
  - False-negative detections (undercounts) occurred at a rate of 3.5, ± 1 percent at ITP and 3.8, ± 0.8 percent at MM9 during the last test sequence.

- Cumulative occupancy count errors exceeded the requirement of 5 percent (one space at MM9 and two spaces at ITP) over test periods of 14 and 30 days respectively.
- Manual occupancy count updates were required more often than the required 14 days.
- Average detection response times (the time between transition of a vehicle and update of the database) were 32 seconds at ITP and 35 seconds at MM9 compared to a requirement of 120 seconds.
- The maximum percentage of time the system falsely indicated parking availability could not be tested as neither site reached capacity. The requirement was 5 percent.

- Occupancy vehicle count performance was adversely affected by uncontrolled driving behavior, including driving the wrong way through entries and exits, high-speed tailgating, trailer drops and pickups, and parking outside of marked parking spaces. Some of these problems were fixed by system modifications (e.g., the first two), but others have no known reasonable solutions other than manual occupancy count and update of the occupancy database on a regular schedule.

- The authors were unable to implement a procedure to perform a manual count of parking area occupancy and reliably update the database. For sufficient accuracy, the parking area must be counted and the count entered in the database via Web browser before any vehicles have entered or exited the parking area. Even when the occupancy count was done quickly enough, operators would fail to synchronize to the system time or, due to delayed entry, would enter the wrong time. Operators sometimes neglected the manual occupancy count altogether, presumably because it was not on their daily schedule.

- Uptime performance was compromised by several outages of the cellular telephone modem Internet connection during the test phase. There were no outages of the parking area equipment or of the database server during the test phase and no Internet outages during the last test sequence. Specific uptime results were:
  - System uptime over the test phase was 92 percent, compared to a requirement of 95 percent.
  - Average downtime per incident was 8 hours at ITP, compared to a requirement of 4 hours
  - Planned downtime per week was 0.5 hours at ITP and 1 hour at MM9, compared to a requirement of 2 hours.

- Vehicle classification (as determined in section 2.1.6 of this report) was tested at both ITP and MM9. It was found that without vehicle identification, vehicle classification alone will not help improve the accuracy of the site occupancy in locations that experience trailer drops. Without identification of 100 percent of vehicles, there is no way to determine if a trailer drop was performed and to adjust the occupancy count accordingly.

- Vehicle classification (as determined in section 2.1.6 of this report) reduces the accuracy of parking lot occupancy counts. At the both ITP and MM9 vehicle classification was shown to have a negative impact on occupancy counts. Separating passenger vehicles from trucks did not improve occupancy reports as passenger vehicles parked in truck parking spaces.

CONCLUSIONS AND RECOMMENDATIONS

- The system vehicle detection performance of 96.2 percent at MM9 and 96.5 percent at ITP may be adequate for the intended purpose. The entry and exit errors are not balanced, causing occupancy count errors to accumulate. More work is needed to determine the source of this problem.
- Uncontrolled driving behavior adversely affects occupancy count and is not amenable to improved entry/exit performance. The most reliable solution is to perform manual occupancy count updates on a regular, preferably daily, schedule.
- A better procedure is needed to perform manual occupancy count updates. The authors recommend a cellular telephone application so the database may be accessed from the parking area and the database server can acquire the time automatically.
- Based on the results at MM9 and ITP, the authors recommend that parking area occupancy not be based on vehicle classification, regardless of the accuracy of the classification system. Vehicle classification reduces the accuracy of the occupancy count and increases the number of manual resets in locations with trailer drops. In locations without trailer drops, vehicle classification without 100 percent accuracy will also reduce occupancy count accuracy and increase the frequency of manual resets.
- The weakest link in system reliability was the cellular telephone modem Internet link. An alternate supplier could be sought or service could be changed to a hard-wired link, such as DSL or cable modem.
- Accuracy and performance requirements should based on experiments from real-time information dissemination.

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1. PROJECT OVERVIEW

1.1 INTRODUCTION

This document is the final report for Phase I of the SmartPark Parking Availability Magnemometry Evaluation Program.

1.2 GOALS

The goal of the program was to conduct a field evaluation of magnetometer technology to be used in a real-time truck parking availability information system. The evaluation system consisted of vehicle detection equipment located at two sites, linked wirelessly and by Internet to a database and server at the research facility (see Figure 1). The database maintains real-time-status of truck traffic and parking availability at the sites and its contents are available to authorized users via Web pages designed by the study team. Under Phase I the equipment was operated October 2007–January 2010.

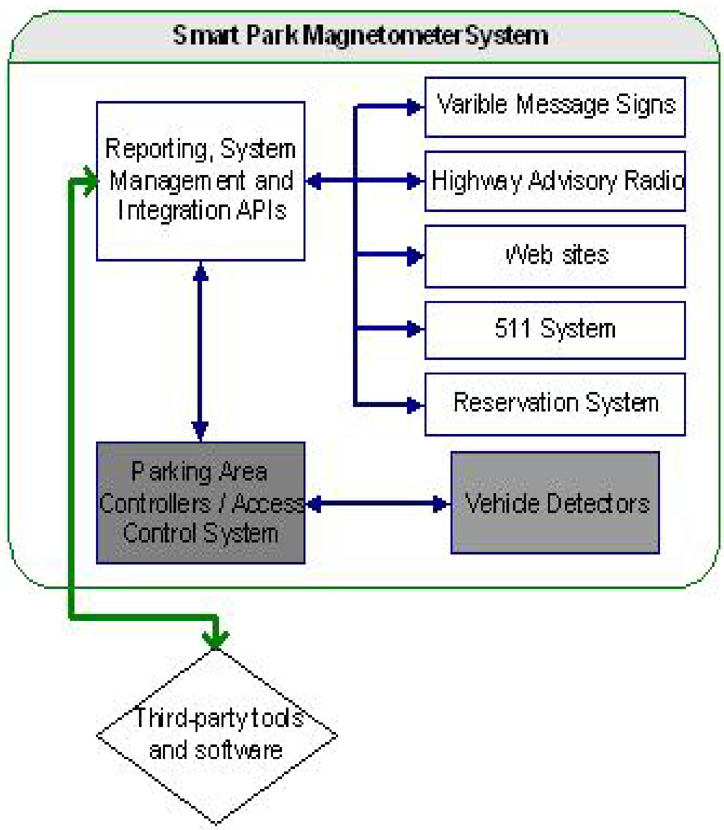


Figure 1. SmartPark System Layout

Vehicle detectors, placed in truck parking spaces and at entrance and exit ramps, indicate the status of parking spaces, either by direct detection or by counting the number of entering and exiting vehicles. The information in the database may be made available to drivers by multiple means: direct access to the database Web site by the truck driver or through an intermediary such as SmartRoute; through a reservation system with privately owned areas, by highway advisory radio; with roadside variable message signs; by text message access to the database; as well as other methods.

1.3 APPROACH

The SmartPark system was designed using off-the-shelf technology and installed at two test sites south of Boston near the intersection of Interstate 95 and Interstate 495. Ground truth video cameras were installed at both sites to assess the accuracy of the SmartPark magnetometer sensors. Once commissioned, the system was updated on a regular basis to address unanticipated behavior of the parking area users. The performance presented in this report represents the results of the last evaluation cycle.

1.4 SCHEDULE

The program was conducted in three stages. The project started in March 2007 and the evaluation stage was completed in September 2009. Status reports were provided monthly throughout the project.

Planning and procurement: The project plan, concept of operation, performance requirements, and a detailed equipment list were generated during this stage.

Development and installation: The required software was developed, test plans were written, system tests were performed, and the equipment was installed, first at the Interstate Travel Plaza (ITP) test site, and subsequently at the mile marker 9 (MM9) test site. Installation activity was completed in December 2008.

Operation and evaluation: Evaluation commenced as soon as the system became operational. Unanticipated problems were addressed as they arose and performance tests repeated multiple times to continually assess the effect of the improvements being implemented. The operational stage was completed in August 2009 and evaluation was completed in September 2009.

2. TEST DESCRIPTION

2.1 TECHNOLOGY

The Proof of Concept installations use proprietary vehicle detection technology and components. The primary component is a vehicle detection unit (VDU) that is buried in pairs in each parking space and entry/exit lane. The VDU senses the presence, absence, or transition of a vehicle and transmits the detected signature via a proprietary wireless network to a database server in the facility. The database server processes the transmitted signature to determine detection, direction, speed, and classification of the sensed vehicles and maintains counts of entries, exits, cumulative parked vehicles and the status of each instrumented parking space.

Each VDU communicates with the parking area relay (PAR) either directly or, if the distance is too great, through one or more base station unit (BSU) relays. The PAR communicates with the database server over a leased Internet connection, either hardwired or by open cellular telephone modem. Both SmartPark installations use a cellular telephone connection to the Internet. The database server automatically provides a variety of data to the user community via various types of connection. This can consist of various Web pages directed to browsers, information sent to message signs, computer generated radio messages, computer generated cellular telephone responses, as well as others. The Phase I tests are limited to Web pages available only to authorized participants. The generic system arrangement is shown in Figure 2.

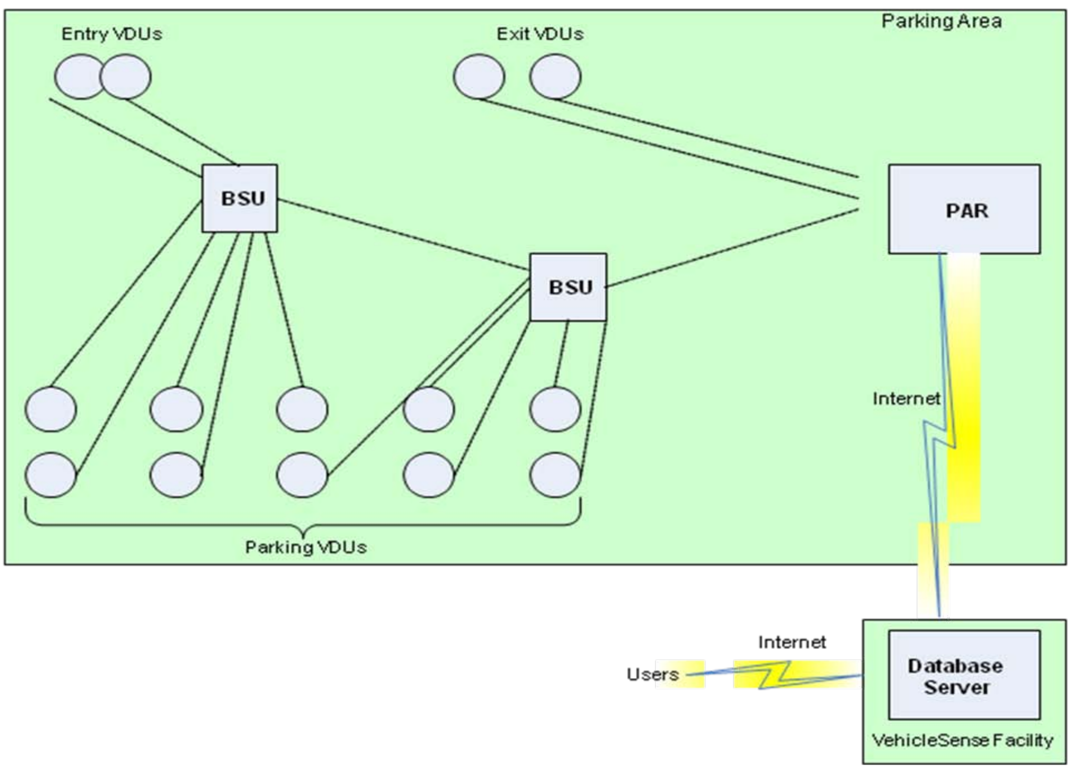


Figure 2. Generic System Arrangement

The wireless network operates in the 915 megahertz (MHz) industrial, scientific, and medical (ISM) band. The communication protocol supports packet checksums to prevent data corruption, incorporates retries and the use of multiple communication channels to deal with potential interference and dense operational deployments. It uses “keep alive” messages (i.e., packets periodically sent from each VDU to the server to indicate that the VDU is still operational).

2.1.1 Vehicle Detection Units

The VDU consists of a multi-axis magnetic sensor, a radio, a low-power controller, and a long-life battery, all packaged in a sealed cylinder 3 inches (75 mm) in diameter and 5.5 inches (140 mm) in length.

A device is installed beneath the roadway surface by core drilling a hole in the roadway, placing the device into the drilled hole, and filling the drilled hole with asphalt patch. Once installed, a VDU establishes and maintains communication with its PAR. See Figure 3.

Figure 3. VDU Installed in Roadway

VDUs are low cost, have a battery lifetime of 5–7 years, and are intended for permanent installation, free of the periodic maintenance required of all other sensors. Installation time is about 5 minutes, minimizing interruptions to parking operations, and is considerably less expensive than wired sensors. Their operation is unaffected by weather or lighting conditions and they do not impede road maintenance.

VDUs used for exit/entry sensors and for space sensors are identical physically and essentially identical in operation. All VDUs in a parking installation are synchronized to the real-time clock in the PAR. The pairs of sensors used for entry/exit are further synchronized within milliseconds so the direction and speed of transitioning vehicles may be measured with sufficient accuracy.

2.1.2 Base Station Unit

BSUs relay messages from VDUs that are too far from the PAR to communicate directly. BSUs can be linked together to permit communication over arbitrarily long distances.

A BSU consists of a radio, low-power controller, and a battery, usually packaged in a small National Electrical Manufacturer's Association (NEMA) 4 enclosure and mounted on a sign pole or existing structure.

BSUs are routers that simply pass packets of data from one node to the next according to the network routing schedule. If a BSU is lost from service, the network automatically reforms using the remaining BSUs. The BSU battery life is 6–12 months. Batteries are replaced during scheduled maintenance. Figure 4 shows the BSU at the MM9 entry mounted on an existing light pole.

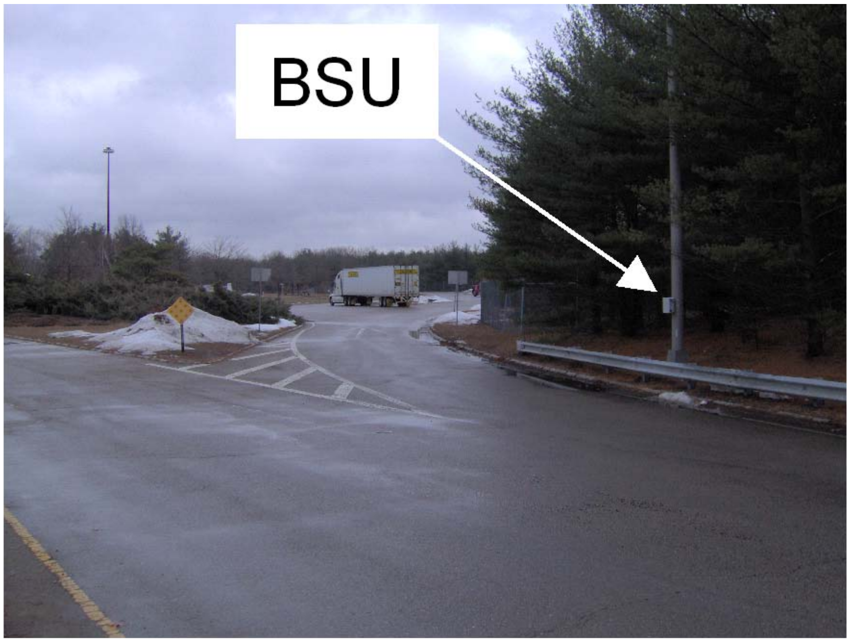


Figure 4. BSU at MM9 entry

2.1.3 Parking Area Relay

The PAR is a computer interfaced to an ISM radio and a cellular telephone modem or Ethernet device and housed in a NEMA4 enclosure (Figure 5). It is typically powered by a hardwired connection to a local utility, but solar systems or motor/generator units are primary power options.

Figure 5. PAR Installation at MM9

All radio communication between the database server and the parking installation flows through the PAR radio. The PAR performs the following functions:

- Aggregates packets from the network nodes and repackages them for transmission to the database server using the https protocol.
- Receives configuration commands for the VDUs and BSUs from the database server using https and transmits them to the appropriate nodes.
- Implements PAR configuration commands from the database server.
- Monitors the status of the Internet connection and restarts the cellular telephone modem as required.

The PAR can be controlled and monitored from any Internet connection using remote access services. This facility simplifies maintenance, particularly when multiple facilities are in operation.

2.1.4 Database Server

The database server is a computer with a high speed Internet connection located in Cambridge, MA. A single server accommodates both test sites.

The core of the server is an addressable relational database that stores raw data from the parking sites, performs algorithmic operations on the data, and generates occupancy records. Weather data, including temperature, rainfall, and wind speed, is collected periodically from the automated surface observing system at nearby Taunton (MA) Airport and stored in the database. A variety of Web pages are available to system users and can be extended to perform a number of automatic announcement applications.

2.1.5 VDU Siting

Parking area occupancy can be determined either by monitoring the status of each space in an area or by counting the number of entering and exiting vehicles and accumulating the difference. The former has an inherent advantage in that errors should be random and non-cumulative. However, it is subject to other errors that are described in more detail in section 3 and, because it requires more VDUs, is more expensive. The latter approach can have cumulative errors and therefore requires manual count updates on a periodic basis. Determining which approach is optimal for a given installation depends on the site characteristics, including whether the site is a parking-only or mixed use facility.

Space monitoring for passenger vehicles may be performed with a single VDU per parking space. Truck parking needs at least two VDUs per parking space to accommodate trucks of various lengths and to detect passenger vehicles in truck parking spaces (Figure 6). In the test installation, the two VDUs in each space were centered in the space and separated by 20 feet (6 meters). Both VDUs were centered longitudinally in the space. Each VDU communicated independently with the database server.

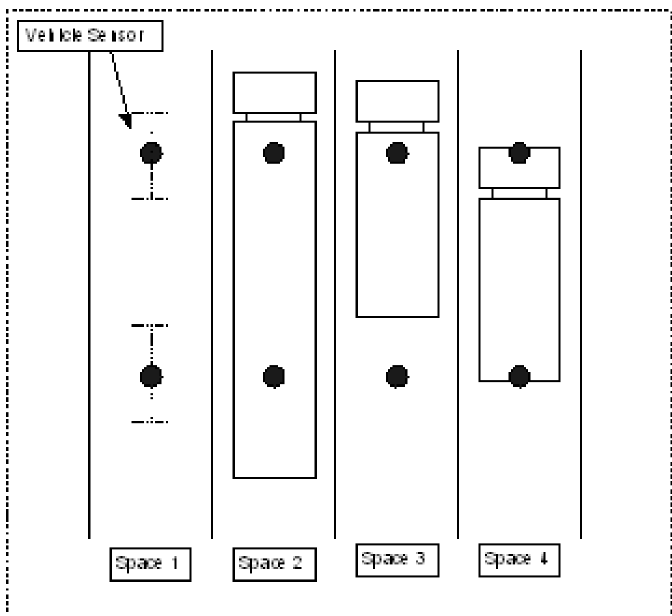


Figure 6. VDU Location for Space Monitoring

Entry/exit counting also requires two VDUs per lane, primarily to determine vehicle direction and secondarily to determine vehicle speed and class. The general layout is shown in Figure 7 and the specific installation at ITP is shown in Figure 8. The VDUs are spaced 6 feet (ft), or 1.8 meters (m) apart in the center of the lane. A vehicle transitioning both at 60 mi/h will result in a delay of approximately 164 ft (50 m) between the signatures from the two VDUs. The length of time the vehicle spends over each VDU determines its classification. Each VDU communicates independently with the database server.

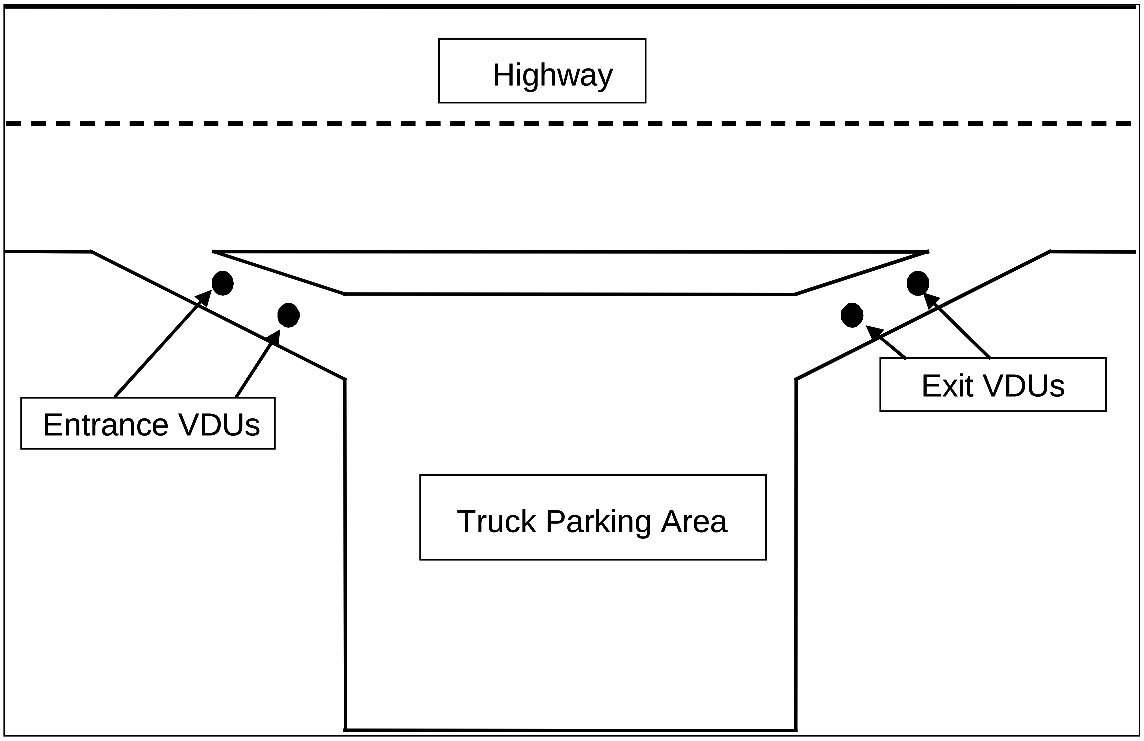


Figure 7. VDU Entry/Exit Configuration

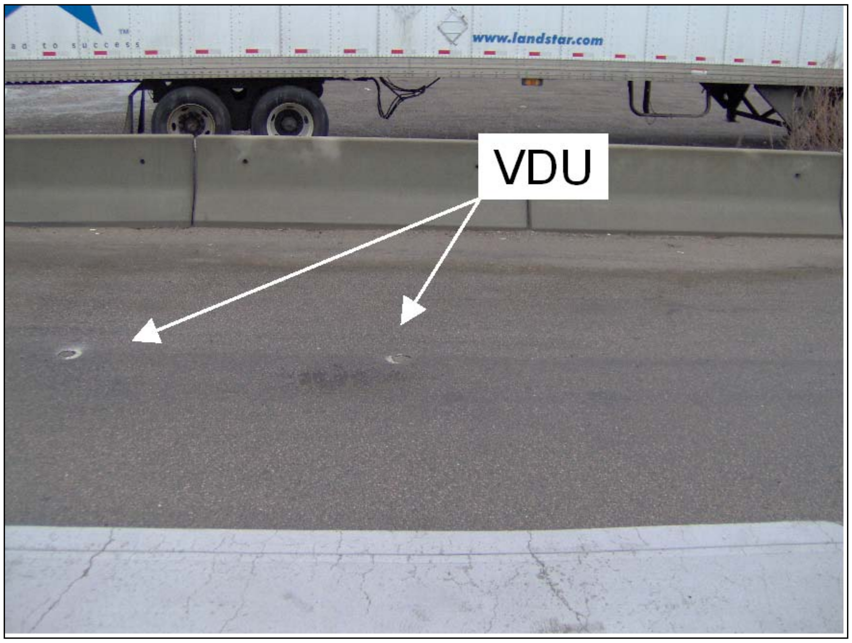


Figure 8. VDUs in Exit Lane at ITP

2.1.6 Detection and Classification

When a VDU detects a change in magnetic field, it collects a time record of the field strength until the activity stops. The time record is an Event, the basic unit collected by the detection/classification processor (DCP) in the database server. The DCP uses rules-based algorithms to extract the needed information from the collection of events.

To determine the direction of a vehicle moving in an entry/exit lane, the DCP computes the difference between the high resolution time stamps from the two VDUs in the lane. The sign of the result indicates the direction of travel. The quantitative time difference between the correlated signatures (Events) from the two VDUs, in conjunction with the VDU spacing, is a measure of vehicle speed.

To determine vehicle classification of a vehicle moving in an entry/exit lane, the DCP uses the measurement of vehicle speed and the amount of total time the vehicle has spent over each of the VDUs. The speed measurement multiplied by the total event time determines the length of the vehicle. The length of the vehicle is then converted into one of two categories, 2/3 axle vehicle or 4+ axle vehicle.

When a vehicle stops for a long time in an entry/exit lane or dithers back and forth, it presents a particular challenge for the DCP because single events are fragmented into multiple events that must be stitched back together. Tailgating vehicles moving at a relatively high speed in an entry/exit lane also require care in handling because what should be multiple events are merged into a single event that must be untangled.

After each test sequence, discrepancies were analyzed and the DCP algorithms re-optimized using both heuristic and automatic regression techniques. A subset of the data collected in the database was used for optimization and the remaining portion was used to test the performance after optimization. As a result, performance improved continually. The location of the DCP in the database server was beneficial because that processor was more capable than others in the chain (e.g., the PAR) and had immediate access to the entire database.

2.1.7 Web Server

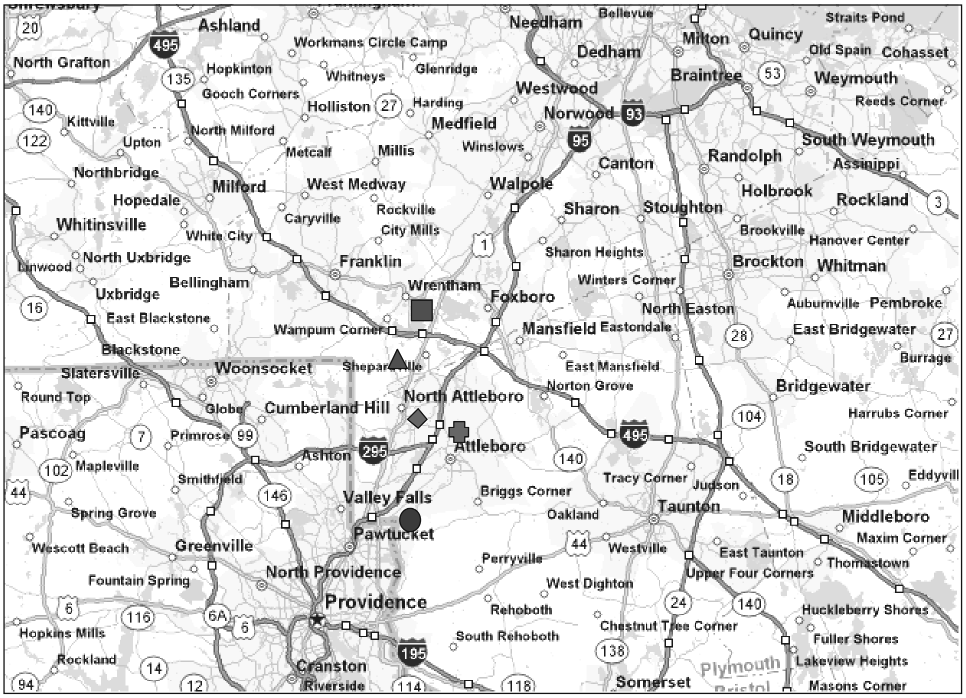
The Web server operates on the database server computer, providing Internet access to the database to project participants.

2.2 TEST LOCATIONS

The two test sites used in Phase I are:

- MM9: a public rest area on Interstate-95 northbound at mile marker 9 in Mansfield, MA.
- ITP: a private truck stop in Wrentham, MA on U.S.-Route 1 approximately 1 mile north of exit 14 on Interstate-495.

The test sites are located on the map in Figure 9. The three other sites shown on the map are intended for Phase II.



LEGEND

Mile Marker 1

Mile Marker 9

Mile Marker 8

Interstate Travel Plaza

Citgo Travel Plaza

Figure 9. Map of Test Sites

MM9 (Figure 10) has separate sections for cars and trucks and can accommodate 27 trucks in marked parking spaces plus considerable room to park outside marked parking spaces. A single entrance and a single exit to the truck parking section are located at opposite ends of the rest area. A visitor center, attended during working hours, provides utility power for the PAR. The truck exit and entry lanes were outfitted with entry/exit sensors and each of the truck parking spaces was been outfitted with parking space sensors.

Figure 10. Aerial Photo of MM9

ITP (Figure 11) has unmarked parking space for approximately 35 trucks. The entry and exit lanes are in parallel lanes, separated by an island, and controlled by automatic gates. The utility power on the island to operate the gates was used to power the PAR. The associated fueling facility is on the other side of a two-lane road. The truck exit and entry lanes were outfitted with entry/exit sensors. There were no parking space sensors.

Figure 11. Aerial Photo of ITP

2.3 TEST REQUIREMENTS

The performance standards to be measured and assessed are described in the project documents titled *Performance Requirements*, *Field Operations Test Plan*, and *Evaluation Plan*. Portions of the documents are reproduced in Appendix A. The test plans, obviously, are intended to represent the requirements of an operational system.

Truck drivers typically park either in publicly owned roadside rest areas or at privately owned truck stops. In the absence of a reservation system, a driver must stop at every location along the driver's route to determine parking space availability. If parking spaces are not available at a given location, the driver must travel to the next. Parking areas are not evenly spaced; if a driver finds no parking space at the last area before a long stretch of road, the driver has two choices: park illegally along the roadside or continue driving illegally in violation of hours-of-service rules. A method is needed for a unified communication system to show parking availability.

The required elements of such a system are:

- A means of automatically detecting parking space status, either by monitoring individual parking spaces or by monitoring ingress and egress in controlled parking areas.
- A central database to maintain parking status and reservation information.
- Means for drivers to access the database information.
- Controlled access in reserved parking areas (exists at truck stops).

The system must:

- Maintain a count of vehicles in a parking area and, thus a count of available parking spaces within some tolerance.
- Be easy and inexpensive to install and maintain.
- Operate unattended continuously.
- Operate in all weather and lighting conditions.
- Disseminate availability information by various means.
- Provide a means for manually resetting the count of available parking in the event of discrepancy.
- Maintain a record of vehicle entrance and exit events, and system errors.

2.4 GROUND TRUTH

When assessing the reliability and accuracy of a sensor system as was done on this project, it is necessary to have an alternate ground truth sensor against which to compare performance. The ground truth sensor must have performance far in excess of the required system performance. If the ground truth sensor and the system sensor under test produce a different result, which one is to be believed? The authors elected to use recorded video that could be viewed manually. With adequate resolution and lighting, a human observer can detect and classify vehicle transitions with zero errors.

Ideally, the ground truth sensor would provide video coverage of the entire parking area so each space could be monitored and manual counts done routinely. Providing adequate coverage of the complete area at either site proved to be too costly as many cameras mounted at extreme heights would be needed. Even then, problems of parking space occlusion by trees and other vehicles would remain. In the end the authors elected to monitor the entry and exit lanes only. Because the manual detection and classification process has zero errors, the authors were able to start with a manual audit of the area and to maintain an accurate count of available spaces.

Both test areas were instrumented with Axis video cameras interfaced to single-board computers with 300 gigabyte removable disk drives. The cameras have automatic irises and adapt well to varying light levels. They are programmed to run at two frames per second, which is adequate to capture multiple frames of vehicles traveling at up to 60 mi/h. The camera systems were hardwired to local utility power at both sites. Each disk drive can hold more than 120 days of video and the drives were swapped on a schedule to provide uninterrupted coverage.

At ITP, a single camera was located on the island between the entry and exit lanes, close to the VDU sensors, and approximately 5 feet above the roadway. The camera has a field of view of approximately 15 degrees. See Figure 12. The entire width of both lanes and a small part of the parking area is captured in the frame and the frame is large enough to capture an entire tractor trailer entering or exiting in either lane. The camera's low light level capability augmented by nearby street lights provided satisfactory performance even on dark nights. Utility power to run the camera was available on the island.

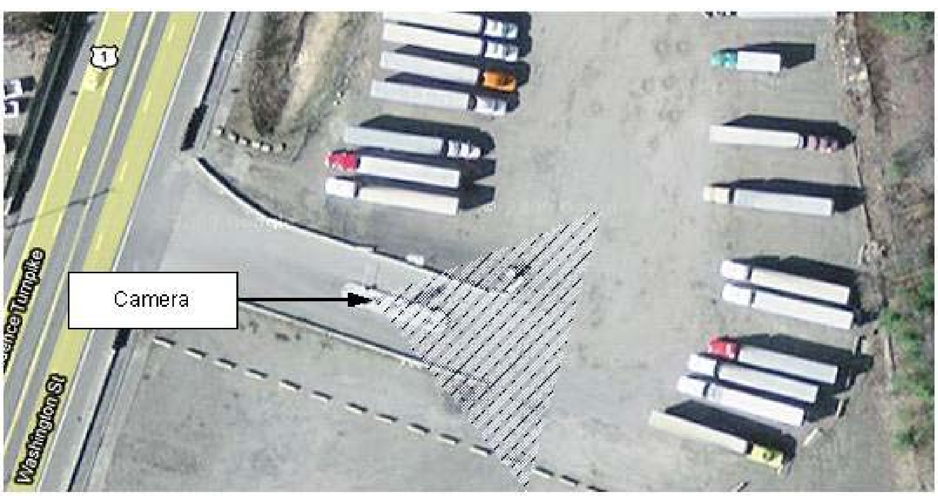


Figure 12. Ground Truth Camera at ITP

At MM9, separate cameras (Figure 13 and Figure 14) were installed at the entry and exit lanes to the truck parking area. The cameras were mounted on street light poles approximately 12 feet above the roadway and 30 feet outbound of the VDU sensors. Both cameras pointed toward the parking area and provide a view of 200 feet of roadway. The entry camera has a view of the first bay of parking spaces. The field of view accommodates a complete tractor-trailer from the passenger side and vehicle separation is easily deduced. The street lights provided adequate lighting under all conditions. Utility power to operate the systems was extended to both locations by the Massachusetts Department of Transportation at the authors' request.

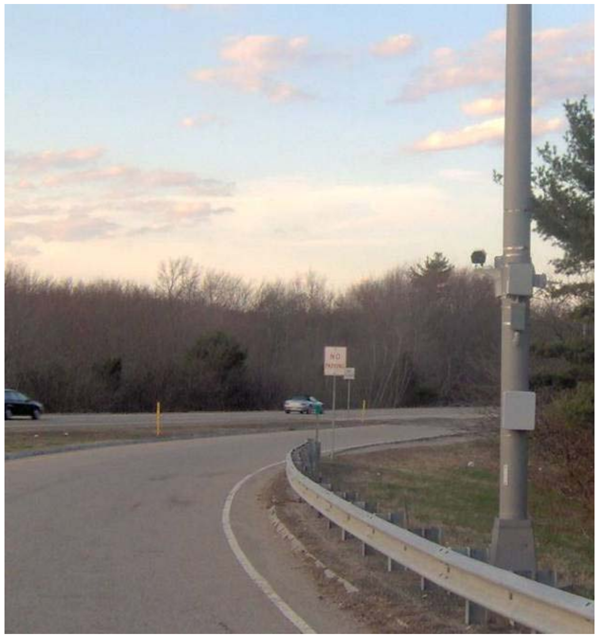


Figure 13. Ground Truth Camera at MM9 exit

Figure 14. Ground Truth Camera at MM9 Entry

Data reduction was a low-tech operation. The captured video (Figure 15) was viewed on a computer monitor and vehicle transitions recorded manually. The recorded data included the time of transition, direction of travel, and vehicle type. Vehicle types included passenger car, truck or tractor without trailer, tractor trailer, and other. Additional description is provided for vehicles classified as other, (e.g., tow truck with towed vehicle).

Figure 15. Camera View at MM9 Exit

The record was subsequently compared to the detections and classifications recorded in the database by the proprietary system and performance measures were calculated.

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3. TEST RESULTS

Formal tests were performed in accordance with documents: *System Requirements, SmartPark, Phase I,* and *Field Test Plan, SmartPark, Phase I.* Additional informal performance tests were conducted as well. The system requirements tables are reproduced in Appendix A.

The system requirements:

- Functional.
- Performance.
- Interface.
- Data.
- Nonfunctional.

All of the functional requirements were met with the following deviations.

Paragraph 3.1.5 specifies a minimum separation of 20 feet between vehicles at speeds between 5 mi/h and 50 mi/h. Twenty feet at 50 mi/h represents serious tailgating with a time spacing of about 0.25 seconds. A requirement that specified separation in terms of time instead of distance would have been more appropriate. The system can count vehicles spaced as closely as 1 second apart (still close tailgating), corresponding to separations of 7 feet at 5 mi/h and 75 feet at 50 mi/h.

Paragraph 3.1.8 requires a means to reset the occupancy count based on a manual audit. The system has a means for resetting the count through a Web page that performs as specified. However, the manual audit procedures used during the testing were inadequate. The primary failure was entry of the wrong time, due either to not synchronizing with the system time or delaying the entry inordinately. The latter occurred because the occupancy count was performed by walking through the parking area and the data was entered was done inside the building, often after attending to other matters outside. Also, operators often failed to conduct manual audits when they were scheduled at odd times or less often than daily.

The authors recommend a cellular telephone application wherein the data are entered directly from the parking area and the parking system captures the current system time. Additionally, manual audits should be scheduled daily so they are more likely to be performed.

Paragraph 3.1.14.1.1 requires a list of all spaces and status is available on a Web page. The Web page was provided, but individual space monitoring was not fully implemented because the associated ground truth system was too expensive to implement and because the unanticipated driving behavior (described in section 3.1) reduced the value of individual space monitoring in maintaining occupancy count. The decision was made to concentrate resources on improving the entry/exit performance.

The interface requirement to provide access to the database information through a Web browser was met. The data requirements were met with the exception of those related to individual space monitoring as described above. And, the nonfunctional requirements were met.

3.1 UNCONTROLLED BEHAVIOR

The initial testing at ITP, immediately after deployment, revealed a number of activities that distort parking area occupancy count, irrespective of sensor accuracy. Subsequent testing at MM9 showed similar and additional problems. Design changes were made to address a number of these problems. Others were not amenable to solution and will contribute to occupancy count errors irrespective of the sensor type and its detection and classification accuracies.

The problematic activities:

- A vehicle crosses an entry or exit in the wrong direction.
  - This activity was observed frequently at ITP, particularly during periods when one gate was left up. Even when both gates were down, cars would sometimes go through the wrong way by veering around the gate.
  - Less often at MM9, cars reversed on the entry or exit lanes or make a U-turn and drive through the wrong way (as shown in Figure 16).
  - The solution was to incorporate directional capability. The original installation used one VDU per exit/entry lane. A second VDU was added with the capability to maintain the time stamp synchronized to within 50 milliseconds. A direction routine was added to the DCP.
  -

Figure 16. Vehicle Entering through Exit Lane at MM9

- A vehicle stops or reverses over the entry/exit sensors.
  - If a vehicle stops, stops and reverses, or dithers back and forth over the entry or exit VDUs, an unsophisticated system may misinterpret the activity as multiple vehicles proceeding through the gate or as some vehicles entering and others leaving. If both VDUs are not transitioned, it is not possible to determine vehicle direction or length. The DCP algorithms were optimized to properly interpret the various type of activity.
- More than one vehicle parks in a space.
  - A single truck parking space at MM9 may accommodate one tractor trailer, two single-unit trucks, or three passenger vehicles (as shown in Figure 17). A vehicle shorter than a tractor trailer may be parked anywhere in the parking space, rendering it unavailable to any other vehicle. Absent knowledge about the complete area of each parking space and some very sophisticated processing, it is not possible to determine unused availability.
  - The solution is to assume that each space has no more than one vehicle. The result will be to undercount the number of available spaces. That is, there may be more spaces available than the parking system indicates. The indicated count requires updates with manual audits on a regular basis

Figure 17. Multiple Trucks per Parking Space at MM9

- Two vehicles enter the parking area, but only one leaves.
- A disabled vehicle was observed limping in and subsequently being towed out. The disabled vehicle was parked in a truck parking space. Later, a tow truck entered the area, pulled into the parking space with the disabled vehicle and towed the disabled vehicle out of the parking area. The entry and exit lane sensors recorded two vehicles arriving and one leaving.

- In a similar scenario, a recreational vehicle (RV) and a passenger vehicle may enter the area separately. Subsequently, the RV tows the passenger vehicle out of the area, registering two entries and one exit resulting in more spaces available than the parking system indicates. Again, the indicated occupancy count requires updates with manual audits on a regular basis.

- One vehicle enters parking area and two leave.
  - An RV may enter towing a car. The RV and the car may leave separately. The parking system will indicate the availability of more parking spaces than are available.
  - The only solution is to maintain a reserve of spaces for this occurrence and to perform a manual audits on a regular schedule.

- Trailer Drops.
  - Truckers often drop trailers for extended periods.
  - More than two VDUs per parking space would be needed to reliably distinguish between a tractor trailer in a parking space and a dropped trailer.

- Trucks move inventory around in the parking area.

- Vehicles park outside of marked spaces.
  - Trucks often park outside of the marked parking spaces at MM9 even when marked parking spaces are available. The result is to undercount the number of available parking spaces.
  - The only way to deal with this behavior using space sensors is to locate sensors on a grid, covering the entire parking area, an uneconomical solution. As in several situations described below, more space will be available than the parking system indicates. The indicated occupancy count would require updates with manual audits on a regular basis.

- One vehicle uses two or more spaces.
  - A vehicle will sometimes park on the line between parking spaces, using two parking spaces, or will park perpendicular to the lines, using three or more parking spaces. This behavior is less frequent when the area is near capacity so is not likely to result in unavailable parking spaces being offered.

3.2 OCCUPANCY AND AVAILABILITY

The goal of SmartPark Phase I was to evaluate the magnetic technology for the purpose of informing trucks of available parking spaces. To report occupancy accurately both entry and exit vehicle counts were used, as well as the classification of each vehicle that entered and exited each location.

Several types of test, both formal and informal, were used to assess the quality of occupancy and availability counts. These included:

- Detection/Classification statistics, wherein the result reported by the DCP of each vehicle transition was compared to the manual assessment of the same event viewed on the ground truth video.
- Cumulative occupancy error, defined as the difference between the database cumulative occupancy count and a manually constructed occupancy count from the exit/entry ground truth video.
- Audited occupancy count error, in which the database occupancy figure is compared with a manual onsite audit. The test sequences were performed multiple times with each sequence followed by system improvements to address the problems that were found. The results described below are based on the last sequences of 30 days at ITP and 14 days at MM9.

3.2.1 Detection/Classification Statistics

The DCP accepted transition events from the entry/exit lane VDUs, determined which were valid detections, computed the vehicle direction, and classified the vehicle into one of two categories: 2/3 axle, or 4+ axle. Each valid detection modified by vehicle direction, resulted in an increment or decrement of the occupancy count.

To determine the DCP accuracy, its results were reconciled with a manual inspection of the ground truth video. Table 1 shows sample reconciliation for entry transitions at MM9 on July 30, 2009 between the times of 17:50 and 20:53. Column 1 indicates whether the vehicle was detected by the VDU. Columns 2 and 3 indicate whether the DCP has detected the transition, Columns 4–8 show the manual (ground truth) classification, and column 9 is the DCP classification. The fifth vehicle in this sample was an undetected passenger vehicle. The next-to-last vehicle was missed by the DCP.

The following definitions were used for manual classification:

- Vehicles: All Federal Highway Administration (FHWA) vehicle classes that entered or exited the parking area under their own power.
- Tractor Trailers: FHWA vehicle classes 8–13
- Single Unit: FHWA vehicle classes 4–7 without trailers
- Passenger Vehicles: FHWA vehicle classes 2 and 3 without trailers
- Other Vehicles: FHWA vehicle classes 1–15 and classes 2 and 3 that were towing other vehicles.

Table 1. Sample Classification Results at MM9

DCP Vehicle Type	VDU Detect	DCP Detect	DCP Miss	Pass. Veh.	Single Unit	Trac. Trail.	Other	Comment
4+ axle vehicle	1	1				1		
2/3 axle vehicle	1	1			1			
4+ axle vehicle	1	1				1		
4+ axle vehicle	1	1				1		
				1				
2/3 axle vehicle	1	1			1			
4+ axle vehicle	1	1				1		
4+ axle vehicle	1	1					1	pv towing trailer
2/3 axle vehicle	1	1		1				
4+ axle vehicle	1	1				1		
4+ axle vehicle	1	1				1		
4+ axle vehicle	1	1				1		
4+ axle vehicle	1	1					1	pv towing trailer
2/3 axle vehicle	1	1			1			
2/3 axle vehicle	1	1		1				
4+ axle vehicle	1	1				1		
4+ axle vehicle	1	1				1		
4+ axle vehicle		1				1		
			1	1				
2/3 axle vehicle		1		1				

DCP performance for the last test sequence is summarized in Table 2 and Table 3 for ITP and MM9.

Table 2. DCP Results for 30 days at ITP 12 a.m. July 9, 2009—12 a.m. August 8, 2009

Measurement	Number	Percent	Margin of Error
Number of trucks	1,067	86.0	
Number of cars	171	13.8	
Number of others	3	0.2	
Number of vehicles	1,241	100	
Overcount (false positive detection)	0	0	+/- 0
Undetected by VDU	12/1,241	1.0	+/- 0.5
Undercount (false negative detection)	44/1,241	3.5	+/- 1.0
Correct classification of all vehicles	975/1,241	78.6	+/- 2.3
Correct direction of detected vehicles	1156/1,229	94.1	+/- 1.3
Test duration (hours)	720		
Approximate hours of daylight	442.5	61.5	
Approximate hours of darkness	246.5	34.2	
Approximate hours of twilight	31	4.3	
Approximate hours of rain	15	2.1	
Minimum/Maximum temperature (F)	58/89		
Highest wind gust (mph)	43		

Table 3. DCP Results for 14 days at MM9 12 a.m. July 20, 2009—12 a.m. August 3, 2009

Measurement	Number	Percent	Margin of Error
Number of trucks	1,346	65.5	
Number of cars	606	29.5	
Number of others	104	5.1	
Number of vehicles	2,056	100.0	
Overcount (false-positive detection)	0	0	+/- 0
Undetected by VDU	3/2,056	0.1	+/- 0.2
Undercount (false-negative detection)	78/2,056	3.8	+/- 0.8
Correct classification of all vehicles	1,895/2,056	92.2	+/-1.2
Correct direction of detected vehicles	1,974/2,053	96.2	+/- 0.8
Test duration (hours)	336		
Approximate hours of daylight	206.5	61.5	
Approximate hours of darkness	115.0	34.2	
Approximate hours of twilight	14.5	4.3	
Approximate hours of rain	6.3	1.9	
Minimum/Maximum temperature (F°)	62/87		
Highest wind gust (mi/h)	43		

Margins of error based on the sample sizes are shown where appropriate. The margin of error is calculated for a 95 percent confidence interval assuming Gaussian sampling statistics using the equation shown in Figure 18.

$$e = \sqrt{\frac{z^2 p(1-p)}{N}}$$

Figure 18. Equation for calculating margin of error.

Overcounts or false-positive detections represent vehicle detections signaled by the DCP that did not occur. Undercounts or false-negative detections represent vehicle transitions that did occur, but were not detected by the DCP. Overcounts did not occur since the VDU detection thresholds were optimized early in the program. Undercounts were more prevalent at ITP because vehicles were more likely to stop or reverse over the VDUs at ITP than at MM9. See the discussion below regarding direction errors. Other undercounts were due to tailgating. Two vehicles passing through an exit/entry point in close succession may be detected as one vehicle if they are too close together (i.e., closer than 1 or 2 seconds apart).

The vehicle direction was deduced correctly 94.1 percent of the time at ITP and 96.2 percent of the time at MM9. ITP had poorer performance due to vehicles more often stopping over the VDUs and reversing or dithering. When a vehicle transitioned continuously over both VDUs, a single event (time record) was generated by each VDU with a clear time difference between the two events. This scenario was relatively easy for the DCP to process. Conversely, when a vehicle reversed or dithered, multiple events were generated. Sometimes several events were generated by the first VDU with relatively large differences in time stamps before a single event was generated by the second VDU. This scenario was harder for the DCP to process correctly and led to more errors.

Lighting, rain, and wind had no effect on performance, but are reported for completeness. The last test sequences were in the summer with relatively warm temperatures. During previous sequences, temperatures ranged well below freezing. No degradation in performance was evident as a result of temperature variances.

3.2.2 Cumulative Occupancy Error

The cumulative occupancy error is the difference between the database cumulative occupancy count and a manually constructed cumulative occupancy count from the exit/entry ground truth video. It is an assessment of the capability of the entry/exit lane sensor system, but does not account for the uncontrolled behavior described above.

With randomly distributed detection errors occurring at equal rates at entries and exits, the net error will average zero and the occupancy count error will not drift appreciably. This is not borne out by the data.

Figure 19 and Figure 20 are graphs of the occupancy error plotted against time. For unknown reasons, the errors grow in one direction due to undercounting at the ITP exit and the MM9 entry.

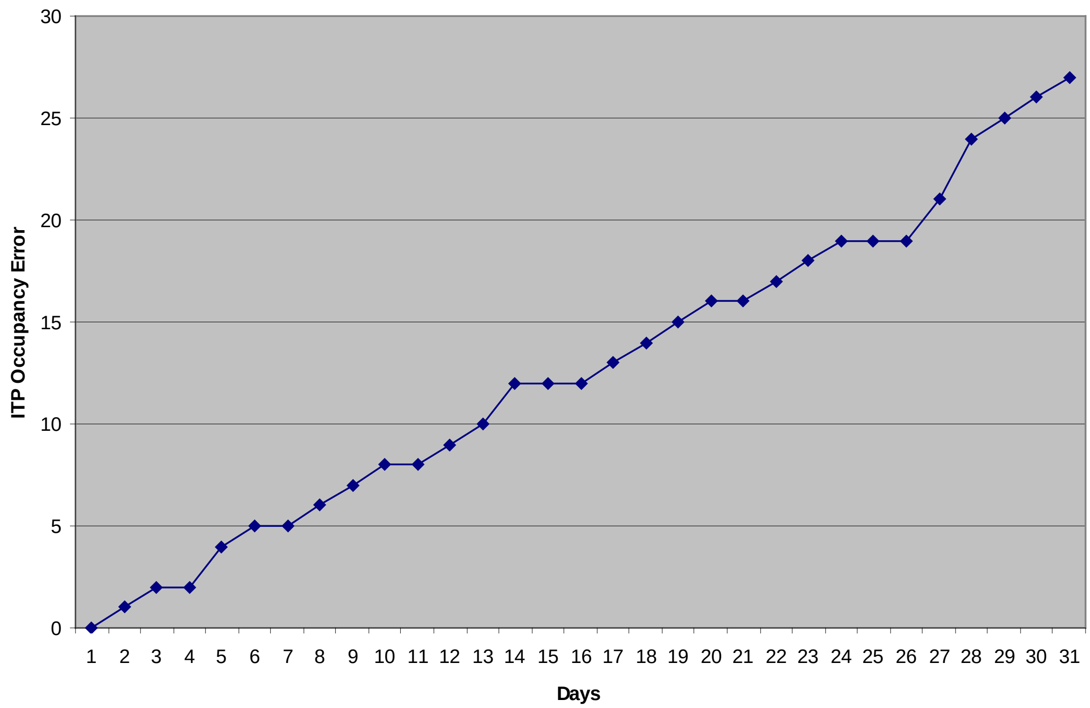

Figure 19. Occupancy Count Error Versus Time at ITP

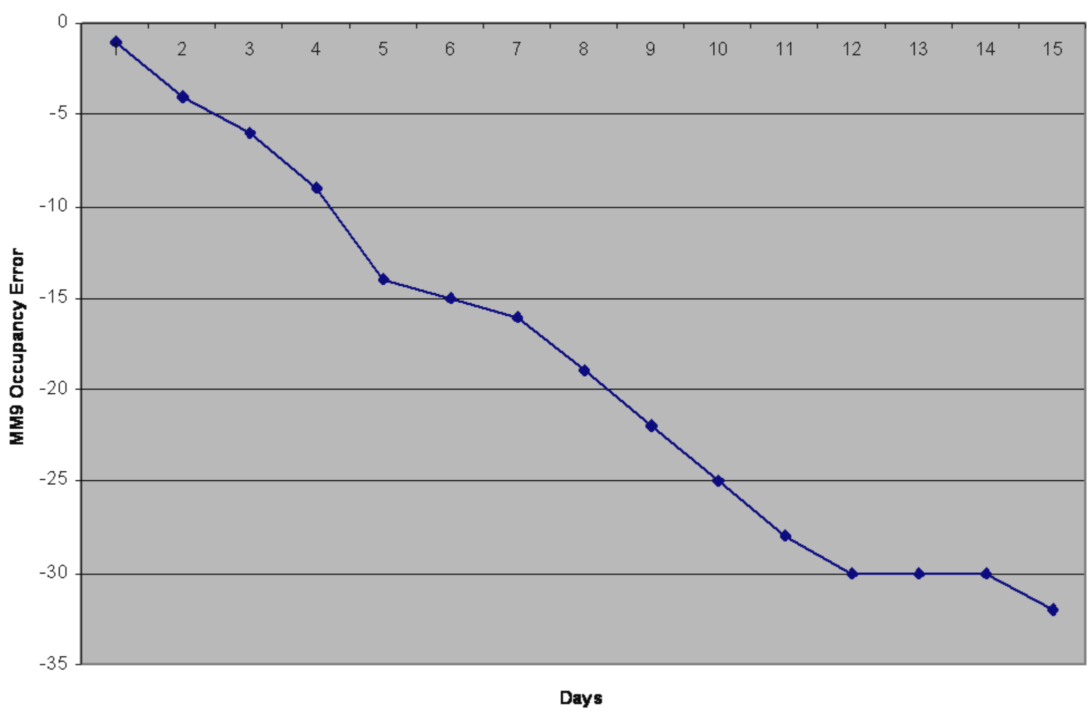

Figure 20. Occupancy Count Error Versus Time at MM9

The Performance Requirements related to occupancy are listed in Table 4.

Table 4 Summary of Occupancy Testing Results

Test Plan Parameter	Reqt	ITP	MM9	Result	Note
3.2.1 – Percentage of time the system will falsely indicate that parking spaces are available when every parking space is occupied.	<5%			Fail	1
3.2.2 – Percentage that the system will falsely indicate that the parking area is full when parking spaces are available.	<5%			Fail	1
3.2.5 – Time between required resets of vehicle occupancy (days)	>14			Fail	2
3.2.7 – Deviation between system determined occupancy and actual occupancy.	+/- 5%			Fail	3

Note 1. During the test period, the parking areas were never full therefore, tests 3.2.1 and 3.2.2 could not be made directly. When the site was selected prior to the start of the contract, the site was often full, but usage has declined since then. This is not significant because the occupancy count error indicates whether a false indication will be made when the occupancy approaches the parking area capacity. The tests reported did not account for uncontrolled behavior. The percentage of time that unavailable parking spaces are offered was likely to be less than reported because vehicles parked more than one to a parking space or outside of marked parking spaces leave more parking spaces available. Conversely, the area is more likely to be shown as full when parking spaces are available more often than shown. Although the preferred situation is to report with complete accuracy, if that is not possible, it is better to not offer unavailable parking spaces because that may leave a truck driver, depending on the parking space, with limited options upon arrival at the parking area.

Note 2. Specification 3.2.5 is poorly constructed because it does not specify under what conditions a reset is required. (A reset means performing a manual audit of the parking area and replacing the indicated occupancy count with the actual occupancy count.)

Note 3. Specification 3.2.7 is probably too restrictive in that it is only +/–1 space at MM9 and +/– 2 spaces at ITP. Since ITP has random parking, the area's capacity may vary by more than 2 spaces depending on how efficiently trucks are parked.

3.2.3 Audited Occupancy Count Error

In a manual audit occupancy count test, the occupied parking spaces in an area were manually counted and immediately compared to the occupancy count shown in the database. The occupancy count must be executed and compared before any vehicles have entered or left the area. The authors were unable to perform this test properly due to ongoing problems with the manual audit process.

3.2.4 Classification Challenges

There were a number of challenges in both determining vehicle classification and applying vehicle classification to the occupancy calculation. Determining vehicle classification became a challenge when vehicles either slowed and stopped, and sped up when entering or exiting the parking area. The vehicle classification becomes even more difficult when vehicles moved forward and backward multiple times over the VDUs when either entering or exiting the parking area.

Even if the classification algorithm was 100 percent accurate, applying the information to the selected sites (ITP and MM9) would not increase the accuracy of the occupancy count, but would decrease the accuracy. There are two explanations for this unexpected outcome:

- Every vehicle occupies a space—At ITP, the vehicle class is irrelevant to the occupancy count. Each vehicle, regardless of the class occupies one parking space. Therefore, adding the classification determination provided no additional benefit to the truck drivers.
- Trailer drops negatively impact occupancy counts—The occupancy calculation had a 50 percent chance of being wrong when a trailer and its tractor were present in the facility. For example, a tractor trailer is in the parking area. The tractor drops the trailer and leaves as a bobtail tractor. There is no way to determine which tractor left the facility and the current occupancy for the whole parking area, until the combined tractor trailer leaves. Until the combined tractor trailer leaves, the system could not know if there are two parking spaces occupied (trailer and bobtail tractor) or one parking space occupied (tractor trailer combined). Furthermore, if another bobtail tractor enters, the system would not know if there are three parking spaces occupied (trailer and two bobtail tractors) or two parking spaces occupied (tractor combined with trailer and a bobtail tractor).

3.3 DETECTION RESPONSE TIME

The detection response time was the time difference between a vehicle transition and the availability of the updated occupancy count in the database. It is sometimes referred to as latency.If the Internet link between the PAR and the database server is sluggish or out-of-service, the PAR buffed all data for up to several weeks. Thus, a threshold should be defined to distinguish long latencies from system downtime.

3.4 SYSTEM UPTIME

System uptime was affected by unplanned outages and by excessive long scheduled maintenance times. Table 5 is a summary of the uptime results for the last 9 months of the program.

Table 5. Summary of Uptime Performance for 9 Months (January 2009–September 2009)

Test Plan Parameter	Reqt	ITP	MM9	Result
3.2.3 – System uptime per site (percent)	> 95	98	87	Fail
3.2.4 – Average downtime per incident (hours)	< 4	8	16	Fail
3.2.6 – Planned downtime per site (hours/week)	< 2	0.5	1.0	Pass

Uptime was monitored on the system components as well as on the entire system. Since both test sites were fully installed and debugged, there were no outages of either the parking area components, including the PAR, or of the database server. The cellular telephone Internet link between the PAR and the database server, operated without interruption for the last 3 months of the program, including throughout the last test sequence. However, there were Internet outages at both test sites earlier in the program.

4. FINDINGS AND LESSONS LEARNED

The SmartPark Magnetometer system FOT resulted in the following findings and lessons learned:

- Driver behavior ultimately determines the accuracy of the parking area occupancy count. Even with perfect entry/exit and parking space detection, (as described in Section 3.1) will lead to discrepancies. The best way to mitigate the discrepancies is by performing periodic manual audits and updating the parking database.
- If a deployed system is sending vehicle detection and classification information over a radio network, the network should possess enough bandwidth to accommodate additional reporting requirements. Additional reporting may be necessary after the initial installation of equipment and the driving patterns at the sites are understood.
- Manual audits are subject to errors if not administered properly. We encountered recurring problems during the tests when operators forgot to perform an audit, delayed entry of the data, or entered the wrong time stamp.
  - Audits must be done on a regular, preferably daily, schedule. Experience has shown that if the audit is scheduled less often than daily, there is a tendency for the audit to be neglected.
- The means to enter audit data must be simple and intuitive. We suggest, by example, a cellular telephone application allowing direct contact with the database from the parking area with the time stamp acquired automatically by the database server.
- A sufficient tolerance must be allocated for the parking area occupancy count to accommodate the errors described above yet not offer parking spaces when none are available. Our self-imposed tolerances of one parking space at MM9 and two parking spaces at ITP were too restrictive. Indeed, with random parking at ITP, its capacity may vary by more than two parking spaces depending on how efficiently trucks are parked on a given day.
- Vehicle classification (as determined in Section 2.1.6) reduced the accuracy of the overall parking occupancy count and in some cases rendered the system unusable. For example, if a trailer drop is incorrectly detected, the occupancy count will either need a manual reset, or all the tractor trailers to exit before the error can be corrected (assuming the rest of the classifications are correct).
- The reliability of service with a cellular telephone modem requires further study. It is not known whether other vendors provide better service. In parking areas that are less tolerant of downtime, a hardwired Internet connection may be a better option.
- The capability to transmit raw data to the database server for detection/classification processing was beneficial. The database server was a more capable computer than those earlier in the chain and made the full database immediately accessible. More sophisticated algorithms were analyzed and implemented more quickly than would have been possible if organized differently. Additionally, the algorithms may be tailored more easily to a specific parking area based on experience.

- The initial requirements were determined without knowing the usage patterns or throughput of the parking areas. Based on observed usage patterns and assuming no uncontrolled behavior (e.g. two vehicles in, one out, trailer drops, etc.) MM9 and ITP would require an entry/exit accuracy of 99.998 percent assuming an average stay of 4 hours, and 99.993 percent assuming an average stay of 8 hours to pass requirements discussed in Section 3. The accuracy rate also assumes the system undercounts the same vehicles on the entry and exit lane and does not overcount any vehicles. With uncontrolled behavior the accuracy requirements would be higher. There is currently no existing off-the-shelf technology that would meet the accuracy requirements or be cost effectively maintained by either the State Department of Transportation or the private operator.
- The pairing of the site attributes (staffed versus unstaffed, pure truck parking versus mixed vehicle parking, controlled versus uncontrolled), parking behaviors (short term versus overnight/multiday, and trailer drops); and equipment attributes (measurement capabilities, maintenance requirements, and cost) should be compared prior to the selection and installation of monitoring equipment. For Phase I, ITP and MM9 exhibited all of the site and parking attributes. These attributes affect how the system should operate:
  - Staffed versus unstaffed. During staffed hours, vehicles tend to follow the stated signs of the facility. Once the parking area becomes unstaffed, vehicles will drive anywhere in and out of the parking area wherever a vehicle can fit (e.g. over grass medians).
  - Pure truck parking versus mixed vehicle parking. Mixed vehicle parking tends to have more varied parking patterns than pure parking.
  - Controlled versus uncontrolled. The presence of gate arms would likely reduce, but not eliminate the uncontrolled behavior.
  - Short term versus overnight/multiday parking. The length of parking stays will decrease the accuracy of the occupancy count, as errors take longer to automatically correct. Assuming equal errors in the entry/exit detection and classification, if a vehicle is undercounted or overcounted upon entry, the error will not be corrected until the vehicle exits. The longer the vehicle stays in the facility the longer the error persists.
  - Trailer drops Trailer drops will decrease the accuracy of occupancy counts.
- Both the cost of maintenance and the ease of maintaining the system are critical to the long-term success of any parking management system. During Phase I, the operators at both MM9 and ITP were responsible for day-to-day maintenance of the systems. It is assumed any truck parking system will rely on the parking operator to perform day-to-day system maintenance. If the equipment is either too expensive (more than $5,000 per lane) or too complex (a cashier should be able to operate it), then the system will not be able to be maintained by the parking operator, leading to increased operations cost.

5. SUMMARY AND CONCLUSIONS

- The system vehicle detection performance of 96.2 percent at MM9 and 96.5 percent at ITP may be adequate for the intended purpose. The unbalanced error rates at the entries and exits require further investigation.
- Uncontrolled driving behavior adversely affects occupancy count. The most reliable solution is to perform manual occupancy count updates on a regular, preferably daily, schedule.
- A better procedure is needed for performing manual occupancy count updates. We recommend a cellular telephone application so the database may be accessed from the parking area and the database server can acquire the time automatically.
- A weak link in system reliability is the cellular telephone modem Internet link. Options are an alternate supplier be sought or service be changed to a hardwired Internet link.
- Accuracy and performance requirements should be based on experiments from real-time information dissemination.

APPENDIX A—SYSTEM REQUIREMENTS

The system requirements tables are reproduced below from *System Requirements, SmartPark Phase I, Rev E,* May 6, 2008.

Table 6. Functional Requirements

Paragraph	Requirement	Reason/Justification/Source
3.1.1	A means of automatically detecting parking space status by:	
3.1.1.1	(a) monitoring individual spaces, or	So the system can detect the presence of vehicles.
3.1.1.2	(b) monitoring ingress and egress in controlled areas	So the system can detect the presence of vehicles.
3.1.2	A central database to maintain parking status information	So the system reliably indicates when the parking area is full.
3.1.3	A means for stakeholders to access the database information.	So the system reliably indicates when the parking area is full.
3.1.4	The system must be able to count vehicles entering and exiting the facility	So the system reliably indicates when the parking area is full.
3.1.4.1	The system must be able to detect and resolve any discrepancy in count between the individual space sensors and the entrance / exit sensors in mixed parking	So the system reliably indicates when the parking area is full.
3.1.5	The system must be able to count vehicles at varying separations (minimum distance of 20 feet between vehicles) and speeds (5 mi/h to 50 mi/h) entering and exiting the facility	So the system reliably indicates when the parking area is full.
3.1.6	The system must operate in weather (–20 –60 C, wind speed less than 50 mi/h, up to 90% humidity) and ambient lighting conditions	So the system is inexpensive to operate and maintain.
3.1.6.1	The system will conform to part 15 of the FCC rules regarding radio devices operating in the 915 MHz ISM Band.	So the system is inexpensive to operate and maintain.
3.1.7	The system must maintain a count of the available parking in the facility and provide this count to authorized remote users	So the system reliably indicates when the parking area is full.
3.1.8	The system should provide a means for resetting the count of available parking in the event of discrepancy	So the system reliably indicates when the parking area is full.
3.1.9	The system should maintain a log of vehicle entrance and exit events and system errors.	So the system reliably indicates when the parking area is full.
3.1.10	For each space at the Marker 9 area, a record will be generated for each ingress and egress from the area and the cumulative count of vehicles in the area and a record will be generated for each time a vehicle enters or leaves a space.	So the system reliably indicates when the parking area is full.
3.1.11	For the ITP, a record will be generated for each ingress and egress from the area and the cumulative count of vehicles in the area.	So the system reliably indicates when the parking area is full.

Paragraph	Requirement	Reason/Justification/Source
3.1.12	There will be means to adjust the cumulative occupancy count with a physical occupancy count.	So the system is inexpensive to operate and maintain.
3.1.13	A record will be generated for each maintenance event.	So the system is inexpensive to operate and maintain.
3.1.14	**Web pages will provide (for the MM9 area):**	
3.1.14.1.1	A list of the parking spaces and current status.	So the system reliably indicates when the parking area is full.
3.1.14.1.2	A cumulative count of vehicles in the area and number of available parking spaces.	So the system reliably indicates when the parking area is full.
3.1.14.1.3	Listing of uptime statistics (Unplanned system downtime, planned system downtime, communication response time, system count resets)	So the system reliably indicates when the parking area is full.
3.1.14.2	**Web pages will provide (for the ITP):**	
3.1.14.2.1	A cumulative count of vehicles in the area	So the system reliably indicates when the parking area is full.
3.1.14.2.2	Listing of uptime statistics (Unplanned system downtime, planned system downtime, communication response time, system count resets)	So the system reliably indicates when the parking area is full.
3.1.14.3	For system maintenance (reporting)	So the system is inexpensive to operate and maintain.
3.1.14.3.1	A listing of statistics for each maintenance event.	So the system is inexpensive to operate and maintain.
3.1.15	Maintenance and installation (system interaction)	So the system is inexpensive to operate and maintain.
3.1.15.1	Tools will be available to calibrate and test each device at time of installation.	So the system is inexpensive to operate and maintain.
3.1.15.2	Battery replacement can be performed without interrupting system operation.	So the system is inexpensive to operate and maintain.
3.1.16	Detection accuracy entering or exiting parking area for passenger vehicles (cars and light pick-ups)	So the system reliably indicates when the parking area is full.
3.1.17	Detection accuracy entering or exiting parking area for single-unit trucks	So the system reliably indicates when the parking area is full.

Table 7. Performance Requirements

Paragraph	Parameter	Requirement
3.2.1	Percentage of time the system will falsely indicate parking space is available when every parking space is occupied.	<5%
3.2.2	Percentage the system will falsely indicate the parking area is full when parking spaces are available.	<5%
3.2.3	System uptime per site	95% (8.4 hours unscheduled downtime per week)
3.2.4	Average downtime per incident	4 hours
3.2.5	Time between required resets of vehicle occupancy	2 weeks
3.2.6	Planned downtime per site	2 hours per week
3.2.7	Deviation between system-determined occupancy and actual occupancy.	+/- 5%
3.2.8	Detection response time (time between detection of an event and availability of record in database.)	2 minutes

Table 8. Data Requirements

Paragraph	Requirement	Reason/Justification/Source
3.4.1	For each parking space at the MM9 area, a record will be generated for each ingress and egress from the area and the cumulative count of vehicles in the area and a record will be generated for each time a vehicle enters or leaves a parking space.	So the system reliably indicates when the parking area is full.
3.4.1.1	Date, time, MM9, ingress	So the system reliably indicates when the parking area is full.
3.4.1.2	Date, time, MM9, egress	So the system reliably indicates when the parking area is full.
3.4.1.3	Date, time, MM9, cumulative count of vehicles as determined by the difference between the capacity (27) and the difference between the ingress count 3.4.1.1 and egress count 3.4.1.2	So the system reliably indicates when the parking area is full.
3.4.1.4	Date, time, MM9, parking space 1, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.5	Date, time, MM9, parking space 2, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.6	Date, time, MM9, parking space 3, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.7	Date, time, MM9, parking space 4, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.8	Date, time, MM9, parking space 5, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.9	Date, time, MM9, parking space 6, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.10	Date, time, MM9, parking space 7, occupied (yes or no)	So the system reliably indicates when the parking area is full.

Paragraph	Requirement	Reason/Justification/Source
3.4.1.11	Date, time, MM9, parking space 8, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.12	Date, time, MM9, parking space 9, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.13	Date, time, MM9, parking space 10, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.14	Date, time, MM9, parking space 11, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.15	Date, time, MM9, parking space 12, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.16	Date, time, MM9, parking space 13, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.17	Date, time, MM9, parking space 14, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.18	Date, time, MM9, parking space 15, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.19	Date, time, MM9, parking space 16, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.20	Date, time, MM9, parking space 17, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.21	Date, time, MM9, parking space 18, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.22	Date, time, MM9, parking space 19, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.23	Date, time, MM9, parking space 20, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.24	Date, time, MM9, parking space 21, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.25	Date, time, MM9, parking space 22, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.26	Date, time, MM9, parking space 23, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.27	Date, time, MM9, parking space 24, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.28	Date, time, MM9, parking space 25, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.29	Date, time, MM9, parking space 26, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.30	Date, time, MM9, parking space 27, occupied (yes or no)	So the system reliably indicates when the parking area is full.
3.4.1.31	Date, time, MM9, truck parking space available count as determined by count of occupied individual parking spaces	So the system reliably indicates when the parking area is full.
3.4.1.32	Date, time, MM9, discrepancy in count between truck space available count as determined by individual parking space vehicle detectors 3.4.1.31 and that determined by 3.4.1.3	So the system reliably indicates when the parking area is full.

Paragraph	Requirement	Reason/Justification/Source
3.4.1.33	Date, time, MM9, resolution of discrepancy in 3.4.1.32	So the system reliably indicates when the parking area is full.
3.4.2	For the ITP, a record will be generated for each ingress and egress from the area and the cumulative count of vehicles in the area.	So the system reliably indicates when the parking area is full.
3.4.2.1	Date, time, ITP, ingress	So the system reliably indicates when the parking area is full.
3.4.2.2	Date, time, ITP, egress	So the system reliably indicates when the parking area is full.
3.4.2.3	Date, time, ITP, cumulative count of vehicles as determined by the difference between the capacity and the difference between the ingress count (3.4.2.1) and the egress count (3.4.2.2)	So the system reliably indicates when the parking area is full.

Table 9.Nonfunctional Requirements

Paragraph	Requirement	Reason / Justification / Source
3.5.1	The system must be easy to install (less than 10 minutes per parking space) and maintain	So the system is inexpensive to operate and maintain.

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