A PORTABLE, WIRELESS INDUCTIVE-LOOP VEHICLE COUNTER

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A PORTABLE, WIRELESS INDUCTIVE-LOOP VEHICLE COUNTER

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SUMMARY

This thesis descries the evolution and testing of a fully portable, inductive loop vehicle counter system. As a component of the NFS *Embedded Distributed Simulation for Transportation System Management* project, the system's cellular modem transmits real-time data to servers at Georgia Institute of Technology. From there, the data can be fed into simulations predicting travel behavior. Researchers revised both the detector circuit, and the temporary, reusable loop pad several times over multiple rounds of field testing. The final tested version of this system demonstrates the efficacy of uncommonly small inductive loops. When paired with a reliable data transmission channel, the system was shown to capture nearly 96% of actual through traffic.

Chapter 1 Introduction

1.1 Background

The research reported in this thesis is conducted as part of an NSF-sponsored study, *Embedded Distributed Simulation for Transportation System Management*. The study envisions large-scale, real time distributed networks where vehicles themselves play an active role in predicting future traffic demand[1].

A component of the distributed simulation effort is simulating traffic flows on large-scale roadway networks in real time. To better understand and predict driver behavior, the simulations are enhanced with real-world traffic data provided by fixed detectors. Sensing of Bluetooth® and mobile phones in passing vehicles is another detection method. The ultimate goal of the overarching research effort is to predict the effectiveness of an embedded, distributed transportation management system. In the envisioned system much of the computational work for the simulations would be pushed to the vehicles themselves, operating on an 'ad-hoc' or asynchronous basis. In a recent implementation, participant vehicles are instrumented with simulator software for modeling the roadway network in their immediate vicinity. Further, the simulation envelopes around individual vehicles might overlap (see Figure 1), thus improving overall system accuracy and robustness. Initial tests on a modeled ten-intersection corridor, with twenty vehicles, and then on a 10x10 grid with 40 vehicles, validate the potential effectiveness of this approach over a range of traffic conditions [1].

Cameras, inductive loops, and possibly other roadside detection technologies are utilized in the initial stages of the project. This thesis covers the research performed on a developed portable inductive loop detector.

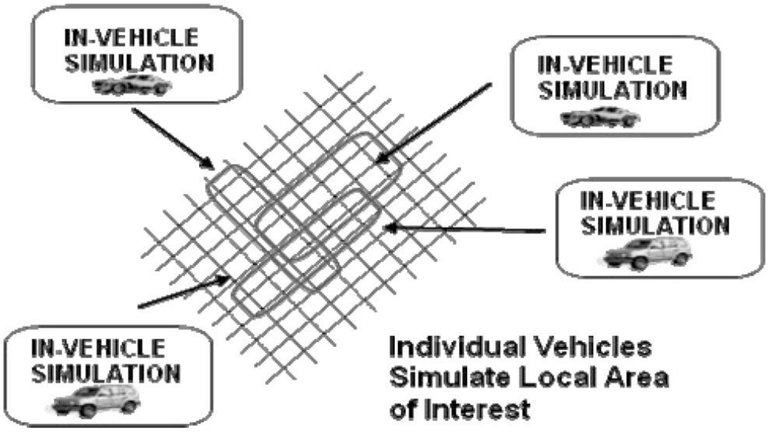


Figure 1 - In-Vehicle Simulation [1]

1.2 Problem and Motivation

For fixed in-road detection, transportation agencies traditionally saw-cut a rectangle (or some variation) into the pavement, insert an inductive loop, and seal the cut with binder. Another long cut is required to patch to the signal cabinet, which usually contains the detector hardware. Performing such work for temporary installations, i.e., for collecting a few weeks of data for research purposes, is generally cost-prohibitive and likely unacceptable to most agencies.

The problem this thesis addresses is the development of a detection device for short-term data collection. With the assumption that existing infrastructure cannot be permanently altered, challenges for this research include finding a method that can withstand a deployment up to several weeks. In addition, for short-term tests (on the order of hours) it is desirable that the developed system be self sufficient regarding power needs. As such, the system would have to run on battery power. Finally, the system must record and stream detections in real-time to a server off-site. All these challenges point to the need for a simple, easily deployed, low-cost solution.

1.3 Document Overview

This thesis first reviews applicable literature on detection technologies and temporary detection applications, and then, literature on network simulation. The text also discusses the evolution of the developed wireless detector system and presents observations and data from extensive field tests of the system. The thesis closes with conclusions and ideas for future improvements.

Chapter 2 Literature Review

This literature review has three components: a review of detection technologies (as candidates for the portable detector), the latest “state of the art” applications of loop detection (the selected technology for the temporary deployment), and a review of efforts conceptually similar to the NSF Embedded Distributed Simulation project. This literature provides a contextual framework highlighting the potential ITS applications of the portable detector.

2.1 Vehicle Detection

The most comprehensive and relevant resource for vehicle detection is Klein’s *Traffic Detector Handbook* [2], last updated in 2006. This section is framed around the rich information available in this 700-page handbook. Additional literature, when cited, elaborates on individual technologies. Inductive loops and their related literature are reviewed at the end of this section.

2.1.1 Overview of Technologies

2.1.1.1 Video Image Processing

Video Image Processing (VIP) entails the mounting of video cameras above roads to capture the passage of vehicles. These systems electronically monitor the color of video pixels and use changes in color or brightness to identify the passage of a vehicle through the frame. VIP comes in three varieties. *Tripline* detectors require linear detection zones along the road to be predefined. *Closed Loop* systems significantly widen the detection field, to the point of tracking individual vehicles along the road and sensing lane changes.

Data Association VIP identifies vehicles at the pixel level. Such detectors in turn can identify vehicles between cameras, which is useful for calculating link travel time.

The optimal placement of a VIP camera is 30-50 feet above the roadway to discern the gap between individual vehicles [2]. At this height, many lanes can be monitored at once. While installing a VIP system is not intrusive to the roadway, the technology has shown other significant disadvantages. Weather such as heavy rain and snowfall are known to affect video detectors. Sun shining directly in the lens is another reported problem. Further, these systems are less effective at night and require street-lighting. As such, depending on the conditions where they operate, VIP systems can report a sizeable number of misses and false positives when compared to magnetic detection technologies.

2.1.1.2 Magnetic Sensors

Magnetic sensors work by detecting local changes in Earth's magnetic field due to the presence of vehicles passing over the sensor. These detectors are generally less intrusive to pavement, and consequently last longer than inductive loops. There are two major kinds of magnetic detection technology, *Magnetic Detector* and *Magnetometer*. The Hi-Star® portable counter employs a newer third technology, *Giant Magnetoresistance.*

2.1.1.2.1 Magnetic Detectors (aka Microloops)

Magnetic Detectors are "simple and rugged" [2]. The devices are always mounted perpendicular to the flow of traffic and require a lead-in cable. For the most part, they can only detect moving vehicles. (The model 702 from 3M® can detect stopped vehicles, but only when installed in rows of three and with specialized software.) The cores, containing several coils of fine, wound wire, are usually tunneled 1-2 feet below the pavement. While this configuration is resistant to climate and vehicle wear, installation can be cumbersome. One model, however, is mounted flush with the pavement, has dimensions of 3 x 5 x 20 inches, and is enclosed in cast aluminum housing.

In 2009, Middleton et al. [3] at the Texas Transportation Institute published a comprehensive comparison study of a wide-area radar detector, the Sensys® Magnetometer (see Magnetometers, below), and the Global Traffic Technologies Magnetometer – which is actually a microloop. The researchers installed all three sensors near the Texas A&M campus, or, in nearby Austin. Their study evaluated the products for signalization applications, including red light running and dilemma zone protection. Like other magnetic detectors, the GTT unit had difficulties with slow or stopped vehicles. While the unit detected the stationary vehicle, the detection often "dropped out" for a moment – resulting in an overcount. The researchers also contacted a number of nationwide jurisdictions and recorded their experience with each product. The City of Arlington, TX, had installed the GTT microloops but reported the units stopped working. According to Middleton, the individual who had more information on the failures no longer worked for the city.

Installation of the GTT microloop cost about $3400 to monitor the stop bar of a two-lane intersection, and at six lanes the cost reaches $10,000 [3]. The other two technologies, installed, also easily cost in the thousands. Those costs will be detailed later in their respective sections.

2.1.1.3 Magnetometers

Magnetometers are typically installed in a circular, vertical bore in the pavement. Unlike Magnetic Detectors, these devices contain at least two narrow wrappings of wire. One is mounted vertical to sense disturbances in the vertical component of Earth's magnetic field, and the other, usually mounted parallel to traffic flow, captures the horizontal component. This robust, compact design enables magnetometers to detect stopped vehicles, hold a vehicle presence for a long time, and be resistant to picking up detections from an adjacent lane (known as crosstalk). The bore is often 18" deep, making these detectors especially popular in the northeast where climate stresses pavement and damages wiring close to the surface.

An emerging class of magnetometers are wireless and run off a battery. These self-powered vehicle detectors (SPVDs) are housed in enclosures several inches square, embedded in the pavement, and last for several years on one charge.

2.1.1.3.1.1 Sensys® Magnetometer

The SPVD marketed by Sensys® appears frequently in the literature. The manufacturer observes that loops are "notoriously unreliable" and touts that their rugged units can run ten years on a charge [4]. The California Center for Innovative Transportation at UC Berkeley [5] tested the Sensys® against loops and video. The researchers spent just over an hour drilling cores in six lanes to house the sensors, a significant time savings over inductive loops which can require an hour each. Further, the sensor's count accuracy and ability to track vehicle speed (between two detectors) was virtually identical to inductive loops. The units did require, however, an access point mounted to a pole and connected to AC power.

In the Middleton et al. [3] comparison cited above, the researchers reported having to drill a 4-inch core into the pavement to house one sensor. They reported accuracy validating the California study, although there was an overcount rate of 3-8%. Baltimore, Farmers Branch near Dallas, and Harris County (Houston) TX also provided positive feedback on the Sensys® system. Middleton et al., however, warned that the devices would be destroyed by surface milling when pavement is resurfaced. Further, the researchers lamented an episode involving buggy firmware in the sensors, and tech support issues.

Middleton reports that one sensor node costs $450, plus $3000 for the access point. Installation costs were additional.

2.1.1.3.2 Giant Magnetoresistance

Giant Magnetoresistance, or GMR, is not covered in the *Traffic Detector Handbook*. The effect was discovered in 1988 by Albert Fert of the University of Paris-South, and Peter Grünberg of Germany's KFA Jülich Research Centre. Both shared the 2007 Nobel Prize in Physics for their work. They discovered that electrons of the same spin encounter unexpectedly high resistance when passing through thin strips (nanometer-scale) of material with alternating spin. This discovery has contributed to the miniaturization, and accuracy, of magnetic sensors. GMR is now common in contemporary hard drives, and was cited by one of Fert's colleagues as central to the success of portable music players like iPod [6].

The Hi-Star® Traffic Counter, marketed by Quixote Transportation Technologies (now owned by Vaisala instruments), employs GMR sensors to detect changes in Earth's magnetic field when a vehicle is present [7]. Due to the effectiveness of GMR an extremely small, surface-mounted device is possible. Overall footprint of the aluminum enclosure is about the size and thickness of a DVD case. The latest versions of the device can capture vehicle class, speed, length and roadway temperature. However, the device (enclosed in a protective rubber shell) must be nailed or screwed into the pavement. Hi-Star® is designed for short term traffic study use, and must also be physically removed to download the count data [8].

According to Tapconet, (telephone quotation supplied June 23rd 2010), one Hi-Star® NC100 (which only performs vehicle count) costs $1200. On July 1st, the researchers also obtained a $195 quote for the rubber housing.

Figure 2 - Hi-Star® NC100/200 Detector, and Rubber Housing [8]

Figure 3 - Hi-Star® Traffic Counter Affixed to Pavement in Rubber Housing [8]

2.1.1.4 Microwave Radar

There are two basic types of Microwave Radar sensors: *Continuous Wave* (CW) and *Frequency Modulated Continuous Wave* (FMCW). CW systems detect the Doppler shift of a fixed frequency wave reflected off approaching vehicles. Consequently they cannot detect stationary vehicles, but are useful for reporting speeds. FMCW instead transmits a constantly changing frequency, and measures the time shift of the returned waveform. These systems can thus detect stopped vehicles, and with Doppler, also report speeds. FMCWs, when mounted perpendicular to traffic flow (in a 'side-fired' configuration), can track up to eight lanes at once.

2.1.1.4.1 Wavetronics SmartSensor Advance®

SmartSensor Advance® is an extremely versatile microwave Wide Area Detector [9] marketed by Wavetronix LLC of Lindon, UT. The system is mounted above the road, typically aside the signal head, and features eight user-defined zones. The detection range is 500 feet. Vehicle count and speeds are recorded [10]. However, this detector cannot measure the first 100 feet in front of the sensor. Middleton et al. observe that the SmartSensor® is inappropriate for detection at the stop bar unless a new pole is installed downstream of the intersection.

Middleton et al. mounted a SmartSensor® from a signal pole. The unit reported a higher volume than other detectors, though there were some false positives from turning vehicles and standing queues. The city of Denton, TX and Utah DOT were pleased with the product [3]. To detect dilemma zones at highway speeds, a complete SmartSensor® installation runs between \$8,000 and \$12,000 for a two-lane approach, and approaches \$25,000 for a five-lane approach. Sensys®, by comparison, runs between \$7,000 and \$16,000 for this same configuration [3]. Middleton et al. contended that the chief advantages of the SmartSensor Advance® are accuracy and reliability.

2.1.1.5 Passive Infrared

Like VIP, Passive IR cameras are mounted above traffic and do not transmit any energy on their own. They measure heat generated by or reflected off vehicles. Such systems can still be affected by sun glint and inclement weather, but not to the extent of VIP. As such, Passive IR systems are somewhat more accurate than VIP. The rule-of-thumb is that if a person can see the vehicle, passive IR can as well. XTralis sells a combined Ultrasonic and Infrared Detector, and claims ±3% accuracy [11]. In 1999 dollars, these sensors run \$700-\$1200 plus installation [2].

2.1.1.6 Laser Radar

Laser Radar Detectors are mounted directly above passing vehicles. Several beams are sent out at once. By tracking reflected beams, both the speed and presence of vehicles underneath the detector are calculated. Modern units can capture 3-D images of passing vehicles. Laser radar units are adversely affected by heavy fog (visibility less than 20'), and the units require regular lens cleaning. According to a tech report prepared by IBI Group for Transport Canada, a system for overhead vehicle detection can run $12,000 (Canadian) [12]. The AutoSense II Laser Radar, according to the manufacturer, has a 99.9% detection accuracy [13].

2.1.1.7 Ultrasonic

Ultrasonic detectors transmit at 25-50kHz, above the threshold of human hearing. The devices are mounted perpendicular to, or above, passing vehicles. By measuring the return time of reflected pulses, the presence of a vehicle is determined. Some devices send out multiple beams, spaced apart at a fixed angle, and therefore measure vehicle speeds. Other units instead measure vehicle speed using Doppler, but detectors with this ability are more expensive. Ultrasonic detection is widely used in Japan, where government policy discourages cutting pavement. Ultrasonic sensors are susceptible to turbulent air and temperature drift. XTralis sells a combined Ultrasonic and Infrared Detector, and claims ±3% accuracy [11]. According to the *Traffic Detector Handbook*, one ultrasonic sensor can run between $600 and $1900 (in 1999 dollars) [2].

2.1.1.8 Passive Acoustic

These detectors, rather than sending sound pulses, listen for passing vehicles. Models like International Road Dynamics' SmartSonic™ use an array of small microphones mounted above the road. By tracking changes between different parts of the array, vehicle speed is determined by an algorithm assuming average vehicle length. PA detectors are not effective in places with frequent "stop and go traffic," as the detector's algorithms have difficulty in switching between fast and slow flows. Further, they can be affected by cold temperatures. Middleton et al. at Texas Transportation Institute tested the SAS-1 PA detector from SmarTek®, and found accuracy of about 95% at freeway speeds, with variations of ±10% ground truth during congestion [14]. Acoustic sensors, according to the Traffic Detector Handbook, cost between $3100 and $8100 before installation (in 1999 dollars) [2].

2.1.1.9 Piezo Electric

This technology converts physical stresses into an electrical signal. While piezo is not described in the *Traffic Detector Handbook*, Vijayaraghavan at University of Minnesota [15] implemented a system in 2008 constructed of inexpensive off-the-shelf parts. His setup consists of a 6' metal rod, with four piezo elements on either end. The system is coupled with a simple transmitter with range of 100.' Notably, the device is self-powered from the energy harvested from the passing vehicles.

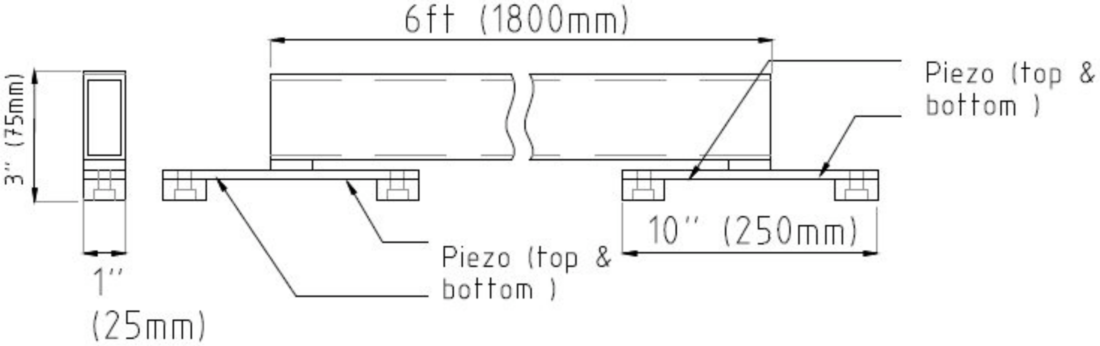


Figure 4 - Piezo-Electric Detector System [15]

For the experiment, the researchers constructed ramps to guide test vehicles over the assembly. The harvested energy, from each axle, was roughly proportional to vehicle weight. The researchers touted the low cost of their unique system. However, a slot must be cut in the pavement to house the detector over the long term.

2.1.1.10 Inductive Loops

The last detection technology covered in this literature review is Inductive Loop Detection, or ILD. ILD remains one of the oldest and most widely used technologies.

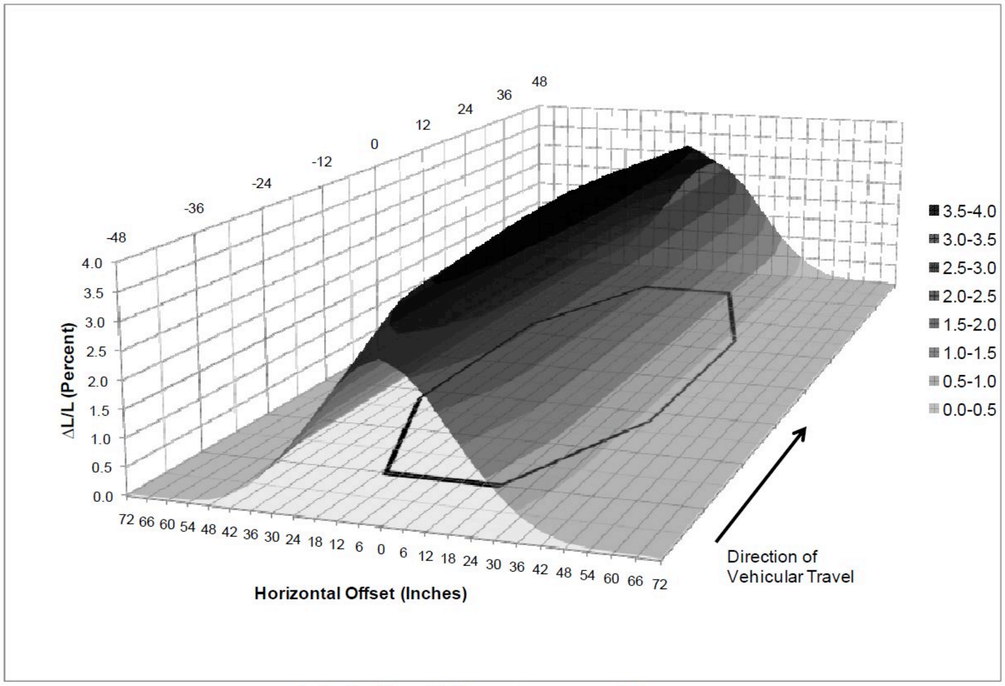
2.1.1.10.1 Theory

An ILD system consists of one or more loops of wire embedded in the pavement by means of saw cuts. The detector circuitry, usually integrated into the signal cabinet, transmits current between 10 to 200 kilohertz. A magnetic field is thus generated inside the loop.

The loop serves as an inductor, with inductance proportional to the area enclosed within, and turns of wire squared. Inductance is inversely proportional to the "length" of the loop, which is essentially the thickness of the bundled wires

When a vehicle passes over the loop, its steel mass induces eddy currents in the loop wire, which reduces inductance and therefore changes the oscillation frequency. In the *Handbook*, 100μH (micro-Henries) is established as the minimum inductance for an effective loop. NEMA specifies that detectors operate with loops varying between 50 and 700μH.

Day and Brennan et al. [16], in a 2009 study, mapped out the inductive response of loops. They set up a wood frame, with aluminum and steel sheets propped overhead. This allows the sheet to move latitudinally and longitudinally, and also in 6-inch height increments.



(a) 6 ft × 6 ft octagonal loop.

Figure 5 - Three-Dimensional Plot of Inductance Response to Galvanized Steel Sheet Elevated 12 Inches from the Pavement [16].

The *Handbook* also defines a “quality factor” Q for an inductive loop, which indicates the resonant efficiency of the inductor. Q depends on L_S, the series inductance of the loop, R_S, the loop’s series resistance, and ω is the oscillation frequency of the detector circuit. L_S itself also varies with ω.

$$Q = \omega L_S / R_S$$

A low quality factor suggests large energy losses within the loop. Quality factors below 5 are generally not effective for detection. Further, water seeping into the saw cuts can substantially increase resistance and reduce the quality factor. Increasing the number turns in the loop does increase the quality factor; however, past about six turns there are diminishing returns for typical roadway loop [2]. The same holds for vertical detection distance, as noted in the *Handbook*: “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.”

2.1.1.10.2 Hardware

A typical ILD system consists of several components. The loop and lead-in wire are saw-cut into the pavement and sealed with binder. The lead-in wire connects to lead-in cable inside a “pull box” accessible at roadside. Both lead-ins are a twisted pair, which reduces the noise pickup and crosstalk of these components. The final component is the detector circuitry itself, integrated into the signal controller cabinet.

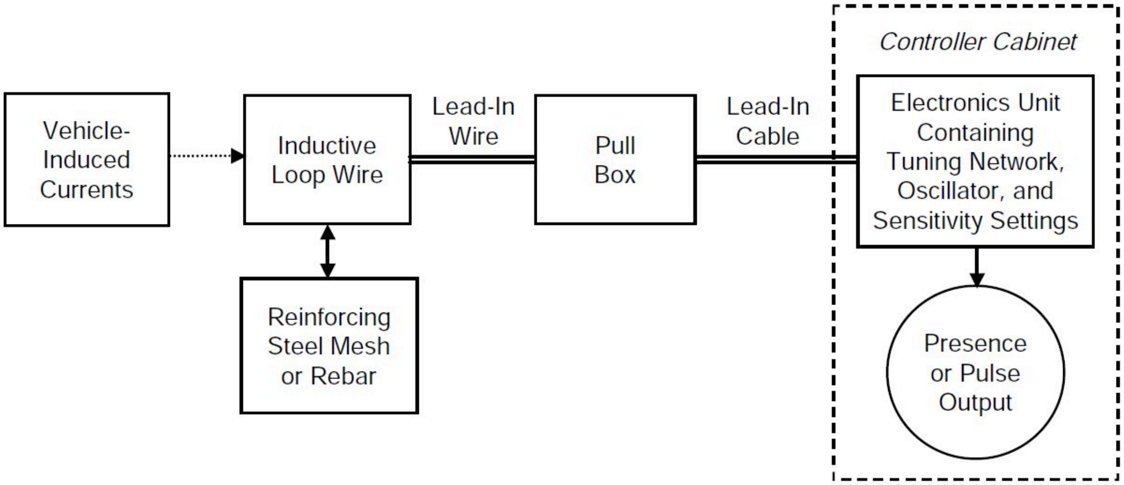


Figure 6 – Components of Typical Inductive Loop System [2]

2.1.1.10.3 Reliability

ILD systems are most prone to fail at the loop itself, or at the connection between the lead-in wire and lead-in cable. One Federal Highway Administration (FHWA) survey in New York State reported that 25% of loops were out of commission at any one time. Early electronics units were analog, and used a fixed frequency. These were susceptible to climate drift, where temperature alters the inductance of the loop and adversely affects accuracy. Modern detector units are fully digital, and track change in inductance as indicated by changing oscillator frequency. Automatic tuning against loop size and weather drift is also standard.

2.1.1.10.4 Configuration

A typical loop size is 6 feet square, but varies widely. “Short loops” are shorter than 20 feet, while “long loops” are longer and require only 1-2 turns. As large size increases failure rate, many agencies are instead using a series of smaller loops. These “sequential short loops” (SSLs) are effective on smaller vehicles, and are not as susceptible to inter-lane crosstalk. A common loop configuration is the quadropole, where two long, narrow and adjacent loops of opposite polarity occupy one lane. These have proven effective with bicycles, when ridden down the “spine” of the quadropole. Day and Brennan et al. [16] concluded that, for detecting passenger vehicles, quadropoles are not as sensitive down the center spine as originally claimed when they emerged in the 1970’s.

A configuration of two “chevrons” in series has also been successful in detecting small vehicles. Despite several searches of the literature, applications of inductive loops smaller than a foot square could not be found.

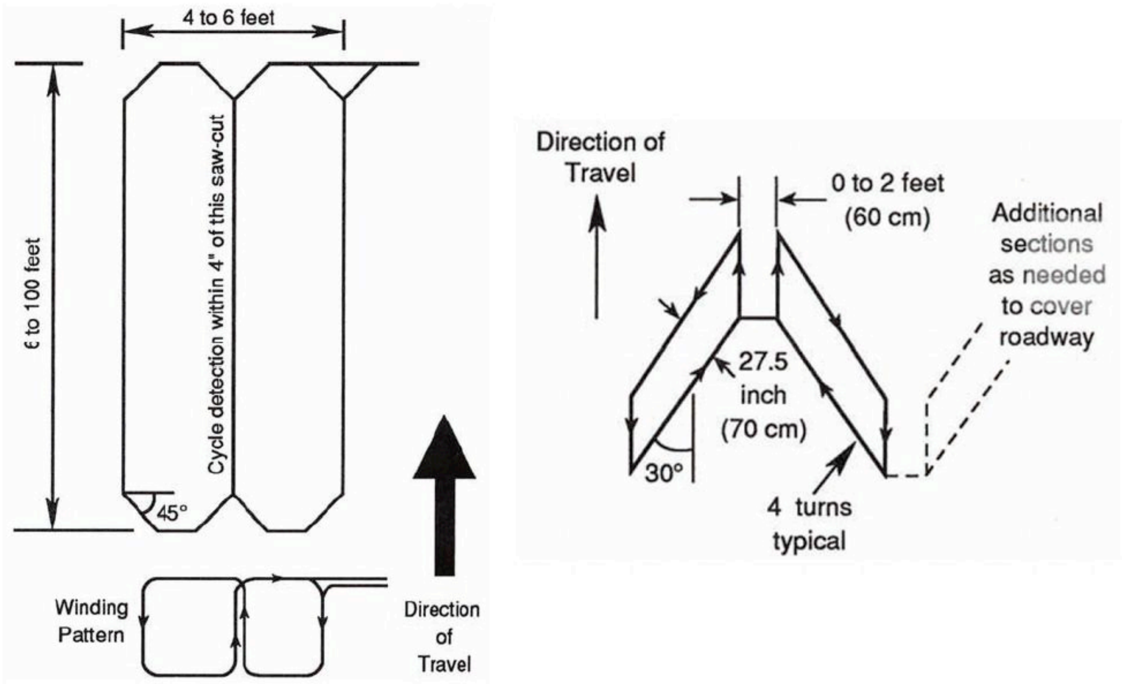


Figure 7 - Quadropole (left) and Chevron Loop Configurations [2]

2.1.1.10.5 Contemporary Inductive Loop Technology

All ILD systems feature an inductive loop, lead-in wiring, and a detector unit tracking the inductance change caused by vehicle presence. For this research project, the most important component would be the detector circuit.

2.1.1.10.5.1 Detector Manufacturers and Products

The researchers searched the Internet for loop detector manufactures and identified their latest products. Desired features include a small footprint, 12VDC operation, compensation for climate drift, and reasonably low power consumption. Another useful feature is adjustable sensitivity, the ΔL/L (inductance change) which will trigger a detection.

For integration into a portable battery-powered system, NEMA or similar rack- and shelf-mount form factors are not optimal. The two-channel DSP-222 [17] marketed by Diablo Controls, for example, follows the NEMA form factor and is nearly seven inches wide. The large size would require a larger shared enclosure, making the system less portable. Further, DSP-222 also consumes up to 100mA, which would adversely affect the system's battery life. Fortunately, several small-footprint and low-power detectors are targeted at the gate control market and are listed below. All these detector units are significantly less expensive than the other technologies described in this literature review.

Table 1 - Inductive Loop Vehicle Detectors Targeted at the Gate Control Market

Vendor	Product	Features	Power usage	Price
Diablo Controls	DSP-7LP [18]	Very small "micro" form factor (1.5" x 3" x 1.6") 10-30v AC/DC Non-adjustable sensitivity Compensation for environmental changes Loops between 20 and 1200µH	1ma at idle	$76.95 (http://www.accesstransmitters.com)
	DSP-15 [19]	PCB (2.9" x 4.1") 10-30v AC/DC Ten selectable sensitivity levels Optional "sensitivity boost" mode Compensation for environmental changes Loops between 20 and 1000µH Presence, or pulse on exit/entry	60mA (observed)	$88.50 (http://www.accesstransmitters.com)
Eberle Design Inc.	LMA-1400 Deflectometer^{TM} [20]	4.1" x 2.7" x 0.75" Loops between 20 – 2500 µH Ten selectable sensitivity levels 12-32 VDC, or 14-28 VAC "Sensitivity Boost" feature Non-volatile memory stores loop fault diagnostic history LED readout of loop frequency Sensitivity adjusts to temperature Presence, and pulse on entry/exit modes	85mA minimum	$120.00 (http://www.proteccontrols.com)
EMX Industries	D-TEK Vehicle Loop	2.7" x 4.1" Loops between 20 – 2000 µH Ten selectable sensitivity	60mA (low power	$95.00 (est. based on similar products on http://www.gatesnfe

	Detector (board) [21]	levels 12V AC/DC version Sensitivity adjusts to temperature Presence, and pulse on entry/exit modes	version)	nces.com)
	MVP D-TEK™ (box) [22]	3.3” x 2.6” x 3.7” Loops between 20 – 2000 μH Three selectable frequencies, automatic sensitivity boost 9 VDC – 240 VAC Sensitivity adjusts to temperature Presence, and pulse on entry/exit modes	19mA @ 12VDC	$97.45 (http://accesstransmitters.com)
Northstar Controls	NP2-ESL [23]	2.4” x 2.3” x 0.8” Loops between 20 – 1500 μH Four selectable sensitivities, four selectable frequencies 12VDC	5mA nominal, 20mA relay energized	unknown
PEEK Traffic	625X [24]	3” x 1.5” x 3.5” Loops between 18 to 1800 μH Six selectable sensitivity levels 12-24 VDC Presence, and pulse on entry/exit modes (pulse length 100-150 mS)	60mA (est from 1.2 VA rating)	$167.00 (http://www.gateequipment.com)
Reno A&E	Model H1 [25]	2.5” x 2.75” x 0.85” Loops between 20 to 1000 μH Eight selectable sensitivity levels 12VDC Sensitivity adjusts to temperature Presence, and pulse on entry/exit modes Response time between 12ms (low sensitivity) and 160ms (high sensititivity)	21mA max	$130.00 (http://www.proteccontrols.com)

2.1.1.10.5.2 Temporary & Preformed Loops

Klein et al. note that a number of temporary loops are on the market, although state agencies might make their own. “Mat type” loops are usually smaller than saw-cut loops, 3 x 6 to 4 x 6 feet. These are durable rubber mats, nailed in place, and secured on the edges with heavy-duty adhesive tape. The lead-in is also protected with tape. Mat-type loops are for the most part reliable, except under heavy truck traffic, where “some of the mats did not last more than a few hours” [2].

LIS, Inc. [26] sells a product which is a five-layer “sandwich,” where loops of wire are secured between an “adhesive bituminous rubber compound coupled with a high-density polyethylene film” and, on top, a woven polypropylene mesh. The assembly also features adhesive on bottom, with a paper backing removed before installation. No nails are required. Unlike the “Mat Type” loops, LIS’s product is also hollow in the center. LIS customizes loops to order. On May 13th, 2010, the firm quoted the researchers a price of just $150 for an 18” x 24”, six turn loop.

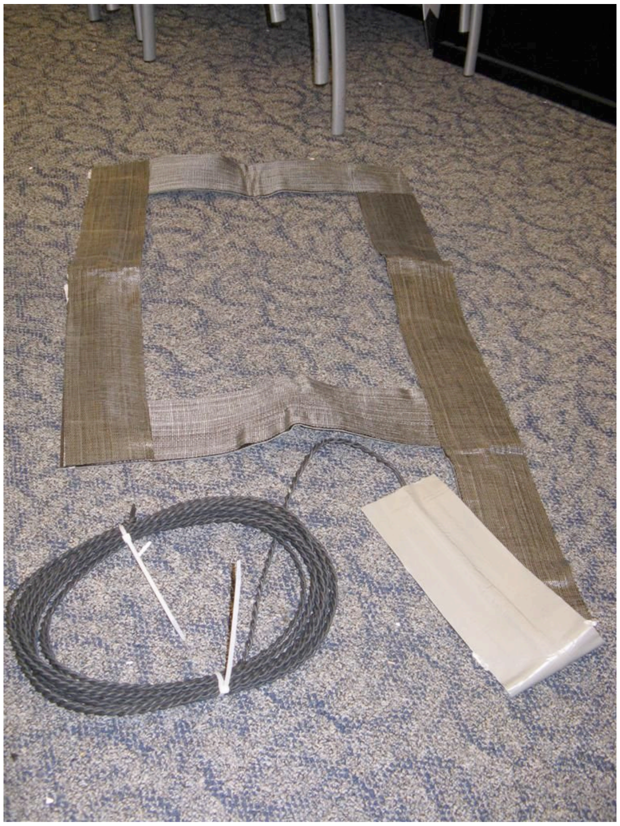


Figure 8 - 18" x 24" Preformed Loop Manufactured by LIS, Inc., With Peel-Off Adhesive and Twisted Lead-In Wires

Nevada DOT experimented with temporary loops, and came up with a similar setup. They eventually settled on a bitumen tape from Polyguard Products to protect the 4-turn, 4 x 6 foot loop. It proved to be extremely reliable, and was still functioning after a year. In fact, the loops eventually became embedded in the asphalt pavement.

While not explicitly designed for temporary uses, pre-formed loops are also available. These have the advantage of portability. They feature a protective casing that shields the wire (once installed in the saw-cut) from debris, moisture and deteriorating pavement. PVC pipe and fiber-reinforced hydraulic hose are common protective materials. One such product, cited in the *Handbook*, is the InstaLoop^{TM} sensor, with a flexible protective sleeve. InstaLoops can fit within the common ¼” sawcut groove, and feature adjustable size. However, this product appears to be discontinued. Never-Fail Systems [27] currently sells a similar product (with fixed size), and there are others on the market.

2.1.1.10.5.3 Vehicle Speed

The most straightforward way to determine vehicle speed using loops is to set up two loops, spaced a known distance apart, and determine the time between detections. The *Handbook* warns that highly sensitive loop systems can exhibit longer response times. This, in turn, can introduce significant error in speed calculation.

An emerging body of research is focused on determining vehicle speed from the detection signature from one loop. Doing so requires a “G factor” which represents the average length of passing vehicles, which is comparing to the inductive signature [28]. Tok et al. (2009) [28] attacked this problem using neural networks. The researchers obtained the actual vehicle speeds using dual loops. Then, based on signatures from one loop, they assigned vehicles into five clusters based on the signature lengths and slew rates (slope of rise). A regression model was run on each cluster, designed to predict actual speed using these two factors. The neural network was trained with these same factors to assign single loop signatures to a cluster. The network also uses the cluster’s regression model to predict actual speed. This approach was able to predict actual speeds within a couple of percent, improving over previous efforts.

2.1.1.10.5.4 Vehicle Classification & Reidentification

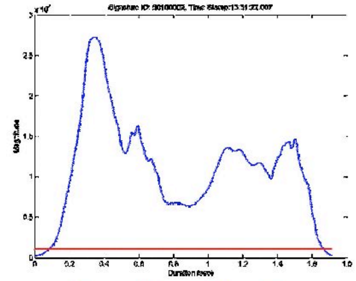
Inductive loops can also be used to “identify” a vehicle based on its inductive signature. Blokpel (2009) finds ILD to be a desirable alternative to video for reidentification due to the technology’s relatively low cost [29]. Reidentification is typically achieved with double loops, to factor in vehicle length and speed. This method unfortunately can have high error rate because of the variability of speed estimates. Blokpel’s research tackles the problem of Reidentification using just one loop.

In the first stage, the Blokpel defines a matrix filled with the $u_{i,j}$, the differences between *i* entry and *j* exit signatures. An algorithm scans this matrix by column and finds the element with the smallest difference. In cases where an entry signature has more than one exit signature match (a false positive), the algorithm cross-references against rows to find the next most-likely match. In cases where input and output loops are different sizes, a finite impulse response (FIR) filter is employed to equate entry and exit signatures. The scheme was tested against 70 vehicles on a Dutch motorway. Blokpoel claims nearly 100% accuracy when matching between identical loop sizes, and 88% between different loops. Interestingly, the most effective loop size was a meter square.

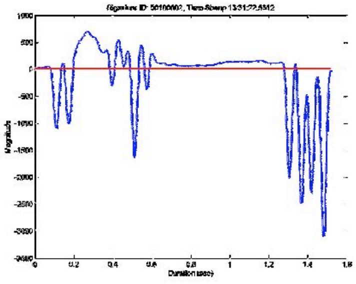
Cetin and Nichols [30] tackled the same problem in 2009. Although they use weight-in-motion (WIM) sensor data, they state their method can be applied to other detection technologies. Their method is similar to Blokpoel’s, although they achieved the best results when employing a Bayesian method employing real-world training data. These researchers achieved 99% accuracy on a sample of 947 vehicles.

2.1.1.10.5.4.1 Vehicle Reidentification Using the Blade^{TM} Inductive Sensor

Tok and Ritchie [31] tackled a similar problem, the classification of commercial vehicles, using a new inductive loop technology. The Blade^{TM}, developed by Inductive Signature Technologies in Knoxville TN, features a 9cm-wide loop of wire. The loop is surface mounted to the lane between two layers of bituthane asphalt tape, and spans the entire lane. When coupled with an “advanced ILD card,” the system captures data at 1200 samples per second and produces higher resolution signatures than standard inductive loops.



Round Loop Signature



Blade ^{TM} Signature

Figure 9 - Blade^{TM} System Installed at Truck Weigh Station, and the System's High-Resolution Signature Compared to Standard ILD [31]

Tok and Ritchie installed two Blades closely together, traversing the entry lane of a weigh station at a twenty degree angle. During the five hours of data capture, 1029 commercial vehicles passed over the assembly. The researchers isolated two dozen features of each vehicle's drive and trailer assembly in each signature. The model, which was first calibrated on 720 vehicles, achieved 99% accuracy in matching axle configuration, 74% with drive unit body classification, 84% with trailer unit body, and 81% when combining all three together to describe a vehicle. The Blade, due to the relative ease of its installation, is a compelling technology which merits further study.

2.2 Intelligent Transportation Systems (ITS) & Distributed Simulation

The NSF *Embedded Distributed Simulation* project features real-time data streamed from vehicle detectors and in-vehicle simulators. The literature reflects a wide variety of ITS applications with similar approaches.

Li et al., 2008, [32] proposed a system featuring Vehicle-Infrastructure Integration (VII), whereby roads and vehicles continuously communicate with each other on construction status, congestion, incidents, and so forth. The communication standard may include cellular, Bluetooth®, or other means; such vehicles are designated as "probes." Travel time estimates from probe vehicles can vary greatly, depending on the probe penetration rate. Li also cites the 25% absolute relative error of Inductive Loop Detectors (ILD), and the general inadequacy of point detectors in forecasting travel time.

Li's approach is to fuse these two data sources together to increase the accuracy of predicted travel time. The author configures a six-intersection VISSIM® model of El-Camino Real near Palo Alto, CA. Like in the *Embedded Distributed Simulation* Project, probe vehicles are instrumented with on-board equipment [33]. Once a simulated probe vehicle comes within 400 feet of roadside equipment (or RSE, which are intersections, interchanges and other locations with instrumentation), the onboard computer ‘dumps’ its data. Records from ILD and traffic signals have a resolution of 1-5 seconds and are continuously updated. Using a neural network to “fuse” the two data sources, Li’s model tracked ground truth better than point data or probes alone. The critical measure of effectiveness was travel time.

In a similar study, Park et al., 2007, [34] developed a larger, nine-node VII network. This scheme, Persistent Travel Cookies (PTC), is a “distributed on-line database system for transportation management using cooperating roadside and in-vehicle communication devices.” All vehicles are instrumented with onboard communication devices which talk to roadside beacons. Consequently, each vehicle maintains logs of past trips, signal states at visited nodes, and so forth. With this aggregation of trips, the future travel of vehicles is inferred. An advantage of the PTC system is that vehicles store their trip data, not a Traffic Management Center, and that computations are distributed across beacons and even vehicles. By these means, the signal plan of one node is constantly optimized. The authors simulated vehicles in the network using historical traffic demands for 14 days. For each hour over the 14 days, 5000 PTC-equipped vehicles were generated. Each vehicle was given a randomly selected origin, a randomly selected “likely” destination, and a randomly selected “alternate” destination. The simulation sends vehicles to their “likely” destination 80% of the time. Over an hour-long simulation, the average trip time fell from 272.6 seconds using fixed signal control, to 262.5 seconds under actuated control, and then 256.6 seconds using PTC.

These examples alone show the potential of vehicle detection and simulation in optimizing transportation networks. The literature reflects instances where actual vehicles and detection come into play. In 2009, El-Faouzi and Lawrence Klein [35] took trip data from a 7-km stretch of French motorway. The first set, from 2003, spanned seven days while the second set, from 2004, was five days. The data included ILD detections and all toll records, including electronic toll collection (ETC), cash, credit card, and so forth. The authors use a statistical "fusion" strategy to merge individual data sources to predict travel time. This strategy, which uses Dempster-Schafer inference, is compared to ground truth (taken as the entirety of all toll data). The researchers' method generally outperformed the individual data sources, except in cases where ETC penetration rates were high.

This thesis is focused however on an individual ITS application: the temporary deployment of a non-intrusive detector. In the literature there are many similar applications showing the potential of smaller-scale deployments. Persaud, Oloufa et al, 2010, [36] installed a dynamic speed monitoring system, over two summer months, at a rural, trumpet-style interchange in Florida. The loop ramp, signed for 35mph advisory, is partially 'hidden' by an adjacent bridge. That, along with speeding, contributes to a high incidence of vehicle overturns. The data collection spanned two summer months in 2007, with a "before" and "after" period. The authors installed a temporary, solar powered Dynamic Speed Monitoring (DSM) system. This radar-based system includes a sign, mounted some 250 feet before the start of the ramp, informing drivers of their speed. Both the "before" and "after" datasets were adjusted to omit rainy periods, which in Florida can be intense and sporadic. The authors observed speed limit compliance increasing from 56% to 78%. The system was less effective at night and over weekends, and most effective against high speeds.

Persaud et al [36] note however that the loop's radius indicate a 25mph advisory limit as opposed to the posted 35. In a personal email communication [37], Persaud explained that they did mention this to Florida DOT (FDOT). However the regulatory "level of effort" to change the sign was beyond the scope of their research. The advisory remained at 35mph.

In a similar application, Harb and Radwan et al (2009 & 2010) [38, 39] used Remote Traffic Microwave Sensor (RTMS) detection to optimize traffic flows along I-95 construction zones in Florida. The sensors were installed at merge points and coupled with Portable Changeable Message Signs (PCMs). In the first study, two lanes merged to one, while three lanes dropped to two in the follow-up. The PCMs would advise the driver on when to merge. This "Motorist Awareness System" (MAS) was in each case configured to advise drivers to merge earlier, or later (closer to the pinch point). In both studies, the MAS increased throughput. The earlier study only showed statistically significant improvement with early merge, while the second study indicated that late merge outperforms early under heavy traffic.

Notably, the authors of these studies indicated difficulty with the data collection. In both cases, weather and contractor logistics issues postponed or interrupted data collection. Further, the MAS requires detection equipment housed in a moderately-sized, weather-resistant trailer. This "traffic detection station" is wirelessly linked to a central computer base station. With the narrow shoulders of construction zones, the authors reported that installation of the equipment was "almost impossible."

2.3 Conclusions

This literature review reveals the depth and breadth of detection technologies. ILD tends to be a cheaper and more mature detection technology than the others. For example, many of the non-intrusive technologies must be mounted on a pole well above the traveled way, rendering the system non-portable. The other technologies, while likely exceeding the accuracy of ILD, are more expensive. The literature makes clear that ILD has the potential to form a simple, cheap, reliable, and highly portable system with zero installation costs. For the aims of this research (see 3.1, *Methodology*), these ILD characteristics are extremely desirable.

What is also clear from this literature review is the uniqueness of a portable, wireless ILD detector. While ILD is a mature technology, no wireless applications were found in the literature. Further, applications using small and portable inductive loops were not apparent. Therefore, the researchers expect the project to be fruitful, and one with many potential applications.

Chapter 3 Equipment Testing and Results

This chapter describes the evolution of the portable loop detection system and tests on early versions. Tests performed with the mature, robust version of the system are next described in detail.

3.1 Methodology

3.1.1 Goals

Early in the development of this system, several core goals were defined:

1. Portability and quick deployment
2. Low cost
3. Wireless capability

These conditions support the larger goals of the NSF Simulation project. These detectors needed to be installed anywhere in a short time as dictated by current project needs. Wireless capability allows data to be streamed in real time, to research servers for further processing and distributed simulation modeling. Cost is a broad and constant concern in any transportation system.

Two series of tests were performed. The first series consisted of "trial and error" whereby a system design was achieved through an iterative process. During these early tests little formal data was collected, with assessment of the performance based on observation. The goal of those tests was to achieve quick turn around time in system redesign. Those tests were followed by a second series of tests in which formal analysis was conducted of the system performance under a series of fine-tuned configurations.

3.1.2 Evolution

3.1.2.1 Communications Link

Early on, the researchers decided to use technology from Phase IV of the *Commute Atlanta* Study. Commute Atlanta, funded by FHWA, Georgia Department of Transportation (GDOT), and Georgia Tech, monitored the travel behavior of Atlanta-area drivers.

Phase IV monitored buses and freight, including trucks and trains. Here, an off-the-shelf monitoring product from V-Santana® was employed. Their RSN1000 Fleet Management Device is a brick-sized 'black box' featuring a Global System for Mobile Communications (GSM) modem, and Global Positioning System (GPS) capability. While the RSN1000 is designed to run off standard automotive 12v, Phase IV tethers the unit to a 33 amp-hour (AH) 12v 'gel' battery, slightly smaller than a car battery. Both the RSN and battery have separate, portable climate-resistant cases.

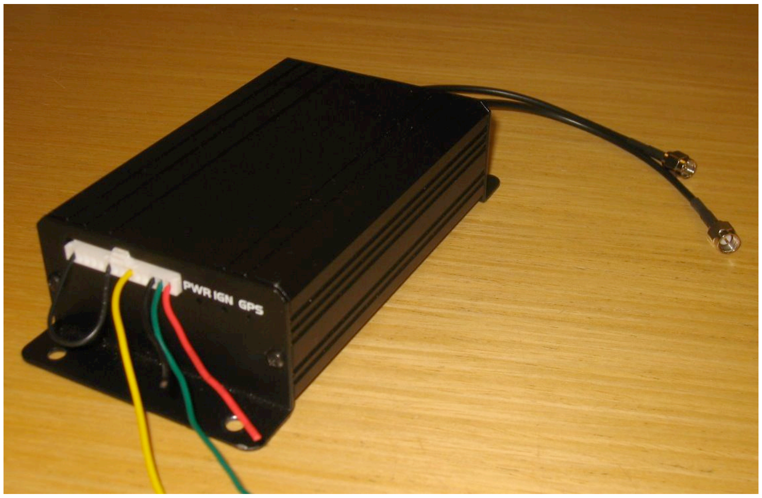


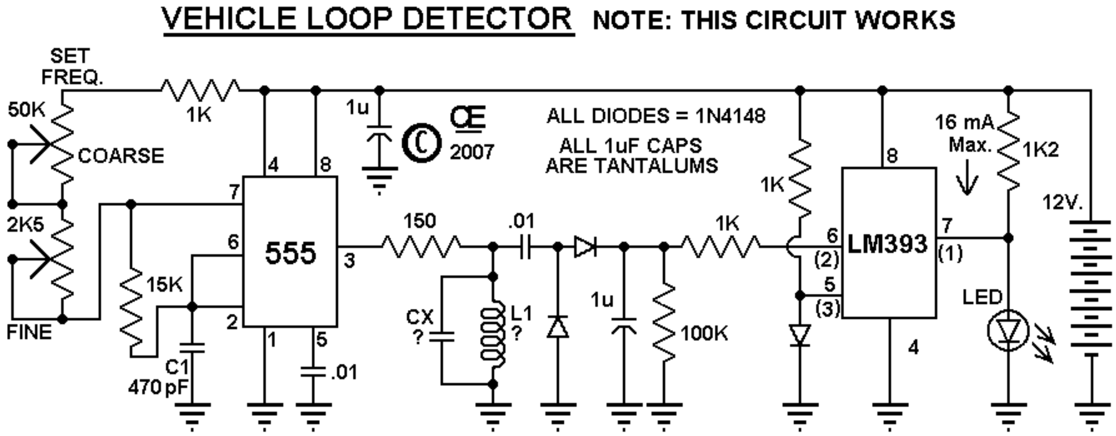
Figure 10 - RSN1000, Showing Leads For GSM And GPS Antennas

The RSN1000, which retailed for approximately $300 but is no longer available, is an extremely versatile device. The unit allows customization of two outputs and three inputs. Therefore, interfacing the RSN1000 to an inductive loop detector is possible. Further, the RSN can stream detections, over GSM, in near real-time to servers at the Civil Engineering Department. From that point, detections could be then streamed to the web for public viewing.

3.1.2.2 Detector

3.1.2.2.1 Hobby Circuit

In the interest of cost, simple (and mostly analog) circuits were first considered. Through Internet searches, the researchers found a web site containing an extensive selection of easily-assembled analog circuits including a vehicle detector [40]. All the parts for the detector circuit could be purchased for about ten dollars. The parts include resistors, capacitors, diodes, a 555 timer chip, a LM393 comparator chip, and potentiometers for calibration.



VEHICLE LOOP DETECTOR NOTE: THIS CIRCUIT WORKS

A TYPICAL COIL FOR L1 MIGHT BE 6 FEET IN DIAMETER, WITH 4 TURNS OF WIRE.
A TYPICAL CAPACITOR FOR THIS COIL WILL POSSIBLY BE A .47 uF, MYLAR OR DISK TYPE.
OR IT CAN BE REDUCED TO ACCOMIDATE SMALLER COILS.
C1 CAN ALSO BE CHANGED IN VALUE, IF NEEDED.
ADJUST "FREQ. SET" SO THE LED JUST LIGHTS UP, WHEN A VEHICLE IS OVER THE COIL.
AND CHECK THAT IT GOES OFF WHEN VEHICLE IS REMOVED. OR FINE TUNE.
*** NUMBERS IN BRACKETS ARE NOT USED ON PCB.

Figure 11 - Simple Detector Circuit [40]

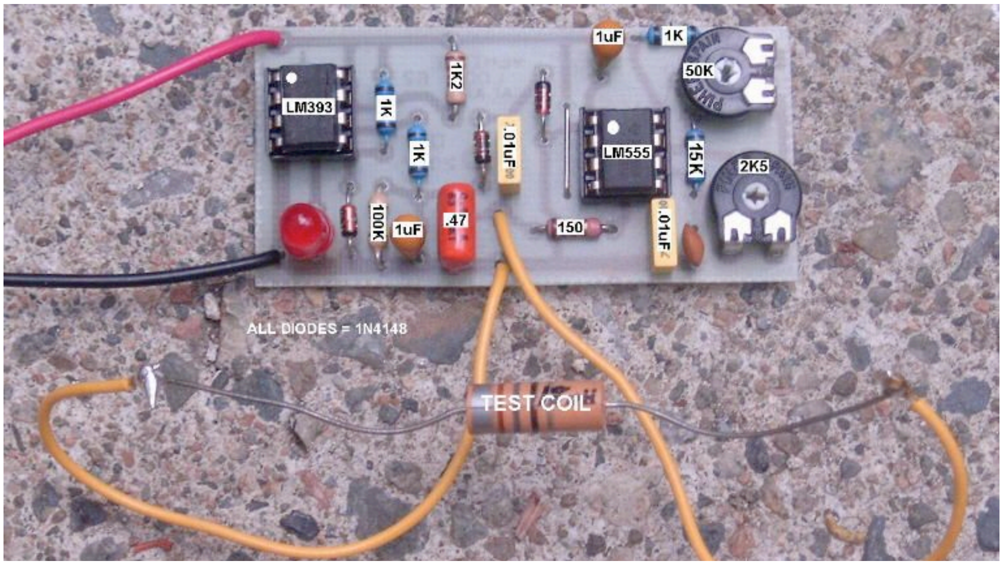


Figure 12 - Simple Detector Circuit on Provided PCB [40]

The researchers ordered parts for four detectors, including credit-card sized PCBs to mount the parts. It was found that the unit consumes about 100mA, in addition to the 75-150 mA drawn by the RSN1000. After field testing, the researchers decided that this circuit was not sufficient to meet the project needs. It was susceptible to climate drift and performed poorly with high-bed vehicles. More details on the testing of this circuit are covered below under “Experiments.”

3.1.2.2.2 Diablo Controls

Due to the limitations of the first circuit, the researchers investigated mature detector circuits using digital signal processing technology. Several products are listed in the literature review (see “Detector Manufacturers and Products”). Two detectors from Diablo Controls Inc., headquartered near Chicago Illinois, were chosen for further testing.

The first, the DSP-7LP detector, retails for about $80. This unit is small (the size of a credit card, and an inch thick) and is intended for solar powered parking gate applications. The red LED indicates a detection; further, the green LED indicates a short or open circuit in the loop depending on blink rate. This unit consumed only a few milliamps in rest state when tested with a digital multimeter.

The second, the DSP-15, is designed for “all parking, drive-through and access control applications.” This unit improves on the 7LP by introducing 10 sensitivity levels. It also features a “sensitivity boost” mode which increases sensitivity during a vehicle detection (also known as a “call.”) Additional functionality supports call delay, call extension, and entry/exit pulses [19]. This unit, when tested in-house, consumed about 57 mA in rest state, and 60 mA during a call.

Both units performed substantially better than the first circuit (see below under “Experiments.”) DSP-15, in fact, performed very well when coupled with small loops.

As such, the researchers settled upon this circuit for the final field tests described in this thesis.

The RSN1000 consumes, on average, 125mA of current. When coupled with the DSP-15, this system would function for about a week when coupled with the 33AH gel battery.

Figure 13 – Diablo Controls DSP-7LP Vehicle Detector [18]

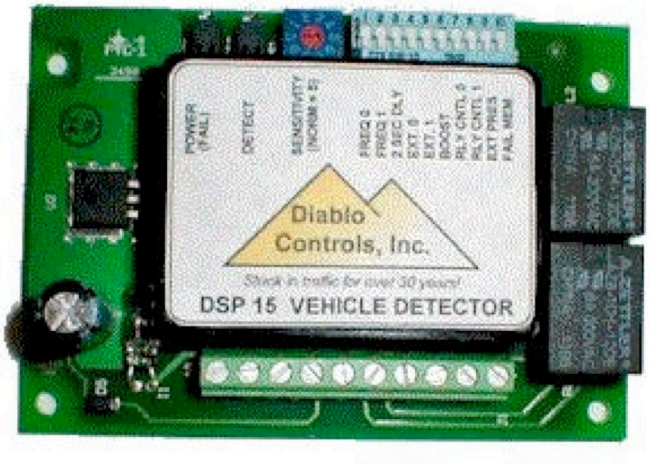


Figure 14 - Diablo Controls DSP-15 Vehicle Detector [19]

3.1.2.3 Loop and Housing

A unique challenge of this project is securing the loop onto the pavement in a non invasive, temporary, and rigid manner which maintains the loop geometry. During the early “trial and error” tests, the researchers employed black foam-rubber “shop mats” available at hardware and auto parts stores. The material, about half an inch thick, is black and easy to cut. Tests using this material employed a two-layer design. The first layer, which rests on the pavement, has a groove cut out to house the loop (see Figure 16). The second layer rests atop the first, protecting the loop. Amazing Goop™, a very strong rubber cement, glues the two layers together. Polyken™ tape, an industrial-strength duct tape, secures the assembly to pavement.

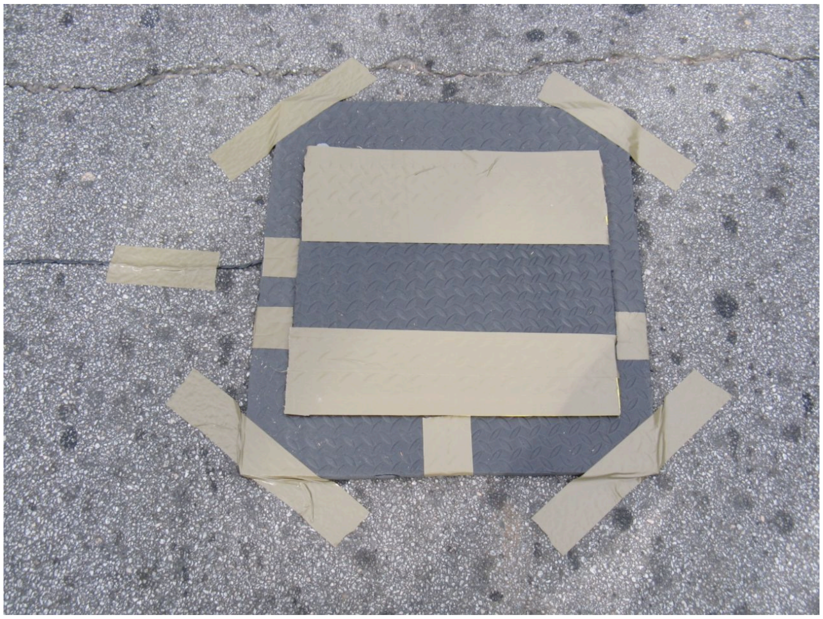


Figure 15 - First Generation Shop-Mat Loop Pad (12” x 17” loop)

Figure 16 - First Generation Shop-Mat Loop Pad, Bottom Side Showing 17" X 34" Loop

Figure 17 – First Generation Loop Pad (17" X 34" Loop) Affixed to Eastbound Ferst Drive on Georgia Tech Campus

The most recent experiments refined this approach by using a heavier mat of recycled tire, available from McMaster-Carr ™ Supply Company. These sheets, 5/8 inches thick, are not as prone to shifting on the pavement as the foam rubber. Therefore, the overall footprint is substantially smaller.

The protective top layer is a thinner layer of foam rubber similar to shop-mat. Between the two is a thin, flexible sheet of vinyl normally used as protective liner for bathtub installation. The recycled tire mat, however, is very dense and must be bored out with a wood router to house the loop.

Figure 18 – Second Generation Loop Assembly Made of Recycled Tire, and Close-up of Electrical Interconnect

Figure 19 - Recycled Tire Loop Assembly, Underside

Lead-in wires are hand-spun twisted pairs, wrapped in electrical tape. For the loops, the researchers used rigid rectangular objects, most notably plastic file-folder crates, to secure the wires before wrapping in electrical tape. The same crates delineate the ring cut from the foam rubber or recycled tire. Nearly all loops employ 14-gauge wire, the same size commonly used by state transportation departments. The exceptions were a few unusually small loops tested in the later stages of this research.

3.2 Experiments

3.2.1 First Field Test – Hobby Circuit

3.2.1.1 Location and Configuration

Researchers first tested the system on the Georgia Tech campus on February 13, 2009 at approximately 2pm. This half-hour deployment, along eastbound Ferst Drive just before State Street, was largely qualitative in the sense that no hard data (including vehicle count and successful detections) were recorded. The system featured the hobbyist detector circuit, and a "first generation" foam rubber mat. The loop was 12 x 17 inches, with three turns in the loop.

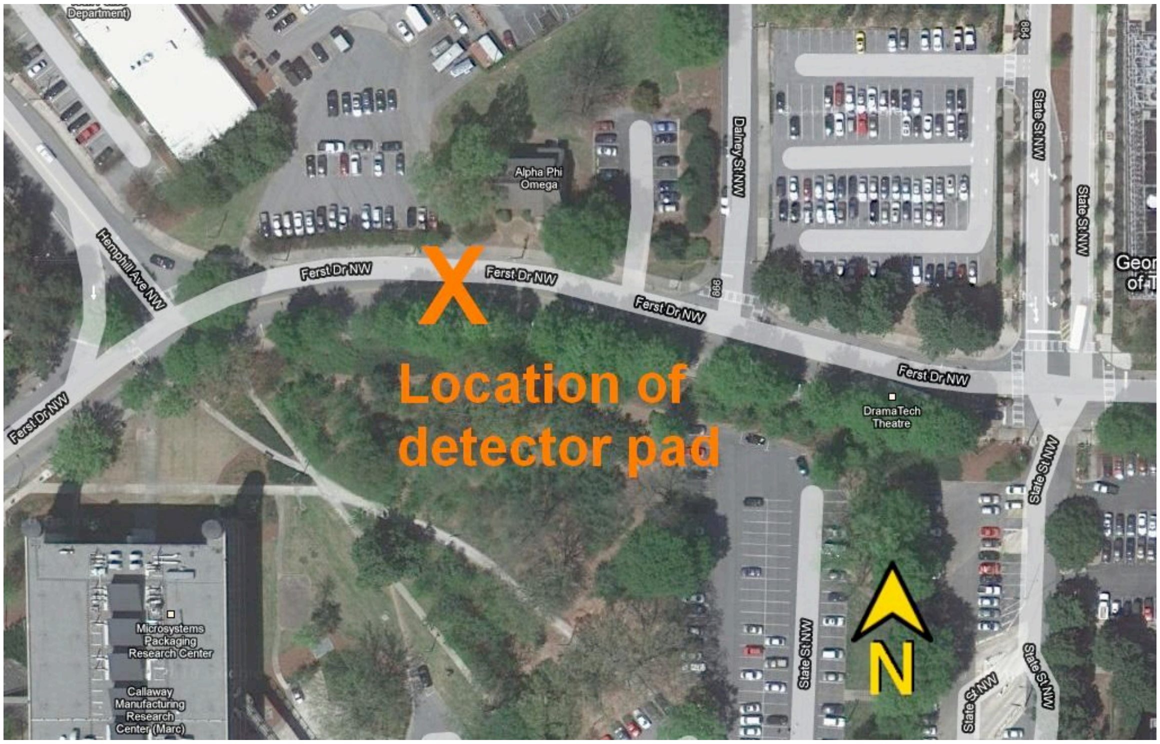


Figure 20 - Location of February 2009, May 2009 & Summer 2010 Tests Along Eastbound Ferst Drive (Google Maps)

3.2.1.2 Results

The portable detector appeared to detect about 2/3 of passenger vehicles. Further, it streamed detections to the web. However, the detector missed a substantial number of buses, trolleys and high-bed trucks. Some vehicles avoided the pad, which was small and multi-colored. Further, the system was highly susceptible to frequency "drift." The researchers frequently re-tuned the detector to operate accurately without remaining stuck permanently at a call. Temperature variations may have contributed to this problem. The researchers thus decided to try larger loops with more turns.

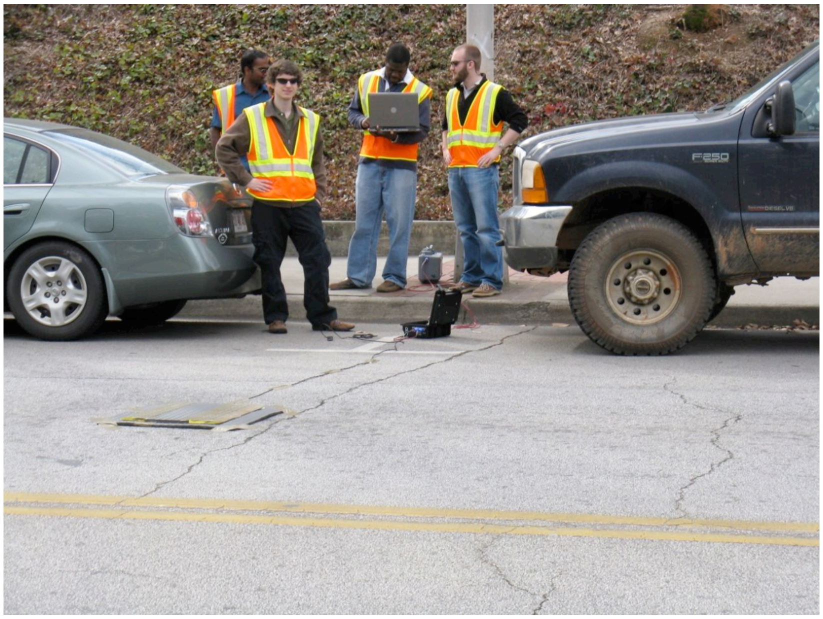


Figure 21 – First Field Test, 2/13/09

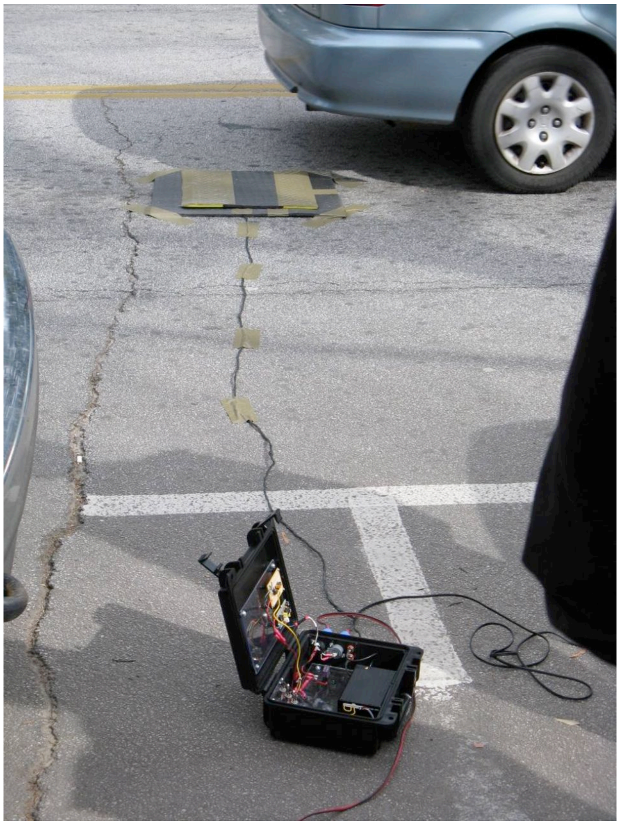


Figure 22 – First Field Test, 2/13/09, Showing RSN1000 and Detector in Enclosure

3.2.2 Second Field Test – Hobby Circuit

3.2.2.1 Pre-Test

An informal "cabinet test" was performed to predict the efficacy of the larger loops. By placing a ruler against a steel cabinet in the researchers' laboratory at Georgia Tech, the detection distance between the pad and cabinet is measured. While not a simulation of a field test, the cabinet test is a useful proxy because, like a car, the cabinet is a similarly large metal object.

The small 3-turn loop from the first field test, over 16 detections against the cabinet, was detected at a mean 12.8" inches with the hobby circuit. Using a 17" x 34" loop with four turns increased this mean distance, over six detections, by approximately one inch.

3.2.2.2 Location and Configuration

The 17” x 34” loop with four turns, and a second 17” x 34” loop with eight turns, were tested on the Georgia Tech Campus starting at 10:00am on April 24, 2009. Testing lasted less than an hour. As with the first field test, no data were recorded.

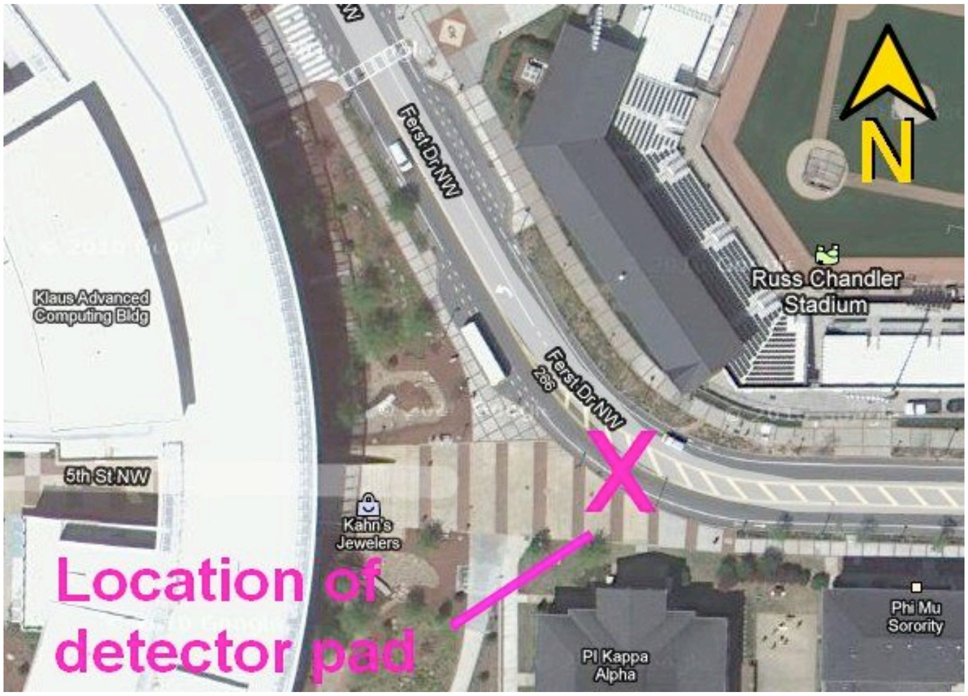


Figure 23 - Location Of Second Field Test, on Eastbound Ferst Drive Near the Klaus Computing Building (April 2009) (Google Maps)

3.2.2.3 Results

The performance with heavy vehicles was still poor, and frequency drift remained a problem. Overall, about a third of vehicles continued to be missed, resulting in a clear need for a significant system redesign.

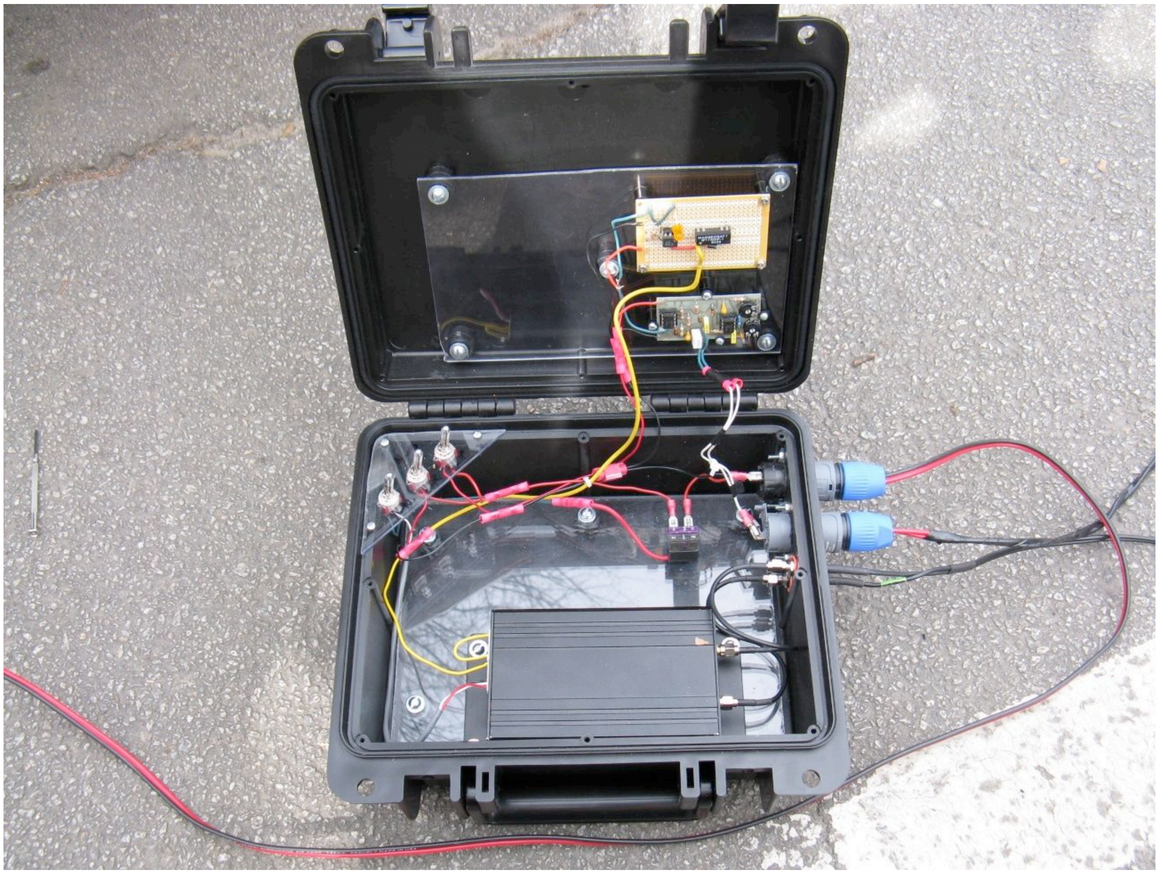


Figure 24 - RSN 1000 (Bottom) in Enclosure With Hobbyist Loop Detector Circuit (Bottom Right Corner on Lid)

3.2.3 Third Field Test – Diablo DSP-7LP

The researchers selected the Diablo Controls™ DSP 7LP detector as a potential solution. In preparation for the third field test, this detector was bolted into the enclosure next to the original hobby circuit.

3.2.4 Location and Configuration

The system with DSP-7LP was field tested on May 15th 2009, at 10:30AM. The location of the test was the same as the previous February: eastbound Ferst Drive between Hemphill Avenue and State Street. Researchers deployed the 8-turn, 17” x 34” loop. Testing lasted less than an hour, and traffic moved freely.

3.2.4.1 Results

The DSP-7LP proved far more accurate than the hobbyist circuit. The system detected all trucks and buses. Researchers noted a small detector output lag of few tenths of a second compared against actual vehicle presence. The system tended to miss fast-moving vehicles (above 40mph, per the researchers’ qualitative judgment). All told, the detector captured over 87% of all vehicles passing over or grazing the pad. This positive result would later correlate with greater detection distance during the cabinet test.

Table 2 - Field Observations From Third Field Test

	Cars	Large SUVs & vans	Buses (**)	Trucks*	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	83	59	5	1	5	1	0	**154**
Not detected	14	4	0	0	0	1	1	**20**
Detected, grazing pad	5	6	0	0	0	0	0	**11**
Not detected, grazing pad	2	2	0	0	0	0	0	**4**
Success rate (all detections/total touching pad)	84.6%	91.5%	100.0%	100.0%	100.0%	50.0%	0.0%	**87.3%**

** "Trucks" are large, heavy duty trucks up to and including 18-wheelers. "Large SUVs & Vans" include large pickup trucks such as the Ford F-150. Smaller pickups are "Cars."*

(**) One bus was double-counted.

3.2.5 Streamlining & Fourth Field Test – DSP-7LP

Building upon this success, the next goal was to streamline the system. First, the recycled rubber mat from McMaster-Carr was selected for the new loop housing. As mentioned before, this material has the advantage of weight, durability and thus, smaller footprint. The mat for this loop was 5/8" thick.

3.2.5.1 Pre-Test

The researchers set about to shrink the loop, and used the "Cabinet Test" as a guide. The test was performed with the DSP-7LP on January 25th and 27th, 2010. The large 8-turn loop (from the third field) test averaged an impressive 20.5" inches clearance from the cabinet over ten runs. It was found that a smaller, 12" x 25" with six turns nearly equaled this performance at 19.98". Therefore, this size was chosen for the fourth field test.

Table 3 - Cabinet Test Of Configurations Used For Third And Fourth Field Tests

large loop, 8 turns (17"x34") Distance in inches	medium loop, 6 turns (narrow rectangle 12"x25") Distance in inches
21.00	19.50
19.00	20.50
20.75	20.75
21.50	19.50
21.50	18.00
20.25	20.00
21.75	18.00
20.25	20.75
18.75	21.50
20.50	21.25
20.53	***19.98***

Respective maximum detection distance from detector pad to cabinet

3.2.5.2 Location and Configuration

The fourth test occurred on February 23rd, 2010 at approximately 4pm. The location was also on Ferst Drive, but westbound between State and Atlantic Streets. Researchers deployed the 12" x 25" loop in the new rubber pad. Data collection lasted approximately half an hour.

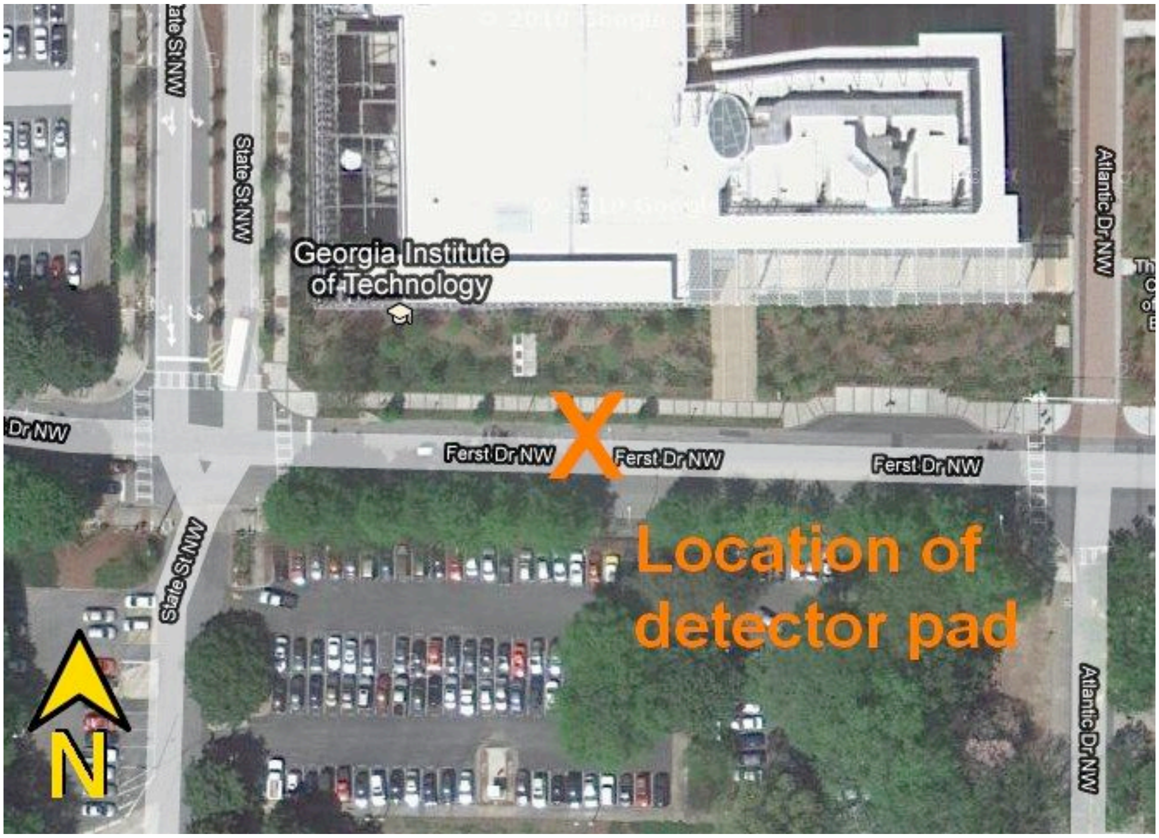


Figure 25 - Location of Fourth Field Test, on Westbound Ferst Drive, February 23, 2010 (Google Maps)

3.2.5.3 Results

The system again performed well, detecting over 93% of the 145 vehicles passing over or grazing the pad. This test however is not a direct analogue to the previous test. This test was conducted at a different location, and due to the time of day there was higher traffic flow with several standing queues. Further, the researchers used somewhat different methodology for classifying trucks.

Table 4 – Field Observations From Fourth Field Test

	Cars	Large SUVs & vans	Buses	Trucks*	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	47	26	5	9	5	0	0	**92**
Not detected	1	1	0	3	0	1	0	**6**
Detected, grazing pad	31	8	0	3	0	1	0	**43**
Not detected, grazing pad	1	2	0	1	0	0	0	**4**
Success rate (all detections/total touching pad)	97.5%	91.9%	100.0%	75.0%	100.0%	50.0%	0.0%	**93.1%**

* *Here, the vehicle classification methodology is slightly different. "Trucks" include large pickups.*

Figure 26 - Philip Blaiklock and the Detector System (Third Field Test)

Figure 27 - Loop Assembly Detecting an 18-Wheeler (Third Field Test)

Figure 28 - Vehicle Detection During Fourth Test

Figure 29 - System During Fourth Field Test. Battery Enclosure is on Left

3.2.6 Fifth Field Test – DSP-7LP & DSP-15

To further refine the system, the researchers began testing with the Diablo Controls DSP-15. The researchers deployed both this detector and the DSP-7LP for a direct comparison.

3.2.6.1 Pre-Test

Ahead of the fifth field test, the DSP-15 was tested in lab, with the 6-turn loop, against the cabinet. During the test (on May 12th, 2010) four sensitivity levels were tested: 0, 5, 9, and 9 with sensitivity boost. These settings respectively averaged, over ten runs each, 5.6", 19.0", 27.0" and 29.5". This highest sensitivity level outperformed the DSP-7LP by a large margin in lab, and was therefore selected for this field test.

Table 5 - Cabinet Test Results of the DSP15 Detector at Various Sensitivity Levels

6-turn loop, narrow rectangle 12"x25" Distance in inches			
Sensitivity Level 0	Sensitivity Level 5	Sensitivity Level 9	Sensitivity Level 9 plus "sensitivity boost"
7.25	16.25	19.25	34.50
4.25	16.00	25.25	33.00
5.00	17.50	28.00	33.00
5.75	20.25	26.25	29.00
4.75	20.50	26.50	26.00
5.75	20.25	27.00	29.00
5.50	19.50	27.00	24.75
6.00	21.25	27.75	22.75
5.50	18.75	31.50	32.00
5.75	19.50	31.00	31.00
5.55	***18.98***	***26.95***	***29.50***

Respective maximum detection distance from detector pad to cabinet

3.2.6.2 Location and Configuration

The researchers started testing the DSP-7LP at 11:30am on May 14th 2010, and collected data through 1:00pm. The researchers installed the pad on eastbound Ferst Drive on the

Georgia Tech Campus, between Hemphill Avenue and State Street (the same location as the first field test). The loop had six turns, at 12x25 inches. At 1:00, the DSP-15 was swapped into the enclosure, and set to sensitivity level 9 with "sensitivity boost." Testing resumed at 1:10 for another ninety minutes. Traffic moved freely during both tests.

3.2.6.3 Results

During the first ninety minutes, 337 vehicles were observed passing over or grazing the loop. The DSP-7LP detected approximately 80% of these vehicles. During observation, researchers made a qualitative judgment of vehicle speed. A few dozen "fast" moving vehicles (at least 40mph) passed over or grazed the pad. The system failed to detect about half of such "fast" vehicles.

Table 6 - Field Observations from Fifth Field Test, with DSP-7LP Detector

	Cars	Large SUVs & vans	Buses	Trucks*	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	143	82	11	5	8	3	0	**252**
Not detected	25	17	1	3	0	0	0	**46**
Detected, grazing pad	13	3	0	1	0	1	1	**19**
Not detected, grazing pad	9	9	0	0	0	2	0	**20**
Success rate (all detections/total touching pad)	82.1%	76.6%	91.7%	66.7%	100.0%	66.7%	100.0%	**80.4%**

** "Trucks" are large, heavy duty trucks up to and including 18-wheelers. "Large SUVs & Vans" include large pickup trucks such as the Ford F-150. Smaller pickups are "Cars."*

Over the second ninety minutes, 365 vehicles passed over the detector pad. This configuration performed exceptionally well. 100% of all 365 vehicles were detected, including ones grazing the loop. Even though the Diablo DSP-15 is designed for parking gates, this detector successfully caught all “fast” vehicles. Further, calls precisely tracked vehicle presence, with no if any discernible delay. However, a few buses, trucks and trolleys were double-counted due to high clearance.

Table 7 - Field Observations From Fifth Field Test, with DSP-15 Detector

	Cars	Large SUVs & vans (**)	Buses (**)	Trucks* (**)	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	192	101	12	10	9	8	0	**332**
Not detected	0	0	0	0	0	0	0	**0**
Detected, grazing pad	26	6	0	0	0	1	0	**33**
Not detected, grazing pad	0	0	0	0	0	0	0	**0**
Success rate (all detections/total touching pad)	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	0.0%	**100.0%**

* *"Trucks" are large, heavy duty trucks up to and including 18-wheelers. “Large SUVs & Vans” include large pickup trucks such as the Ford F-150. Smaller pickups are “Cars.”*

(**) One SUV (with trailer), one bus and two trucks were double-counted.

Figure 30 - Fifth Field Test, 5/14/2010, Along Eastbound Ferst Drive

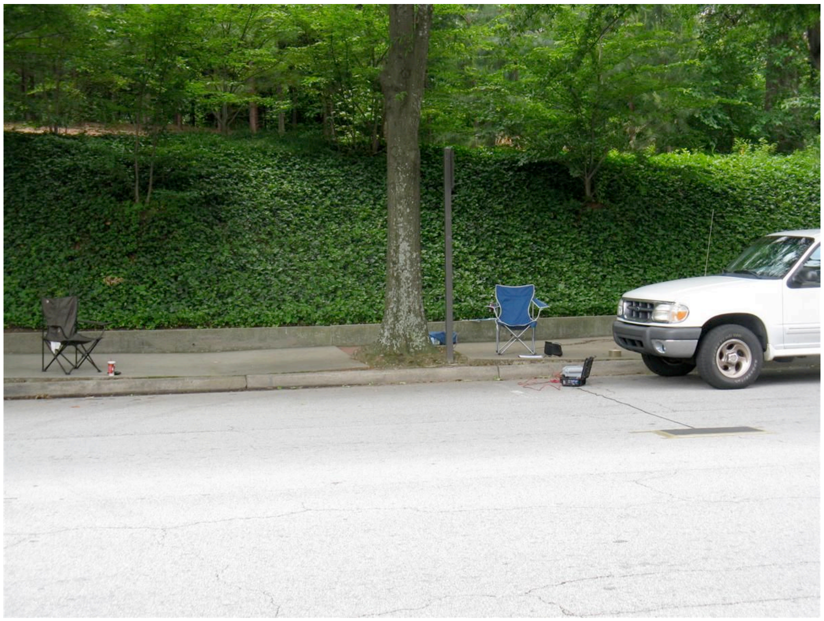


Figure 31 - Wide-Angle View of Test Site (Fifth Field Test) From Other Side of Ferst Drive. Portable Chairs Were Set Up for the Observers

Figure 32 - Detector Pad Affixed to Pavement (Fifth Field Test)

Figure 33 - DSP-7LP Detecting a Campus Bus (Fifth Field Test)

Figure 34 - DSP-15 Detecting A Georgia Tech "Golf Cart" (Fifth Field Test)

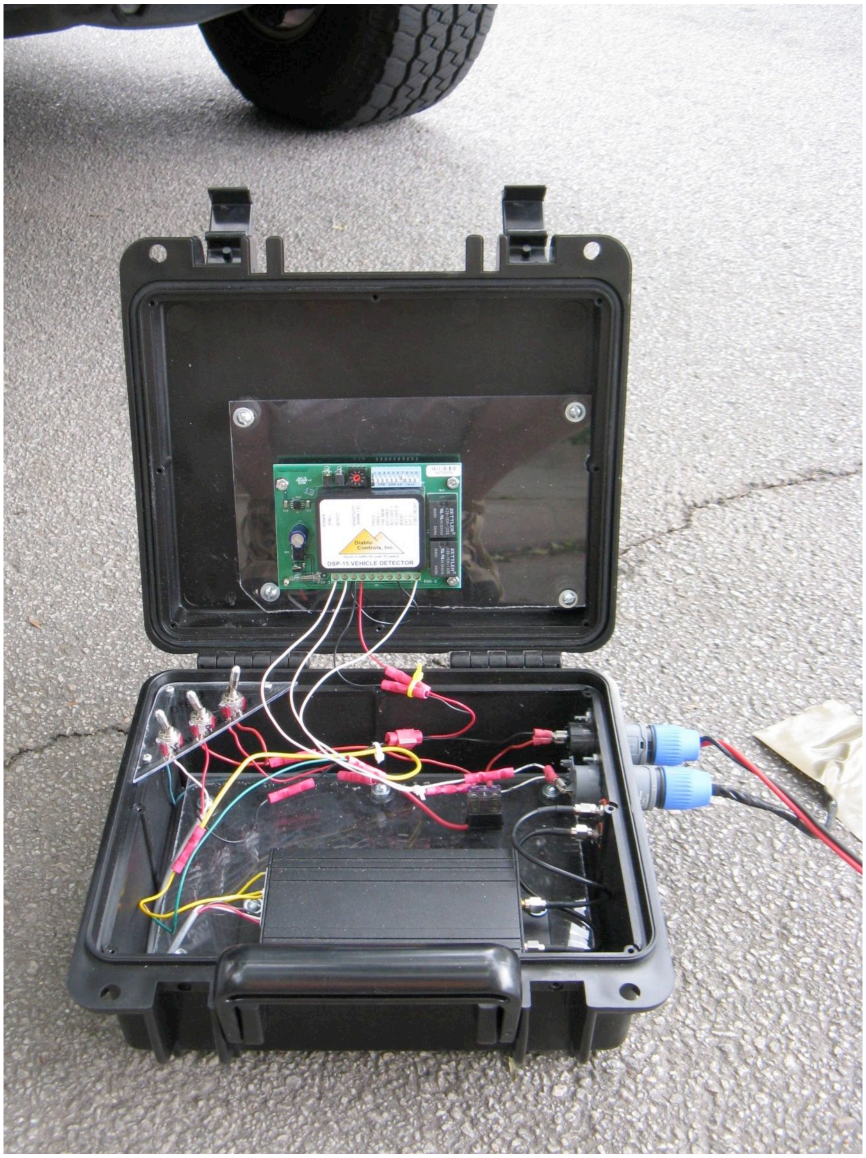


Figure 35 - Electronics Enclosure With DSP-15 Installed (Fifth Field Test)

3.2.7 Sixth Field – DSP-15 and Small Loops

In lieu of DSP-15's exceptional performance when mated with a moderate-sized loop, the researchers decided to try minimizing the size of the loop to improve the portability of the system.

A hexagonal loop, with a diameter of about ten inches, was chosen to maximize the surface area within the loop with respect to circumference. While the Detector Handbook [2] notes that loop effectiveness reaches diminishing returns at about six turns, the reference is silent on very small loops. Therefore, the researchers felt that increasing the number of turns well beyond six might be needed to increase performance.

Four loops were fashioned for testing. They featured, respectively, 6, 12, 29 and 88 turns of wire. The first two used standard 14 gauge wire, the 29-turn used thinner twenty-gauge wire, while the 88-turn used a very thin, single-stranded 28 gauge wire. This wire, including shielding, is roughly the thickness of common recreational fishing line. For all four loops, just one lead-in wire was fashioned. The lead-in is detachable from the hexagonal loops by means of "quick connects" crimped on the wire ends. For added durability, the crimp joints were soldered in place.

All four loops can be swapped in and out of a common mat. The same recycled tire material was used; however, an additional eighth inch of foam was added between the tire material and vinyl liner, and bored out, to make room for the thicker loops. This new mat was ¾" thick.

3.2.7.1 Pre-Test

These four configurations were then "Cabinet Tested" in the lab on May 26th and 27th, 2010. The DSP-15 rejected the 6-turn loop. The detector's auxiliary (green) LED flashed rapidly, indicating a short circuit. With its small surface area, the circuitry likely read an inductance too small to be useable.

The DSP-15 accepted the other three loops. During cabinet testing, a greater variation in detection distance from the cabinet was apparent. Therefore, two runs of ten detections were performed for each loop.

With DSP-15 set to sensitivity level 9 and "sensitivity boost" enabled, the unit detected the cabinet from an average 14.0" away using the 12-turn loop. Increasing to 29 turns only modestly increased this mean distance, to 15.2."

After the first few detections, the 88-turn loop would not release its call once fully withdrawn from the cabinet. The configuration was stable once sensitivity boost was disabled, but overall performance was disappointing. The 88-turn loop only detected the cabinet from a mean 10.0" distance. Sensitivity level 8, with sensitivity boost on, performed similarly at 10.2" inches.

Based on cabinet test results, the 12 and 29-turn loops were chosen for field testing. However, the cabinet test did not indicate a likely high accuracy. Configurations earlier cabinet-tested to 20" effectiveness corresponded to 80-90% field accuracy (DSP-7LP), while cabinet tests on the order of 12" corresponded to about 60-70% field accuracy (hobby circuit).

Table 8 - Cabinet Tests Ahead of Sixth Field Test

Very small loops, hexagonal with 10” max diameter, mated to DSP-15 detector							
Sensitivity Level 9 & “sensitivity boost” Distance in inches				Sensitivity Level 8 & “sensitivity boost” Distance in inches		Sensitivity Level 9 Distance in inches	
12 turns: run 1	12 turns: run 2	29 turns: run 1	29 turns: run 2	88 turns: run 1	88 turns: run 2	88 turns: run 1	88 turns: run 2
17.00	16.50	18.00	20.00	6.50	7.00	6.00	6.50
17.50	14.00	14.50	18.50	7.50	11.00	10.00	10.50
12.00	12.50	15.00	13.50	9.00	12.00	10.00	11.50
12.00	13.50	15.50	13.50	9.00	11.00	10.00	11.50
13.50	14.00	15.00	14.50	9.00	10.50	10.50	10.50
13.50	12.50	13.00	14.00	9.50	11.00	10.50	10.50
15.50	14.00	15.00	15.50	10.00	11.50	9.00	11.50
15.50	13.50	13.00	13.00	10.50	10.50	10.50	10.50
12.50	13.00	16.50	17.50	10.50	11.00	11.50	10.00
14.00	13.50	15.00	13.50	11.50	10.50	11.00	11.50
14.30	***13.70***	***15.05***	***15.35***	***9.30***	***10.60***	***9.90***	***10.45***

Respective maximum detection distance from detector pad to cabinet

Figure 36 - Small Detector Pad With Four Hexagonal Loops (10" Diameter). From Left: 6 Turns, 12 Turns, 29 Turns, and 88 Turns of Wire

Figure 37 - Detachable Lead-In Wire

3.2.7.2 Location and Configuration

The researchers tested the small 12- and 29-turn loops on Wednesday, June 2nd, 2010. The pad was again installed on eastbound Ferst Drive on the Georgia Tech Campus, between Hemphill Avenue and State Street. Testing with the 12-turn loop commenced at 12:05pm and lasted 90 minutes (with the detector set at sensitivity level 9 with sensitivity boost). Testing with the 29-turn loop commenced at 1:55pm and paused at 3:00pm. At that time, sensitivity had to be reduced to 8 (with sensitivity boost), the setting successfully used for the last 25 minutes of testing. Traffic flowed freely during all observations.

3.2.7.3 Results

The DSP-15 detector exceeded the researchers' expectations. With the 12-turn loop, the unit detected over 98% of the 339 vehicles observed passing over or grazing the pad. All failures occurred with SUVs or "Tech Trolleys," a Georgia Tech bus service. A double count occurred with one bus, and with one SUV. Over a dozen "fast" vehicles were observed, and all were successfully detected. Due to the small size of the pad and the unusual width of the travel lane, researchers noticed a large number of drivers avoiding the pad.

Table 9 - Field Observations From Sixth Field Test, with DSP-15 Detector (at Sensitivity Level 9 With Sensitivity Boost) Mated to Small 12-Turn Loop

	Cars	Large SUVs & vans (**)	Buses (**)	Trucks*	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	189	81	12	9	9	8	0	**308**
Not detected	0	2	0	0	1	0	0	**3**
Detected, grazing pad	16	7	0	0	1	1	0	**25**
Not detected, grazing pad	0	2	0	0	0	0	1	**3**
Success rate (all detections/total touching pad)	100.0%	95.7%	100.0%	100.0%	90.9%	100.0%	0.0%	**98.2%**

* *"Trucks" are large, heavy duty trucks up to and including 18-wheelers. "Large SUVs & Vans" include large pickup trucks such as the Ford F-150. Smaller pickups are "Cars."*

(**) One SUV and one bus were double-counted.

At 1:55pm the 29-turn loop was installed in the pad, and testing resumed. The researchers also tallied vehicles avoiding the pad. At about 3:00pm, the DSP-15 failed to release a call. The device was immediately dialed down to level 8 (with sensitivity boost) and testing continued for the final 25 minutes.

For the first 65 minutes, 257 vehicles passed over or grazed the loop. All were successfully detected. One car and one bus were double-counted. An additional 24 vehicles, or 8.5% of all observed, fully avoided the loop (many of the 24 were golf carts and motorcycles).

Over the remaining 25 minutes, 82 more vehicles were observed passing over or grazing the loop. Two fast cars grazed the pad and were not detected by the system, yielding accuracy of nearly 98%. An additional seven vehicles, or 7.9% of the total, avoided the pad.

As with the larger loops, there was little if any discernible call delay during the sixth field test. The results indicate that very small, 12-turn loops produce excellent performance with the DSP-15. However, adding more turns of wire risks an unstable system with false calls. No matter the amount of wire, 98% appears to be the highest achievable accuracy with these very small loops.

Table 10 - Field Observations From Sixth Field Test, with DSP-15 Detector (at Sensitivity Level 9 with Sensitivity Boost) Mated to Small 29-Turn Loop

	Cars (**)	Large SUVs & vans	Buses (**)	Trucks*	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	157	48	10	12	7	7	0	**241**
Not detected	0	0	0	0	0	0	0	**0**
Detected, grazing pad	12	2	0	0	0	2	0	**16**
Not detected, grazing pad	0	0	0	0	0	0	0	**0**
Vehicle avoids pad	*13*	*3*	*0*	*0*	*0*	*3*	*5*	***24***
Success rate (all detections/total touching pad)	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	0.0%	**100.0%**
Percentage avoiding pad	7.1%	5.7%	0.0%	0.0%	0.0%	25.0%	100.0%	**8.5%**

** "Trucks" are large, heavy duty trucks up to and including 18-wheelers. "Large SUVs & Vans" include large pickup trucks such as the Ford F-150. Smaller pickups are "Cars."*

(**) One car and one bus were double-counted.

Table 11 - Field Observations From Sixth Field Test, with DSP-15 Detector (at Sensitivity Level 8 with Sensitivity Boost) Mated to Small 12-Turn Loop

	Cars	Large SUVs & vans	Buses (**)	Trucks*	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	44	16	2	4	2	2	0	**70**
Not detected	0	0	0	0	0	0	0	**0**
Detected, grazing pad	5	5	0	0	0	0	0	**10**
Not detected, grazing pad	2	0	0	0	0	0	0	**2**
Vehicle avoids pad	*4*	*2*	*0*	*0*	*0*	*0*	*1*	***7***
Success rate (all detections/total touching pad)	96.1%	100.0%	100.0%	100.0%	100.0%	100.0%	0.0%	**97.6%**
Percentage avoiding pad	7.3%	8.7%	0.0%	0.0%	0.0%	0.0%	100.0%	**7.9%**

** "Trucks" are large, heavy duty trucks up to and including 18-wheelers. "Large SUVs & Vans" include large pickup trucks such as the Ford F-150. Smaller pickups are "Cars."*

(**) One bus was double-counted.

Figure 38 - Detector Pad with 12-Turn Loop. Looped Tape is Applied to Affix Pad to Pavement (Sixth Field Test)

Figure 39 - Detector Pad on Pavement (Sixth Field Test)

Figure 40 - Test Site for Sixth Field Test

3.2.8 Seventh Field Test – DSP-15 and Intermediate-Size Loop

While the accuracy of the very small loops was excellent and far better than expected, many drivers avoided the pad due to its size and the relatively wide lane at the test site. To address this issue, and improve upon the small loop's 98% performance, the researchers decided to experiment with a wide, narrow loop form factor.

A loop size of 8 by 20 inches was settled upon, intermediate between the small hexagon and the larger 11" x 25". Based on the performance of these previous loops (12 and 6 turns respectively), the new intermediate loop was woven with ten turns.

As with these predecessors, a mat of recycled tire was built to house the loop. Due to thickness of the wiring, this mat was ¾" thick. The mat featured two outlets for the lead in wire: one on the long side, the other on the short side. That way, the pad orientation could be easily changed between longitudinal and traverse to the flow of traffic.

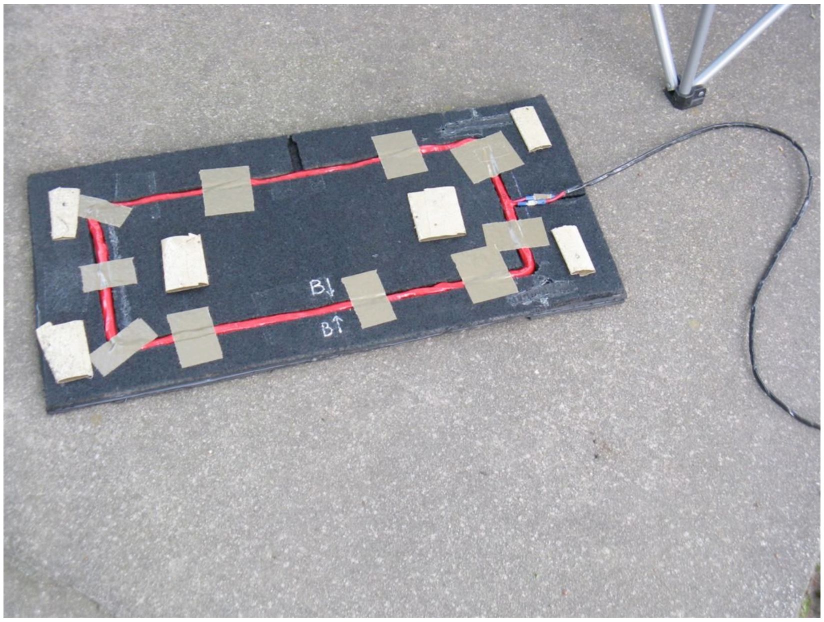


Figure 41 – Underside Of Intermediate-Sized Loop in Mat, Configured for Longitudinal Mount

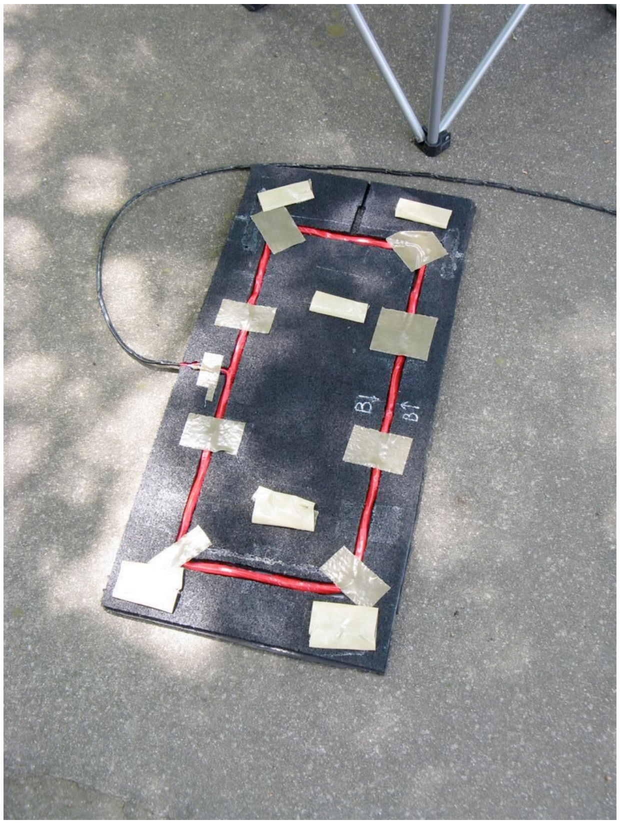


Figure 42 - Underside of Intermediate Loop in Mat, Re-Configured for Transverse Mount

3.2.8.1 Pre-Test

The field performance of the very small loops greatly exceeded what the cabinet test predicted. However, the same test with the new loop was performed to maintain formality of test procedure. Further, the new loop's cabinet performance relative to the very small loop would be relevant, given that both loops were mated to the same detector (DSP-15).

The intermediate loop was cabinet tested on June 10th and 11th, 2010. The highest sensitivity setting was chosen, level 9 with sensitivity boost. After a few minutes of testing, the detector failed to release a call. Thus, the sensitivity level was dialed back to 8 (with sensitivity boost). Over two ten-detection runs, the system successfully detected the cabinet at a mean 19.8". This improvement over the small loops' 14-15" cabinet performance predicted even stronger field accuracy.

Table 12 - Cabinet Tests Ahead of Seventh Field Test

10-turn loop, narrow rectangle 8”x20” Distance in inches	
Sensitivity Level 8 plus “sensitivity boost”	Sensitivity Level 8 plus “sensitivity boost”
16.00	15.50
17.50	20.50
21.00	21.00
20.00	19.50
19.50	17.50
21.50	20.00
22.00	21.00
20.50	20.50
23.00	20.00
19.50	20.50
20.05	***19.60***

Respective maximum detection distance from detector pad to cabinet

3.2.8.2 Location and Configuration

The intermediate loop was tested on Monday, June 15th. Starting at 1:05pm, two blocks were scheduled: the first with traverse mount, the second with longitudinal mount. The researchers hoped to improve on the pad avoidance rate of the very small loop with at least one of these orientations. After the first 90-minute test, the researchers removed the loop pad and re-oriented the loop wire 90 degrees. Once re-orientation was complete, at 2:55, a short 15-minute test with longitudinal mount began.

For both tests, the DSP-15 was set to sensitivity Level 8 (plus sensitivity boost) to match the successful cabinet test. Traffic flowed freely during the experiment.

3.2.8.3 Results

The traverse configuration successfully detected 99.6% or vehicles driving over or grazing the pad. Only one of these 227 vehicles, a fast-moving car grazing the pad, failed detection. However, the avoidance rate, at 16.5%, was significantly higher than with the very small loops. As before, motorcycles and golf carts tended to avoid the pad. The researchers also spotted a number of motorists slowing down while approaching the pad.

Table 13 - Field Observations From Seventh Field Test, with Intermediate-Size 10-Turn Loop Pad Mounted Traverse to Traffic. The DSP-15 Detector Was Set to Sensitivity Level 8 With Sensitivity Boost

	Cars	Large SUVs & vans	Buses	Trucks* (**)	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	115	39	10	8	8	0	0	**180**
Not detected	0	0	0	0	0	0	0	**0**
Detected, grazing pad	37	6	1	1	0	1	0	**46**
Not detected, grazing pad	1	0	0	0	0	0	0	**1**
Vehicle misses pad	*26*	*8*	*0*	*0*	*0*	*8*	*3*	***45***
Success rate (all Ds/tot on pad)	99.3%	100.0%	100.0%	100.0%	100.0%	100.0%	0.0%	**99.6%**
Percentage avoiding pad	14.5%	15.1%	0.0%	0.0%	0.0%	88.9%	100.0%	**16.5%**

**"Trucks" are large, heavy duty trucks up to and including 18-wheelers. "Large SUVs & Vans" include large pickup trucks such as the Ford F-150. Smaller pickups are "Cars."*

(**) One truck was double-counted.

During the fifteen minute longitudinal-mount test, 52 vehicles were observed passing over or grazing the pad. All were detected. An additional eight vehicles (mostly cars) avoided the pad. While the dataset for longitudinal mount is smaller, its 13.3%

avoidance rate wasn't significantly smaller than traverse mount. This avoidance rate, and the 16.5% rate observed from traverse mount, are about double that of the smaller loops.

Table 14 - Field Observations From Seventh Field Test, with Intermediate-Size 10-Turn Loop Pad Mounted Longitudinal To Traffic. The DSP-15 Detector Was Set to Sensitivity Level 8 with Sensitivity Boost.

	Cars	Large SUVs & vans	Buses	Trucks*	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	32	10	3	1	1	1	0	**48**
Not detected	0	0	0	0	0	0	0	**0**
Detected, grazing pad	2	0	1	0	0	1	0	**4**
Not detected, grazing pad	0	0	0	0	0	0	0	**0**
Vehicle misses pad	*6*	*1*	*0*	*0*	*0*	*1*	*0*	***8***
Success rate (all Ds/tot on pad)	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	0.0%	**100.0%**
Percentage avoiding pad	15.0%	9.1%	0.0%	0.0%	0.0%	33.3%	0.0%	**13.3%**

* *"Trucks" are large, heavy duty trucks up to and including 18-wheelers. "Large SUVs & Vans" include large pickup trucks such as the Ford F-150. Smaller pickups are "Cars."*

Figure 43 - Intermediate Size Loop Deployed Longitudinally, During Seventh Field Test

Figure 44 - "Tech Trolley" Driving Over Intermediate-Sized Loop Mounted Traverse (Seventh Field Test)

Figure 45 - Test Site on Eastbound Ferst Drive with Intermediate-Size Loop Mounted Longitudinal

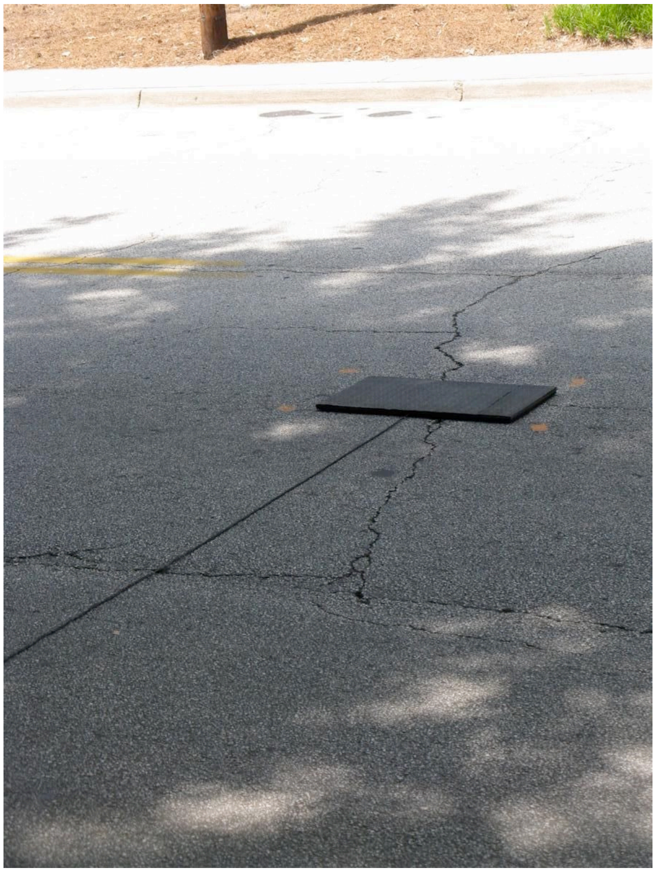


Figure 46 - Intermediate Size Loop Deployed Longitudinal to Traffic, During Seventh Field Test

3.2.9 Eighth Field Test – DSP-15, Small Loop and Streaming Data

3.2.9.1 Location and Configuration

For this eighth and final field test, the researchers chose the very small 12-turn hexagonal loop for its demonstrated accuracy and portability. Further, the pad was spray painted with light gray "Fleck" enamel. The researchers hoped the paint would blend the pad with the surrounding pavement, and reduce the problem of drivers avoiding the pad.

The researchers elected to test the system during the late afternoon peak period. They deployed along eastbound Fifth Street, between Spring and West Peachtree Streets.

This test, unlike the others, was fully “online” as well, with the GSM uplink from the RSN1000 to Georgia Tech’s VMT server activated. The server data was then pushed to a VMT website. This allowed the researchers to track detections, in real time during the test period, with web-enabled mobile phones.

Testing started at 3:15 and lasted through 5:56. Traffic was mostly free flow at the start of the testing period, but sporadic standing queues appeared after 4:00pm and were more frequent near the end of the test period.

The DSP-15 was initially set to sensitivity of nine (with sensitivity boost), the configuration successfully tested on June 2nd with the small twelve-turn loop. The detector almost immediately failed to release a call. The unit was dialed back to sensitivity level 8 (with boost).

Figure 47 - Location of Eighth Field Test, on Eastbound Fifth Street Between Spring and West Peachtree Streets (Google)

3.2.9.2 Results

For ten minutes, 25 through vehicles were observed passing the test site. None avoided or missed the pad, and all were detected. One vehicle, which grazed the pad, was double-counted. Ten minutes later, a moment after the sun came out, the detector again failed to release a call. The sensitivity was reduces to 7 (with boost), and continued.

Through 4:10 pm, 99 eastbound through vehicles were observed. Three of the 99 missed or avoided the pad. The other 96 passed over or grazed the pad, all of which were successful detections. At 4:10 pm, another unreleased call occurred when the sun came out. Temperature was apparently triggering false calls within the detector's sensitivity margins.

Table 15 - Field Observations From Eighth Field Test, with Small 10-Turn Loop Pad Spray-Painted Fleck Gray. The DSP-15 Detector was Set to Sensitivity Level 7 with Sensitivity Boost

	Cars	Large SUVs & vans	Buses	Trucks* (**)	Trolleys	Golf Carts	Motor-cycles	OVERALL
Detected	64	12	0	1	4	0	0	**81**
Not detected	0	0	0	0	0	0	0	**0**
Detected, grazing pad	6	7	0	2	0	0	0	**15**
Not detected, grazing pad	0	0	0	0	0	0	0	**0**
Vehicle misses pad	3	0	0	0	0	0	0	***3***
Success rate (all Ds/tot on pad)	100.0%	100.0%	0.0%	100.0%	100.0%	0.0%	0.0%	**100.0%**
Percentage avoiding pad	4.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**3.0%**

* *"Trucks" are large, heavy duty trucks up to and including 18-wheelers. "Large SUVs & Vans" include large pickup trucks such as the Ford F-150. Smaller pickups are "Cars."*

(**) *One truck was double-counted.*

The researchers reduced the sensitivity to 5 (with boost). The detector remained stable at this setting for the rest of testing. An additional 335 through vehicles passed over or grazed the pad, and were observed as detections. The unit failed to detect another eleven vehicles, six of which were grazes. This yielded an overall detection rate of 96.8%. Fourteen through vehicles (or 3.5% of all observed) missed or avoided the pad.

Table 16 - Field Observations From Eighth Field Test, with Small 10-Turn Loop Pad Spray-Painted Fleck Gray. The DSP-15 Detector was Set to Sensitivity Level 5 with Sensitivity Boost.

	Cars (**)	Large SUVs & vans	Buses	Trucks* (**)	Trolleys (**)	Golf Carts	Motor-cycles	OVERALL
Detected	253	32	0	0	8	0	0	**293**
Not detected	4	0	0	0	1	0	0	**5**
Detected, grazing pad	39	2	0	1	0	0	0	**42**
Not detected, grazing pad	3	3	0	0	0	0	0	**6**
Vehicle misses pad	10	1	0	0	0	0	3	**14**
Success rate (all Ds/tot on pad)	97.7%	91.9%	0.0%	100.0%	88.9%	0.0%	0.0%	**96.8%**
Percentage avoiding pad	3.2%	2.6%	0.0%	0.0%	0.0%	0.0%	100.0%	**3.9%**

* *"Trucks" are large, heavy duty trucks up to and including 18-wheelers. "Large SUVs & Vans" include large pickup trucks such as the Ford F-150. Smaller pickups are "Cars."*

(**) *Two cars, one truck and seven trolleys were double-counted.*

Double-counting of high bed vehicles (particularly "Tech Trolleys") remained an issue. This frequently occurred once sensitivity was dropped to 5. During the 161 minute test period, twelve double-counts were observed (mostly high-bed vehicles like Trolleys).

The site is across the street from a parking lot. Over the 161 minutes of testing, the researchers spotted an additional 21 vehicles turning in to this parking lot. Seven of these turning vehicles, passing over or clipping the pad, were detected.

Overall, the researchers observed 475 detections during the eighth field test. This figure includes the 12 double counts. These data indicate a 94% "capture rate," which is 475detections, divided by 505 total observed passenger vehicles. If just the 4:10-5:56 window is considered, and the turning vehicles ignored, the "capture rate" improves to nearly 96%.

Table 17 - Summary Of All Traffic Observed During Eighth Field Test

	3:15-3:25	*3:25-4:10*	*4:10-5:56*	*3:15-5:56 (turning)*	*Total*
Detected	25	96	335	7	463
Not detected	0	0	11	0	11
Misses pad	*0*	*3*	*14*	*14*	*31*
Percentage missing	*3.5%*			*66.7%*	*6.1%*
Total Observed Passenger Vehicles					*505*
Double counts	1	1	10	0	12
CAPTURE RATE					**94.1%**
CAPTURE RATE between 4:10-5:56, omit turning vehicles					**95.8%**

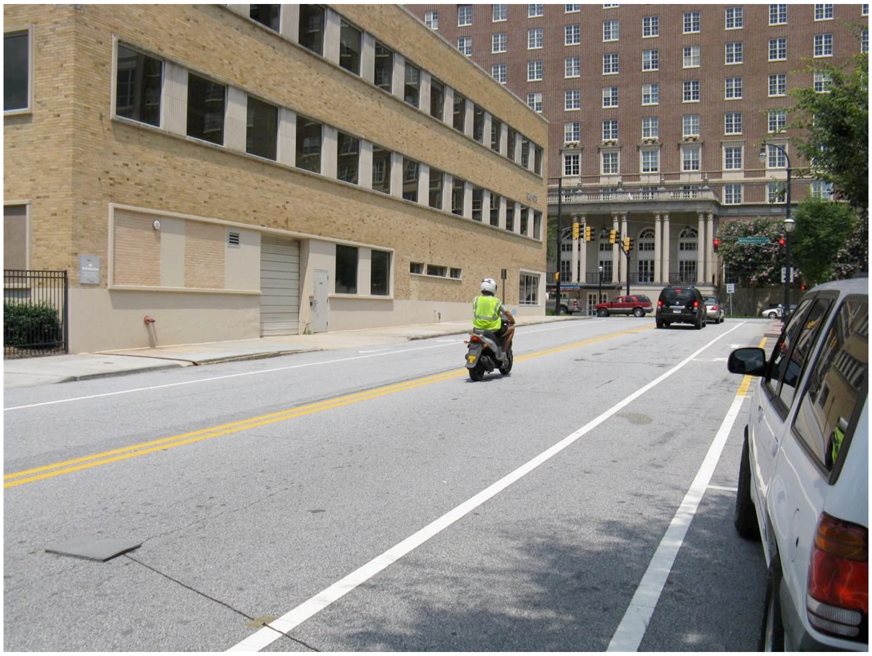


Figure 48 - Eastbound View Along Fifth Street at Test Site (Eighth Field Test)

Figure 49 - Closeup of Detector Pad

Figure 50 - Dr. Michael Hunter, Philip Blaiklock and Nick Wood Collect Data at Test Site

Figure 51 - Dr. Randall Guensler Follows Detections on his Mobile Phone with Web Access

Figure 52 – Close-Up of Detector Pad, Showing “Fleck” Paint Blending with Pavement

Figure 53 - Standing Queue on Eastbound Fifth Street

Chapter 4 Conclusions and Future Work

This research explored several new angles in vehicle detection with inductive loops. Many rounds of field testing yielded a mix of unexpected, and often encouraging, results. These findings lay the groundwork for new and exciting lines of research.

4.1 Small Loops

A ten-inch wide hexagonal loop, coupled with the right detector, reliably detected up to 97% of all vehicles passing over or grazing the pad containing the loop. The test results revealed the unexpected effectiveness of very small inductive loops, a topic unexplored in the literature.

Twelve turns of wire provided the best performance. Adding more turns can, in theory, further increase the inductance of the loop and its sensitivity. However, the quality factor (Q) of an inductor is inversely proportional to its resistance. More turns of wire means higher resistance, and more lost energy within the inductor. Physical space also becomes a problem with many turns of wire. Past twelve turns, a thinner gauge must be used to fit the wire within the detector pad. Thinner gauges of wire introduce even higher resistance per unit length. For example, the 14-gauge wire used in most of this research (and typically by DOTs) introduces 2.5 ohms per 1000 feet. Twenty-gauge wire, employed in the small 29-turn loop, quadruples the resistance to 10.1 ohms per 1000 feet. The 28-gauge wire, necessary for fitting 88 turns into the pad, pushes the resistance to 64.6 ohms per 1000 feet [41]. The series resistance, therefore, of the 88-turn loop is 89 times that of the 12 turn loop. This high resistance explains why this loop was less effective when tested against in-lab the cabinet, and why the 29-turn loop offered only a slight improvement over the 12-turn loop.

Another observed limitation of small loops is a tighter sensitivity margin. The 12-turn small loop often failed to release a call at higher sensitivity settings (or smaller ΔL/L). With a lower overall inductance, slight changes in inductance caused by temperature swings can easily impact the system. Sensitivity level 5 (with sensitivity boost) ultimately proved reliable in the field during summer daytime, under direct sunlight and shade. The field testing results, at the end of the day, do validate the *Traffic Detector Handbook*'s guidance that loop surface area is the controlling factor for loop effectiveness.

4.2 Driver Avoidance

This system's chief advantage, portability, proved to have a potential drawback. The avoidance rates of small and medium-size pads may indicate that drivers may attempt to avoid objects affixed in the center of the lanes. This appeared to be less of a problem during earlier tests, with larger loop pads (although hard data on miss-rate was not recorded). But, larger pads are less portable. The compromise "intermediate" loop size (8" x 20") proved most troublesome. Approximately 1 out of 7 motorists missed or avoided this pad.

It is important to note that these high avoidance rates also occurred on a two-lane section of Ferst Drive with a wide traveled way. The standard 12-foot lane was not striped. Here the small detector pad had an avoidance rate of about 8%. After the researchers painted this pad fleck-gray, and deployed the unit on the striped 12-foot lane along Fifth Drive just off campus, the miss rate was halved. Whether the pavementcolored paint, the lane striping, or some other factor contributed most to this result remains unclear.

4.3 Choice of Detector

In the course of this research, the detector unit selected for integration into the portable detector affected accuracy more than any other system component. The lab 'cabinet test' predicts field performance only when the new configuration and the baseline configuration share the same detector circuit. Further, upgrading from the hobbyist circuit to the DSP-7LP substantially improved the field performance of the 17" x 34", 8-turn loop. Likewise, the DSP-15, set to medium sensitivity and coupled with a very small loop, outperformed all configurations with DSP-7LP. This is no surprise, for the DSP-7LP is a comparatively simple, low-power device.

The exact response time however, of the DSP-15 (in milliseconds) was not available to the researchers as of this writing. In the field, the detector appeared to respond to vehicle presence within a tenth of a second or so. In any event, field results show that detector units targeted at the access control market may potentially be effective in counting fast-moving vehicles.

4.4 Future Work

Vehicle avoidance of the pad results in undercounting of traffic volumes. The researchers would like to further test the small, spray-painted pad to gauge its avoidance rate on wide, unstriped lanes. If it's comparable to the 8% rate observed on the unstriped lane of Ferst Drive on campus, other means of addressing the avoidance issue should be explored. Possible solutions include a long, narrow loop spanning the width of the lane (similar to the Blade [31]). A small loop could be secured underneath a white thermoplastic “through arrow,” emulating the appearance of a typical pavement marking. Another potential strategy against avoidance is to tether small loops together in series.

The detector pads crafted from recycled tire remained fully intact during field testing, and can be used again. The unit housing the very small loop, for example, withstood six hours of light-to-moderate traffic during the tests described in this thesis. Further testing would determine the long-term durability of these temporary pads. An alternative solution for long-term testing is the 18” x 24” temporary loop from LIS Inc., custom-made for the researchers. This unit, while intended for one use, is designed for deployment at construction zones and would likely last weeks in the field. Over a long-term test, the total power draw of the system, and its battery life, would also be more thoroughly evaluated.

Future versions of the system might integrate all components, including a thin laptop-size battery, a small form-factor GSM modem, and a detector PCB, within the pad assembly itself. For such a setup, a lower-power detector solution is preferable. The researchers also need to examine the efficiency and effectiveness of the GSM communication channel.

4.5 Closing Remarks

This system is, to the researchers’ knowledge, the first fully portable, inductive loop vehicle counter. The researchers observed the system detecting nearly 96% of applicable through vehicles within one striped lane. This work also advances the applications of very small inductive loops, smaller than one square foot.

Further, the system is relatively inexpensive. The tested configurations consist of several hundred dollars of off-the-shelf components, cheaper than the commercial solutions described in the literature. While some challenges remain, the unique system described in this thesis holds significant promise.

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