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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

TRAFFIC DATA COLLECTION AND ANONYMOUS VEHICLE DETECTION USING WIRELESS SENSOR NETWORKS

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16. Abstract

New traffic sensing devices based on wireless sensing technologies were designed and tested. Such devices encompass a cost-effective, battery-free, and energy self-sustained architecture for real-time traffic measurement over distributed points in a transportation system. A weather-resistant enclosure was designed and manufactured to protect the sensor from traffic impacts on the highway. This scalable technology can monitor traffic parameters such as flow, occupancy, point speed, and vehicle classification on road systems in real-time. The data collector device is also equipped with a memory card reader, which makes it suitable for temporary installation and short-term data collection. In addition to traditional traffic parameters, the sensors can measure and report the temperature of their surroundings because they are surface-mounted. The sensors developed as a result of this project are also capable of capturing a digital magnetic signature of vehicles within any intervals required by clients. The digital magnetic signature was processed to calculate traffic volume, vehicle speed, and vehicle length estimation for classification. With the help from SHA and Inter County Connector staff, five sensors were permanently deployed and thoroughly tested on a section of the ICC.

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1. Introduction

Traffic congestion and associated effects such as air pollution pose major concerns to the public. Congestion has increased dramatically during the past 20 years in the 85 largest U.S. cities. During this time, the number of hours lost each year by an average driver to congestion has increased by 300 percent. In the 13 largest cities, drivers now spend the equivalent of almost eight work days each year stuck in traffic [1, 2]. Increasing the capacity of the roadways is expensive and, in some areas where land is scarce, is not an option. Improving the efficiency of the current transportation system through the implementation of advanced technologies may alleviate traffic congestion and decrease the vehicle crash-related fatality rate. Real-time traffic surveillance is one of the most important components of this approach.

Traffic congestion may be alleviated by improving the efficiency of the current transportation system through the implementation of advanced technologies. Real-time traffic surveillance is one of the most important components of such an approach, and real-time travel information is useful for advanced travel advisory systems. Emergency management agencies such as police, fire stations, and ambulance dispatchers may also benefit from real-time traffic information in routing their vehicles through the transportation network to save lives. Roadway safety and efficiency will be significantly enhanced by employing remote sensing and communication technologies capable of providing low-cost, scalable, and distributed data acquisition of road conditions. Such Intelligent Transportation System (ITS) applications require distributed acquisition of different traffic metrics such as traffic speed, volume, and density. In such systems, automated traffic control is possible only through real-time traffic information over distributed points on the transportation system. The existing measurement technologies are bending plates, pneumatic road tubes, piezoelectric sensors, inductive loops, infrared, microwave-doppler/radar, passive acoustic, video image detection, and Bluetooth devices. The existing data acquisition technologies in transportation systems suffer from the following drawbacks:

- **Energy efficiency*:*** Most of the existing technologies need to be constantly connected to a main power source or battery. Connection to the main power source limits deployment of the instruments, and using batteries imposes regular maintenance cycles [3].
- **High cost*:*** The majority of technologies require expensive instruments, which inhibit cost effectiveness of large-scale and distributed traffic measurements.
- **Installation and maintenance:** Most existing technologies need significant maintenance and calibration and are costly to install. Installation costs may include wiring of the instruments to power sources or the wiring required for communication.
- **Scalability*:*** The majority of existing technologies cannot be deployed on a large scale due to limitations such as installation cost, wiring, availability of energy sources, etc.
- **Low-speed and offline measurements:** The lack of low-cost real-time communication between measurement points and the decision-making centers inhibits fast and automated decision making.

The main goal of this project was to develop an inexpensive and scalable wireless sensor network prototype, which encompasses a cost-effective architecture for real-time traffic measurement over distributed points on a transportation system. Energy is one of the main challenges of a large-scale deployment of sensors. A possible solution is to design sensors that harvest the needed energy from ambient vibration or from the sun. The sensors use ultra-low power complementary metal oxide semiconductor (CMOS) technologies, which make the communications devices extremely energy efficient. The sensors are capable of performing simple sensing operations such as traffic count measurement. And, by means of low-range radio transmissions, the devices form a wireless mesh network. The sensors are able to obtain their required energy from the vibration in the road surface and added solar sensors, and, therefore, do not need batteries or access to a main power source. Figure 1 shows a simplified schematic of the sensor network.

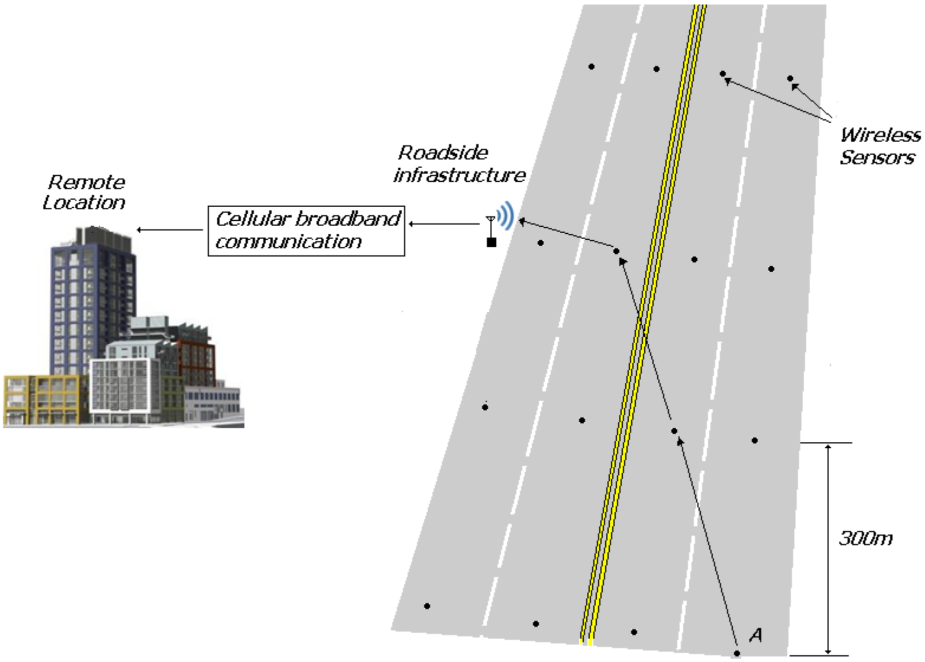


Figure 1. Traffic Measurement using wireless sensor network

As Figure 1 shows, sensors are deployed on the road surface and a remote sensor can communicate with roadside infrastructure through a multi-hop path.

The architecture has the following advantages over the existing methods:

- **Energy efficiency:** The sensing and measurement architecture uses a minimal level of energy and uses state-of-the-art low-power sensing, amplification, and communication technologies.
- **Broad range of measurement:** With the sensor networking architecture, several types of traffic measurements can be performed. Examples of some measurements include: Traffic volume and density, traffic speed, classification of vehicle types (e.g., based on length). Furthermore, with a larger density, the sensors can provide an end-to-end communication medium.
- **Ease of installation:** Compared to existing systems, the system requires minimal installation effort. For each traffic measurement point, the system requires a roadside data collection point and installing a few wireless sensors on the road surface. Because sensors are both small and wireless, lane closure time and traffic disturbance for the installation is minimal and not labor intensive.
- **Endurance:** Since the sensors do not require batteries, calibration, or any other type of maintenance after installation, the system has a very long life expectancy.
- **Low maintenance requirements:** Because the measurement devices do not need wiring or batteries, their maintenance demand is minimal.

The developed sensor architecture is specific to ITS applications where energy harvesting makes the best use of both vibration energy from the road surfaces and solar energy. Also, the wireless sensors are equipped with the necessary instrumentation components such as anisotropic magnetoresistance elements for the purpose of detecting vehicles.

2. System Design and Architecture

The traffic detection devices developed in this project harvest their required energy from their environment to power up the sensing element and telecommunication modules and, thus, do not need batteries. The sensing part uses magnetic sensors for detecting vehicles and the communication is wireless. In summary each device includes the following components (Figure 2):

- **Sensing elements:** The main sensing element is a magnetic sensor that generates a digital signature of a passing vehicle based on disturbance of the magnetic field caused by the ferromagnetic material of the vehicle.
- **Solar panel:** A small, thin solar panel is placed on the top section of the devices and is protected by a heavy-duty transparent fiber glass casing to turn ambient light energy into electricity.
- **Super capacitor:** This part is an environmentally friendly capacitive media for storing harvested energy from solar and vibration sources.
- **Circuit and antenna:** This component includes a communication antenna and the necessary circuits for wake-up scheduling, instrumentation, amplification, and communication.

All the above components are integrated into a custom designed snow plow-safe casing with an overall thickness of about 0.5 inches. An electronics-friendly silicon sealant makes the devices weather resistant. Deployment is done on the road surface using adhesive materials. The following sections describe the technical details.

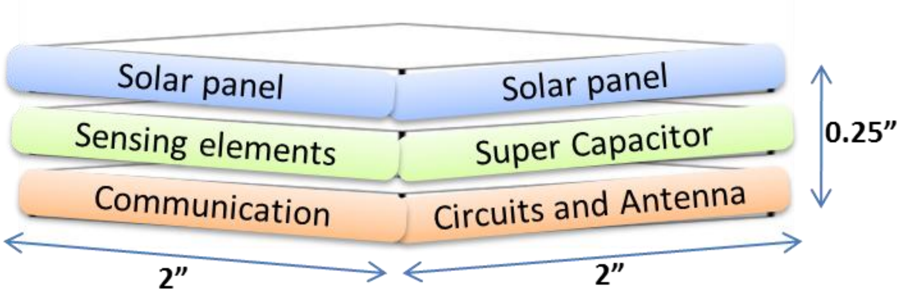


Figure 2. Components of the wireless traffic detector device

2.1. Microcontroller Selection

Finding an appropriate microcontroller that supports wireless communication and that is energy efficient and fast enough to handle the magnetic sensor is crucial. Based on past experience, the research team targeted and extensively tested two microcontrollers during the design phase. These included the Peripheral Interface Controller (PIC) and Texas Instrument-based microcontrollers.

After some preliminary investigation, Texas Instrument (TI) microcontroller CC2430 was selected. This chip represents the Chipcon’s second-generation ZigBee-compliant platform. It is a System-on-Chip (SoC) solution that combines the industry-leading radio 2.4 GHz transceiver of the IEEE 802.15.4-compliant CC2420 with an industry-proven, compact, and efficient 8051 microcontroller.

The family of CC2430 microcontrollers comes in three products: CC2430-F32, CC2430-F64, and CC2430-F128. The main difference between these chips is the amount of flash memory on board, which are 32, 64 and 128 KB with 8 KB of RAM. The CC2430 family uses Chipcon's SmartRF®03 technology platform and is designed in 0.18 micrometer CMOS, available in a small 7 x 7 mm, 48-pin package. One of the most important advantages of these chips are their energy efficiency. In reception and transmission modes, the microcontrollers consume approximately 27 mA and 25 mA, respectively. In sleep mode, the CC2430 microcontrollers consume 7uA. Because of the ultra-low power consumption in sleep mode, small battery can sustain the chips for several years. These chips can be programmed for any ZigBee wireless node, including coordinators, routers, and end devices. Most importantly, the protocol stack (Z-Stack) is provided by Texas Instruments, which makes the development period considerably shorter.

In the middle of this project, a new version of this chip was introduced, the CC2530. The new chip provides a larger flash memory (up to 256 KB), which makes it suitable for ZigBee PRO applications. The larger memory size of this chip allows for on-chip, over-the-air-download to support in-system reprogramming. As a result, the microcontroller used in the prototype devices was replaced with CC2530 to build the new version of the hardware. Necessary modification in the embedded code accommodated the updated features.

2.2. Energy Harvesting

The traffic sensors are energetically self-sufficient and, therefore, environmentally friendly. In addition to reducing the energy consumption, the required energy is harvested from the environment. This project used solar panels. Although ambient light is a good source of energy, it fluctuates with the time of the day, weather conditions, and the season (days are shorter in the winter and longer in summer). Thus, the energy-harvesting component has to account for these factors. To keep the sensors functioning without sunlight, energy must be stored during the day.

Several brands and types of solar panels were performance tested in order to select appropriate components. The solar panel was protected by applying clear resin in the final design.

2.3. Enclosure Design

In order to deploy prototype sensors for conducting experiments in traffic, an appropriate enclosure is needed to protect the devices against harsh road conditions. Instead of designing a customized case, commercially available road studs were adopted. To develop a housing for the electronic parts, necessary modifications were made to the cases in the University of Maryland machine shop.

Another important consideration was to protect devices against humidity and rain. EasyCast, a product from TAP Plastics, made the devices waterproof. Additionally, several TAP Plastics molds were used to cast the resin in proper shapes. Figure 3 shows examples of a round shape casting on the left and a surface mount rectangular shape on the right.

Figure 3. Protecting the electronic parts using a weather resistant epoxy

To protect the devices against the weight of a vehicle, commercial road studs were modified to accommodate casted electronic parts (Figure 4).

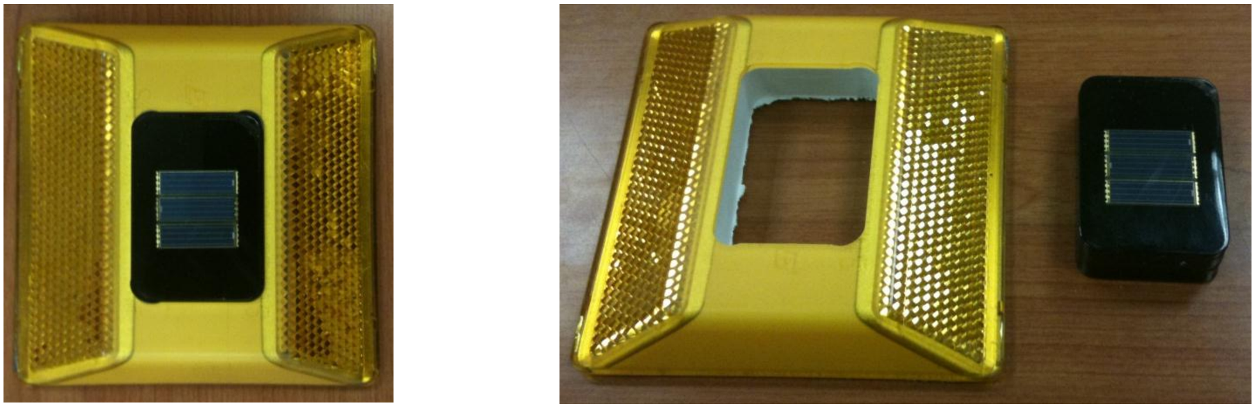


Figure 4. Housing sensors cast inside a commercial road stud

To prevent driver distraction, the final prototype was painted a dark color. Figure 5 shows a prototype device before and after painting.

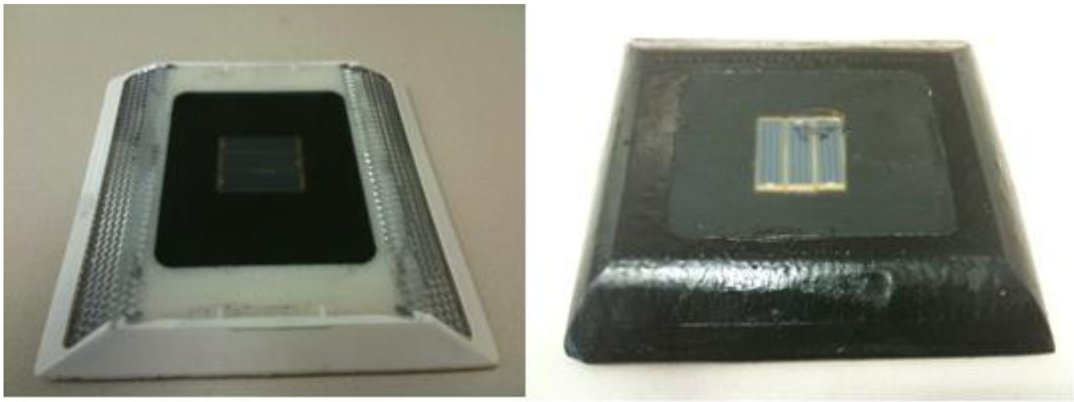


Figure 5. Initial wireless traffic sensor prototype

Metal-based cases made from an aluminum alloy were also considered as an alternative. Although these cases were stronger, the main issue was significant degradation of the radio frequency (RF) signal. Figure 6 shows a prototype device in aluminum case.

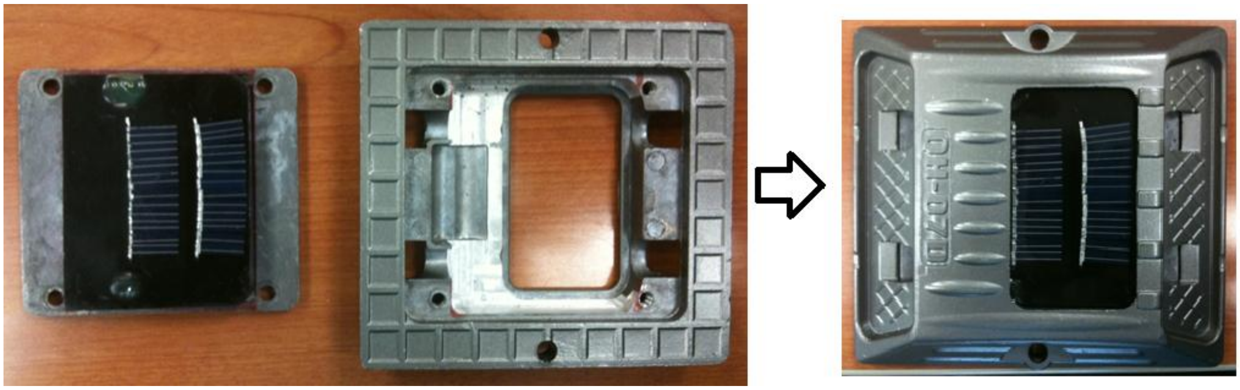


Figure 6. Aluminum version of the initial wireless traffic sensor prototype

The research team selected a material that satisfies all the requirements of the project, including strength and transparency for the wireless signal, after conducting extensive research on the candidate materials to make a custom enclosure for the device. This material, Lexan, is a polycarbonate polymer. It is very durable – indeed, it is used for bullet-proof windows. Additionally, it is clear, which allows the RF signal to pass through it with minimal blocking effect. With the Manual on Uniform Traffic Control Devices (MUTCD) and other traffic safety considerations in mind, an AutoCAD drawing of an enclosure was created. The drawing was sent to the professional staff at the University of Maryland machine shop to build cases with a thickness of 11 mm (Figure 7). The sensors deployed on MD 200, the Inter County Connector (ICC), were based on this durbale, weather-proof enclosure.

Figure 7. Wireless traffic sensor in Lexan enclosure

In order to examine the strength of the case in real conditions, several experiments were conducted by applying extreme pressure to the sensor. A 2002 Honda Accord was positioned in front of the sensor and accelerated over the enclosure at a high speed. The scenario was repeated multiple times to test that the device can sustain the pressure. Operation of electronic and energy harvesting parts was monitored before, during and after the experiments. Figure 8 illustrates the experiment.

Figure 8. Enclosure resistance test under real road conditions

2.4. Roadside Collector

One of the main components of the traffic detection system is the roadside collector, which collects data from the sensors deployed nearby on the road. This component acts as a gateway between the Zigbee-based network and the IP network over which the data is carried. Since a permanent source of power may not be always available on the side of the road, solar energy was selected as the power source. The communication part is based on a CDMA modem that works on Verizon's wireless network. The design does not specify that a particular wireless provider must be used; other equipment, such as GPRS modems by AT&T, can also be used. Figure 9 shows the modem.

Figure 9. Wireless modem for real-time data transmission

The collector box must be waterproof so that it can withstand adverse weather conditions. Additionally, the box's energy harvesting should be able to provide enough energy for all internal components including the modem, ZigBee collector and the other hardware in the box. It must also have batteries to save energy in case the weather is cloudy for several days in a row.

In order to capture and save the collected data from sensors, a local backup system on an SD memory card was considered. The advantage of such system is the portability of the SD card and applications for offline data collection without service disruption. Additionally, SD memory cards are large enough to store data for several months. The roadside collector box should be able to provide the energy required for this offline data recorder. Figure 10 illustrates the final product, which is capable of offline data collection, real-time data transmission, and energy harvesting

Figure 10. Roadside data collection unit

3. Vehicle Detection and Magnetic Signatures

The vehicle detectors developed in this project work on a per-lane basis. The devices have a square shape with approximate dimensions of 2” x 2” x 0.5”. A magnetic sensor embedded in each device measures the earth’s magnetic field in absence of a vehicle. When a vehicle passes the proximity of a sensor, a strong disturbance is made to the measured magnetic signature of the vehicle due to the large mass of steel and other ferromagnetic material in the vehicles. The signature is collected in three dimensions, each of which has a wave form.

3.1. Magnetic Sensors Principle

Magnetic sensors detect a vehicle's signature by measuring the change in the magnetic lines of flux caused by the change in field values produced by a moving ferrous metal vehicle (Figure 11). There are two types of sensors that can be used for vehicle detection using magnetic field measurement: Anisotropic magneto-resistive (AMR) sensors and giant magneto-resistive (GMR) sensors. AMR sensors are directional sensors and can provide only an amplitude response to magnetic fields in their sensitive axis. Multi-axis AMR sensors can be made by combining the measurement of multiple one-axis sensors [4]. GMR sensors can also be used for low magnetic field sensing. These kinds of sensors have a broad sensitivity to amplitudes with little directionality.

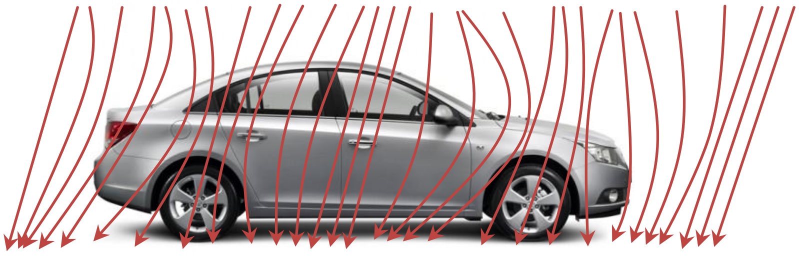


Figure 11. Perturbation of Earth's magnetic field by a ferrous metal vehicle

The main difference between AMR and GMR sensors is their linearity. Whereas AMR sensors' response to the change in the magnetic field is linear, the same is not true for GMR sensors. In order to use GMR sensors for detecting vehicles, its response must be linearized using a nearby magnetic bias field. This linearizing can be achieved through either a permanent magnet or a direct current-driven solenoid to gain improved linearity.

In this project, the performance of both AMR and GMR sensors was evaluated. The first design was based on the GMR sensors. Experiments were carried out in which the type of vehicle and its orientation were changed. The GMR sensors were capable of detecting a passing vehicle in all conditions. However, non-linearity of the sensors was an issue. External magnetic bias was used to linearize the sensors as much as possible; however, non-identical magnetic bias complicated the sensor calibration. In other words, the linearization process was complex and low performing.

The AMR sensors consist of magneto-resistive elements oriented on a wheatstone bridge; the resistance of magneto-resistive elements change when exposed to a magnetic field. These elements are made of permalloy thin films that achieve a resistance of approximately 1000 ohms. In the absence of any magnetic field, the values of the elements are matched within one ohm of each other. In the resulting bridge, the opposite elements are identical.

One of the challenges of using magnetic sensors is the effect of Earth’s magnetic field. The readout signals from the sensors change with the orientation of the installed sensors on the road because Earth’s magnetic field intensity changes in different directions. To mitigate this issue, an adaptive gain amplifier was used.

3.2. Magnetic Signature

Earth's magnetic field provides a baseline for magnetic fields that is relatively constant with a fixed sensor installation. A nominal value for Earth's magnetic field strength is approximately 0.5 gauss, so the readout of each axis ranges 0.0 gauss ± 0.7 gauss. Once vehicles come into proximity of the sensor, the level of magnetic field varies depending on the mass of the ferrous materials in the body of the vehicle. (It should be noted that vehicles' bodies consists of both soft- and hard-iron materials because the two types of iron have different effects on magnetic flux. Soft iron concentrates magnetic flux into the material and does not have any remnant flux generated within the material. Hard iron, on the other hand, causes flux concentration as well as remnant flux generation. (Flux density is in the order of hundreds of gauss and the remnant flux caused by hard iron is less than ± 2 gauss.)

The concentration of Earth's magnetic flux caused by soft irons will generally increase the flux amplitude. This increment is usually less than half of the residual bias value at the sensor location. As a result, the magnetic sensors should see a few tens to hundreds of milligauss of Earth field bias, with up to ± 3 gauss of spikes. The vehicle detection system in this project mostly deals with the level of change of the magnetic field instead of dynamic peaks generated by the vehicle.

3.3. Vehicle Detection and Speed Estimation

Installing two detectors in one lane that are separated by a predetermined distance in the direction of traffic allows for the measurement of vehicles' speed based on the signature's time difference. After finding the speed of a vehicle, its length can be estimated.

In a series of experiments, two sensors were placed a small distance $V = \Delta d/\Delta t$ apart, with their sensitive axes aligned in the same direction. A moving vehicle creates the same signature that is read by the two sensors, but displaced in time Δt (Figure 12). A vehicle's speed can then be calculated from $V = \Delta d/\Delta t$, where V is speed. Synchronization of the sensors is a very important factor and directly affects the accuracy of the speed calculation.

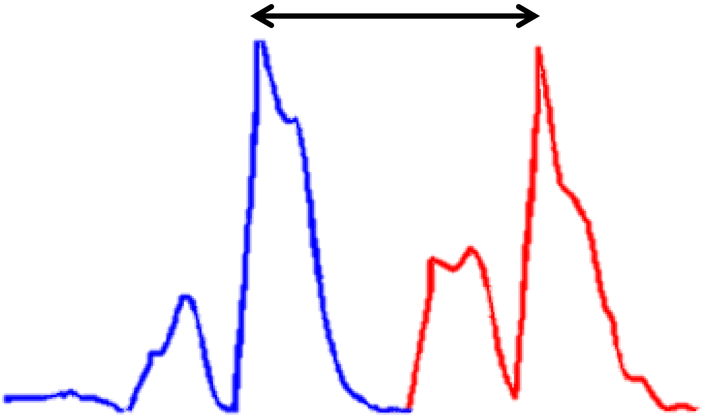


Figure 12. Speed measurement based on magnetic signature collected by two sensors

A series of experiments for sensor calibration, synchronization, and speed measurement were conducted on the University of Maryland campus. As illustrated by Figure 13, the distance between the two sensors (S1 and S2) is 29 ft. Because of the technical limitations and safety considerations in the parking lot, the speed of the vehicle was approximately15 MPH. In order to have a ground truth, video was captured as the experiments were conducted. The accurate speed was then calculated based on frame-by-frame analysis of the video.

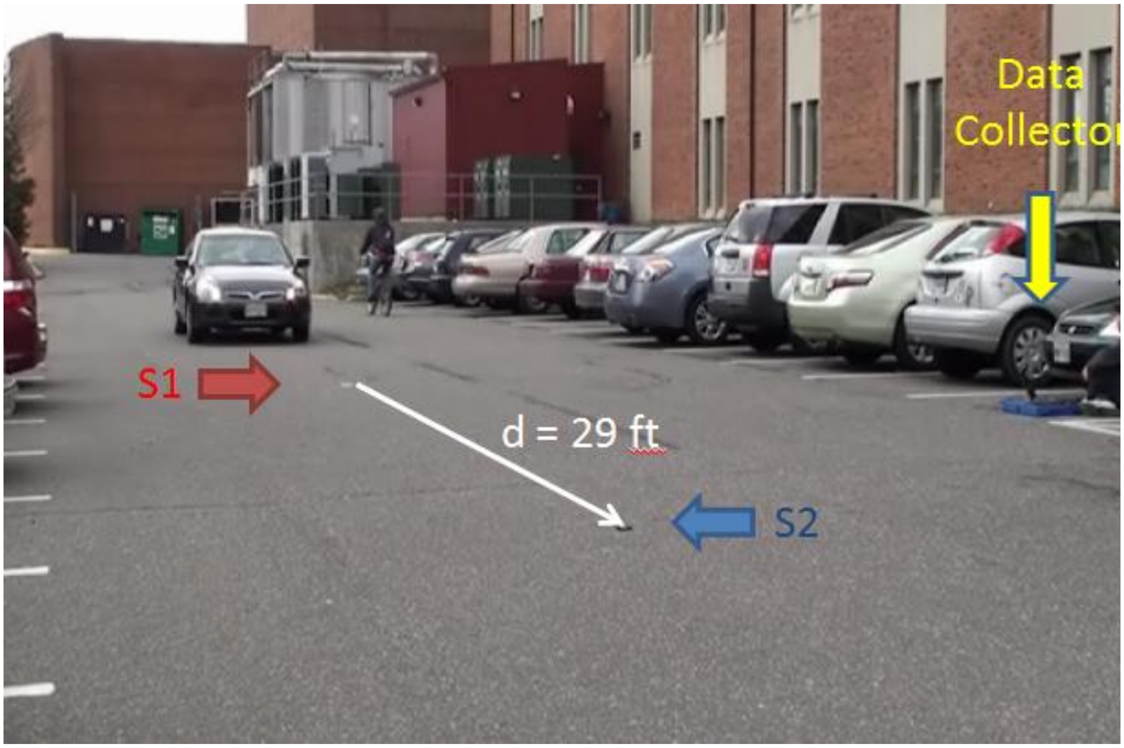


Figure 13. Vehicle detection and spot speed estimation experiment

Figure 14 shows the magnetic signature of the test vehicle captured by sensors S1 and S2 in the X, Y, and Z axes. As illustrated by the figure, the signature of the vehicle along the different axes has a similar pattern. However, due to noise, the different sensitivity of sensors, and the occasional packet loss during communication, speed along the different axes varies slightly. To have a more accurate result, the results over all axes were averaged. The numbers used in Equation 1 were calculated from a comparison of the local maximum points on the corresponding axes in three dimensions.

$$\overline{V_S} = 1/3\left(\sum_{i\in\{x,y,z\}} V_i\right) = \frac{14.22+15.32+13.92}{3} = 14.48 \text{ mph} \qquad \text{Eq (1)}$$

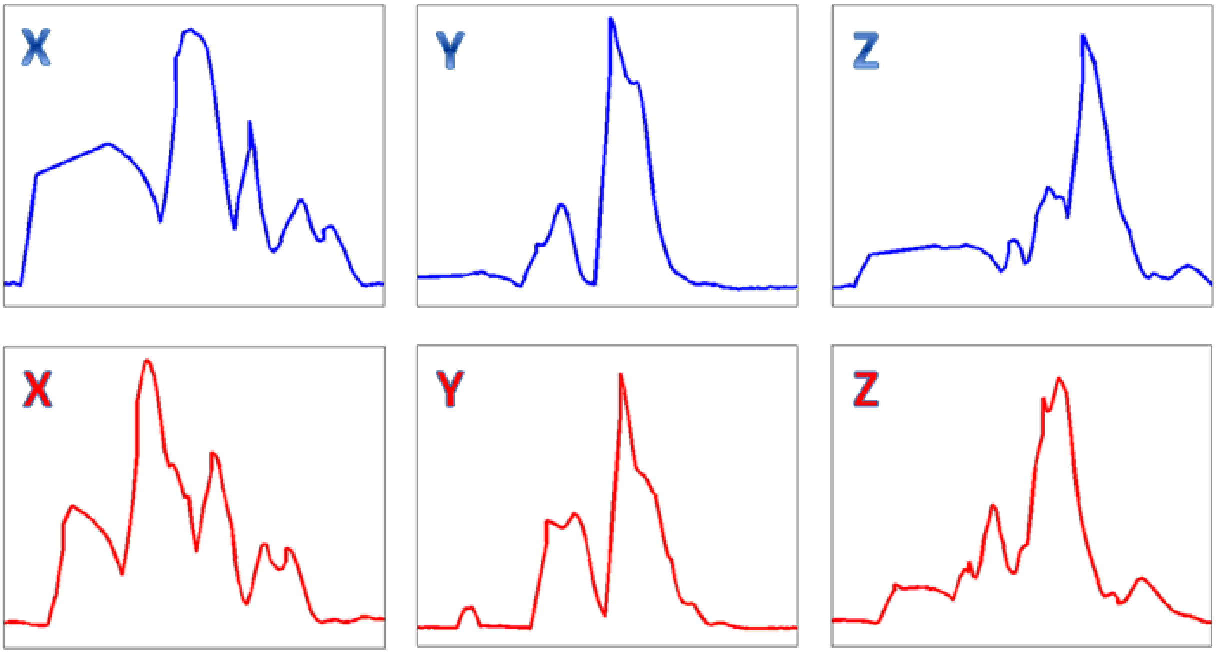


Figure 14. Magnetic signature of a vehicle in three direction captured by two sensors

In order to verify this calculated speed, video captured from a high-definition camera with a frame rate of 29 frames per second was used. Thirty-nine frames elapsed between when the vehicle passes over the first detector and when the vehicle passes over the second detector (Figure 15). The total time between when the vehicle passed over the first and second detectors was approximately 1.345 seconds (Equation 2).

$$\Delta t_{cam} = \frac{\text{frame \#}}{R_f} = \frac{39}{29} = 1.345s \qquad \text{Eq (2)}$$

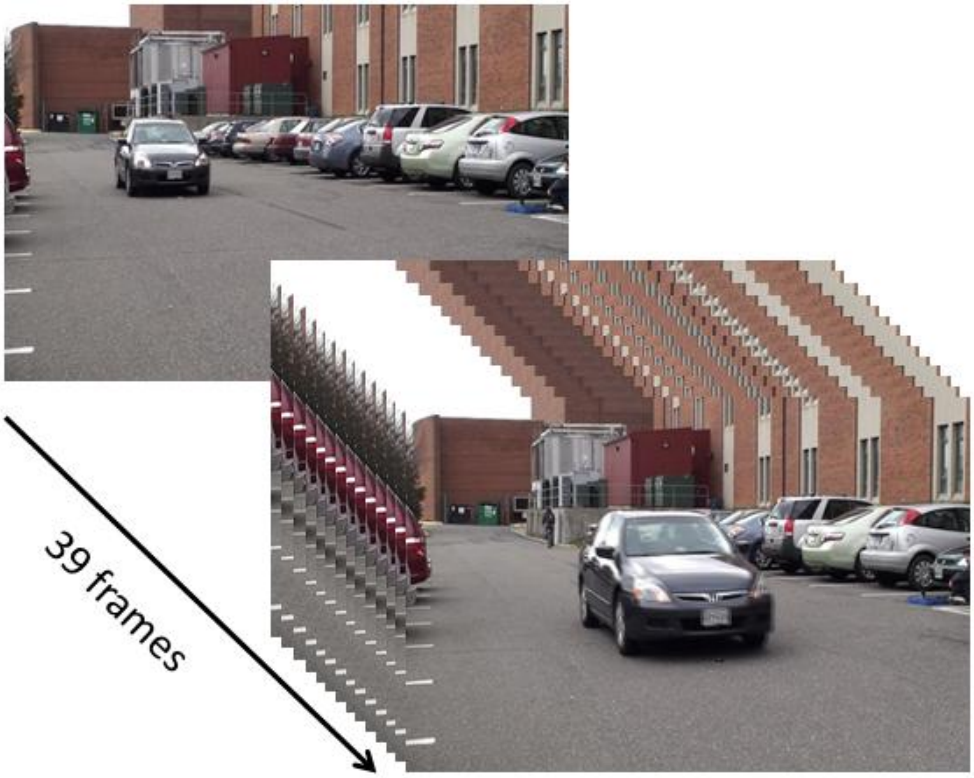


Figure 15. Analysis of high definition video for ground truth speed measurement

Repeating the experiment revealed an average 10 percent error in speed measurement compared to the ground truth.

3.4. False Detections

One of the biggest challenges when dealing with magnetic sensors is false alarms. False alarms occur because changes occur in the magnetic field at the sensor's location. These false alarms can be caused by non-vehicular sources or vehicles traveling in adjacent lanes. Additionally, false alarms can happen in highway settings with moving vehicles or in parking lot settings with static vehicles. The worst-case false alarm scenario happens when a large truck in an adjacent lane creates enough flux that it triggers a sensor in an empty lane (Figure 16). As a result, the sensor may mistakenly detect a vehicle and over count the number of vehicles traveled in its lane. To address this problem, a series of experiments was conducted to determine whether the detection threshold should be increased. Although this increase lowers the possibility of false detections and over counting, it causes the sensor to not to count some small cars and motorcycles. Results of the experiments were used to adjust the detection threshold on all three axes to reduce the probability of false detections. Another source of false alarm is the constant fluctuation of Earth's magnetic fields. However, this fluctuation is negligible when compared to the other sources of the false alarm. Finally, rapid changes in temperature may result in some offset on the measurement bridge. This problem was mitigated by programming the microcontroller to reset the sensing element in predefined intervals.

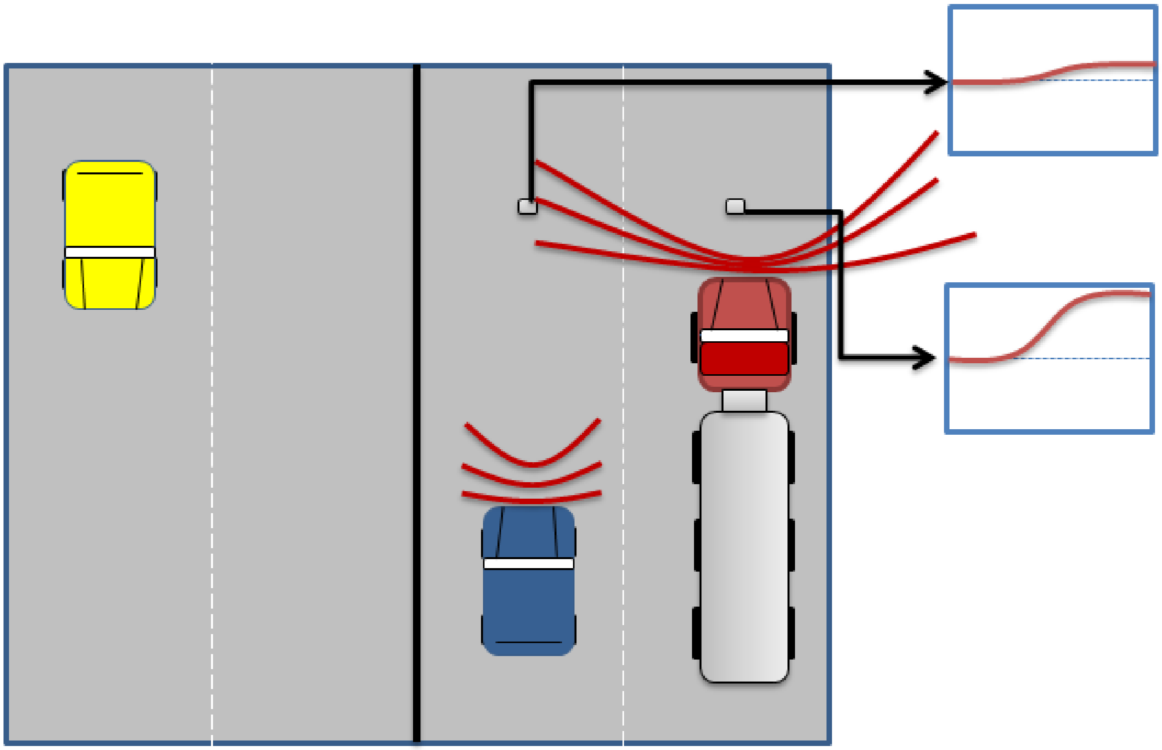


Figure 16. False detection

4. Test Deployments

The goal of this project was to develop prototypes that work in a real traffic environment and not just in a lab. After designing and building the enclosure, several devices were deployed and tested on the University of Maryland campus and a highway.

4.1. System Deployment on the UMD Campus

Multiple experiments were first conducted on UMD campus roads before highway deployment and testing of the devices. The results were used to improve the sensors and the roadside collector. To analyze the signal reception for the collector, the collector unit was installed on the roof of the four-story engineering building; the accompanying sensors were deployed on Campus Drive, which runs in front of the building. This configuration allowed us to test the communication range and the energy harvesting abilities of the sensors and the collector. Figure 17 shows testing the data collection unit with a unidirectional antenna on top of the engineering building; Campus Drive can be seen just below the solar panel.

Figure 17. Data collection unit with unidirectional antenna deployed on the UMD campus

During the test deployment, the magnetic signatures of vehicles on Campus Drive were collected and sent to the remote server in the lab. Data from video cameras were also collected and a side-by-side comparison of video and sensor data was performed. The results were used for sensor calibration. All deployments on campus were temporary and sensors were secured on the road surface using duct tape.

4.2. Testing Adhesive for Permanent Installation

In order to prepare for highway deployment, several commercial adhesives were acquired and tested. The goal of this phase was twofold: To make sure the sensors would stay in place after the deployment and to ensure driver safety. Experiments were conducted on an unopened section of the Maryland 200, the Inter County Connector. A hammer drill with chisel was used to dig a rectangular hole 0.5 inches deep into the pavement. A sensor was put in the hole and an asphalt-friendly epoxy was applied to the area. (The epoxy was mixed with some paint to make the final deployment less noticeable to the drivers.) The UM team and ICC personnel visited the installation site after a week to make sure that sensors were safe to deploy on the target section of the ICC, which was located on the operational part of the ICC. Figure 18 shows the efforts for testing the installation steps and materials for highway deployment.

Figure 18. Testing adhesive and testing installation steps for freeway deployment

4.3. Deployment on Inter County Connector (ICC)

After testing the system on the UMD campus and on an unopened section of the ICC, SHA personnel introduced the project team to Inter County Connector staff to discuss deploying the sensors on a new portion of the ICC before it opened for public use. The goal of the deployment was to detect vehicles, calculate volume, speed, and length-based classification on a lane-by-lane basis. Figure 19 shows a map of the deployment site. The location is easily accessible and has enough shoulder room for follow-up maintenance visits.

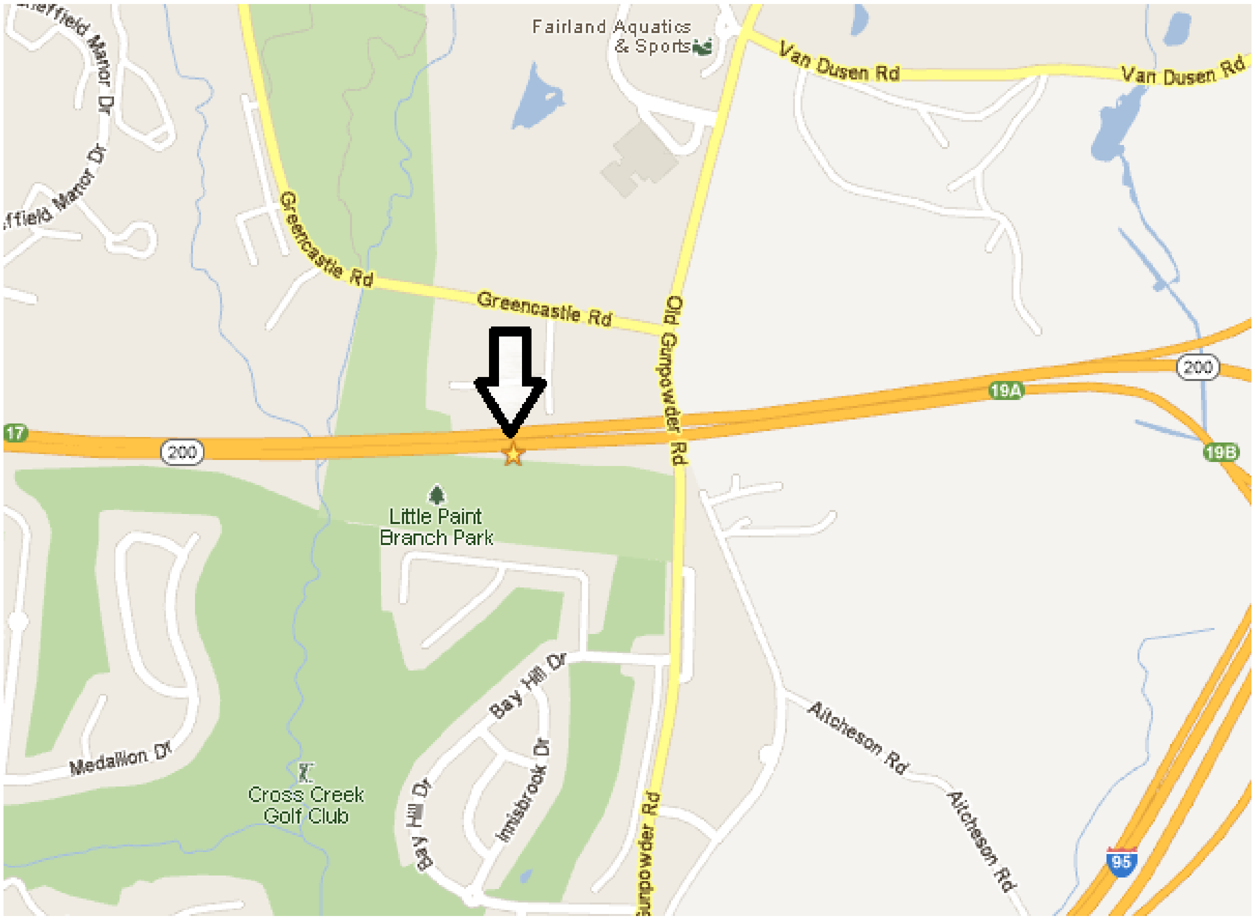


Figure 19. Map of the wireless sensor deployment on the Inter County Connector highway

Five sensors were deployed on this three-lane section of the highway: One sensor in each lane for vehicle counting, and an additional two sensors in the outer lane for speed and length calculations. Figure 20 shows the arrangement of all sensors and the roadside collector. The sensors on the outer lane have a 25-ft. separation.

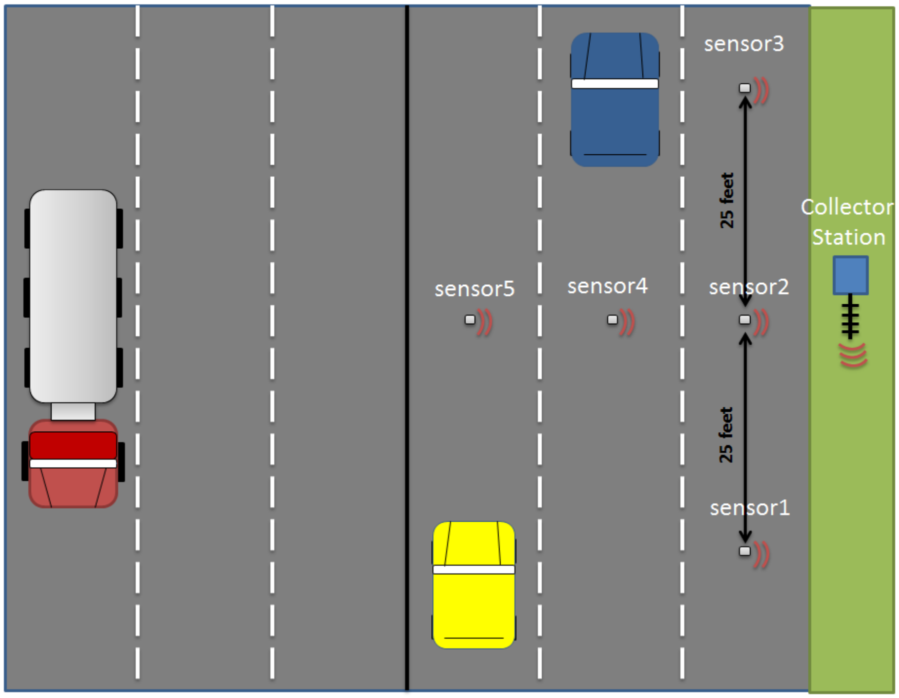


Figure 20. Arrangement of the wireless sensors on Inter County Connector test site

Furthermore, sensors were installed in the middle of the lanes. Figure 21 shows this step.

Figure 21. Measuring and marking the location of sensors for installation

After marking the location of the sensors, each sensor was carefully installed using the same procedure described in section 4.2. Figure 22 shows the installation steps. (Blue tape was used to avoid making cosmetic damage to the pavement after applying the epoxy.)

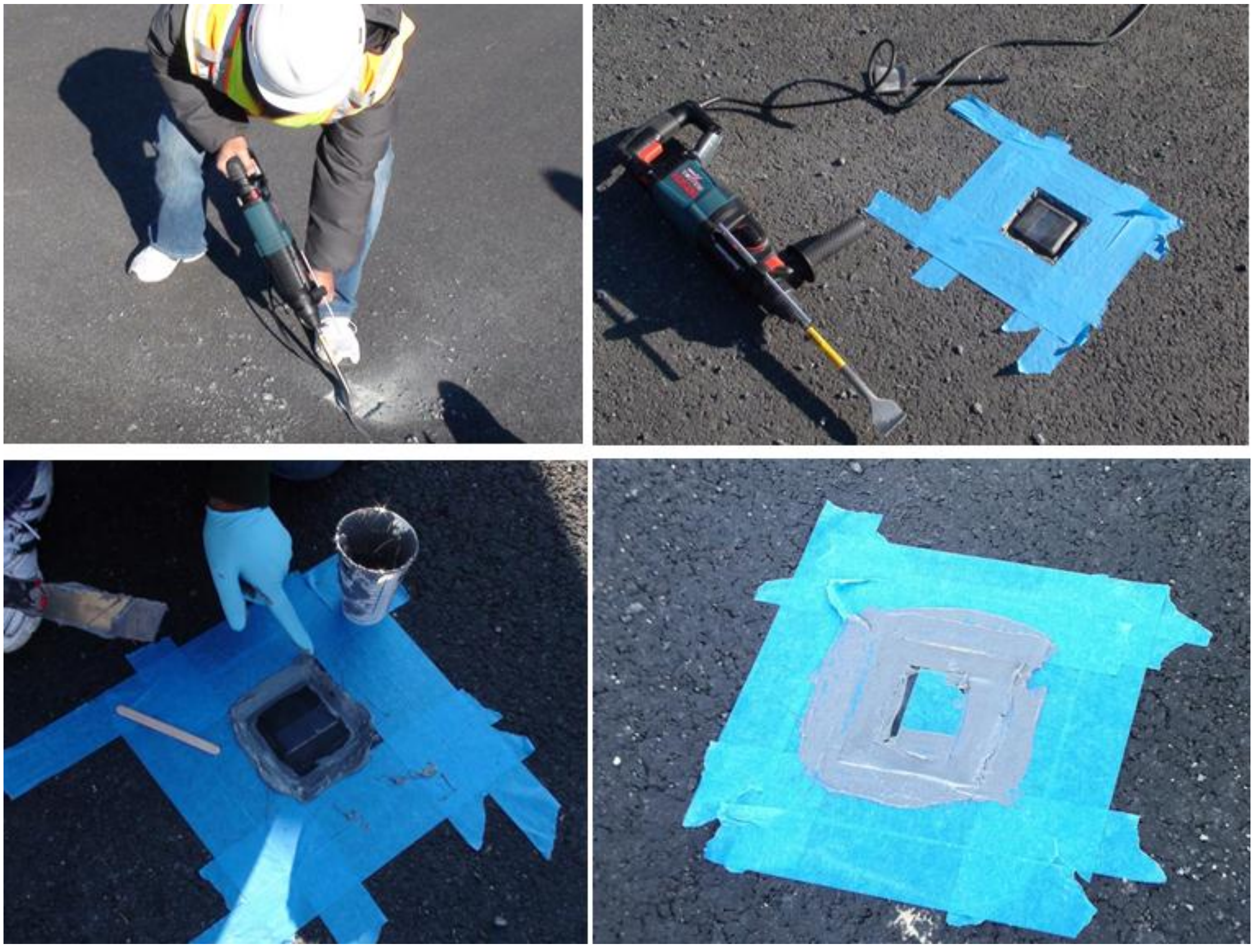


Figure 22. Installing wireless traffic sensors on the Inter County Connector pavement

After removing the tapes only the solar panel window of the senor remained exposed for energy harvesting. It should be noted that sand was applied to the surface of the sensor to prevent it from reflecting sunlight to the driver’s eyes. Additionally it improves the performance of the solar panel by attracting more light. As a result of this procedure, the sensors are barely noticeable on the road. Figure 23 shows the final results after installation.

Figure 23. Test segment of the Inter County Connector after sensor installation

After deploying sensors on the ICC, an appropriate location for the roadside collector was identified on an uphill next to the road. The roadside collector was mounted on a metal pole and was secured in a heavy bucket. The roadside collector and the mount were secured to the wall using metal ties. Figure 24 shows the installation and calibration of the unit. The roadside collector was set up to send the data to a remote server on UMD’s campus. As discussed earlier, the collector also has the capability to save a copy of the collected data on an SD memory card in the unlikely event that the communication link fails.

Figure 24. Roadside data collector installation on Inter County Connector test site

5. Signal Processing and Test Results

As discussed earlier, the magnetic signature of vehicles passing over these sensors is used for detection, counting, speed estimation, and length-based classification. Therefore, processing vehicle signature data in order to convert them to volume, speed, and other information is a crucial task.

Upon capturing the raw data, the microcontroller processes the data for information extraction. Specifically, the noise must be separated from data in this process. Additionally, there is a low-frequency offset in the data that must be eliminated because of the offset of the sensors, and the effects of temperature drift and Earth’s magnetic field.

The data can be processed either in a distributed scheme (i.e., within individual sensors) or in a centralized scheme (i.e., in a server). Each method has advantages and disadvantages. Distributed data processing has much lower data transmission, which results in significant energy savings. This is especially useful during the intervals during which the traffic rate is low (such as late evening hours and weekend days). Distributed processing also reduces the amount of data collected by the server, thus lowering the processing load on the server side. However, due to the limited low-processing capability of microcontrollers, sophisticated algorithms cannot be implemented in the sensors. Therefore, in the current deployment uses distributed data processing.

In order to do this a finite impulse response (FIR) filter was used to remove the effects of high-frequency noise and low-frequency offset. Since the signals are discrete in time, the Z-transform function was used to design the filter. In order to decrease the effect of high-frequency noises, additional zero points at z = j and z = -j were designed. To eliminate the low-frequency offset, zero points at z = 0 and z = -1 were used. To enhance the signal, four complement poles were applied at:

$z = 1/2\left(\frac{\sqrt{2}}{2} + j\frac{\sqrt{2}}{2}\right)$, $z = 1/2\left(-\frac{\sqrt{2}}{2} + j\frac{\sqrt{2}}{2}\right)$, $z = 1/2\left(-\frac{\sqrt{2}}{2} - j\frac{\sqrt{2}}{2}\right)$ and $z = 1/2\left(\frac{\sqrt{2}}{2} - j\frac{\sqrt{2}}{2}\right)$

As a result, the final Z-transform function is:

$$T(z) = \frac{Y(Z)}{X(z)} = \frac{(z-1)(z+1)(z-j)(z+j)}{\left(z-1/2\left(\frac{\sqrt{2}}{2}+j\frac{\sqrt{2}}{2}\right)\right)\left(z-1/2\left(-\frac{\sqrt{2}}{2}+j\frac{\sqrt{2}}{2}\right)\right)\left(z-1/2\left(-\frac{\sqrt{2}}{2}-j\frac{\sqrt{2}}{2}\right)\right)\left(z-1/2\left(\frac{\sqrt{2}}{2}-j\frac{\sqrt{2}}{2}\right)\right)} = \frac{(z^2-1)(z^2+1)}{(z^2-\frac{1}{4}j)(z^2+\frac{1}{4}j)} = \frac{z^4-1}{z^4+\frac{1}{16}} \quad \text{Eq(3)}$$

Therefore:

$$T(z) = \frac{Y(Z)}{X(z)} = \frac{1-z^{-4}}{1+\frac{1}{16}z^{-4}} \qquad \text{Eq(4)}$$

The transformation function in Equation 4 and filtering mechanism were coded in the microcontroller. Figure 25 is an example of magnetic signature (top, blue), the processed version (pink), and the detection signal (bottom, blue). In this figure, the original signal was filtered to bell curves by eliminating noises and offsets. Then, using a threshold comparison, the sensor can make a detection on a vehicle above it.

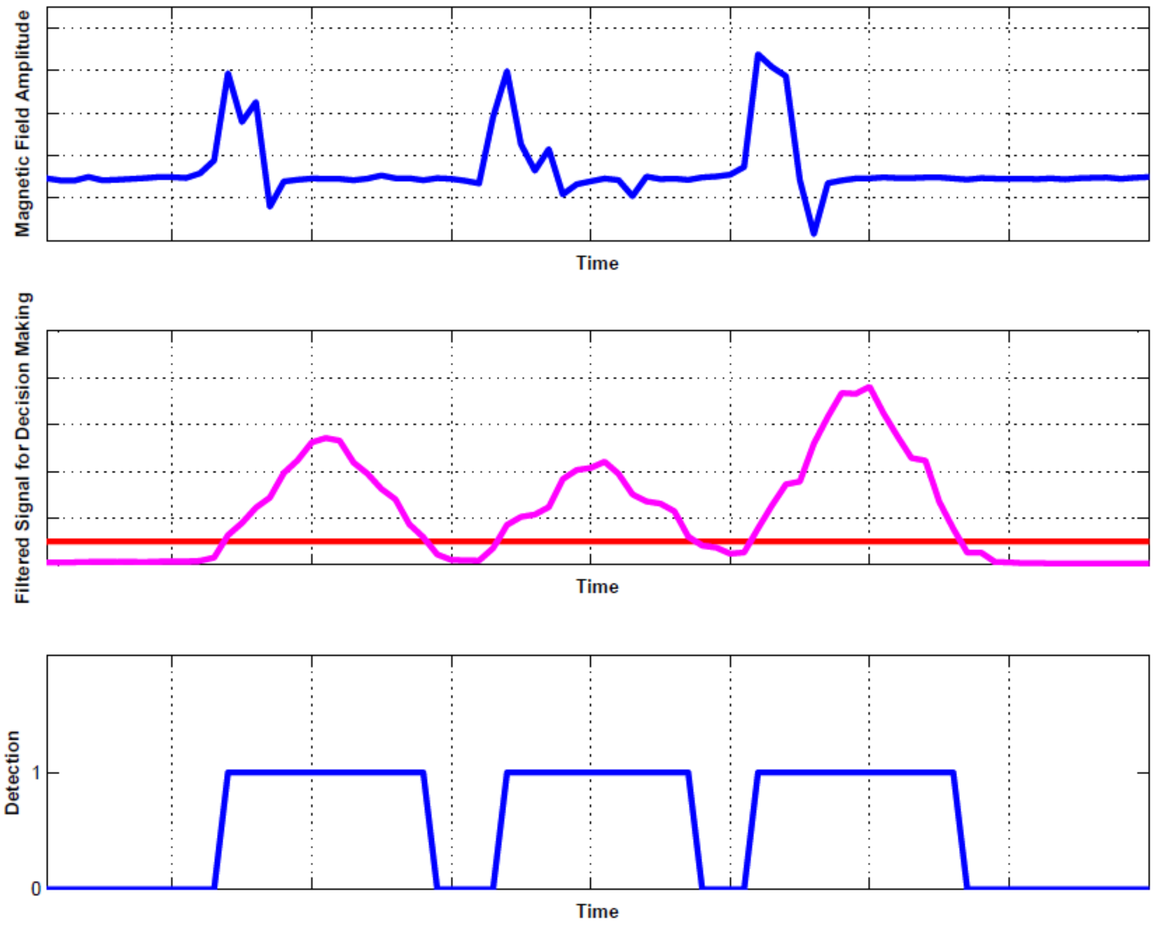


Figure 25. Sample of magnetic signature signal processing and detection results

5.2. Distributed Data Processing

In the test deployment of sensors on the ICC, the Earth's magnetic field is sampled at 100Hz -- sensors automatically calculate the baseline magnetic field of their environment upon deployment. Once a sensor detects a change from the baseline magnetic field level, the sensor goes into a processing state to determine the presence of a vehicle. A specific algorithm is designed and implemented in the sensor, which operates on thresholds. A predefined value in each sensor is specified (the baseline magnetic field level) to which the measurement of magnetic fields on the X-, Y-, and Z-axes are compared.

If a vehicle is detected, the sensor collects data about how long it takes the vehicle to travel over the sensor. (These times are not directly related to the length of the vehicle – they are also a factor of the vehicle's speed. For example, a long vehicle may travel at a high speed. Therefore, a sensor would collect a short time signature for that vehicle.) In order to have an accurate estimate of a vehicle's length, the vehicle's speed needs to be determined first. Figure 26 depicts the length of signatures collected during different times of the day by one of the sensors on ICC.

Figure 26. Length of the digital signature signal for a sample time interval

Figure 27 shows a detailed version of the signature length for a seven-minute interval. As noted in the figure, 14 vehicles passed over the sensor.

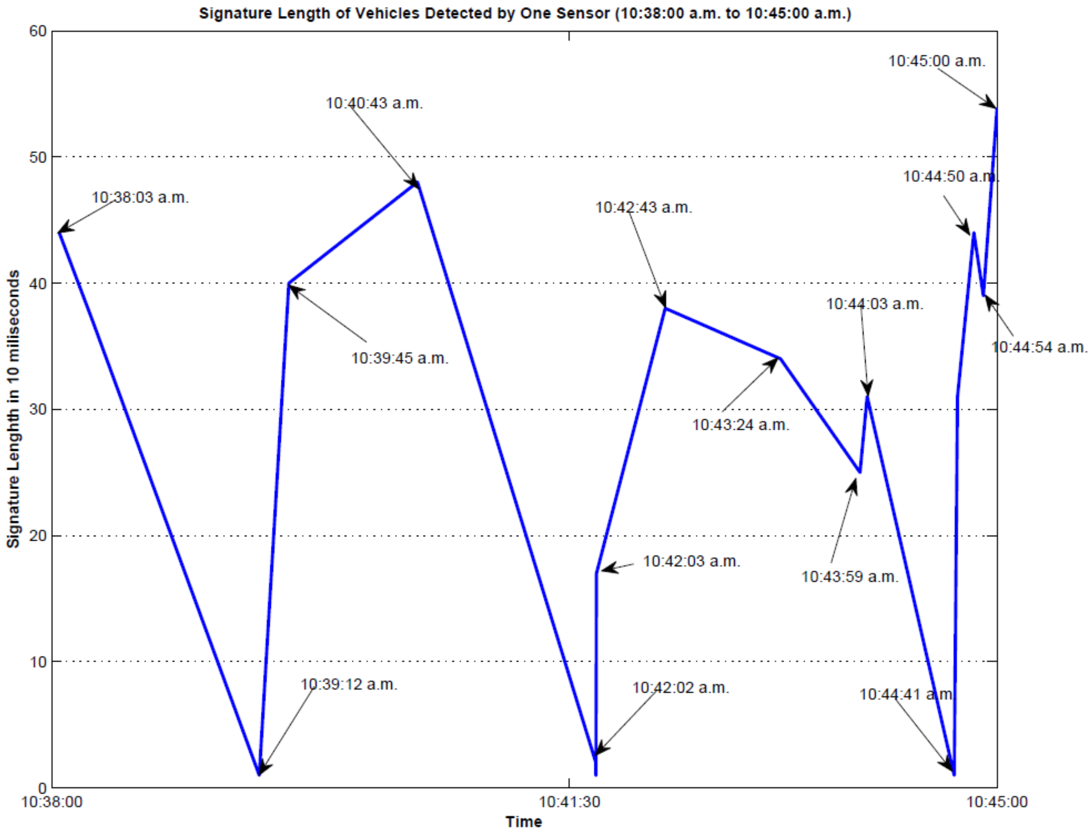


Figure 27. Details of the digital signature signal for a seven-minute interval

Vehicle counting can be extracted from the above signal using some basic calculations. Sample vehicle counting results are shown in Figure 28.

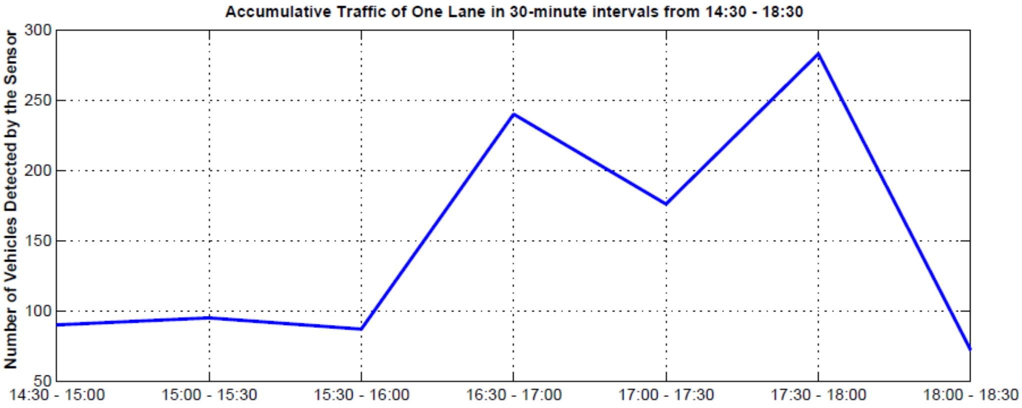
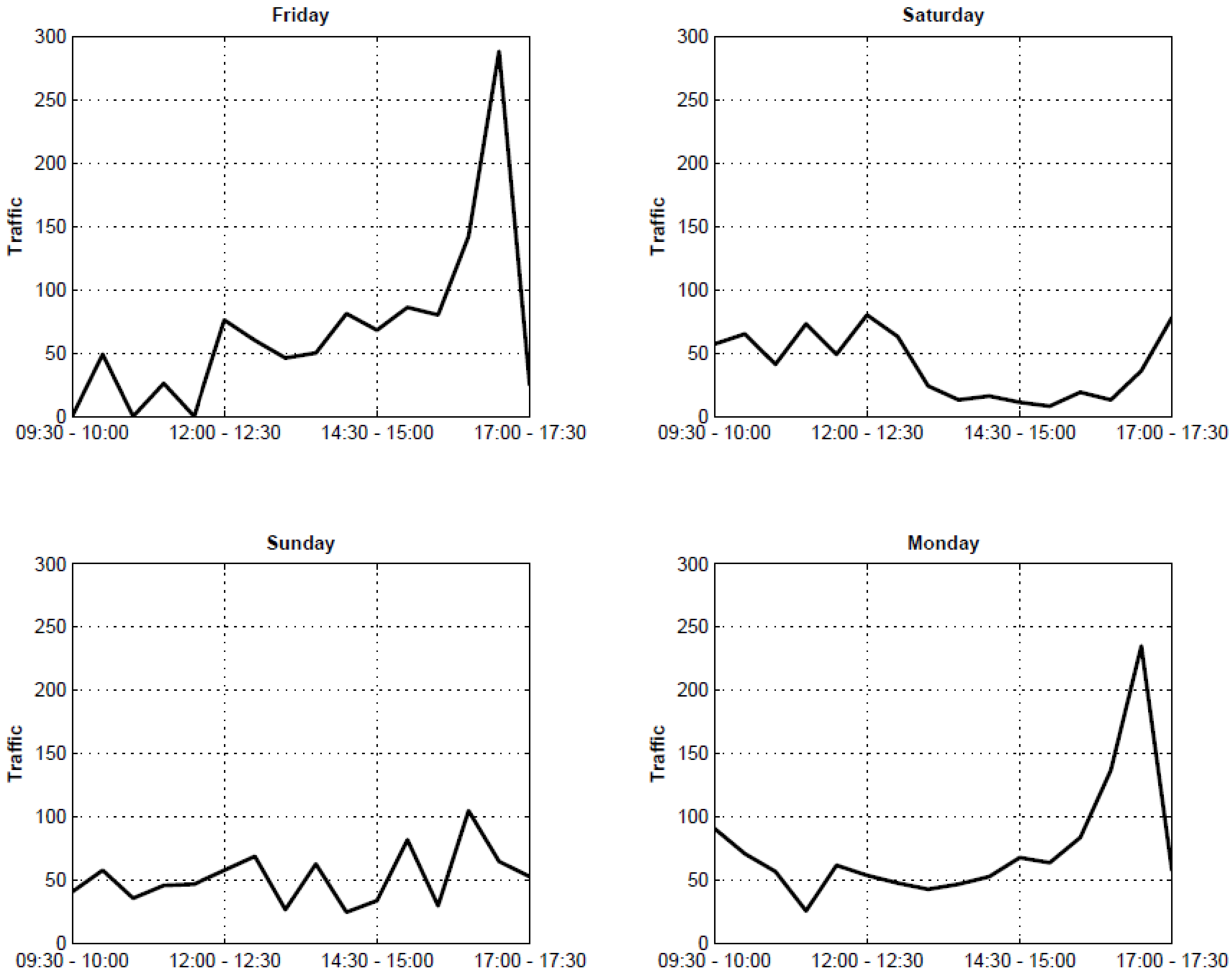


Figure 28. Lane volume data extracted from the digital signature

Vehicle-counting data from one sensor on different days of a week is shown in Figure 29. Similar patterns exist for days that compose a typical work week. For example, during Friday's evening rush hour, one can see a peak in the values, indicating that nearly 300 vehicles passed over the sensor. On weekend days, however, a generally flat vehicle count was observed. The count, however, is higher Saturday morning than Saturday afternoon.


Friday

Saturday

Sunday

Monday

Figure 29. Sample volume data reported by one senor for different days of the week

A side-by-side comparison of traffic volume between different lanes is illustrated in Figure 30. The blue line represents the middle lane and the red line shows the lane closest to the road's shoulder. According to this figure, the morning peak period occurred around 9:00 a.m. and the vehicle count is almost the same for the lanes (approximately 55). However, in the middle of the day, approximately 1:00 p.m., the middle lane is used more. In low-volume traffic conditions, drivers tend to drive in the middle lane.

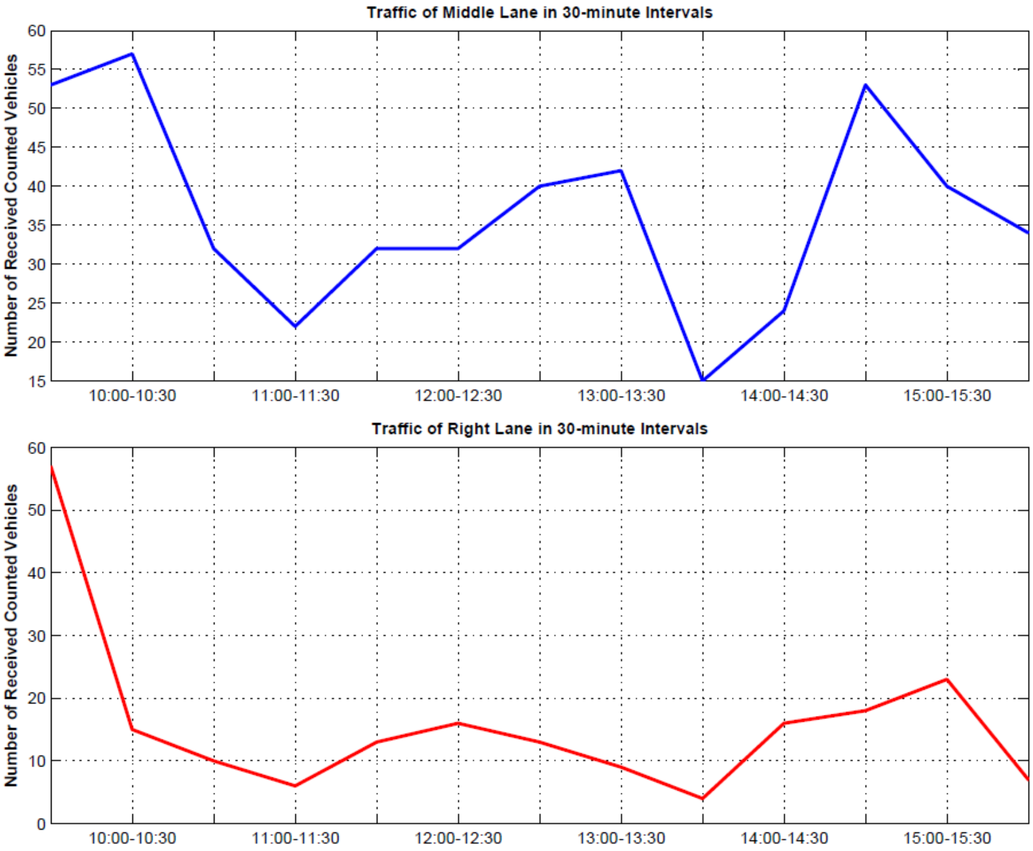


Figure 30. Lane-by-lane comparison of traffic volume

The signal-processing algorithm is sensitive to the threshold parameter. The threshold parameter depends on both the environment and the average speed of vehicles. One of the main challenges faced during the test deployment was to set this threshold to an appropriate level. Despite extensive effort and multiple experiments on UM's campus, the parameters that resulted from those trials could not be applied to highway conditions that differed in traffic volume and number of lanes (Campus Drive has only one lane in each direction). Modifications to these parameters were necessary to prepare sensors for freeway conditions. Another challenge that the firmware of the sensors could not be changed after the sensors were deployed, so over-the-air programming of the devices was not possible after deployment. These challenges were addressed by programming into sensors a series of threshold levels and by using the most appropriate parameter after calibration. One advantage of this effort was to analyze the marginal impact of different threshold values by comparing it to the ground-truth collected by video imaging.

5.3. Speed Measurement

The speed of a vehicle can be determined by using two sensors deployed on the same lane with a predefined distance between them. (This method assumes that a vehicle does not change lanes in the 25 ft. between the ICC sensors.) The time offset for the signature of the same vehicle on the two sensors is used to estimate the speed.

In Figure 31, the red and blue lines show the data from two sensors in one lane. Since there are three sensors on the rightmost lane of the ICC deployment, the signature time offset can be matched based on the two farthest sensors, which are approximately 50 ft. apart.

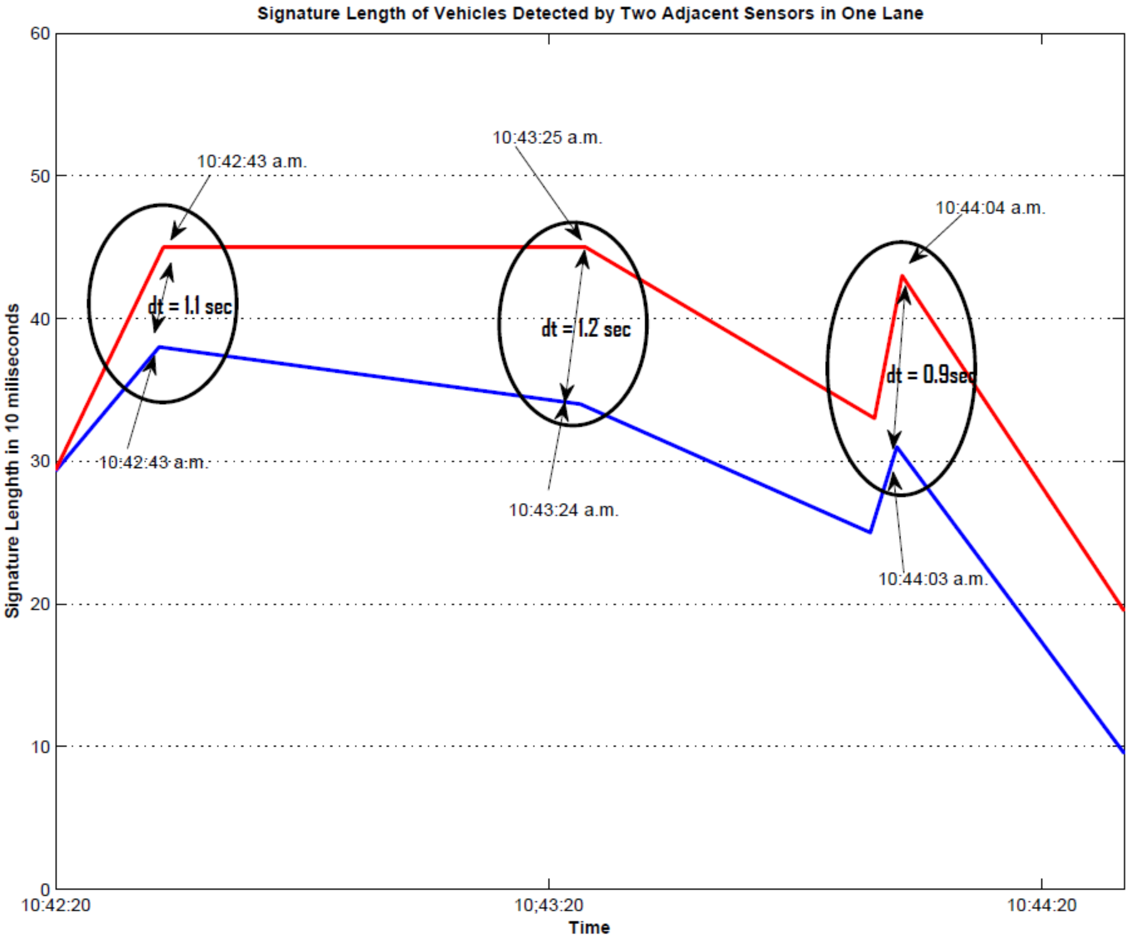


Figure 31. Signature offset measurement between two consecutive sensors

Figure 32 shows that the distance between the two sensors is traversed in approximately five seconds for two sample vehicles. This results in an estimated speed of 50 mph for each vehicle. (The time offset can also be used for estimating the vehicle length. In this example while both vehicles have similar speed, the length of the first vehicle is approximately 12 - 15ft. and the second vehicle is approximately 18 - 21ft. Length-based calculations will be discussed more fully in section 5.4.)

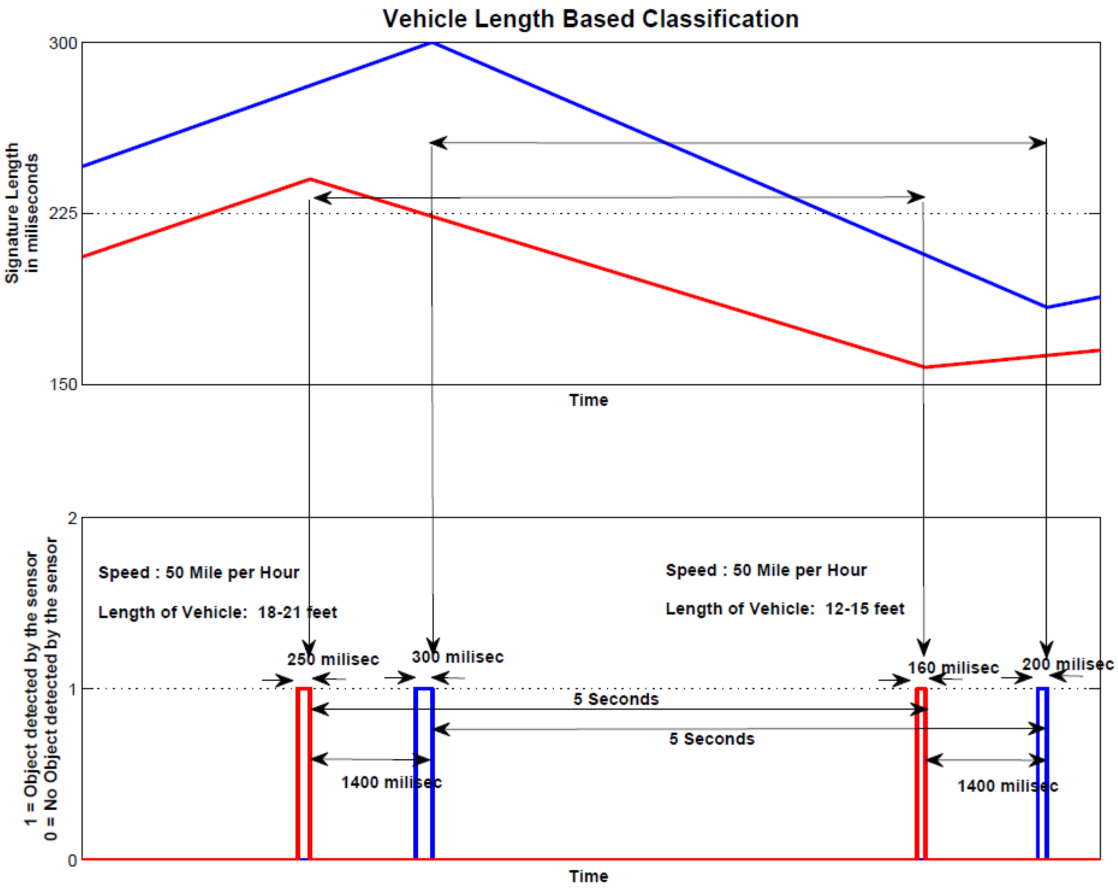


Figure 32. Signature offset measurement for speed estimation

The above calculations are accurate only if time in both sensors is synchronized. To make sure sensors are synchronized, each packet was stamped with the local time obtained from the cellular modem, which is synchronized with a remote Internet server. The raw measurement of the sensors can also be sent back if a specific event needs to be watched more closely.

5.4. Length-based Classification

After receiving the packets from the installed sensors, the data collector puts a time stamp on each packet. Because the coordinator’s internal time is continuously updated through the modem connection, a synchronized array of events (e.g., detection of vehicles, or keep-alive signal) are always obtained from two consecutive sensors. Additionally, there is a low chance that one car can overtake the other in the short distance between two sensors, considering typical highway speeds on the highway.

As discussed earlier, after a vehicle’s travel time is estimated, further signal processing can help estimate the length of a vehicle. Figure 33 shows sample signature matching for vehicle classification for a series of traveling vehicles. This figure shows the travel time of vehicles reported by two sensors in the same lane. The pulses in the middle and bottom part of the figure show the time during which the vehicle passes over each sensor. Because sensor 1 is ahead of sensor 2 in the lane, the pulses are timely separated. In Figure 33, the lengths for the corresponding vehicles were matched with the same color.

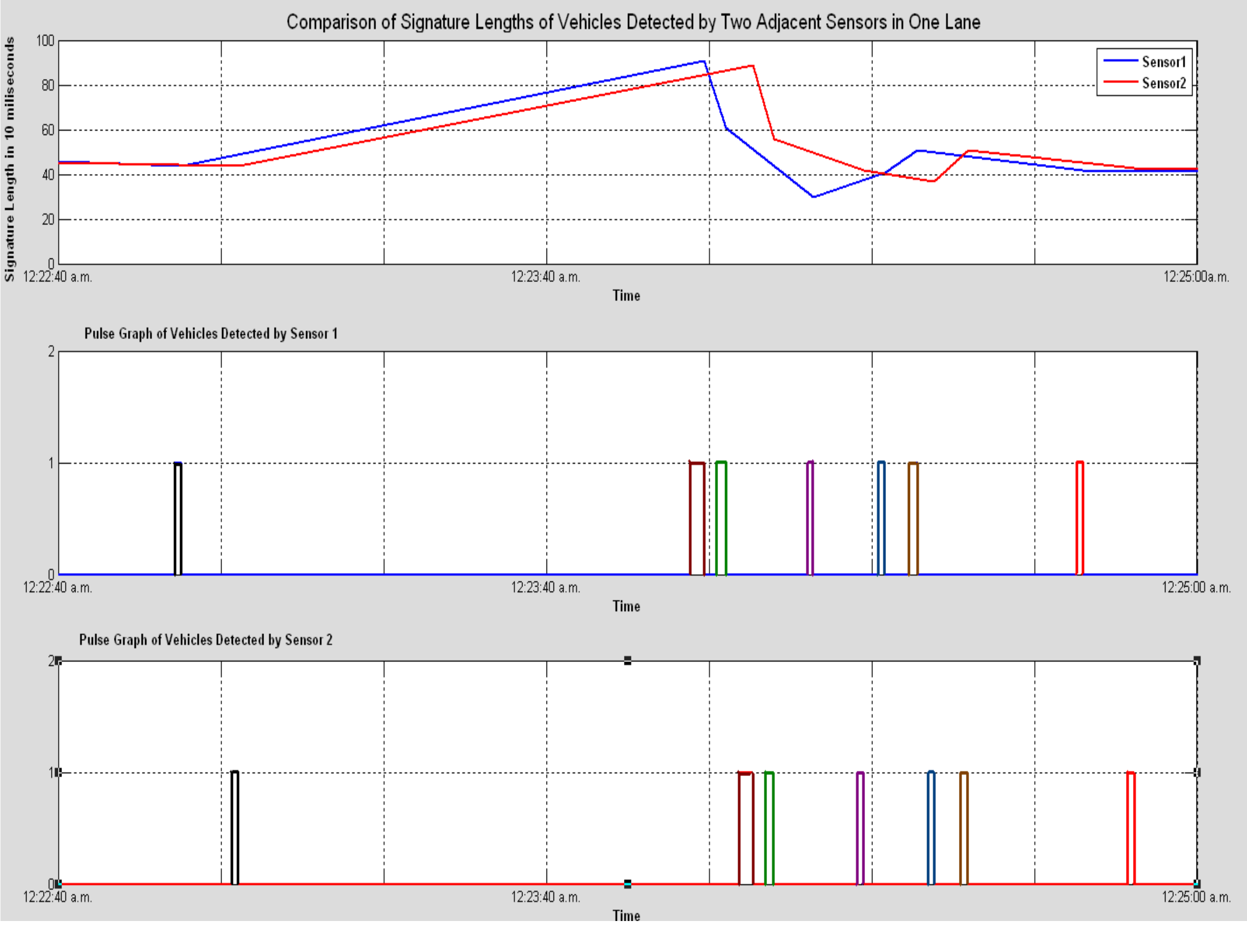


Figure 33. Signature matching for length based classification

The classification algorithm is summarized in the flow chart shown in Figure 34.

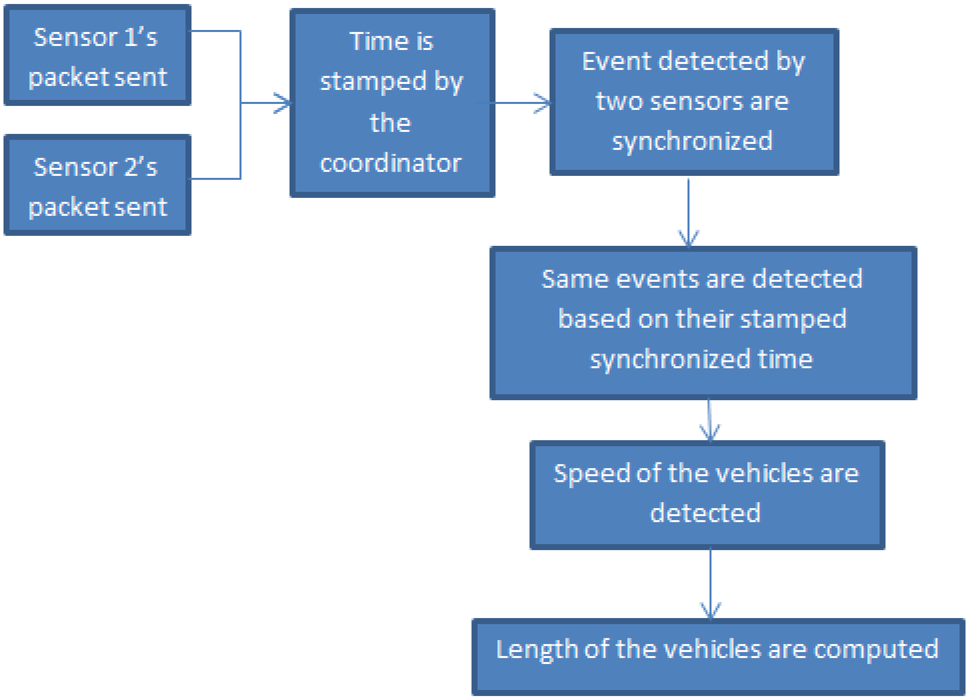


Figure 34. Event-matching and signature-processing for vehicle length estimation

5.4. Energy Harvesting

The performance of the energy-harvesting circuit on the unit was satisfactory during daylight hours. However, the devices could not save enough energy from daylight hours to cycle through to next morning. It is important to note that this report was prepared based on data collected in the winter, when availability of solar hours is lowest and least intense of any time in the year. Figure 35 shows that the energy storage unit has enough charge to function until approximately 3 p.m. After 3 p.m., the sensors began to use their reserved energy because of a lack of sunlight. Sensors can continue operating until the voltage drops below 2.6v, which happened approximately 6:30 p.m. during the course of experiment. This problem can be ameliorated by changing the dimensions of the solar panel, increasing storage capacity, and making improvements to the software and hardware.

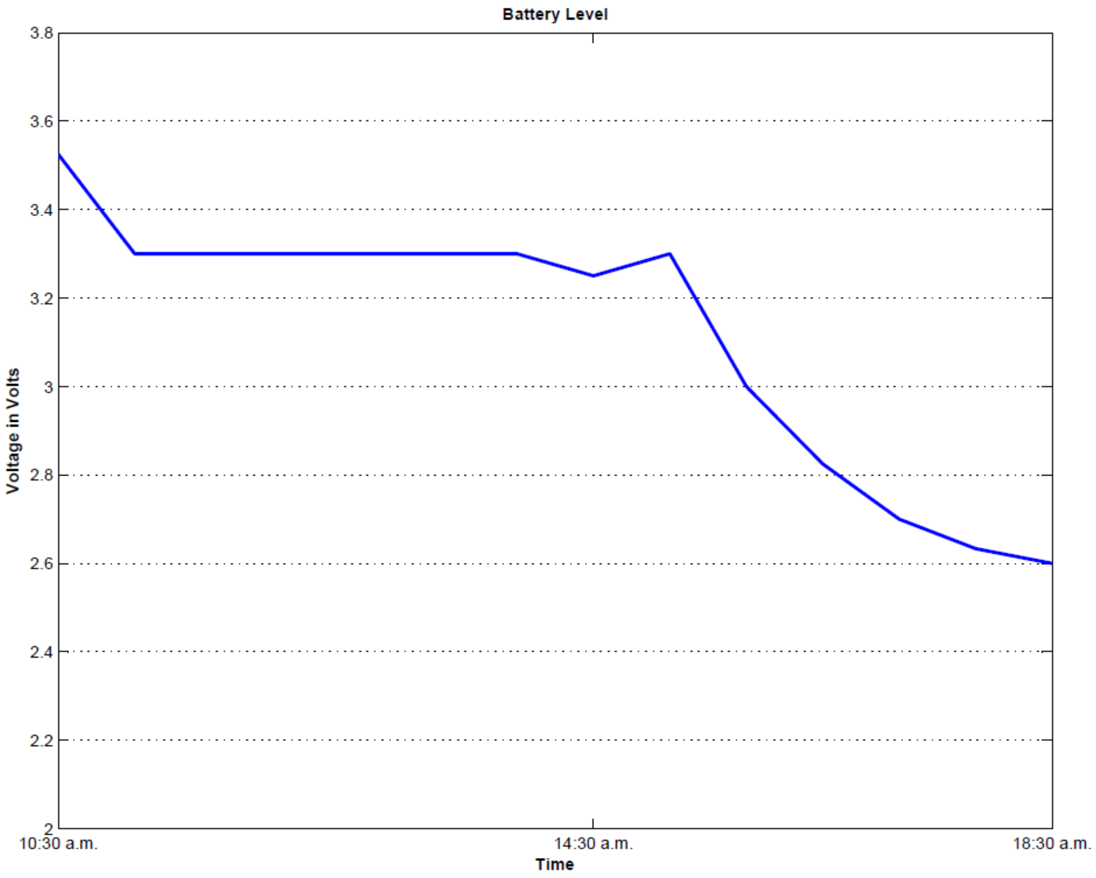


Figure 35. Voltage level of a sensor in a sample day

6. Conclusions and Future Research

New traffic sensing devices based on wireless sensing technologies were designed and tested. Such devices encompass a cost-effective, battery-free, and energy self-sustained architecture for real-time traffic measurement over distributed points in a transportation system. This scalable technology can monitor traffic parameters such as flow, occupancy, point speed, and vehicle classification on road systems in real-time. The data collector device is also equipped with a memory card reader, which makes it suitable for temporary installation and short-term data collection. A weather-resistant enclosure was designed and manufactured to protect the sensor from vehicle impacts on the highway. In addition to traditional traffic parameters, the sensors can measure and report the temperature of their surroundings because they are surface-mounted. The sensors developed as a result of this project are also capable of capturing a digital magnetic signature of vehicles within any intervals required by clients. The digital magnetic signature was processed to calculate traffic volume, vehicle speed, and vehicle length estimation for classification. With the help from SHA and Inter County Connector staff, five sensors were permanently deployed and thoroughly tested on a section of the ICC. Lane-by-lane data on this segment of the highway is reported and archived in a server on the UM campus. The results indicate that the developed wireless vehicle sensing architecture can be adapted for a range of traffic management applications. Direction for future research includes:

- The sensors developed as a result of this project are capable of collecting high-resolution magnetic signatures, which, after signal processing, can be used for anonymous vehicle matching and tracking. The experiments conducted during the course of this project show the reliability of the magnetic signatures data collection and the potential for travel time and OD estimation. However, given energy limitations, further research is needed to develop ultra-efficient signal processing algorithms for signature-matching purposes. Transmitting a high-resolution signature is energy intensive. To overcome the energy constraint, the devices built for this project took advantage of a modified and condensed version of the digital signature to re-identify vehicles based on their length and to provide length-based classification. However, with further research and modifications in hardware and software, obtaining and communicating higher resolution signals will be possible. In the final month of the project schedule, a new ultra-low-power AMR sensing element was introduced to the market. This new AMR sensing element provides a greater sampling rate and requires much less energy compared to current elements available in the commercial market. The flexibility of the hardware design in this project will allow adoption of such technologies. Further research is needed to implement efficient and advanced signal processing algorithms in the microcontroller so that important features of the signal can be extracted to reduce the signature into information before transmitting to the data collector.

- In this project, the sensors were surface-mounted. However, in special infrastructures (such as tunnels where only two lanes exist), these sensors can be modified to be wall-mounted. This adaptability will make the installation of sensors easy and will also allow for data collection on these critical facilities with high granularity. Additionally, the energy harvesting component of these sensors can be eliminated and replaced with a battery pack to increase reliability of the data collection system and to address the lack of ambient light in tunnels. The operators will still be able to monitor traffic volume, speed, headway, and occupancy for each lane. Mounting sensors on tunnel walls will allow for the accurate measurement of the queue length if incidents happen and traffic backs up in the tunnel.
- New technologies for travel-time measurement (such as Bluetooth sensors) collect a sample from the traffic stream and estimate the travel time for a particular segment. Although the data provided by such technologies (such as travel time and average speed) provided by such technologies is useful, having traffic volume data on the corresponding segments is needed to understand the dynamics of the underlying traffic conditions. The sensors developed in this project can be modified to synchronize with Bluetooth detectors and provide an accurate picture of the dynamics of underlying traffic conditions. By

developing sensors that combine Bluetooth and wireless magnetic technologies, the penetration rate of Bluetooth can be measured. The system can also be used for analyzing vehicular movements and traffic patterns at locations where highways merge or split. Applications include dynamic message sign (DMS) operation analysis and highway OD estimation. An additional limitation of Bluetooth detectors and probe-based data such as INRIX travel time is that they are incapable of separating data by lane, which necessitates additional devices for collecting data to monitor traffic conditions. However, the wireless magnetic sensors developed for this project can supplement these Bluetooth detectors and probe-based technologies.

- The sensors created for this project were developed to collect data about highway traffic in which vehicles travel at relatively high speeds. However, the sensors can be modified and calibrated for arterial operations. By deploying multiple sensors at intersections, the presence of vehicles and the length of the queue behind the stop bar can be measured and communicated to the signal controller.

7. References

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