South Jersey Real-Time Motorist Information System: Technology and Practice

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ABSTRACT

Intelligent Transportation Systems (ITS) aim at reducing travel time by controlling the existing transportation infrastructure through use of state-of-the-art technology. One of the current emphasis areas in ITS is improved coordination of existing, as well as future infrastructure to improve the safety and reliability of surface transportation systems and to be able to restore the transportation system to normalcy in case of a disaster. Many ITS technologies, such as smart card technology, Global Positioning System (GPS) on cargo trucks, weigh stations, E-Z pass technology, traffic sensors, and wireless communication, which are aimed to increase the efficiency of the transportation services can now be used to ensure the security of the surface transportation system in the event of unexpected emergencies.

One of the similar efforts launched in New Jersey, by the New Jersey Department of Transportation (NJDOT) is the project entitled “South Jersey Real-Time Motorist Information System” aimed at rapid deployment of available ITS surveillance and communication technologies to monitor traffic on the basis of need at different locations in the South New Jersey network. The proposed system is a highly mobile traffic surveillance system that is made of mobile self-sufficient systems called Sensor Processor and Communication Units (SPCU) and accompanying communication and data collection capabilities for sensor unit to exchange information with the traffic control center.

In this specific version of the system, congestion alerts are disseminated to selected motorists through pagers. In this proposed system, the basic novelty is to have portable sensor units that can be installed easily at any location on the transportation network without any delays for establishing power and communication connections to the infrastructure. This rapid deployment capability of the system is in accordance with the new efforts to develop easy to deploy traffic surveillance systems to better manage the transportation system during any type of disaster situation.

This system was first tested in a highly congested portion of the South Jersey highway network on highways I-76 and I-676 in New Jersey that lead to two major area bridges - the Walt Whitman and the Ben Franklin, which connect the cities of Camden and Philadelphia. In this paper, we present the technical overview and the advantages of this system, and its evaluation procedure as performed by the Rutgers researchers. We also present the problems faced during the implementation of such a prototype system, and finally list the lessons learnt, along with future plans for deployment.
SECTION 1. INTRODUCTION

ITS aims at reducing congestion by controlling the existing transportation infrastructure using state-of-the-art technology. One of the current emphasis areas of ITS is to improve the safety and reliability of surface transportation system, and be able to restore the transportation system to normalcy in case of a disaster. Many ITS technologies, such as smart card technology, Global Positioning System (GPS) on cargo trucks, weigh stations, E-Z pass technology, traffic sensors, and wireless communication which are aimed to increase the efficiency of the transportation services can now be used to ensure the security of the surface transportation system in case of unexpected emergencies.

In response to this increased awareness of the need for better and more innovative surveillance systems, on June 13, 2002, USDOT issued a request for a model deployment to augment the existing surveillance and monitoring system to increase the security of surface transportation. In fact, this request issued by USDOT emphasizes the need for more widespread and efficient use of “information technology” solutions for improved surface transportation system security and reliability under specific situations and scenarios (ITS America Web Site).

In New Jersey, with the similar effort, the NJDOT launched the project entitled “South Jersey Real-Time Motorist Information System” aimed at rapid deployment of available ITS surveillance and communication technologies to monitor traffic on a demand by demand basis at different locations in South Jersey network. From historical observations it is well known that southern New Jersey highways have already reached high traffic congestion levels due to the demand between the Camden County and the Philadelphia business district. The main objective in this project was to develop easy to deploy traffic surveillance system and a real time motorist information system and to test on highways I-76 and I-676 in NJ that lead to two bridges, the Walt Whitman and the Ben Franklin, which connect Camden and Philadelphia cities. The parties involved in this project are:

- New Jersey Department of Transportation Bureau of Transportation Technology
- NJDOT, Traffic Operations – South Jersey Division
- Rutgers University, NJ
- New Jersey Institute of Technology
- L-3 Communications Inc.
- Cross County Connection Transportation Management Agency

Any type of major natural or man-made disaster necessitates rapid response measures for effective management of the transportation network. The key for effective traffic management in such a scenario is real-time surveillance capability that will allow the traffic operation center (TOC) to understand the situation not only at the disaster location, but also in the of the network to evacuate people from the disaster area. For example, in the event of a hurricane, where there is a day or two to evacuate the people, it is highly desirable to have a system that can be deployed along the evacuation routes in a short time after the evacuation decision becomes imminent.

Unfortunately, the deployment of existing surveillance systems using state-of-the-art technology takes an unacceptably long time due to the time required for providing power and
communication for the sensors to be completely operational. Moreover, the design and implementation of a central data gathering and processing system that can communicate with the deployed sensors is a time consuming task that cannot be attempted for such time-dependent emergencies. Thus, a traffic surveillance system that can be deployed in less than few hours can be of important use in acquiring real-time surveillance at the key routes of the network.

The proposed system in this project is a highly mobile traffic surveillance system that is made of mobile self-sufficient systems called Sensor Processor and Communication Unit (SPCU) and accompanying communication and data collection capabilities for sensor unit to exchange information with the traffic control center. The novelty in this proposed system is to have portable sensor units that can be installed easily at any location on the transportation network without any delays for establishing power and communication connections to the infrastructure.

In this specific demonstration project, the following steps were taken prior to deploying the proposed system:

- **Determination of the sensor locations in the test network**: Real-time and effective traffic advisory is only possible if the travel conditions over the test network are detected in a timely manner. This, in turn, depends on the effectiveness of the deployed surveillance system. A careful selection of the sensor locations is very important for the accurate representation of travel conditions along the test network (See section 3.2.1).

- **Development of an Integrated Traffic Surveillance and Communication Architecture**: A traffic surveillance and communication architecture that will ensure real-time traffic data acquisition including traffic volumes, speed and occupancy were developed (See section 2.1).

- **Development of Real-Time algorithms for estimating congestion levels**: The real-time data collected by the deployed system were used to generate simple, yet useful, information to be sent to motorists traveling on this test network (See section 2.2.2).

- **Dissemination of the Motorist Advisory Information**: This can be accomplished using different information dissemination techniques including cell-phones, pagers, a web page for pre-trip information users, highway advisory radio and VMS for en-route information users. In this specific version of the system, congestion alerts are disseminated to selected motorists through pagers. Pagers, being considerably inexpensive and commonly used when this idea was contemplated, sufficed in proving that the necessary information could be disseminated successfully.

Next, in section 2, we describe the various technical aspects of the proposed system. Section 3 outlines the system evaluation work conducted by the Rutgers Team. Finally, Section 4 talks about the future work and lessons-learned.
SECTION 2. SYSTEM DESCRIPTION AND TECHNICAL OVERVIEW

2.1. System Components

In anticipation of the need for such a system, NJDOT in cooperation with Rutgers University and L-3 communications Inc. has built a prototype system that is shown in Figure 1. The system has 3 principal components:

- Traffic Sensors
- Sensor Processor and Communications Unit (SPCU)
- Central Monitoring and Reporting Station (CMRS)

****Insert FIGURE 1 Prototype Sensor Processor and Communication Unit (SPCU)****

Figure 2 is a pictorial diagram of the existing system and the operation of its components. Roadside traffic sensors can view multiple lanes of traffic from an elevated mounting location at roadside and read parameters such as traffic volume, occupancy and speed. Two types of traffic sensors are used in the system: RTMS (Remote Traffic Microwave Sensors) and Acoustic Sensors. Both types of traffic sensors can observe the traffic speed, occupancy and volume.

The SPCU contains a Cellular Digital Packet Data (CDPD) modem and antenna (for wireless communication), batteries and solar panel for power, GPS for determining its current position, and a computer processor for on-site data processing and decision-making.

Each sensor connects via cable to the SPCU. The SPCU and the sensor are mounted on the same structure. The connection from the internal modem to any cellular phone tower is established by a wireless connection using a cellular phone antenna. The SPCU is capable of receiving configuration data and commands using the same wireless channel.

At the TOC, traffic sensor data received via the Internet access point is routed to a CMRS. It is a Pentium-class desktop PC running Microsoft Windows and a suitable Web Browser. As part of the current prototype system, a website developed by L-3 Communications Inc. collects, logs and processes the incoming data and generates messages to be disseminated to motorists, via pagers, whenever traffic conditions change (See Section 2.2.2). The website also provides a view for use by the system administrator to configure and troubleshoot the system. Configuration includes functions such as adding or deleting traffic sensor stations, setting parameters remotely at the sensor stations, viewing a table of sensors and GPS locations and interrogating sensors that appear to be faulty.

Figure 3 is a picture of a SPCU unit and a traffic sensor mounted on a pole alongside highway I-76.
The existence of a central monitoring and reporting station enables the TOC to locate traffic sensors at any location in the network where traffic surveillance is required, and still be able to collect, log and process data, and disseminate traffic information without any time consuming processes. This type of system architecture is well fit for highway traffic safety and security, where rapid response measures need to be taken.

2.2. System Overview

Originally, 6 SPCU were installed; however, one unit was damaged due to an accident after its installation and now there are currently 5 SPCUs in the network. Three of the sensors are acoustic and two are radar sensors. Figure 4 demonstrates the current locations of the sensors on the South Jersey highway network. The selection of these specific locations is based on the experience of the agencies involved in the project. As seen in Figure 4, all five sensors are installed on I-76 and I-676 that lead to the Walt Whitman Bridge and the Ben Franklin Bridge, respectively. Since the project only deals with the peak morning traffic, the sensors are installed in the northbound direction. The exact sensor locations are given as follows:

Sensor 1. Route 42 and Hwy 55 (Acoustic)
Sensor 2. I-76 and I-295 (Radar)
Sensor 3. I-76 and Hwy 130 (Acoustic)
Sensor 4. I-676 and Morgan Blvd Exit (Radar)
Sensor 5. I-676 and Mickle Blvd Exit (Acoustic)

2.2.1. Power Management

Traffic sensors can be scheduled to collect data at any time period with any desired frequency. These options can easily be changed from the CMRS configuration menu. Previously, the data collection frequency was 30-seconds at every 5 minutes and 10 minutes for peak and off-peak periods, respectively. However, due to power shortage in sensor operations, the frequency of data collection is set to 30 seconds frequency every 10 minutes during rush hour and every 30 minutes at other times in this project.

There is an inevitable trade off between the accuracy of traffic information due to frequent data collection and the power consumption. The total power used by the SPCU varies with the traffic-sampling rate. As samples are taken more frequently, power utilization increases. As mentioned earlier, the SPCU is powered by a solar panel. The power used cannot exceed the average power provided by the solar panels or the lead acid battery internal to the SPCU will discharge and the unit will stop working. A 50W solar panel is used for this demonstration project, which produces between 7 and 9 Amp-hours per day of electric power. The lower and upper range corresponds to winter and summer operation, respectively. Table 1 lists typical SPCU power consumption for
two different traffic sampling schedules and two different peak operating durations (L-3 Communications System, 2002). It can be seen in Table 1 that a single 50W panel cannot support 5-minute peak and 15-minute off-peak data collection frequency in wintertime. The demonstration project started in the beginning of Summer 2001; this explains why the data collection frequency had to be altered to 10-minute peak and 30-minute off-peak frequency after Fall 2001.

***Insert TABLE 1 SPCU Power Consumption***

It is apparent that higher frequencies of data collection will result in quicker detection of congestion. Possible remedies for the limitations of solar power operations, without changing the data collection frequency, are using bigger size solar panels or multiple solar panels in parallel.

2.2.2. Detection of Congestion & Dissemination of Information by Pagers

The sensors report actual vehicle speeds and traffic volume by lane. When any sensor reports a change in speed (i.e., a change in speed bin) the most recent speed sample from all sensors is reported in the pager message. Default speed bin edges are set to Red: 0-10 mph, Yellow: 10-30 mph, Green: >30 mph. These can also be remotely changed from the CMRS configuration menu.

*Hysteresis* is applied to speed bin edges to reduce nuisance reports when traffic speeds hover in the neighborhood of a bin edge. This prevents sending multiple pager messages to motorists. When the measured speed crosses a bin edge in the negative direction, that bin edge and all higher bin edges are increased by the *hysteresis* value. When the traffic speed crosses a bin edge in the positive direction, that speed bin edge and all lower bin edges are reset to the original value. The default *hyseteris* value is 10 mph and is remotely configurable from the CMRS. *(Example: Hysteresis=10 mph. When speed changes from 45 mph to 5 mph - new bin edges are 40 (30+10), 20(10+10) for green and yellow boundaries. When traffic reaches 21-40 mph, the yellow bin edge is reset to 10 mph; when traffic exceeds 40 mph, the green bin edge is reset to 30 mph)¹.*

Any time any of the sensors detect a change in traffic speed bin, an alert is sent to all pagers listing the sensor location, color condition, and average speed, in parentheses, at each of the five locations. A typical pager message would appear as follows:

**** Insert FIGURE 5. Motorist Pager Alert Message ****

Since this was a demonstration project, the parties involved in this project wanted to make sure that the information could be successfully delivered to the selected motorists. As mentioned earlier, the reason why pagers were favored was due to the fact that they were inexpensive and widely used at the time this project was initiated. The information may also be transmitted to cell-phones, VMS signs with wireless access, and a web page designed for motorists.

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¹ It takes only 5 seconds for the SPCU to transmit data to CMRS
SECTION 3. SYSTEM EVALUATION METHODOLOGY

It is of ultimate importance to deploy a system that is up-and-running, and to maintain provision of reliable and useful information to motorists. Accuracy and reliability of the system and the compliance of motorists are conditional in this type of systems. Once the motorists realize that the congestion information received is not valid, they start to lose their confidence in the system, and will disregard the information. The consequence of this fact may result in total failure of the system in case of a disaster scenario. Thus, the deployed system must be evaluated comprehensively to assure the system reliability.

This demonstration project is identified as an ITS deployment initiative. The Federal Highway Administration identifies six national goals for ITS projects (FHWA Web Site):
1. Improve safety of the nation’s surface transportation system.
2. Increase the operational efficiency and capacity of the surface transportation system.
3. Reduce environmental costs associated with traffic congestion.
4. Enhance present and future productivity.
5. Enhance the personal mobility and convenience and comfort of the surface transportation system.
6. Create an environment in which the development and deployment of ITS can flourish.
Table 2 shows the compliance of the project with the national ITS goals:

***Insert TABLE 2 Relationship between ITS Goals and the Project Goals***

The majority of the project duration involved the design, development and deployment of an innovative surveillance system as described above. However, being a demonstration project, the main objective in this project is to evaluate:

- System Performance
- System Reliability

The steps taken for ensuring the system performance and reliability are:

(1) We evaluated the accuracy and performance of the installed sensors to make sure that the collected data from the sensors match with the actual traffic flow characteristics. The evaluation of the sensors with ground truth data is presented in the following subsections.

(2) Second, it is very important that the system is capable of disseminating “reliable” traffic information to drivers in a “timely” manner. We conducted surveys of the selected motorists if they received accurate information (Section 3.2.2). The motorists were informed about the traffic conditions only by the speed bins. However, in the future, if the proposed system is utilized for disseminating travel time information, then reliability of traffic information will be directly related to the accuracy of travel time estimation. Hence, we evaluated the travel time estimation accuracy using a simulation model of the southern New Jersey highway network (Section 3.2.1).

The following subsections provide brief description of each evaluation tests performed. Table 3 summarizes these tests and their goals.
3.1. Evaluation Tests and Results – Phase 1: Sensor Testing

3.1.1 Sensor Testing 1 (ST-1): The sensor data is tested to detect failures related to the operation of the installed sensors. It is important to make sure that all the sensors are up-and-running regularly to avoid giving invalid information. This test is designed to evaluate the System Performance goal of this project. The trouble log is recorded by L3-Communications if any failure occurs with the operation of the sensors. The summary of this log is shown in Table 4.

3.1.2 Sensor Testing 2 (ST-2)
There are 3 different types of data collected by the sensors, namely vehicle counts, speed and, occupancy. Since it is almost impossible to collect speed and occupancy values at the site, we collected ground truth data (i.e. videotaping) to ensure that the data obtained by the sensors are within a reasonable range of accuracy compared to the data collected. The vehicle count data was extracted from the video using an Image Processing Unit. The statistical results of this comparison are provided in Table 5.

Table 5 contains summary information about the individual vehicle count data for each sensor. For each sensor data with the corresponding ground truth data, we performed a paired-\( t \) test and formed a 95% confidence interval for the mean of differences of each data set.

For example for sensor 4, the paired t-test is performed as follows:

\[
\bar{x} = 6.07 \text{ (sample mean)} \\
S = 25.81 \text{ (standard deviation of the sample)} \\
a = 0.05 \\
n = 15 \text{ (number of data points)} \\
\text{Confidence Interval (CI)} = \bar{x} \pm t_{n-1,\frac{\alpha}{2}} \frac{S}{\sqrt{n}} \\
\text{CI for sensor 4} = 6.07 \pm 2.145 \times \frac{25.81}{\sqrt{15}} = [-8.23, 20.36]
\]
It is evidenced in Table 5, with 95% probability, that the confidence interval constructed for Sensor 1 does not cover zero, while the other confidence intervals formed for the rest of the sensors do.

It should be mentioned that the sensors used in the system are tested numerous times by the manufacturers before advertised in the market. Therefore, 3 possible factors that might have led to the insufficient results of our statistical analysis can be listed: (1) Aggregation of Sensor Data: As mentioned before, sensors collect data for 30-second time frames and aggregates it for one minute at every 5 minutes. On the other hand, ground truth data reflects averages of continuous traffic counts at every 5 minutes. In short, sensor data is actually a 30-seconds data sampling from a continuous traffic aggregated to 5-minute intervals. This fact obviously affects the results. (2) Normality Assumption: The confidence interval formed by the paired-t test is exact when the sample size approaches infinity. As the number of our observations is small, the confidence intervals formed for each sensor could be far from 95% confidence level. (3) Ground Truth Data: Due to the hardships of data collection along I-76 and I-676 (i.e. limited shoulder width at sensor locations), the ground truth data is not sufficient enough to perform a sufficient statistical analysis.

3.2. Evaluation Tests and Results – Phase 2: System Wide Testing

3.2.1 System Wide Performance Test 1 (SWPT-1)

This evaluation procedure includes the validation of the accuracy of the travel time/congestion information generated using the traffic data gathered from the sensors. Although this demonstration does not consider travel time estimations, SWPT-1 is necessary to observe how well the sensors operate in conjunction with travel time/congestion estimation algorithms for the study network.

There are various practical and methodical limitations to real-time travel time collection such as (1) The high number of data required to statistically validate the evaluation results, (2) Synchronization of the collected data with the sensor data. Therefore, we decided to carry out this evaluation process using simulation. PARAMICS traffic simulation software is used to simulate the study network. The simulation network modeled for Ozbay and Bartin (2003 a - b) is adopted for our analysis.

PARAMICS is a suite of high performance software tool for microscopic traffic simulation. Individual vehicles are modeled in fine detail for the duration of their entire trip, providing accurate traffic flow and congestion information, as well as enabling the modeling of the

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2 As mentioned earlier the evaluation the sensors were collecting data at every 5 minutes. Later, due to power limitations, 10-minute interval was used.

3 T-test employs the central limit theorem, which states that if the sample size is sufficiently large, the averages of the samples will be approximately distributed as standard normal.

4 See Law and Kelton (1991) pp.535-536 for examples that show the variation in confidence level with different sample sizes.
interface between drivers and ITS (Abdulhai et al, 1999). Besides being an effective microscopic traffic simulator, it has several advantages over other existing traffic simulation tools:

- Excellence in modeling highly congested networks and ITS infrastructures
- Advanced vehicle-following and lane-changing behavior simulation capability
- Capability of incorporating driver and vehicle performance measures
- Batch mode operations for statistical studies
- Application Programming Interface (API) option, which enables users to modify the simulation routine for testing their own models.

The study area under consideration is approximately 90 square miles. Only major highways and freeways are included in the model, whereas the secondary roadways are modeled as demand connectors to the major highways. The modeled network includes all the geometric details of the existing infrastructure. An Origin- Destination demand matrix was obtained from Delaware Valley Region Planning Committee (DVRPC) and aggregated to a smaller size for modeling purposes. The modeled network was validated based on the AADT data reported by NJDOT at 32 different locations. Figure 6 shows a screenshot of the network modeled in PARAMICS.

In order to evaluate the system using simulation, the detectors in the simulation model should give close traffic data readings to the actual sensor readings. For this purpose, we ran the simulation for \( n = 6 \) times to construct a 95% confidence interval for the means of the selected performance measures, namely route travel time and average network travel time (Note that \( n = 6 \) replications assure that the mean of each performance measure has a 97.5% confidence interval based on Bonferroni Inequality. See Law and Kelton (1991) pp. 560 and Banks and Carson (1985) pp. 467-468 for details).

Table 6 shows the comparison of detector speed and vehicle counts gathered by simulation and the actual sensor readings obtained from the database. The intervals given in the table are the 95% confidence intervals for the means of each data source. It can be stated that the simulation readings are sufficiently close to the actual sensor readings.\(^5\)

**** Insert TABLE 6. Confidence Interval for Sensor Data and Simulation ****

As mentioned earlier, the sensors, at the desired frequency, collect traffic data over a thirty-second observation window and aggregate it for 1-min at every 5 minutes during peak period. We set the “detectors” in the simulation model at the exact locations where they are deployed. Detectors were coded to simulate the deployed sensors with the same frequency and type of data collection using the API functions of PARAMICS: Every time the sensor detects a vehicle, the speed and vehicle count data are collected for the lane the vehicle is traveling.

\(^5\) Only Sensor 2 shows lower speed values; however the offset is not large enough to enormously affect the travel time estimation.
\[ S_{i,j,k} : \text{Average Speed (veh/hr)} \]
\[ V_{i,j,k} : \text{Vehicle Count (veh/h)} \]

where, \( i \) : detector index  
\( j \) : lane index  
\( k \) : time period index  
\( t \) : length of time period (mins)

For the current deployment \( i = 1,2,...,5 \) and the desired data collection frequency is \( t = 5 \text{ min} \). At the end of each time period, \( k \), the average speed of detector \( i \), \( \bar{S}_{i,k} \), is the weighted average of average speeds at each lane:

\[
\bar{S}_{i,k} = \frac{\sum_{j=1}^{n} S_{i,j,k} V_{i,j,k}}{\sum_{j=1}^{n} V_{i,j,k}}
\]

Here, we assumed a very simple travel time estimation function as suggested by Rice and van Zwet (2002):

\[
T(k) = \sum_{i=1}^{m-1} \frac{2d_i}{\bar{S}_{i,k} + \bar{S}_{i+1,k}}
\]

where, \( T(k) \) = Estimated Travel Time for time period \( k \) (seconds)  
\( d_i \) = Distance between sensor \( i \) and \( i-1 \) (miles)  
\( m \) = Number of sensors in the system

A Note on Travel Time Estimation Methodology

Equation (2) computes the average of each \( \bar{S}_{i,k} \), and assumes a constant speed profile between two consecutive detectors. It should be clear that the constant speed profile approach would yield erroneous results if the traffic flow changes considerably between the detectors. A hypothetical speed profile is shown in Figure 7, where the fluctuating line represents actual speed profile on a freeway segment at time period \( k \); whereas the straight line is the estimated average speed profile between sensors. The fluctuating speed profile is often encountered on freeways where there exists heavy merge of traffic from an on-ramp, causing lower speeds on the freeway upstream (see 0 - 0.2 miles on x-axis). The real travel time value computed based on the actual speed profile shown in Figure 7 is 3.12 minutes, while the estimated value is 1.63 minutes. It is clear that the closer the estimated speed profile to the actual speed profile, the more accurate the estimation will be. Gazis and Knapp (1971) attempt to define a more complex speed profile represented by polynomial functions by using the available sensor data. Coiffman (2002) attempts to estimate vehicle trajectories using loop detectors, where the author extrapolates local traffic conditions around the detectors and extends it for the link. There are myriad of studies in
the literature dedicated to travel time estimation/prediction, majority of these studies focus on
filtering the sensor readings or using historical observations to improve travel time function. For
details, readers may refer to Zhang and Rice (2001), Rice and van Zwet (2002), Dailey (2001),

However, the accuracy of estimation is not always based on the employed travel time estimation
algorithm. It also depends on the selected locations and the number of the sensors. Suppose, we
had an additional sensor at \( x = 0.2 \) miles; then, using equation (2), the estimated travel time
would yield 3.31 minutes, approximately 40% increase in accuracy with respect to the two-
sensor configuration. On the other hand, if the additional sensor was placed at \( x = 0.80 \) miles,
then the estimated travel time would yield 2.30 minutes. In short, no matter how good the
estimation method is, the location and number of sensors are important factors in accurate travel
time estimation. There are only a few studies in the literature dedicated to determining the
optimal number and location of traffic sensors. Yang and Miller-Hooks (2002) and Sherali et al.
(2002) approach the problem as maximizing the coverage of real-time information. They weigh
the candidate location of sensors with the travel time variability of that location. The basic idea
in the problem formulation is that there is no necessity in deploying sensors on freeway segments
where the travel time variance does not vary significantly. The problem is then to select amongst
the links where travel time highly varies to maximize the benefit. This approach is promising in
finding the right number and location of sensors, only if we have accurate knowledge of travel
times on selected links once monitored. As we have seen on Figure 7 that depending on the
speed profile, this assumption might fail. Sherali et al. (2002) employs Automatic Vehicle
Identification (AVI) reader technology that collects real travel time data from equipped vehicles.
In the case of AVI technology the results present optimal locations; however, the system is not as
widely used as loop detectors or RTMS sensors. Yang and Miller-Hooks (2002), on the other
hand, do not explicitly utilize a travel time estimation methodology.

In this paper, we do not specifically deal with determining the optimum number and location of
sensors. We present the system performance in terms of travel time estimation accuracy with the
current system capabilities. However, we performed several simulation analyses to highlight the
importance of this problem.

Table 7, Figures 8 and 9 provide the results of our simulation analysis for 2 sensor configuration
scenarios under incident and no-incident cases during 3-hours peak period. The second
configuration with additional two sensors is analyzed to observe if the system gains any benefits
in terms of better travel time estimation. As mentioned in Section 1, traveler information systems
are most needed in the event of irregular traffic characteristics. In order to analyze the system
performance under such conditions, we simulated both configurations with the presence of a 25-
minute incident on I-76. It is unambiguous that although incidents are random events, due to the
geometric aspects and traffic flow characteristics; certain links have higher probability of
incident occurrence rates. The selection of the incident link is based on NJDOT’s annual crash
rates report (http://www.state.nj.us/transportation). The selected link has a high incident
occurrence rate of 12.8%. 
The results provided in Table 7 represent the confidence interval of absolute error between the estimated route travel time, $T(k)$, and the average actual travel time, $\overline{T_A}(k)$. $T(k)$ is calculated using equation (2). $\overline{T_A}(k)$ is collected by probe vehicles in simulation. Each time period $k = 5$ minutes, we calculate the absolute difference ($\varepsilon$) between $T(k)$, and $\overline{T_A}(k)$ of vehicles that start their journey within that time period. We ran the simulation with different random number seeds till we obtain a 90% confidence level for the expected $\varepsilon$ with a relative error of 8%.  

Our results show that the error in travel time estimation is between 36 – 41 seconds, and 156 – 180 seconds, for no incident and incident cases, respectively. Figure 8 and 9 show the plots of travel time estimation for each scenario.

The results show that the improvement due to additional two sensors is insignificant both in incident and no incident scenarios. Nevertheless, these results will vary considerably with (1) Incident Characteristics, such as location, duration or severity degree, (2) Sensor Locations: Depending on the vehicle speed profile along the route, different selection of sensor locations would yield different results. (3) Travel Time Function: Different travel time functions will yield different results. We used equation (2) due to its simplicity and accuracy as stated in Rice and van Zwet (2002).

Therefore, a more comprehensive simulation analysis should consider all these factors simultaneously. However, for large simulation network models such as the one analyzed here, the number of replications needed to construct a desired confidence interval for $\varepsilon$ may be a lot higher than one would expect. For example, we conducted around 50 replications to obtain 90% confidence level for each results provided in Table 7.

We conclude from on our simulation analyses that increasing the number of sensors does not always improve the accuracy of travel time estimation. Therefore, simulation analyses are very useful in testing the performance of sensor configurations under various traffic characteristics.

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6 If we construct 100 independent 90% confidence intervals based on other independent simulation runs, we would expect $\overline{\varepsilon}$ to have a relative error of at most 8% with respect to unknown real mean ($\mu$), in approximately 90 out of 100 cases. In the remaining ~10 cases, the relative error of $\overline{\varepsilon}$ would be greater than 8%.

7 One replication takes around 25 minutes on a Dell Workstation PWS530, 2.20GHz computer
3.2.2 System Wide Performance Test 2 (SWPT-2)

In order to verify the validity of the information sent to the pagers, the Rutgers Team designed a survey to be answered by selected volunteer commuters and NJDOT emergency vehicle drivers. This survey was used to gather information about day-to-day experiences of users with the pagers programmed as part of this project. These drivers who are familiar with the Camden Philadelphia highway network, were asked to fill up a daily survey form that compares the experienced traffic conditions with the traffic conditions estimated by the system. The participants included the South Jersey Emergency Service Patrol, Delaware Valley Regional Planning Commission (DVRPC) and CCCTMA staff. The basic idea behind the survey was to examine the information disseminated to the pagers. Basically, as they received messages on the pagers warning of congestion, the volunteer drivers would verify the current traffic condition if they were driving on the alerted congested area. They also would specify any congested conditions, including their averages speeds, even if the page did not give a congestion alert. This way, the system would be evaluated from the drivers’ point of view.

As observed during the project, the pagers have disseminated correct congestion information when the system is up and running. However, during the majority of survey period, the system was down due to server / surveillance problems as indicated in Table 4. Although due to the initial problems with the system, during the time period surveys were conducted, the survey forms were not helpful to obtain surveyors’ opinions. Later there were enough survey results verify the operational and content accuracy of the pagers and information. It was thus safely concluded that the pagers performed well once the initial problems with the system were resolved.

SECTION 4. CONCLUSIONS AND FUTURE WORK

As mentioned earlier, this project is aimed at evaluating the effectiveness and accuracy of the implemented motorist information system. Currently the developed system is rather limited in the number of mobile units, 5 in total; however, it is significant as a proof of concept that helps us understand the system characteristics and the possible problems that might be faced in the future. Therefore, during the first step of this project, all participating agencies involved in the study have had enormous experience regarding the potential of the proposed system and several practical issues, such as problems associated with using pagers for information dissemination, calibration of the sensors, etc.

Now that the system is deployed and tested, and any potential technical problems are known, additional units can be built to cover major alternative routes to divert motorists in the event of non-recurrent congestion. There are still several tasks that have to be conducted to ensure an effective and system:

(1) In order to best estimate / predict route travel times in a study area, optimal number and location of sensors need to be determined prior to the deployment This is a network-oriented task and should be analyzed with a powerful simulation tool first. For any selected route
in this particular network, the designed surveillance system can be simulated and the optimal number of sensors and their locations can be estimated under various traffic characteristics.

(2) **Frequency of data collection needs to be studied and suggestions need to be made for the existing / future surveillance system and power limitations.** As mentioned earlier, the time frame and frequency of sensor data collection can be remotely changed from a central monitoring and reporting station located at the TOC. However, due to power limitations, the duration and frequency of data collection were held at a minimum rate. Although the power shortage problem is resolvable, it will still be necessary to determine an optimal data collection frequency where both power usage is minimized and route travel times can be estimated accurately.

(3) **Information dissemination capabilities of the system have to be further studied and enhanced in cooperation with the participating agencies.** In this project, the system deployed has proven to effectively detect congestion and disseminate alerts to motorists by pagers. In order to provide information to a greater number of motorists, other means of dissemination have to be studied. For example, Ozbay and Bartin (2003 b) showed the positive impact of VMS information on marginal costs of drivers on the southern NJ highway network. Similarly, Goel et al. (2003) reported some promising improvements in travel time savings with the proposed vehicle-to-vehicle travel time dissemination technology in the same highway network. These studies show that there are potential benefits of deploying traveler information systems on this network.

**Acknowledgements**

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(7) Ozbay, K. and Bartin, B. "Estimation of Economic Impact of V.M.S. Route Guidance using Micro Simulation", in Economic Impacts of ITS : Innovation and Case Studies. Accepted for Publication. Title of Series: Research in Transportation Economics, Elsevier Science, 2003 (b)

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TABLE 1. SPCU Power Consumption

<table>
<thead>
<tr>
<th>Peak Sampling Interval (minutes)</th>
<th>Off-Peak Sampling Interval (minutes)</th>
<th>Peak Operating Hours/Day</th>
<th>Radar Power (Amps-hr)</th>
<th>Acoustic Power (Amps-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>15</td>
<td>6</td>
<td>5.28</td>
<td>7.68</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>12</td>
<td>6.88</td>
<td>8.88</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>6</td>
<td>2.88</td>
<td>5.88</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>12</td>
<td>3.68</td>
<td>6.48</td>
</tr>
</tbody>
</table>
### TABLE 2. Relationship between ITS Goals and the Project Goals

<table>
<thead>
<tr>
<th>ITS Goals</th>
<th>Improve Safety</th>
<th>Increase Efficiency</th>
<th>Reduce Environmental Costs</th>
<th>Enhance Productivity</th>
<th>Enhance Personal Mobility</th>
<th>Promote ITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improve System(^8)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improve System Reliability</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

\(^8\) System here means the portion of the network used as the deployment area.
TABLE 3. Evaluation and Testing of the project goals and objectives

<table>
<thead>
<tr>
<th>Goal 1</th>
<th>Evaluate System Performance</th>
<th>Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Evaluate SCPU performance by testing how often the system fails to deliver traffic information</td>
<td>ST-1</td>
</tr>
<tr>
<td>2.</td>
<td>Evaluate the accuracy of each sensor using ground truth data</td>
<td>ST-2</td>
</tr>
</tbody>
</table>

Goal 2 | Evaluate System Reliability | Tests |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Evaluate the accuracy range of estimated route travel time by sensor data compared to ground truth data</td>
<td>SWPT-1</td>
</tr>
<tr>
<td>2.</td>
<td>Evaluate the correctness of congestion alert sent by pagers using commuter surveys</td>
<td>SWPT-2</td>
</tr>
</tbody>
</table>

TRB 2004 Annual Meeting CD-ROM  Paper revised from original submittal.
### TABLE 4. NJDOT Motorist Information System Trouble Log Summary

<table>
<thead>
<tr>
<th>Failure Type</th>
<th>Equipment</th>
<th>Number of Failures</th>
<th>Duration of Failure (days)</th>
<th>Total Number of Site Visits for Resolution (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor Data</td>
<td>SPCU – all units</td>
<td>1</td>
<td>Various</td>
<td>6</td>
</tr>
<tr>
<td>Sensor Data</td>
<td>SPCU-Sensor 1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sensor Data</td>
<td>SPCU-Sensor 2</td>
<td>4</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>Sensor Data</td>
<td>SPCU-Sensor 5</td>
<td>1</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>Server Failure</td>
<td>CMRS</td>
<td>6</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>No Pager Messages</td>
<td>CMRS</td>
<td>1</td>
<td>31</td>
<td>-</td>
</tr>
<tr>
<td>Power Outage</td>
<td>CMRS</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Server Transfer</td>
<td>CMRS</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>
### TABLE 5. Paired-t Confidence Interval for Ground Truth and Sensor Data Difference

<table>
<thead>
<tr>
<th></th>
<th>Sensor 1</th>
<th>Sensor 2</th>
<th>Sensor 3</th>
<th>Sensor 4</th>
<th>Sensor 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean of Differences</td>
<td>-82.38</td>
<td>18.17</td>
<td>23.8</td>
<td>6.07</td>
<td>11.2</td>
</tr>
<tr>
<td>Number of Observation Points (Every 5-minutes)</td>
<td>13</td>
<td>6</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Standard Deviation of Difference in Vehicle Counts</td>
<td>40.54</td>
<td>109.92</td>
<td>85.66</td>
<td>25.81</td>
<td>32.45</td>
</tr>
<tr>
<td>t-value (confidence interval is 95%)</td>
<td>2.179</td>
<td>2.571</td>
<td>2.145</td>
<td>2.145</td>
<td>2.145</td>
</tr>
<tr>
<td>95% Confidence Interval for Difference of Sample Means</td>
<td>[-106.88, -57.89]</td>
<td>[-97.21, 133.54]</td>
<td>[-23.64, 71.24]</td>
<td>[-8.23, 20.36]</td>
<td>[-6.77, 29.17]</td>
</tr>
<tr>
<td>Zero Covered?</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>
### TABLE 6. Confidence Interval for Sensor Data and Simulation

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Speed (Simulated)</th>
<th>Speed (Sensor Data)</th>
<th>Counts (Simulated)</th>
<th>Counts (Sensor Data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor 1</td>
<td>[44.01, 52.21]</td>
<td>[47.24, 50.87]</td>
<td>[89, 102]</td>
<td>[94, 108]</td>
</tr>
<tr>
<td>Sensor 2</td>
<td>[33.98, 45.85]</td>
<td>[59.48, 62.82]</td>
<td>[54, 97]</td>
<td>[66, 80]</td>
</tr>
<tr>
<td>Sensor 3</td>
<td>[50.71, 51.26]</td>
<td>[53.98, 57.12]</td>
<td>[76, 85]</td>
<td>[75, 90]</td>
</tr>
<tr>
<td>Sensor 4</td>
<td>[63.73, 67.62]</td>
<td>[62.14, 67.96]</td>
<td>[30, 50]</td>
<td>[25, 33]</td>
</tr>
<tr>
<td>Sensor 5</td>
<td>[63.29, 65.12]</td>
<td>[60.44, 64.86]</td>
<td>[14, 30]</td>
<td>[17, 25]</td>
</tr>
<tr>
<td>Scenarios</td>
<td>No Incident</td>
<td>Incident</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------</td>
<td>-----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) Current Configuration - 5 Sensors</td>
<td>[36.76, 41.85]</td>
<td>[156.19, 179.40]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) Modified Configuration - 7 Sensors</td>
<td>[41.25, 46.76]</td>
<td>[150.18, 174.62]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** (1) The results are based on 90% Confidence Interval for $\overline{\epsilon}$ and 8% relative error with respect to real error, $\mu$. (2) The route distance is approximately 7 miles. (3) The values are in seconds.
FIGURE 1 Prototype Sensor Processor and Communication Unit (SPCU)
FIGURE 2 System Architecture
FIGURE 3 Sensor Picture
FIGURE 4 Current Sensor Locations
FIGURE 5. Motorist Pager Alert Message

NJDOT TRAFFIC ALERT: 42N & 55 YELLOW (29**)---
42N & 295 GREEN (53) ---
42N & 130 GREEN (46) ---
676N & Morgan GREEN (59) ---
676N & Mickel GREEN (69) ---

---

9 42N here refers to I-76 Northbound on the highway network
Figure 6 Highway Network modeled in PARAMICS
Figure 7 A Hypothetical Freeway Speed Profile
FIGURE 8 Comparison of Travel Time Estimation – No Incident (Current vs. Modified Configuration)
FIGURE 9 Comparison of Travel Time Estimation (Current vs. Modified Configuration)