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PRIVATE-SECTOR PROVISION OF CONGESTION DATA

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EXECUTIVE SUMMARY

Transportation agencies are facing an increasing need for traffic data. As information technology advances, agencies now have alternative means to acquire this data beyond the traditional model of using an agency-owned network of point sensors (most commonly, inductive loop detectors). In this report, one emerging alternative, the use of wireless location technology (WLT) to collect vehicle probe data, is explored in detail. The purpose of the executive summary is to highlight key findings that are described more fully in the body of the report.

Technology

The state-of-the-practice in WLT-based traffic monitoring is to use cellular hand-off data (and other associated cellular system data) to estimate vehicle positions as they traverse the transportation system. This hand-off data must then be processed in order to assign vehicles to roadways and to derive overall traffic performance measures.

Note that WLT-based traffic monitoring is just one means by which to collect probe-based traffic data. For example, an alternative with increasing popularity is to use GPS vehicle

locations from fleet management firms as a source of probe data. In many cases, traffic data firms are combining probe data from GPS-equipped fleets and WLT to generate traffic data. This report focuses on the WLT approach, but much of the content of this report is applicable regardless of the technology used to collect probe data.

Business Environment

There are currently a small number (less than 10) of firms that are positioned to provide traffic data services to transportation agencies. These firms are generally rather small. They obtain the probe data that they need to derive traffic data through agreements with the large cellular providers. The traffic data firms generally see their primary markets to be (a) selling data to private information firms and (b) selling data (and sometimes other services) to transportation agencies.

To date, these firms have been primarily in the technology and business development stages. Nearly all projects with public sector clients have been demonstration or research efforts – few have actually been “true” data service provision agreements. Essentially, these projects may be considered as “venture capital” – providing funds to explore and develop this new means of acquiring traffic data. However, recent projects have moved the firms much closer to transition to true service provision agreements.

Data Provided

WLT-based traffic monitoring systems/services generally provide average link travel time and speed data. The links are generally longer than links used for traditional point sensor systems (i.e. those commonly used for transportation agency traffic management systems)– on the order of 1-2 miles. Measurement time intervals (also referred to as the polling interval) are generally roughly 5 minutes in length.

Data Accuracy/Availability

Simulation models of WLT-based traffic monitoring systems indicate that this technology can feasibly provide quality traffic data. However, most of the past deployments have failed to consistently provide sound data. Current deployments are still in the evaluation phase, but early anecdotal evidence suggests that the data is beginning to provide acceptable accuracy/availability. Evidence is also suggesting that the WLT-based systems are more adept at covering heavily traveled urban freeways as opposed to arterials and more lightly-traveled facilities.

Costs

As mentioned earlier, nearly all data services to date have been based on research and demonstration projects. The costs of these projects vary widely, and it is unclear if the costs charged by the vendors on those projects would sustain their business model in the long term. Therefore, unfortunately, there are no reliable sources on which to base a projected data service cost structure. At this stage, agencies will need to diligently negotiate arrangements without experience to fall back on.

Legal Issues

A comprehensive review of federal law reveals no legal impediments to deriving traffic stream data from WLT, provided only aggregate information on wireless subscribers (like link speed and travel times) is released. Individually identifiable information, including individual locations, could be protected by wireless legislation. This could act as a barrier to using these systems to provide individual-level origin/destination data.

INTRODUCTION

Transportation agencies are becoming increasingly focused on efficiently operating the transportation system. High-quality, reliable traffic condition data is a critical input for nearly all operational activities. Performance measurement, real time control, and traveler information initiatives all rely on traffic condition data. As a result, more and more agencies are seeking ways to acquire high-quality speed and travel time data from across the roadway network. While the use of a "network" of point sensors to monitor traffic conditions has been, and continues to be, the most widely used approach in the public sector, a concept that is gaining increasing attention is purchasing traffic data from a private sector provider. Given that the private sector does not have universal access to the right-of-way to install point sensors, they have largely turned to probe-based approaches for traffic monitoring. By tracking a series of positions of a sample of traveling vehicles, it is theoretically possible to generate speed and/or travel time estimates for roadway links. However, before the public sector enters into significant agreements to purchase data, it is important that agencies understand the capabilities and limitations of such services.

The key challenge to implementing a probe-based traffic monitoring system lies in collecting a representative sample of vehicle positions in both time and space. Two primary approaches have been considered in the past by private sector firms. The first approach is the use of wireless location technology (WLT) to automatically and anonymously locate wireless devices (such as cellular phones) as they traverse the road system. The second approach is to locate floating vehicles equipped with GPS devices as they travel. Both approaches have both unique and shared attractive characteristics. This report focuses on the use of WLT-technology in probe-based monitoring. However, given their similarities, much of the guidance provided is applicable regardless of the technology used to collect probe data.

An important characteristic of WLT-based traffic monitoring is the exceptionally large pool of potential probes that may be located. As of September 2006, it was estimated that over 72 percent of households in the United States had wireless service (*1*). This represents an extremely large set of potential probe vehicles, which could make implementation of WLT-based approaches viable. While this concept seems to be attractive, there are still a number of unanswered questions as to whether these systems can reliably provide high-quality traffic condition data. As a result, it is necessary to review completed and ongoing deployments to identify the capabilities and potential limitations of WLT-based monitoring systems.

RESEARCH OBJECTIVES AND SCOPE

There have been a number of deployments of WLT-based traffic monitoring systems both in the United States and abroad. These deployments have occurred under a broad range of roadway conditions, technology platforms, and legal/institutional frameworks. Likewise, a number of deployments of these systems are currently underway. There is a need to estimate the potential abilities of these systems, as well as to provide guidance to transportation agencies to use in structuring agreements to purchase traffic data collected using WLT. This research specifically sought to:

- Critically examine the ability of deployed WLT-based monitoring to produce accurate and reliable traffic condition data.
- Assess "lessons learned" from past and ongoing deployments of this technology
- Determine potential legal barriers to utilizing this technology for traffic data collection
- Develop guidance that transportation agencies may use to assist in entering into agreements with firms selling traffic data services based on WLT, including the development of requirements and methods to perform system evaluation.

RESEARCH METHODOLOGY

The methodology used in this research consisted of five major tasks. Past deployments of WLT-based traffic monitoring were reviewed first. Next, the status of a number of ongoing deployments in the United States was examined. A limited simulation study was then performed to try to understand in greater detail the potential performance of currently deployed systems, as opposed to early generation systems which had already been reviewed. A review of legal and privacy issues that could impact the deployment of these systems was also performed. The results of these prior steps were then synthesized to provide guidance to assist transportation agencies as they consider entering into agreements to purchase traffic data developed from WLT systems.

Review of Past Evaluations of WLT-based Monitoring

The first major task was to review past instances where WLT-based monitoring systems were evaluated. Field deployments in the United States and internationally were examined in order to identify what data had been produced in past evaluations. The examination of field deployments summarized the technology used to produce traffic data, the accuracy of the data reported, the availability of data, as well as any institutional issues with deploying the system. Simulation studies that examined WLT-based traffic monitoring were also analyzed. While the simulation studies do not represent the results of real world deployments, they offer some further insight into the factors that impact the performance of these systems. These studies are particularly useful in isolating discrete traffic and system design factors that impact the performance of WLT-based monitoring systems.

Review of Ongoing Deployments

While the review of past deployments offers insight into the performance of WLT-based traffic monitoring systems, the industry and the technology is changing at a very rapid pace. As of the time that this report was written, a large number of WLT-based traffic monitoring systems were in varying degrees of deployment across the United States. In many cases, the underlying approach to generating traffic data has changed significantly from that used in early generation tests of WLT-based monitoring. Interviews were conducted with transportation agencies and vendors involved with a subset of these deployments in order to learn more about the technology being used, the results of any preliminary tests, and the nature of any contracting and business plans in place. The specific ongoing deployments examined are:

- Atlanta, GA. Vendor: Airsage
- Atlanta, GA. Vendor: Cellint
- Baltimore, MD. Vendor: Delcan
- Kansas City (Missouri and Kansas). Vendor: Cellint
- Missouri (statewide). Vendor: Delcan

Simulation Analysis

The review of ongoing deployments revealed that most are utilizing a very different approach to monitoring vehicles than was used in most early generation WLT systems. Most recent deployments are utilizing a technique that is generically termed a "handoff based" approach to generate traffic speed and travel time data. The operation of this technology is discussed in more detail later in this report. There are very few studies available that have looked specifically at handoff-based approaches to generating traffic data, so it is difficult to assess the capabilities of these systems based on past performance of WLT-based deployments and older simulation studies. Most of the ongoing deployments had not been formally evaluated, which means that little quantitative data on the performance of these systems is available.

As a result, a simulation test bed was developed that allowed the performance of handoff based technologies to be explored in greater detail. The test bed combined a microscopic traffic simulation model with an emulation of a handoff based system. This model was used to assess both the availability and accuracy of speed estimates that were generated using two simulated case studies. The operation of the simulation and the results of the analysis are discussed in detail later in this report.

Survey of Transportation Professionals

Given that WLT-based traffic monitoring is still relatively new and transportation agencies do not have a significant level of experience with the technology, the research team sought to gain insight as to how public agencies might seek to use data from such systems. In January 2006, the researchers conducted a web survey to address this objective. This survey also sought to determine what levels of accuracy and availability would be required from a probe-based traffic monitoring service. The survey was publicized through several internet mainlining lists, as well as through the Transportation Research Board Freeway Operations Committee.

Assessment of Legal Issues

Privacy concerns are often perceived as a potential barrier to deploying WLT-based monitoring systems. In fact, several deployments of this technology have received significant media coverage that highlighted potential concerns about "Big Brother". A legal review of relevant federal law was performed to assess whether there were potential barriers to using WLT for traffic condition monitoring. Three specific areas were investigated: relevant wireless communications legislation, Constitutional privacy issues, and potential implications of the Freedom of Information Act. The legal review focused purely on federal law, and did not attempt to assess whether there were any state-specific legislation that could impact the use of these systems.

Development of Guidance for Agencies Considering Purchase of a Traffic Data Service

The last major task was to develop guidance for states that are interested in entering into agreements with private sector firms utilizing WLT for traffic data collection. Major findings from the survey, past deployments, simulation studies, and ongoing deployments were synthesized to develop guidance on:

- Contracting and development of requests for proposals (RFPs)
- Data ownership and usage issues
- Measures of effectiveness for evaluating WLT-based systems
- Data collection methods for examining performance of WLT systems

Collectively this guidance provides comprehensive information to assist agencies in how to select a vendor, develop a contract, and evaluate a traffic data service.

SYSTEM CHARACTERISTICS

The first major task in this research is to define the characteristics and capabilities of WLT-based monitoring systems. In this section, the underlying technology is briefly described, the results of past field deployments are discussed, and relevant simulation studies are reviewed. This provides a broad picture of the experiences to date with WLT-based traffic monitoring.

Types of WLT-based Monitoring Systems

WLT-based monitoring systems rely on anonymously tracking the movements of wireless devices located in vehicles, such as cellular phones. Speeds and travel times can be derived from this location data, provided that the location information is of sufficient quality and the positions can be accurately "matched" to the roadway network. The travel times of a sample of wireless probes are measured and then used to estimate the characteristics of the overall vehicle population. Several technological approaches have been used in order to generate the location data that is necessary to support WLT-based traffic monitoring. Before discussing individual deployments, it is useful to discuss the different technologies available to generate location data in WLT-based monitoring systems.

In general, the wireless communications network knows the approximate location of any phone that is turned on in order to route calls efficiently. As a result, most WLT-based systems can use any phone that is turned on as a potential probe vehicle. In most cases, the phone does not have to be in use, although better location data is often available from those phones that are making calls since they are registering their location more frequently.

The location estimates used in WLT systems can generally be generally categorized into two groups. The first group of technologies attempt to provide precise locations of individual wireless devices that could be potentially anywhere on the roadway network. This produces a latitude and longitude for each individual wireless device. This group will be referred to as "point location systems." The second group uses the characteristics of the cellular communications network to identify regions where a device is likely located and then hone in on specific travel routes by looking at past history of the device. In this report, this second group of technologies is termed "handoff based systems", since they use rely heavily on the "hand-off" of a wireless device as it transitions from communicating with one cell tower to another. Each method is briefly discussed in the following sections.

Point Location Systems

The first approach where individual latitude and longitude information are generated was often attempted in early generation deployments of WLT, and builds on work underway to support the Federal Communications Commission (FCC) E-911 mandate as well as the development of location based services. Two approaches are available to generating this specific type of latitude-longitude data: network-based systems and handset-based systems.

Network based systems use the wireless network to estimate the approximate location of a wireless device. This can occur in several ways. One approach uses triangulation to estimate the position of a wireless device. The signal characteristics of the wireless device as seen by multiple cellular towers are examined to determine its approximate location. This process triangulates the location of the device by looking at angle of arrival and signal strength. Another approach uses a calibrated database of signal characteristics to identify locations. In this case, test vehicles drive the roadway network before the WLT system is brought on-line. The signal characteristics of the test vehicle are recorded at the cellular tower and stored in a database. The signal characteristics of subsequent wireless probes traveling on the road are then compared to the observed signal characteristics stored in the database, allowing the system to determine which road a vehicle is traveling on. Many early generation deployments used a network-based approach to location estimation. Those early generation deployments often had to have equipment installed at cellular locations to perform location estimation which acted as an impediment to the use of this technology. The triangulation and signal analysis-based approaches tend to have more error in the location estimates than other methods.

Handset based systems rely on global position system (GPS)-enabled phones to transmit very accurate location data. In this case, GPS location information is transmitted by the phone back to the wireless provider. Handset-based systems are being used by most wireless carriers to support E-911 requirements, but no instances of WLT-based traffic monitoring using handset based systems have been located. The advantage of a handset based system is that the location data is of very high quality, but it relies upon an active identification of a phone's location.

Handoff-Based Systems

Another type of WLT-based traffic monitoring systems is handoff-based systems. Handoff-based systems use the operational characteristic of wireless networks to help estimate vehicle positions along a road. In order to understand handoff-based systems, it is useful to review some basic information about how cellular networks operate. All cellular phones operate on a limited frequency range set aside by the FCC. A key concept in cellular communications is the reuse of frequencies. When a cellular network is being designed, cells that are immediately adjacent to one another must use different frequency ranges to process calls (*2*). If there is enough distance between cells, however, frequencies can be reused. Figure 1 illustrates this, depicting each frequency range by a letter. Notice the letters are repeated once the cell is separated by enough space. This allows cells to use the same frequency without interfering with one another since the signal can only travel a certain distance. The size and shape of the cells is determined by geographic conditions, cellular use within the cells, and the service provider, although hexagons are often used as a simple, theoretical representation of cell shape.

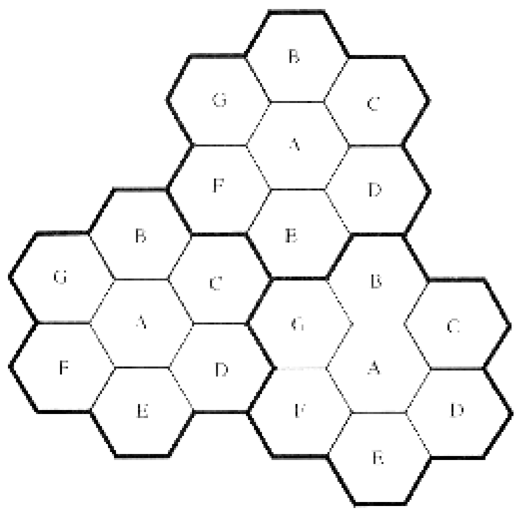

Figure 1. Theoretical layout of cells.

As a user traverses the roadway network, calls must be transferred between cells in a seamless manner. To make calls, a voice channel must be open and assigned to that cellular phone until the call is ended. The transfer of a cellular phone call from one tower to another, during which the cellular phone is assigned a new frequency, is referred to as a handoff. Handoffs are initiated when the strength of the cellular signal at the current base station falls below a preset threshold. At that point, adjacent cells measure the signal strength of the device in question, and the call is reassigned to a new cell that can accommodate the call.

For seamless voice communications to occur, wireless networks must know when a call transitions between cells. By tracking the handoffs between cells, it is conceptually possible to determine which road is a vehicle is traveling on and derive travel time information. Most recent deployments of WLT-based monitoring systems have utilized this approach. Figure 2 shows a simple example of how a handoff-based system would work. A vehicle is traveling on Route 276 between cells 1 and 4. As the vehicle moves from cell 1 to cell 2, a handoff is executed. This occurs between each transition between cells. By looking at the history of the handoffs, it is possible to determine that the vehicle is traveling on Route 276. Speeds and travel times can then be derived by looking at the time that elapses between handoffs. This approach differs significantly from the point location method in that locations are only estimated during handoffs. The network and handset based approaches describes in the previous section could potentially provide a location anywhere on the network, not just at handoff locations.

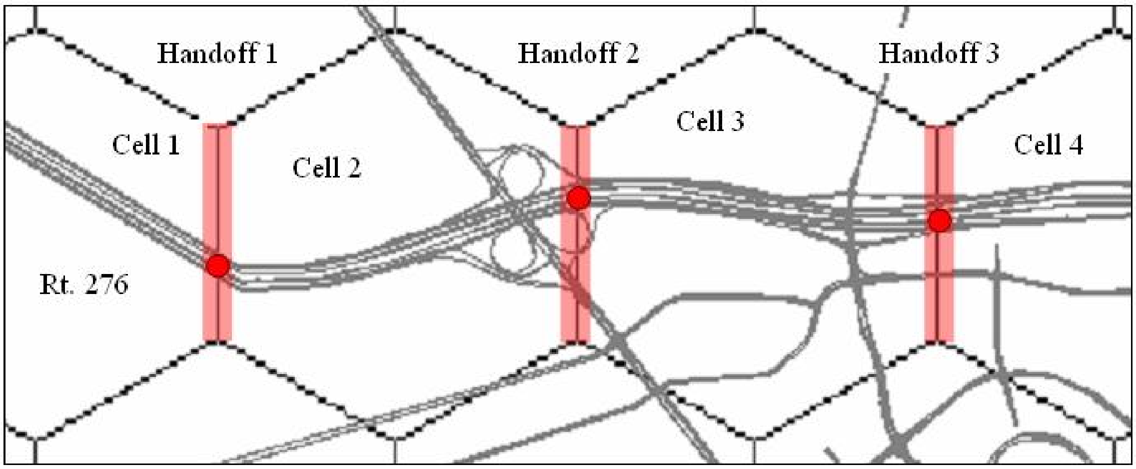

Figure 2. Example of Handoff-based Monitoring.

The example shown in Figure 2 has some simplifications. First of all, the boundaries between cells are not fixed, static points in reality. They exhibit some spatial variability depending on the volume of cellular traffic, atmospheric conditions, and other factors influencing the communications network performance. Also, most handoff-based systems makes use of additional data available from the cellular network. For example, within a cell, the system generally tracks phones to “sectors” (i.e. subzones of a cell) – this data can be used to track sector hand-offs as well.

Results from Completed Deployments

A number of deployments of WLT-based monitoring systems have occurred since the mid-1990s. These deployments can be broadly categorized into those that were independently evaluated and those that did not have an independent evaluation. This section presents results from seven field tests that had an independent entity evaluate system performance. The findings from the independent evaluations of WLT systems are presented chronologically in this section. There are six additional deployments that were completed that either lacked a formal evaluation or the evaluation was performed by the vendor themselves. Those deployments that lacked a formal, independent evaluation are summarized in a prior NCHRP state-of-the-practice document that was published on the internet (*3*).

CAPITAL Test

The first major operational test of wireless location technology was conducted over a 27-month period starting in 1994 on I-66, I-495, and various state routes in Virginia (*4*). This project was named CAPITAL (Cellular APplied to ITS Tracking And Location), and was the result of a cooperative agreement between the Federal Highway Administration (FHWA), the Virginia Department of Transportation (VDOT), the Maryland State Highway Administration (MSHA), Raytheon E-Systems, Farradyne Systems Inc., and Bell Atlantic NYNEX Mobile (*4*). Raytheon E-Systems provided the equipment to locate and track cellular phones, while Farradyne Systems provided the traffic management information system to convert cellular location data to traffic data. Bell Atlantic provided the communications network infrastructure. The University of Maryland performed an independent evaluation of the system.

The CAPITAL project used Bell Atlantic NYNEX Mobile's cellular network. Call detection and location equipment were physically located on 8 cellular towers in the area. This equipment was used to gather location data on calls handled at each individual tower. Cellular calls were detected when they were initiated in the test area. The location of the phone was then calculated using the signal's line of bearing and time of arrival as seen by multiple eight-element antennae installed on each of the towers. If a cellular phone was estimated to be on a roadway of interest, multiple measurements were performed to calculate the vehicle's speed.

By the end of testing, wireless telephones could be located within an average of 107 meters of their actual position. The accuracy of the position estimates improved considerably as the number of towers providing directional information increased. The evaluators noted that accuracies on the order of 5 to 25 meters might be needed to perform accurate speed estimation for a network. Although the location estimates were reasonably accurate, speeds could only be determined for 20 percent of all wireless phones that were located. In order to calculate speed, at least four position estimates had to be identified for each phone, and this occurred only 20 percent of the time. As a result, link speed estimates could not be estimated for the network. The lack of long vehicle tracks appeared to be caused primarily by a lack of sophisticated methods to match vehicles to the roadway network. While the CAPITAL test showed that wireless phones could provide reasonably accurate positional data, it was unsuccessful in producing traffic information that would be useful to DOTs or motorists.

US Wireless Corporation Tests

The now defunct US Wireless Corporation was a very active vendor of WLT-based systems in the late 1990s, with deployments in Billings, Montana, San Francisco/Oakland, and the Washington, D.C. metropolitan area. Only the San Francisco/Oakland and Washington, D.C. tests included an independent evaluation, however. The US Wireless system relied on their RadioCamera technology, which used location pattern matching technology to recognize signatures of incoming radio frequency (RF) signals and associate them with the specific locations from which they originated (*5*). The relative power, direction of arrival, number of dominant reflections, and multipath phase and amplitude were examined and compared to a reference database to determine the likely location of the cellular device on the transportation network.

A deployment of the RadioCamera technology occurred in the San Francisco Bay Area in 2000. This particular test involved the University of California – Berkeley and US Wireless, and focused on I-580 and a major arterial in Oakland (*6*). US Wireless provided 44 hours of wireless data to UC-Berkeley researchers to analyze. The researchers found that the position estimates generally had a 60-meter accuracy, although 66 percent of all probe vehicle tracks had at least one data point that deviated from the caller's actual position by more than 200 meters. The researchers noted that the call lengths were generally very short, with a median call length of only 30 seconds. This made it very difficult to estimate speeds on links since position estimates were not available for long distances. The researchers were also not able to match 60 percent of vehicles to a roadway link.

Another deployment of the RadioCamera technology occurred in the Washington D.C metropolitan area between 2000 and 2001 (*7*). The deployment was a partnership with the VDOT, MSHA, and US Wireless. The goal of the project was to prove the feasibility of WLT on congested freeways and arterials (*8*). The system was scaled to track 160 phone calls every 2 seconds, generating 4800 data points every minute. The University of Virginia and the University of Maryland were responsible for evaluating the system.

Although more data was generated than in earlier deployments, the RadioCamera system was still unable to generate the quality or quantity of data that would be necessary to support traffic monitoring (*8*). No data were generated in approximately 5 percent of the 10-minute intervals analyzed, so no traffic condition estimates could be created. The results from the intervals that did have samples showed wide variations in speed estimates. I-495, a congested urban freeway, had a mean speed error of approximately 8 mph, with some intervals having speed estimates that had more than 20 mph error. The arterials monitored had a mean speed of 6.8, with a maximum error of 23.2 mph. There was inconsistency in the number of samples generated for different links, resulting in these large variations in speed estimation error.

Lyons, France Test

The French government collaborated with Abis/A Probing Technology and SFR (a cellular carrier) to test a WLT-based traffic monitoring system in the area around Lyon, France in 2001. Two roadways were used for the field test: a 32 km rural freeway and a 4 km urban freeway (*9*). The specific details of the technology used to locate cellular devices and match them to the roadway network are vague, and it is unclear whether the technology tested was handoff based or based on WLT signal analysis (*10*).

The results of the tests showed some inconsistency in performance between the rural freeway and the more urban site. The WLT-based estimates were compared against data generated by inductive loop detectors and probe vehicles. The rural freeway showed good agreement between the cellular phone data and the loop detector data, but the urban freeway showed large variations between the WLT and the loop and probe data. For that route, the WLT estimates were between 24 and 32 percent higher than what was obtained using probe vehicles. Differences were even larger when the WLT estimates were compared to loop detectors.

Munich, Germany Deployment

The cellular carrier Vodafone tested a WLT-based traffic monitoring system in 2003 on a rural section of the German Autobahn north of Munich (*11*). The data produced by the WLT-based system was compared to travel times generated from probe vehicles and inductive loop data. The probe vehicle data was created from data obtained from taxi companies. The WLT-based traffic data was developed using what appears to be a handoff-based technique.

The Institute of Transport Research served as the evaluator for the project. The evaluation found that the WLT data showed a great deal more variation than the probe vehicle data. Speeds were consistently underestimated in one direction of travel and overestimated in the other direction of travel. Errors of 20 to 30 km/hr were commonly observed when the WLT was compared to the probe vehicles and loop detectors. The authors also note that this was a simple roadway network with only a single route traveling through the wireless cells. More complex roadway networks may not be able to be monitored as effectively.

Tel-Aviv, Israel Deployment

In early 2005, the WLT provider ITIS, Inc. participated in a test along the Ayalon freeway in Tel-Aviv, Israel (*12*). The ITIS technology uses handoff-based approach to traffic monitoring. Ben-Gurion University served as the evaluator for the project, but the evaluation was funded in part by ITIS. The evaluation compared the relative performance of the WLT-based system traffic condition estimates to those produced by loop detectors, which were spaced approximately every 500 meters. Data were compared between the loops and the WLT system for a 24-hour period using 5-minute intervals for data aggregation.

The researchers reported that the WLT speed estimates contained more variation than the loop detector data (*12*). Sample sizes were sometimes small, however, which may reduce the accuracy of some WLT estimates. During the night hours, the amount of data greatly decreased which limited the ability of the system to produce estimates during those periods. The second focus of the evaluation was on estimating travel times for the entire length of the roadway. Generally speaking, the researchers found good agreement between the inductive loops and the WLT system during daytime, uncongested conditions. The congested periods show differences between 10 and 30 percent between the loops and the WLT data. Some limited comparisons were also performed using 25 floating car travel time runs. Four of the 25 travel time runs were substantially longer than the loop and cellular data. Of the remaining 21 runs, the WLT data was within 20 percent of the data collected from the floating car runs.

Hampton Roads, Virginia Deployment

Beginning in 2003, the firm Airsage began a project to demonstrate a handoff-based traffic monitoring system in the Hampton Roads region of Virginia. This deployment was funded by VDOT and FHWA, and the University of Virginia performed an independent evaluation of the system. The WLT system was used to monitor approximately 90 centerline miles of freeways and arterials. The AirSage technology works by mining handoff data that is already collected by cellular service providers. Data on cellular handoffs, as well as transitions between sectors of a cell, is processed to estimate a vehicle's location on the roadway network. These locations are then used to determine speed and travel time information on the network.

The University of Virginia performed an evaluation of the AirSage system in December 2005 (*13*). It should be noted that the vendor anticipated that major improvements to their system would occur in 2006, and that the evaluation was performed prior to implementing those improvements. The evaluation results show that the under congested conditions, 68 percent of the AirSage speed estimates have an error greater than 20 miles/hour. Performance also tended to be worse under congested conditions than during free flow. In the original project scope, AirSage proposed that travel time estimates would be produced on the reversible HOV facility on I-64 and confidence measures for traffic data records would be produced. However as of December 2005, neither HOV travel times nor confidence measures could be produced. Overall, the December evaluation concluded that the traffic monitoring system could not produce acceptable travel time estimates in its current form.

Summary of Past Field Deployments

Table 1 summarizes the results of independent evaluations of past deployments of WLT-based systems. As noted earlier, there was shift starting around 2003 where the technology transitioned from being based on WLT signal analysis and triangulation to handoff-based techniques. Handoff analysis appears to be the state-of-the-art in most recently completed field deployments. Another common trend is that there were no documented cases where a transportation agency had performance requirements for deployed systems. The deployments were often treated as test cases or research projects, and the vendors were not asked to meet any performance benchmarks. Likewise information on business models or cost structure was also not mentioned in the deployment evaluations, likely because the deployments were treated as experimental tests of a new technology.

Results from the evaluations to date have generally shown that these systems have had difficulty generating data that could be used for operational purposes. The earliest deployments encountered significant difficulty in determining the true location of a cellular phone on the roadway network, creating cases where speed data were often limited. Later deployments using WLT signal analysis and trilateration could generate speed estimates, but they often had significant errors. Early deployments also often neglected to report the distribution of speed errors or define system performance relative to roadway characteristics like traffic volume.

More recent deployments using handoff-based technology have not encountered the data availability problems of the early generation WLT deployments, but the quality of speed estimates was still questionable in most cases. The deployments in Munich and Hampton Roads showed some significant errors in speed estimation while the results from Tel Aviv show better ability to estimate speeds.

TABLE 1 Summary of Deployment Results

Location	Year	Vendor	Performance Requirements?	Type of Technology	Results
Washington, D.C.	1994-1997	Raytheon, Farradyne, Bell Atlantic	No	WLT signal analysis using triangulation	• Only 20 percent of probes generated speeds • Could not consistently monitor traffic
San Francisco and Oakland	2000	US Wireless	No	WLT signal analysis using pattern matching	• 60 meter mean location accuracy • 60% of locations could not be matched to road • No usable traffic data generated
Washington, D.C.	2000-2001	US Wireless	No	WLT signal analysis using pattern matching	• 5% of 10-min intervals had no data • 6 to 8 mph mean speed estimation error • Some intervals had errors > 20 mph
Lyons, France	2001	Abis/A	No	Unclear	• Good agreement at one site, speed overestimated by 24 to 32 percent at another
Munich, Germany	2003	Vodafone	No	Handoff-based analysis	• Errors between 20 and 30 km/hr common
Hampton Roads, VA	2003-2005	AirSage	No	Handoff-based analysis	• 68% of speed estimates had errors > 20 mph • No reliability measures could be generated
Tel Aviv, Israel	2005	ITIS	No	Handoff-based analysis	• Limited data during off peak hours • WLT estimates different from floating car and loop data by 10 to 30 percent during congested conditions

Results from Published Simulation Studies

A number of studies have also used simulation as a way to gain further insight into the performance of WLT-based traffic monitoring systems. Simulation provides an opportunity to examine the role of a large number of factors in a controlled environment, allowing for specific variables to be examined in detail. The simulation environment can eliminate many of the technology- or site-specific variables that can make it difficult to generalize the results of the field deployments. The limitation of the simulation studies is that they often must make a series of assumptions in modeling these systems that may or may not accurately reflect the capabilities of actual systems put on the road.

Past simulation studies range from examinations of the technical operation of a WLT-based system to assessments of sampling characteristics required to support traffic monitoring applications. One limitation of the past simulation studies is that they have tended to simulate a more GPS-like location estimating process, rather than a handoff-based process. As a result, it is difficult to fully extend most simulation results to handoff based systems. A more detailed discussion of many of these simulation studies can be found in the prior state-of-the-practice report published on the internet for this project (*3*).

The earliest attempt to use simulation to investigate the performance of a WLT-based monitoring system was performed by the French transportation research organization, INRETS, in 2000 (*14*). They used a discrete event simulation of traffic flow to investigate potential sample sizes and accuracies of a WLT-based system. The simulation found that travel times could be estimated to within 10 percent if at least 5 percent of vehicles served as probes. Locations were estimated in a GPS-like manner with a potential location error of 150 meters.

In 2001, Lovell examined a hypothetical network-based WLT system in an attempt to characterize the impact of several factors on the accuracy and sensitivity of the system (*15*). Two network-based location algorithms were tested, and the impact of a number of system design parameters were investigated. The simulation results showed that network-based systems could only provide a general characterization of traffic flow, but could not provide accurate speed estimates.

Researchers from Finland examined location estimation from a signal analysis perspective in 2002 (*16*). They compared the location accuracy of a wireless signal propagation model to a simple method whereby locations were assumed to be at the wireless tower with the highest signal strength. Hypothetical roadway and wireless networks were used for this analysis. Average position errors were around 280 meters for the signal propagation model, and over 1100 meters for the more simplistic model. The researchers did not examine speed or travel time in their research.

In 2003, Cayford and Johnson examined the impact of a number of factors on the potential availability of WLT-based traffic data (*17*). Specifically, they examined location accuracy, the frequency at which location estimates were generated, and the spatial density of probes. Depending on probe penetration, location estimation accuracy, and location update frequency, the researchers found that systems were likely to be able to provide data on between 85 and 90 percent of roads in a 5-minute interval. Those results are based on the network they tested, and there was no attempt to ascertain whether the data generated was sufficient to produce reasonable estimates of traffic conditions.

Research conducted by Fontaine and Smith continued to explore the role of system design in dictating the performance of WLT-based systems (*18*). Their research focused on assessing the quality of speed estimates generated by handset based and network-based WLT systems. The researchers used a test bed combined an emulated WLT-based monitoring system emulation with the microscopic traffic simulation model VISSIM. This test bed was used to examine a variety of system design, traffic, and geometric characteristics through a combination of tests on simple geometric networks and case studies of simulated complex, real world traffic conditions. That research found that map matching, frequency between readings, and location errors were significant factors in dictating system performance. Likewise, geometric and traffic characteristics were also major factors in the accuracy of speed estimates. One limitation of this research, however, is that it did not explicitly look at a handoff-based monitoring approach.

Ran et al performed an attempt to model a handoff-based approach to traffic condition estimation (*19*). The researchers used Bayesian Estimation Theory to examine speed estimation accuracy. The simulations assumed that all the cells had a similar size and the base stations have a common technical specification. The simulation developed speed estimates on 5 links, and a Monte Carlo simulation was developed to perform test real world data from a typical segment of urban expressway. The simulation provided consistent speed estimates of between .97 and 1.94 root-mean-squared errors for 100 runs of a Monte Carlo simulation. Accurate speed estimates were produced, but the network only consisted of 5 links that were uncongested with infrequent intersections.

Table 2 summarizes some of the major findings that have been derived from the simulation models. The simulation studies have generally shown that WLT-based monitoring should be able to provide reasonable traffic condition estimates, provided that location errors are low, networks are not complex, and sample sizes are reasonably large. When the simulation studies are looked at collectively with the field deployments, two common limitations are often seen. First, many of the simulation efforts have looked at networks that are very small, simple geometrically, and lack many of the potentially complex traffic and geometric features that would be encountered in the real world. Second, only the study by Ran had attempted to model the handoff-based approach to WLT. Recent trends in field deployments suggest that this approach is currently being used by most vendors. Thus, while the simulation studies provide some valuable information, more work is needed to fully understand the capabilities of WLT-based monitoring systems, especially those using a handoff-based approach.

TABLE 2. Summary of WLT simulation studies.

Author	Year	Approach	Results	Limitations
Ygnace, Remy, Bosseboeuf, and Da Fonseca	2000	Discrete event simulation of GPS-like WLT	Travel times with 10 percent if 5 percent of vehicles are probes	Simple geometric conditions, unclear map matching methods, limited factors evaluated
Lovell	2001	Analysis of network-based WLT	Network-based systems could not produce accurate speed estimates	Simple network, used technology paradigm that is not in use in practice
Roos, Myllymaki, and Tirri	2002	Signal propagation model	Location errors averaged 280 meters	Used hypothetical networks, no attempt to derive traffic information, used network-based location approach
Cayford and Johnson	2003	Handset based and network-based simulation	Between 85 and 90 percent of roads had a speed estimate	Simulation and map matching method not described, did not assess potential quality of speed estimates
Fontaine and Smith	2004, 2005	Microscopic traffic simulation combined with emulation of handset and network systems	Map matching, location accuracy, and roadway geometric and traffic conditions are major influences	Did not examine handset based systems
Ran, Qui, and Cheng	2006	Monte Carlo simulation of handoff based system	Speed estimates were generally accurate	Network was relatively simple with no congestion and few intersections

DESCRIPTION OF ONGOING DEPLOYMENTS

Private firms are currently operating a number of WLT-based monitoring systems throughout the United States. Five cases are reviewed in this section. The deployment characteristics, technology, contracting details, and preliminary results are addressed for each deployment.

Atlanta – Airsage (Contact Point: Mark Demidovich, Assistant. State Traffic Operations Engineer, Georgia Department of Transportation)

The Georgia DOT is currently contracting with Airsage to evaluate the feasibility of using cellular probes to derive traffic data. The $750,000 project, which began in the summer of 2005, is considered a research and development effort. The project, which has had a 6-month extension, is currently scheduled for completion in March of 2007. The pilot project covers primarily rural freeway (I-75) between the southern portion of metro Atlanta to Macon, as well as a small number of arterials, resulting in a total of approximately 80 miles of coverage.

The Airsage system is a handoff-based WLT traffic monitoring system. A more full description of Airsage's technology is presented above in the review of the Hampton Roads, Virginia deployment.

Given that the project is a research and development, "feasibility" effort, Georgia DOT did not develop performance requirements for the procurement. The quality of the data will be evaluated in the project by a subcontractor to Airsage. As of the date of the writing of this report (October 2006), data had just started being produced by the system. The evaluation effort has yet to begin. Data is being provided to Georgia DOT on a 24/7 basis, with 5 minute update rates. Georgia DOT has no restrictions on how it may use the data.

Missouri - Delcan (Contact Point: Troy Pinkerton, Traffic Liason Engineer, Missouri Department of Transportation)

The Missouri DOT (MoDOT) is in the process of pursuing a very aggressive implementation of WLT-based traffic monitoring. In 2005, they issued a RFP for companies to provide travel data for 5,500 miles of interstate and primary routes in the sate. The RFP called for an initial test in a single metropolitan area and subsequent expansion throughout the state. The RFP asked for the vendor to also support various TMC functions and provide an internet-based traveler information interface. The proposal did not specify that WLT-based monitoring be used, but a vendor utilizing this technology was selected.

On December 2, 2005, a contract was approved with Delcan to provide such a traffic monitoring and traveler information system. The project was conceived as a public-private partnership and the contract was for a 2-year term with an option for 3 1-year extensions. The contract cost of the deployment was $3.075 million per year for the first 2 years. Initial press releases from MoDOT called for data to begin flowing by February 2006, with the system operational within 6 months. That initial data from the metropolitan areas was to be evaluated for a 2 week period before a decision to proceed with the broader statewide project was made. After the award of the contract, the original cellular provider backed out of the agreement with Delcan. As of October 2006, Delcan does not have an agreement with a provider that allows use of the data. They have a teaming agreement with a different vendor which they hope will evolve into a formal agreement by the end of 2006. If this occurs, they will be able to proceed with deployment of the system. Since the contract was milestone-based, MoDOT has not spent any money to date.

The MoDOT project manager indicated that they will allow the project to proceed and hope that a new agreement with a cellular provider can be reached. The manager further indicated that it was possible that the agreement with Delcan would be re-scoped, since it was probable that the new cellular provider would not be able to provide full coverage of the state. Instead, the system coverage would likely be confined to the major urban areas and interstates. Assuming that a cellular provider is brought under contract and the contract is revised, MoDOT would like to see the full implementation of the state system by the end of the 2^{nd} quarter of 2007. MoDOT does plan to conduct an independent evaluation of the system. The Missouri Transportation Institute has been contacted about performing this evaluation, but the evaluation is on hold until a cellular provider can be brought on board and the system can be deployed.

The Delcan system (using partner ITIS Holdings' WLT technology) uses an approach which fuses data from WLT-based monitoring and GPS vehicle probes. The WLT system relies on monitoring cellular handoffs, and then pattern recognition software and an accompanying traffic model estimate speeds. The system is also using a number of GPS-equipped vehicle fleets to augment the cellular phone data. These are expected to include national fleets, parcel delivery companies, and taxi companies. MoDOT has asked the vendor to provide two sets of speed estimates: one derived from using both GPS probes and the WLT system, and one using only the WLT system. This was done so that MoDOT would have a clear understanding of what the WLT system was contributing the condition estimates. MoDOT wanted to see if the traffic monitoring system would still be viable if no GPS probes were used. The project manager indicated that they did not want to see the GPS data substituted for the WLT estimates. No sensor data from the traffic management centers is being fused with the Delcan data. The system is expected to produce link-based travel time and speed data on a condition map. The map would color code links based on current conditions.

MoDOT indicated that privacy concerns were been raised by a number of groups about this project, although public information efforts have helped to resolve these concerns. Individually identifiable data is kept behind the firewall of the wireless communications provider. MoDOT also indicated that the data resides on the vendor server and that MoDOT does not own any of the data. Aggregate data on speeds and travel times are provided to MoDOT in 1-minute intervals on a link-wise basis. The MoDOT project manager indicated that while Delcan owns the data, MoDOT does not have any restrictions on how they use the aggregate data. Delcan reserves the rights to the raw data, but MoDOT can use the link-based data to support traveler information, performance measure, planning model development, or whatever else they like.

MoDOT did report some data that was provided by the vendor prior to the termination of the contract with the initial wireless provider. Delcan performed test drives to assess the accuracy of the path matching methods that their system used. According to Delcan, 95 percent of test drives on interstates were matched to the correct route, and 85 percent of test drives on urban roads were correctly matched. These results have not been verified by a third party.

No formal performance requirements were specified in the MoDOT RFP. While MoDOT indicated that they would examine items like travel time accuracy, system availability, and data latency in their evaluation, they did not set any benchmarks for those items. They have indicated that the deployed system is not expected to provide traffic volume, occupancy, or any lane-specific data.

Baltimore – Delcan (Contact Point: Mike Zezeski and Glenn McLaughlin, Maryland State Highway Administration)

The Maryland Department of Transportation is currently involved in a public-private partnership project with Delcan and ITIS Holdings to deploy and operate a regional traffic monitoring system. While the partnership is using "traditional" data collected by Maryland DOT (i.e. through point sensors and incident reports), much of the data is collected from anonymous probes (both from GPS-equipped fleets and a WLT-based system). The project is focused on the Baltimore metropolitan region. The project was initiated in September of 2004 as a 2 year project. However, recently, Maryland DOT has extended the project for 6 additional months. Maryland DOT provided $1.9 million for the project from a federal earmark. All matching funds for the earmark are being provided by the private sector partners. The project is structured as an operational test, not as a data service agreement.

The technology used by Delcan and ITIS Holdings for WLT-based monitoring is the same that is being used in the Missouri deployment, described above. As with the Missouri case, the original provider of cellular data ceased providing the raw data after the project began (in February 2006). To date, an alternate source of cellular data has not been secured, although Maryland DOT has been told by Delcan that they expect to have this resolved by January 2007. When available, data was provided from the system at 5-minute intervals on links that are defined largely by existing digital maps and cellular boundaries (roughly 0.5 – 1.5 miles in length).

Given that the project is an operational test, Maryland DOT did not define detailed data quality requirements. However, the agreement does impose clear restrictions as to how the DOT can use the traffic data. For example, Maryland DOT has the right to post travel time information based on the data to variable message signs, but they are not permitted to post detailed data on their CHART website (i.e. anything beyond general speed ranges on a color-coded condition map). This has presented the DOT with the challenge of effectively "segregating" within their operations software – to allow them to use data that they collect freely, while ensuring data from this partnership is not used in an unauthorized manner.

Maryland DOT has contracted with the University of Maryland to conduct a formal evaluation of the quality of the WLT-based traffic data. Note that the university collected baseline comparison data for the evaluation in January – February 2006 when raw cellular data was still available. While the final report from the university had not been released at the time of this report, preliminary results are available. The evaluation considered both link speed– which is defined as the speed measured for a short directional highway segment (similar to the notion of links in a point sensor system, with link lengths on the order of ½ to 1 mile), and path travel time – which is the total travel time over multiple links. Figure 3 below illustrates the accuracy of link speed estimates from the WLT-system (note, this does not reflect data from GPS-based fleet data). Note that on limited access freeways, the system generally delivers link speed estimates with 20% error or less, 75% of the time. Performance is significantly worse for the arterial facility, MD 40. Figure 4 illustrates accuracy of the WLT-based system in measuring path travel times. Again, while performance on the arterial is not strong, the WLT-based system delivers path travel time measures that have 20% error or less about 90% of the time.

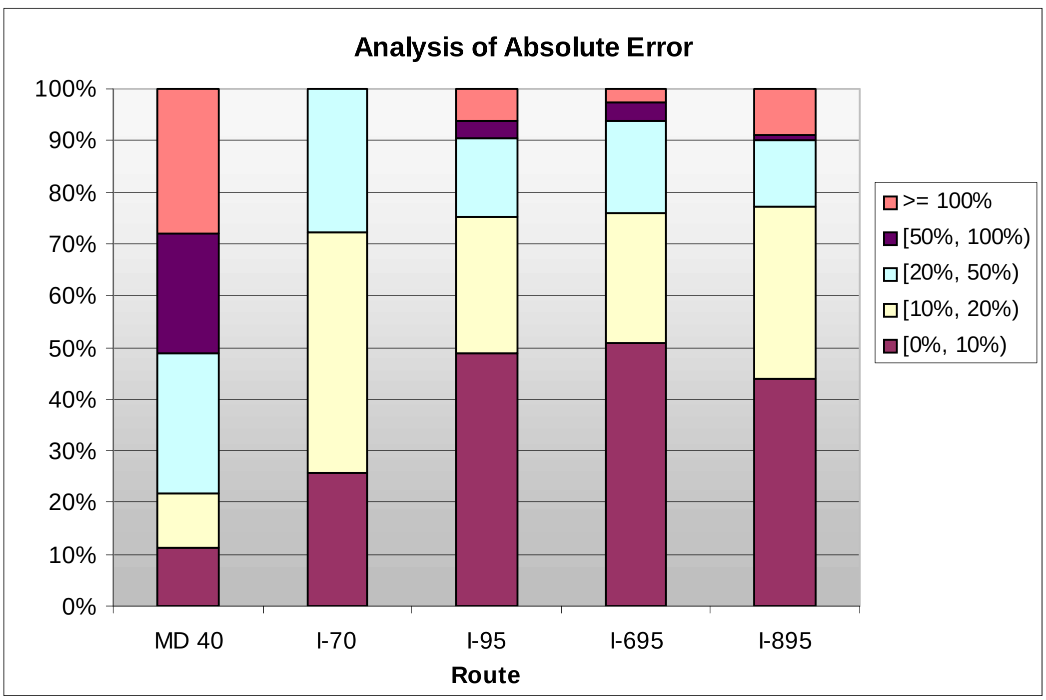

Figure 3 - Link Speed Accuracy

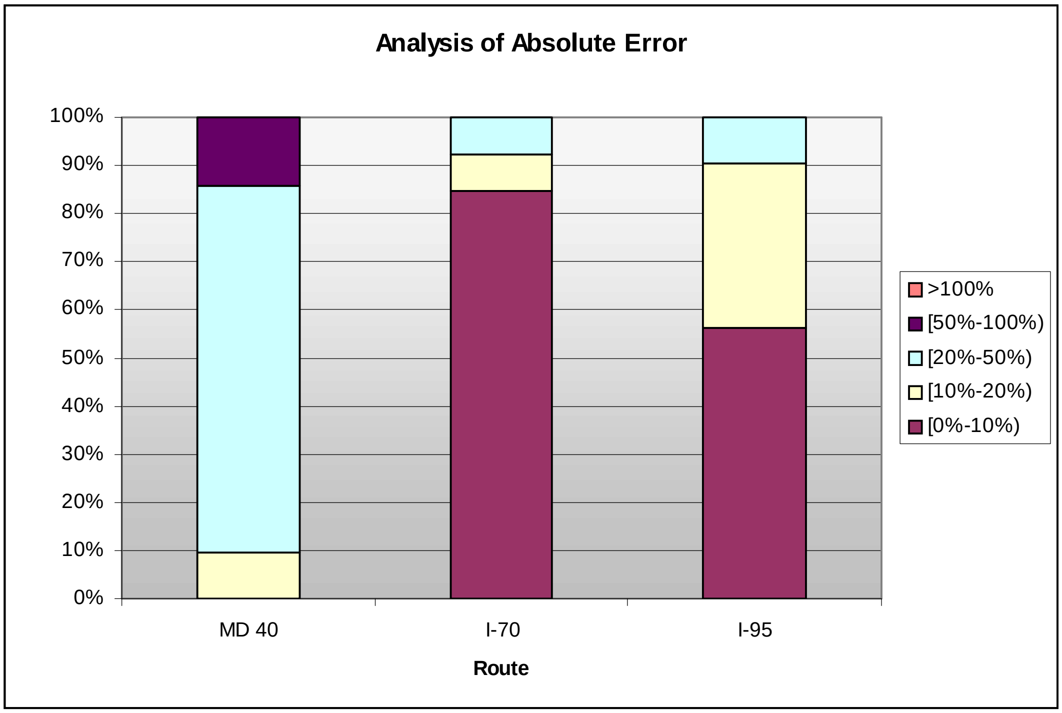

Figure 4 – Path Travel Time Accuracy

Kansas City (Contact Point: K. Mark Sommerhauser, ITS Projects Manager, Missouri Department of Transportation)

In February 2006, the KC Scout traffic management center in Kansas City signed an agreement with the vendor CellInt to perform a test deployment of CellInt's TrafficSense system on a portion of I-435 with an active construction project. This was a no-cost agreement between the two groups, with KC Scout providing personnel to perform an independent evaluation of the system and CellInt performing a no-fee deployment of the TrafficSense technology.

Because of the nature of the agreement, there has been no discussion of cost structure or data ownership of a full scale system. The KC Scout manager stated that those issues would be addressed if a long term relationship is pursued with the vendor. As of late 2006, the project in Kansas City is structured more like a research project than a data service.

The TrafficSense system monitors the control channel of cellular phones, and uses pattern matching algorithms to correlate a vehicle's estimated location to the roadway network. The vendor states that they can measure speeds and travel times in links as small as 250 meters. CellInt operates under a somewhat unique business model. In addition to traffic monitoring, the vendor offers a cellular network communications optimization program. A wireless provider receives the optimization service in return for providing access to CellInt so that they can gather the required information to perform traffic monitoring. The vendor states that providing this service to the wireless company helps encourage a strong relationship between the two groups, helping to ensure that the wireless company remains involved in deployments.

A formal evaluation of the CellInt deployment was recently completed (note that at the time this report was finalized, the evaluation report was not yet available). Speed data collected by TrafficSense was used to produce a traffic condition web site where speeds were color-coded based on the level of congestion. The analysis of the TrafficSense system consisted of three major efforts:

- a visual check to ensure whether the system appeared to identify known incident conditions
- A visual check to ensure whether the color-coded segments were accurate
- A detailed analysis that examined accuracy and availability of the segments over a prolonged period.

The project manager stated that the ultimate goal of the system would be to provide travel time information, including information that could be displayed on outlying VMSs where there is no existing sensor infrastructure. The speed data that is being returned is currently aggregated by link in 2.5 minute intervals. TrafficSense measured speed data for 44 days in June and July of 2006. These data were used to perform a "blind" comparison between the speeds returned by the TrafficSense system and those that were detected by the existing KC Scout loop detector sensor network. Part of this examination focused on slowdowns where the speed decreased by at least 10 mph within 10 minutes while speeds transitioned between more 50 mph and less 50 mph. The blind comparison between sensors and TrafficSense data showed an average latency in the data of about 4 minutes. The average difference in speeds between sensors and TrafficSense was less than 5 mph, and the TrafficSense system was estimated to be functional approximately 99 percent of the time.

Following the blind study, inductive loop detector data was passed to CellInt to help assist in the calibration of the system. According to the KC Scout contact, CellInt indicated that it is helpful to periodically calibrate the model based on existing conditions. This was occurring approximately monthly during the course of the initial evaluation. The relationship with CellInt is still ongoing, and CellInt was expected to start producing travel time data in late 2006. Those travel times will be compared against probe vehicle travel time runs, as well as algorithms that KC Scout is testing that will generate travel times off of the data from the inductive loop detector network.

Atlanta – Cellint (Contact Point: Mark Demidovich, Asst. State Traffic Operations Engineer, Georgia Department of Transportation)

The Georgia DOT is currently involved in another initiative to purchase traffic data from Cellint Traffic Solutions, Ltd, a private-sector provider using WLT technology. In this project, Georgia DOT was seeking a means for a short-term data source for a 10-mile section of the Georgia 400 freeway which serves the northern suburbs of Atlanta. Georgia 400 is part of the agency's NAVIGATOR traffic management system, but its "traditional" surveillance infrastructure was made temporarily unavailable due to construction. Note that the technology used by Cellint in Atlanta is the same as that they are using in Kansas City (see description above).

Georgia DOT used a "negotiated contract" as the contracting vehicle for the project. This allows the DOT to expedite procurement of small ticket projects (less than $50,000). The DOT did include a set of requirements in the RFP. The requirements stated are shown below:

Performance Requirements and Schedule

GDOT issued a request for proposals (RFP) that sought to deploy a low-cost solution that meets GDOT's performance criteria and can be rapidly deployed and integrated into NAVIGATOR. Given the loss of important data along high traffic sections of SR 400, GDOT gave priority to those solutions that can be operational within 45 days of contract award and that have the ability to offer additional traffic flow and incident detection information along neighboring roads (such as SR 9 / Roswell Rd and Peachtree Dunwoody Roads at a minimum). Proposals were required to reflect a period of operation of 6 months, with the potential extension at the sole option of GDOT. The RFP included several definitive performance requirements. They required that vendors, at a minimum, demonstrate that their technology could:

1. Provide trip times and/or average speeds along predetermined segments of roadway.
2. Identify a potential incident within the coverage area based on speed reduction over a 0.5 mile stretch of the covered primary roads.
3. Isolate the source of the incident to within +/- 250 meters of the location of the incident.
4. Starting from 75 days from notice to proceed, this traffic flow and incident detection system will be benchmarked against video detection sensors (those which are still functioning in the covered route). The system must provide in average similar capabilities for incident detection as the video detection system, with variance of 2 sigma or better.

The schedule requirements stated above were not, however, met in the project. It took a period of 8-10 months before data was made available to GDOT. At this point, data were provided at an update rate of 2.5 minutes and for links that are consistent with those of GDOT's detector system (i.e. 1/3 mile). At this point in time, there is no information available as to the quality of the data. There are also no plans to conduct an independent evaluation.

SIMULATION OF HANDOFF BASED SYSTEMS

The review of the recently completed and ongoing field tests indicates that the marketplace is moving towards a handoff-based approach to WLT. Unfortunately, little quantitative data is publicly available about the performance of this approach, and most simulation studies have only examined potential factors that might impact handset or network-based WLT-based systems (*14,17,18*). Simulation studies of handoff-based systems are much more limited (*19*). Given that recent trends indicate that handoff-based systems are becoming the technology of choice, an exploratory simulation study of handoff-based systems was performed to try to gain further insight into the factors that might impact their performance.

Simulation Framework

A WLT-based traffic monitoring simulation that combined the microscopic traffic simulation VISSIM with a custom emulation of a WLT system that had previously been developed, and this framework was modified to examine a handoff-based approach (*18*). In the modified program, a hexagonal network of hypothetical cellular tower coverage areas was input into the program. Vehicle locations were recorded when a vehicle crossed the boundaries between adjacent cells. By looking at a series of these transitions, it was possible to select the road that a vehicle was likely traveling on and generate a speed estimate. The framework of the simulation is shown in Figure 5.

The simulation represents a simplification of how handoff-based technology works in several respects. First, the boundaries of the cellular tower coverage areas were assumed to be static, and all cells were assumed to be the same size. In reality, the boundaries between cells are extremely complex and overlap one another. They are also dynamic, and change in response to communications traffic, weather conditions, and other factors. Cell sizes also vary according to topography and expected call load. Second, only transitions between cells were used to generate speed estimates. Many current systems rely on additional data streams to augment their data quality, such as transitions between sectors in a single cell.

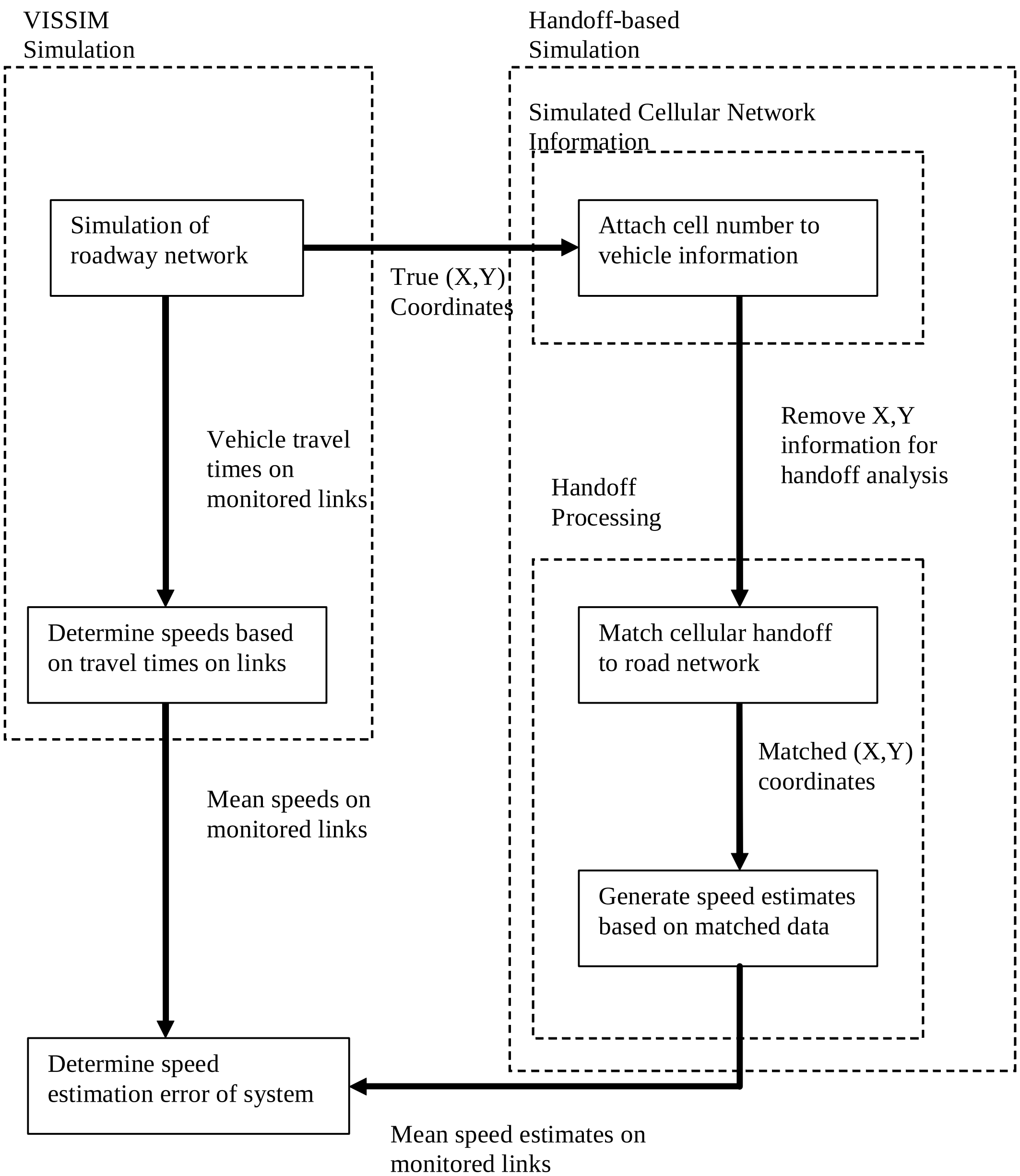

Figure 5. Simulation Framework.

Simulation Methodology

Two different roadway networks were simulated to assess the potential performance of a handoff-based monitoring system in contrasting situations. The first network simulated was the Tyson’s Corner area in suburban Washington, D.C.. The Tyson’s Corner network consisted of a mix of congested urban arterials and congested urban freeways. The size of this roadway network was relatively small, with only 9.6 centerline miles of arterial roads and 11 centerline miles of freeway being monitored. The data to construct this model was acquired from the Virginia Department of Transportation (VDOT) Northern Virginia District.

The second network was from the Hampton Roads region in southeastern Virginia. This was a large regional network that extended from Williamsburg in the north through the Norfolk/Virginia Beach area. It was originally constructed to support VDOT's hurricane evacuation planning. This model covers a large regional freeway system, and the arterial system is not explicitly modeled or monitored. In both cases, the hexagonal cellular network was assumed to overlay the roadway network so that cells tended to be centered on major roadways, a practice commonly seen in cellular system design. Characteristics of each site are summarized in Table 3.

TABLE 3 Simulation Network Characteristics

Roadway Network	No. of Arterial Miles Monitored	No. of Signalized Intersections	No. of Freeway Miles Monitored	No. of Freeway Interchanges
Tyson's Corner	9.6	32	11	7
Hampton Roads	0	0	65	53

The goal of these simulations was to provide a high-level analysis of the potential capabilities of handoff-based monitoring systems. Specifically, the simulations were used to examine the effect of three different factors on the ability of a simulated handoff-based system to generate accurate speed estimates. The factors examined were:

- **Individual roadway:** By examining performance by roadway type, differences in performance based on geometric conditions or level of access control could be assessed.

- **Cell size:** Three different cell sizes were examined: 1, 3, and 5 square miles. Proprietary network data from a major cellular carrier showed that these areas are roughly equivalent to an urban cell, a small suburban cell, and a moderate suburban cell, respectively. All cells were modeled as hexagons. Since the Hampton Roads network was a large regional model, only the 3 and 5 square mile sizes were evaluated on that network.

- **Probe Penetration:** Three levels of probe penetration (i.e. the number of vehicles with cellular phones that could be "tracked") were examined to assess the impact of the number of vehicles being monitored on system performance. A total of 20, 40, and 60 percent of vehicles in the network were monitored. This roughly corresponds to having 1, 2, or 3 wireless carriers participate in the monitoring program.

A full factorial experimental design using a general linear model (GLM) was used to assess the impact of these factors on speed estimation accuracy. The speed estimation accuracy was defined as the absolute difference between the true speed on the roadway link (from the VISSIM model) and the estimated speed. Speed results were summarized in 5-minute intervals, and the resulting error values were compared to determine the effectiveness of the system.

Simulation Results

Table 4 shows the results of the GLM analysis of the various factors on both simulated roadway networks. The results indicate that the specific roadway, cell size, and roadway and cell size interaction showed a statistically significant impact on speed estimation accuracy. Neither the main effect of probe penetration nor any of its interactions were significant. The primary impact of the probe penetration variable was to dictate the number of vehicles that were monitored. The lack of statistical impact indicates that all levels of probe penetration tested appeared to produce an adequate number of samples for speed estimation purposes. Thus, it appears that having even one major wireless carrier participate in a project should produce sufficient samples to generate adequate speed estimates.

TABLE 4 Results of Factor Analysis on Absolute Speed Accuracy

Source	Tyson's Corner		Hampton Roads	
	F Statistic	Significant?	F Statistic	Significant?
Roadway	45.11	Yes	8.563	Yes
Cell size	83.98	Yes	13.30	Yes
Probe Penetration	0.062	No	0.006	No
Roadway × Cell Size	5.914	Yes	3.619	Yes
Roadway × Probe Penetration	0.470	No	0.019	No
Cell Size × Probe Penetration	0.200	No	0.058	No
Roadway × Cell Size × Probe Penetration	0.222	No	0.010	No

Table 5 shows the speed estimation error by roadway on each network. Although this factor is significant for Tyson's Corner, from a practical perspective all roads are monitored fairly well. The percentage errors are sometimes large, with errors approaching 20 percent due to low overall speeds, but the results from the Tyson's Corner case generally shows acceptable results for a congested urban network. The Hampton Roads case shows much more variability by roadway, however. Mean errors vary between 1 and almost 8 mph by roadway, and in some cases errors in speed estimation exceed 100 mph. It appears that the very large errors in estimation are created by two factors. First, roadways with interchanges with complex geometry tended to have problems estimating speed in the vicinity of those interchanges. Also, the way that the cellular network overlays the roadway network appeared to be a significant factor in generating large errors. If a specific roadway link is in cell for just a short distance, errors in location estimation can generate huge speed errors. This problem is particularly evident when interchanges occur near the boundaries between cellular coverage areas. The larger variance in speeds at these locations appears to create problems in speed estimation. However, it should be possible to create a heuristic procedure that could identify and eliminate outliers for the data, while still detecting true shifts in the mean speed on the link.

TABLE 5 Mean Absolute Speed Error by Roadway

Network	Road	Mean Link Speed (mph)	Mean Speed Error (mph)	Percentage Error	Max. Speed Error (mph)	95th % Confidence Interval for Error	
						Lower Limit	Upper Limit
Tyson's Corner	SR 7	17.4	1.30	7.48	8.75	1.12	1.48
	SR 123	12.0	2.26	18.8	8.07	2.08	2.44
	SR 276	50.2	2.32	4.62	12.6	2.16	2.48
	I-495	16.1	1.25	7.77	10.4	1.05	1.45
Hampton Roads	I-64	57.5	7.64	13.3	374	6.82	8.46
	I-264	59.7	3.48	5.83	22.1	1.50	5.46
	I-464	57.7	1.11	1.93	4.00	0.00	8.68
	I-664	65.6	4.16	6.33	156	2.59	5.73

Table 6 shows the impact of cell size on overall speed estimation error. For the Tyson's Corner case, the 1 square mile cell size produced better speed estimates than the 3 or 5 mile cell sizes. In this case, it appears that reducing the size of the cell appeared to better capture localized changes in traffic flow. The 3 and 5 square mile cells overlaid the network in very similar ways, so performance was very similar between the two. The Hampton Roads network also showed that smaller cell sizes produced more accurate results. The smaller cell sizes appear to improve the ability of the system to produce accurate results.

TABLE 6 Mean Absolute Speed Error by Cell Size

Network	Cell Size (mi^2)	Mean Speed Error (mph)	Percentage Error	Max. Speed Error (mph)	95th % Confidence Interval for Error	
					Lower Limit	Upper Limit
Tyson's Corner	1	0.977	3.64	8.07	0.83	1.13
	3	2.195	9.82	10.41	2.04	2.35
	5	2.175	9.61	12.62	2.02	2.33
Hampton Roads	3	2.866	4.72	81.26	0.81	4.92
	5	6.732	11.30	374.3	5.33	8.14

While the interaction of roadway and cell size was significant, it appears that this is simply an extension of the main effects of those two factors. The implication of these results is that the way that the cellular network overlays the roadway network is of critical importance in dictating the effectiveness of handoff-based systems. The results imply that urbanized areas with smaller cells will be monitored more effectively than regions where cellular coverage areas are larger. It also implies that sections of roadway that are just barely contained within a cellular coverage area may not be able to be monitored effectively. The simulation does appear to indicate that the handoff-based systems do have the potential to be able to effectively generate traffic data, and it appears that the approach has considerable promise.

SURVEY OF TRANSPORTATION PROFESSIONALS

In January 2006, the researchers conducted a web survey that was designed to assess how agencies might potentially utilize WLT-based traffic monitoring systems. This survey also sought to determine what levels of accuracy and availability might be desirable in such a system. The survey was publicized through several internet mailing lists, as well as through the Transportation Research Board Freeway Operations Committee. Responses to the survey were limited, with less than 20 people completing the survey. The respondents were evenly balanced between state transportation agencies, local agencies, the private sector, and researchers. Although the sample size was limited, several interesting findings were noted.

First, respondents were asked about which functions they would like to support with purchased traffic data. Performance monitoring and measurement was cited by every respondent to the survey. Traveler information was mentioned by about 70 percent of respondents. Incident detection, real time control, and planning model support were noted by between 50 and 65 percent of respondents.

There was some variation in opinion about which measures of effectiveness were most important when evaluating a private sector data system. Survey respondents were asked to rate measures on a scale of 1 to 5, with 5 being extremely important and 1 being not at all important. The measures with the most respondents ranking the measure as either a "4" or "5" were:

- Accuracy of freeway traffic condition estimates (speed or travel time) – 84 percent ranked highly
- Percentage of time that traffic condition estimates are available on the freeway system – 75 percent ranked highly
- Annual cost of continuing operations – 75 percent ranked highly
- Initial cost of deploying system – 67 percent ranked highly
- Accuracy of arterial network traffic condition estimates (speed or travel time) – 67 percent ranked highly

The following measures were ranked highly the least often:

- Percentage of arterial network monitored – 50 percent ranked highly
- Percentage of time that traffic condition data is available on the arterial network – 41 percent ranked highly

Respondents were also asked the percentage of time that the system should be producing data for several applications. The results are shown in Table 7 below.

TABLE 7. Desired Data Availability for Different Applications.

Application	Percent of Time Data is Available		
	Minimum	Maximum	Median
Traveler information	50%	95%	80%
Performance measurement	25%	100%	85%
Incident detection	50%	100%	95%
Real time operations and control	75%	100%	95%

Similarly, respondents were asked for the minimum speed estimation accuracy desired for several applications. The results are shown in Table 8 below.

TABLE 8. Desired Speed Estimation Accuracy for Different Applications.

Application	Desired Speed Estimation Accuracy (mph)		
	Minimum	Maximum	Median
Traveler information	3	10	5
Performance measurement	3	10	10
Incident detection	3	15	5
Real time operations and control	3	20	5

Even though the sample size of the survey is limited, is does show some of the difficulty in defining standard measures of performance. There was sometimes significant variability in how the respondents answered the questions. Generally speaking, there appeared to be the highest interest in supporting performance measurement and the least amount of interest in arterial applications. Respondents generally wanted systems to be available between 80 and 95 percent of the time, with speed estimation errors of between 5 and 10 mph.

LEGAL AND PRIVACY FRAMEWORK

Agencies are often concerned with how the public will perceive WLT-based monitoring systems. Although all locations are generated and processed anonymously, there is the potential that the public will perceive this as an invasion of their privacy. Relevant federal law was examined to better define the legal framework that exists around WLT-based traffic monitoring. Three major areas were examined: telecommunications legislation, constitutional privacy concerns, and the Freedom of Information Act. The review concluded that there are no substantive legal barriers to deploying these systems, provided that the wireless communications provider has safeguards on individually-identifiable information in place.

The Wireless Communications and Public Safety Act

Wireless Communications and Public Safety Act of 1999 (hereinafter referred to as the Customer Proprietary Network Information (CPNI) statute) has direct implications on WLT-based traffic monitoring systems (*20*). This statute is administered by the Federal Communications Commission (FCC), which has promulgated regulations in order to carry out the requirements of the statute (*21*). The statute and the regulations also provide the legal framework for analyzing how location data collected by wireless providers can be used.

Definition of CPNI and Aggregate Information

The CPNI statute explicitly defines CPNI as "information that relates to the…location…of use of a telecommunications service subscribed to by any customer of a telecommunications carrier, and that is made available to the carrier by the customer solely by virtue of the carrier-customer relationship" (*22*). In contrast, aggregate information is defined as "collective data that relates to a group or category of services or customers, from which individual identities and characteristics have been removed" (*23*). Aggregate information, for example, would be data that merely discloses the volume of users in a certain location or area without disclosing individual customer location characteristics. However, if the information contains data that allows someone to track the movements of individual users, then it is CPNI. The distinction between data that does not contain individual customer identities and characteristics and data that does is extremely important in determining the privacy protections afforded to the data under the statute.

Statutory Protection

The CPNI statute only directly applies to telecommunication companies and not to third party vendors, contractors, or users of the information (*24*). As a result, transportation agencies or WLT vendors could not directly be held liable under the statute for a violation. However, an agency could potentially suffer indirect consequences in the event that a telecommunications company's disclosure of location information was found to be a violation of the statute. One such consequence is sunk costs. The FCC has the statutory authority to issue a cease and desist order to a telecommunications company that it finds in violation of the statute (*25*). A cease and desist order directed at the telecommunications company would stop the data flow to the agency; and if the agency's benefit from the data hinges on the ability to monitor data for a certain length of time, then such an order could result in sunk costs. In other words, a DOT will have funded the WLT deployment, but a cease and desist order would halt the project. Second, while the language of the statute does not implicate a transportation agency, the party that provides the data to the DOT could attempt to use contractual provisions to place certain duties on the DOT, such as liability for damages in the event of a statutory violation. Still, since the statute applies directly to telecommunications companies, they will be subject to legal action initially.

The common law notion of ownership- that it is merely a bundle of rights that entitle the possessor the use and enjoyment of the property- applies to CPNI. However, the telecommunications companies' ownership rights are limited by the CPNI statute. In establishing privacy requirements, section (c)(1) of the CPNI statute states:

> *Except as required by law or with the approval of the customer*, a telecommunications carrier that receives or obtains customer proprietary network information by virtue of its provision of a telecommunications service shall only use, disclose, or permit access to *individually identifiable* customer proprietary network information in its provision of (A) the telecommunications service from which such information is derived, or (B) services necessary to, or used in, the provision of such telecommunications service, including the publishing of directories (*26*).

Although this section of the statute creates a presumption that CPNI is protected, it also creates four exceptions that exempt information from protection.

The first exception is use or disclosure of information with the customer's permission, which *would allow* the telecommunications company to disclose otherwise protected CPNI. This provision is carried out by FCC regulations and will be discussed in a later section.

The second is disclosure of information as required by law. Although the CPNI statute mandates disclosure for emergency response purposes, there is nothing in federal law that would require the company to disclose the information for traffic monitoring purposes (*27*).

The third provision that exempts CPNI from protection only relates to using the CPNI for telecommunications services. Thus, it would not affect a transportation agency's usage of CPNI (*28*).

Finally, this section of the statute implies that CPNI that is not "individually identifiable" is not protected by this provision in the statute. One reading of this provision is that it establishes another category of data that is separate from individually identifiable CPNI and aggregate information. However, such a reading does not comport with the remainder of the statute. An alternate reading is that this section of the statute is merely contemplating scenarios where the company receives CPNI and then strips the individually identifiable characteristics from the CPNI to create aggregate information. This reading is supported by other sections of the text. For example, in section (c)(3) the statute says that "a telecommunications carrier that receives [CPNI] by virtue of its provision of a telecommunications service may use, disclose, or permit access to aggregate customer information other than for purposes described [above]" (*29*). Thus, it appears that the CPNI statute only creates two categories of data received or obtained from customers: individually identifiable CPNI and aggregate customer information. The statute generally protects the former, but not the latter.

As a result, the data that a transportation agency ultimately uses must be categorized as either individually identifiable CPNI or aggregate customer information. The essential point of analysis is whether the individual customer can be identified with the data that is being used or disclosed. One might think that merely stripping the individual's identity is sufficient to transform it into aggregate information. However, the text of the statute uses the term "individually identifiable." This is more appropriately understood to mean information that ***enables*** a third party to identify an individual. Moreover, the statute explicitly defines aggregate information to include information where both the customer's identity ***and*** the customer's characteristics have been removed. Thus, creating aggregate information requires more than merely removing the name of the individual from the CPNI (*23*). This raises the question of what else must be removed.

One characteristic that is of concern is individual location information. This information could enable a third party to identify an individual since the information would likely disclose where the individual travels to and from. This logic is supported by the fact that the text of the statute explicitly mentions "location of use" in the definition of CPNI. Thus, location information for a particular person is likely to be seen by the courts as an individual customer characteristic that has not been removed. Accordingly, such information is protected as individually identifiable CPNI, and the FCC and the courts would require that the telecommunications company seek customer approval of the use and disclosure of the information. On the other hand, if the telecommunications company is disclosing information about the volume of customers in a certain area or the average travel speed of its customers in a certain area and all individualized characteristics have been removed from that data, then it would likely be classified as aggregate customer information, and no approval would be necessary. In other words, providing individual origin-destination information is likely prohibited, even if identifying characteristics are stripped from the calls. If this data were needed, it could be aggregated into traffic analysis zones to provide origin-destination information while not being classified as individually-identifiable CPNI. Link-level average speed estimates are also not likely to be classified as individually identifiable CPNI.

Statutory and Regulatory Requirements for Obtaining Customer Approval

Should a vendor or agency desire to obtain individually identifiable CPNI, the FCC regulations set out specific requirements that the telecommunications companies must follow to obtain customer approval for the use and disclosure of protected CPNI, FCC regulations also define the provider's duties to protect the CPNI once it does have customer approval. The regulations declare that approval can be written, oral, or electronic as long as it is in compliance with FCC rules that are set out in the regulations (*30*). Furthermore, the regulations allow for two different approval processes: opt-out and opt-in. Opt-out is defined as a method where the customer is deemed to have consented if the customer has failed to object within the waiting period described by regulation after the customer is provided notification in accordance with regulations (*31*). Opt-in is defined as the customer's express consent after notification is provided in accordance with regulations (*32*). Either method can be used if the use or disclosure of the CPNI is for the purpose of marketing or providing communications-related services to that customer (*33*). However, if the CPNI is for other purposes, such as traffic monitoring, then the telecommunications company must use opt-in approval (*34*). Finally, as suggested above, the regulations set out specific requirements to which the telecommunications company must adhere in providing notice to its customers. Notice must include, among other things, the types of information that constitute CPNI, the entities that will receive the CPNI, the purposes for which the CPNI is to be used, and the steps the customer must take to grant or deny access to the CPNI (*35*).

The distinction between the opt-in and opt-out methods can be difficult to make. The essential difference between opt-in and opt-out is whether or not there is express consent of the customer. Where the terms of the contract explicitly declare that the company will use CPNI, and the customer explicitly agrees to those terms and conditions, the customer has opted in. The fact that a wireless agreement details the steps the customer would have to take in order to grant or deny access to CPNI is of no consequence because the regulations require such information in both opt-in and opt-out notifications (*36*).

Many contracts for wireless service contain CPNI provisions that must be classified as an opt-in. Examination of wireless provider agreements available on the internet shows that while providers use varying language, they are consistent in restricting their own use and disclosure of CPNI to the purpose of providing and marketing telecommunications related services (*37*). Furthermore, while some of the agreements do not mention disclosure to third parties, others do (*35*). Those that do mention 3rd party disclosures are in accordance with regulations, which allow disclosure for the purpose of providing or marketing telecommunications-related services to the customer and on the condition that the contractors enter into a confidentiality agreement with the telecommunications company that contains certain consumer CPNI protections (*38*). Such confidentiality agreements are not accessible, but they probably have language that limits disclosure in several ways. First, the regulations require that the agreement limit the use and disclosure of CPNI to purposes related to marketing or providing the communications-related services for which that CPNI has been provided (*39*). Second, the agreement must restrict the vendor from disclosing the CPNI to any other party. Third, the agreement must require that the vendor have appropriate protections in place to ensure the confidentiality of consumers' CPNI.

It is unclear whether the regulations pertaining to third party contractors apply only to situations where the telecommunications provider has approval to use CPNI for providing and marketing communications-related services. However, while the confidentiality requirements of vendors may not apply in situations where the telecommunications company has permission to use CPNI for other purposes, none of the wireless provider agreements examined allow the wireless provider to use or disclose CPNI for other purposes. It is also unclear how the regulations affect the vendor's ability to provide aggregate information based on CPNI. Thus, without knowing the terms of agreement between the third party and the wireless provider, it is difficult to assess whether an agency could even obtain aggregate information from the third party vendor without exposing the vendor to some type of contractual liability.

Furthermore, the regulations on the customer approval process have been changing in recent years due to legal challenges. For example, the regulations previously required an opt-in scheme, and did not allow providers to use the opt-out scheme. In a legal challenge, a federal appellate court vacated the regulations because the FCC failed to show that the regulations restricted no more constitutionally protected commercial speech than necessary to serve the state interests; and as a result, the regulations violated the First Amendment (*40*). Thus, while the regulations currently in place are applicable to the current approval process, this could change if the regulations are challenged in court on constitutional grounds.

Constitutional and Privacy Issues

Recently, the FCC has mandated that wireless providers be able to provide location estimates for wireless calls in order to support 911 response (*41*). Privacy advocates are concerned about how this location data may be used and are worried about the potential privacy implications of having this type of data readily available. They specifically protest the government possessing the capability of tracking an individual's movement, both in real-time and historically, and the potential for abuse of the data gathered using this capability.

There are a number of constitutional concerns that affect the use of data of this type by a governmental agency. Cellular phone location technology has already been used outside the realm of the Enhanced 911 program in a number of cases. In a number of cases, cellular usage data has been used to locate suspects or establish a person's movements (*42*). In these instances, law enforcement did not have to obtain a warrant because the cellular phone owners did not have an expectation of privacy, as they knew or should have known that cellular phone companies keep active records of numbers dialed, calls received, and the cellular phone towers contacted. However, there are questions as to whether the location information should be private even if the dialed phone number is not. The constitutional arguments against governmental use of location data mainly apply to search and seizure and the possible use of the data as evidence at trial. Restrictions on use would probably be less strict for WLT-applications, as the data will be used solely for traffic monitoring purposes and not as evidence of wrongdoing.

The Fourth Amendment has been applied to protect against unreasonable search and seizure within the realm of monitoring communication and electronic surveillance technologies. In ***Smith v. Maryland*** the court established that in order to invoke the protection of the Fourth Amendment one must demonstrate a "legitimate expectation of privacy that has been invaded by government action" (*43*). In *Smith*, the court found that a pen register that collected phone numbers dialed by defendant was not protected, as all telephone users should know that they are conveying their calls to the telephone company, and that the phone company is making permanent records of the numbers they dial. Therefore, the individual does not have a valid expectation of privacy, as they know the information is being conveyed to a third party. The Court also stated that the "Fourth Amendment does not prohibit the obtaining of information revealed to a third party and conveyed by him to Government authorities, even if information is revealed on the assumption that it will be used only for a limited purpose and the confidence placed in the third party will not be betrayed" (*44*). Hence, an individual cannot expect the information, such as cellular phone location data, which is routinely conveyed to the telephone company to remain private.

There are two elements to showing a legitimate expectation of privacy. The first is that the individual had a subjective expectation of privacy and the second is a normative inquiry as to whether there is a reasonable expectation recognized by society (*45*). Applied to wireless location data, one could argue that an individual is knowingly conveying information to a third party through the act of owning a cellular phone, and therefore there is no expectation of privacy. However, location data is collected intermittently even if an individual has not placed or received a phone call. Therefore, there is a seeming lack of intent to convey this information on the part of the cellular phone owner, which is normally present when an individual actively uses the phone. This creates a question as to whether one should be subjected to surveillance simply by the passive act of owning a cellular phone. It appears that in the current judicial environment, the answer would be yes.

Another argument against Fourth Amendment protection of location data is that it would be gathered while the individual is on public roads, and when an individual is traversing a public road they are not entitled to an expectation of privacy. It was established in *Katz v. United States* that the Fourth Amendment "protects people, not places. What a person knowingly…seeks to preserve as private, even in an area accessible to the public, may be constitutionally protected" (*46*). In that case, the FBI attempted to record half of a wireless conversation because it occurred in a public telephone booth. It was declared an illegal search because the defendant still had a reasonable expectation of privacy as to the words uttered into the mouthpiece of the phone after shutting the door to the phone booth. However, his location in the phone booth and the number dialed were both admissible as he was clearly visible, standing in a public place, and the number was conveyed to a third party, removing all expectation of privacy.

This idea of a lack of location privacy in a public place was furthered in *United States v. Knotts* where the court clearly stated that tracing an individual using a "beeper" attached to a car was not a violation of the Fourth Amendment because there can be no expectation of privacy on a public road (*47*). Motor vehicles themselves do not provide protection from public scrutiny; therefore an individual on a public road is subject to normal observation. The use of a tracking device does not provide any more information than that which could be provided by an individual performing routine surveillance. As applied to use of cellular phone location data, vendors hope to track the movements of cars on public roads, and the software is supposedly capable of filtering out all those cellular phones, which are not in vehicles. Therefore, under the *Knotts* decision, it appears that collection and use of this data does not create a constitutional issue, as it is only an enhanced means of collecting data that could otherwise be obtained through surveillance of public roads.

The Impact of Freedom of Information Laws

The Federal government and all state governments (*48*), have passed some sort of "open records" law that applies to the political subdivisions and agencies of the government (*49*). While the specific names of the statutes vary, they are commonly labeled "Public Disclosure Act" or "Freedom of Information Act (FOIA)." Underlying such measures is the ideal of maintaining an open, democratic society, in which the actions of the government are transparent to the citizens. FOIAs further this goal by explicitly requiring governmental bodies to release certain of their records to the public. The term 'record' is normally defined quite broadly to include writings, work products, data compilations, and other information used by the bodies (*50*). In addition, all public records are typically deemed to be open to the public unless protected by a specific exemption, which exceptions are usually narrowly construed. While the number of exemptions for each FOIA varies, it can be as high as 600 for some states (*51*).

WLT-based traffic monitoring involves the manipulation and use of data compiled by cellular phone companies as to the location of that company's customers on the road system. This information would be given to a state transportation department—which is, of course, a state agency—for traffic monitoring and transportation planning. As such, the information that a transportation agency would manipulate and utilize would qualify as agency records under any FOIA, and thus would have to be made available to the public upon a request made under such acts. This fact has numerous practical implications for the WLT-based monitoring.

The U.S. Code encompasses two sections that are in tension on the privacy rights involved in information collected by the federal government: The federal FOIA (*52*) and the Privacy Act of 1974 (*53*). The federal FOIA creates a broad presumption that records of federal agencies should be made open to the general public. However, subsection (b) of that section lists specific ***exemptions*** to the general public disclosure requirement, including one that covers all exemptions from disclosure imposed by any statute other than the FOIA. The most likely statute for this exception is the Privacy Act of 1974, which restricts the disclosure of agency records that include:

> . . . any item, collection, or grouping of information about an individual that is maintained by an agency, including, but not limited to, his education, financial transactions, medical history, and criminal or employment history and that contains his name, or the identifying number, symbol, or other identifying particular assigned to the individual, such as a finger or voice print or a photograph (*54*).

This definition's creation of extensive exceptions to disclosure for individualized information directly conflicts with the broad mandate of the federal FOIA, and the Supreme Court and lower federal courts have consistently held that exemptions from public disclosure under the Freedom of Information Act must be narrowly construed (*55*). Applying these rulings to the extensive exceptions to disclosure in the Privacy Act of 1974 seems to shrink the scope of those exceptions somewhat. However, in ***U.S. Dept. of Justice v. Reporters Committee***, the Supreme Court has found that both categorical and individualized balancing tests can be used by the courts when weighing the competing interests of individual privacy and the ideal of open government (*56*). This decision gives courts wide leeway in deciding cases that involve conflicts within the federal FOIA and the Privacy Act. Most of the cases in this area have involved criminal or personnel records, thus it is not completely certain how a federal court would rule in a situation involving data collected using WLT. It is reasonable to assume that equal leeway would be afforded to the courts in performing such balancing tests in that context as well, however.

Given the fact that the federal FOIA and the Privacy Act of 1974 only apply to *federal* agencies, this analysis obviously has limited application in the present context: WLT-based traffic monitoring creates methods through which state or local governments can monitor traffic, and as long as the proposed program remained at the state level, without any federal agency efforts attached to it, the federal FOIA and Privacy Act of 1974 would not apply. Nevertheless, this analysis remains important because the federal FOIA and Privacy Acts are quite similar to many state statutes that apply to state agencies; thus, the aspects of the analysis done under these federal statutes parallels an analysis that would likely apply under typical state statutes.

Since FOIA laws require exceptions to be narrowly construed in favor of public disclosure, it is possible that a balancing test performed by the courts could result in mandatory disclosure of individually identifiable CPNI. If this were to occur, then a specific exception would need to be crafted by the state legislature. However, the general protection of individual information set forth in both the Privacy Act of 1974 and state laws similar to the federal FOIA make it unlikely that individually identifiable CPNI collected by the government through a program similar WLT-based monitoring would be subject to public disclosure requirements. As a result, it does not appear that FOIA concerns represent a barrier to deploying WLT systems.

Summary – Legal Analysis

If telecommunications companies or their vendors sanitize individually identifiable CPNI in such a way as to transform it into aggregate information, then there are no legal concerns with transportation agencies obtaining and using that information. However, if the information contains individually identifiable characteristics, such as an individual's name or location, then it is likely to be protected under the CPNI statute and FCC regulations as "individually identifiable" CPNI. This would make it very difficult for agencies to obtain and use the individually-identifiable information for non-emergency purposes relating to transportation.

Although there are not likely any constitutional or FOIA concerns with telecommunications companies and their vendors releasing individually identifiable information, the CPNI statute and FCC regulations make it difficult for them to do so in four ways. First, most telecommunications companies do not have explicit permission from their customers to use such data for purposes not related to telecommunications. Second, FCC regulations require confidentiality agreements between telecommunications companies and their contractors that protect any individually identifiable CPNI possessed by the telecommunications company. Third, statute and FCC regulations allow the FCC to issue a cease and desist order to a telecommunications company and its contractor if they are found to be in violation of the statute. Fourth, if the contractor violates the agreement, the telecommunications company may seek a remedy for breach of contract.

It appears that WLT-based monitoring can be used to provide aggregate information, but providing individual level data (such as individual origins and destinations) is prohibited without a customer's consent. This type of data could be provided if wireless users opt-in to the program, however. If this is not done, data must be provided in aggregate form where no single wireless device could be individually identified, even if the data were rendered anonymous.

GUIDANCE

Based on a synthesis of information concerning WLT-based traffic monitoring systems presented in the previous sections, the research team has reached the following conclusions:

- It is feasible to collect freeway traffic data of reasonable accuracy and availability using WLT-based systems.
- There are no obvious legal barriers to using this technology to produce link condition estimates
- There are significant risks involved with this approach, most notably:
    1. Lack of maturity of technology
    2. Involvement of multiple companies in the "data stream"
- Numerous demonstration projects have been undertaken. At this stage, agencies interested in acquiring such data should seek to enter into well-defined data service agreements with vendors.
- Transportation agencies must have a clear understanding of their requirements before entering into any further agreements

These conclusions indicate that agencies should consider WLT-based traffic monitoring as viable. Furthermore, given the fact that other alternative probe-based traffic monitoring systems are also being operated by the private sector (for example, mining GPS data from fleet management firms), it is feasible for agencies to enter into traffic data service agreements. The purpose of this section is to provide concrete guidance for agencies to consider when entering into such agreements.

Purchase of Travel Time Data Service

Given the very early stage of this industry, it is not possible to accurately estimate the cost of purchasing a travel time data service. Limited experience with these services cannot be used with any assurance since, in nearly all cases, the services were demonstration projects, not production-level systems. In addition, agencies must understand that the price of the service will depend heavily on the limitations (or lack thereof) that are placed on data use. Interviews with travel time data service firms have revealed that the companies will charge significantly more for data as the purchaser requires greater and greater ownership and flexibility in its use. This is due to the fact that this may limit the company's ability to sell the same data to other customers (such as other governmental agencies and private information providers).

Based on a review of previously-used contracting vehicles and discussions with representatives from both transportation agencies and traffic data providers, the research team is suggesting that agencies use a "competitive demonstration" procurement approach when entering into travel time data service agreements. The intention of this approach is to encourage continued competition and opportunity in the industry, while providing transportation agencies with a means to manage the risk they are taking when shifting from agency-owned equipment for data collection to the purchase of a data service. Note that it is important that the agency approach the procurement as the purchase of a service – not a construction project. While the proposed procurement approach is unconventional, and may appear to be aggressive, it is important to state that the research team presented the approach to a number of the most knowledgeable and experienced individuals in this field in the public and private sectors. The individuals unanimously agreed that the approach is practical, reasonable, and can be implemented.

Proposed Competitive Demonstration Procurement Approach

The proposed procurement approach consists of four major steps:

1. Issue RFP

   The agency should begin by issuing a request for proposals for companies to enter into an agreement to provide a travel time data service. It is recommended that the agreement should be for a 1 year period, with options to renew annually for up to 3 years. In order to allow companies to provide as informative proposals as possible, it is critical that the agency include a full, detailed set of requirements with the RFP. Guidance for developing these requirements is provided later in this report.

2. Short-List

   Based on the proposals received, the agency should select a short-list of firms (recommended to be comprised of 3 or fewer service providers) to move on to the competitive demonstration phase. It is recommended that an agency use the following criteria in selecting the short-list:

   - Public sector references
   - Proposed cost structure
   - Demonstrated ability to meet requirements (preferably based on performance in previous deployments/markets)

- Demonstrated ability to provide a long-term, stable service (this may include documentation describing established relationships with the firms raw data sources – i.e. cellular companies, etc.)

3. Competitive Demonstration

   In this phase, the short-listed firms will be directed to “activate” their service in the area to be monitored, providing traffic data as specified in the requirements. This data should be provided for this phase for a period of 1 month. During this time, the agency should collect extensive validation data. It is recommended that agencies utilize GPS-equipped floating vehicles using the procedure developed by the research team that is fully described in the Appendix. Note that in order to provide potential vendors with full information as they consider competing for the agreement, the RFP should contain information describing how the service will be evaluated.

   At the completion of the 1 month evaluation period, the agency should select a firm(s) to negotiate with based on their demonstrated ability to meet spatial and temporal requirements

   Note that, based on interviews with the major traffic data service companies, it is evident that most have aggressive national expansion plans. Thus, this competition phase will not be as onerous as it may appear. It is reasonable that agencies can expect provision of the 1-month service at no cost for evaluation. Furthermore, the national expansion plans also will allow the companies to activate their service quickly once the notice is given.

4. Negotiate Agreement

   As stated earlier, agencies are currently at a disadvantage in that there are no examples that may be referenced when seeking to determine if costs proposed by private firms are fair and reasonable. Therefore, particularly in early procurements, the agencies must be diligent in the negotiation phase in order to obtain a fair price for the service.

Requirements

As described in the procurement section, it is essential that transportation agencies develop clear, detailed requirements to guide traffic data service agreements. There are many reasons for this; some of the key reasons are presented below:

- Probe-based monitoring is significantly different than traditional point-sensor networks traditionally used by agencies. In many cases, requirements for point-sensors (i.e. very short polling intervals, high accuracy requirements at the “point”, etc.) are not appropriate for probe-based systems.
- Clear requirements are needed to drive acceptance testing and on-going lifecycle testing.
- Traffic data service providers must have a clear idea as to agency expectations in order to make an informed decision as to whether or not to invest in a demonstration phase in the procurement method.

A discussion of requirements for traffic data services is presented below, organized by "category" of requirement. Specifically, requirements are discussed in the following broad areas:

- Spatial coverage requirements
- Temporal requirements
- Measurement requirements
- Data quality requirements
- Service availability requirements
- Data quality validation requirements
- Data usage requirements

In each category, a discussion is presented followed by a specific "straw-man" set of requirements for the category. **Note that the straw-man requirements presented in this report are intended to serve as a starting point for agencies. In all cases, it is essential that agency staff study and refine the requirements in order to create a set of requirements that reflect their priorities and needs. The straw man requirements should not be used indiscriminately, and are not be appropriate for all applications.**

Spatial Coverage Requirements

This category of requirement addresses the key question of which facilities to monitor for travel time and speed information. In addition, this category also includes how a facility should be "segmented" for monitoring (in other words, how links should be defined).

Clearly, given that a probe-based system relies of sampling a sufficient number of vehicles to estimate traffic conditions, agencies cannot reasonably require coverage for very low-volume roads. It is recommended that agency staff identify facilities for coverage based on local needs (i.e. those that are frequently congested and/or that provide connectivity for a large number of vehicles), or based on a volume threshold (for example, using annual average daily traffic (AADT)).

Defining the link structure for spatial coverage is particularly challenging when addressing spatial coverage requirements. Given that probe-based systems are very different from traditional point sensor networks, agencies should resist the temptation to set "blanket" link sizes on the order of ½ mile. Rather, the link definition should be based on logical "breaks" in facilities where one would expect the potential for differing traffic conditions (such as at an interchange or major at-grade intersection). Table 9 shows the straw man requirements for spatial coverage.

TABLE 9. Straw Man Spatial Coverage Requirements.

The traffic data service will provide data on the following facilities:
 	
• Interstate Highways
  o Segmented in links bounded by interchanges
• Other Limited Access Highways
  o Segmented in links bounded by interchanges
• Major Urban Arterials
  o Segmented in links bounded by major intersections
 	
Notes:
 	
• Agencies may wish to use an AADT threshold to identify facilities in classes 2 and 3 above. The following thresholds have been identified in previous work the research team did for VDOT.
  o Limited Access : Directional AADT of 40,000 or greater
  o Arterials: Bidirectional AADT of 20,000 or greater
• Agencies may wish to consider use of draft requirements identified by FHWA for use with SAFETEA-LU 1201 (FHWA Docket No. FHWA-06-24219)
  o ”Major Highways: We propose that, as a minimum, major highways to be monitored by the systems implemented under the real-time system management information program include all National Highway System (NHS) routes and other limited access roadways. In metropolitan areas, major arterials with congested travel should be included in the coverage areas of systems implemented under the Real-time System Management Information Program.”

Temporal Requirements

Temporal requirements deal with two important aspects of the traffic data service – (a) the times-of-day to collect traffic data, and (b) the “polling interval” for traffic data measurement (in other words, how often should a travel time measure be generated).

Based on a consideration of the transportation agency data users, it is clear that traffic data is of use primarily during times of peak usage on a facility. At “off” times (i.e. in the middle of the night), it is usually sufficient to assume free flow conditions. Furthermore, given that the set of potential probes is significantly smaller during “off” hours, experience has illustrated that the systems will struggle to produce traffic data measures during these times. Therefore, in order to keep the costs and effort reasonable, it is suggested that transportation agencies not require 24/7 collection of travel time data from WLT systems.

Finally, short polling intervals (i.e. the time period over which traffic data is compiled for each measure) on the order to 1 minute are certainly desirable in that they allow for quick identification of disruptions to traffic flow. However, short intervals are difficult to achieve given current technology. Longer intervals, such as 1 hour, will not meet traveler information and traffic management of agencies. Thus, it is suggested that agencies consider balancing the need for a quick identification of traffic disruptions with the capabilities of current systems. Table 10 shows the straw man temporal requirements.

TABLE 10. Straw Man Temporal Requirements

Traffic data shall be provided from 6:00 am – 7:00 pm on weekdays (excluding holidays) at 5 minute polling intervals. Note: This set of straw-man requirements is poorly suited for many areas (i.e. those with significant weekend traffic or late-evening event traffic). Agencies should tailor these requirements to suit local traffic characteristics.

Measurement Requirements

This category of requirements defines the specific types of traffic condition measures that a vendor would be expected to produce. It is important to state that individual vehicle travel times or speeds are not likely to be needed by the vast majority of transportation applications. In fact, even in current operations where the speed of every vehicle traversing a point detector is measured and is available, this high resolution of data is rarely, if ever, used. Rather, summary statistics are used. This should also be the case with probe-based traffic data.

From a statistical perspective, it is clear that travel time and speed are random variables. The values of samples of these measures over a period of time (i.e. the travel times of individual vehicles) will vary. This variability will be due to differences in drivers, vehicles, weather, measurement error, etc. To summarize a random variable, basic statistics are generally collected – mean, variance, 85th percentile, etc. In general, an agency will only use the mean value of travel time or speed– especially in traveler information. However, there will be times when the variance (standard deviation) will be used – for example, in travel variability measures for performance measurement.

Finally, it will be important to know the number of samples used to derive an average link travel time or speed so that an agency will have some knowledge of the “validity” of the measure. In other words, means and variances derived from small samples are certainly more likely to be erroneous than those measured from large samples. While this concept is indisputable, interviews with a number of companies providing probe-based traffic data revealed that the number of samples may be a misleading indicator of data quality. In many cases, given the uncertainty inherent in deriving traffic data from “non-traffic” data sources – not all samples are of the same quality. Thus, an agency may want to allow some other form of data quality measure to be substituted for the number of samples. Table 11 summarizes the straw man measurement requirements.

TABLE 11. Straw Man Measurement Requirements

The following data shall be provided for each link monitored in the system at each measurement time interval (to be defined in the temporal requirements). Note that the units for travel time shall be minutes, and speed shall be miles/hour.

- Mean travel time and speed
- Standard deviation of travel time and speed
- Number of samples used to calculate the statistics
  - Allow the substitution of a well-defined "confidence" rating for each travel time/speed measure
- Maximum travel time and speed observed during the interval
- Minimum travel time and speed observed during the interval

Data Quality Requirements

A critical concern regarding travel time data is its quality. The quality of travel time and speed data can be considered in three ways:

1. Absolute Percentage Error

   This measure of quality is defined as the absolute value of the percentage difference between the sample mean measure and the "true" mean measure during a polling interval. Given that monitored links will be of different lengths, carrying traffic at different speeds, the use of a "unitless" percentage error measure is more reasonable that using a measure such as absolute travel time error.

   Since absolute percentage error accounts for different link length and speeds, there is no need to establish different requirements for different types of links (i.e. freeways vs. arterials). While at first glance it may seem desirable to impose strict absolute percentage error requirements (such as a maximum of 5%), it is important to consider the use of the data. For the majority of agency applications, the critical role of traffic data is to identify significant changes in travel conditions. Even relatively large percentage errors will still allow an agency to distinguish these changes. For example, consider a 4-mile freeway link with a "normal" average speed of 60 miles/hour. Thus, in normal circumstances the link would require a 4-minute travel time. Assuming 20% error – the measured travel time would be, on average, either 3.2 or 4.8 minutes. Now, assume an incident has reduced traffic speeds to an average of 30 miles/hour on the link. In this case, the average travel time would be 8 minutes. Again, with 20% error – the measured travel time would be, on average, either 6.4 minutes or 9.6 minutes. Thus, even in the worst case, the comparison of link travel times would be between 4.8 minutes and 6.4 minutes – still clearly indicating a significant increase in travel time.

2. Error Bias

   While it is most important that the traffic data purchased proves to result in reasonable absolute percentage error, it is also important to consider if the data service consistently produces measures that are greater than, or less than, "true" measure. This concept is referred to as bias. Error bias will be measured as the average percentage error (not the absolute value). An unbiased set of data will have an average percentage error of 0. The average percentage error will increase as the bias becomes more significant.

   Bias is particularly a problem with the performance measure application of travel time data. For example, performance measures will quantify differences of the performance of various regional systems throughout a state. Thus, if the bias was high in one region, and low in another, the measures would indicate a much larger difference in conditions than what actually exists. Therefore, it is recommended that an agency require average percentage errors (not absolute value) for all links (aggregated, not on a one-by-one basis) to be within +/-10% of the "ground truth" travel time.

3. Data Availability

   Data availability refers to the ability of the system to produce traffic data estimates consistently for each link during each measurement time interval. In traditional, point-sensor monitoring systems, data are not available when sensors or communications fail. In probe-based data collection systems, data will not be available when equipment fails and during intervals in which no samples are collected on a particular link. Data availability is measured simply as the percentage of measurement intervals when traffic data estimates are delivered. Note that the valid delivery of a "traffic data estimate" occurs when the estimate is based on some amount of data collected during the polling interval. In other words, estimates that are purely based on "imputation" (for example, the historical average) are not considered a valid estimate in terms of the availability requirement.

Table 12 summarizes some straw man requirements for all three of these data quality measures.

TABLE 12. Straw Man Data Quality Requirements

Traffic data shall meet the following quality requirements: • Link travel time and speed measures shall have a maximum of 20% average <u>absolute</u> percentage error when compared to ground truth data. This requirement is applicable on a link-by-link basis (i.e. the error measured at each link shall meet this requirement). • An aggregate of link travel time and speed measures shall have a maximum of 10% average percentage error when compared to ground truth data. This requirement is applicable on average to all links monitored by the system. • Travel time measures shall be provided for 90% of all measurement time intervals for all links. Note: Agencies may wish to consider use of draft requirements identified by FHWA for use with SAFETEA-LU 1201 (FHWA Docket No. FHWA-06-24219). This document calls for 85% accuracy (assumed to equate to a 15% average absolute error) and 90% availability.

Service Availability Requirements

Currently, most firms offering probe-based traffic monitoring data must acquire the probe data that they use to derive traffic data from another company or set of companies. Without this source of data, the firm cannot provide its traffic data service. Therefore, it is in an agency's interest to require confirmation that the firm has in place the necessary provisions to ensure that they can provide their service for the period of the agreement.

Some have suggested, for example, that firms provide copies of contracts that they have with cellular providers as a way to accomplish this. However, given the competitive nature of the industries, this is often not a feasible option. Therefore, it is suggested that agencies be as flexible as possible in terms of accepting service availability confirmation. Table 13 outlines the straw man requirements for service availability.

TABLE 13. Straw Man Service Availability Requirements

The agency shall be provided with documentation to prove that the traffic data service will remain available throughout the life of the agreement. Examples of desirable documentation include: • Copies of agreements with cellular providers • Commitment letters from cellular provider management • Contingency plans for replacement of probe data when sources are "lost" In the event that the service is not available, the agency shall have the right to terminate the agreement due to the inability of the firm to meet data accuracy and availability requirements.

Data Quality Validation Requirements

Given that an agency is entering into a substantial financial commitment when procuring a traffic data service, it is imperative that it protect its investment by instituting a long-term data quality validation program. The program should begin upon the competitive demonstration phase of procurement, and then continue throughout the life of the agreement.

Note that it is important to provide a "fair" comparison to the travel time data being acquired. This means that the use of point detectors and other, non-link measurement techniques, should be minimized in collecting baseline (i.e. comparison) data. An ideal way to collect travel time data is through GPS-equipped floating car runs. A detailed validation procedure based on GPS data collection is detailed in the Appendix of this report. Table 14 provides straw man data quality validation requirements.

TABLE 14. Straw Man Data Quality Validation Requirements

The agency shall conduct an evaluation of the short-listed firms' data during the competitive demonstration phase of procurement. Based on the firms' demonstrated ability to meet the agency's requirements, the agency, the agency shall choose to enter into negotiation with 0, 1, or more firms. Once the agency enters into an agreement with a firm, the following validation testing regime will be followed: • Annual Data Quality Validation Testing o The data service provider shall be provided with a written annual baseline data collection and data quality analysis plan one month prior to the annual validation testing. This plan will be negotiated and agreed-upon by both parties. In the event that the parties cannot come to an agreement, the purchaser shall have the right to terminate the agreement. o The annual service acceptance testing effort shall consist of baseline data collection over the period of 2 consecutive weekdays. The data service provider shall provide all traffic measures to the purchaser during this testing period. The purchaser will collect baseline data as outlined in the plan using either its own forces or a 3rd party independent organization. o In the event that the data analysis demonstrates that the traffic data does not meet requirements, the purchaser shall have the right to terminate the agreement. • Quarterly Self-Reporting of Data Quality o Upon negotiation of an agreement, the data service provider shall provide the purchaser with a quarterly data validation plan. This plan shall document the data collection method and sampling approach that will be used, the time period of data collection, and the links to be tested. Note that part of this plan shall be documentation of the format in which data availability for the previous quarter will be reported. This plan will be negotiated and agreed-upon by both parties. In the event that the parties cannot come to an agreement, the purchaser shall have the right to terminate the agreement. o On a quarterly basis, the data service provider shall deliver the results of their self-assessment of data quality for the previous quarter, using the quarterly test plan agreed upon at the outset of the agreement. The data service provider shall also deliver the "raw" baseline data collected (in most cases, this will be the GPS logs for the floating car runs). o In the event that the data analysis demonstrates that the traffic data does not meet requirements, the purchaser shall have the right to terminate the agreement.

Data Usage Requirements

In the past, transportation agencies have primarily collected needed data using agency-owned resources. In this case, the agency, naturally, has unlimited rights as to how to use this data. However, traffic data service companies currently working in this market are selling data to multiple clients – including traveler information services. To protect their market (and their other clients), some may wish to restrict an agency's rights to use the data for certain applications (for example, the provision of traveler information). The purpose of the data usage requirements are not to ensure that an agency has unlimited use of purchased data (this will certainly require a very steep cost), but rather to clearly state key uses that an agency sees for this data and to protect the agency's ability to use the data as needed. This will likely serve a significant role in the cost of the services provided, and will help ensure that the agency can use the data for the functions intended. Table 15 provides a straw man requirement for data usage.

TABLE 15. Straw Man Data Usage Requirements

- The agency shall have the right to use traffic data purchased from the data service provider for all internal agency applications. This includes the right to archive the data and use it for an unlimited period of time.
- The agency shall have the right to use travel time data to provide direct traveler information using the following means:
    - 511
        - Telephone
        - Internet
    - Variable Message Signs
    - Highway Advisory Radio
- The agency shall not share the data directly with other organizations. This, however, excludes the purchaser's right to create visualizations of the data (i.e. maps, graphs, etc.) for presentation and distribution.

CONCLUSION

Based on results from early system deployments and from simulation studies, it can be concluded that WLT-based traffic monitoring is a feasible approach to collecting traffic data on heavily traveled roadways. While the research team has concluded that this is feasible approach, it is important to note that there has yet to be a long-term, "production-level" deployment of this technology in the United States. Given this fact, and other associated technical and institutional/business risks associated with this approach, it is prudent for transportation agencies to take specific actions to mitigate the risks as they seek to utilize this data to support their programs. This report provides specific guidance to support agencies in entering traffic data service agreements.

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24. *See* 47 U.S.C. § 222(a) (2005).

25. 47 U.S.C. § 205(a) (2005).

26. 47 U.S.C. § 222(c)(1) (2005), emphasis added.

27. 47 U.S.C. § 222(d)(4) (2005)

28. *See also* 47 U.S.C. § 222(d) (2005)

29. 47 U.S.C. § 222(c)(3) (2005).

30. 47 C.F.R. § 64.2007(a) (2005).

31. 47 C.F.R. § 64.2003(i).

32. 47 C.F.R. § 64.2003(h).

33. 47 C.F.R. § 64.2005(b)(1).

34. 47 C.F.R. § 64.2005(b)(3).

35. 47 C.F.R. § 64.2008.

36. 47 C.F.R. § 64.2008(c)(3).

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38. *See* 47 C.F.R § 64.2005(b)(2) (2005).

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51. See, e.g., Fla. Stat. ch. 119.01 et seq..

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APPENDIX
RECOMMENDED EVALUATION PROCEDURE

This appendix presents an objective, methodical, and cost effective procedure developed to evaluate probe-based monitoring systems that generate link condition estimates. The procedure is suitable for application to the wide range of probe-based monitoring systems currently in development, and particularly focuses on the use of information technology resources in an effort to keep personnel costs to a minimum.

A summary of the procedure is presented in Figure A-1. Four major steps are involved in the evaluation procedure, including baseline data collection, data reduction, temporal match, and comparison. This procedure starts by collecting the ground truth traffic data, or baseline data, against which the probe monitoring system data are compared. Then, the baseline data are reduced to support further processing. In order to provide for a fair comparison, the critical step of temporally matching the link monitoring system data and the baseline data follows. Finally, the matched link data and baseline data are compared from two perspectives: accuracy quantification and temporal traffic condition comparison.

Step 1: Baseline Data Collection

Step 2: Data reduction
- GPS data post-processing
- Spatial processing
- Travel time/link speed derivation

Step 3: Temporal Match

Step 4: Comparison
- Accuracy quantification
- Temporal traffic condition comparison

Figure A-1 Link Monitoring System Evaluation Procedure

Baseline Data Collection

The purpose of this step is to collect a sufficient sample of baseline traffic data in a form that allows for a “fair” comparison with probe monitoring system data. The research teams has explored several baseline data collection approaches, including vehicle identification, use of point sensors, and floating vehicles. These approaches have their own advantages and disadvantages. For vehicle identification approach, check points are set along the routes, and vehicles passing the check points are registered and re-identified so that the travel time between adjacent check points can be calculated. This approach can yield direct travel time data given the correct identification of the same vehicle passing the adjacent check points. However, the predefined check points might not be consistent with the start/end points for each link defined in the probe monitoring system, especially in the case when the road network is sizeable and a large number of links are defined. In addition, the reidentification of vehicles is not easily accomplished, particularly in an automated manner. For the point sensor approach, travel time and link speeds have to be estimated from the point data. This is undesirable since no direct measure of the true traffic condition is available for comparison with the probe monitoring system data. As a result, the evaluation of the system based on the estimated travel time and link speed might not be “fair.”

The procedure discussed uses the floating car approach to collect baseline travel time and link speed. In this approach, vehicles equipped with GPS devices are driven with the flow of the traffic, allowing for link speed and travel time to be collected directly. The GPS device automatically stores the location (latitude, longitude) and time every 1 second as the vehicle travels, forming a detailed path log for the floating car. Then, the path of the floating car can be dynamically segmented according to the link definition of the monitoring system (or systems) under evaluation. This is a critical consideration. Given that probe monitoring systems generally include links of varying size, the GPS “tracks” allow the baseline data to be tailored to exactly match the link definitions in the probe monitoring system.

Baseline Data Collection Procedure

From a conceptual perspective, the floating car data collection procedure is straightforward. First, a vehicle is equipped with a GPS device; then a driver operates this vehicle with the flow of traffic. While driving, the GPS device automatically logs latitude/longitude points and times. The log files are then post-processed using a Geographic Information System (GIS) to derive the desired travel time and link speed information.

An important consideration in conducting the baseline data collection is to ensure that the baseline data effectively represents the population mean speeds and travel times. In addition to asking the drivers to operate the vehicles with the flow of traffic, an admittedly vaguely defined goal, numerous floating car runs are recommended in order to minimize the impact of variance in driver behavior and stochastic traffic conditions. Moreover, in order to experience different traffic conditions for each car, a short time interval, such as five minutes, is recommended for staggering the starting time for floating cars along the same route.

To provide an example of the magnitude of the baseline data collection effort, consider the Hampton Roads evaluation of the Airsage link monitoring system. In this effort, six floating vehicles were used – staggered at 5 minute intervals throughout peak periods. Over a period of four days, 29 floating car runs were conducted in the region. This comprised 83 hours of total travel time data and 2,530 miles of total travel distance. In total, 147,000 GPS points were collected.

Data Reduction

Baseline data reduction involves three steps: GPS data post-processing, spatial processing, and travel time/speed derivation. In data reduction, the application of GIS software is critically important due to its ability in processing the GPS tracks of the floating vehicle runs.

GPS Data Post-processing

The purpose of this step is to post-process the GPS data collected in the baseline data collection. First, GPS point information, including latitude, longitude, and timestamp, is extracted from the output files from the various GPS devices. Then, the timestamp for each GPS point is further converted from the UTC (Coordinated Universal Time) time format that is default for many GPS devices into the local time for the study network. Note that though the UTC timestamp could be used to derive the true travel time and link speed since only relative time is needed in the derivation, the time conversion into local time is necessary to guarantee an appropriate temporal matching between the link monitoring system data and the baseline data. Finally, the post-processed GPS points are converted into layers for further processing in GIS software.

Spatial Processing

The purpose of this step is to associate the floating vehicle GPS "track" points with the link monitoring system-defined links. The association is accomplished through the spatial join feature provided by GIS software. A spatial join is a spatial operation supported by a typical GIS system, in which the attributes of one geographic object are appended to another object's attribute table based on proximity of the two objects. In this effort, the geographic objects involved in the spatial join are the poly-lines – indicating the links defined by the link monitoring system and the GPS points of the floating vehicle tracks. The spatial join is graphically demonstrated in Figure A-2.

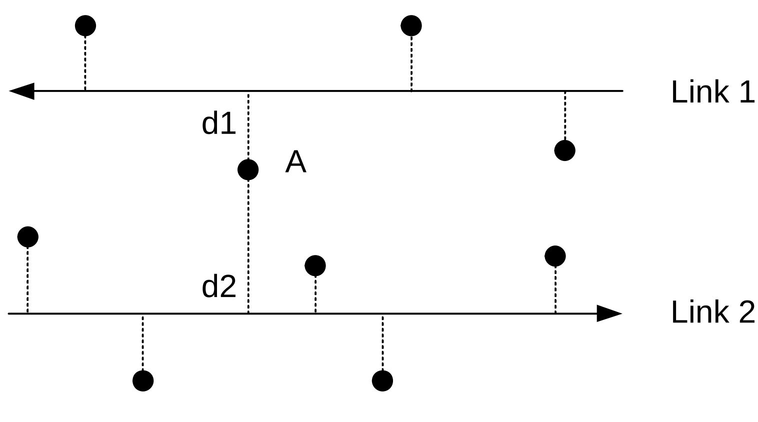


Figure A-2 Demonstration of Spatial Join

In Figure A-2, the dots represent GPS points from the floating vehicle tracks (note that the points will vary about the "true" track of the vehicle due to random error in the GPS system, and errors in the underlying map database). The solid lines, links 1 and 2, are directional links on the same roadway in a link monitoring system. The spatial join will simply match each dot (GPS point) to the nearest link. For example, in the case of point A, distance d1 is less than distance d2, therefore, the spatial join will associate this point to link 1, adding link 1 as a new attribute in point A's attribute table. Note that when the links are extremely close to each other (i.e. very narrow medians), the spatial join might be invalidated (due to the GPS positioning error), and in such a case, manual visual tracking of the GPS points has to be performed in order to assign GPS points to the links correctly. This can be done relative easily by looking at the progression of points through time. However, it should be noted that the spatial join tool is quite powerful, and such visual tracking does not have to be performed frequently.

After the spatial join assigns a link to each floating vehicle GPS time/location record, an index field, usually driver ID, is added to each record for differentiating the drivers who collect the data. Then, the spatial processing results are sorted by the index field and the timestamp.

Travel Time and Speed Derivation

The research team developed a custom JAVA program to process the resulting GPS track attribute tables created in the previous step. Essentially, the JAVA program searches the timestamps for each driver. The timestamps corresponding to the "switch" of links (i.e. moving from link C to link D) are deemed as the entering and exiting timestamps for each link. These timestamps are then recorded and used to calculate the travel time of that floating vehicle on the link. Afterwards, the aggregate link speed is derived by dividing the link length by the travel time. In the derivation of travel time and link speed, only the first and last GPS points for each link are used and the intermediate GPS points are ignored. This is by design. While the research team could have calculated intermediate speeds between each GPS track point (i.e. every 1 second), GPS error would have resulted in significantly erroneous instantaneous speed estimates. Given that the only thing of interest is the aggregate link speed, it was most logical to simply look at link entry and exit times.

Following this procedure in the Hampton Roads Airsage evaluation, a total of 1,755 link speed/travel time baseline records were generated (thus, it is evident that the vast majority of the 147,000 GPS points were "mid-link" points not needed for use in this research).

In summary, after data reduction, two tables – (1) baseline data and (2) link monitoring system data, will be ready with each record characterized as in Figure A-3. Note that there will be a single record for each link for each reporting interval for the link monitoring system. On the other hand, there will likely be multiple baseline records that fall partially within each reporting interval for each link. The challenge of reconciling this will be addressed in the temporal match step of the procedure.

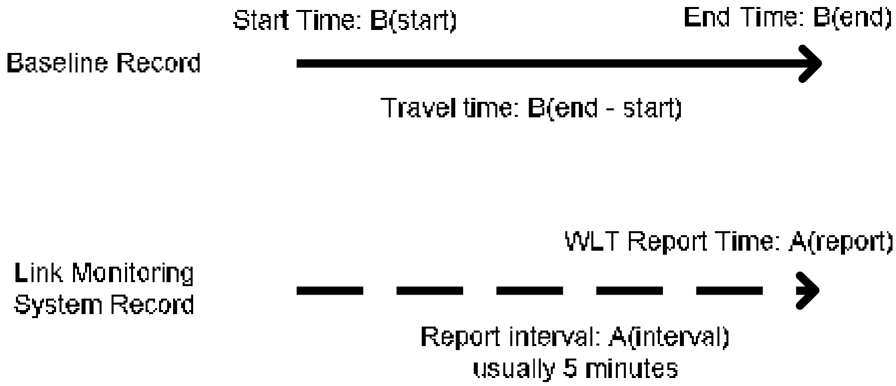


Figure A-3 Characteristics of Baseline Record and Link Monitoring System Record

Temporal Match

In order to complete comparison of the baseline and link monitoring system data, a critical step is to temporally match records. In other words, the corresponding baseline records that best "fit" reporting intervals for each link of the probe monitoring system data must be found.

Based on a careful examination of the data characteristics, a baseline record is deemed as "matching" a probe monitoring system record according to the four rules described in Figure A-4 (note that the solid line represents the time interval for the baseline data and the dashed line represents the time interval of the probe monitoring system data). According to these rules, for a probe monitoring system record and baseline record for the same link ID, a match is claimed if any of the four rules is satisfied. Rules (1) and (4) are straightforward – records are matched if the interval of one record is completely contained by another record. For rule (2) and rule (3), a match is claimed on the condition that at least ¾ of a baseline interval (the "true" travel time) is overlapped with a link monitoring system reporting interval. Note that the purpose of these rules is to ensure a comparison of data for the same time interval and over the same link.

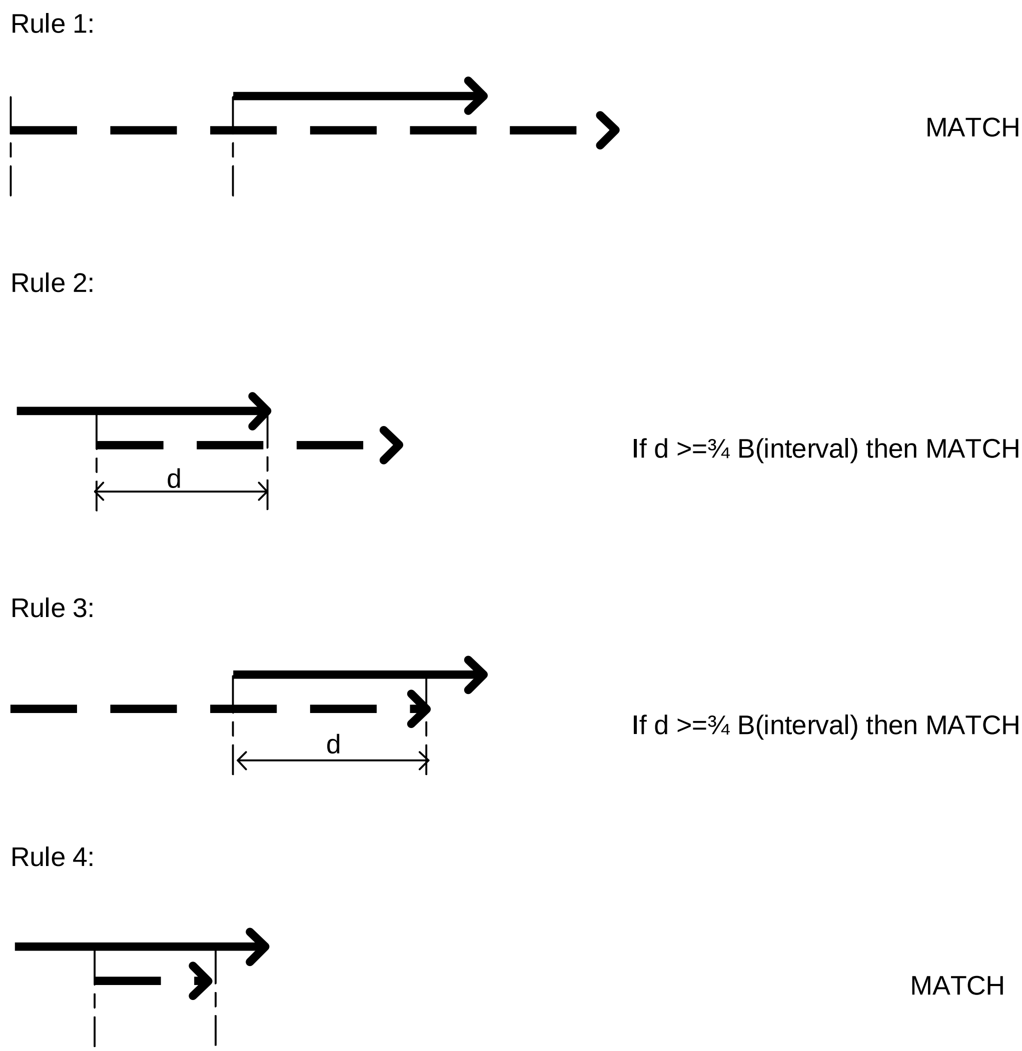


Figure A-4 Temporal Matching Rules

Based on these rules, the baseline data and probe monitoring system data can be matched and organized together. Note that in this process, it is possible to find multiple baseline records for each probe monitoring records due to the presence of multiple floating car runs. In such a case, the multiple baseline records are averaged to find the traffic condition information that corresponds to the probe monitoring system data. After the matching process, a complete table relating the baseline data and probe monitoring data together is ready for a direct comparison.

Again, using the Hampton Roads Airsage evaluation as an example, a total of 1,046 "matches" were found (out of a possible 1,755 baseline records – a 60 percent match rate). In other words, the research team was able to directly compare baseline data to 1,046 segment/time traffic condition estimates provided by the Airsage monitoring system. The 40 percent of baseline records that were not matched were due to combination of timing problems and missing records from the Airsage system (in other words, the monitoring system did not produce a speed estimate for the link in question during these time intervals).

Comparison

In the proposed evaluation procedure, two comparison approaches were utilized, accuracy quantification and temporal traffic condition comparison. As the name implies, accuracy quantification is intended to numerically quantify the errors of the link monitoring system, where error is defined as the difference between the monitoring system data and baseline data. The other approach is intended to provide visual indications as to the quality of the monitoring system data.

Accuracy Quantification

Given the significant challenge of measuring traffic, any customer of traffic data will expect and accept some level of error in a link monitoring system. However, it is critical to understand the magnitude of this error in order to assess how the data may be used. In discussions with transportation agencies during this project, it is clear that a link monitoring system must perform well in different "categories" of traffic conditions. Therefore, the evaluation procedure quantified accuracy in four classes of baseline speeds for freeways, as described in Table 16.

TABLE 16 Speed Categories

Group Index	Baseline Speed Range
1 – Severe Congestion	0-30 mph
2 – Moderate Congestion	30- 45 mph
3 – Light Congestion	45- 60 mph
4 – Free Flow	>60 mph

Then, in each speed category, the average absolute error was computed. In addition, the distribution of the absolute error was investigated by calculating the percentage of link monitoring system records that produced errors in 5 mile/hour bins (i.e. bin 1 - (0, 5], bin 2 - (5, 10], bin 3 - (10, 15], bin 4 - (15, 20], bin 5 - (20, ∞)) for each speed category. To provide an example, Tables 17 and 18 present these results for the evaluation of the Hampton Roads Airsage system.

TABLE 17. Average Speed Error – Airsage Hampton Roads

Group Index	Average Speed Difference (mph)
1 – Severe Congestion	24.69
2 – Moderate Congestion	8.52
3 – Light Congestion	8.65

4 – Free Flow	9.49

TABLE 18. Speed Error Distribution – Airsage Hampton Roads

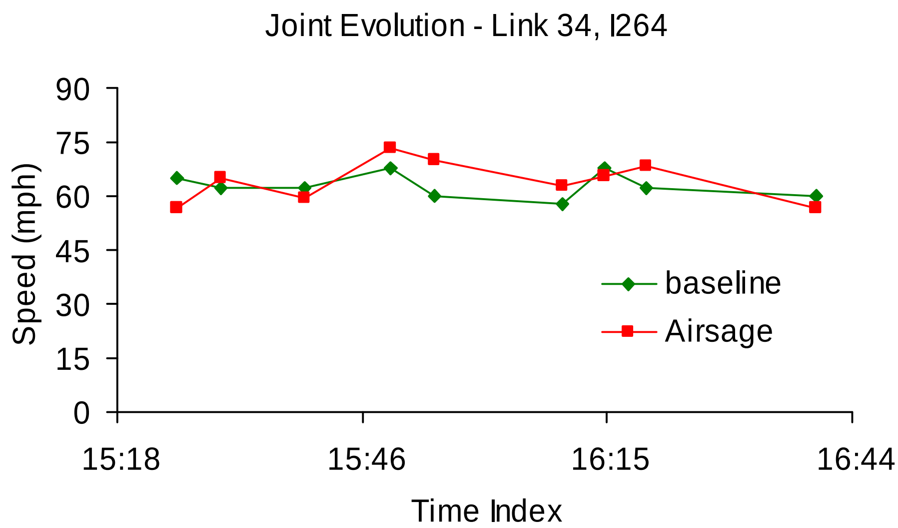
Group	0-5 mph	5-10 mph	10-15 mph	15-20 mph	> 20 mph
1 – Severe Congestion	1.41%	2.11%	12.68%	26.76%	57.04%
2 – Moderate Congestion	44.62%	25.27%	11.83%	7.53%	10.75%
3 – Light Congestion	38.36%	26.37%	16.78%	11.30%	7.19%
4 – Free Flow	40.61%	25.59%	12.68%	7.28%	13.85%

The results from the Airsage Hampton Roads evaluation illustrate the need to consider both the average error and error distribution. Table 17 makes it quite clear that this particular link monitoring system is unable to produce acceptable results in low-speed congested conditions, while errors appear "reasonable" in uncongested conditions. However, when considering Table 18, it is evident that the system does have problems under free flow speeds as well. For example, one will note that in nearly 14% of the cases, the system reports speeds with 20 mile/hour errors under free flow conditions. Such "bad misses" will make the data difficult to use in many traffic management applications.

Temporal Traffic Condition Comparison

Though the average error and bin-based error distribution for each congestion level are informative, visual comparison between the link monitoring system data and the baseline data provides more insight into data quality.

In the temporal traffic condition comparison, for selected links, the traffic condition data reported by the link monitoring system are plotted together with the baseline data in a time series graph. The time series plot is used to illustrate the evolution of traffic conditions over time. Based on the examination of the time series plot, a large departure of the two series indicates the inadequacy of the link monitoring system. Figure A-5 illustrates these plots for two links from the Hampton Roads Airsage evaluation. In this case, link 34 on Interstate 264 illustrates acceptable performance, while link 437 on Military Highway illustrates the inability of the Airsage system to identify building congestion.



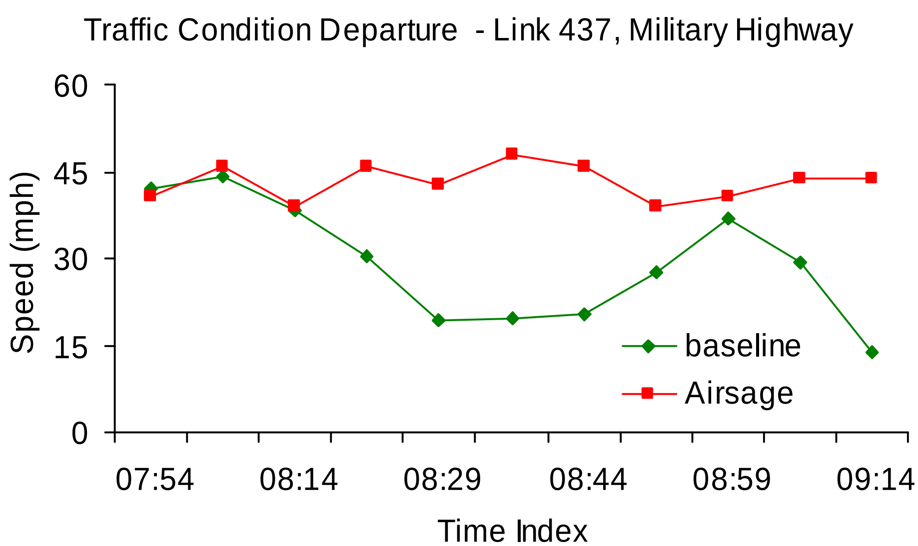


Figure A-5 Temporal Traffic Condition Comparison – Airsage Hampton Roads