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APPLICATION OF TRAVEL TIME INFORMATION FOR TRAFFIC MANAGEMENT

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16. Abstract

This report summarizes findings and implementations of probe vehicle data collection based on Bluetooth MAC address matching technology. Probe vehicle travel time data are studied in the following field deployment case studies: analysis of traffic characteristics on key routes during a special event (the Brickyard 400 race in Indianapolis, IN); assessment of delay to motorists during road construction; assessment of motorist compliance with work zone speed limits with and without heavy police enforcement; analysis of route choice during road construction in northwestern Indiana; and evaluation of winter operations on a signalized arterial. In addition to these case studies, the data collection equipment infrastructure was used to collect data for several other concurrent projects that focused on measuring arterial travel time. A discussion of the results from those studies is also provided. In addition to case implementation summaries, Appendixes provide recommendations for sensor deployment height and the construction of efficient SQL queries.

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EXECUTIVE SUMMARY

APPLICATION OF TRAVEL TIME INFORMATION FOR TRAFFIC MANAGEMENT

Introduction

Using conventional methods, it is extremely costly to measure detailed traffic characteristics in high quality spatial or temporal resolution. For analyzing travel characteristics on roadways, the floating car method, developed in the 1920s, has historically been the most used assessment tool. Measuring traffic patterns, such as estimating origin-destination (O-D) matrices, has traditionally required the establishment of cordons with many observers recording license plate numbers which are later cross-referenced. Both applications are very labor intensive because of the need to employ human observers over many hours, meaning that the cost per data point is prohibitive for data collection for anything besides limited studies.

This report documents techniques developed in Indiana to use Bluetooth MAC address matching for obtaining probe vehicle data. The term "probe vehicle" means the direct measurement of individual vehicle travel times by matching vehicle identifiers between two locations in a traffic network. However, the data reduction techniques are applicable to other probe vehicle technologies such as vehicle re-identification techniques (e.g., matching detector response patterns), real-time tracking of vehicle trajectories using GPS units or cell phones and *connected vehicle* technology, currently under development by USDOT.

Findings

Throughout this study, the following findings were implemented by the Indiana Department of Transportation.

1. An eight-foot vertical height was recommended when deploying Bluetooth sensors.
2. Real-time monitoring of the Bluetooth probe data first developed in conjunction with the 2008 Brickyard 400 race was subsequently used during several special events by the INDOT TMC.
3. Real-time monitoring of the 2009 I-65 Lake County construction work zone and subsequent after action reviews have been used for several subsequent reviews of work zone traffic conditions.
4. A 2010 study of the traffic patterns and network impact associated with closing the Cline Avenue Bridge in Northern Indiana was used by INDOT decision makers in identifying traffic mitigation measures.
5. Statistical processing techniques were developed that used probe data to assess the impact of traffic signal retiming efforts to develop business cases for retiming signalized corridors. In one example, the impact of re-timing eight signals on Saturday had a positive economic impact of approximately $500,000 in estimated user savings over a one-year period.

Implementation Recommendations

Perhaps the most important contribution of SPR-3410 is that outcome assessment, based upon observed changes in corridor probe data, has become a widely accepted, day-to-day practice by INDOT operations engineers. There remain opportunities to expand these techniques to other applications such as assessing winter operations and using commercial data sources to characterize statewide congestion and mobility for prioritizing future capital program investments.

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1. PROJECT OVERVIEW

1.1 Introduction

Using conventional methods, it is extremely costly to measure detailed traffic characteristics in high quality spatial or temporal resolution. For analyzing travel characteristics on roadways, the floating car method, developed in the 1920s, has historically been the most used assessment tool. Measuring traffic patterns, such as estimating origin-destination (O-D) matrices, has traditionally required the establishment of cordons with many observers recording license plate numbers which are later cross-referenced. Both applications are very labor-intensive because of the need to employ human observers over many hours, meaning that the cost per data point is prohibitive for data collection for anything besides limited studies.

In recent years, however, the *probe vehicle* paradigm has begun to dramatically reduce the cost of each data point by automating the process. In this report, the term "probe vehicle" means the direct measurement of individual vehicle travel times by matching vehicle IDs between two locations in a traffic network. This report focuses on the use of Bluetooth MAC address matching for the development of the data set. However, most of the data reduction techniques are applicable to other probe vehicle technologies as vehicle reidentification techniques (e.g., matching detector response patterns), real-time tracking of vehicle trajectories using GPS units or cell phones and *connected vehicle* technology, currently under development by USDOT.

This report summarizes progress made in the state of Indiana on the deployment of travel time data collection infrastructure and example uses of that data in numerous case studies. While the specific data set used in this report consists of in-house Bluetooth MAC address monitoring data collectors, the techniques developed using these data sets could be applied to any number of alternative probe vehicle technologies.

1.2 Dissemination of Research Results

The following is a list of papers prepared in part during the course of this project *(1–6)*:

- Wasson, J. S., S. E. Young, J. R. Sturdevant, P. J. Tarnoff, J. M. Ernst, and D. M. Bullock. Evaluation of Special Event Traffic Management: The Brickyard 400 Case Study. *JTRP: Other Publications and Reports,* Paper 4, 2008. DOI: 10.5703/1288284314655.
- Brennan, T. M., J. M. Ernst, C. M. Day, D. M. Bullock, J. V. Krogmeier, and M. Martchouk. Influence of Vertical Sensor Placement on Data Collection Efficiency from Bluetooth MAC Address Collection. *Journal of Transportation Engineering*, Vol. 136, No. 12, December 2010, pp. 1104–1109. DOI: 10.1061/(ASCE)TE.1943-5436.0000178.
- Haseman, R. J., J. S. Wasson, and D. M. Bullock. Real Time Measurement of Work Zone Travel Time Delay and Evaluation Metrics Using Bluetooth Probe Tracking. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2169, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 40–53. DOI: 10.3141/2169-05.
- Hainen, A. M., J. S. Wasson, S. M. L. Hubbard, S. M. Remias, G. D. Farnsworth, and D. M. Bullock. A Sampling Technique for Estimating Route Choice and Travel Time Reliability using Field Observations of Bluetooth Probe Vehicles. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2256, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 43–50. DOI: 10.3141/2256-06.
- Wasson, J. S., G. W. Boruff, A. M. Hainen, S. M. Remias, E. A. Hulme, G. Farnsworth, and D. M. Bullock. Evaluation of Spatial and Temporal Speed Limit Compliance in Highway Workzones. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2258, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 1–15. DOI: 10.3141/2258-01.
- Brennan, T., C. M. Day, J. Wasson, J. Sturdevant, and D. M. Bullock. Assessing Opportunities and Benefits of Alternative Winter Operation Timing Plans for Signalized Arterials. *Journal of Transportation of the Institute of Transportation Engineers*, Vol. 1, Issue 1, 2011, pp. 59–76.

In addition, to these technical papers, one MP3 data was prepared that contained CB audio traffic associated with a Work Zone speed study.

- Hainen, A. M., S. M. Remias, G. H. Goble, J. S. Wasson, and D. M. Bullock. *Citizen Band (CB) Radio Communication Commenting on Indiana State Police Enforcement Activity*. Joint Transportation Research Program Data Set, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2010. DOI: 10.4231/3dzvr.1288284313124.

These technical papers were prepared throughout the project and distributed to key INDOT stakeholders to facilitate early implementation of the research findings. The following sections of the technical report summarize key findings and reference Appendixes that contain these targeted implementation papers.

The data collection equipment developed during SPR-3410 was also used in concurrent arterial travel time studies at Purdue University *(7–13)*.

2. DEVELOPMENT OF TRAVEL TIME MEASUREMENT METHODOLOGY

Vehicle travel time is arguably the most important metric for characterizing highway system performance. Traffic engineers have conducted floating-car studies since the beginning of the automobile era. In this type of study, a detailed trajectory for one probe vehicle is generated for a particular path in a system. This study provides a detailed spatial resolution (for a single vehicle), but a poor temporal resolution (only one data point over the total journey time). Vehicle reidentification techniques, such as license plate matching, can yield many data points over a similar amount of time, but are costly to execute using traditional methods.

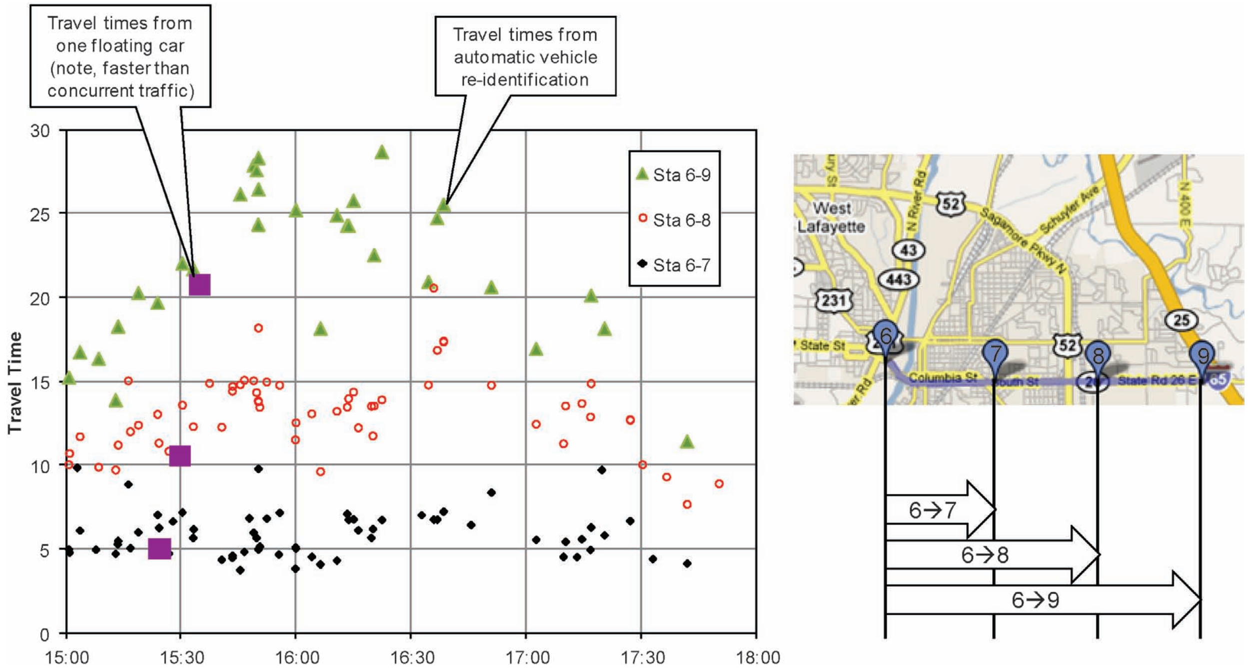


Figure 2.1 Comparison of travel time data points from a floating-car with automatic vehicle reidentification *(15)*.

Automatic vehicle reidentification techniques have emerged in the past several years, enabling much more efficient collection of individual vehicle travel times.

Bluetooth MAC address matching was demonstrated as a low-cost means of generating this type of data in 2008 by traffic engineers in Indiana and Maryland. In Indiana, the prototype unique vehicle ID detector consisted of a laptop with a USB Bluetooth transceiver[1] on a long cable. A Linux OS environment was used to incorporate scripts to automatically sync time and log vehicle IDs whenever the OS was booted. Booting from a flash drive made it possible to convert nearly any laptop into a data collection machine simply by plugging in the dongle and the flash OS.

Early studies in 2008 included analysis of traffic patterns along major corridors in the Indianapolis area, documented in a June 2008 *ITE Journal* article *(14)*. A study of traffic patterns at the Brickyard 400 race was also undertaken, in partnership with researchers from the University of Maryland (as discussed later and in Appendix B). Based on these initial successes, engineers at INDOT began to develop deployments of permanent stations for travel time measurements.

At Purdue University during the Fall 2008 semester, a special course in traffic operations (CIVL 597T) included a study of vehicle travel times in the greater Lafayette, IN area after the end of a football game at the university stadium. Figure 2.1 shows the results of the data collection effort along SR 26 in Lafayette, Indiana. The plot shows travel times between a monitoring station at SR 26 and SR 43, and three upstream stations leading to I-65. The three corresponding points from a floating car are indicated on the plot as well. The travel times characterize an increase and gradual decrease in travel times corresponding to an exodus of football spectators following the end of the game. The findings were the basis of an ITE webinar in December 2008 *(15)*.

An early portable deployment configuration consisted of a small form factor PC running on battery power (a car battery and an inverter were used) with an attached Bluetooth transceiver for measuring travel times. This assembly fit into a durable, weatherproof plastic case. The interior of one of these "Bluetooth cases" is shown in Figure 2.2. A series of these were deployed in SPR-3410 (see Figure 2.3). Although these first generation cases (Figure 2.3) ultimately became

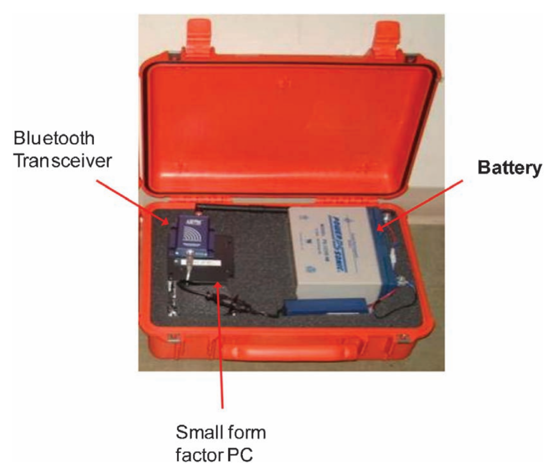


Figure 2.2 Interior of a "Bluetooth case" (photograph from *[16]*).

[1]Bidirectional (transmit/receive) communications are necessary to reproduce the measurement prototype.

Figure 2.3 Portable Bluetooth cases used in SPR-3410.

obsolete, they provided an important platform that allowed researchers to develop mobile deployment strategies that were subsequently used with commercial equipment provided by Traffax that was used in studies later in the project (see Figure 2.4).

The transceiver for the Bluetooth transceiver was mounted in a tall PVC pipe as shown in Figure 2.5(a), which was necessary for obtaining an adequate sample size (as discussed later). The cases were secured to roadside infrastructure in field studies, as shown in Figure 2.5(b). A number of permanent stations were also established, starting with "tie-wrap" installations at traffic signal cabinets, as shown in Figure 2.6(a), where a laptop was left in the cabinet to record vehicle IDs, and the Bluetooth transceiver was literally secured to the cabinet using tie-wraps. This prototype led to more secure, permanent installations as shown in Figure 2.6(b). Similar monitoring stations were estab-

a) Road sign.

b) Road sign.

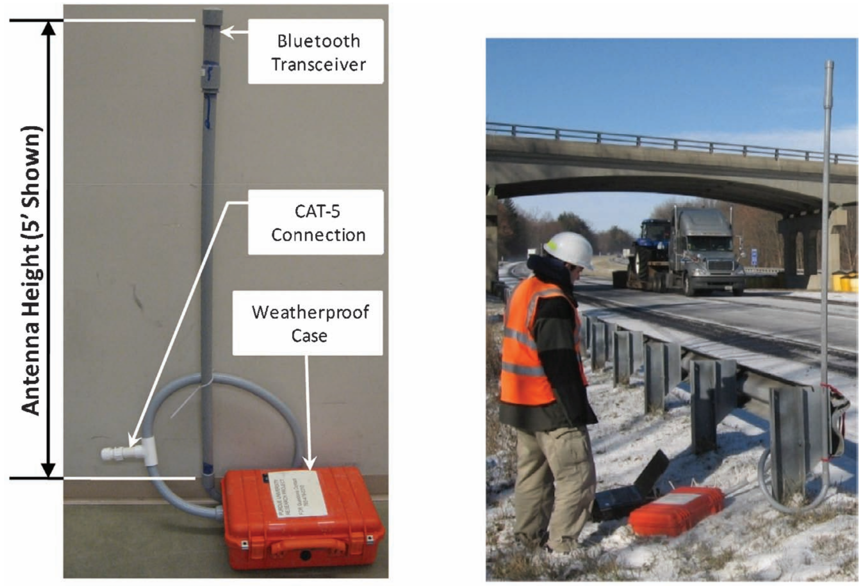
c) Light pole.

d) Interior of INDOT facility.

e) Traffic signal cabinet.

f) Other roadside electrical equipment.

Figure 2.4 Example temporary Bluetooth case deployments.



(a) Probe vehicle sampling equipment (b) Field installation.

Figure 2.5 Bluetooth monitoring equipment *(2)*.

(a) Temporary"tie-wrap"station. (b) Permanent station.

Figure 2.6 Bluetooth monitoring stations.

lished next to freeways, with continuous power made available by the roadside ITS infrastructure, such as dynamic message signs.

Deployment costs today vary by equipment and location. Portable, battery-powered cases cost approximately $4000. Permanent stations can be deployed at a cost between $100 and $1000, depending on the available infrastructure that the location.

The next challenge in deploying Bluetooth travel time monitoring was the development of the necessary data architecture for converting the raw data (observed vehicle IDs) into the final, more relevant data (travel times). First, it was necessary to constrain the match-finding searches to defined time windows, such as to prevent "false" matches (such as the same vehicle appearing on the same roadway 8 hours apart) and to reduce the computation time of the matching procedures. Next, it was desired to move the computational platform for data analysis from offline prototypes to online, real-time operations. More detailed discussion of the data methodology is provided in the following section, and in Appendix A.

Figure 2.7 shows a block diagram of the architecture for real-time travel time measurement developed in

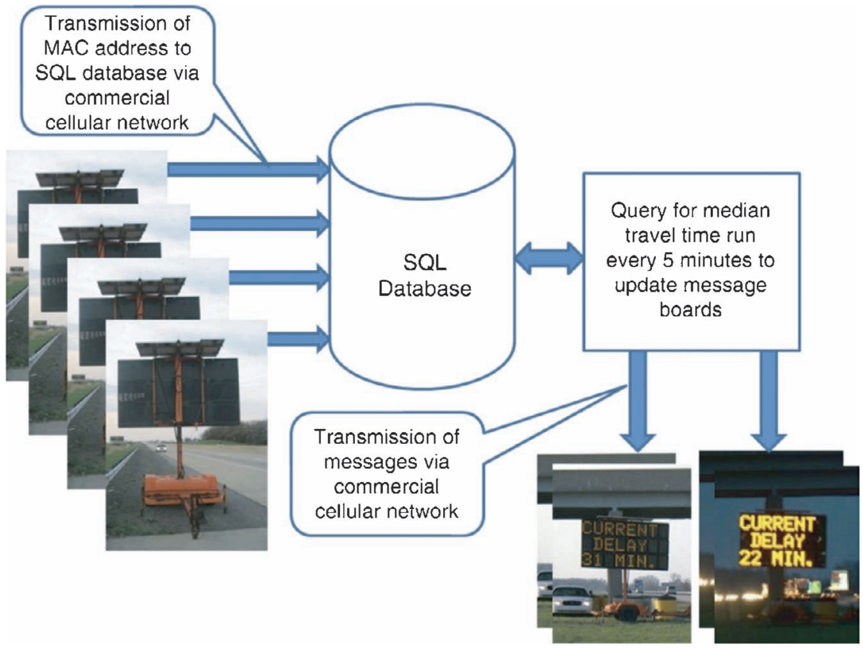


Figure 2.7 Data architecture for real-time collection and display of probe vehicle travel times *(3)*.

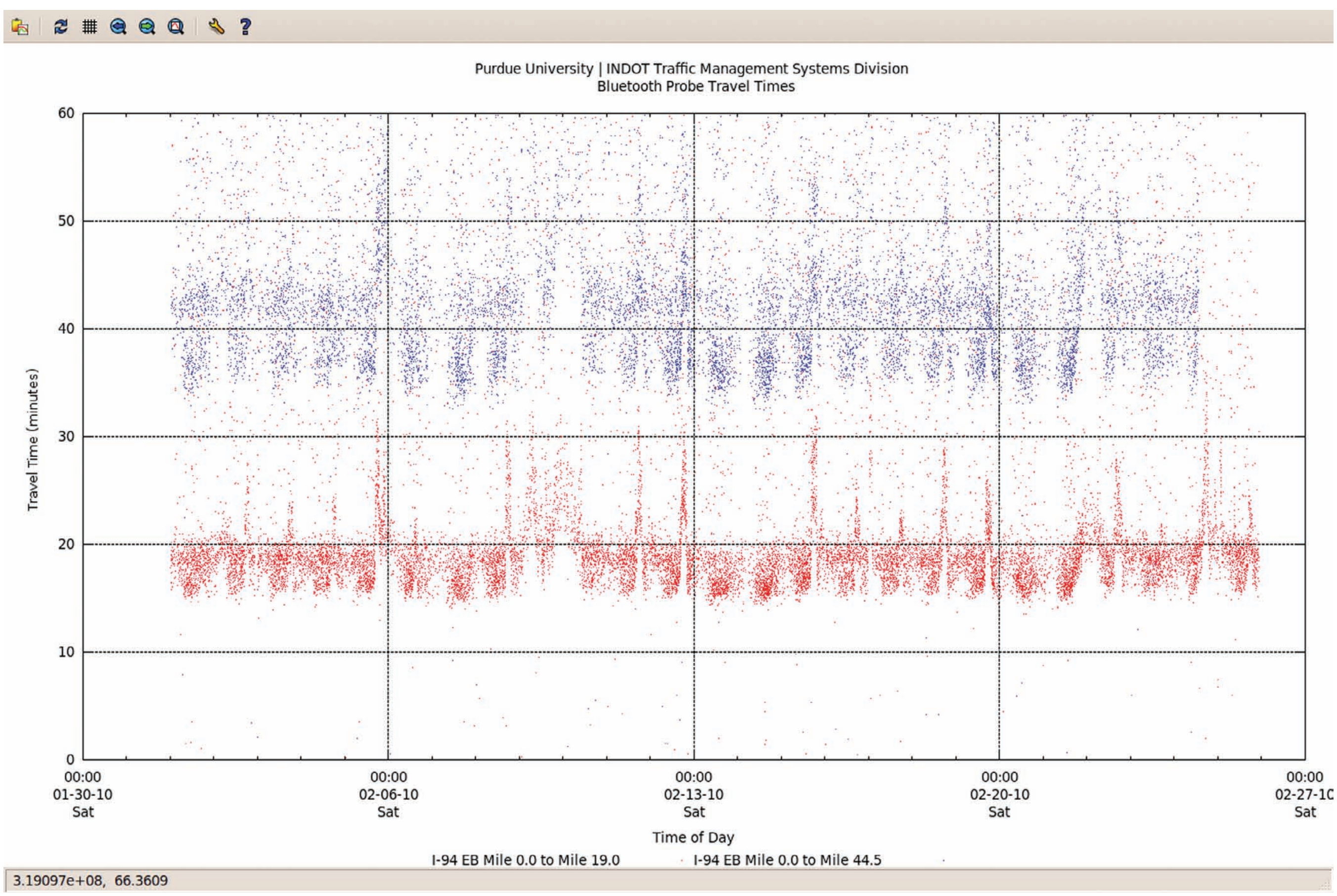


Figure 2.8 Web-based integrated travel time data dashboard.

collaboration with INDOT in 2008–2009. Observed vehicle IDs from individual monitoring stations were transmitted to a central server at the Indianapolis Traffic Management Center over a commercial cellular data network. Permanent and semi-permanent monitoring stations uploaded this information in real-time, while the temporary Bluetooth cases did not have connectivity and had their data collected and ingested manually. Vehicle IDs from connected stations were used to measure travel times in real time, which were then used to display expected wait times to the public. Figure 2.7 shows an example of dynamic message signs used to display real-time information to motorists entering a work zone along I-65 in Northwest Indiana. The data was also available to engineers using prototype dashboards as shown in Figure 2.8.

3. SUMMARY OF FINDINGS

3.1 Data Architecture for Probe Vehicle Travel Time Measurement

As mentioned previously, one challenge in this project was defining the necessary database structures to solve the problem of matching travel times across multiple points within a system over long periods of time. While some algorithms exist for solving this problem, limitations of existing methodologies are (1) they are often used like an opaque "black box" where the internal matching parameters are unknown; and (2) the number of unique vehicle IDs to be matched in this application is greater than can be efficiently handled by transparent but simple pattern-matching algorithms. Finally, it was also desired to formulate the problem not as a mathematical abstraction, but rather in the context of actual SQL queries that could be directly applied to real data.

Part of the complication arises due to the fact that vehicle IDs may be recorded multiple times (often many times) by the monitoring equipment, as illustrated in Figure 3.1. A vehicle moving along a roadway passing by two detection zones may be recorded several times within each detection zone, leaving several options for the travel time measurement. For example, the "first-first" measure would compare travel times from the first recorded vehicle ID at both detectors. Ideally, travel times would be calculated from the same relative vehicle-detector orientation at both locations.

The attached (Appendix A) study documents the SQL queries for producing travel time matches. Three strategies are used to formulate the queries; a relatively simple match, and then two subsequent layers of filtering based on time interval bins. These functions are able to improve the quality of the matching process. The documented queries are able to yield efficient vehicle reidentification travel time measurements based on unique vehicle IDs. These queries are now used to process vehicle IDs in the INDOT network of Bluetooth monitoring devices, which was in 2010 ingesting approximately 6,000,000 vehicle IDs across 30 monitoring stations.

Full details of the matching procedure are detailed in Appendix A.

3.2 Impact of Sensor Height on Data Collection Efficiency

One of the challenges in deployment of Bluetooth enabled sensors was the configuration of the transceiver for detecting mobile Bluetooth devices. In early deployments of the portable Bluetooth data collection units (Figure 3.2), it was found that higher antenna mounting resulted in a substantial increase in unique vehicle IDs. For this reason, PVC encased antennas were attached to the Bluetooth cases to increase the sensitivity of each data collection unit. However, there was no empirical evidence at the time regarding the efficiency of each antenna. A study was undertaken to find the most effective antenna height.

Five Bluetooth cases were prepared with antenna heights spanning the range of 0 ft (no antenna) to 10 ft in 2.5-ft increments. These were deployed along the southbound shoulder of I-65 on December 7–8, 2008, as shown in Figure 3.2. It was also of interest to understand the impact of lateral offset from the opposing (northbound) lanes. For example, would the 114-ft distance to the right northbound lane (Figure 3.3) result in substantially fewer northbound detections compared to southbound detections?

The results in terms of the number of detected probe devices are summarized in Figure 3.4. In this case, the majority of detected vehicle IDs are successfully matched because there are no entries or exits on the section of I-65 where the cases were deployed. The total number of detections was found to increase with height. The percentage difference between northbound and

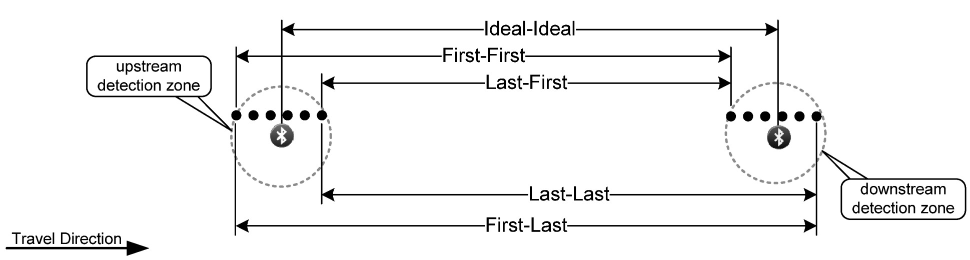


Figure 3.1 Pattern matching options for probe data.

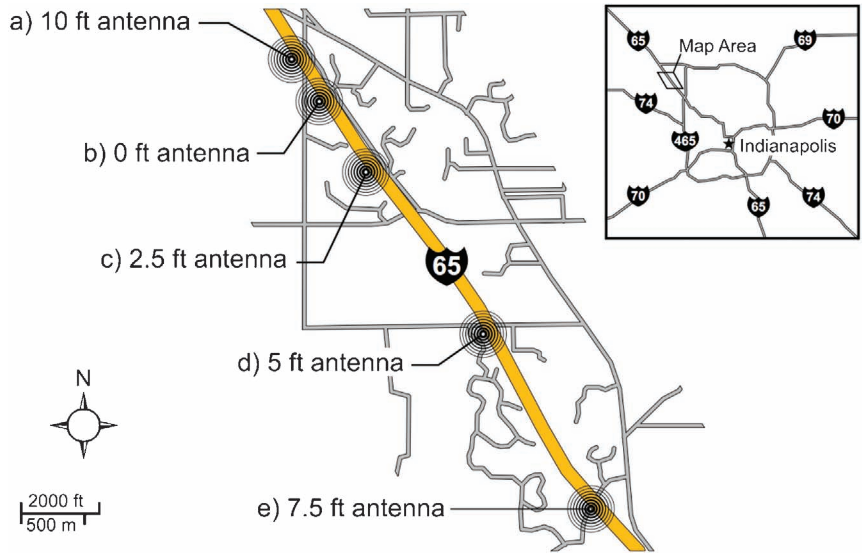


Figure 3.2 Equipment deployment in this study *(2)*.

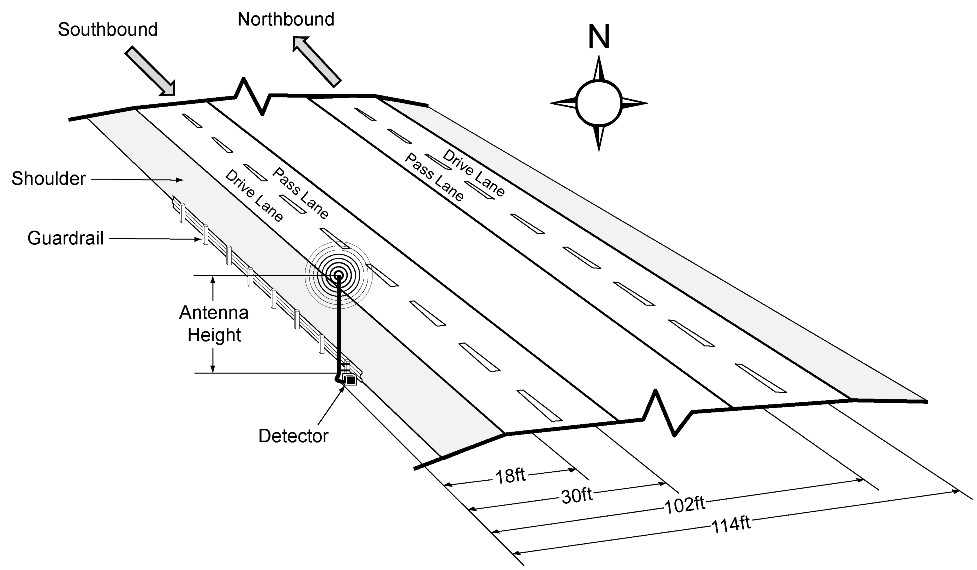


Figure 3.3 Lateral offset of lane centerlines from probe vehicle monitoring equipment mounted at guardrail *(2)*.

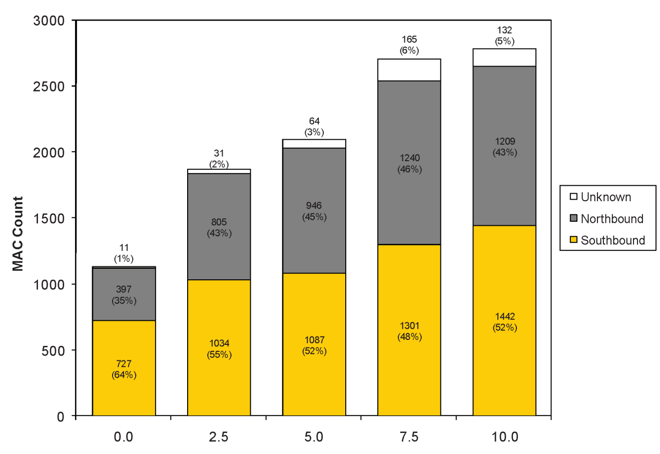


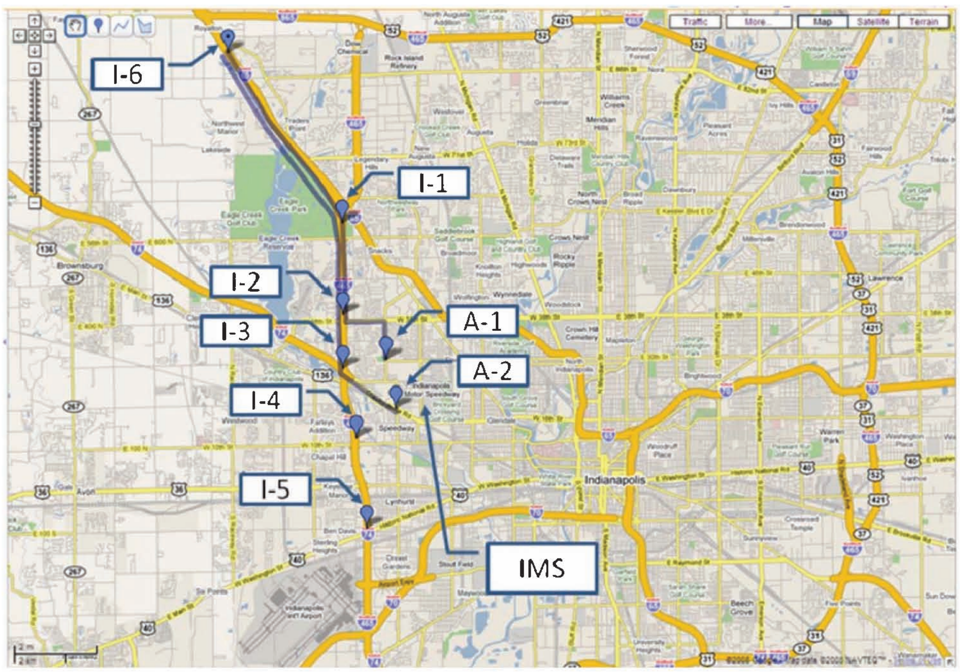
Figure 3.4 Counts of detected vehicle IDs (MAC addresses) by antenna height and direction *(2)*.

southbound detections, reflecting the influence of lateral displacement, was also found to change with height. In this case, the 7.5-ft antenna performed best; the other antenna heights detected more southbound than northbound vehicles. The 10-ft antenna had slightly more detected vehicle IDs, but was biased to the southbound lanes. From these results, it was recommended to use an antenna height of approximately 8 ft.

Further details may be found in the reprint of the paper in Appendix B.

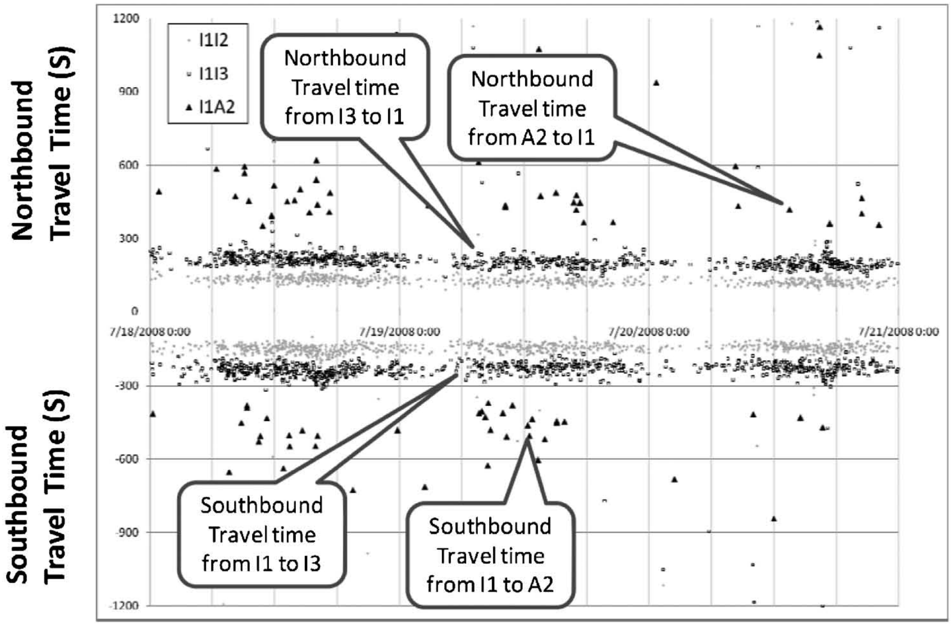
3.3 Active Traffic Management during the Brickyard 400

Active traffic management is one of the most promising potential agency uses of travel time data.

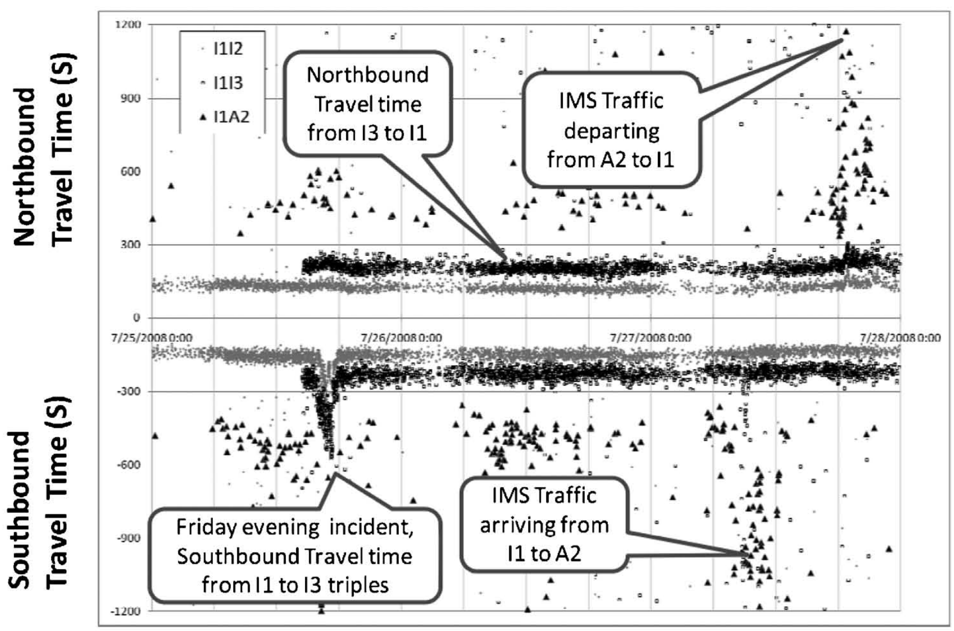


Site Code	Data Collected July 18-20, 2008	Data Collected July 25-27, 2008	Location
I-1	MAC Address	MAC Address	I-465 (Exit 20) at I65, Median between I-465 lanes
I-2	MAC Address	MAC Address	I-465 (Exit 17) at 38th Street, Northwest Quadrant
I-3	MAC Address, Speed, and Volume	MAC Address, Speed, and Volume	I-465 (Exit 16) at I74, Northwest Quadrant
I-4		MAC Address	I-465 (Exit 14) at 10th Street Northeast Quadrant
I-5		MAC Address	I-465 (Exit 12) at Washington Street, Northwest Quadrant
I-6		MAC Address, Speed and Volume	I-65 (MM 127.8)
A-1	MAC Address	MAC Address	Moller Road at W. 30th Street, West side of T-Intersection
A-2	MAC Address	MAC Address	North Lyndhurst Drive at Crawfordsville Road, West approach

Figure 3.5 Equipment deployment during the Brickyard 400 study *(5)*.



(a) July 18-20, 2008.



(b) July 25-27, 2008.

Figure 3.6 Travel time plots comparing non-event to event conditions *(5)*.

To test the characteristics of travel behavior and motorist travel time during a typical operational situation where active traffic management strategies would be employed, Bluetooth monitoring devices were deployed at various locations in the Indianapolis area during a special event (the Brickyard 400 race in July 2008) during which INDOT traffic management center (TMC) personnel were actively monitoring and making decisions on freeway operations. Data collection was also undertaken during typical conditions to compare travel times.

Figure 3.5 shows a map of the locations of the deployed sensors and their relationship to the location of the Indianapolis Motor Speedway (IMS), and a table indicating active data collection preceding the event (July 18–20) and during the event (July 25–27). The "A-2" station represents the preferred route from the IMS to I-465. Figure 3.6 shows plots of travel times along

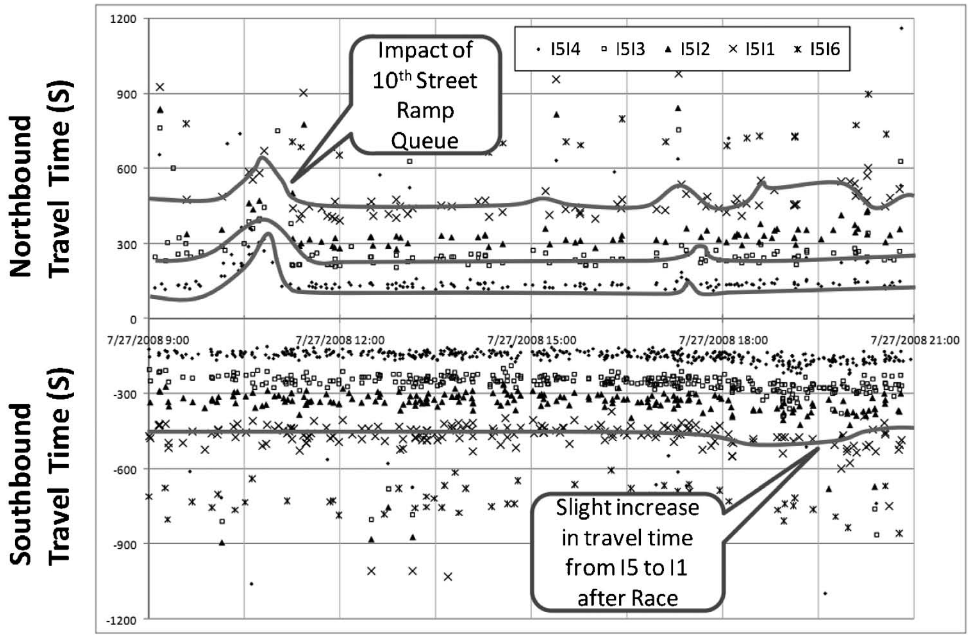


Figure 3.7 Plot of travel times on I-465 during the Brickyard 400 *(5)*.

(a) *10:25 am*. Ramp queue causing 2-mile backup on I-465 across three lanes.

(b) *10:35 am*. Northbound I-465 flow highly restricted by the exit ramp queue.

(c) *10:44 am*. Northbound I-465 ramp closed.

(d) *11:05 am*. Northbound I-465 queue cleared; I-465 flow normalized and ramp reopened.

Figure 3.8 Images of I-465 exit at 10th Street, impact of exit ramp spillback on freeway operations, and results from ramp closure *(5)*.

various segments of the route from station A-2 to the I-465/I-65 interchange (I-1). Figure 3.6(a) shows travel times during typical weekend conditions, while Figure 3.6(b) shows conditions during the race day weekend, with spikes in travel times occurring due to a traffic accident on Friday night, and increased traffic entering and leaving the IMS on Sunday.

Figure 3.7 examines travel times on I-465 between station I-5 and the four stations to the north (I-3, I-2, I-1, and I-6). The stratification in the lines is indicative of increasing travel time on each section. The plots indicate slight increases in southbound travel times after the race, but this trend is rather slight. A more interesting feature in this plot is the spike in northbound travel times during the morning which can be explained by queuing at the I-465 exit ramp for 10th Street (Figure 3.5, Station I-4). Long queues were forming at this location due to many motorists using the ramp to reach the IMS and insufficient capacity on the surface street adjacent to the freeway exit. The growing queue had the cascading effect of encouraging other motorists heading to the IMS to join the back of the queue and take the same exit. The resulting congestion is illustrated in Figure 3.8(a), which shows a traffic camera view of the exit. In Figure 3.8(b), the sparse traffic flow on I-465 north of the exit indicates the severity of the traffic restriction. Based on these conditions, INDOT traffic management staff closed the 10th street ramp at 10:44 am (Figure 3.8[c]), after which the conditions on I-465 returned to normal (Figure 3.8[d]). These events correspond with the travel time spike in Figure 3.7.

This paper was one of the first to demonstrate the use of vehicle ID matching for evaluating active traffic management tactics in special events. The travel time view not only is able to attach a quantitative measure of travel time to the incident, but also shows how the TMC staff action was effective at eliminating the bottleneck, not only within the immediate vicinity of the traffic camera field of view, but along a greater length of the freeway.

Full details of the study are contained in the attached paper in Appendix C.

3.4 Analyzing Work Zone Traffic Impacts

One objectives of SPR-3410 was to investigate the feasibility of using probe vehicle travel times for innovative contracting purposes. To pursue this effort, a study was undertaken to measure travel times during interstate road construction to see whether the impacts could be effectively quantified. In 2009, road construction on a major freeway segment (I-65 in northwest Indiana) presented an opportunity to test the methodology in those conditions. About 1.4 million vehicle IDs were collected over a period of 12 weeks. In those 12 weeks, real-time delay estimates were displayed to motorists as illustrated in Figure 3.9. The display graphics in this figure correspond to the indicated travel time trends revealed in the underlying data plot.

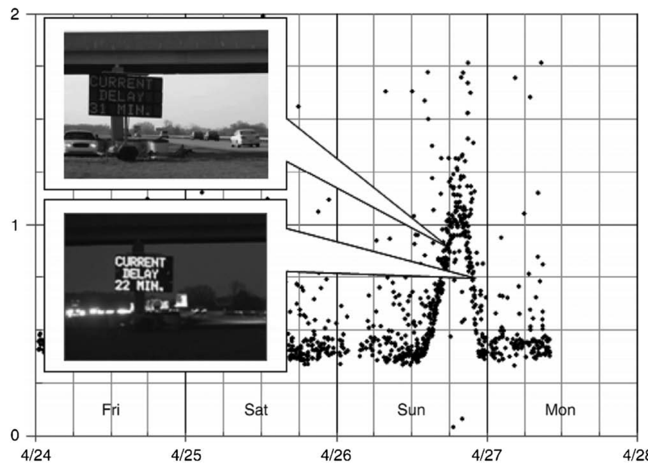


Figure 3.9 Example messages displayed to motorists on I-65 at different times of day *(3)*.

In the 12-week analysis period, 422 hours of excessive delay (i.e., delay times greater than 10 minutes) were observed. Bluetooth monitoring stations on signed detour routes were deployed to measure whether the dynamic message signs would encourage motorists to use those routes, but no such impacts were observed.

In addition to those findings, the travel time data illustrates the impact of ending a lane restriction (going from one open and one closed lane to two open lanes), as shown in Figure 3.10. Although both the "before" and "after" conditions in this scenario were undersaturated, opening the second lane resulted in a travel

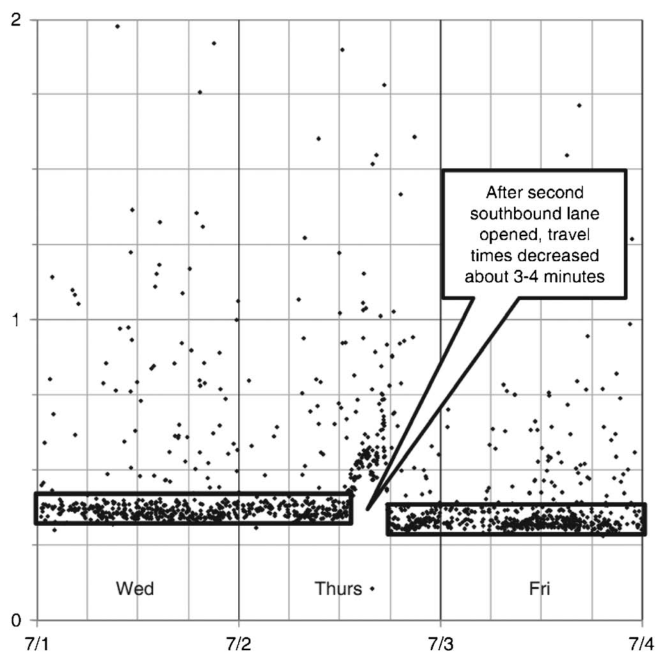


Figure 3.10 Impact of changing from one open lane to two open lanes on a freeway section *(3)*.

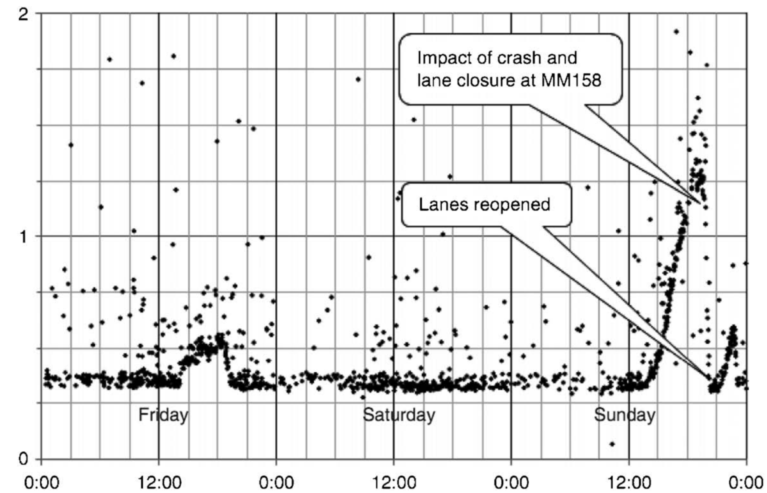


Figure 3.11 Impact of a crash and lane closure on freeway travel times *(3)*.

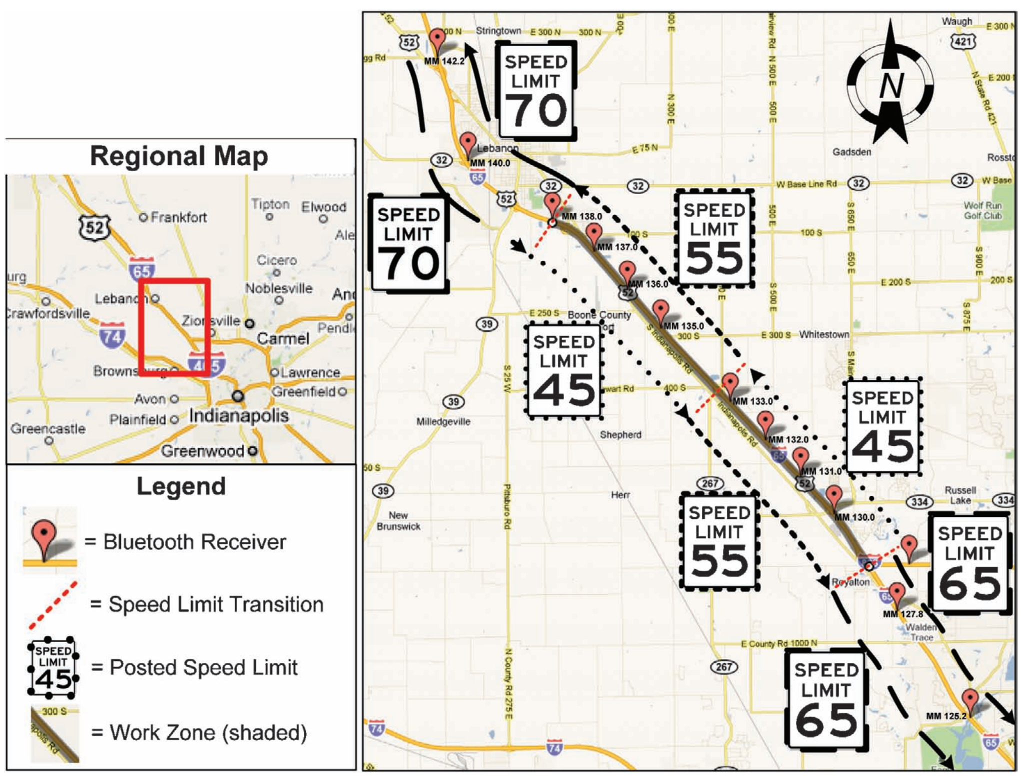


Figure 3.12 Map of study section.

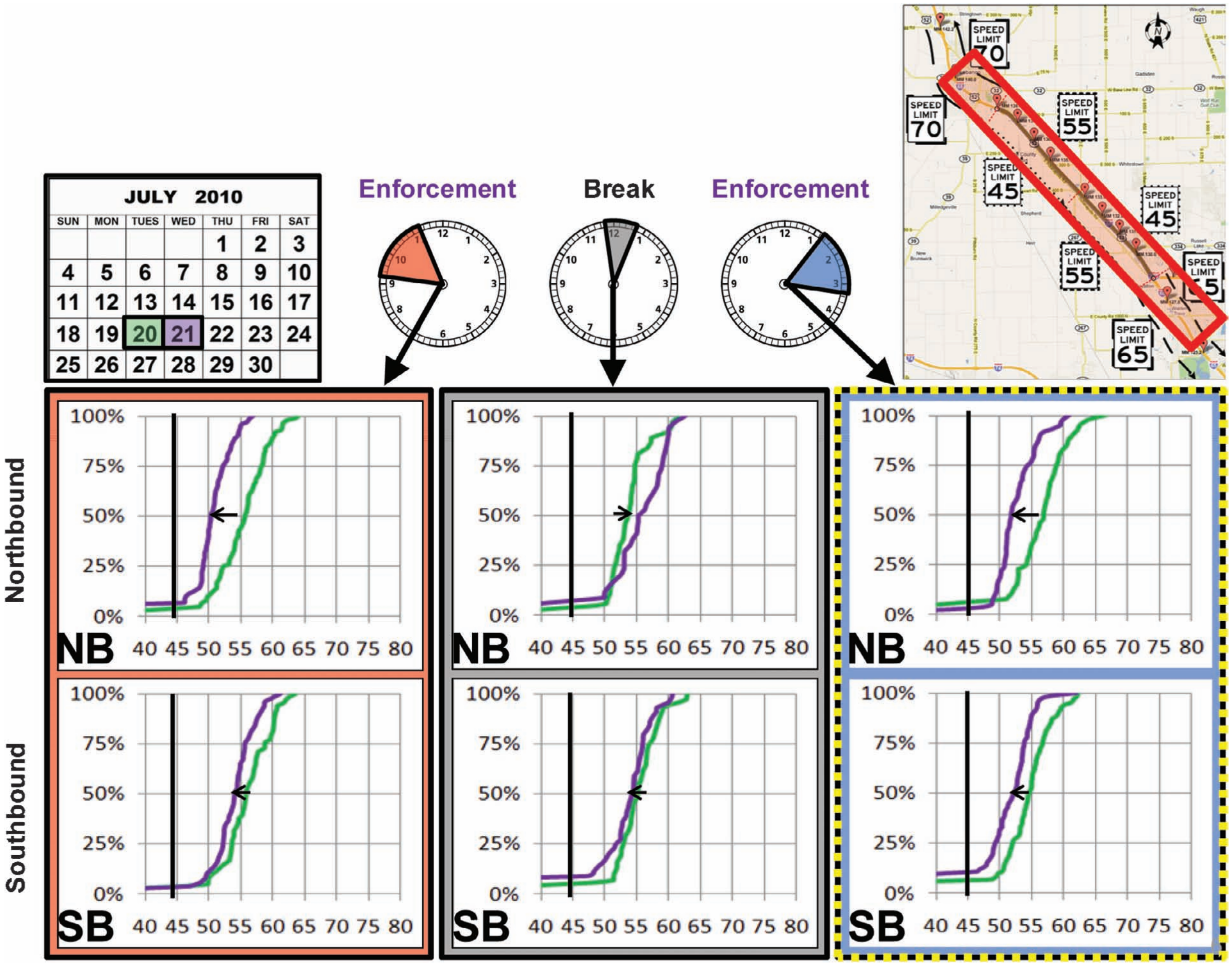


Figure 3.13 Impact of enforcement on freeway work zone speeds: Cumulative frequency diagrams of speed (derived from measured travel time) with and without work zone speed enforcement.

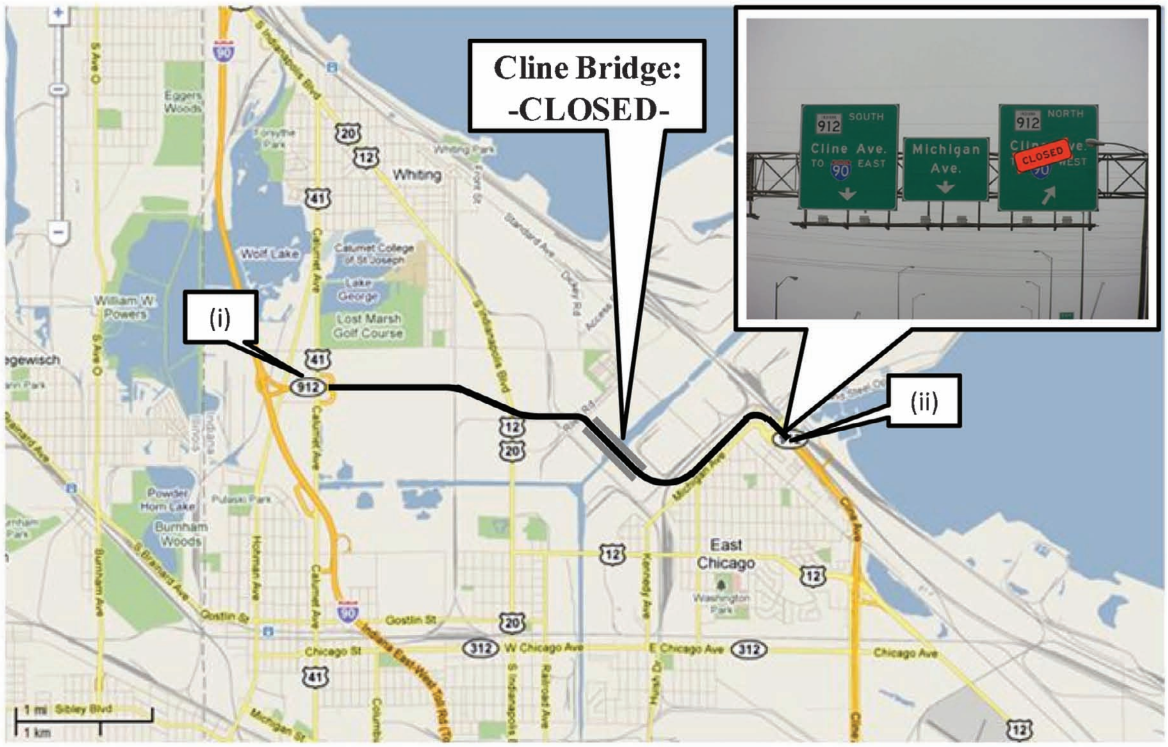
time reduction of approximately 4 minutes on the section. The impact of crashes on travel times were also observed, as illustrated in Figure 3.11. This plot shows a severe increase in travel time due to a crash and lane closure during moderate traffic. The trends correlate with an observed capacity drop (as determined from volume measurements) from 1800 veh/h to 550 veh/h.

Full details are available in the reprint of this paper attached as Appendix D.

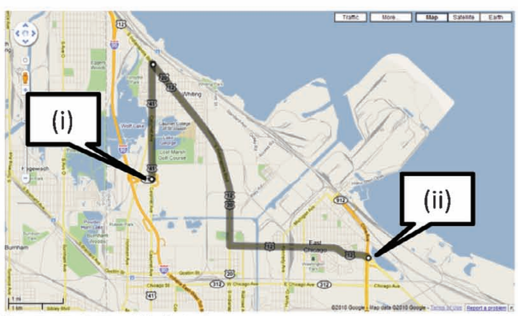
3.5 Impact of High Visibility Speed Enforcement on Motorist Behavior in Work Zones

In 2010, a study was undertaken as part of SPR-3410 to determine the impact of increased speed enforcement on motorist compliance with work zone speed limits. This study is likely the largest study to date in which extensive travel time measurements were coordinated with enforcement activities. The study took place on a section of I-65 north of Indianapolis, shown in Figure 3.12. The normal speed limits of 70 and 65 mph on the section were reduced to 55 and 45 mph. On July 21, 2010, the Indiana State Police (ISP) coordinated an enforcement blitz on the section in conjunction with travel time data collection activities. This enforcement blitz included twelve patrols on the section, ensuring that the enforcement activity was highly visible to motorists during the same time period. Measured travel times were used to derive measured speeds during the same time period. A short MP3 audio file of the CB traffic commenting on the blitz can be found at: http://dx.doi.org/10.4231/3dzvr.1288284313124.

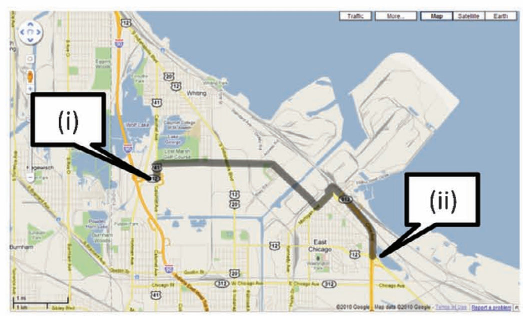
The influence of visible, heightened speed enforcement is illustrated in Figure 3.13. These plots are cumulative frequency diagrams of speed for the northbound and southbound directions during three time periods on July 21. The purple lines in these plots indicate speeds during the enforcement period, while the green line indicates speeds during a normal day. During the AM period, when there was heavy enforcement, speeds were found to significantly reduce in both the northbound and southbound directions.



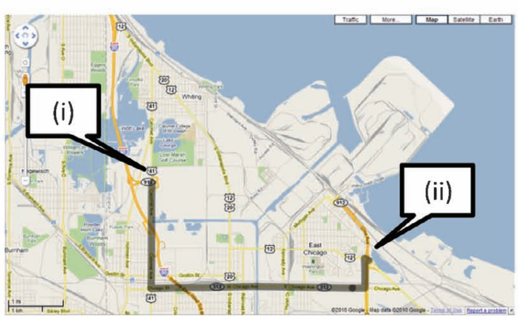
a) Indiana State Road 912 Route prior to Cline Avenue Bridge closure.



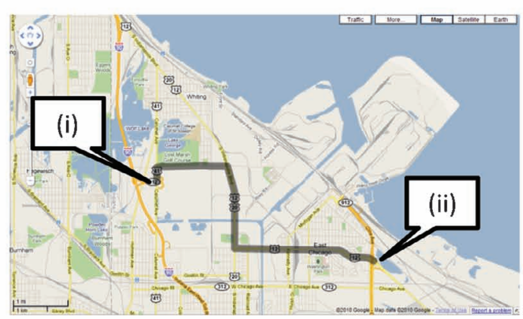
b) INDOT official detour.



c) Unofficial route.



d) Local route.



e) Hybrid route.

Figure 3.14 Study area. Callouts indicate (i) west end Indiana SR 912 detour junction and (ii) east end Indiana SR 912 detour junction *(4)*.

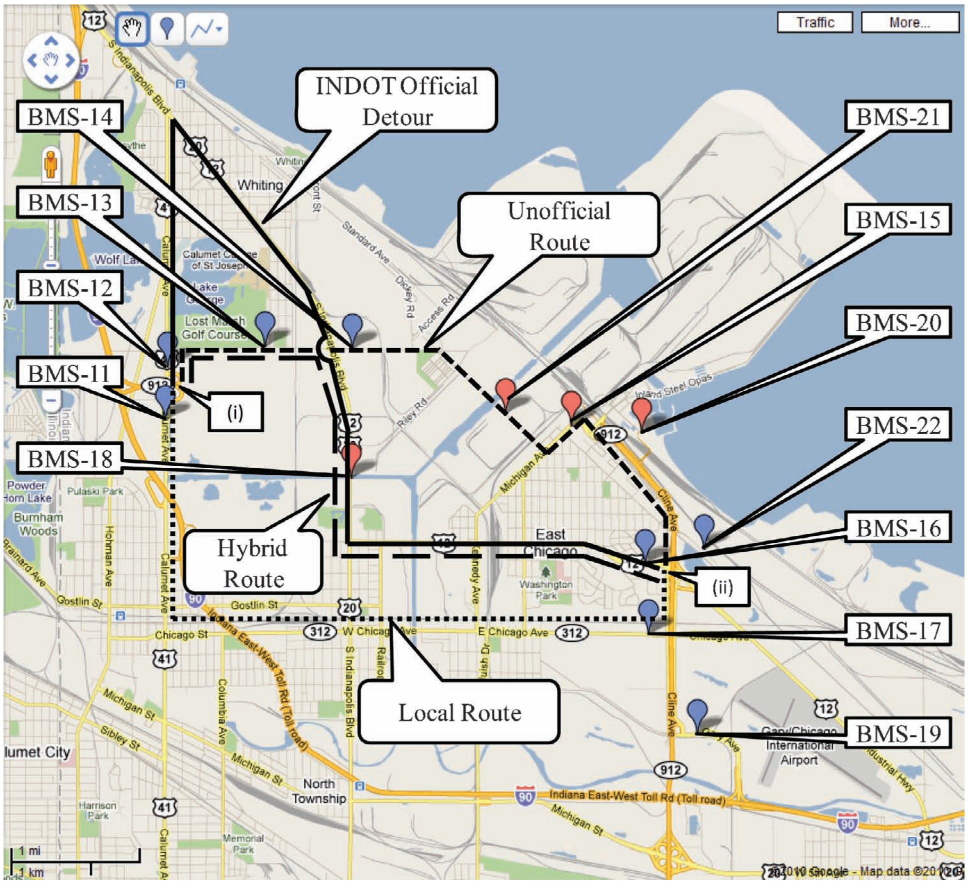


Figure 3.15 Bluetooth monitoring stations (BMS) placed to capture traffic routes between (i) west end and (ii) east end of Indiana SR 912 *(4)*.

Around noon the ISP patrols broke for lunch, and police presence on the section was reduced; speeds recovered to the same levels as the non-blitz observations. During the PM period of heavy enforcement, speeds once again reduced. The results clearly show that heavy enforcement does have a significant impact on motorist speeds in work zones, and the reductions indicate an upper bound on what can be reasonably achieved by enforcement activities. The results also suggest that the effects are limited only to the enforcement periods. As shown in Figure 3.13, motorist speeds during the break quickly returned to non-enforcement conditions.

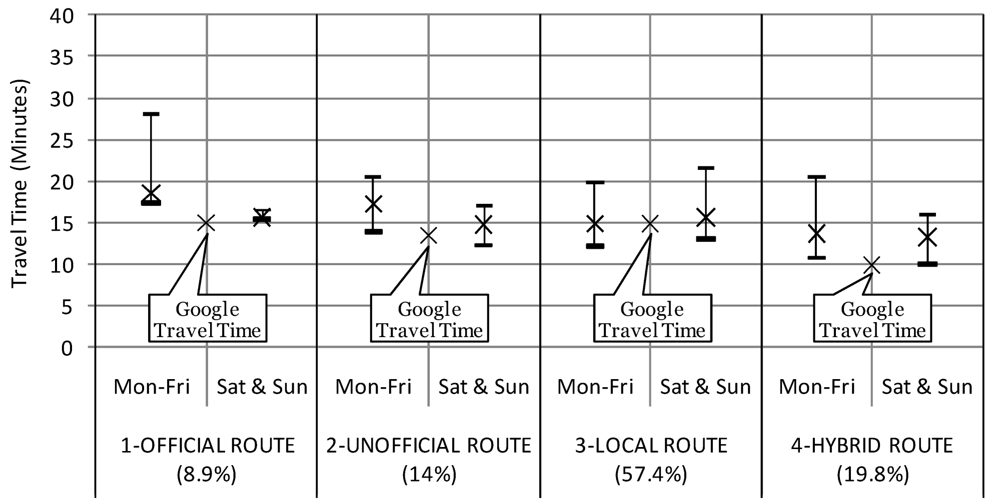
Full details are available in the paper reprint attached as Appendix E.

3.6 Analyzing Motorist Route Choice during a Road Closure

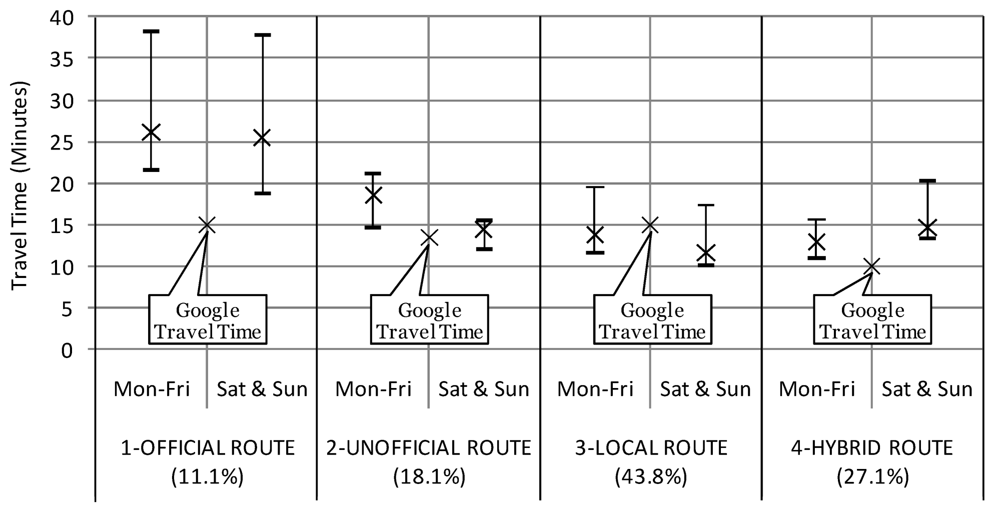
This study investigated the impact of the unplanned closure of the Cline Avenue bridge in northwest Indiana. Figure 3.14(a) shows a map of the affected area. Figure 3.14(b) shows the official signed INDOT detour route, while Figure 3.14(c), Figure 3.14(d), and Figure 3.14(e) show the other possible routes likely on major area roads. Bluetooth monitoring equipment was deployed throughout the affected area as shown in Figure 3.15. Observed vehicle ID matches suggest that use of the signed detour was relatively low, with only 9% of observed vehicles using the official route in Figure 3.14(b). The usage rates of the routes shown in Figure 3.14(c), Figure 3.14(d), and Figure 3.14(e) were 14%, 57%, and 20% respectively. The results are not entirely surprising considering that the official route is longer than the others. The travel time data also shows that the official route takes more time than the others, particularly in the westbound direction, as shown in Figure 3.16.

The trends suggest that most drivers using the closed route are locals with sufficient knowledge of area roads to favor using shorter routes. The results illustrate that MAC address matching is a more cost-effective vehicle ID technology for obtaining O-D patterns than the conventional technique, license plate matching.

In addition to the route choice findings, several other observations are made from the travel time



a) Eastbound route.



b) Westbound route.

Figure 3.16 The 25th, 50th, and 75th percentiles of measured travel times for alternative routes *(4)*.

data. For example, Figure 3.17 shows a sudden spike in travel times illustrating the occurrence of non-recurring congestion and high delays on a particular road section. Figure 3.18 shows the increases in travel time due to tidal flows along two alternate directions on a route, which correspond to the beginning and ending of work shifts at a local manufacturing plant.

Full details of the results may be read in the attached reprint in Appendix F.

3.7 Winter Weather Impacts on Signalized Arterials

To determine if coordination will benefit a signalized arterial, one of the factors that needs to be known is how dispersed a platoon of vehicles becomes as it travels through the system. As quoted in the *Traffic Control Systems Handbook (17)*, Page 3.35:

> When a platoon of vehicles is released from a traffic signal, the degree to which this platoon has dispersed at the next signal (difference from profiles at releasing signal) in part determines whether significant benefits can be achieved from signal coordination.

Traffic flow characteristics used for signal timing plan design are almost always based upon normal operational conditions, i.e., clear weather. In addition, direct field observation of platoon arrivals during peak volume periods are often used to field tune traffic signal offsets. However, field observation and tuning of traffic signal offsets during winter weather conditions are not scalable and raise safety concerns.

The research defined a set of procedures that use high resolution event-based traffic controller data to directly measure traffic flow and coordinated platoon characteristics. The use of high resolution data allowed

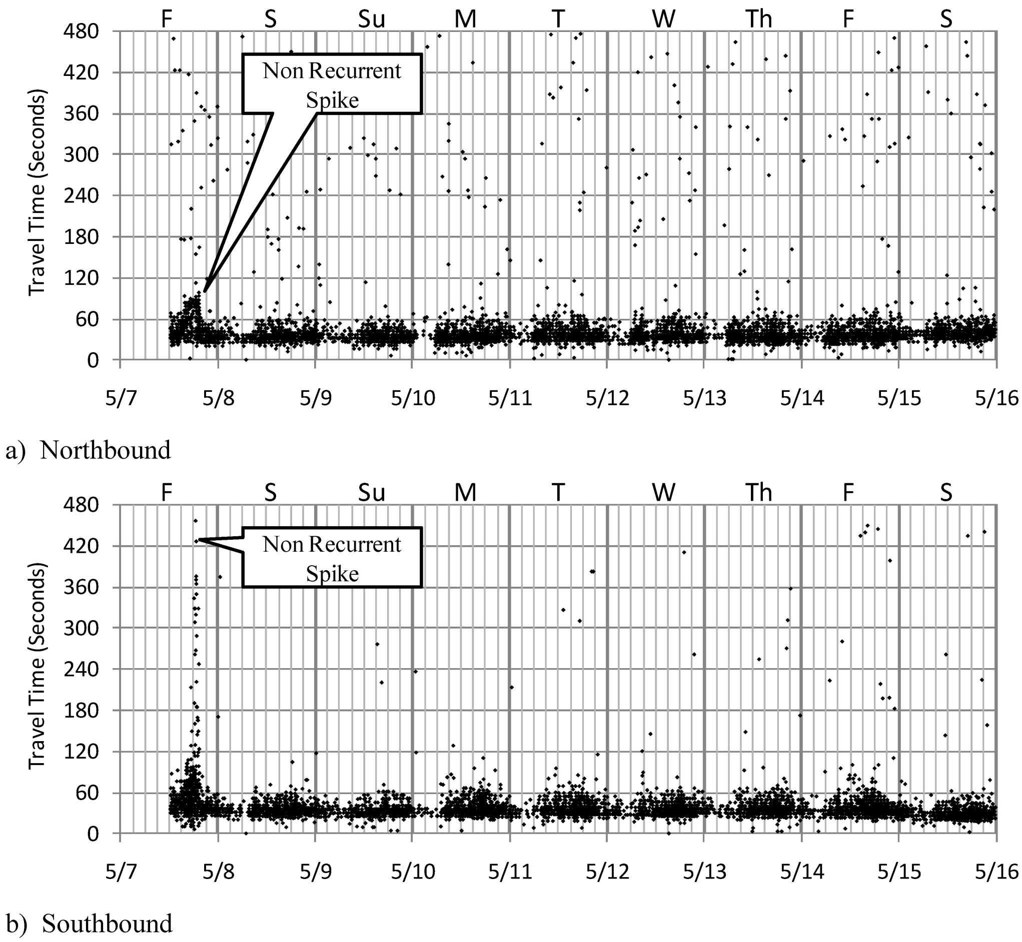


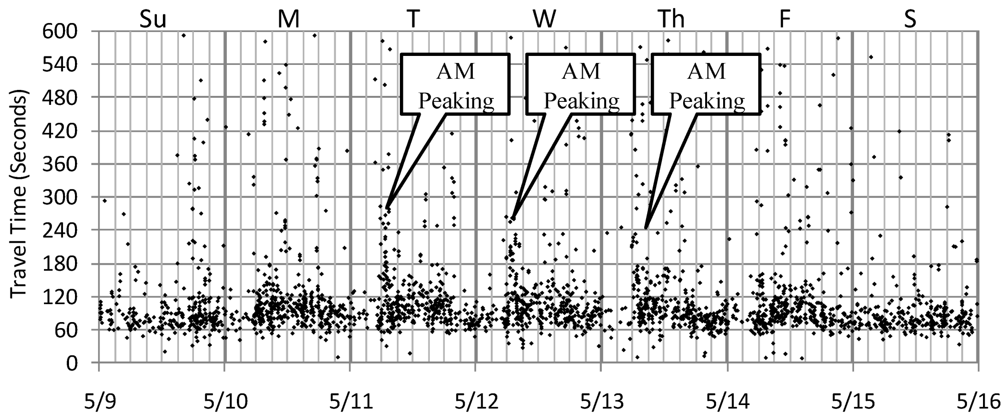
Figure 3.17 Travel time data that illustrates an example of nonrecurring congestion along a section of US 41 spanning the interchange with Indiana SR 912 *(4)*.

the visual display of the interaction of signal phase information with respect to advance detection cycle-by-cycle.

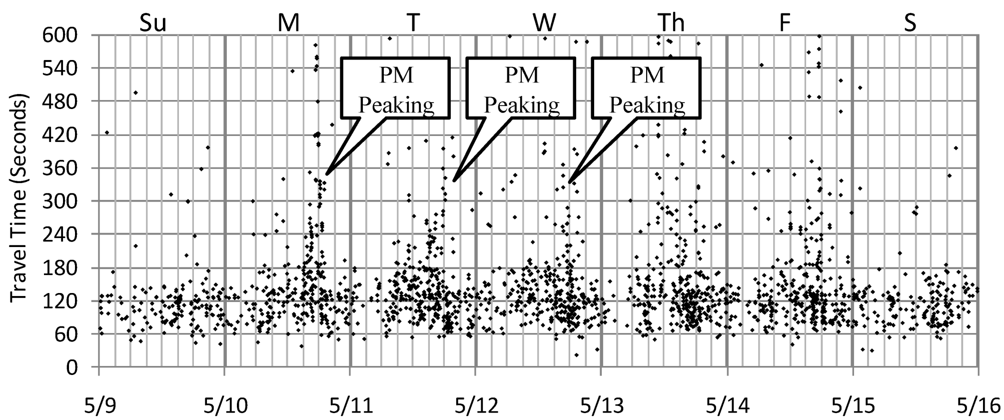
Corridor travel speeds were obtained from the Bluetooth probe travel, while the platoon characteristics are obtained from high resolution event-based traffic control data. These concepts were used to evaluate the need for signal coordination during an adverse weather event. As would be expected, there was an increase in corridor travel time during observed snow events; however, there were still platoons observed at the site. When compared to a clear weather day, the travel time and presence of platoons indicate that there is an opportunity to improve coordination during a snow event.

A 1.6-mile (2.6-km), 4-intersection, coordinated portion of SR 37 in Noblesville, Indiana, is shown in Figure 3.19. Each of the intersections I-01, I-02, I-03, and I-04 have the capability of logging high-resolution controller data (phase and detector status changes) at a resolution of 0.1 seconds *(5)*. Two permanent Bluetooth sensors for collecting unique vehicle IDs (BT-01 and BT-04) were also deployed at intersections I-01 and I-04 respectively.

Ten days of travel time are displayed for the northbound (Figure 3.20[a]) and southbound (Figure 3.20[b]) directions. During the 10-day data collection, a snow event occurred on Thursday, January 7th, 2010, which can be compared to a clear weather day; Thursday, January 14th, 2010. Comparing the travel time plots for these two days, the snow event travel times (Figure 3.20[a], callout "i" and Figure 3.20[b], callout "iii") have a noticeable increase compared to a clear weather day (Figure 3.20[a], callout "ii" and Figure 3.20[b], callout "iv") for both the northbound and southbound directions. The coordinated arterial is optimized to minimize the delay in the southbound direction in the AM Peak under clear weather conditions. The southbound direction serves the majority of the vehicle volume during the AM Peak period (an approximate 70/30 directional split during normal AM operations). These travel times are perhaps more



a) Westbound (station BMS-15 to BMS-21)



b) Eastbound (station BMS-21 to BMS-15)

Figure 3.18 Travel time data that illustrate recurring congestion during peak periods caused by work shift changes at an area manufacturing plant *(4)*.

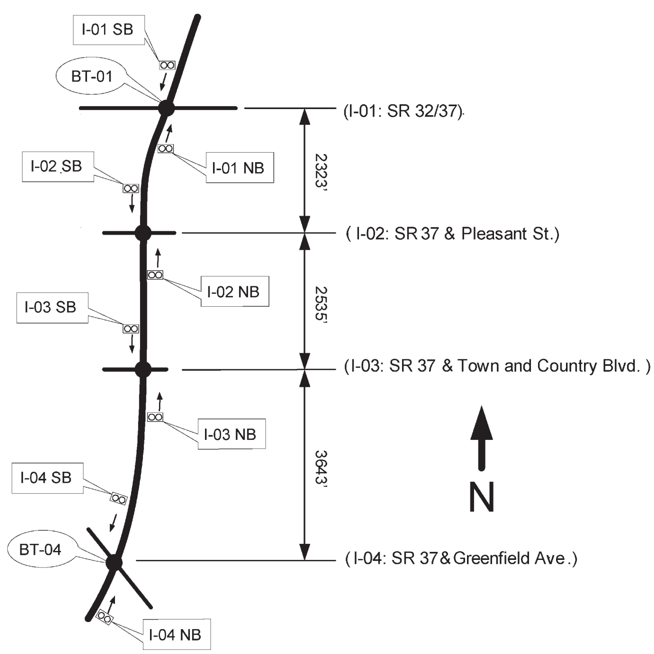
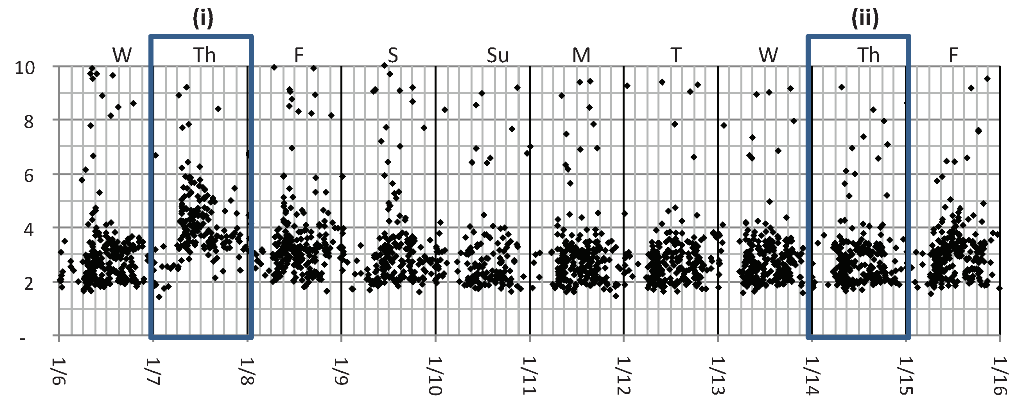
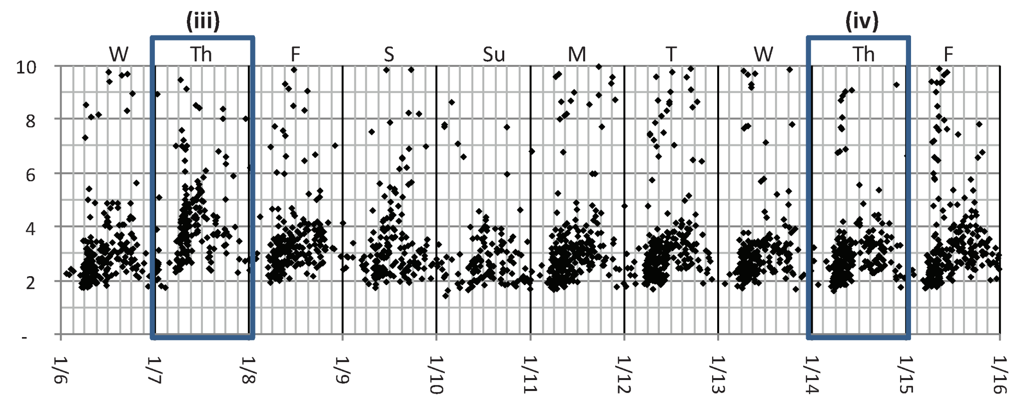


Figure 3.19 Equipment deployment on SR 37 during this study *(6)*.



a) Northbound.



b) Southbound.

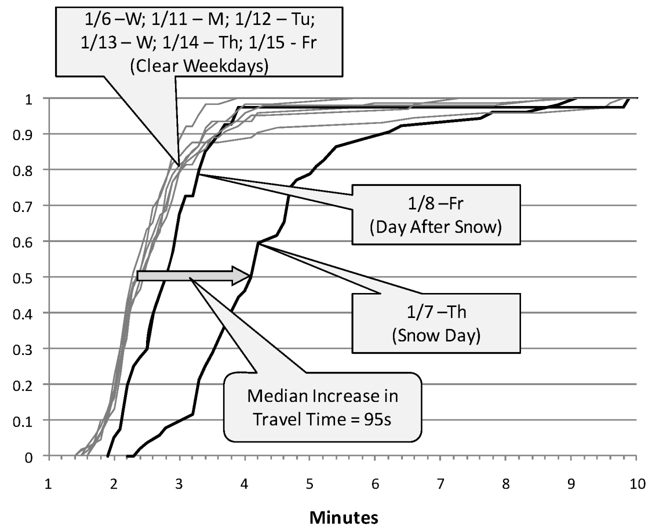
Figure 3.20 Probe vehicle travel times (minutes) along SR 37. Callouts (i and iii) indicate snow conditions; (ii and iv) indicate clear weather conditions *(6)*.

effectively compared during particular time periods using cumulative frequency distribution (CFDs), as shown in Figure 3.21. In addition, a slight increase in travel time is observed on January 8, 2010, the day after the snow event occurred. This could be due to residual snow and ice remaining from the previous day's snow event. A statistical box-plot distribution, which displays the quartiles (25th, 50th, and 75th percentiles) of the probe vehicle observations, is shown in Figure 3.22. The changes in travel time correlate with changes in measured vehicle headway, as illustrated in Figure 3.23.

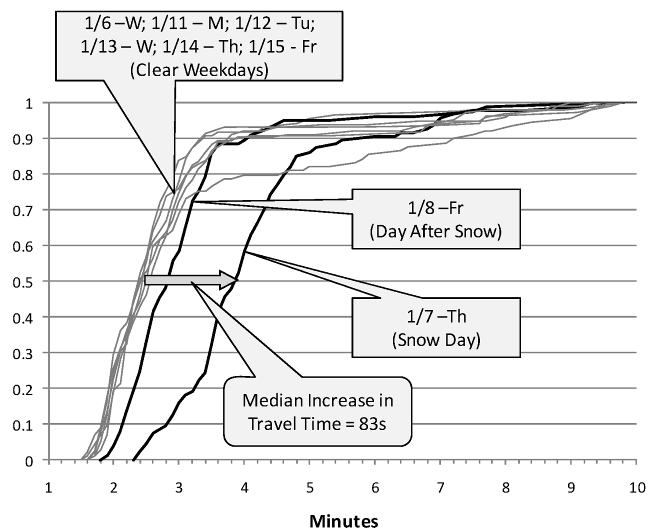
Measurements of the platoon during the southbound AM Peak is presented in Figure 3.24. These histograms represent the frequency of vehicle arrivals at a given amount of time following the beginning of green at the *upstream* intersection. Because of the increased in link travel speeds as observed earlier, the expected modal arrival time of the platoon shifted by approximately 15 seconds, which can be seen if we compare Figure 3.24(a), callout "i" to Figure 3.24(b), callout "iii." Also represented in the graph is a full-width half-max measurement (FWHM), which is the x-axis distance between the start (M_s) and end (M_e) of the region defined where the peak of the arrival distribution is at half of its maximum value. The FWHM was used to quantify the change in platoon dispersion due to snowfall.

Figure 3.25 explains a visualization tool called the *Purdue Coordination Diagram (7,8,9)*, which was used to analyze the impacts of winter weather on signal coordination. The cyclic flow profile concept *(18)* is represented in Figure 3.25(a). This is a representation of the likelihood of vehicle arrivals at a given time during the cycle; in this example, a distribution of the probability of green is also overlaid. The actual event data for a single cycle is shown in Figure 3.25(b). If this profile of one signal cycle's phase state and arrival data are rotated, it is possible to display several cycles in succession, as in Figure 3.25(c), making it possible to visualize platoon arrivals (e.g., Figure 3.25[c], callout "i").

By comparing the PCDs from the snow event (in Figure 3.26, left column of PCDs) to clear weather (Figure 3.26, right column), it is possible to observe changes in the travel times and dispersion of platoons. During snow conditions at I-03 and I-04, the considerably more spread out platoon begins to arrive later in the cycle resulting in a portion of the platoon arriving

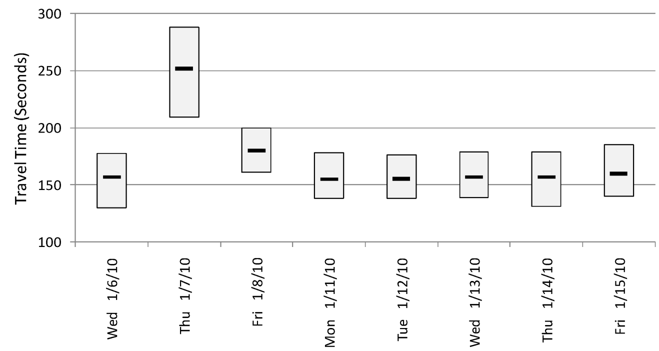


a) Northbound BT-04 to BT-01

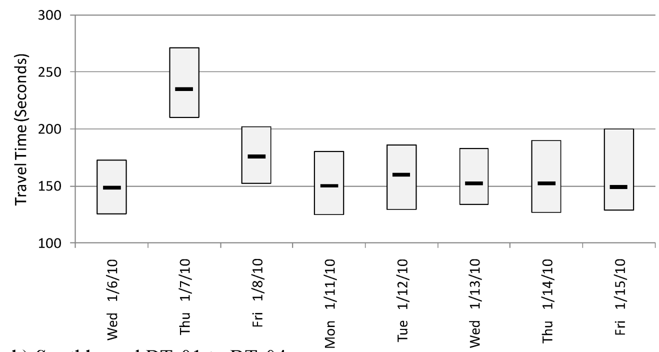


b) Southbound BT-01 to BT-04

Figure 3.21 Cumulative frequency of probe vehicle travel times along SR 37 during AM Peak 06:00 – 09:00 ($\leq$ 10 minutes) *(6)*.

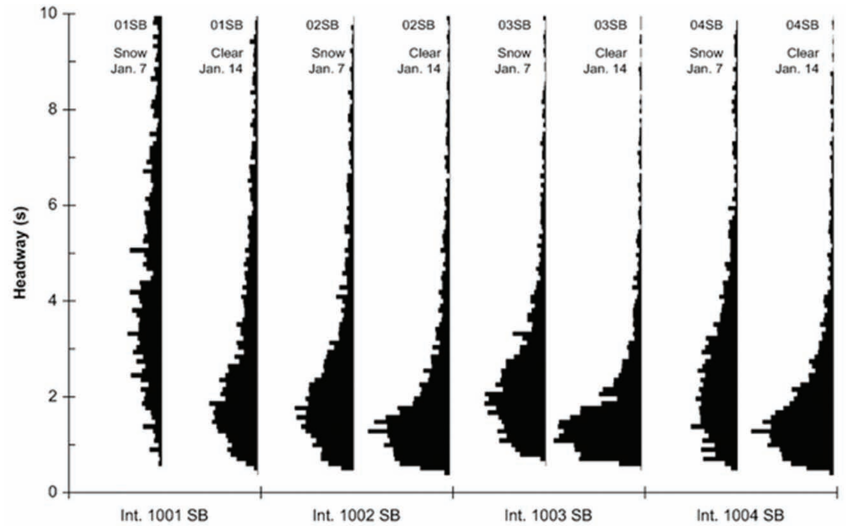


a) Northbound BT-04 to BT-01

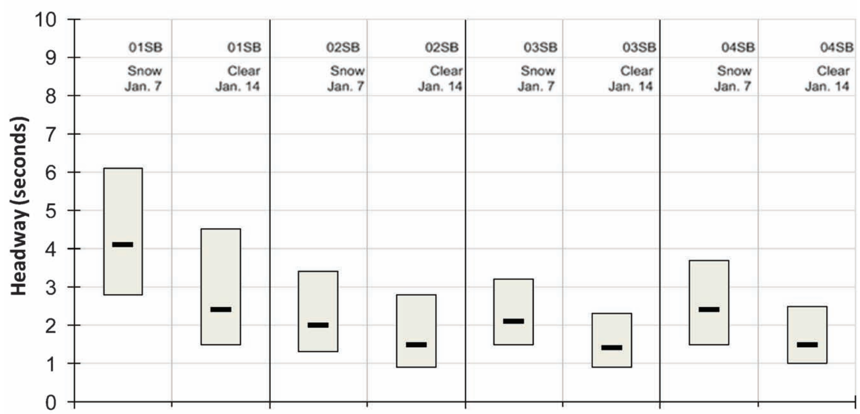


b) Southbound BT-01 to BT-04

Figure 3.22 Box-plot distributions (indicating the 25th, 50th, and 75th percentiles) of vehicle travel times on SR 37 *(6)*.

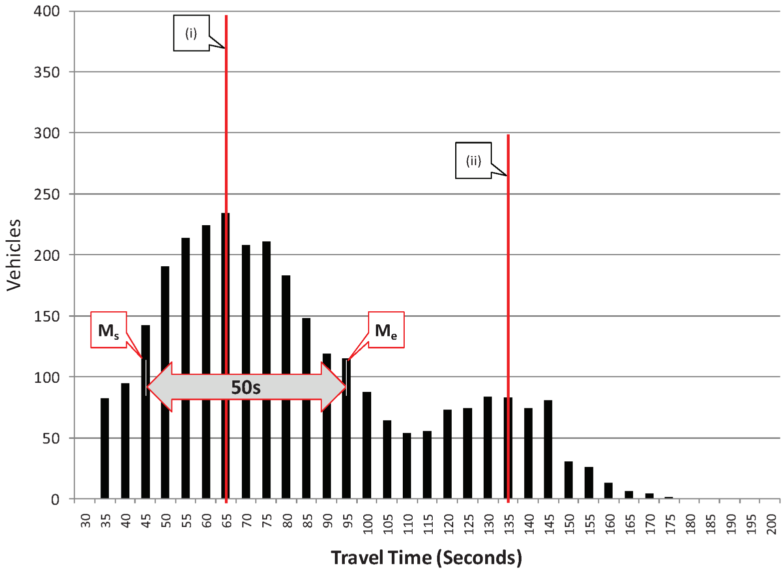


a) Aggregate southbound AM Peak 06:00–09:00 approach headways.

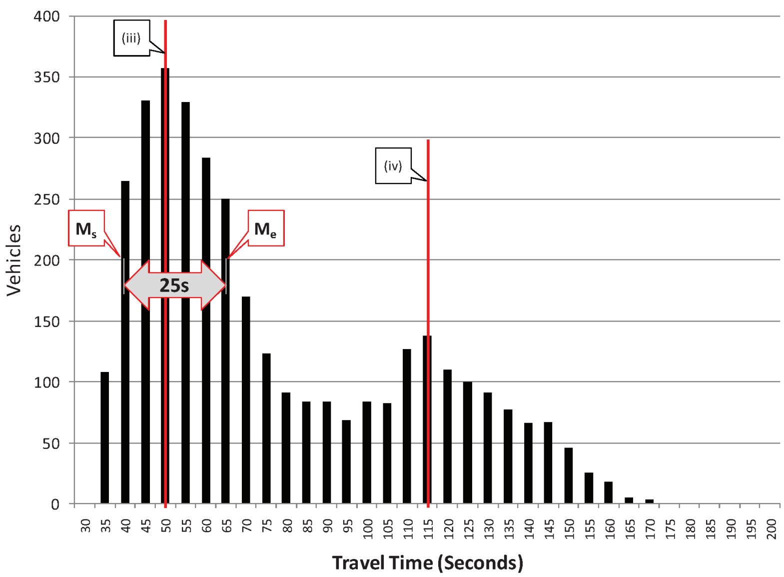


b) 25th, 50th, and 75th quartile box-plot distribution of AM Peak 06:00–09:00 approach headways (above 10 seconds).

Figure 3.23 Southbound SR 37 approach headways during Thursday snow (7-Jan. 2010) and clear weather (14-Jan. 2010) conditions *(6)*.

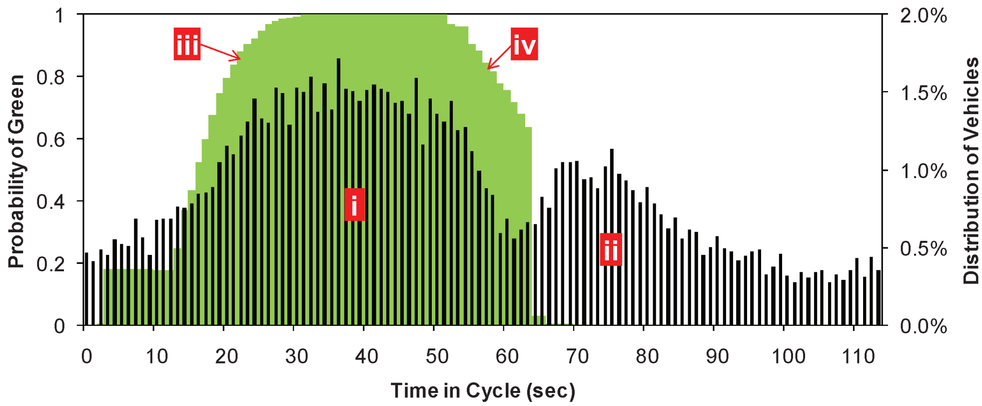


a) Southbound arrival time at I-02 SB Detector referenced to I-01 SB BOG, AM Peak 06:00–09:00 (snow event on Thursday 7-Jan. 2010).

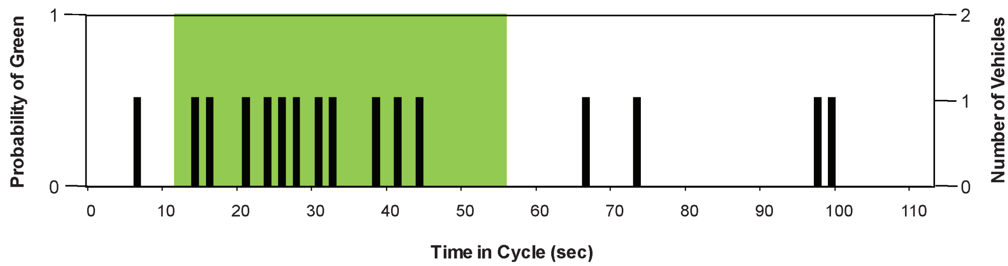


b) Southbound arrival time at I-02 SB Detector referenced to I-01 SB BOG, AM Peak 06:00–09:00 (clear weather on Thursday 14-Jan. 2010).

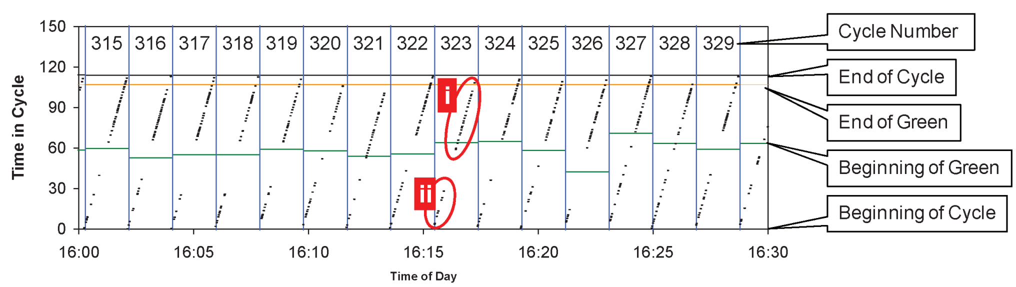
Figure 3.24 Observed platoon shift and dispersion at I-02 under snow and clear conditions *(6)*.



(a) Coordination profile for 504 cycles.



(b) Coordination profile for one cycle.



(c) PCDs depiction of arrivals over several cycles.

Figure 3.25 Components of the PCD introduced as an extension of coordination profiles *(6)*.

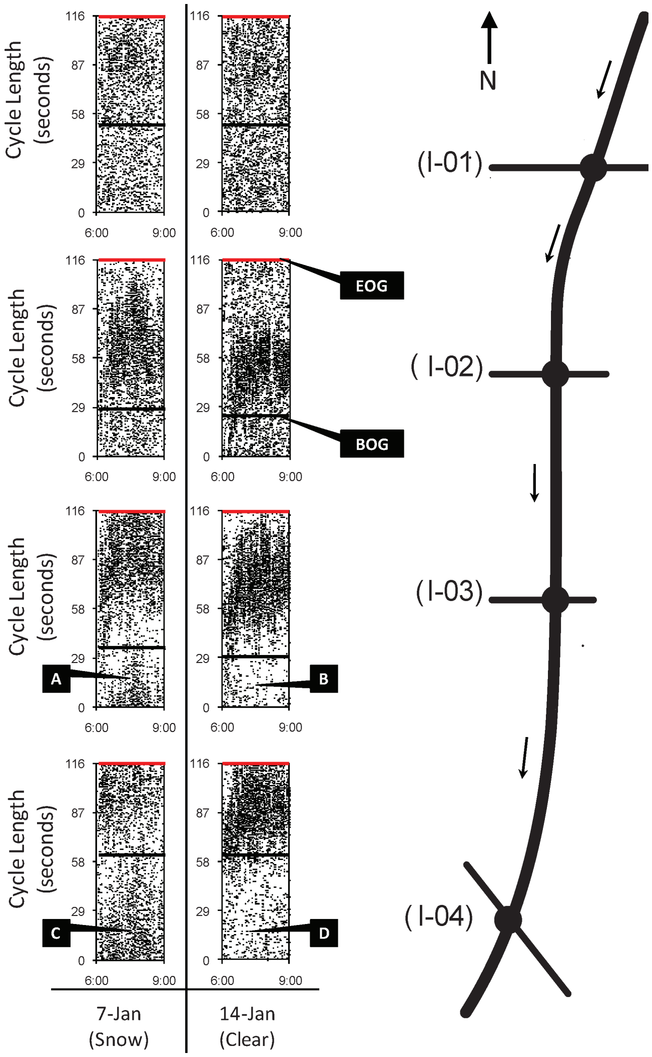


Figure 3.26 PCD comparison of AM Peak 06:00–09:00 during Thursday snow (7-Jan. 2010) and clear weather (14-Jan. 2010) conditions *(6)*.

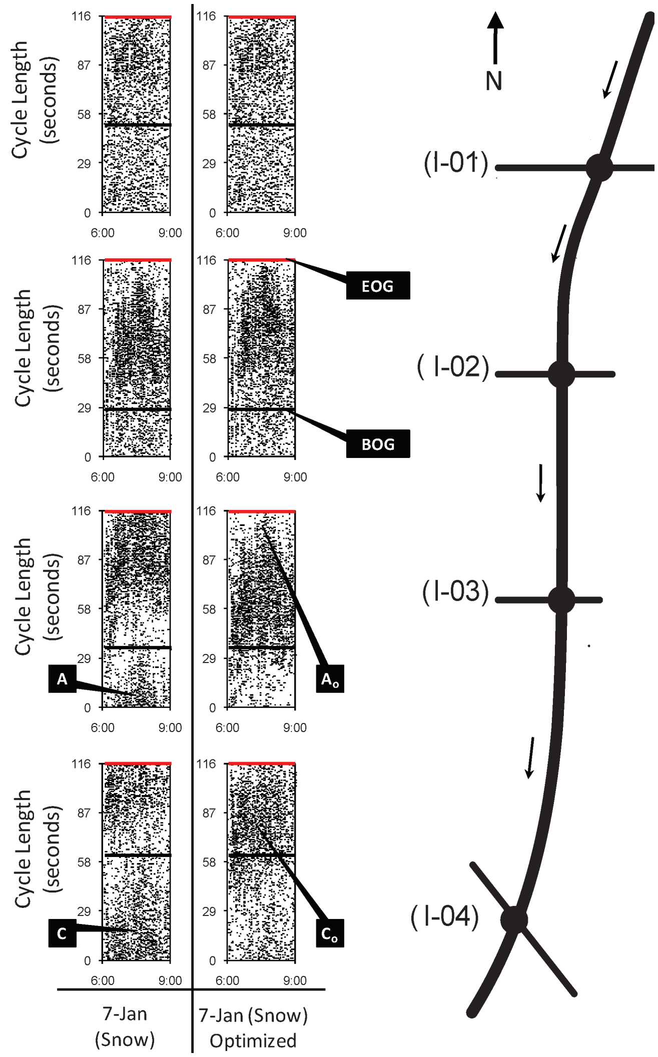


Figure 3.27 Comparison of southbound SR 37 PCDs for normal offset times and proposed optimal offsets to minimize delay for AM Peak 06:00–09:00 during Thursday snow (7-Jan. 2010) conditions *(6)*.

on red (callout "C"). From these graphs, it is apparent that there are opportunities to adjust the coordinated signal offsets times to promote platoon arrivals on green and thus improve coordination during a snow event. The results of the optimization procedure are shown in Figure 3.27. The left column here represents the observed conditions during the snow event, while the right column shows the predicted platoon arrivals if the optimal offsets (southbound only) were implemented.

There is a considerable opportunity to reduce delay by adjusting offsets to move vehicle arrivals to the beginning of green rather than the end of green. For example, delay is minimized at I-03 by shifting the platoon arrival (Figure 3.27, callout "A") to an earlier part of the cycle (Figure 3.27, callout "Ao"). These potential improvements, which amount to a possible 26.7% decrease (3.0 seconds per vehicle) in overall corridor delay for the southbound direction, as explained in more detail in Appendix G. The greatest opportunity to reduce delay in the southbound direction was found at I-04, where a reduction of 9.8 seconds per vehicle could be achieved. When analyzing the overall corridor system delay, the results indicate a potential 22.1% reduction in total vehicle delay, if offsets are optimized for the southbound direction, or a 23.1% reduction in delay if offsets are optimized for both southbound and northbound directions.

Full details may be found in the attached reprint in Appendix G.

4. CONCURRENT ARTERIAL TRAVEL TIME STUDIES

During the course of SPR-3410, several studies on traffic signal performance measures were undertaken at Purdue University in which signal timing improvements were studied. To evaluate the impacts of those changes, the monitoring equipment organized under SPR-3410 was deployed to measure arterial travel times. This section briefly reviews those results.

The first study of this type was organized in June-July 2009 as part of NCHRP 3-79A *(7,8,9)*. Bluetooth cases were deployed on a section of SR 37 spanning four intersections as shown in Figure 4.1. The PCD progression visualization method, explained earlier in Figure 3.25, was used in conjunction with associated performance measures to predict the impacts of changes to the signal offsets. The offsets for Saturdays were optimized using a heuristic search. Figure 4.2 shows the impact on the Saturday travel times, with Figure 4.2(a) indicating the longer travel times on Saturdays compared to the well-timed weekday plan, and Figure 4.2(b) showing the reduction in travel time from optimizing the offsets.

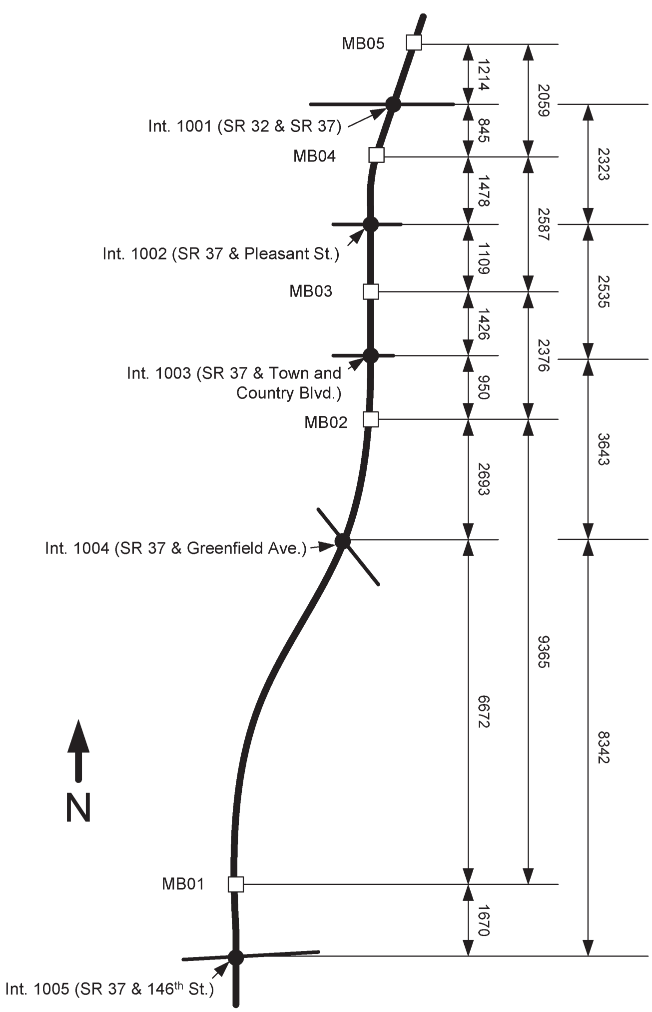


Figure 4.1 Map of the SR 37 Corridor showing midblock and intersection Bluetooth data collection equipment, as deployed in 2009.

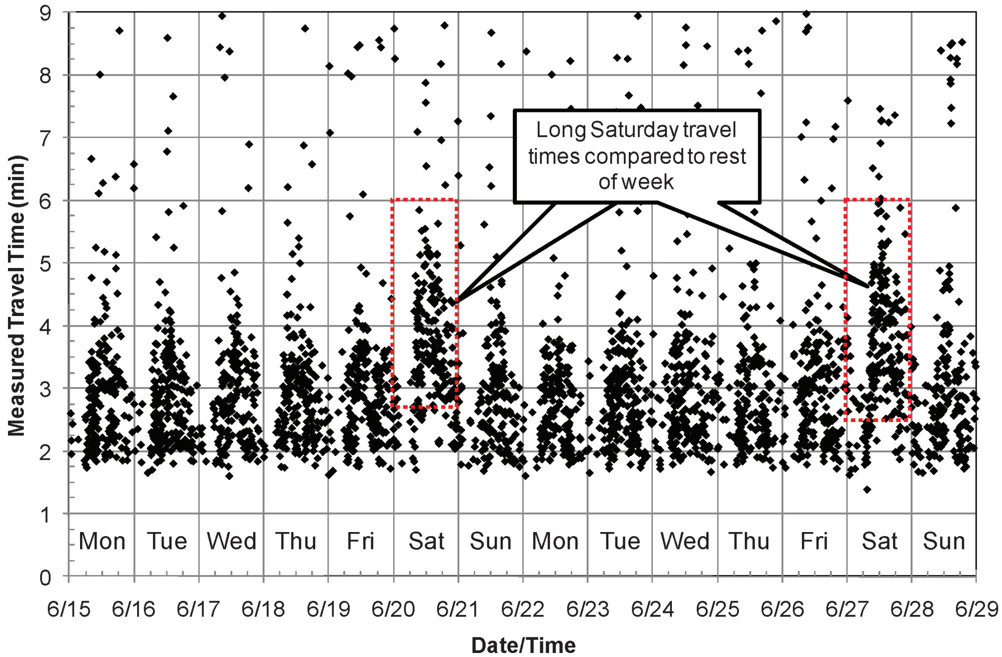
Figure 4.3 shows CFDs of the travel times for the northbound and southbound through vehicles on this section as measured with temporary Bluetooth cases at midblock locations (Figure 4.3[a], Figure 4.3[b]) and at semi-permanent stations established at the signal cabinets (Figure 4.3[c], Figure 4.3[d]). Midblock stations provided a more accurate measure of the travel time, and about a 1 minute savings in both directions was observed. The intersection stations show the 1-minute saving in the northbound direction, since that was attributed to improvements at the two intersections in the middle of the section, but they do not show the 1-minute improvement in southbound travel time that could be attributed to improvements at the southern endpoint where the vehicle ID matches were made. These findings show that intersection-based monitoring stations, while convenient to set up because of the availability of power at signal cabinets, are unable to see the impacts of signal operations at their local intersection.

In 2010, as part of SPR-3209, offsets were optimized again on SR 37 *(10,11)*, this time for eight intersections spanning the entire coordinated section north of I-69, as shown in Figure 4.4. As before, offsets for Saturday operations were optimized, using more formal optimization techniques *(19)*, and with four alternative optimization objectives tested during different weeks of the study. The results are shown in Figure 4.5, which shows CFDs for travel times in the southbound and northbound directions for the entire arterial (Figure 4.5[a], Figure 4.5[b]), the northern section (Figure 4.5[c], Figure 4.5[d]), and the southern section (Figure 4.5[e], Figure 4.5[f]). The four series in these plots correspond to the following alternative objectives:

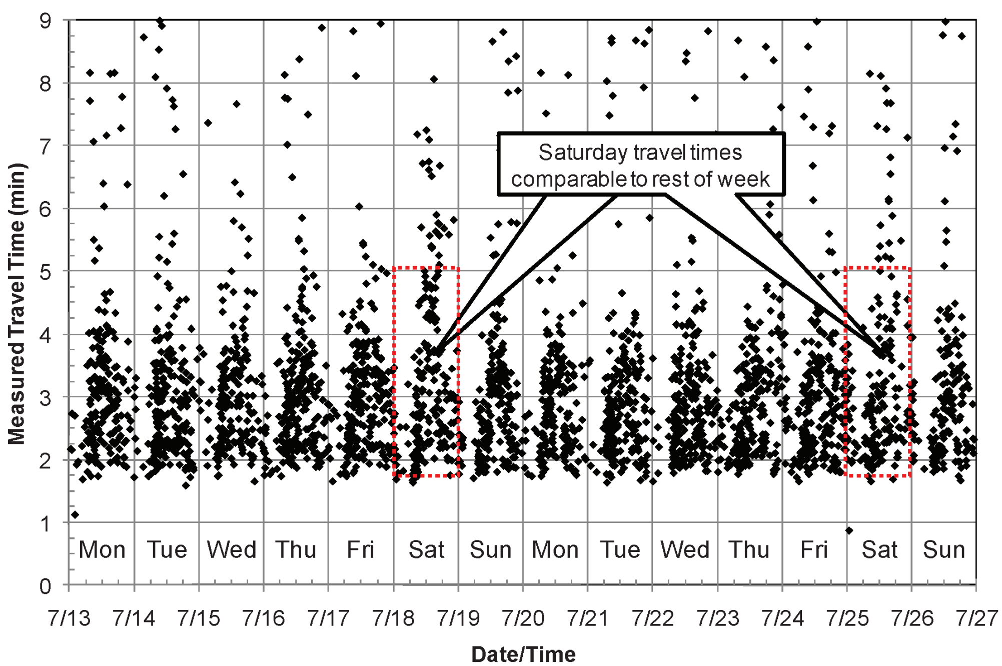
I. Minimize delay.
II. Minimize delay and stops.
III. Maximize arrivals on green.
IV. Maximize arrivals on green with queue clearance time.

As illustrated in Figure 4.5, there was generally little difference between the four different objectives compared to the baseline. That is, satisfactory operation was achieved using any of the four tested objectives. Not surprisingly, the largest improvements were observed in the southern section, which had not been included in the prior year's optimization activities. Improvements were also achieved for northbound vehicles on the northern section. Based on the travel time measurements, the overall value of the retiming activity was estimated at approximately $500,000 over a year *(10)*.

Concurrent with the 2010 data collection activity for the retiming study, travel times were also measured to estimate the impact of coordinating the 22:00–24:00 time period on Saturdays, which had previously

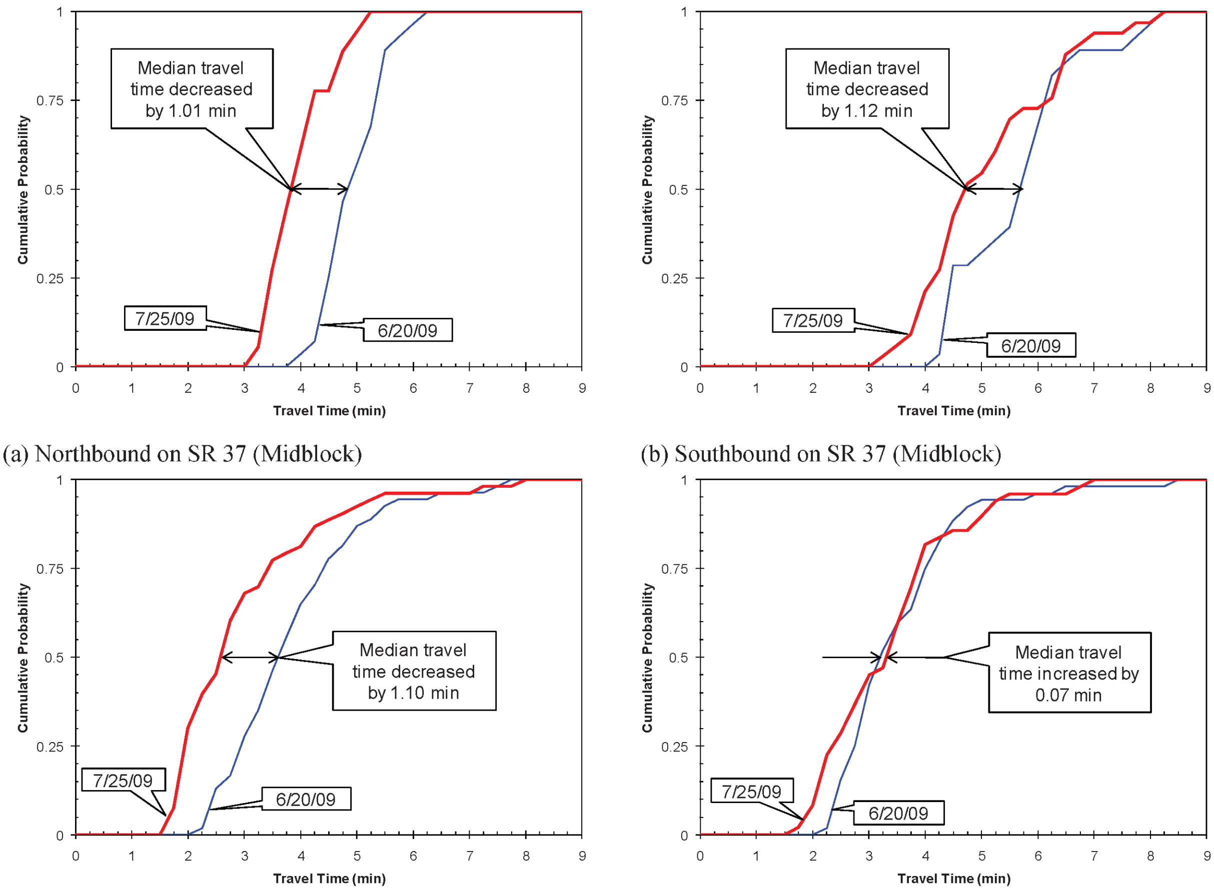


(a) Before offset adjustment (N = 4797).



(b) After offset adjustment (N = 5401).

Figure 4.2 Northbound travel times along SR 37 (from Int. 1004 to Int. 1001).



(a) Northbound on SR 37 (Midblock)

(b) Southbound on SR 37 (Midblock)

(c) Northbound on SR 37 (Intersection)

(d) Southbound on SR 37 (Intersection)

Figure 4.3 Saturday (09:00–13:00) travel time cumulative distribution functions.

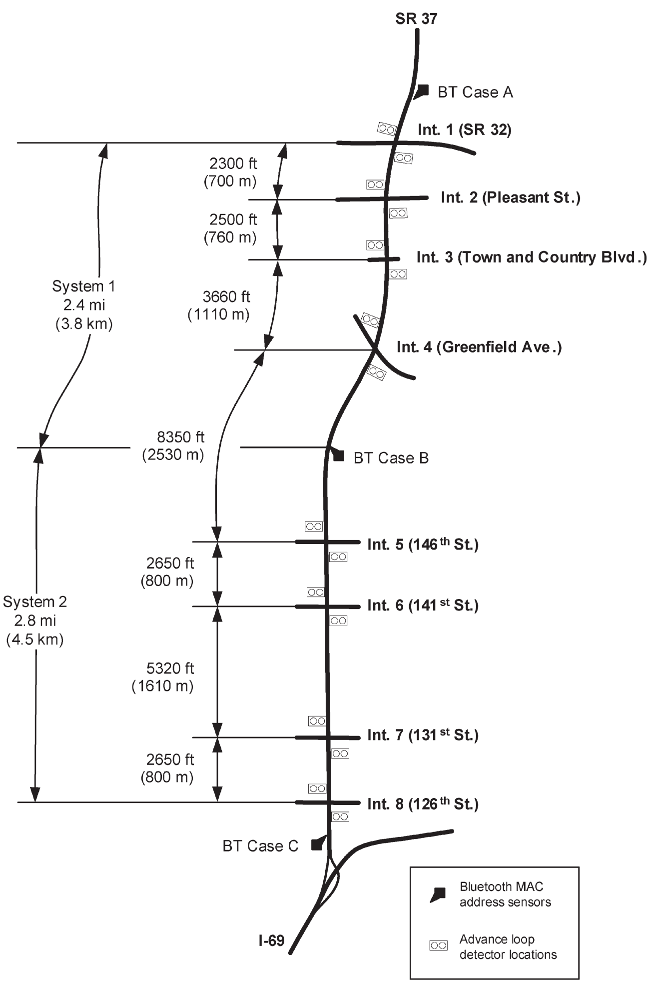
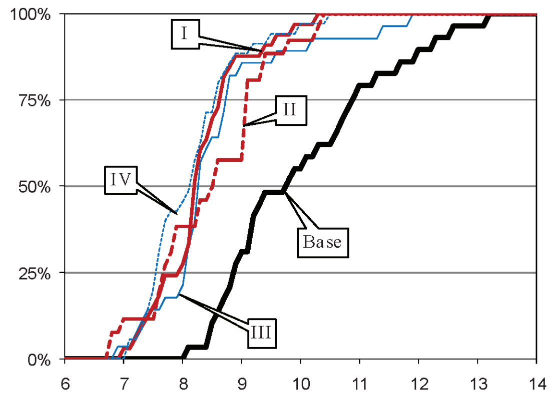
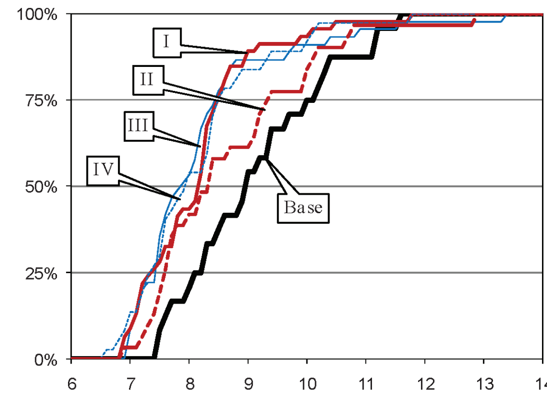


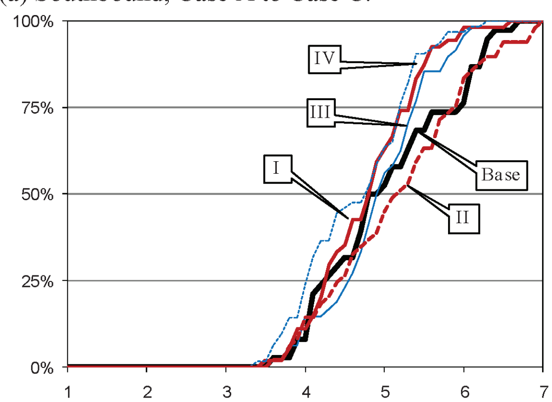
Figure 4.4 Map of the SR 37 Corridor (with equipment as of May 2010).



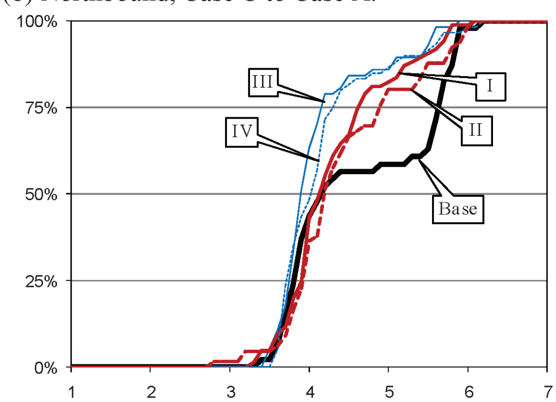
(a) Southbound, Case A to Case C.



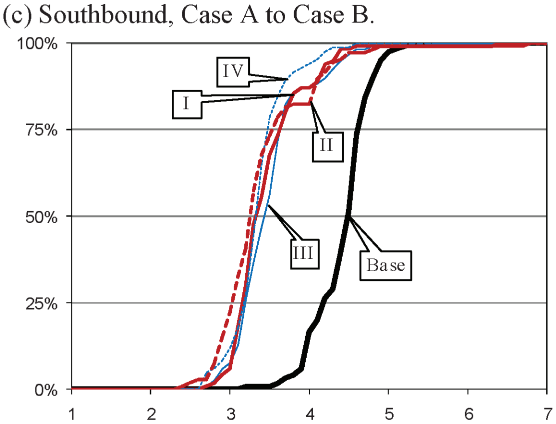
(b) Northbound, Case C to Case A.



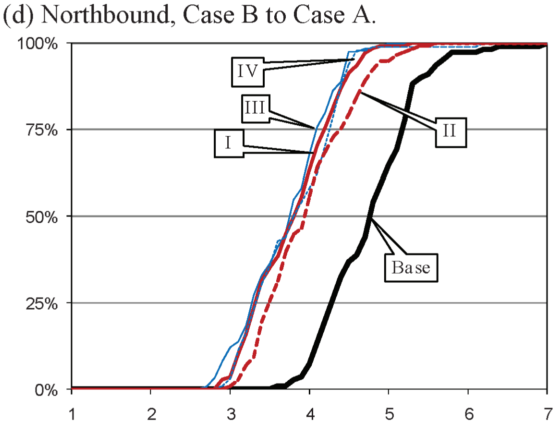
(c) Southbound, Case A to Case B.



(d) Northbound, Case B to Case A.



(e) Southbound, Case B to Case C.



(f) Northbound, Case C to Case B.

Figure 4.5 Cumulative frequency diagrams of probe vehicle travel times for alternative objective functions, Saturday, 15:00–18:00.

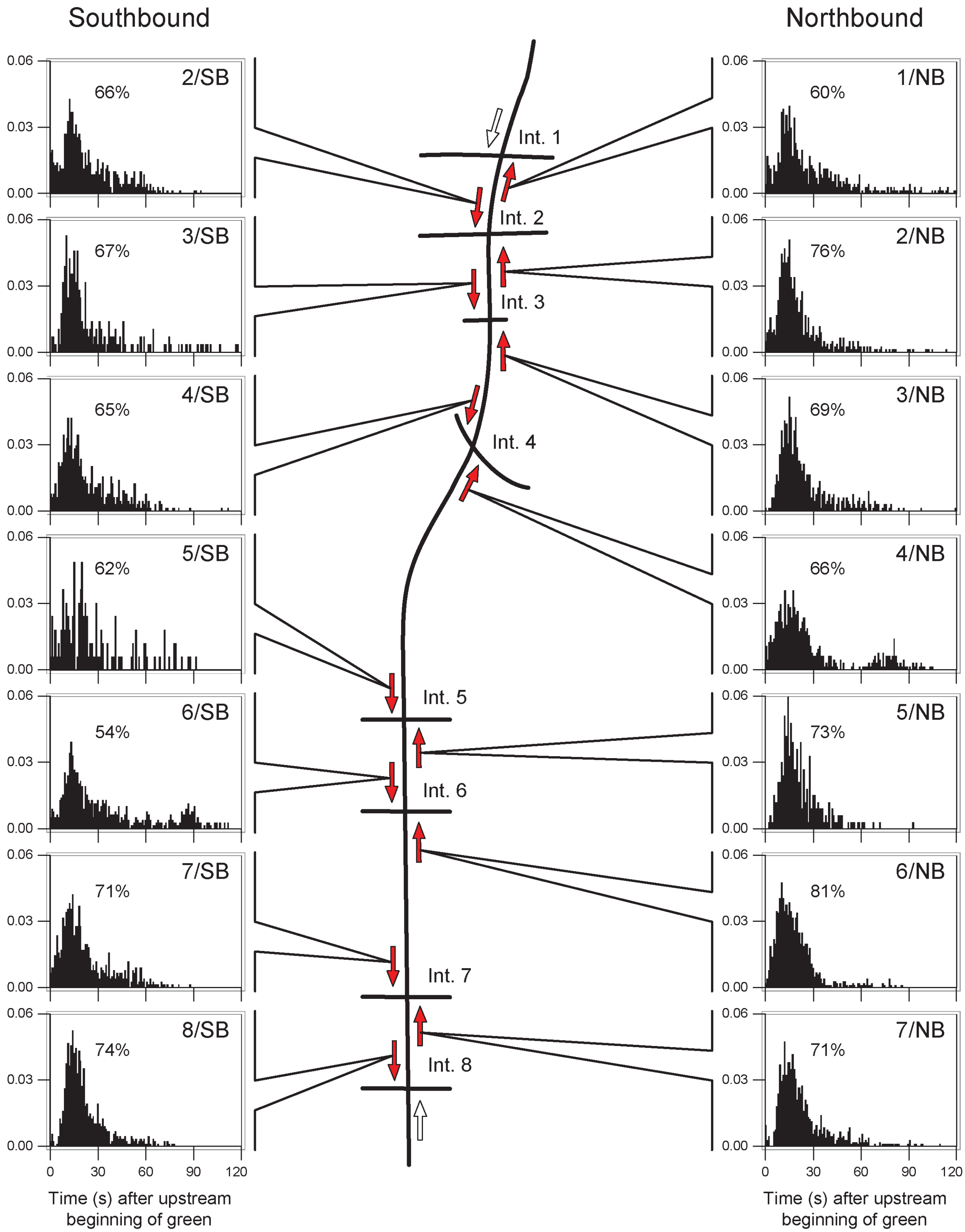
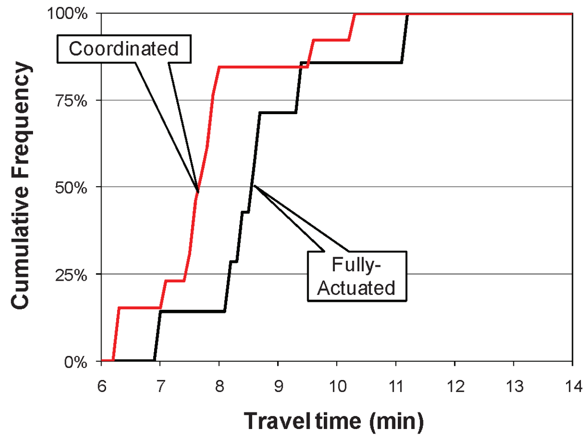
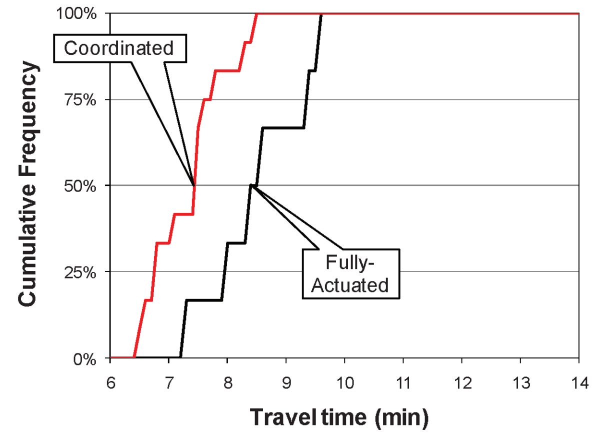


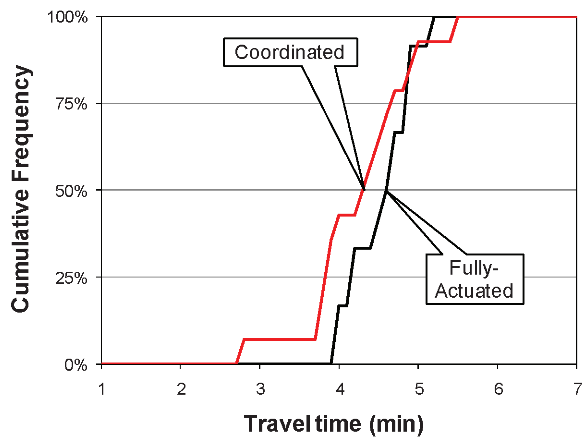
Figure 4.6 Platoon profiles on SR 37 measured during fully actuated, non-coordinated operation by linking downstream arrivals to the upstream beginning of green (adjusted for travel time to the downstream intersection). The numbers show the percentages of vehicles arriving in the first 25 seconds of the distributions.



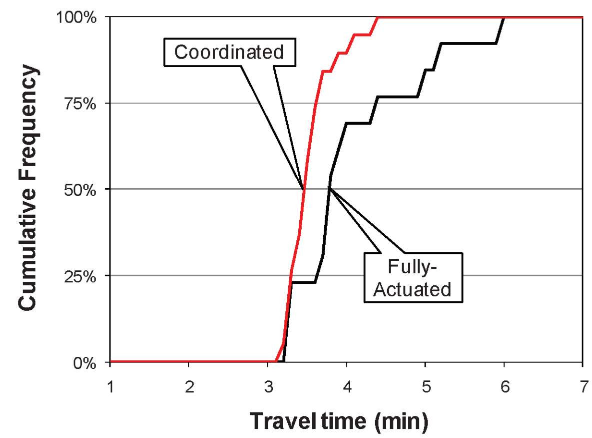
(a) Southbound, Case A to Case C.



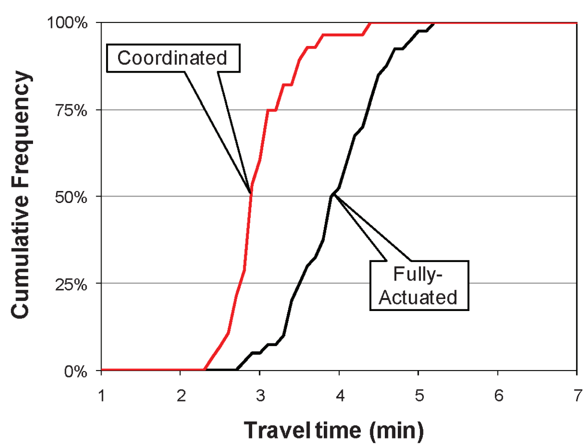
(b) Northbound, Case C to Case A.



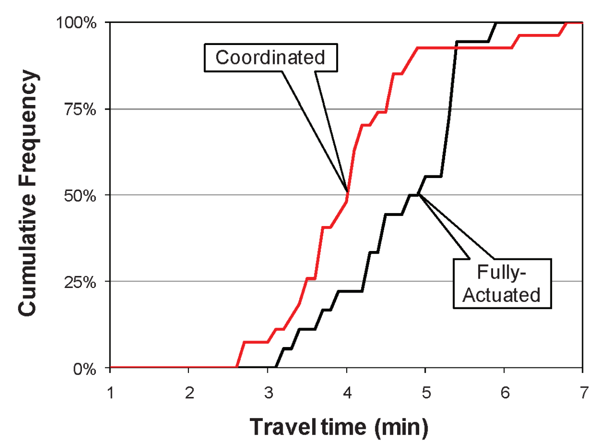
(c) Southbound, Case A to Case B.



(d) Northbound, Case B to Case A.



(e) Southbound, Case B to Case C.



(f) Northbound, Case C to Case B.

Figure 4.7 Cumulative frequency diagrams of probe vehicle travel time (minutes).

operated as fully-actuated and not coordinated. The presence of platoons was observed using the methodology illustrated in Figure 3.24. That is, by linking downstream vehicle arrivals with the upstream beginning of green, it was possible to observe aggregated platoon profiles in a traffic stream even without a fixed signal cycle. These platoons are illustrated in Figure 4.6. Based on the evidence of significant platoons during the 22:00–24:00 time period, the decision was made to extend the coordination pattern to include these hours. The resulting impact on measured arterial travel times is shown in Figure 4.7. These plots reflect measurements at the case deployment configuration shown in Figure 4.4. Overall travel times on the corridor were improved by approximately 1 minute in both directions, with most of the improvement occurring in the southern section.

These studies demonstrated the effectiveness of vehicle reidentification technologies such as Bluetooth MAC address matching at characterizing travel times on signalized corridors. The impact of signal coordination parameters, such as offsets in traditional control, are clearly demonstrated in the results from travel time measurements. The effects of implementing coordination during off-peak hours on arterial travel time were also demonstrated. The use of the MAC address matching methodology developed in SPR-3410 greatly improved the quality of the results in these papers, which would otherwise have relied upon other less accurate estimates of performance. The lessons learned in these studies continue to inform current research on extending travel time monitoring techniques to signalized arterials.

5. CONCLUSION AND SUMMARY OF IMPACT

This report has summarized the results of SPR-3410 and the use of probe vehicle data generated by matching vehicle IDs using Bluetooth MAC address sensing technology. Research findings improving the methodology were documented, including the queries used to derive travel time information from the raw data (Appendix A), and a study into the impact of sensor design, specifically the vertical clearance of sensor antennas, on detection efficiency (Appendix B). The remainder of the report is dedicated to numerous case studies where travel time data was deployed:

- The impacts of traffic management activities during a special event were measured using travel time data (Appendix C).
- Delays due to road construction were measured, as well as the prevalence of motorist usage of detour routes (Appendix D).
- Motorist response to a work zone speed enforcement blitz was documented, demonstrating the effectiveness of enforcement at controlling speeds during the period of visible enforcement (Appendix E).
- Motorist routing choices during an unexpected bridge closure were measured using vehicle reidentification data (Appendix F).
- The impacts of winter weather on signalized arterial operations were measured (Appendix G).

Perhaps the most important contribution of SPR-3410 is that outcome assessment, based upon observed changes in corridor probe data, has become a widely accepted, day-to-day practice by INDOT operations engineers.

Additionally, the lessons learned from numerous field studies making use of this data have been documented in several research papers that have contributed to the state of the practice on a national scale. These results have been very timely in light of the proliferation of probe vehicle based monitoring techniques throughout the country, and the rapid growth of numerous companies now selling travel time data based on numerous monitoring technologies.

APPENDIX A. DATABASE ARCHITECTURE AND QUERY STRUCTURES FOR PROBE DATA PROCESSING

Wasson, J. S. and D. M. Bullock. "Database Architecture and Query Structures for Probe Data Processing." Working paper, January 12, 2012. http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=1&article=2994&context=jtrp&type=additional

APPENDIX B. INFLUENCE OF VERTICAL SENSOR PLACEMENT ON DATA COLLECTION EFFICIENCY FROM BLUETOOTH MAC ADDRESS COLLECTION DEVICES

Brennan, T. M., J. M. Ernst, C. M. Day, D. M. Bullock, J. V. Krogmeier, and M. Martchouk. Influence of Vertical Sensor Placement on Data Collection Efficiency from Bluetooth MAC Address Collection. *Journal of Transportation Engineering*, Vol. 136, No. 12, December 2010, pp. 1104–1109.

DOI: 10.1061/(ASCE)TE.1943-5436.0000178

APPENDIX C. EVALUATION OF SPECIAL EVENT TRAFFIC MANAGEMENT: THE BRICKYARD 400 CASE STUDY

Wasson, J. S., S. E. Young, J. R. Sturdevant, P. J. Tarnoff, J. M. Ernst, and D. M. Bullock. Evaluation of Special Event Traffic Management: The Brickyard 400 Case Study. *JTRP: Other Publications and Reports,* Paper No. 4, 2008.

DOI: 10.5703/1288284314655

APPENDIX D. REAL TIME MEASUREMENT OF WORK ZONE TRAVEL TIME DELAY AND EVALUATION METRICS USING BLUETOOTH PROBE TRACKING

Haseman, R. J., J. S. Wasson, and D. M. Bullock. Real Time Measurement of Work Zone Travel Time Delay and Evaluation Metrics Using Bluetooth Probe Tracking. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2169, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 40–53.

DOI: 10.3141/2169-05

APPENDIX E. EVALUATION OF SPATIAL AND TEMPORAL SPEED LIMIT COMPLIANCE IN HIGHWAY WORKZONES

Wasson, J. S., G. W. Boruff, A. M. Hainen, S. M. Remias, E. A. Hulme, G. Farnsworth, and D. M. Bullock. Evaluation of Spatial and Temporal Speed Limit Compliance in Highway

Workzones. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2258, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 1–15.
DOI: 10.3141/2258-01

APPENDIX F. A SAMPLING TECHNIQUE FOR ESTIMATING ROUTE CHOICE AND TRAVEL TIME RELIABILITY USING FIELD OBSERVATIONS OF BLUETOOTH PROBE VEHICLES

Hainen, A. M., J. S. Wasson, S. M. L. Hubbard, S. M. Remias, G. D. Farnsworth, and D. M. Bullock. Estimating Route Choice and Travel Time Reliability with Field Observations of Bluetooth Probe Vehicles. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2256, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 43–50.
DOI: 10.3141/2256-06

APPENDIX G. ASSESSING OPPORTUNITIES AND BENEFITS OF ALTERNATIVE WINTER OPERATION TIMING PLANS FOR SIGNALIZED ARTERIALS

Brennan, T., C. M. Day, J. Wasson, J. Sturdevant, and D. M. Bullock. Assessing Opportunities and Benefits of Alternative Winter Operation Timing Plans for Signalized Arterials. *Journal of Transportation of the Institute of Transportation Engineers*, Vol. 1, Issue 1, 2011, pp. 59–76. http://amonline.trb.org/12jgpu/30

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