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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

EVALUATION OF DYNAMIC MESSAGE SIGNS AND THEIR POTENTIAL IMPACT ON TRAFFIC FLOW

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16. Abstract

Maryland State Highway Administration (SHA) has a rich data archive of the messages posted to the Dynamic Message Signs (DMS) and the time stamps when they were posted and taken down. The archive also contains traffic information surrounding the DMS signs, such as traffic volumes and speeds from various point or probe-based sensors. In this project, the research team used this data archive to study the impact of DMS messages on traffic conditions. Multiple Bluetooth sensors were deployed on a major travel corridor in the Baltimore Metropolitan Area to determine vehicle travel times and to monitor traffic diversions.

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Executive Summary

The need to convey accurate travel information to motorists has become increasingly important with the increase in traffic volume and the lack of additional roadway capacity. Knowledge of rapidly changing traffic conditions gives drivers the option to modify their behavior in order to avoid delays and dangerous situations. Highway Dynamic Message Signs (DMS) are often referred to as the most visible form of ITS technology. Installed in conjunction with other technologies of an Advanced Traveler Information System (ATIS), they enhance drivers' knowledge of the highway network. In Maryland, there are more than 80 DMS installed on major Interstates, highways and arterial roads.

The Maryland State Highway Administration's Coordinated Highways Action Response Team (CHART) routinely posts messages on both portable and fixed DMS. While most agree that DMS are a valuable way to reach motorists and convey important information, there has long been speculation that DMS messages may adversely affect traffic conditions. Recent publicity surrounding the new travel time messages on DMS have rekindled this debate. The question remains: Will a message posted onto a DMS adversely affect traffic? If so, do all types and lengths of messages have this potential, or do only certain types and lengths of messages pose a threat? This study attempted to answer this important question.

Another important measure of the value of a DMS message is its credibility. It is vital that travelers believe messages displayed on a DMS are factual and accurately describe roadway conditions. Without consistently valid information, road users will begin to ignore DMS messages. In the case of travel-delay messages, phrases such as "Major Delays," "Heavy Delays," and "Expect Congestion" have been used to describe traffic conditions. The most recent trend has been to post messages containing travel-time estimates. In order to determine the accuracy of such messages, this study examined the traffic conditions under which they were displayed. Specifically, Bluetooth travel-time and route-diversion data were collected for the analysis.

This project took advantage of a data analysis framework equipped with a database capable of importing data from CHART, RITIS and Bluetooth detectors and employing data-mining techniques to perform before-and-after analysis of traffic conditions with respect to a message display. In addition to traffic pattern analysis, the system can visualize data from several sources in accordance with message timelines.

This study also investigated claims that DMS messages have the potential to cause congestion and safety risks. The Remote Traffic Microwave Sensor (RTMS) speed data and logs of DMS messages were collected and analyzed. Messages were categorized into three types based on the ideas proposed by Ridgeway (2003): Danger/Warning (Type 1), Informative/Common Road Conditions (Type 2) and Regulatory/Non-Traffic-Related (Type 3). The primary analysis consisted of examining the effect of message display (off-on), removal (on-off), and switching

(between any two types of messages) on traffic speeds over two consecutive five-minute periods. In all three cases, the speeds in the first five minutes were compared to the speeds in the following five minutes via paired *t*-tests. Overall, 2,268 cases were identified and examined. The results showed that when messages were displayed (off-on), users slowed down most often in response to Type 1 messages, followed by Type 2, and then Type 3. It can be speculated that the higher incidence of slow-downs in response to Type 1 messages may be because of the low frequency with which they were displayed or the conditions that caused the message to be displayed. The average decrease in speed over all off-on cases was -3.13 mph; decreases occurred in 17.1 % of cases. Speeds increased or were unaffected in 82.9% of cases. Also, DMS displaying travel time messages did not show a higher propensity for slow-downs than DMS displaying other types of messages. The on-off analysis indicated that average speeds increased more often than they decreased in response to message removal. When broken down by message type, no clear pattern was observed. Under message-switching condition, average traffic speeds increased as often as they decreased. The overall findings from the before-after analysis indicate traffic is unaffected by message appearance, removal or switching in the majority of cases, with the remaining cases representing relatively small effects on traffic speeds.

The secondary analysis examined average speeds over 12 two-week periods to determine aggregate effects of message display on traffic speeds. Type 1 messages have the largest effect on average traffic speeds. Type 2 messages at most result in average speeds 4 mph below the overall average during periods with no messages. In only three cases did this reduction represent an average speed below the posted speed limit, and only one of these had a corresponding overall average speed above the speed limit. Type 3 messages had the smallest negative impact on average speeds. In most cases, average speeds were higher during these messages than during times of no messages. The results of this study indicate that DMS message display is not likely to cause congestion. It is important to note that speed changes observed in this study cannot be wholly attributed to DMS because there are many other factors unaccounted for, such as weather.

The research team also evaluated localized safety impacts of highway DMS. The accident data from 2007 to 2010 served as the baseline for analyses of traffic collisions in Maryland. The accident data, DMS locations and Annual Average Daily Traffic (AADT) database are projected onto Maryland roadway map in ArcGIS 10.1. In order to perform spot analysis to evaluate whether DMS influenced drivers' operational performance, an impact area of 900 feet was defined for each DMS based on the maximum visibility distance for the average font size on electronic signs. The accident database included 38,718 records, which were filtered, cleaned and purged of data gaps and outliers. After data processing, the number of accidents considered decreased to 23,842 for the four-year study period. The accident database consisted of accident type (property damage, personal injury, and fatality), accident location and county, time and date of the accident and coordinates of accident location. Due to confidentiality concerns, access to police records and accident causes was not possible.

As a part of this project, a case study was performed on Interstate 95 in Maryland. A sample of 70 road segments was chosen based on geometrical homogeneity. Regression analysis was performed based on whether the segment was an impact area or not, if the segment included interchanges or not and what the AADT of the segment was. An unbalanced two-way ANOVA was used to compare mean accident rate in impact areas and other segments. To determine the effects of DMS messages on the rate of accidents, accident rates in DMS impact areas and adjacent segments were compared using paired *t*-tests. The difference in accident rates was tested on two DMS operation statuses (when they displayed messages and when they were blank), using a one-way ANOVA with a pairwise comparison test. Statistical analyses on DMS characteristics, message types, weather conditions and accidents in impact area were performed.

The statistical analyses of accidents in conjunction with weather conditions showed that there were only four accidents in all impact areas that occurred in rainy and snowy conditions. Thirty-two out of 43 accidents were in wind gusts of 0-10 mph, nine were in wind gusts of 10-20 mph, and two were in wind gusts of 20-30 mph.

Additionally, among 50 accidents in DMS impact areas and impact-adjacent areas, 35 collisions were classified as property damage and 15 as personal injury. Analyses on displayed messages showed 11 accidents occurred while Danger/Warning messages were displayed on DMS, 22 occurred during displays of Informative/Common Road Condition messages, and 11 during displays of Regulatory/Non-Traffic-Related messages. Although there are some concerns that Danger/Warning messages cause drivers to slow down, the least number of accidents in DMS impact areas and impact-adjacent areas occurred during the period when Danger/Warning messages were displayed. The findings from all evaluations converge to indicate DMS are a safe tool for disseminating real-time travel information to motorists and do not have significant adverse effects on driver's operation and traffic safety.

In summary, the findings from these evaluations indicate DMS can be an accurate, effective, and safe tool for disseminating real-time travel information to motorists. This research focused on Maryland DMS, so the findings may not extend to DMS operations in other states. Nevertheless, the methodology for evaluating data is applicable beyond Maryland's borders.

This report has been prepared in two volumes. The first volume includes methodology and results of an empirical analysis of the quality, effectiveness and localized impacts of DMS. The second volume covers GIS data processing efforts for mapping accidents and weather data, and the statistical analysis of DMS' impact on accident occurrence.

STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

EVALUATION OF DYNAMIC MESSAGE SIGNS AND THEIR POTENTIAL IMPACT ON TRAFFIC FLOW

Volume I: Empirical Analysis of the Quality, Effectiveness, and Localized Impacts of Highway Dynamic Message Sign Messages

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Abstract

The need to convey accurate, real-time travel information to road users has long been recognized by transportation engineers. One of the primary means to accomplish this is the operation of highway Dynamic Message Signs (DMS), which have been in use for more than 50 years. However, the quality of messages used, the extent of their influence on motorists' behavior and their localized impacts are not well documented. This project introduced Bluetooth traffic detection sensors as a new tool to evaluate the quality of DMS messages and their resulting influence on motorists' route choices. In addition, highway speed sensors were used to determine whether DMS affected traffic speeds. Results indicate DMS messages are accurate in communicating prevailing conditions and can influence drivers' route choices. Speed analyses indicated certain types of messages exert greater influence on traffic patterns than others. Additionally, the majority of message types do not negatively affect traffic speeds.

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Chapter 1: Introduction

1.1: Motivation and Background

The need to convey accurate travel information to motorists has become increasingly important with the increase in traffic volume and the lack of additional roadway capacity. Knowledge of rapidly changing traffic conditions gives motorists the option to modify their behavior in order to avoid delays and dangerous situations. Many states, as part of an Advanced Traveler Information System (ATIS), have installed Dynamic Message Signs (DMS) to help provide motorists this information. Also known as Variable Message Signs (VMS) and Changeable Message Signs (CMS), these electronic signs can display various messages that can be specified by a remote operator or updated automatically. Among others benefits, this capability allows roadway administrators to communicate with motorists about accidents, delays, and in some jurisdictions, travel time.

An important measure of the value of a DMS message is its credibility. It is vital that travelers believe messages displayed on a DMS are factual and accurately describe roadway conditions. Without consistently valid information, road users will begin to ignore DMS messages.

The Maryland State Highway Administration's (SHA) Coordinated Highways Action Response Team (CHART) operates nearly 80 DMS. The signs are located on major highways and their arterial roadways. The DMS often inform motorists of delays, incidents, road closings, and recently, real-time travel times. In the case of travel-delay messages, phrases such as "Major Delays," "Heavy Delays" and "Expect Congestion" describe traffic conditions. Ambiguous phrases such as these do little to inspire confidence in the DMS system unless their meanings are easily understood, consistent and appropriate for the given road conditions.

To determine the meaning and accuracy of such messages, the road conditions during which they are displayed are examined. Specifically, Bluetooth travel-time data was collected and analyzed during the display of various DMS on Maryland's I-95 and I-895 corridors. This project presents the first attempts to use Bluetooth ground truth data to determine the timeliness and accuracy of the DMS messages.

Another important aspect of DMS is their effectiveness. DMS messages should accurately inform motorists of road conditions and if necessary, induce changes in motorists' behavior. A good measure of whether or not a message yields such a change is if users divert or change routes during a period in which a message suggests the same. The unique identification and re-identification capability of Bluetooth sensors allows for an estimate of these diversion rates. We compared detection rates between the current and suggested routes during the period of study to determine the effectiveness of DMS messages in influencing motorist behavior.

Although the quality and effectiveness of messages are important for DMS systems, some are concerned that displaying messages causes localized speed reductions and congestion, increasing danger to motorists. To investigate this concern, DMS systems in close proximity to Remote Traffic Monitoring Sensors (RTMS) were identified. The speed data from these detectors is used to analyze any impacts the display of messages had on the traffic streams during their display.

The findings from these analyses should give comprehensive insight into the performance, quality, effectiveness and effects of DMS in Maryland. State officials will be able to apply these findings and methods to analyze and improve their DMS operations.

1.2: Literature Review

The following sections present a summary of literature relevant to the study of DMS. Study of existing publications will give insight into the previous methods, relevant findings and any benefits or shortcomings others encountered.

1.2.1: Message Quality

DMS are a relatively new but frequently changing technology. As such, a unified standard for displaying messages has not yet been developed. The Manual on Uniform Traffic Control Devices (MUTCD) suggests some formatting requirements such as text size and message length, but it does little to address what warrants the display of certain messages.

In order to be effective, a displayed message must contain a combination of the following elements: problem, location, effect, attention and action (1). These components must be combined in a way that conveys enough information to be useful to motorists while fitting within the limited space on a DMS. The MUTCD specifies that a message be readable at least twice while traveling at the posted speed limit (2). This guideline means motorists have approximately 8 seconds at most to read messages on a DMS in normal weather and roadway conditions (3). These restrictions can be complicated by the occurrence of multiple incidents or less-than-optimal weather or roadway conditions.

Several states developed message hierarchies that rank the relative importance of various message categories should a conflict in message choice arise. In general, messages requiring a change in motorists' behavior (e.g., emergencies, incidents and roadway closures) are near the top of such hierarchies *(*1, 4, 5*).* Messages of moderate importance in the rankings tend to be related to congestion, travel time or weather conditions. If none of the previous conditions occur, some jurisdictions display public service or safety messages, whereas others display nothing. The three levels of the hierarchy are termed Danger & Warning Messages, Informative Messages and Regulatory Messages (6).

In jurisdictions where quantitative travel time information is not available, terms such as "Heavy Delay" and "Major Delay" are often used. There is little explanation about how to define or use these terms. However, *Dynamic Message Sign Message Design and Display Manual* reports the average motorist in Texas interprets "Heavy Delay" as being between 25 and 45 minutes, whereas a "Major Delay" is interpreted as a delay greater than 45 minutes (7). Similarly, a study in England to determine driver response to DMS messages found motorists interpreted "Long Delays" as being between 35 and 47 minutes, whereas they perceived "Delays Likely" as indicating a 10 to 31 minute delay (8). The Minnesota Department of Transportation's *Guidelines for Changeable Message Sign (CMS) Use* specifies that "Major Delay" indicates an incident causing more than two miles of traffic backup and not a length of time (4). These conflicting definitions alone demonstrate the need to evaluate how well DMS messages match the conditions during which they are displayed.

Since state transportation agencies introduced travel time messages on DMS, there have been attempts to validate the accuracy of these messages. In Oregon, travel time messages were derived from loop detector data. To validate the displayed travel times, researchers utilized 87 probe vehicles outfitted with GPS devices. Using paired t-tests, the researchers compared what they called the “ground truth” data to the displayed travel times. Using this method, they determined the travel times were accurate in many cases but suffered from deficiencies during incidents or when detectors were placed poorly (9). Researchers in California used probe vehicles to validate the travel times after designing a model using loop detector data to predict and automatically display travel times on DMS. Eighty-eight probe vehicle runs were made on two different roads. The authors found good agreement between travel times and probe data when sufficient data existed. As a result, the authors concluded it is necessary to validate travel times using probe data prior to deploying DMS travel-time messages (10). These studies demonstrate previous attempts to validate DMS travel-time message using data from probe vehicles. Although the collected data were of high quality, neither investigation produced more than 100 data points. This project utilizes Bluetooth travel time collection for the validation of DMS travel times. As a result we were able to collect a large data set, which yields a higher quality analysis.

1.2.2: Driver Response and Diversion

Revealed preference (RP) and stated preference (SP) surveys of drivers have been used in numerous studies to determine the influence DMS have on drivers. A RP survey combined with an ordered logit model suggested that the propensity of drivers to divert due to a DMS message was correlated to how often drivers encountered a

DMS and whether or not they believed DMS contain useful and trustworthy information (11). In Beijing, a SP survey found that diversion increased as the speed of traffic decreased. Specifically, at speeds under 20 km/h (indicated as serious congestion on VMS) 21.45 percent of drivers say they will divert, whereas when traffic is moving between 20-35 km/h (common congestion) a mere 7.02 percent of drivers expect that they would divert (12). Canadian and British drivers were compared in a SP survey to determine perceived effectiveness of DMS information. The survey revealed evidence to suggest more exposure to DMS leads to an increase in appreciation of the information displayed (13). A combined SP and RP survey performed by researchers at the University of California, Berkeley found that en route travelers were not inclined to divert in response to an Advanced Traveler Information System (ATIS) device unless the device specifically recommended such action or provided specific information about delay time on the preferred route (14). Similarly, a SP survey of Borman Expressway drivers in Indiana revealed a strong correlation relating the type of message displayed to the driver response. It was concluded that message content is an “important control variable for improving system performance” (15). As expected, the importance of trust and specific information weigh heavily on the effectiveness of DMS.

Another method of determining effectiveness of DMS is the examination of loop detector data. A study of DMS effects on traffic was performed in the Hampton Roads area of Virginia. In order to assess these effects, loop detector data from two alternative routes were collected and analyzed along with DMS messages displayed regarding travel delays on the routes. The diversion rates found were very low, which the researchers believed were caused by weak messages, unwillingness to divert and distance from the secondary route. A secondary analysis under a new message system found higher diversion rates; however, there was not enough data to make any conclusions (16). In Ontario, Canada, three years of loop detector data were collected along with DMS messages on the highway 401 express collector. The study was interested in finding the response of traffic to a change in DMS message. The study found the initial diversion reaction to a change in DMS message is significant and the occurrence of a message change plays a vital role in influencing downstream diversion (17). Using loop detector and message characteristic data as inputs, researchers in Minnesota estimated a probit model to estimate diversion as a function of message content. Through this method it was determined VMS messages can significantly influence route diversion. Specifically, when warned by a message, users are more likely to divert than if confronted with congestion (18).

Loop detector data analyses have shown DMS can potentially impact diversion. One caveat to these findings is that loop detector data are unable to identify individual vehicles, so their individual paths cannot be determined with certainty.

1.2.3: Speed Impacts

Several researchers investigated the effects of DMS messages on traffic speed using various methods. At the University of Iowa, researchers used a full-size traffic simulator to investigate the dynamics of travelers' speed in response to DMS and other in-vehicle information systems. They found those who saw DMS messages slowed down in the areas the messages correspond to, but once out of range of the message tended to compensate by increasing their speeds (19). A simulation study by researchers in Sweden found all participants reduced their speeds in response to Incident Warning Systems in the simulation (20). Researchers in Finland found drivers reduced speeds 1-2 km/h in response to a DMS warning of slippery conditions (21). A field study of two DMS by researchers in Norway found vehicles showed "large speed reductions." Through video recording, researchers observed "large proportions" of the traffic stream-braking in advance of the DMS (22). To determine the effects of DMS on traffic slowdowns, researchers at the University of Rhode Island used five-minute interval speed data during the nearest periods when messages switched from off to on and from on to off. They found slowdowns occurred in more than half of the cases examined and particularly during cases of danger messages, although not all instances were statistically significant (23).

These findings seem to indicate that DMS may cause localized speed reductions, but examination of more cases and higher quality data would be useful to further understand these patterns.

1.2.4: Summary

The need for DMS to present accurate, timely and useful messages has been recognized since their inception. Many methods have been used to determine whether these needs are being met. Surveys, simulators and loop detector data have been the most common of these methods in the past and have shown promising results. This project presents Bluetooth detection as an emerging method for evaluating DMS. The ability to anonymously identify and re-identify individual vehicles and users to track travel time and diversion was previously unavailable or prohibitively expensive. The method used in this study should provide a higher quality analysis method than previously available. In addition, the use of high quality one-minute interval speed data for analysis of localized effects will provide finer results than previous attempts.

1.3: Scope

This project covers the Bluetooth analysis of two separate DMS case studies on the same segments and an examination of speed data in proximity to six DMS. The Bluetooth case studies consist of data collected in June-July 2009 and March-April 2011. Both deployments were completed on the same segments of I-95 & I-895 for the examination of DMS # 7701 & #7702. In the first deployment, 20 Bluetooth sensors were used; due to technical difficulties, 19 were used for the second. For both deployments, specific message types were selected and analyzed for timeliness and accuracy. For cases that suggested diversions, analysis of diversion rates as represented by Bluetooth detection sampling were performed. Finally, the localized effects of the DMS were studied through analysis of highway speed data. Two specific analyses were undertaken: the first investigates the effects of message display on speed in two consecutive five-minute periods; the second investigates the speeds over several two-week periods.

1.4: Organization

The organization of the report is as follows: Chapter 2 provides a brief review of Bluetooth technology, the specific sensors used in this study and the data that were analyzed. Chapter 3 presents the efforts and results of the quality and effectiveness analyses based on the Bluetooth analysis. Chapter 4 examines the localized speed effects of DMS message display. Finally, Chapter 5 provides conclusions and recommendations for future work.

Chapter 2: Detection Technology and Data

2.1: Bluetooth Technology

The primary data for this study came from Bluetooth device detection. Bluetooth is a short-distance wireless networking protocol found in many modern electronic devices including vehicles, cell phones, laptops and earpieces. Depending on the power rating of the device, transmission distances range from one up to 100 meters. Consumer devices most commonly use class 2 radios, which have a range of approximately 10 meters.

Each Bluetooth device is assigned a unique identifier known as a Machine Access Control (MAC) address. These MAC addresses allow for the management and proper handling of data. When operating, Bluetooth devices continuously transmit their MAC addresses to locate other devices with which to pair and transmit data. This transmission forms the basis for Bluetooth traffic detection technology, as it allows identification and re-identification of individual devices without depriving motorists of their anonymity. The Bluetooth Special Interest Group provides more detailed information about Bluetooth technology.

2.2: Bluetooth Detectors and Data

In order to take advantage of the traffic information that can be obtained using Bluetooth devices, a specialized detector is required. For this study, detectors developed by the University of Maryland were used for data collection. The detectors are considered off-line because they do not transmit collected data in real time. The main components of the detectors include a large battery, antenna, computer board, GPS unit, and a memory card slot (Figure 2.1). The antenna detects Bluetooth MAC addresses from up to 100 meters and stores them and detection times on a memory card. When the sensors were retrieved, the memory cards were removed and the data was downloaded.

Figure 2.1. Bluetooth Detector Internals

The main processing effort consisted of matching MAC addresses from detector to detector and calculating the elapsed time (Figure 2.2). Because the locations of the detectors are known, the distance between them can be calculated. These data were then used to calculate travel times and space mean speeds. A more detailed explanation of Bluetooth travel time detection for freeway segments can be found in (26). Additionally, the specific processing efforts for this project are discussed in Chapter 3.

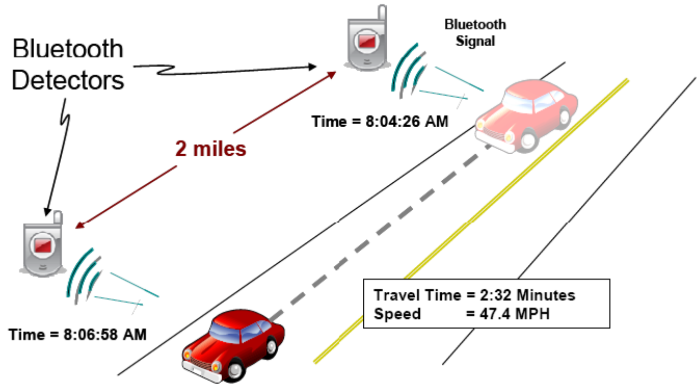


Figure 2.2. Bluetooth Detection Concept of Operation

2.3: Dynamic Message Sign Data

The DMS data used in this study were provided by the Maryland SHA and retrieved through the University of Maryland Center for Advanced Transportation Technology (CATT). Messages are provided in the Markup Language for Transportation Information (MULTI), along with indication of beacon status and timestamps for start and end times. MULTI tags allow users to determine the formatting and the number of lines and panes of messages as they were originally displayed. Using this information, relevant messages could be selected for evaluation based on content and display time. The same message logs were manipulated as described in Chapter 4 in order to assess the impacts of messages on traffic speeds.

2.4: Traffic Speed Data

In order to analyze the localized effects of message display on traffic speeds, high quality speed data were required. The data used to complete this analysis were collected from the Center for Advanced Transportation Technology (CATT) lab and consisted of one-minute interval speed data provided by pole-mounted, side-fired

Remote Traffic Monitoring Sensors (RTMS). In each case, DMS were selected such that the corresponding RTMS was within forward sight distance of the DMS (Figure 2.3).

Figure 2.3. DMS-RTMS Configuration

Chapter 3: Message Quality and Effectiveness

3.1: Deployments and Study Area

The following sections describe the study area, sensor deployment considerations and descriptions of the deployments used.

3.1.1: Study Area

Before deployment of sensors, identification of appropriate locations is required. To maximize the available information from the data, the study area should contain at least one frequently used Dynamic Message Sign. In addition, the roadway should have reasonably high traffic volumes and have available alternate routes and major junctions. For the deployments in this study, sections of Interstate 95 Northbound and its parallel route Interstate 895 were selected (Figure 3.1).

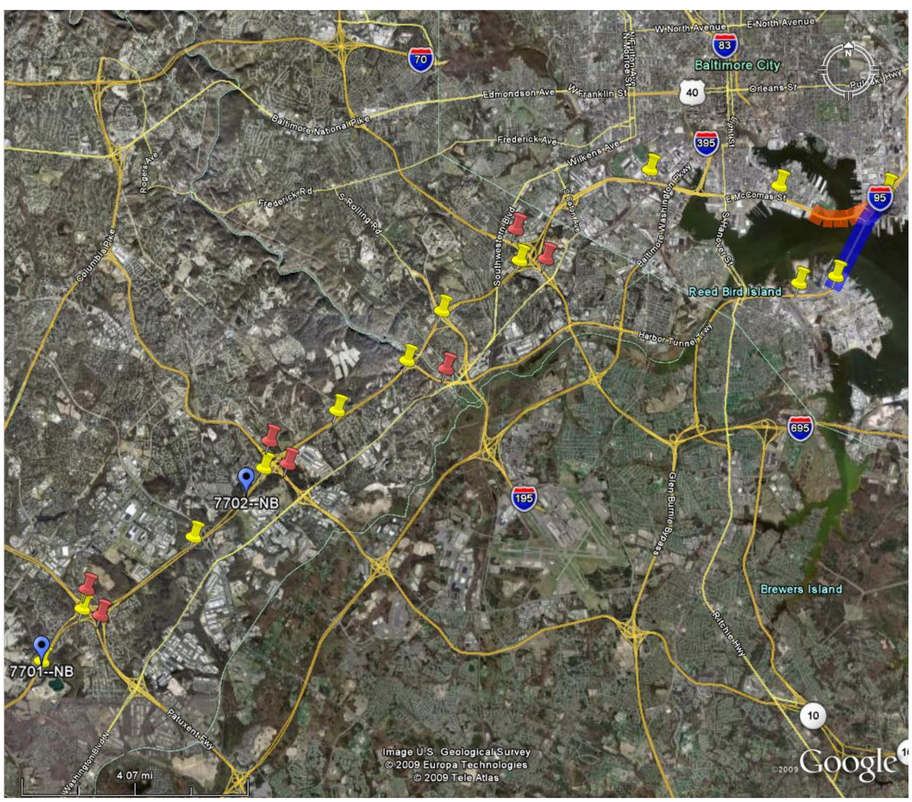


Figure 3.1. Study Area: I-95 and I-895

In Figure 3.1, yellow pins represent Bluetooth sensors deployed for travel time detection, red pins represent Bluetooth sensors deployed for diversion tracking and blue pins represent Dynamic Message Sign locations.

This study area represents a major commuting corridor with three major parallel routes through and around Baltimore (I-95 N, I-895 N, and I-695 E). The DMS selected for evaluation in this area were #7701 and #7702. In the initial deployment, the signs most commonly referenced delays on either I-95 or I-895 and in some cases suggested alternative routes. In the second deployment, the signs adopted real-time travel time information as their primary messages, while displaying delay and other messages as necessary.

3.1.2: Sensor Deployment Considerations

When selecting Bluetooth sensor locations, several factors have to be considered. Primarily, the locations must be in a safe, accessible and secure location. Because the sensors are deployed manually, there must be a shoulder where a vehicle can stop so the operator can safely activate sensors and lock them to a permanent object. The next consideration is the distance between sensors. Due to the 300-foot sensing buffer, an error of up to 600 feet may be encountered. In order to reduce overall errors in travel time and space mean speed, it is desirable to place travel-time detection sensors at least one mile apart. (More information on this error can be found in (26).) Sensors must also be placed on the major diversion routes to detect any vehicles that exit the main road. Therefore, sensors must be placed on diversion routes so they are as close to the main road as possible without being close enough to detect the vehicles on the main road.

3.1.3: Deployment Details

On the morning of June 29, 2009, the deployment team drove to the Maryland Welcome Center rest stop on I-95 N just before the interstate's junction with Maryland Route 32. There, they gave the sensors to an SHA employee and briefed the employee on the deployment plan. The deployment team gave the driver sufficient warning prior to each deployment site in order to allow for safe exiting from the main travel lanes. The Bluetooth sensors were turned on once at their site of deployment. The team waited for the sensor to acquire a GPS signal and then tethered and locked the sensors in position. To supplement the internal GPS, a handheld unit was used to collect latitude and longitude coordinates of the sensor deployments (Figure 3.2).

The UMD team again collaborated with the SHA to retrieve the sensors. On July 7, 2009 around 9 a.m., the deployment crew met with an SHA employee at the same Maryland Welcome Center rest stop. Upon arrival at the sensor locations, the deployment team unlocked the sensors and powered them down, noting any unusual operating conditions (e.g. GPS no longer locked on, powered off prematurely). The Micro SD memory cards were then removed from the sensors and carefully sorted into corresponding cases.

In total, 20 sensors were deployed, each with a corresponding letter from A-T, resulting in 65 links that were designated as virtual Traffic Message Channels (TMCs). For example, I95+XXXAF would represent the link between sensor A and sensor F. These virtual TMCs were later used to match and analyze travel time

Bluetooth Deployment		Proposed		Actual Deployment (6/29/09)				Pick Up (7/7/09)	
Number	Location	Latitude	Longitude	Sensor ID	Actual Latitude	Actual Longitude	Time (AM)	Status	Time (AM)
1	Rest stop prior to DMS #7701 on I-95 N	39.14188433	-76.84554586	AJ	**39°08.570' N**	**76°50.960' W**	9:36	ON	9:55
2	Prior to exit 38B for MD Route 32	39.15477028	-76.82876430	T	**39°09.357' N**	**76°49.890' W**	9:43	ON	9:59
3	MD 32 East off of I-95	39.15046400	-76.82431700	2	**39°08.972' N**	**76°49.423' W**	9:49	ON	10:01
4	MD 32 West off of I-95	39.16308300	-76.83394400	AD	**39°09.753' N**	**76°50.024' W**	9:56	ON	10:07
5	Prior to exit 41B for MD Route 175	39.17542200	-76.79310800	AH	**39°10.341' N**	**76°47.924' W**	10:05	ON	10:15
6	Prior to exit 43A for MD Route 100	39.19247490	-76.77071154	4	**39°11.529' N**	**76°46.291' W**	10:11	ON	10:19
7	MD 100 East off of I-95	39.19192500	-76.76087800	S	**39°11.516' N**	**76°45.653' W**	10:15	ON	10:21
8	MD 100 West off of I-95	39.20278900	-76.77265300	AE	**39°12.134' N**	**76°46.335' W**	10:21	ON	10:27
9	I-95 .5 miles prior to Montgomery Rd	39.20734643	-76.74653437	AG	**39°12.441' N**	**76°44.792' W**	10:28	ON	10:33
10	Prior to exit 46 I-95/I-895 Interchange	39.22034200	-76.72338600	AF	**39°13.220' N**	**76°43.403' W**	10:34	ON	10:36
11	Prior to exits for MD Route 166/I-195	39.23410882	-76.70973274	Q	**39°13.785' N**	**76°42.842' W**	10:39	OFF	10:38
12	Prior to exits for I-695	39.24679896	-76.68531180	1	**39°14.828' N**	**76°41.064' W**	10:44	ON	10:43
13	I-695 East off of I-95	39.24643600	-76.67552200	3	**39°14.675' N**	**76°40.516' W**	10:48	ON	11:02
14	I-695 West off of I-95	39.23822800	-76.68652200	O	**39°15.394' N**	**76°41.568' W**	10:54	ON	10:54
15	Prior to I-95/I-295 Interchange	39.27061100	-76.64474700	AB	**39°16.223' N**	**76°38.578' W**	11:05	ON	11:13
16	Prior to Ft. McHenry Tunnel	39.26612500	-76.59782800	AC	**39°15.953' N**	**76°35.771' W**	11:12	ON	11:18
17	I-895 N .25 miles prior to Washington Blvd	39.21853900	-76.71059400	AM	**39°13.207' N**	**76°42.891' W**	11:54	ON	11:47
18	I-895 N .25 miles prior to Toll	39.24070300	-76.58812200	AL	**39°14.455' N**	**76°35.369' W**	11:30	ON	11:33
19	I-895 after toll, before Tunnel	39.24257800	-76.57896900	AA	**39°14.555' N**	**76°34.378' W**	11:33	ON	11:36
20	I-895 after Harbor Tunnel	39.26500956	-76.56088968	AK	**39°15.921' N**	**76°33.701' W**	11:39	ON	11:26

Figure 3.2. June-July 2009 Deployment-Pickup Locations & Times

data. A total of 893,582 travel time samples were collected. After processing and aggregation by two-minute intervals, 362,901 data points were available for analysis.

In March 2011, more sensors were deployed in a method identical to that used in the 2009 deployment. As in the first deployment, the team met with an SHA employee to transfer and place sensors. Sensors were placed as closely as possible to the locations used in the 2009 deployment in order to make valid comparisons and to simplify post processing (Figure 3.4). Unfortunately, one of the sensors malfunctioned prior to deployment and was not used in the 2011 deployments as a result. Therefore, only 19 sensors were deployed in the 2011 data collection. The sensors were retrieved on April 12, 2011, 14 days after their March 29 deployment. The omitted sensor corresponded to only one missing virtual TMC. This allowed for a total of 64 virtual TMCs. A sketch of sensor placements for both deployments was produced for conceptualization purposes (Figure 3.3). For the second deployment, sensor N was not used.

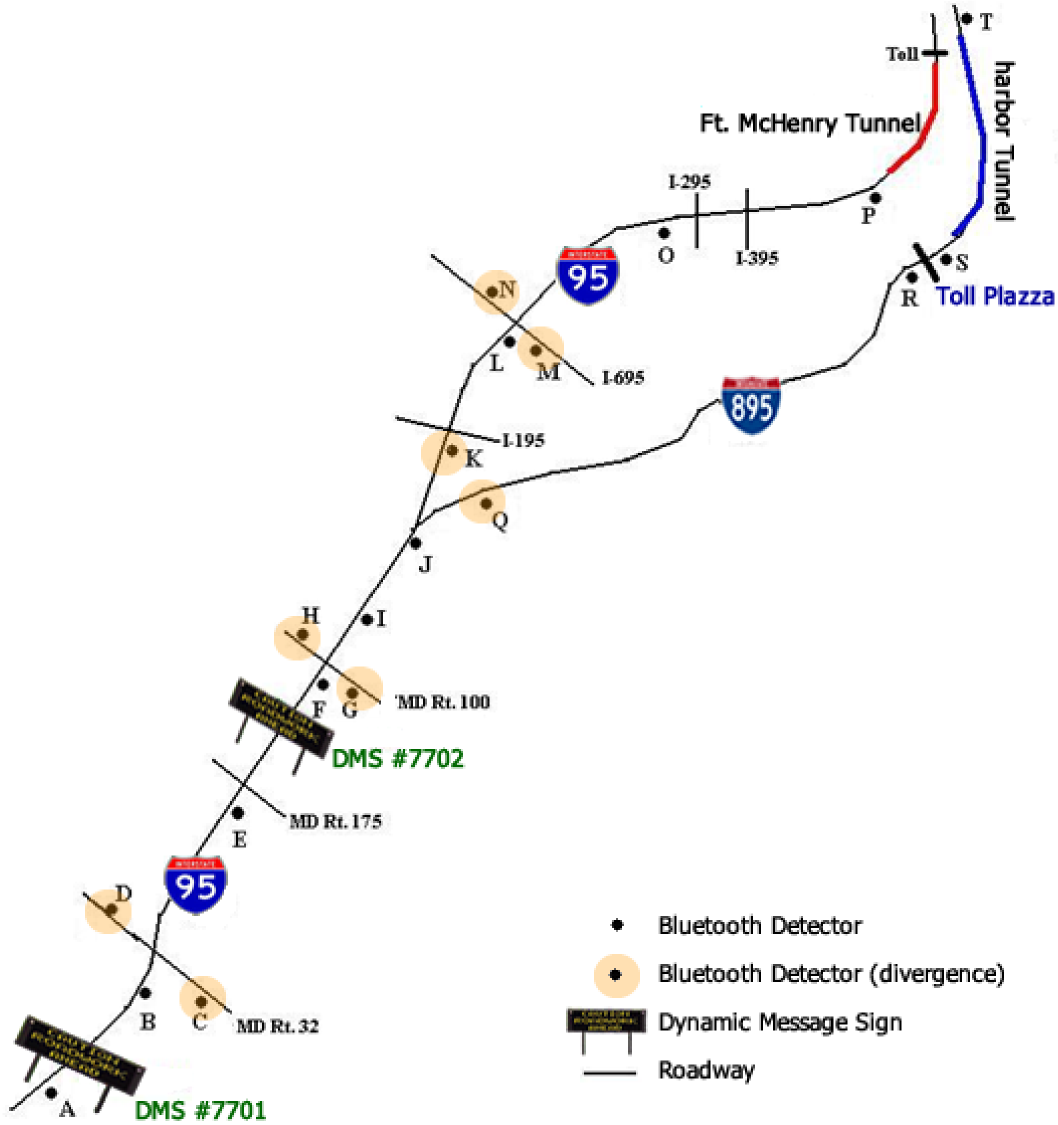


Figure 3.3. Sketch of Sensor Deployments labeled with TMC letter designations

Bluetooth Deployment		Proposed		Actual Deployment (3/29/11)				Pick Up (4/12/11)	
Number	Location	Latitude	Longitude	Sensor ID	Actual Latitude	Actual Longitude	Time (AM)	Status	Time (AM)
1	Rest stop prior to DMS #7701 on I-95 N	39.14188433	-76.84554586	S	**39.14216667**	**-76.84536667**	10:05	OFF	10:06
2	Prior to exit 38B for MD Route 32	39.15477028	-76.82876430	F	**39.15578333**	**-76.83215**	10:12	OFF	10:08
3	MD 32 East off of I-95	39.15046400	-76.82431700	P	**39.15061667**	**-76.82433333**	10:22	OFF	10:10
4	MD 32 West off of I-95	39.16308300	-76.83394400	A	**39.16303333**	**-76.83391667**	1:09	OFF	12:08
5	Prior to exit 41B for MD Route 175	39.17542200	-76.79310800	D	**39.17221667**	**-76.79861667**	10:29	OFF	10:17
6	Prior to exit 43A for MD Route 100	39.19247490	-76.77071154	I	**39.19255**	**-76.7711**	10:35	OFF	10:21
7	MD 100 East off of I-95	39.19192500	-76.76087800	G	**39.19193333**	**-76.76105**	10:39	OFF	10:23
8	MD 100 West off of I-95	39.20278900	-76.77265300	O	**39.20273333**	**-76.77278333**	12:57	OFF	12:01
9	I-95 .5 miles prior to Montgomery Rd	39.20734643	-76.74653437	H	**39.2076**	**-76.74655**	10:48	OFF	10:36
10	Prior to exit 46 I-95/I-895 Interchange	39.22034200	-76.72338600	E	**39.22023333**	**-76.72375**	10:56	OFF	10:30
11	Prior to exits for MD Route 166/I-195	39.23410882	-76.70973274	C	**39.2298**	**-76.7141**	11:57	OFF	11:25
12	Prior to exits for I-695	39.24679896	-76.68531180	T	**39.2464**	**-76.68575**	12:04	OFF	11:28
13	I-695 East off of I-95	39.24643600	-76.67552200	L	**39.24635**	**-76.67558333**	12:09	OFF	11:30
14	I-695 West off of I-95	39.23822800	-76.68652200	-	**-**	**-**	-	OFF	-
15	Prior to I-95/I-295 Interchange	39.27061100	-76.64474700	M	**39.27061667**	**-76.64478333**	12:20	OFF	11:38
16	Prior to Ft. McHenry Tunnel	39.26612500	-76.59782800	Q	**39.26585**	**-76.59623333**	12:29	OFF	11:41
17	I-895 N .25 miles prior to Washington Blvd	39.21853900	-76.71059400	K	**39.21853333**	**-76.71068333**	11:07	OFF	10:43
18	I-895 N .25 miles prior to Toll	39.24070300	-76.58812200	B	**39.24073333**	**-76.5883**	11:15	OFF	10:52
19	I-895 after toll, before Tunnel	39.24257800	-76.57896900	R	**39.2425**	**-76.57906667**	11:21	OFF	10:55
20	I-895 after Harbor Tunnel	39.26500956	-76.56088968	N	**39.26526667**	**-76.56178333**	11:28	OFF	10:58

Figure 3.4. March-April 2011 Deployment-Pickup Locations & Times

3.2: Message Quality

Analyses of message quality and timeliness of selected cases for both deployments are presented in the following sections.

3.2.1: Deployment 1

After collecting and examining message logs, three interesting cases from the first deployment were selected for evaluation (Table 3.1). In all cases, the messages were the same on the two DMS and were shown to drivers for a relatively long period of time. For the evaluation, the Bluetooth travel times were converted to space mean speed and graphs were produced for observation purposes.

Table 3.1. Selected Cases for Deployment 1

Case #	Time Period	Duration	Message Displayed	DMS #
I	7/2/2009 15:45→16:44 (PM)	58 minutes	I-95 MAJOR DELAYS ALT I-895 NORTH OR I-695 EAST	7701 7702
II	7/2/09 16:59→19:18 (PM)	2 hours 18 minutes	I-895 MAJOR DELAYS ALT I-95 NORTH OR I-695 EAST	7701 7702
III	7/1/09 10:20→11:02 (AM)	42 minutes	I-895 NORTH EXPECT CONGESTION AND DELAYS	7701 7702

In the first case, the DMS displayed “Major Delays” on I-95 for approximately one hour during the afternoon peak traffic period on July 2, 2009. The traffic conditions recorded by the Bluetooth sensors on I-95 were examined for a time period slightly before and after this message was displayed to determine the conditions that gave rise to the choice to display and, later, to remove the message.

To determine the validity of the message, links between the first DMS and the Harbor tunnel were examined. Graphs of space mean speed for virtual TMC links AF, AB, BE, EF, FP, FI, IJ, JK, KL, LO and OP, over a time period of 15 minutes before and after the message, were inspected for disturbances. Traffic speed on the link AF, from just before DMS #7701 until just past DMS #7702 was below 35 mph before, during and after the display of the message (Figure 3.55). The links between sensors A and F (AB, BE, EF) displayed similar reductions in traffic speeds throughout the duration of the message, with link AB being the least affected.

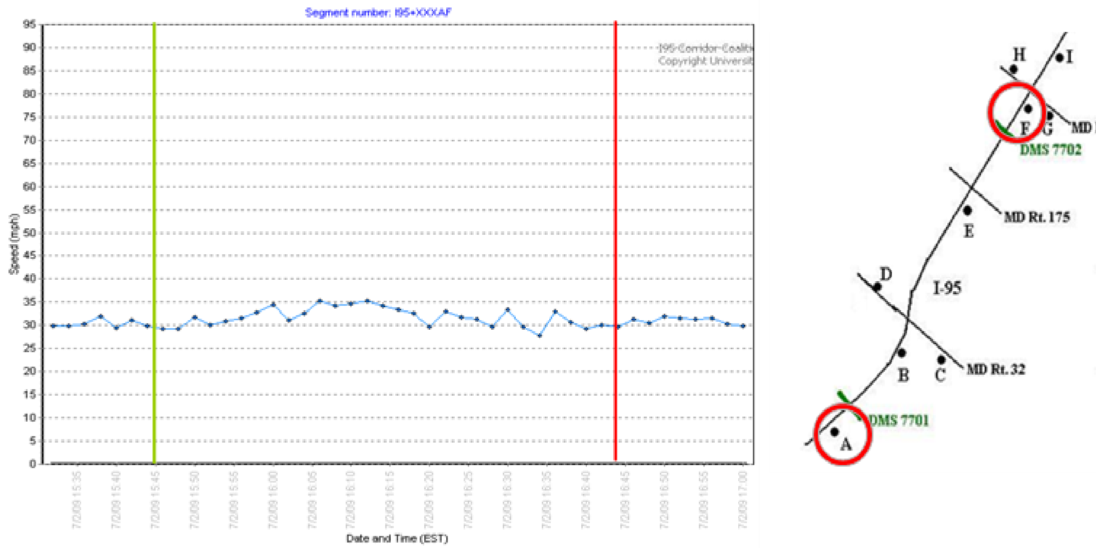


Figure 3.5. Deployment 1, Case I Speed Data for Link AF

Link FP, which covers the overall path from DMS #7702 to the harbor tunnel, shows no major disturbances in space mean speed during the display period (Figure 3.66). Similarly, links FI, IJ, JK, KL, and LO remain relatively stable and maintain speeds above 55 mph for the duration of the message. Link OP, the link closest to the tunnel, shows a slight disturbance from 15:50 to 16:00 in which the speed drops to around 45 mph (Figure 3.7).

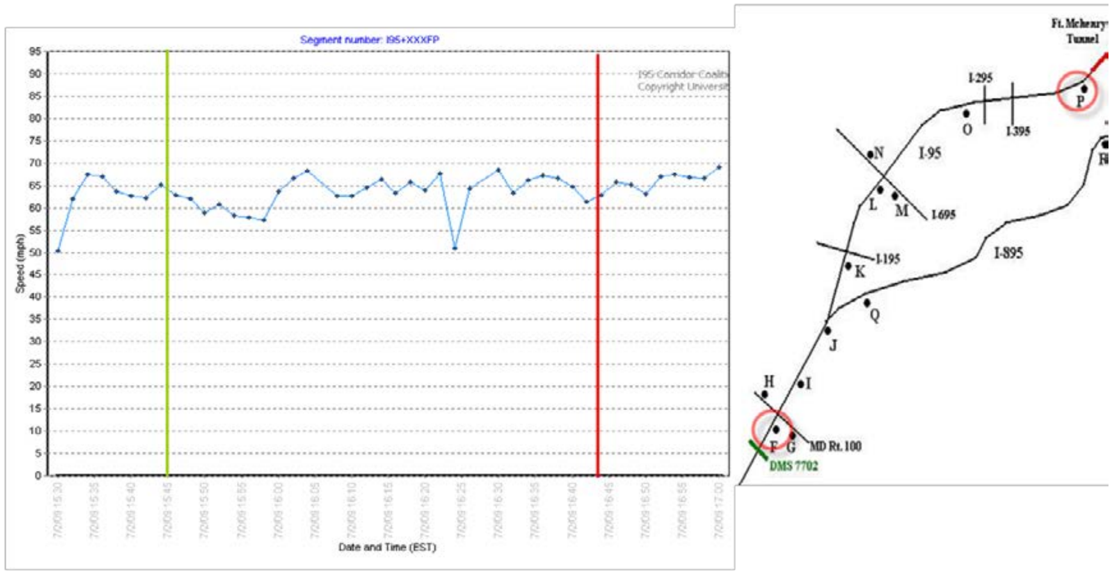


Figure 3.6. Deployment 1, Case I Speed data for Link FP

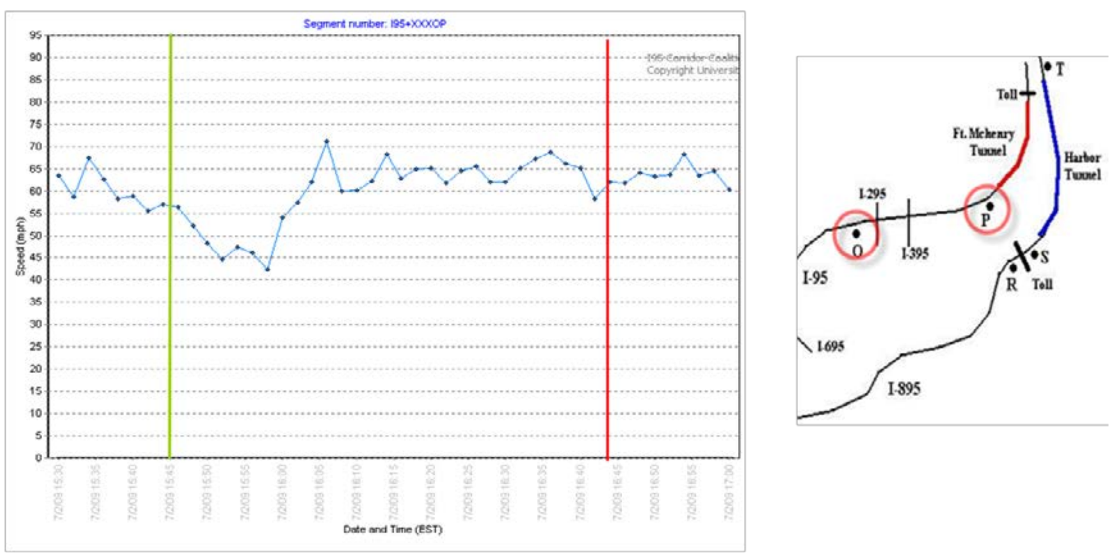


Figure 3.7. Deployment 1, Case I Speed Data for Link OP

In case I, the message appears to be misleading. The speed on link AF was below 35 mph, which could indicate a major delay, however, on the links beyond sensor F the speed of traffic is stable and relatively high. The first DMS (#7701) accurately portrays travel conditions between itself and the next DMS (#7702), but travelers who see the message on the second DMS would not have experienced any congestion between that point and the beginning of the Harbor tunnel, a distance of about 11 miles. Furthermore, the suggestion on the first DMS to use I-895 or I-695E as possible alternatives is not helpful because neither of those choices become available until beyond the second DMS, where the congestion had cleared. The same suggestion on the second DMS is not only inaccurate but may have led to degradation of trust in the DMS system because users continuing on I-95N in spite of the DMS warning would have experienced no reason to divert.

The second case alerts drivers of “Major Delays” on I-895 for two hours and 18 minutes during the afternoon peak period on July 2, 2009. The DMS message is displayed at 16:59 and turned off at 19:18.

In this case, both virtual TMC links on I-895 reveal major disturbances in speed data. Link QR undergoes a speed reduction to below 35 mph from 16:20 to 17:45 (Figure 3.8). Similarly the speed on link ST remains below 25 mph between 16:20 and 18:20 (Figure 3.9). The speeds on both links appear to have returned to relatively normal levels and stabilized by 18:30.

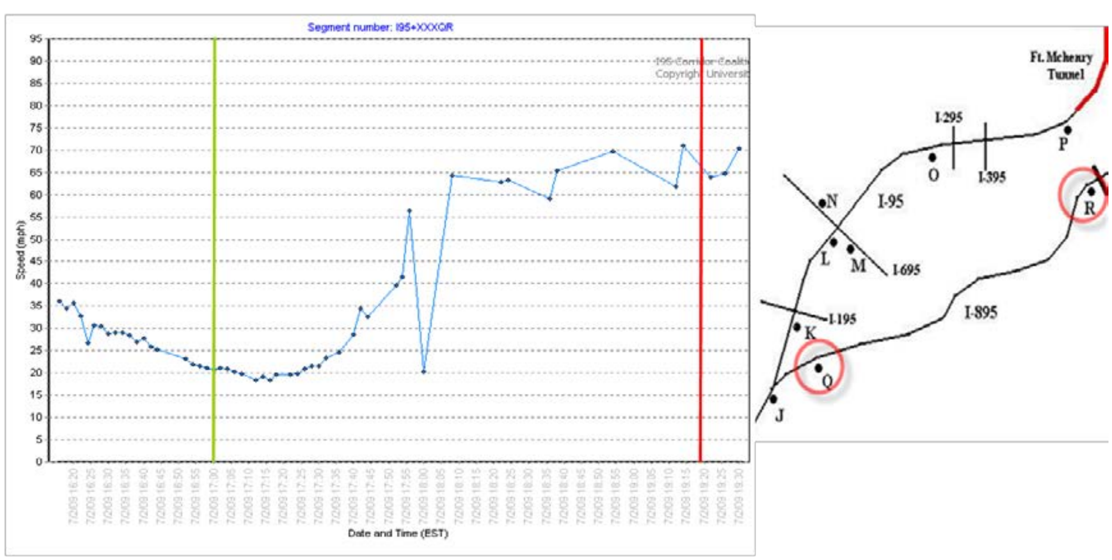
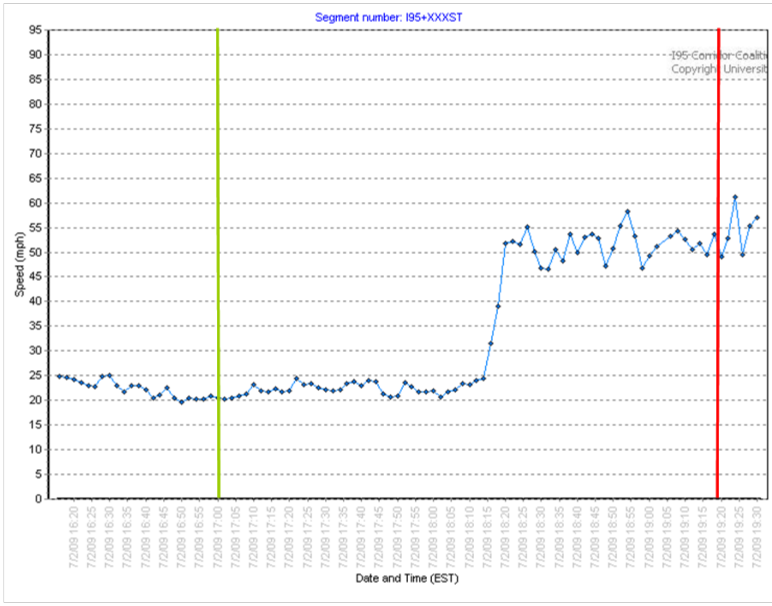


Figure 3.8. Deployment 1, Case II Speed Data for Link QR



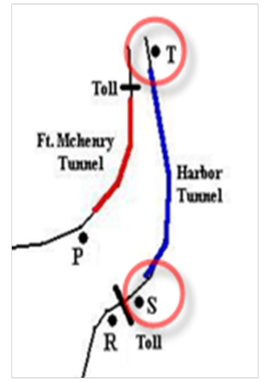


Figure 3.9. Deployment 1, Case II Speed Data for Link ST

For case II, the message appears to have been appropriate given the prevailing traffic conditions. The "Major Delay" message seems to have been prompted by the severity and duration of the drops in traffic speed. However, data reveal the deployment time of the message was at least 25 minutes after the traffic conditions began to deteriorate. In addition, up to 15 minutes prior to deployment of this message the signs were warning of "Major Delays" on I-95 and displayed I-895 as a suggested alternative (Case I). Drivers complying with this suggestion would have found themselves in congestion on I-895 and would likely be displeased with the DMS system. Although the message was displayed appropriately for over an hour, the message was left on for nearly 45 minutes after the link speeds had rebounded to 45 mph or higher. Though drivers seeing the "Major Delays" message may have been happy to find no congestion during these 45 minutes, the credibility of the DMS system would improve if the message was removed in a timely manner.

In the third case, the message states that the road users should “Expect Congestion and Delays” on I-895 North. This message is displayed for 42 minutes approximately one hour after the end of the morning peak period on July 1, 2009.

The Bluetooth derived space mean speed data were examined for links QR and ST on I-895. The data for link QR appears stable and above 55 mph for the time period from 10 minutes before the message until 10 minutes after the message, although the number of data points is limited (Figure 3.10). On link ST, a speed drop occurred 20 minutes prior to the message display (Figure 3.11). Speeds went from above 50 mph to below 25 mph and remained below 25 mph for 10 minutes. When the message came on at 10:20, the speed began to return to normal and stabilized between 45 and 55 mph by 10:40.

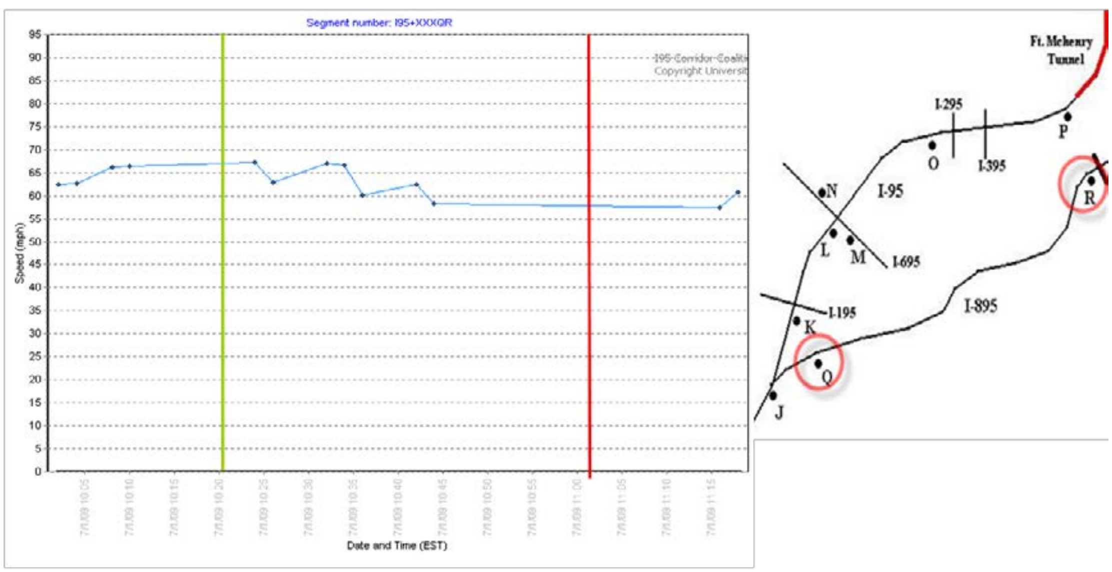


Figure 3.10. Deployment 1, Case III Speed Data for Link QR

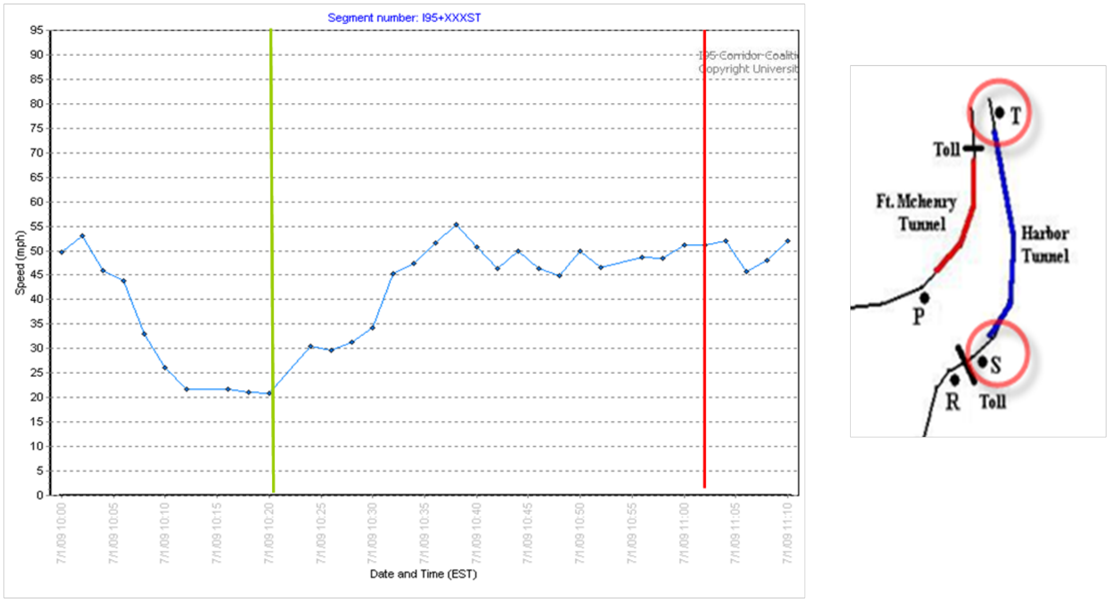


Figure 3.11. Deployment 1, Case III Speed Data for Link ST

The message displayed under these conditions appears to be in reaction to the slowdown in speed in the Harbor Tunnel (link ST) and possibly further north. The message accurately alerts motorists of congestion and delays occurring on I-895; however, it appears to have been posted just as the congestion was beginning to clear. The delay in display of the message may have resulted in some drivers experiencing little or no congestion after having seen the message, once again resulting in devaluation of the DMS system.

In general, the findings from the 2009 deployment reveal that DMS operations could benefit from some adjustments. Although all the messages were warranted by the prevailing traffic conditions and would provide some benefit to drivers, their benefits were diminished by non-timely display and removal. For the DMS system to maintain its credibility, the road conditions experienced by users should match the descriptions on the signs as closely as possible. When messages do not appear in a timely manner, users may experience congestion without warning. Conversely, a message removed late will result in users experiencing no delays when a message warns that a delay exists. Another consideration is the specificity of the messages. In these cases, all of the messages warned of delays on I-95 or I-895 “North”. This description is very vague and could potentially refer to immediate delays or delays that are miles away. More useful messages should contain clear indication of the affected roadway and a specific description of the location of delays.

3.2.2: Deployment 2

In the second deployment, DMS messages often operated independently of each other and displayed travel-time messages by default. During disruptive traffic events, however, the signs tended to act in unison as in the previous deployment. Where differences in content during message display existed, the cases are split by DMS identification number. Several of these cases are analyzed using the techniques in the previous deployment. In addition, some periods in which travel-time messages were displayed were analyzed to assess the accuracy of these messages.

In the first case, the sequence of messages begins at 16:33 and ends at 18:45 on March 31, 2011 (Table 3.2). The first message appears on DMS # 7702 and refers to “Major Delays” on I-895 North of the tunnel. This message persists for 16 minutes until a second pane is added that mentions “Major Delays” prior to the tunnel on I-95 North. At the same time, this single-pane message is displayed on DMS # 7701. At approximately 17:16, both signs begin displaying a message warning of “Major Delays” on both I-95 and I-895 North and recommends I-695 East as an alternate route. In order to analyze these messages, links AF, FL, LP, QR and ST were examined.

Table 3.2. Deployment 2, Case I Messages

CASE I - DMS #	Time Period	Duration	Messages
7701	3/31/2011 16:50→17:16 (PM)	26 minutes	MAJOR DELAYS I-95 PRIOR TO TUNNEL
	3/31/2011 17:16→18:45 (PM)	1 hour 29 minutes	MAJOR DELAYS I-95 AND I-895 NORTH ALT. ROUTE I-695 E.
7702	3/31/2011 16:33→16:49 (PM)	16 minutes	MAJOR DELAYS I-895 N NORTH OF TUNNEL
	3/31/2011 16:49→17:16 (PM)	27 minutes	MAJOR DELAYS I-895 N NORTH OF TUNNEL MAJOR DELAYS I-95 N PRIOR TO TUNNEL
	3/31/2011 17:16→17:17 (PM)	1 minute	MAJOR DELAYS I-895 N NORTH OF TUNNEL MAJOR DELAYS I-95 AND I-895 NORTH ALT. ROUTE I-695 E.
	3/31/2011 17:17→18:45 (PM)	1 hour 28 minutes	MAJOR DELAYS I-95 AND I-895 NORTH ALT. ROUTE I-695 E.

The initial message displayed on DMS #7702 appears to be appropriate as the speeds on link ST (Figure 3.12) are 30 mph below free flow at the message onset (solid green line). This indicates that the delays north of the tunnel on I-895 are spilling back and causing delays in the tunnel itself. Speeds on link QR during the same time show that the delays do not extend below the tunnel (Figure 3.13).

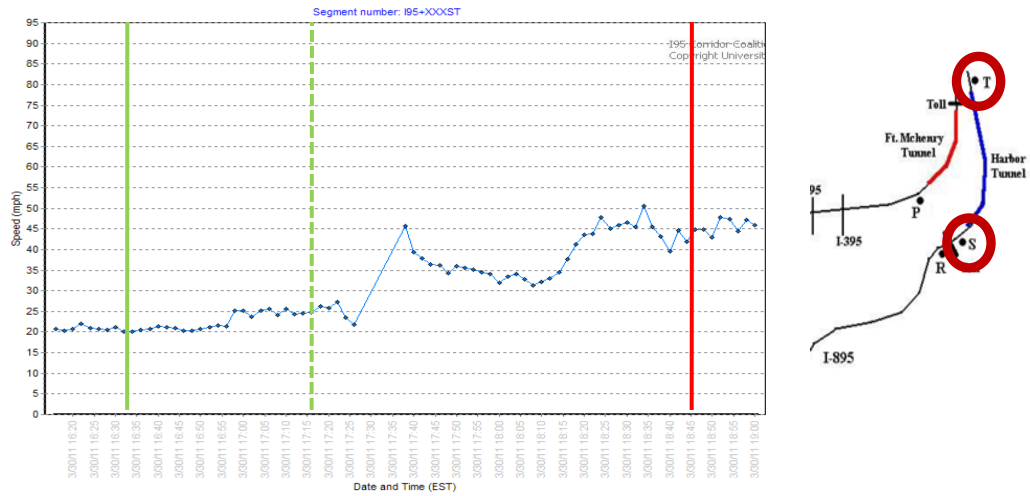


Figure 3.12. Deployment 2, Case I Speed Data for Link ST

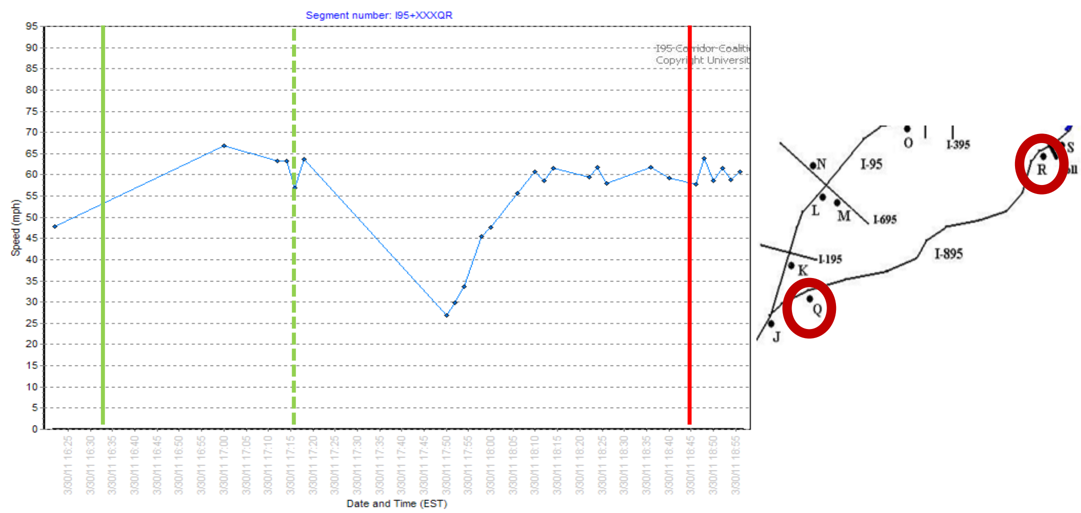


Figure 3.13. Deployment 2, Case I Speed Data for Link QR

At 16:50, both signs began warning of delays on I-95 prior to the tunnel. On link AF, speeds decreased as the message was deployed (Figure 3.14), although speeds are steady on links FL and LP (Figure 3.15, Figure 3.16). The message displayed on DMS #7701 is accurate and appears fairly soon after conditions begin to deteriorate. On DMS #7702, however, there is no indication that the message is yet necessary as the links after it remain unaffected.

Figure 3.14. Deployment 2, Case I Speed Data for Link AF

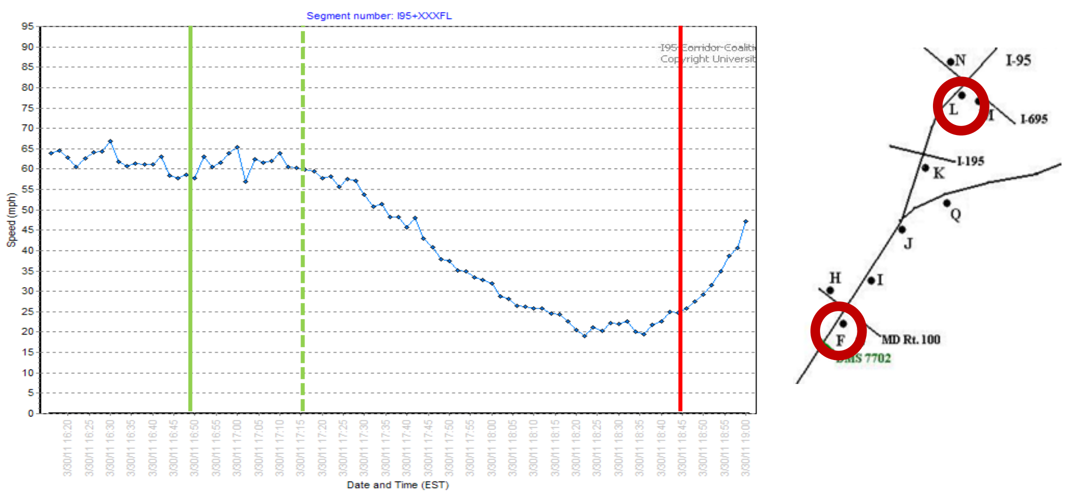


Figure 3.15. Deployment 2, Case I Speed Data for Link FL

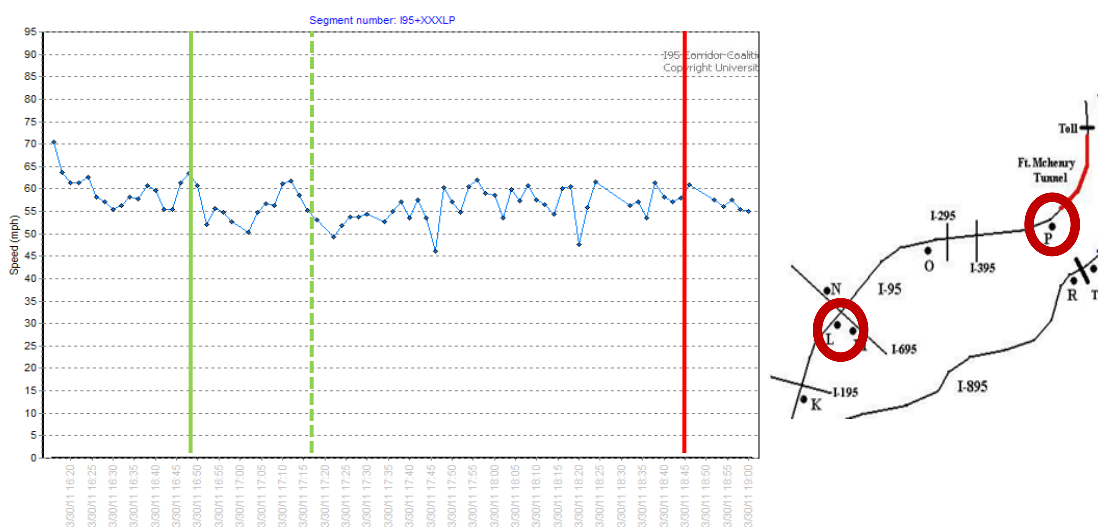


Figure 3.16. Deployment 2, Case I Speed Data for Link LP

For approximately 90 minutes (beginning at 17:16), both signs displayed a message about the delays on I-95 and I-895 North. In addition, they suggested that I-695 East be used as an alternate route. In all figures, this activation is represented by the dashed green line. As observed in Figure 3.14 and Figure 3.15, the negative speed trends on links AF and FL warrant the warning of delays on I-95 North. The speed trends on links QR and ST as seen in Figure 3.13 and Figure 3.12 are seen to decrease or are already low at the onset of the message, supporting the delay warning for I-895. Though the delay warnings are warranted for both roads, the diversion message may be inappropriate. Examination of link FP on I-95 North beyond I-695 reveals no apparent delay. This indicates that continuing on I-95 rather than diverting onto I-695 may be preferred, depending on the condition of I-695.

Messages about a delay on I-95 North were activated just as delays were beginning and were removed as conditions were recovering, except in the case of link LP where no delays were observed during the period. The first message displayed about I-895 North appeared after speeds were already low on link ST. At the time of removal, speeds on I-895 were at normal levels for 20 minutes on link ST and for 30 minutes on link QR. It appears that the message continued until conditions had recovered on both roads, rather than changing the message to refer to only the persisting delays on I-95 North.

The messages in this first case of the second deployment attempted to inform motorists of delays on I-95 and I-895 North. All messages displayed were at least partially warranted and were, for the most part, displayed and removed in a timely fashion. The speed data suggests that diversion onto I-695 East was unnecessary;

although avoiding I-895 by continuing on I-95 North toward I-695 would have been preferred.

The second case occurs during the afternoon peak period on April 1, 2011 (Table 3.3). At 16:27 a message was posted on DMS #7701 and #7702, alerting motorists of Major Delays on I-95 and I-895, north of their respective tunnels. On DMS #7701 this message persisted until 19:14. The message on DMS #7702 was updated at 16:57 with a second pane that noted Major Delays prior to the I-895 tunnel in addition to the delays north of the tunnel. This two-pane message continued until 19:13, when the message reverted to the original one-pane message for one minute. At 19:14, both signs began displaying their default travel time messages.

Table 3.3. Deployment 2, Case II Messages

CASE II - DMS #	Time Period	Duration	Messages
7701	4/1/2011 16:27→19:14 (PM)	2 hours 46 minutes	MAJOR DELAYS I-95 AND I-895 N NORTH OF TUNNEL
7702	4/1/2011 16:27→16:57 (PM)	29 minutes	MAJOR DELAYS I-95 AND I-895 N NORTH OF TUNNEL
	4/1/2011 16:57→19:13 (PM)	2 hours 16 minutes	MAJOR DELAYS I-95 AND I-895 N NORTH OF TUNNEL MAJOR DELAYS I-895 N PRIOR TO TUNNEL
	4/1/2011 19:13→19:14 (PM)	1 minute	MAJOR DELAYS I-95 AND I-895 N NORTH OF TUNNEL

Links ST and OP, the northernmost links on I-895 and I-95 respectively, show space mean speeds at or below 25 mph at the time of message activation (solid green lines), indicating spillbacks from the posted delays north of the tunnels (Figure 3.17, Figure 3.18). It is also evident that these spillbacks persisted for at least 25 minutes on each of these links prior to the message activation. These delays, though, were accounted for by the previously posted travel time messages that indicated higher than normal travel times.

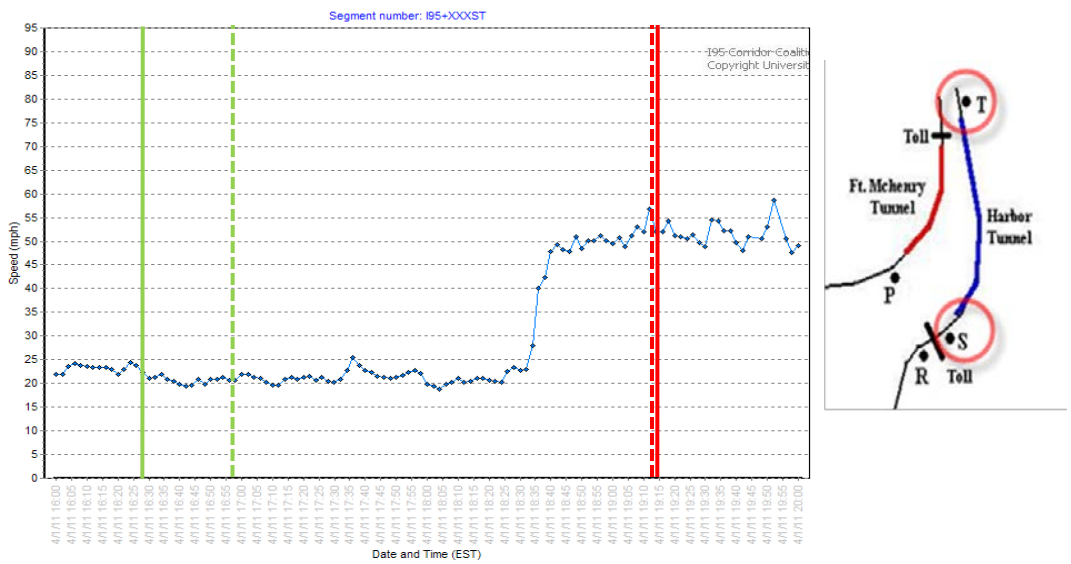


Figure 3.17. Deployment 2, Case II Speed Data for Link ST

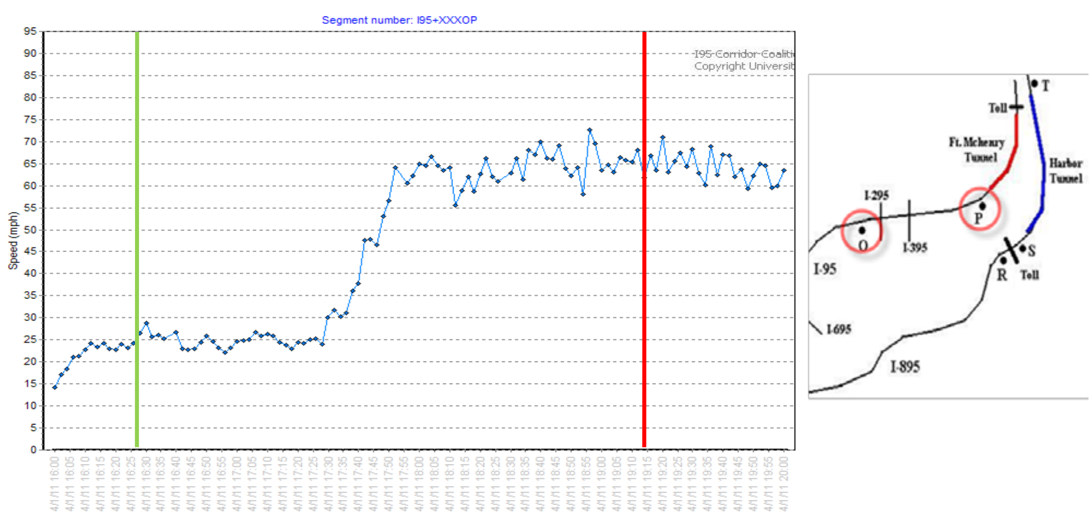


Figure 3.18. Deployment 2, Case II Speed Data for Link OP

When DMS #7702 began warning of delays on I-895 prior to the tunnel (dashed green lines), it was observed that speeds on link QR (Figure 3.19) fell approximately 10 mph since the posting of the original message. The message appeared to be in reaction to this increased congestion.

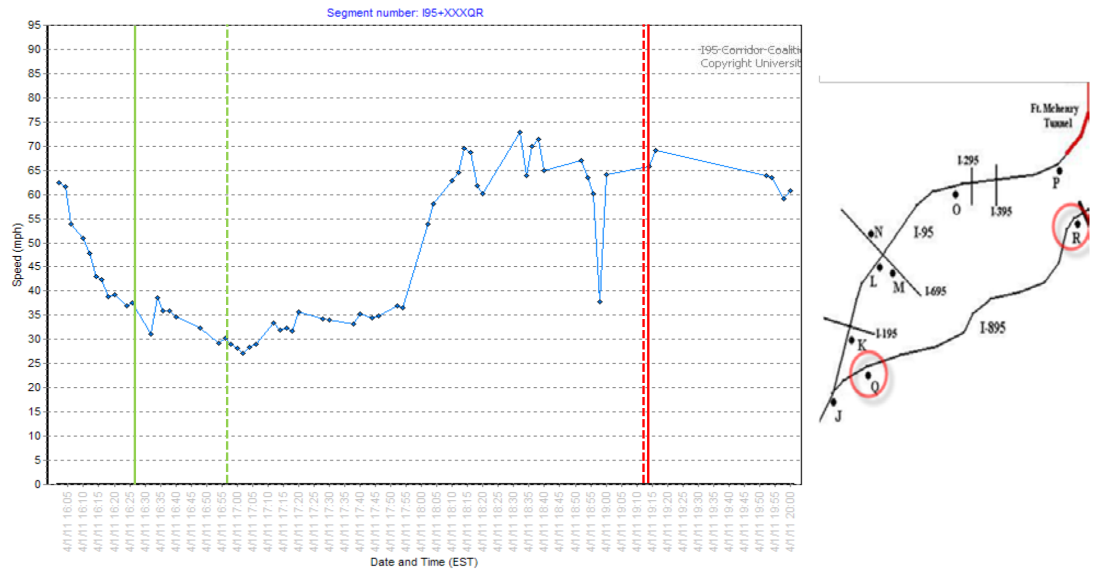


Figure 3.19. Deployment 2, Case II Speed Data for Link QR

Examining link FO (Figure 3.20) reveals no apparent delays on I-95 between DMS #7702 and the interchanges just prior to the Ft. McHenry tunnel. The delays north of the tunnel on I-95 did not spill back as they had on I-895. Therefore, the messages displayed on DMS #7702 were accurate and useful, as there were no unaccounted-for delays occurring on I-95 prior to the tunnel. If motorists chose to avoid I-895 by remaining on I-95 as a result of the DMS message, they would not experience unexpected delays.

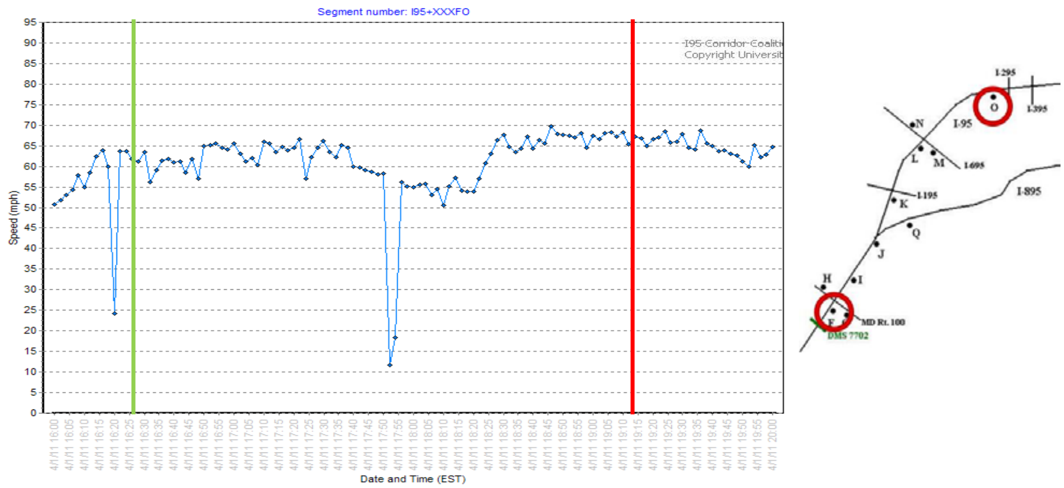


Figure 3.20. Deployment 2, Case II Speed Data for Link FO

On DMS #7701, the message warned only of the delays north of the tunnels for the entire period. Although this message accurately described those conditions, the message failed to warn motorists of the delays on link AF (Figure 3.21) from DMS #7701 to DMS #7702. In this case, users may have benefited from continued display of the default travel time message on DMS #7701, which would have taken into account these delays. Since the information displayed on the sign would not have been useful until after DMS #7702, where it was repeated, users may have found the information inadequate given the prevailing conditions.

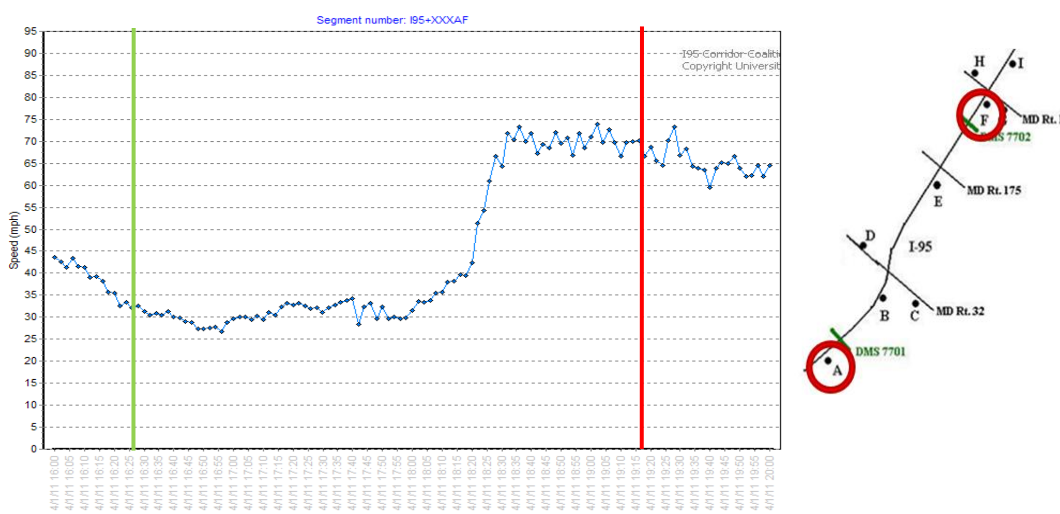


Figure 3.21. Deployment 2, Case II Speed Data for Link AF

At the time of message removal at 19:14, all of the examined links had returned to near free-flow speeds. Although many of the links had been stable for at least 30 minutes, link QR remained unstable until 10 minutes before message removal, meaning the message was maintained until all links had stabilized, as observed in the previous case. Both signs resumed displaying travel-time messages at the end of the period and both indicated free flow conditions.

This second case shows that the DMS communicated accurate and timely information to motorists. The conditions posted were apparent in the data and would have been useful to motorists, although the first DMS could have been used to inform users of the delays prior to the second DMS as well.

The third case was an all-day event resulting from a closure of the Harbor Tunnel on I-895 during the morning peak hour (Table 3.4). At 7:31. both DMS begin alerting drivers of the tunnel closure on I-895 and recommend I-95 North or I-695 East as alternate routes. After 15 minutes, the message was removed and both signs displayed their respective travel time messages until 9:32. At this time, both signs displayed a message that informed users to expect congestion and delays on I-895 North. After approximately three hours, this message was removed from both signs. DMS #7701 resumed displaying travel time messages. Meanwhile, DMS #7702 warned motorists of Major Delays on I-895 and suggested the same alternate routes as in the morning message. The “Major Delay” message persisted on DMS #7702 for approximately six hours and was removed at 18:23.

Table 3.4. Deployment 2, Case III Messages

CASE III - DMS #	Time Period	Duration	Messages
7701/7702	4/2/2011 7:31→7:46 (AM)	15 minutes	I-895 TUNNEL CLOSED ALERNATE ROUTES I-95 N. OR I-695 E.
	4/2/2011 9:32→12:28 (AM/PM)	2 hours 56 minutes	I-895 NORTH EXPECT CONGESTION AND DELAYS
7702	4/2/2011 12:32→18:23 (PM)	5 hours 51 minutes	I-895 MAJOR DELAYS ALT I-95 NORTH OR I-695 EAST

When the initial message was displayed, link ST experienced near free flow conditions (Figure 3.22). For the next 15 minutes there was no Bluetooth data available, which indicated that no traffic passed through the tunnel. This finding corresponds with the message advising of the tunnel closure. During the following 15 minutes, traffic speeds rapidly dropped, stabilizing around 20 mph. At the same time, link QR appeared to be unaffected by the tunnel closure (Figure 3.23). In addition, the recommendation to use I-95 North as an alternate route appeared to be sound, as there were no apparent delays on links AF, FO, or OP (Figure 3.24, Figure 3.25, Figure 3.26).

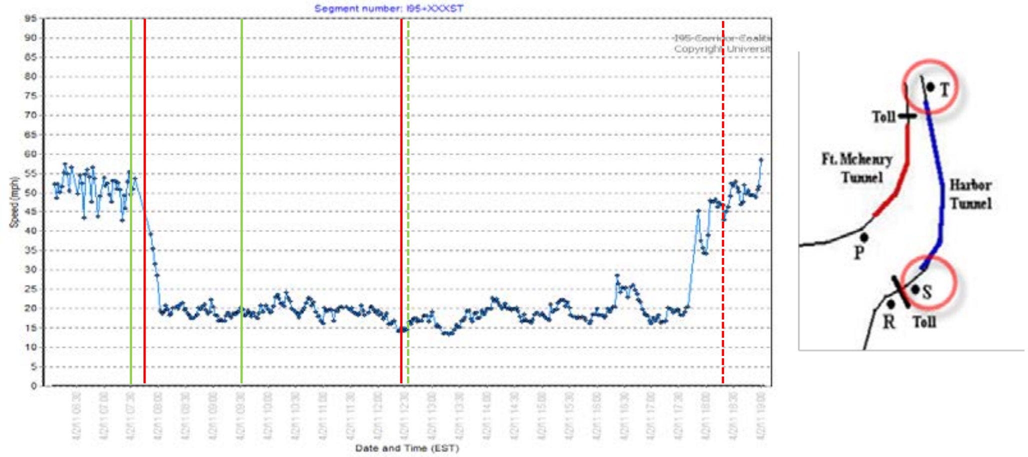


Figure 3.22. Deployment 2, Case III Speed Data for Link ST

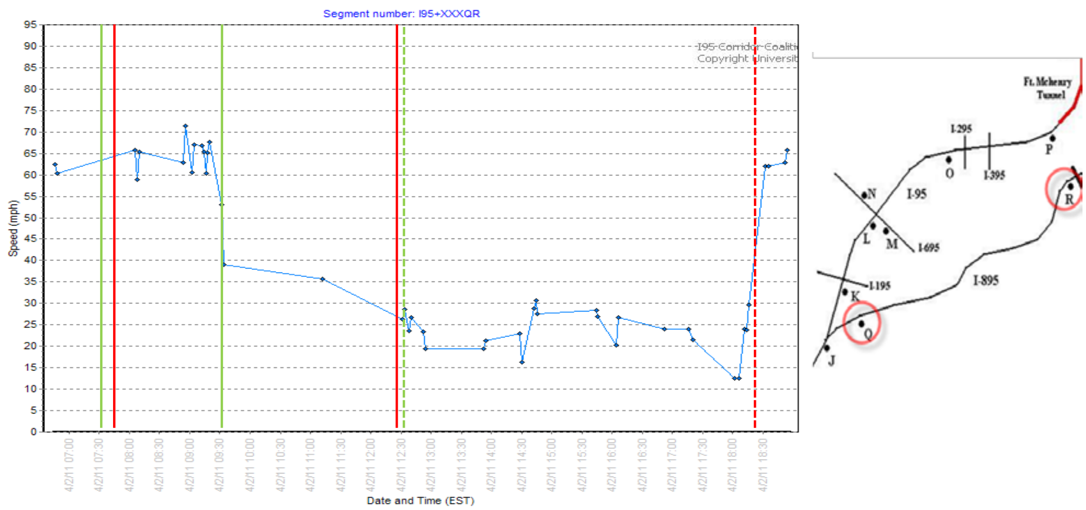


Figure 3.23. Deployment 2, Case III Speed Data for Link QR

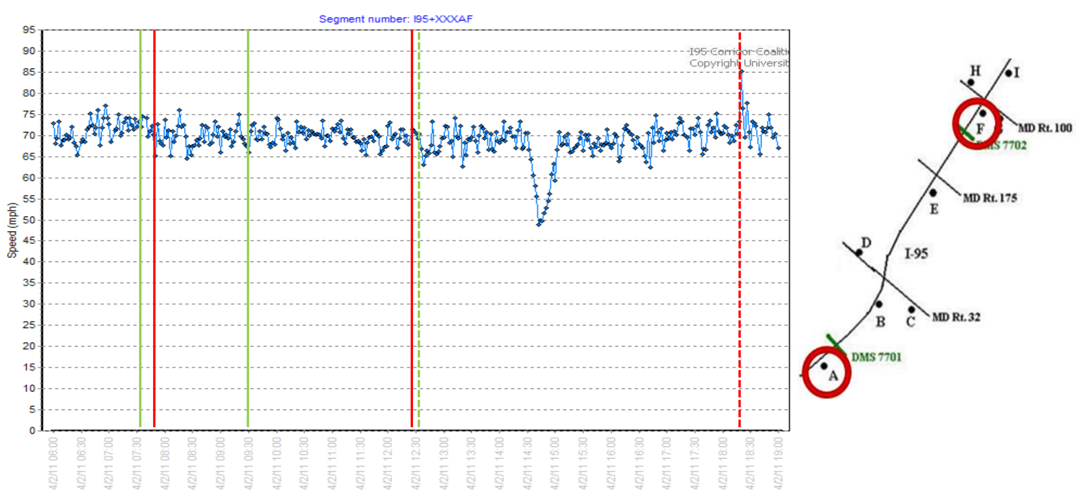


Figure 3.24. Deployment 2, Case III Speed Data for Link AF

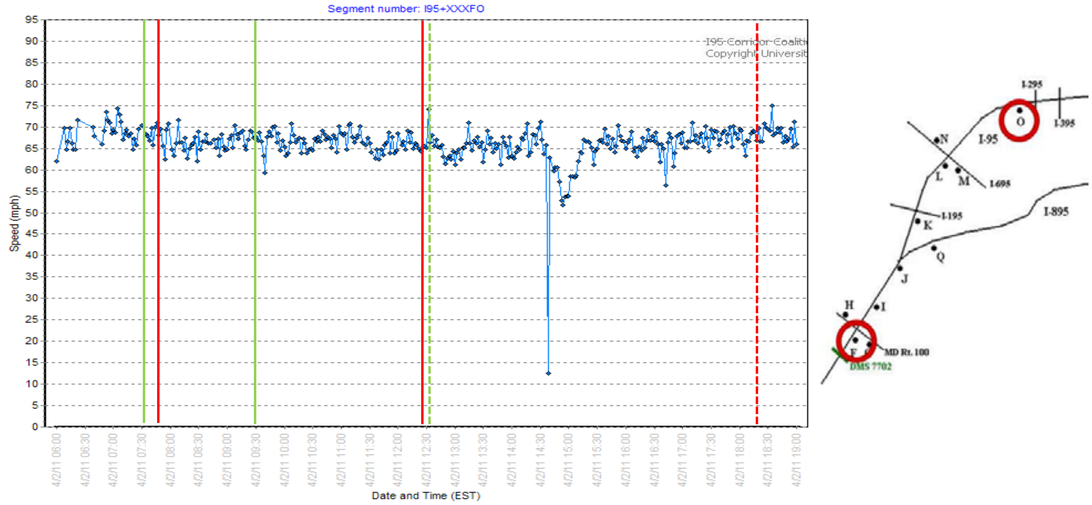


Figure 3.25. Deployment 2, Case III Speed Data for Link FO

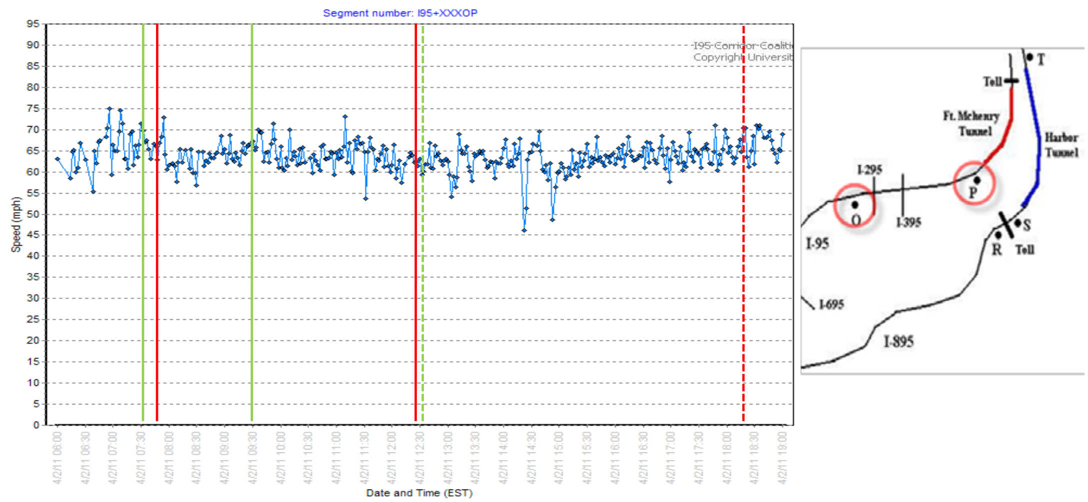


Figure 3.26. Deployment 2, Case III Speed Data for Link OP

Between 7:46 and 9:32, both signs resumed display of travel time messages. All links on I-95 North and I-895 North prior to the tunnel were unaffected by the tunnel delays, so the signs displayed free flow speed-limited travel times. Unfortunately, no warning was given during this time of the delays occurring in the Harbor Tunnel. At 9:32, the congestion in the Harbor Tunnel appeared to have backed up onto link QR, which resulted in speeds dropping to 40 mph. A message warning of “congestion and delays” appeared on both DMS for the next three hours.

During those three hours, speeds appeared to steadily drop on link QR, eventually falling to approximately 25 mph.

At 12:28, the message was removed from both signs and replaced with travel time messages. DMS #7701 continued displaying travel time messages for the remainder of the case period. At 12:32, DMS #7702 replaced its travel time message with a “Major Delay” message relating to I-895 with I-95 North and I-695 East as alternate routes (dashed lines). The message continued for approximately six hours until it was removed at 18:23. The delays cleared on both links QR and ST about 15 minutes before the removal of the message, indicating a timely reaction to traffic conditions. During the same period, the traffic conditions were near free flow and were steady on all links on I-95 North, making it a viable alternate route. In addition, the choice to display travel time on DMS #7701 during this period gave users more information to make their decision on whether to continue on I-95 North.

In this third case in the 2011 deployment, the DMS communicated changing conditions through the day. At each change of message, the conditions observed through the data matched the descriptions displayed. The messages were also updated and removed rapidly with the conditions to which they corresponded. One shortfall during this third case was the morning period, during which both signs reverted to travel-time messages, ignoring delays in the Harbor Tunnel. Because DMS #7702 displayed equal travel times to the Harbor Tunnel and the Fort McHenry Tunnel during this time, motorists may have taken I-895 North only to find heavy delays in the tunnel. Although travel-time information displayed on the DMS was accurate, motorists could have benefitted by being warned of the delays in the tunnel. Overall, this case demonstrated a sound operation of the DMS system through the timely display of high quality messages with useful information.

The cases from 2011 deployment indicate an improvement in the quality and timeliness of DMS messages over the 2009 deployment. In these cases, the messages specifically indicated certain sections (e.g. before or after the tunnel) when necessary, and the Bluetooth-observed conditions supported the accuracy of the messages. In some instances, messages were left on longer than necessary, which meant users experienced no delays even though they were warned of them. On the other side, travel-time messages displayed by default alleviated some problems arising from delay messages being displayed long after conditions had deteriorated. Users would be at least somewhat aware that conditions were worsening as the displayed travel time would be above normal. Again, Bluetooth detection has been demonstrated as a viable tool for analysis of Dynamic Message Signs.

3.2.3: Travel Time Messages

During the 2011 deployment, the DMS were used by default to display real-time travel time information to various destinations. Using the Bluetooth-derived ground truth travel times, the travel times displayed on the DMS can be analyzed for accuracy and timeliness. DMS #7701 displayed travel time from itself to I-695, a stated distance of 11 miles (Figure 3.27). To analyze this segment, the ground truth travel time on virtual-TMC segment AL, from DMS #7701 to the first I-695 Exit ramp, was used.

Figure 3.27. Sample Travel Time Message for DMS #7701

The timestamps from the Bluetooth data were matched to timestamps from the DMS message log; the displayed travel time was then extracted from each message. The Bluetooth travel times were matched in raw format to the displayed travel times and converted to minutes. The average difference between these two data sets and the standard deviations was then determined.

In addition, a comparison to the rounded and capped Bluetooth travel times was made. The rounded and capped data is differentiated from the raw data by taking into account the speed limit and the integer restriction on the signs. On a segment 11 miles long with a speed limit of 65 mph, the minimum legal travel time is approximately 10.15 minutes. Since the signs only display integer values, the minimum travel time displayed is 11 minutes because display of a travel time of 10 minutes or lower implies traffic speeds above the posted speed limit. For this reason, any travel times below 11 minutes are rounded up to 11 minutes. All other travel times are rounded to the nearest integer value. In order to demonstrate the analysis ability of the Bluetooth data, two travel time message cases were selected for evaluation.

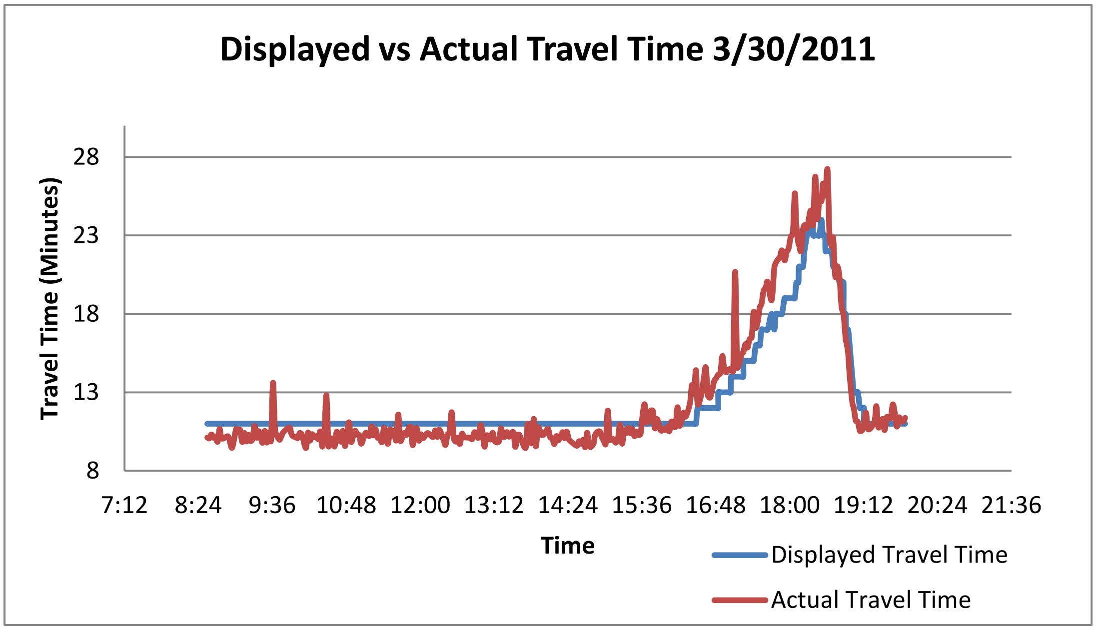


Figure 3.28. Case I, Displayed vs. Actual Travel Time

In both cases, the messages began display in the morning and indicated free-flow travel times. They changed to the display travel times as conditions began to deteriorate. The first case begins at 8:32 March 30, 2011, and ends at 19:52 the same day. Travel times remained at or above free-flow levels until approximately 16:22, at which time travel time on the segment began to increase. The first sign update occurred at 16:30. Travel time continues to increase until approximately 18:30, at which point it leveled off and returned to free-flow conditions by 19:08. (Figure 3.28).

The graph indicates the displayed travel time very closely matched the ground truth travel time with some lag during the period of travel time increase. This lag may be attributed to data acquisition and processing time prior to display on the DMS. It is also notable that the Bluetooth data displays several very high travel times during the free flow period. We speculate the sensors detect vehicles that make stops or diversions between the matched detectors, causing these outliers. As previously mentioned, much of the data during free-flow conditions is below the displayed travel time because of traffic exceeding the speed limit. To account for this, a similar graph where the actual travel time is converted to rounded and capped travel time is produced (Figure 3.29).

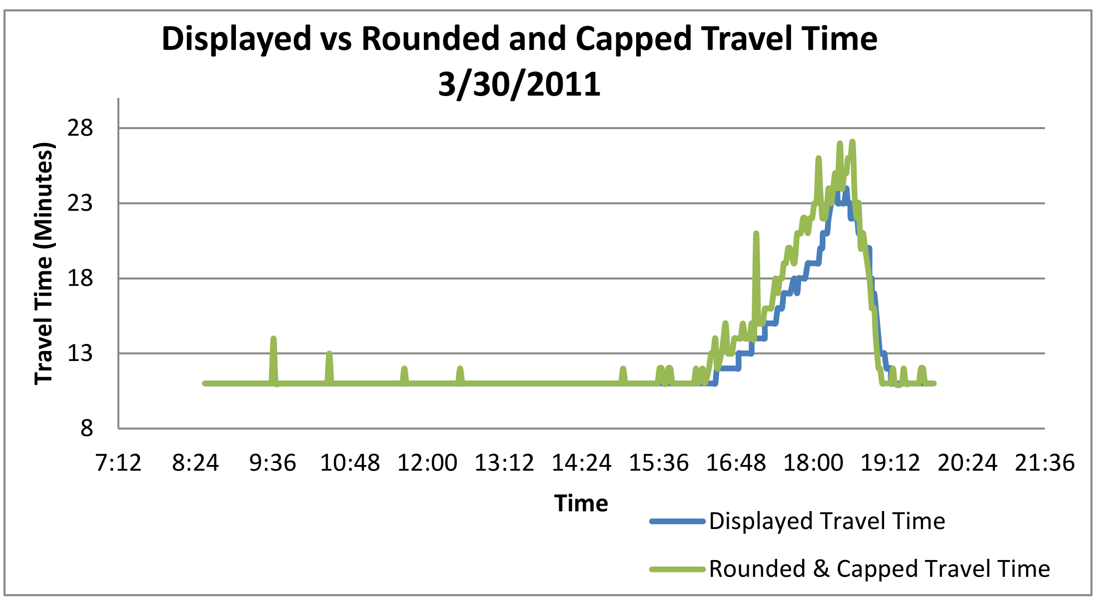


Figure 3.29. Case I, Displayed vs. Rounded and Capped Travel Time

With this manipulation, it is clear travel times displayed during free-flow conditions are accurate. During the congested period, the same lag between actual and displayed travel times is observed. To determine the numerical discrepancies between the displayed and ground truth travel times, the difference between them at each time was calculated as follows:

$$Difference = TT_{actual,t} - TT_{displayed,t}$$

The average and standard deviation of this difference was calculated for both the actual and capped travel times (Table 3.5).

Table 3.5. Case I Travel Time Differences

	Actual	Capped
Average Difference	0.2616441	0.72865854
Standard Deviation	2.4018081	2.22362256

The average difference in both cases indicates actual travel times are slightly higher than the displayed travel times. In the capped case, the higher average value probably results from the free flow times being rounded up. The standard deviations are somewhat high, although certainly a result of the outliers during the free flow period. With the outliers removed, the results change (Table 3.6).

Table 3.6. Case I Travel Time Difference (Outliers Removed)

	Actual	Capped
Average Difference	-0.01027	0.464174
Standard Deviation	1.424859	1.180357

The second case occurs the following day, March 31, 2011, between 5:00 and 16:48. The period primarily consists of free-flow conditions, with increases in travel time beginning at 15:12. (Figure 3.30). At the end of this period, the DMS message was changed to a non-travel time message.

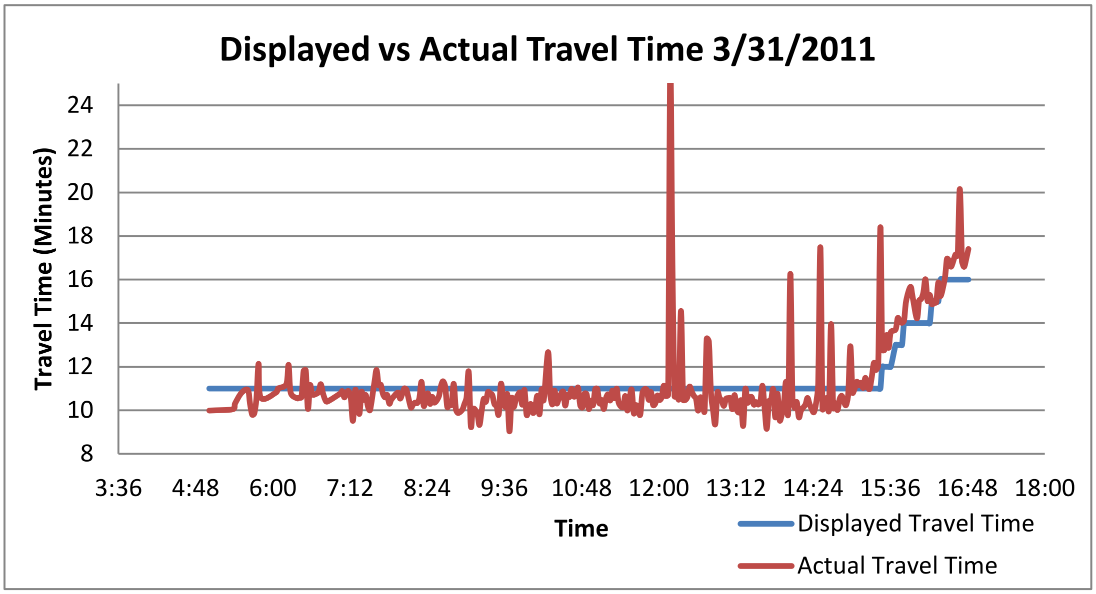


Figure 3.30. Case II, Displayed vs. Actual Travel Time

During free-flow conditions, the actual travel times are very close to the displayed travel times with only a few outliers. When travel time began to increase, the gaps observed are small. Overall, the messages appear to accurately represent the true travel times. The rounded and capped travel time shows similar trends (Figure 3.31).

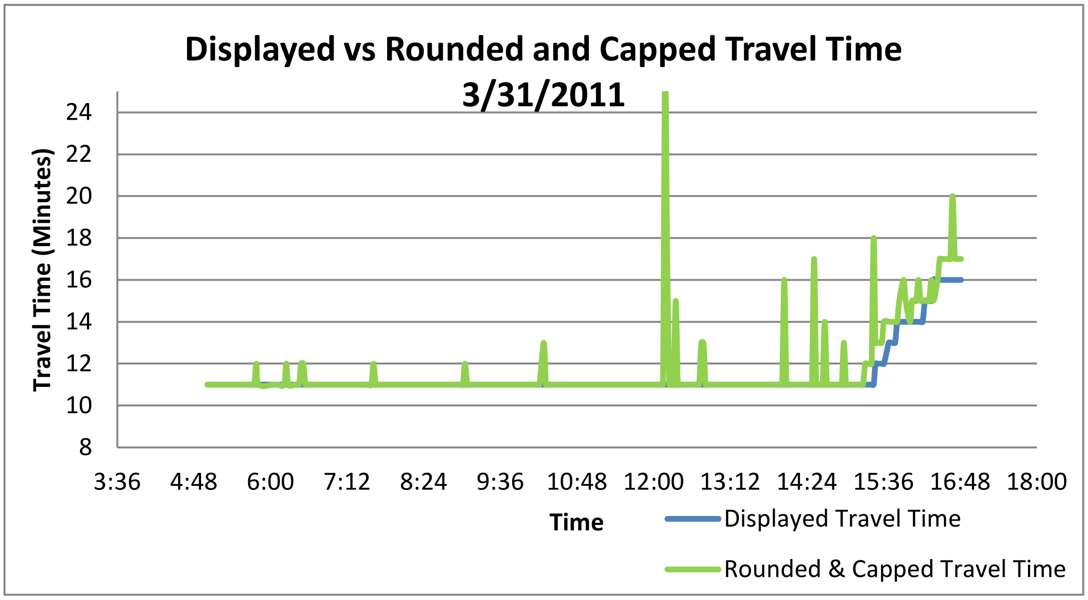


Figure 3.31. Case II, Displayed vs. Rounded and Capped Travel Time

Again it is clear that the display of 11-minute travel time for the majority of the period was justified. There are several instances where travel times go above 11 minutes during this period, but none persist long enough to influence the messages. There is more visible lag between the ground truth and displayed times when rounded, but none appear to be unreasonable. The difference between the actual and displayed travel times was calculated as previously described (Table 3.7).

Table 3.7. Case II Travel Time Differences

	Actual	Capped
Average Difference	-0.0998325	0.3193548
Standard Deviation	1.38101214	1.2005714

These results show the influence of speed limit-capped travel time. When compared with the actual travel time, the displayed times are slightly higher, as expected. By removing the influence of speed limits, the average difference shows the displayed travel times during congested periods were lower than the actual travel times. The standard deviations in both cases are small, indicating a tight spread in travel time differences.

Overall, these two cases show the data and updating system used for DMS travel-time messages provided accurate and mostly timely information to motorists. On average, the difference between the actual travel time and the displayed travel time was less than one minute, with standard deviations, outliers removed, of less than two minutes. These cases also demonstrate that Bluetooth sensors are capable of providing high-quality data of DMS travel times. The methods used are repeatable and applicable to systems in other jurisdictions regardless of their data sources and updating systems.

3.3: Message Effectiveness

The following sections describe the methodology and findings from the using of Bluetooth sensors to evaluate traffic diversion resulting from Dynamic Message Sign messages.

3.3.1: Sensors

Previous attempts to empirically analyze traffic diversion in response to DMS messages have used loop detector data. This type of data gives only traffic counts, so it is impossible to determine the specific path of a given vehicle. On the other hand, Bluetooth detectors are capable of providing a sample of origin-destination data through identification and re-identification of the individual vehicles at consecutive sensors. The drivers' response to the messages displayed on DMS can be studied by analyzing Bluetooth origin destination data (as a proxy for the actual origin destination data) before and after the DMS message display The downside of this approach is that Bluetooth is only a sampling technology with an average 3.5 percent penetration rate (26).

Several sensors were deployed to track vehicle diversion. In order to do this, the sensors were placed such that they would detect vehicles shortly after major diversion or exit points. The primary diversion from I-95 recommended by the DMS was I-895 North. To determine the share of traffic on these alternative routes, detections were matched between sensor J and sensors K and Q (Figure 3.32). In addition, the messages often recommended I-695 East as an alternate route. For these cases, the detections between sensor L and sensors M and O were compared (Figure 3.31).

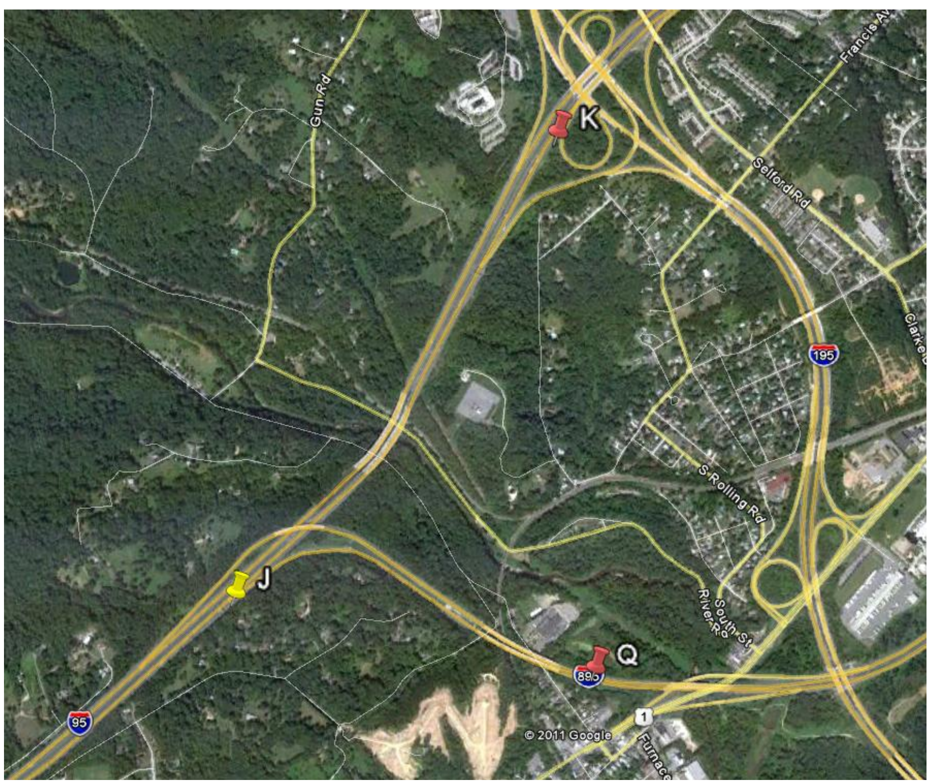


Figure 3.32. I-95 and I-895 North Diversion Point

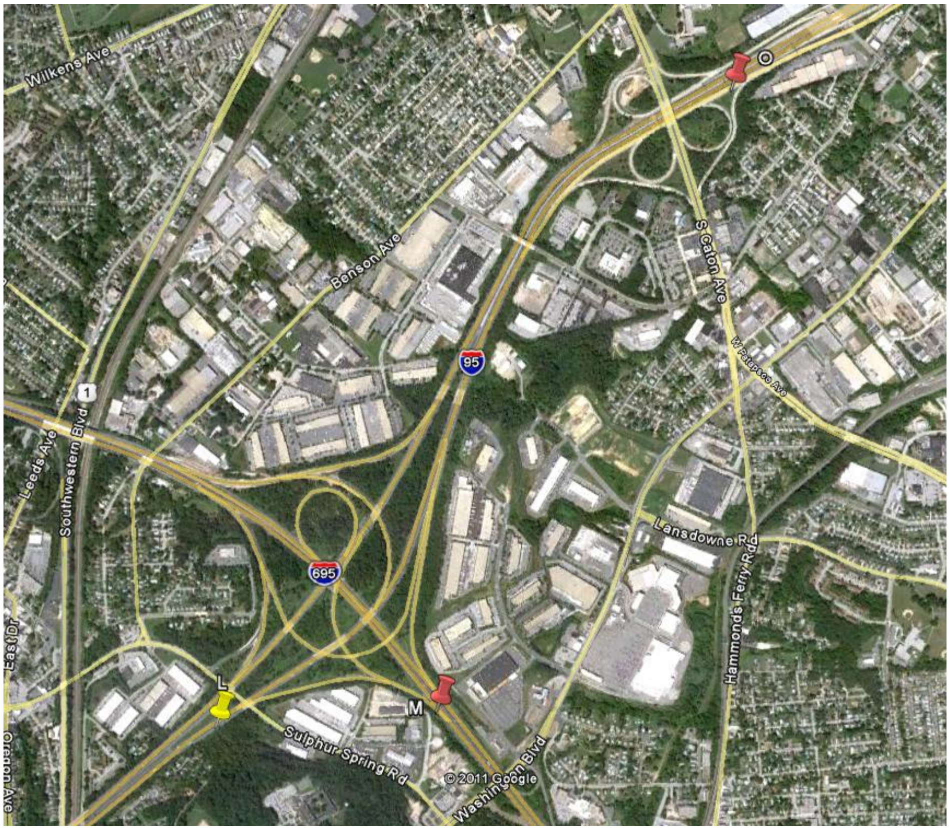


Figure 3.33. I-95 and I-695 Diversion Point

3.3.2: Diversion Analysis

In the first deployment, Cases I and II both displayed messages recommending diversion. Case I recommended using I-895 as an alternate route for 58 minutes. After being blank for 15 minutes, Case II recommended using I-95 for the next 2 hours. The share of traffic diverting on each link is analyzed during the times of the day in which the signs were blank, during the message cases, and during the time between the two messages (Figure 3.34).

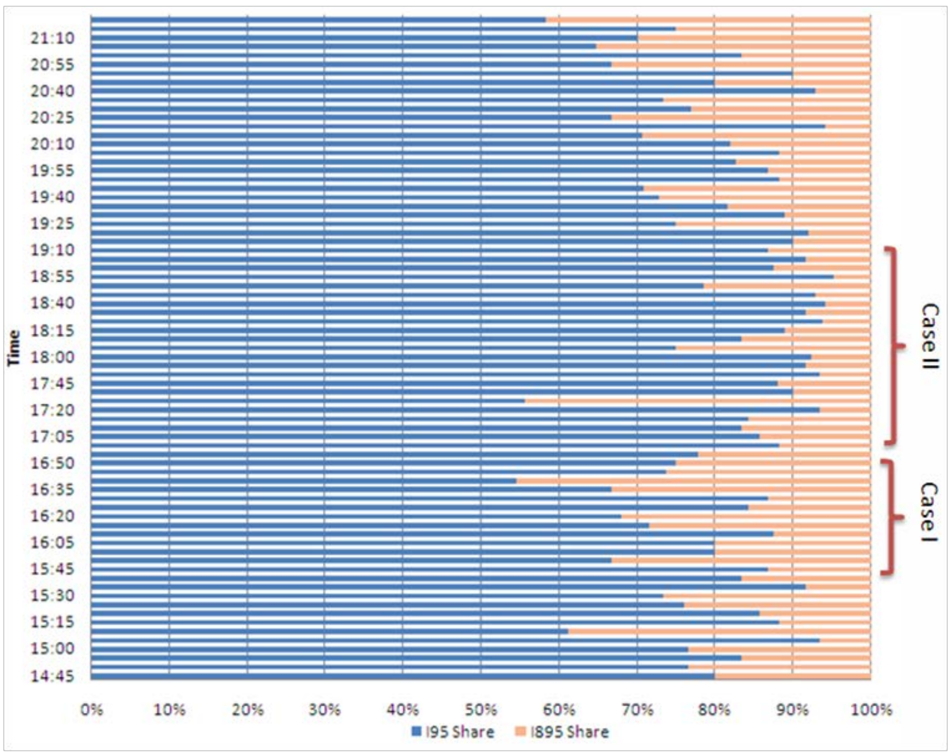


Figure 3.34. Traffic Share During Message Cases Deployment 1

During periods in which the signs were blank, approximately 80% of vehicles continued on I-95 while the other 20% used I-895. When the message in Case I recommended diversion onto I-895, it was observed that the share of traffic continuing on I-95 North dropped by 5 percent. Similarly, when Case II suggested use of I-95 instead of I-895, there was a 7 percent increase in utilization of I-95 (Table 3.8).

Table 3.8. Traffic Diversion Share Between I-95 and I-895 North Deployment 1

Time interval	**Average I-95 Share (%)**	**Average I-895 Share (%)**	**Standard Deviation**
All times with no message on display	80.4	19.6	10.2
Case I: *divert to I895 North or I695 East*	75.5	24.5	10.4
Time between removal of message in case I and display of message in case II	80.3	19.7	7
Case II: *divert to I95 North or I695 East*	87.4	12.6	8.4

In the second deployment, similar diversion messages were posted. On April 6, 2011, DMS #7702 posted three messages recommending drivers to divert away from I-95 through the use of I-895 or I-695. In this deployment, the default posted messages displayed travel time. To determine the baseline diversion shares, times when the DMS displayed free flow travel times were used. Traffic shares were calculated during periods of diversion message display (Figure 3.35).

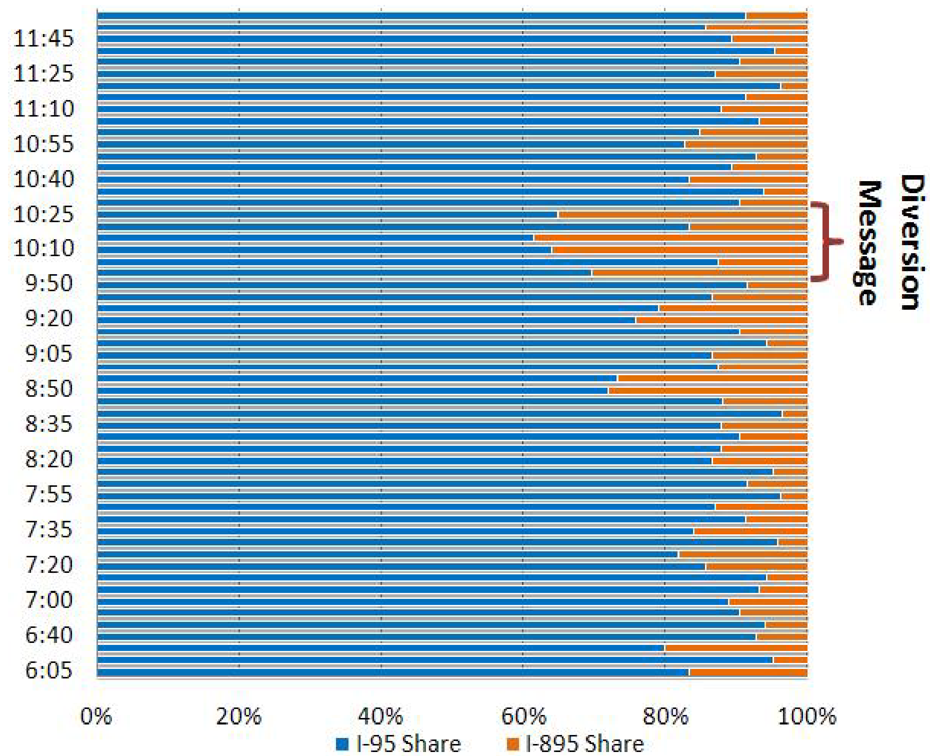


Figure 3.35. Traffic Share During Message Case Deployment 2

During the times the signs indicated free flow travel times, the share of drivers using I-95 instead of I-895 was approximately 89 percent. The proportion of drivers choosing I-95 instead of I-695 East during the same periods was approximately 80 percent. When diversion messages were posted, the average share of drivers using I-95 instead of I-895 dropped approximately 10 percent (Table 3.9). Similarly, those choosing I-95 instead of I-695 East dropped nearly 18 percent (Table 3.10).

Table 3.9. Traffic Diversion Share Between I-95 and I-895North Deployment 2

Time Interval	Average I-95 Share (%)	Average I-895 Share (%)	Standard Deviation
Free Flow Travel Time	88.7	11.3	6.04
Divert to I-895 or I-695	78.5	21.5	12.03

Table 3.10. Traffic Diversion Share Between I-95 and I-695East Deployment 2

Time Interval	Average I-95 Share (%)	Average I-695 Share (%)	Standard Deviation
Free Flow Travel Time	80.1	19.9	10.51
Divert to I-895 or I-695	62.3	37.7	20.90

These findings provide preliminary support for the contention that DMS have modest effect on drivers' route choices. When the messages suggested specific diversions, the Bluetooth detection data showed corresponding shifts in diversion patterns. It must be noted that these numbers serve only as a proxy to the drivers' response because only a fraction of the traffic can be detected using Bluetooth sensors. Although one cannot conclude with certainty that drivers changed their original route as a result of DMS recommendations, the change in the traffic pattern at the time of message display is noticeable and can be interpreted as the effectiveness of the dynamic message signs. These results confirm parts of the findings in (17).

Chapter 4: Localized Impacts

4.1: Motivation

The State of Maryland began providing motorists with nearly real-time travel time information using DMS in January 2010. Although much of the public response to these messages was positive, some motorists and media outlets renewed complaints that DMS messages caused vehicles to slow down, which resulted in congestion and caused safety issues. To investigate these claims, the effects of several highway DMS were evaluated by their proximity to one-minute interval RTMS speed sensors. In total, six DMS-RTMS pairs were selected for evaluation. In all of the cases, the RTMS were installed prior to and within sight distance of the DMS.

The evaluation process consisted of two analyses. The first analysis compared average traffic speeds of vehicles in consecutive five-minute periods during which the DMS operational condition changed. In the second analysis, traffic stream speeds were averaged in two-week periods to determine the impact on traffic under different DMS operational scenarios. The purpose of this study is to determine whether using DMS on Maryland highways presents significant localized safety hazards or congestion problems. The data used and methods are described in detail below.

4.2: Methodology

4.2.1: Data Sources and Preparation

The data used in this analysis were collected from the University of Maryland Center for Advanced Transportation Technology (CATT). The data were DMS message logs for each DMS and one-minute interval speed data provided by pole-mounted, side-fired Remote Traffic Monitoring Sensors (RTMS). In each case, DMS were selected so the corresponding RTMS was within forward sight distance of the DMS (Figure 4.1). Six cases are included in this study (See Table 4.1). For each DMS-RTMS pair, data was retrieved for a period starting January 1, 2010, and ending February 28, 2011. In some cases, data gaps existed such that all months in the range were not available for analysis.

Table 4.1. DMS Locations and Distance to RTMS

DMS #	Distance from RTMS	Location
839	150 ft	I-95 SB @ Exit 55
3316	1800 ft	I-95/495 NB Outer Loop North of MD 202
3317	1900 ft	I-95/495 SB Inner Loop @ Good Luck Road
4401	785 ft	I-695 SB Outer Loop @ Exit 12B
4403	50 ft	I-695 SB Outer Loop @ Exit 10
8557	50 ft	I-895 NB past Ritchie Spur

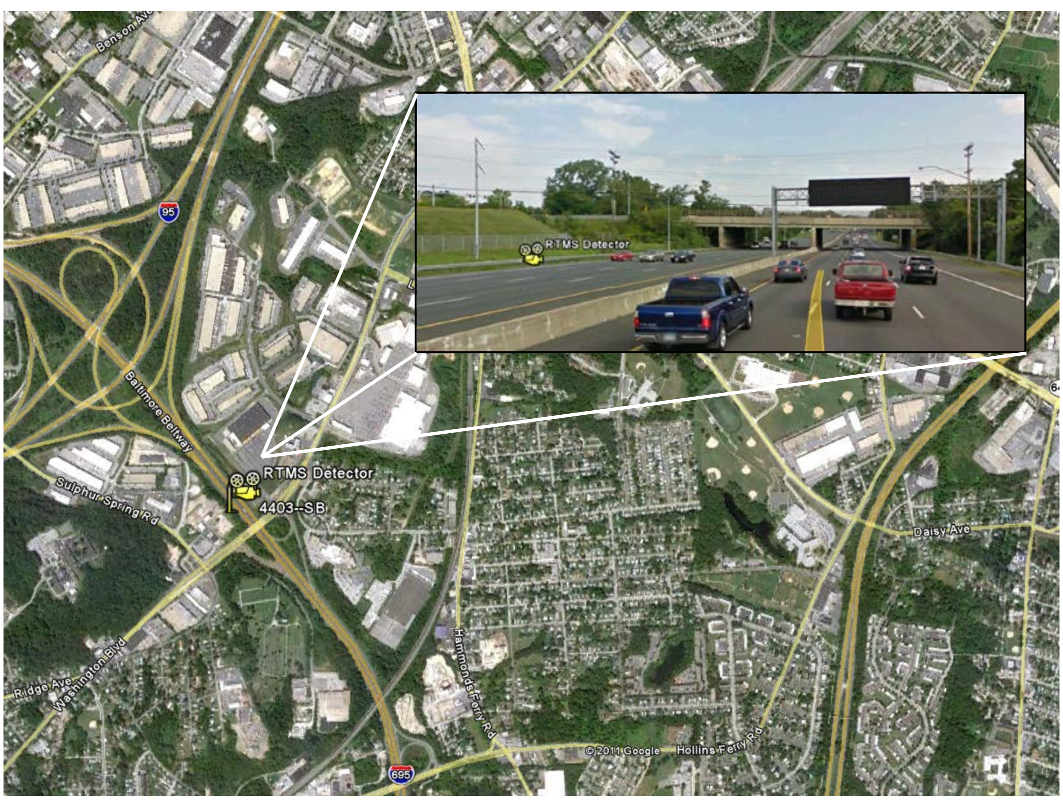


Figure 4.1. Sample DMS-RTMS Pair

In order to analyze these data, the DMS and RTMS data needed to be in the same units. The raw DMS data were in inconsistent time intervals because the time interval was controlled by when messages were initiated, changed or removed. In order to match the DMS data to the one-minute interval RTMS speed data, an Excel Macro code was written to increment the DMS data in one-minute intervals. The resulting minute-by-minute DMS logs were then matched by their timestamps to the RTMS speed data and the corresponding quality scores. Speed data receiving quality scores other than zero (zero indicates a valid score) were discarded. Due to observed inconsistencies in the data and low traffic volumes, the data were filtered to remove observations between the hours of 19:00 and 6:00 the next day. For the first analysis, data from weekends were also excluded.

When necessary, as described in the following sections, messages were categorized into three types based on the ideas proposed by Ridgeway (6). The types are as follows: Danger/Warning Messages, Informative/Common Road Conditions and Regulatory/Non-Traffic Related. Some common messages falling into each category can be seen in Table 4.2.

Table 4.2. Message Categorization Summary and Examples

Message Category	Common Examples
Type 1 **Danger/Warning**	Accidents, Disabled Vehicles, Non-recurring Slow-Downs, Roadway Debris, Unplanned Lane/Tunnel/ Bridge Closures
Type 2 **Informative/Common Road Condition**	Roadwork Closures, Major & Minor Delays, Congestion, Travel Time, Other travel related messages (Fog, Ice, Snow Plowing, Major Events)
Type 3 **Regulatory/Non-Traffic Related**	Work Zone Speeds, Seatbelt Use, Cell Phone Regulations, Motorcycle Awareness, Amber & Silver Alerts, Homeland Security Messages

4.2.2: Consecutive Five Minute Data Analysis

This study examined speed changes in consecutive five-minute periods in which the DMS operational condition changed. The types of operational conditions considered were off-on, on-off and switching. In the off-on condition, the DMS is off in the first five minutes and on with a displayed message in the following five minutes. The on-off condition is the exact opposite (i.e., on and displaying a message for the first five minutes, off for the following five minutes). The final condition, switching, is a situation in which the DMS is on for the entire ten minute investigation period. The two five-minute periods are differentiated by a significant change in the message content.

Cases were selected manually by combing through the minute-by-minute DMS-speed datasets and isolating those instances when the DMS operational condition changed. Each case was then sorted and stored into one of the three operational conditions (off-on, on-off or switching). Cases with congestion (indicated by low traffic speeds) were not included for analysis.

To determine the effects of the changing DMS operational condition on traffic speeds, the one-minute interval speeds in each consecutive five-minute period were compared using paired *t*-tests at 95 percent confidence level. The null hypothesis is that there is no difference in mean speeds between consecutive periods. On the other hand, the alternative hypothesis is that the difference between the means is some value not equal to zero. They are written as follows:

$$H_0: \mu_2 - \mu_1 = 0$$

$$H_1: \mu_2 - \mu_1 \neq 0$$

The total number of significant speed changes was tabulated. For each sample case, the difference in average speed between the first five minutes and the following five minutes was calculated. For significant cases, the overall average speed change was calculated. Each case was then assigned a category per Ridgeway's previously described scheme in order to examine differences in effects over message types.

4.2.3: Aggregate Two Week Speed Analysis

To assess the effects of DMS messages on absolute travel speed over longer periods, two 14-day periods were selected for analysis for each DMS. Each message was assigned into one of the three categories. The messages were then run through the minute-by-minute incrementing macro, and then matched by their timestamps to the one-minute RTMS speed data. As in the previous analysis, speed data and the corresponding messages with a quality score other than zero were discarded.

Using the categorization, average speeds over the two-week periods for each message type were determined. The five averages taken for each two-week period were the overall speed, speed during all messages, speed during no messages, and speeds during type 1, 2, and 3 messages. In addition, the fraction of the observations that fell into each message type was recorded. Using this information, any trends that exist over message types could be identified.

4.3: Findings

4.3.1: Consecutive Five Minute Data Analysis

In total, 2,268 cases of consecutive five-minute DMS operational condition change were analyzed. This total was broken down over the three condition types: off-on, on-off and switching. 842, 701, and 725 cases were available, respectively. Table 4.3 shows the complete breakdown by DMS # and operational condition. As discussed in (*21*), in the off-on condition we expect speeds will tend to decrease due to the added task of message comprehension. Conversely, we would anticipate speeds increasing in the on-off condition since the traffic in the second five-minute period would no longer be influenced by the message. The switching condition presents a situation in which the expected effects are dependent on the messages in the consecutive periods. For instance, it would be expected that a change from a message related to seatbelt use to a message informing drivers of a nearby road closure would result in a speed reduction.

Table 4.3. # Cases by DMS and Operational Condition

DMS #	Off-On	On-Off	Switching	Total
839	96	83	76	255
3316	74	65	146	285
3317	151	76	93	320
4401	215	163	259	637
4403	101	88	68	257
8557	205	226	83	514
	842	701	725	2268

To test these hypotheses, the number of statistically significant cases of speed increases and decreases were tabulated for each DMS and operational condition. These numbers were used to find the percent of cases in which statistically significant increases or decreases were observed. The average speeds over the significant cases were also calculated to determine the extent of the impact.

Off-On

There were significant speed decreases in 144 cases and significant speed increases in 101 cases in which the DMS condition changed from off to on. These numbers represent 17.1 percent and 12.0 percent of the 842 total cases, respectively. In terms of speed, the average decrease over significant cases was -3.12 mph, while the average increase was 2.34 mph. The breakdown over DMS is shown in Table 4.4 and Figure 4.2.

We can infer from these results that in the case of the Off-On condition, drivers tended to slow down more often than they speed up, confirming the general hypothesis. It is observed that the lowest ratios of significant changes in speed occur for the DMS-RTMS pairs that are the furthest apart (i.e. 3316 & 3317). Interestingly, there also appears to be a tendency of those DMS with higher incidence of significant decreases to have a higher incidence of significant increases. This may indicate that the cause of the increases or decreases is not a function of the DMS, but rather the general heterogeneity of the traffic stream.

While the percentage of significant speed changes may suggest a problem exists with respect to message display, the average changes in speed appear to mitigate this concern. Overall, the average speed change for significant decreases is -3.13 mph. Over a ten-minute period, this change in speed is unlikely to cause the congestion reported by some users. Another important consideration is that in 82.9 percent of all cases, there is either no significant change in traffic speeds or there is a significant increase in traffic speed.

Table 4.4. Off-On Summary by DMS

DMS #	**839**	**3316**	**3317**	**4401**	**4403**	**8557**	**Total**
Total Cases	96	74	151	215	101	205	842
# of Significant Decreases	15	9	15	41	13	51	144
% Cases Significant	15.63 %	12.16 %	9.93 %	19.07 %	12.87 %	24.88 %	**17.10 %**
Weighted Average Decrease	-1.80	-2.28	-5.90	-3.15	-3.30	-2.79	-3.13
# of Significant Increases	19	6	13	24	11	28	101
% Cases Significant	19.79 %	8.11 %	8.61 %	11.16 %	10.89 %	13.66 %	**12.00 %**
Weighted Average Increase	1.89	2.92	2.85	2.51	3.50	1.69	2.34

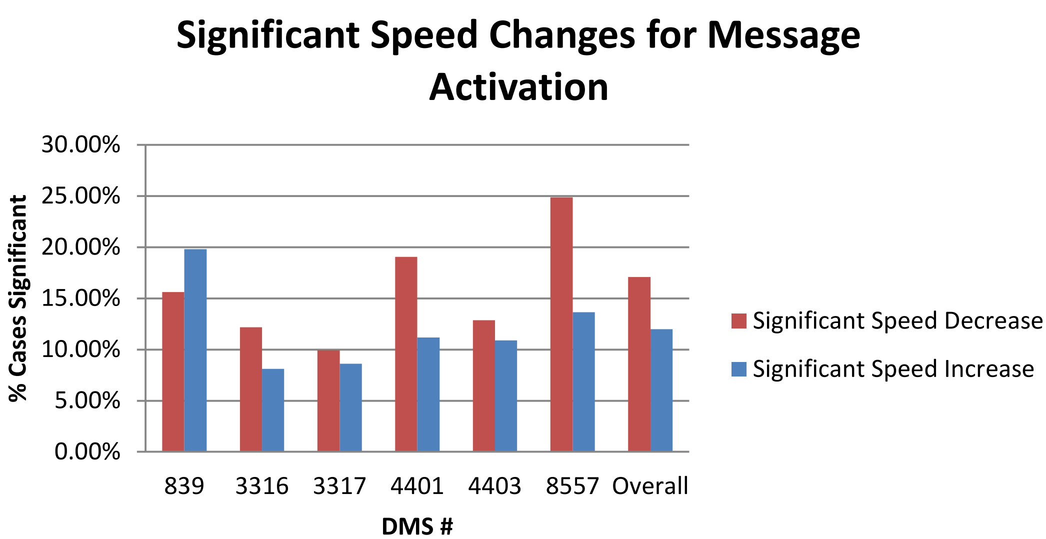


Figure 4.2. Graph of Off-On Summary by DMS

Because many of the concerns about the DMS messages stemmed from a particular message type, namely travel time messages, the overall cases must be broken down into more specific categories. Table 4.5 and Figure 4.3 show the off-on cases disaggregated into message types.

Table 4.5. Off-On Summary by DMS and Message Type

DMS #	839	3316	3317	4401	4403	8557	Total
# Type 1 Cases	11	20	49	33	4	38	155
# of Significant Decreases	2	5	6	12	0	9	34
% Significant	18.18 %	25.00 %	12.24 %	36.36 %	0.00 %	23.68 %	**21.94 %**
# of Significant Increases	1	2	1	2	0	2	8
% Significant	9.09 %	10.00 %	2.04 %	6.06 %	0.00 %	5.26 %	**5.16 %**
# Type 2 Cases	84	35	45	127	68	167	526
# of Significant Decreases	12	1	7	25	9	29	83
% Significant	14.29 %	2.86 %	15.56 %	19.69 %	13.24 %	17.37 %	**15.78 %**
# of Significant Increases	18	1	5	15	5	20	64
% Significant	21.43 %	2.86 %	11.11 %	11.81 %	7.35 %	11.98 %	**12.17 %**
# Type 3 Cases	1	19	57	55	29	56	217
# of Significant Decreases	1	3	2	4	4	13	27
% Significant	100.00%	15.79 %	3.51%	7.27%	13.79 %	23.21 %	**12.44 %**
# of Significant Increases	0	3	7	7	6	6	29
% Significant	0.00%	15.79 %	12.28 %	12.73 %	20.69 %	10.71 %	**13.36 %**

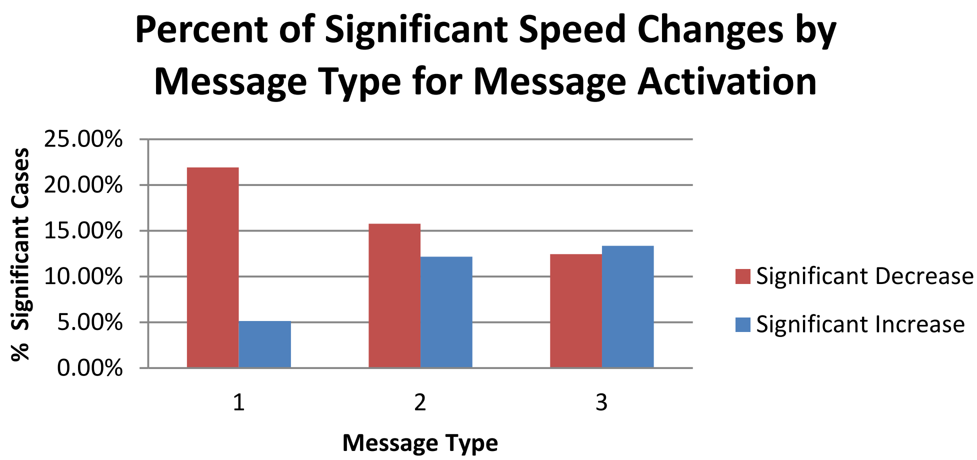


Figure 4.3. Graph of Off-On Summary by Message Type

When grouped this way, the data show the message type that causes significant decreases in speed most often are Danger/Warning messages, followed by Informative/Common Road Condition messages, and finally, Regulatory/Non-Traffic-Related messages. This hierarchy is as expected because Danger/Warning messages are commonly urgent and safety-related and should therefore draw the most attention. Additionally, Danger/Warning messages usually indicate an incident that would create congestion downstream, such as road closures or accidents. Informative/Common Road Condition messages, which include travel-time messages, are usually less urgent and caused a lower proportion of disruptions than Danger/Warning messages, as expected. Interestingly, the two DMS in the study that display travel-time messages, 839 and 3317, did not show an increase in the percentage of significant cases of speed decrease. In fact, such data is lower than the average, and DMS 839 is the only DMS that shows a higher percentage of significant increases than significant decreases for Informative/Common Road Condition messages. The data for Regulatory/Non-Traffic-Related messages indicate these messages either go unnoticed, or users interpret them to mean there are no disruptions ahead, both of which result in speed increases. This finding may be because Regulatory/Non-Traffic-Related messages include information that most drivers already know (e.g., seatbelt and cell phone laws).

The findings from the off-on analysis indicate that in the majority of cases, traffic speeds are either unaffected or increase when messages appear on a DMS. When traffic does respond negatively to the messages, the average decrease in speed is just over three miles per hour. When broken down by message type, the data showed that DMS that include travel-time messages do not produce higher fractions of significant speed decreases than their counterparts.

On-Off

Similar to the off-on analysis, cases were examined for situations in which the DMS switched from on to off. From this analysis, we find that traffic speed decreases significantly in 11.98 percent of cases and increases significantly in 19.69 percent of cases. This finding supports the general hypothesis that drivers will increase speeds as a result of the removal of a message. Looking closer at the data (Table 4.6, Figure 4.4), we find that in four of the six DMS, the discrepancy between significant increases and decreases is much smaller. In fact, in the two DMS where the difference is quite large (i.e. 4401 & 8557), the differences in the off-on analysis were also relatively large compared to the other four. One interpretation from this finding is that those two locations have traffic streams that are much more sensitive to environmental changes than other locations.

Table 4.6. On-Off Summary by DMS

DMS #	**839**	**3316**	**3317**	**4401**	**4403**	**8557**	**Total**
Total Cases	83	65	76	163	88	226	701
# of Significant Decreases	9	10	14	10	11	30	84
% Cases Significant	10.84 %	15.38 %	18.42 %	6.13 %	12.50 %	13.27 %	**11.98 %**
Weighted Average Decrease	-2.01	-2.35	-5.26	-2.70	-3.05	-1.63	-2.68
# of Significant Increases	7	9	13	28	13	68	138
% Cases Significant	8.43 %	13.85 %	17.11 %	17.18 %	14.77 %	30.09 %	**19.69 %**
Weighted Average Increase	2.23	2.91	4.77	2.75	3.36	2.18	2.70

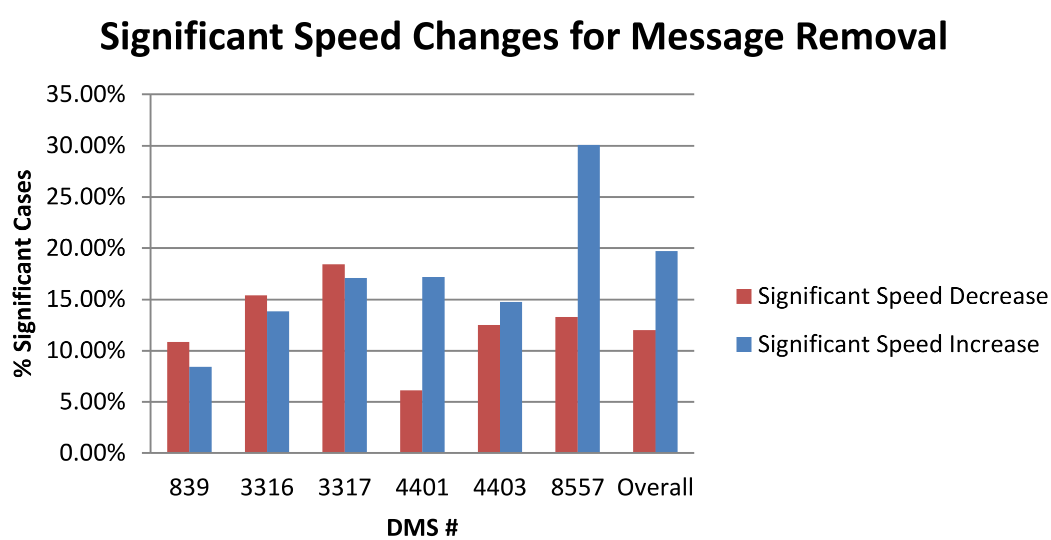


Figure 4.4. Graph of Off-On Summary by DMS

To see if these effects were a function of message type, a similar breakdown was performed as in the off-on analysis. Table 4.7 and Figure 4.5 show the case summary broken down by message categorization.

Table 4.7. On-Off Summary by DMS and Message Type

DMS #	839	3316	3317	4401	4403	8557	Total
# Type 1 Cases	9	18	30	20	3	12	92
# of Significant Decreases	0	4	4	1	0	1	10
% Significant	0.00 %	22.22 %	13.33 %	5.00 %	0.00 %	8.33 %	**10.87 %**
# of Significant Increases	1	3	1	6	3	2	16
% Significant	11.11 %	16.67 %	3.33 %	30.00 %	100.00 %	16.67 %	**17.39 %**
# Type 2 Cases	73	37	46	103	62	159	480
# of Significant Decreases	9	6	6	6	8	23	58
% Significant	12.33 %	16.22 %	13.04 %	5.83 %	12.90 %	14.47 %	**12.08 %**
# of Significant Increases	6	4	6	17	6	57	96
% Significant	8.22 %	10.81 %	13.04 %	16.50 %	9.68 %	35.85 %	**20.00 %**
# Type 3 Cases	1	10	40	40	23	55	169
# of Significant Decreases	0	0	4	3	3	6	16
% Significant	0.00 %	0.00 %	10.00 %	7.50 %	13.04 %	10.91 %	**9.47 %**
# of Significant Increases	0	2	6	5	4	9	26
% Significant	0.00 %	20.00 %	15.00 %	12.50 %	17.39 %	16.36 %	**15.38 %**

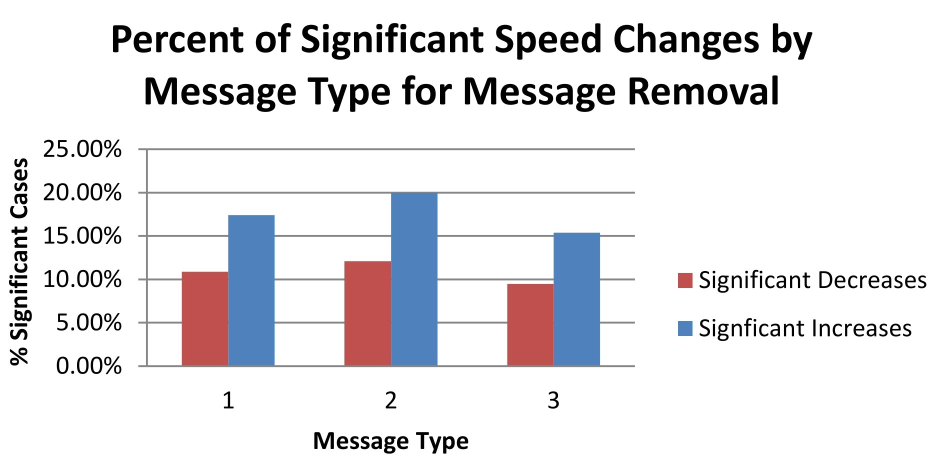


Figure 4.5. Graph of On-Off Summary by Message Type

The findings in this case are less clear. Although all three message types show a higher percentage of cases where drivers significantly increased their speeds than when drivers significantly decreased their speeds, differences among message types are unclear. Informative/Common Road Condition messages show the highest rate of significant speed increases, followed by Danger/Warning messages and finally Regulatory/Non-Traffic-Related. This finding may indicate removing Informative/Common Road Condition messages reduces drivers' cognitive load. Conversely, it could be interpreted that these messages relate to less severe influences on the traffic stream, and thus, speeds are expected to recover more quickly when the messages are no longer applicable. Similar arguments could be made for the other two messages types. In the case of Regulatory/Non-Traffic-Related messages, the relatively low percentage of significant increases is expected due to the low percentage of significant decreases found in the previous analysis.

The findings from the on-off analysis indicate removing a message tended to increase traffic speeds in approximately 20 percent of cases. The average speed increase across these cases was 2.7 mph. Again, these results indicate in most cases, traffic is unaffected by the messages displayed on DMS, and any influence on overall traffic speeds is relatively small.

Switching

In many cases, especially on signs displaying travel-time messages, a DMS message may be supplanted by a more important message, or reverted from an applicable message to a default message. Analysis of these cases revealed drivers significantly sped up in 13.52 percent of cases but significantly slowed down in 11.72 percent. The corresponding changes in speed were -3.14 and 2.44 mph. The similar rates indicate the switching condition does not tend to influence traffic conditions one way more than it does the other.

Table 4.8 and Figure 4.6 show that in four of the six cases, the rates of significant increase and decrease are either identical or nearly so. The other two cases show traffic tends to decrease speed in response to a change in message.

Table 4.8. Switching Summary by DMS

DMS #	**839**	**3316**	**3317**	**4401**	**4403**	**8557**	**Total**
Total Cases	76	146	93	259	68	83	725
# of Significant Decreases	16	18	8	30	10	16	98
% Cases Significant	21.05 %	12.33 %	8.60 %	11.58 %	14.71 %	19.28 %	**13.52 %**
Weighted Average Decrease	-2.21	-2.56	-3.38	-2.60	-3.47	-5.41	-3.14
# of Significant Increases	9	17	8	30	4	17	85
% Cases Significant	11.84 %	11.64 %	8.60 %	11.58 %	5.88 %	20.48 %	**11.72 %**
Weighted Average Increase	2.11	1.97	2.97	2.28	4.50	2.62	2.44

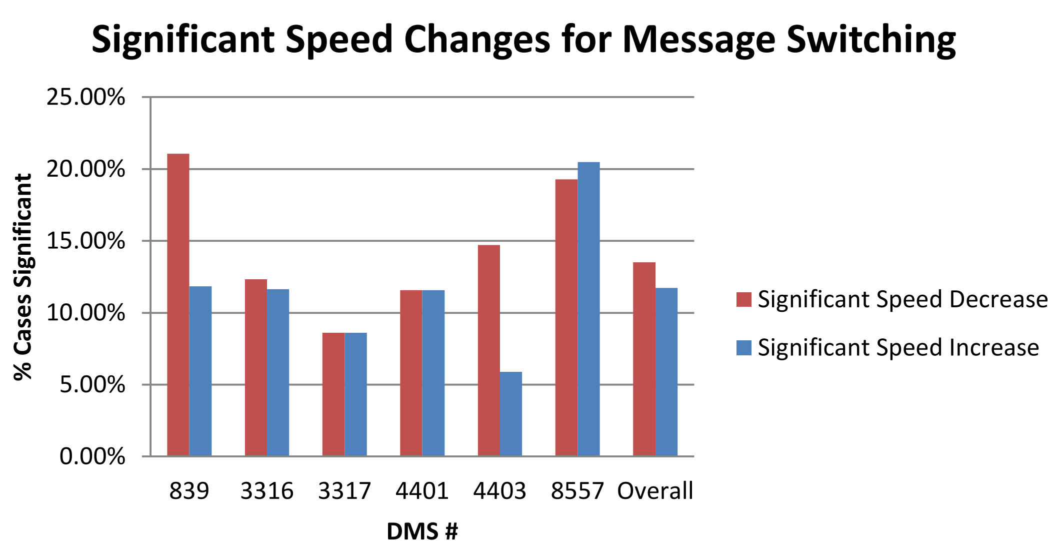


Figure 4.6. Graph of Switching Summary by DMS

In the message-switching condition, there are nine sub-conditions that can occur: 1-1, 1-2, 1-3, 2-1, 2-2, 2-3, 3-1, 3-2, 3-3, where the first number is the starting message type and the second number is the ending message type. (For example, a 2-1 condition could be a switch from a travel time message to an accident message. A breakdown by these sub-conditions is made in Table 4.9. Overall, the percentage of cases of significant increase and decrease are nearly the same. When examined over each DMS, there do not appear to be any appreciable patterns within the data. This is likely due to the low number of cases for each message-switching condition.

After examining 2,268 cases, the data indicate the majority of traffic streams are unaffected by the display, removal or change of a DMS message. In the cases where message initiation influenced a significant decrease in speed, drivers were most sensitive to Danger/Warning messages, followed by Informative/Common Road Condition messages and Regulatory/Non-Traffic-Related messages, respectively. DMS locations that display travel-time messages were not found to be more sensitive to message appearance than those that do not. In the on-off analysis, traffic was found to speed up more often than it slowed down. It is not clear whether this was a result of message removal or of dissipation of the conditions the message described. The switching analysis indicated more evenly split results, indicating no appreciable bias in speed impact during a change from one message to another.

Table 4.9. Switching Summary by DMS and Message Types

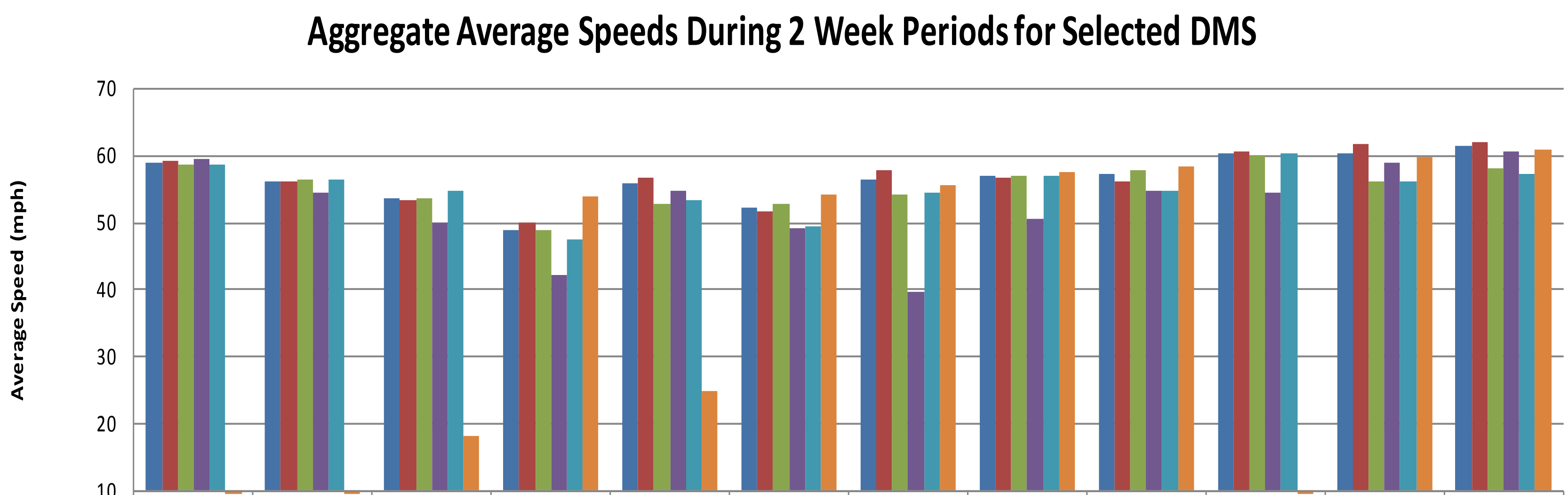
DMS #	839	3316	3317	4401	4403	8557	Total
# Type 11 Cases	1	3	7	1	1	0	13
# of Significant Decreases	0	1	0	0	0	0	1
% Cases Significant	0.00%	33.33%	0.00%	0.00%	0.00%	-	**7.69%**
# of Significant Increases	0	0	2	0	0	0	2
% Cases Significant	0.00%	0.00%	28.57%	0.00%	0.00%	-	**15.38%**
# Type 12 Cases	14	24	8	41	3	12	102
# of Significant Decreases	4	4	0	7	0	5	20
% Cases Significant	28.57%	16.67%	0.00%	17.07%	0.00%	41.67%	**19.61%**
# of Significant Increases	2	2	0	8	0	4	16
% Cases Significant	14.29%	8.33%	0.00%	19.51%	0.00%	33.33%	**15.69%**
# Type 13 Cases	0	5	11	11	3	6	36
# of Significant Decreases	0	0	1	2	0	0	3
% Cases Significant	-	0.00%	9.09%	18.18%	0.00%	0.00%	**8.33%**
# of Significant Increases	0	2	1	0	0	0	3
% Cases Significant	-	40.00%	9.09%	0.00%	0.00%	0.00%	**8.33%**
# Type 21 Cases	15	32	10	42	3	11	113
# of Significant Decreases	2	2	4	6	0	2	16
% Cases Significant	13.33%	6.25%	40.00%	14.29%	0.00%	18.18%	**14.16%**
# of Significant Increases	1	7	1	5	0	2	16
% Cases Significant	6.67%	21.88%	10.00%	11.90%	0.00%	18.18%	**14.16%**
# Type 22 Cases	35	28	16	92	21	35	227
# of Significant Decreases	8	5	1	6	4	5	29
% Cases Significant	22.86%	17.86%	6.25%	6.52%	19.05%	14.29%	**12.78%**
# of Significant Increases	3	2	1	10	3	9	28
% Cases Significant	8.57%	7.14%	6.25%	10.87%	14.29%	25.71%	**12.33%**
# Type 23 Cases	6	24	15	26	13	3	87
# of Significant Decreases	1	3	1	4	2	1	12
% Cases Significant	16.67%	12.50%	6.67%	15.38%	15.38%	33.33%	**13.79%**
# of Significant Increases	2	1	0	2	0	1	6
% Cases Significant	33.33%	4.17%	0.00%	7.69%	0.00%	33.33%	**6.90%**
# Type 31 Cases	0	6	17	11	4	5	43
# of Significant Decreases	0	1	1	2	1	1	6
% Cases Significant	-	16.67%	5.88%	18.18%	25.00%	20.00%	**13.95%**
# of Significant Increases	0	0	1	1	0	0	2
% Cases Significant	-	0.00%	5.88%	9.09%	0.00%	0.00%	**4.65%**
# Type 32 Cases	5	23	9	33	15	10	95
# of Significant Decreases	1	2	0	3	3	2	11
% Cases Significant	20.00%	8.70%	0.00%	9.09%	20.00%	20.00%	**11.58%**
# of Significant Increases	1	2	2	4	1	1	11
% Cases Significant	20.00%	8.70%	22.22%	12.12%	6.67%	10.00%	**11.58%**
# Type 33 Cases	0	1	0	2	5	1	9
# of Significant Decreases	0	0	0	0	1	0	1
% Cases Significant	-	0.00%	-	0.00%	20.00%	0.00%	**11.11%**
# of Significant Increases	0	1	0	0	0	0	1
% Cases Significant	-	100.00%	-	0.00%	0.00%	0.00%	**11.11%**

4.3.2: Aggregate Two Week Speed Analysis

For the same DMS used in the five-minute analysis, two two-week periods were selected for aggregate analysis. These findings should indicate whether the display of certain types of messages result in congestion. Figure 4.7 shows the 12 two-week periods along with their average speeds under different message conditions. Figure 4.8 shows these values normalized over their corresponding overall average speeds. For the most part, the trends show that traffic is most influenced by Type 1 messages.

Overall, Danger/Warning messages accounted for 1.5 percent of the total study times, Informative/Common Road Condition messages for 34 percent and Regulatory/Non-Traffic-Related messages for 12.5 percent. In the remaining time, the signs were blank. The low proportion of time Danger/Warning messages were displayed indicates these messages are unlikely to appear on a daily basis. Therefore, drivers would not be used to the messages and may reduce speeds more to attend to them. In two cases (DMS 3316 and DMS 3317 in January 2011), Regulatory/Non-Traffic-Related messages seem to have had a significant impact on traffic speeds. However, in both cases these messages were displayed for less than one percent of the overall two-week period (approximately 1.5 hours each). This time-length information indicates the messages in these cases could not have caused recurring congestion.

Informative/Common Road Condition messages have the greatest potential to create congestion because of the large proportion of time they are displayed. The findings show speeds during these types of messages ranged from four mph below to one mph above the speeds found when no messages were displayed. These speeds indicate either light or no congestion during message displays. Also, only three of 12 cases yielded speeds more than one mph below the posted speed limit during the times these types of messages were displayed. In two of these three cases, the overall average speeds were already below the speed limit.



	839 Jan '11	839 July '10	3316 Jan '11	3316 May '10	3317 Jan '11	3317 May '10	4401 Jan '11	4401 May '10	4403 Dec '10	4403 Mar '10	8557 Jan '11	8557 May '10
Overall	58.8	56.06	53.43	48.93	55.64	52.21	56.43	56.81	57.24	60.19	60.16	61.22
No Message	59	55.99	53.3	49.87	56.61	51.67	57.67	56.52	56.02	60.53	61.59	61.79
All Message	58.67	56.25	53.66	48.87	52.66	52.79	54.06	56.98	57.8	60.09	56.15	57.95
Type 1	59.32	54.35	49.93	42.03	54.55	49.14	39.6	50.42	54.7	54.25	58.81	60.49
Type 2	58.66	56.29	54.54	47.47	53.15	49.22	54.37	56.77	54.6	60.13	56.02	57.21
Type 3	0	0	18	53.86	24.94	54.12	55.5	57.48	58.35	0	59.57	60.84

Figure 4.7. Aggregate Average Speeds for Two Week Analysis

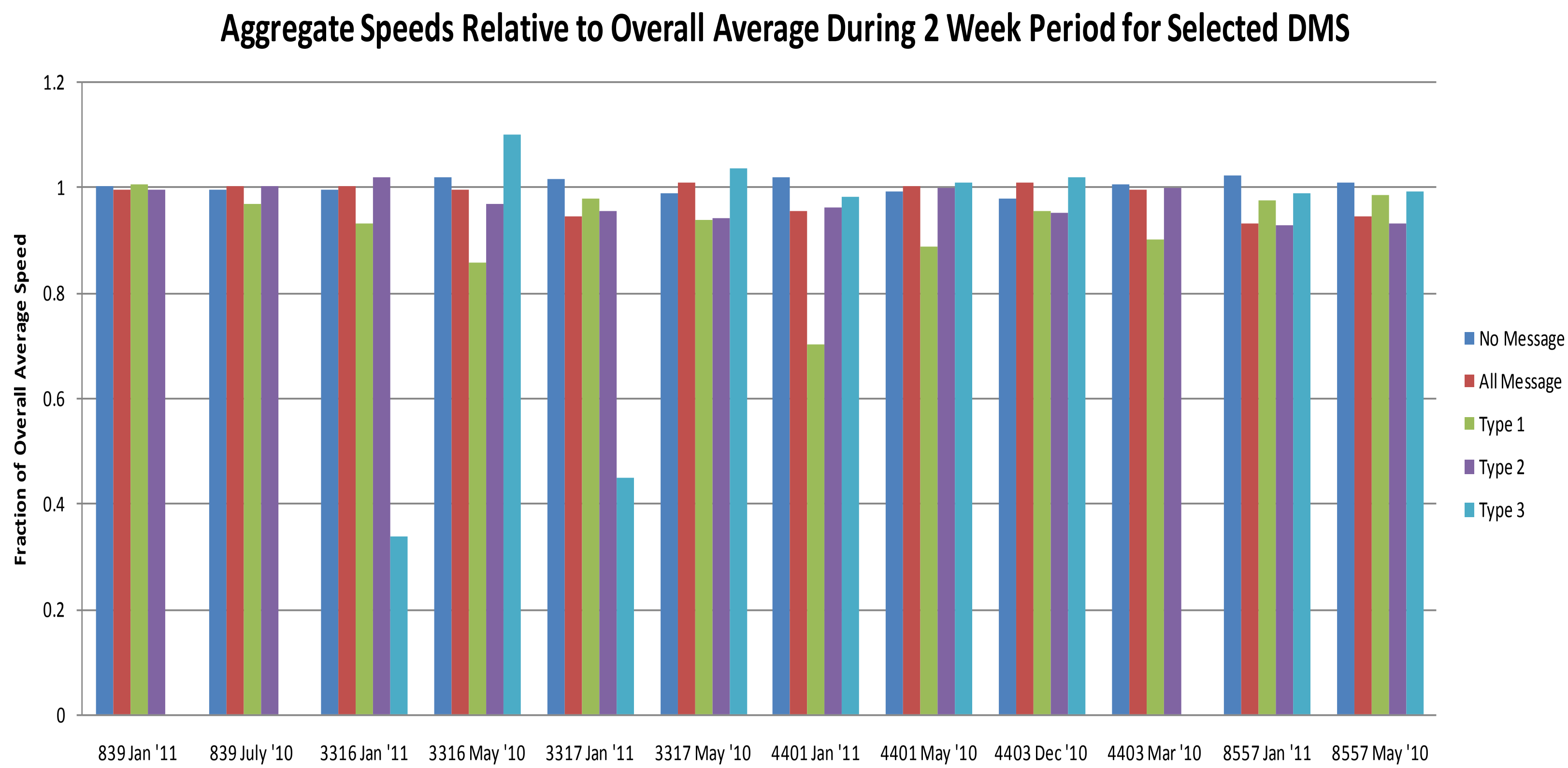


Figure 4.8. Aggregate Speeds Normalized by Overall Average Speeds

In summary, the aggregate analysis shows average speeds during Danger/Warning message display are generally lower than speeds during blank sign conditions. However, the occurrence of these messages is rare and therefore could not be the cause of recurring congestion. Informative/Common Road Condition messages are displayed more often and in some cases resulted in decreased traffic speeds. In the majority of the cases, however, the speeds were not below the posted speed limit. Speeds during Regulatory/Non-Traffic-Related messages are usually higher than the other message types. In the cases where they were much lower, they accounted for less than one percent of the overall study time.

Chapter 5: Conclusions and Future Work

This project presented empirical evaluations of the quality, effectiveness and localized effects of highway Dynamic Message Signs (DMS). This project used Bluetooth sensor technology as a new method for evaluating DMS messages' accuracy and influence on motorist behavior. Two sensor deployments were undertaken for this purpose and several message cases were selected from each for evaluation. To determine whether DMS messages cause localized effects (i.e., drivers change speed), 2,268 cases of message activation, removal and switching were analyzed using RTMS speed data. In addition, the cases were sorted into categories to determine if any trends exist with respect to message types.

The first deployment revealed that the Bluetooth data was an effective tool for evaluating DMS messages. It was determined the messages being displayed accurately described many of the prevailing conditions, although they suffered from late display and removal of messages. In addition, the messages used vague location descriptors, giving drivers no indication of where traffic disruptions were occurring.

The second deployment confirmed the effectiveness and repeatability of Bluetooth traffic detection as a tool to evaluate DMS messages. The second deployment found the DMS system had improved. Messages used more specific terms to describe congestion locations. The messages also provided travel-time messages. The travel-time messages alleviated some of the concerns with late message display because motorists could observe travel times increasing in response to congestion. In some cases, messages were left on longer than necessary, although there were some mitigating circumstances.

In addition to evaluating congestion and delay messages, Bluetooth travel times were used to validate the travel times displayed on the DMS. Analyses of nearly 24 hours of data from two travel time cases revealed the average difference between the displayed and true travel times was less than one mile per hour. This confirms the source data and updating system used on DMS in Maryland is high quality. Nevertheless, the Bluetooth travel time evaluation is applicable to any DMS travel time system independent of the source of the DMS travel-time data.

To determine the effectiveness of DMS messages, counts of Bluetooth detections on alternate routes suggested by the messages were compared. Analyses of three cases showed a 5-20 percent increase of traffic diversion rates on alternate routes during periods when DMS messages recommended drivers take those alternate routes. It can be inferred from this finding that DMS messages influence drivers' route choices. However, because of the sampling rate of Bluetooth sensors, this conclusion must be tentative. Even with this caveat, Bluetooth detection can be used as a powerful tool for evaluation of traffic diversion.

Evaluation of RTMS speed detector data in proximity to DMS revealed that in some cases, traffic streams do decrease speed in response to message activation. Danger/Warning message displays were associated with the highest percentage of speed decreases. An aggregate analysis showed that overall traffic speeds were slower during Danger/Warning messages, although these messages appeared infrequently. Similar analyses on message removal and switching were performed. Overall, the majority of traffic streams either increased in speed or did not change speed in response to DMS messages. The most frequently appearing message was

Informative/Common Road Condition messages. These messages tended to correspond with lower traffic speeds than periods with blank signs. It is unclear whether these reduced traffic speeds are a result of the message display or of the conditions (e.g. accident ahead) to which the messages correspond.

In summary, the findings from these evaluations indicate DMS can be an accurate, effective, and safe tool for disseminating real-time travel information to motorists. This project focused on Maryland DMS, so the findings may not extend to DMS operations in other states. Nevertheless, the methods employed for evaluation are extendable without regard for the DMS location.

In the future, Bluetooth sensors can be used to evaluate DMS in other locations throughout Maryland and other states. More deployments will strengthen the reputation of Bluetooth as a DMS evaluation tool and will build broader knowledge about DMS operations. In order to validate diversion patterns observed through Bluetooth detection, a deployment could be undertaken in parallel with license plate-reading technology. If the findings from such a study showed a strong correlation between Bluetooth and license plate detections, the use of Bluetooth for tracking origin destination and diversion would be strengthened.

To further investigate the localized effects of DMS on traffic streams, the use of small, portable speed sensors could be employed. By spacing such sensors at fixed intervals in proximity to DMS, speed profiles could be built as vehicles approach the signs. In addition, accident data could be analyzed to determine if there are any indications that the existence of a DMS results in higher accident rates.

The methods employed in this project can be applied to any DMS operation and could be used to evaluate locations before and after installation of DMS. It would be informative to learn what effect the installation of a DMS has on a traffic stream in terms of travel time and diversion patterns.

Ultimately, findings from future studies can be used to calibrate traffic simulations and build automated message display and incident detection systems. These technologies would help transportation engineers and planners improve DMS operations and in turn overall network conditions. The broad range of future study will provide challenges and opportunities for many researchers in the coming years.

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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

EVALUATION OF DYNAMIC MESSAGE SIGNS AND THEIR POTENTIAL IMPACT ON TRAFFIC FLOW

Volume II: Impact of Dynamic Message Signs on Occurrence of Road Accidents

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Abstract

Dynamic Message Signs (DMS) are key components of Advanced Traveler Information Systems (ATIS). DMS is used to manage transportation networks, reduce congestion and improve safety by providing motorists with real-time information regarding downstream traffic conditions. Although DMS are intended to improve efficiency and safety of road networks, there have been few studies on the effect of the signs on driver safety or the signs' localized safety effects. This project employs ground truth data as the basis to investigate these matters in Maryland over a four-year period (2007-2010). The results show no significant difference between the accident pattern in the proximity of DMS and onward adjacent segments. An on-and-off study was also conducted on DMS operation status (on/off). These results converge with the previous analysis to suggest there is no meaningful relationship between occurrence of accidents and presence of DMS. Statistical analysis on DMS characteristics and accidents in impact areas were performed.

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Chapter 1: Introduction

1.1. Research Motivation and Objectives

Increasing traffic volumes over recent decades is the compelling motivation to manage transportation networks, increase capacity, enhance communication capabilities of transportation systems, improve safety and reduce congestion. Physically increasing the capacity of roadways and arterials by adding lanes is usually not economically and environmentally justified, and it is an ineffective long-term solution. One of the most popular alternate strategies is to provide travelers with real-time information about downstream traffic conditions using Advanced Traveler Information Systems (ATIS). Two of the main technologies employed in the ATIS effort are Highway Advisory Radio (HAR) and Dynamic Message Signs (DMS). DMS are often regarded as the most visible form of ATIS because they are available equally to all motorists. Maryland State Highway Administration's (SHA) Coordinated Highways Action Response Team (CHART) operates 184 DMS. The signs, located on major highways and arterials, are often used to inform motorists of delays, incidents, road closings and real-time travel estimates. The most popular types of messages displayed on DMS are weather conditions, travel time, construction information, speed limits, incident locations and various other public service announcements, including AMBER alerts. Although DMS are intended to improve the efficiency and safety of road networks, little has been done to study whether the signs affect driver safety. The purpose of this study is to determine if drivers exposed to DMS are distracted by what the signs display and, if so, whether that distraction leads to their involvement in traffic accidents.

Accident data and log of messages data in the study period were acquired from the Center for Advanced Transportation Technology (CATT) Laboratory at the University of Maryland, College Park and from Coordinated Highway Action Response Team (CHART) reports. Quality control and consistency check were conducted on the database. The DMS inventory was obtained from the CATT Laboratory. The DMS types in this investigation include permanently-mounted overhead signs, roadside models and portable signs operated by CHART or Maryland Transportation Authority (MdTA). The roadway network map and AADT of roadway segments were obtained from Maryland Department of Transportation and the SHA, and weather conditions databases were acquired from DOT archival data.

The locations of accidents and DMS and the AADT data were projected onto a Maryland roadway map in ArcGIS 10.1. An impact area was defined to perform spot analysis to evaluate whether DMS influences drivers' operational performance.

A case study was performed on a portion of Interstate 95 in Maryland, a roadway regarded as a major highway. A sample of 70 road segments was chosen based on homogeneity of their geometry. Regression analysis was performed; relevant predictor variables included the segment's status as an impact area (yes/no), whether the segment connects with interchanges (yes/no) and the segment's AADT. Additionally, an unbalanced two-way ANOVA was used to compare mean accident rates in impact areas and other segments.

The study area was divided into five regions, and the nearest central weather station in each region represented the weather condition in each region. The weather database was aggregated for the four-year study period and was joined to the main database based on proximity of weather station to the time and location of the accident. The matching process was performed using SQL queries coded in C++.

The message log database was imported in the SQL server and the main database. If an accident was in an impact area, the assigned DMS was matched with the message displayed at the time of the accident. This matching process was conducted using SQL queries coded in C++.

The integrated database was analyzed in several respects. Accident rates in DMS impact areas and adjacent segments were compared using paired *t*-tests in order to determine the effects of DMS on accidents occurrence.

An on-and-off study compared the results from the previous study. The difference in accident rates was tested on two DMS operation statuses (message display/blank) using a one-way ANOVA with pairwise comparison tests. Statistical analyses on DMS characteristics, message types, weather conditions and accidents in the impact areas were performed.

The findings of this project and the methods used to obtain them are widely applicable so state officials and transportation and ITS agencies can analyze, evaluate and ultimately improve their DMS operations. Although this project focused on DMS operations in Maryland, the methods employed for evaluation can be applied to other locations.

1.2. Organization of the report

This report has five chapters. Chapter 2 reviews the literature on DMS operations, design and type of messages displayed on DMS. Chapter 3 discusses driver behavior, drivers' response to messages and localized safety effects of these signs. It also provides a comprehensive review on study methods and research to evaluate effectiveness and safety effects of DMS. Chapter 4 investigates the relationship between DMS and occurrence of road accidents. It also describes the motivation, methodology, analyses and results of this project. Conclusions and suggestions for future research are found in Chapter 5.

Chapter 2: Background and Literature Review

2.1. Dynamic Messages Signs

The Maryland Manual on Uniform Traffic Control Devices defines a Dynamic Message Sign as “a sign that is capable of displaying more than one message, changeable manually, by remote control or by automatic control.” These signs are called Dynamic Message Signs in the National Intelligent Transportation Systems (ITS) Architecture. DMS are also known as Variable Message Signs (VMS) or Changeable Message Signs (CMS) and can be used by transportation authorities and operating agencies to disseminate travel information on a near real-time basis.

DMS are valuable instruments. The Deployment Tracking Database of Federal Highway Administration has data indicating that more than $330 million has been spent on deploying DMS in the United States (Dudek, 2008). The main goal of DMS is to enhance motorist safety and provide real-time traffic information to motorists, thus allowing them to make intelligent travel decisions.

2.2. DMS Process and Operations

The information displayed on DMS is gathered from a variety of traffic monitoring and surveillance systems, including video detection systems, loop detectors, automatic vehicle identification transponders and toll tags. All data are reported to Traffic Management Centers (TMC). Travel-time messages are derived from applying an algorithm that calculates distance covered in order to determine the estimated travel times from a DMS to a specific destination. The destination is usually a major intersection or interchange. In most jurisdictions, travel-time information is posted during morning and evening peak travel times; the system is usually timed to begin and end at a certain time of day. The TMC operator is responsible for monitoring and interpreting messages as well as making decisions about posting the messages.

2.3. DMS Types

Dynamic Message Signs can be divided into two types regarding method of installation: permanent and portable. DMS may also be equipped with beacons and/or flashing messages.

2.3.1. Portable vs. Permanent Signs

DMS can be permanent (overhead or roadside) or portable. Both permanent and portable DMS are used to manage incidents and inform motorists. Permanent DMS can be installed above arterials, highways, bridges, tunnels and toll plazas. Portable truck-or-trailer-mounted DMS can be dispatched by highway agencies to warn drivers of incidents (e.g., accidents or work zones) in areas where permanent DMS are not practical or available. Trailer-mounted DMS are used to alter traffic patterns near work zones and to manage traffic during special occasions (e.g., sporting events and natural disasters) that necessitate temporary changes in normal traffic patterns. Most manufacturers produce trailers that comply with the National Transportation Communications for Intelligent Transportation System Protocol (NTCIP), which allow the portable trailer to be integrated with intelligent transportation systems. Trailer-mounted DMS can be equipped with radar, cameras, and other sensing devices as part of a smart work zone deployment. Figure 2.1 shows permanent and portable DMS signs.

Figure 2.1. Permanent vs. portable DMS

2.3.2. Dynamic Features

DMS can be equipped with flashing beacons, which are typically installed on top of the message panel. Beacons are usually yellow in color and meet NTCIP requirements for size and shape. Messages displayed on DMS can also flash or blink and are used in areas such as school zones. However, flashing line messages may have an adverse effect on message comprehension of messages (Dudek, 2005), so these types of messages are not very common.

2.4. Message Types

DMS warn motorists about different situations and provide real-time information about traffic, roadway and environmental conditions, location and expected duration of incident-related delays, alternate routes for a roadway closure, redirected routes for diverted drivers and traversable shoulders in the event of a major incident to restore the traffic flow safely (Farradyne, 2000). However, DMS are primarily used to display the following messages (Dudek, 2008):

- Random and unpredictable situations such as crashes, stalled vehicles and spilled loads
- Temporary and preplanned activities such as construction, maintenance or utility operations
- Adverse environmental situations such as fog, floods, ice and snow
- Special events such as road closures for sport games and parades
- Traffic flow operational initiatives such as high occupancy, reversible, exclusive or contraflow lanes
- Certain design features such as drawbridges, tunnels and ferry services
- Travel-time information
- AMBER (America's Missing: Broadcast Emergency Response) alerts to help locate missing people

Ridgeway categorizes messages into three types: Danger/ Warning Messages, Informative/Common Road Conditions and Regulatory/Non-Traffic Related messages. Table 2.1 shows the type and example of messages in this classification.

Table 2.1. Message Categorization

Message Category	**Examples of Displayed Messages**
Type 1: Danger/Warning	Incidents, Disabled Vehicles, Non-recurring Slow-Downs, Roadway Debris, Unplanned Lane/Tunnel/ Bridge Closures
Type 2: Informative/Common Road Condition	Roadwork Closures, Major & Minor Delays, Congestion, Travel Time, Other travel-related messages (Fog, Ice, Snow Plowing, Major Events)
Type 3: Regulatory/Non-Traffic Related	Work Zone Speeds, Seatbelt Use, Cell Phone Regulations, Motorcycle Awareness, Amber Alerts, Homeland Security Messages

2.5. Danger/Warning Messages

2.5.1. Incident Messages

One of the main functions of DMS is to alert motorists of lane closures that are the result of unexpected situations, such as accidents or other incidents that reduce roadway capacity. Messages can be displayed to warn of a traffic incident. However, no message should be displayed if the sign is so far from the affected area that full capacity will be restored before motorists who read the sign would be affected by the disruption the sign warned them of. Conversely, if the incident is confined to an adjoining route such that motorists in that route would be affected, a message should be displayed. Depending on the location, severity and duration of the incident, messages may be displayed up to several hundred miles in advance of the incident. If a situation arises where multiple incidents have occurred downstream from a sign, DMS should alert motorists to the closest incident unless conditions warrant otherwise (NJDOT, 2008).

2.5.2. Road and Vehicle Unpredicted Condition Warning Messages

These messages may inform drivers of special issues with respect to road and vehicle conditions, including changes in roadway alignment or surface conditions, disabled vehicles, vehicle restrictions and advance notice of new traffic-control device installation (Walton et al., 2001).

2.6. Informative/Common Road Condition Messages

2.6.1. Travel Time Messages

Travel-time messages inform drivers any of the five following categories:

1. Travel time on freeways displays the number of minutes required to go from one specified location to another

2. Comparative travel times on the freeway and an alternate route

3. Time saved by taking an alternate route

4. Delays on the freeway

5. Delays avoided by taking the alternate route

2.6.2. Congestion Messages

DMS may be used to display information on traffic conditions when freeways become congested. However, a problem arises because a multitude of situations exist that may be difficult to describe on DMS. In jurisdictions where quantitative travel-time information is not available, terms such as “Heavy Delay” and “Major Delay” are often used. However, little information or guidance exists about how these terms should be defined. The Dynamic Message Sign Message Design and Display Manual indicates the average motorist in Texas interprets “Heavy Delay” as being between 25 and 45 minutes, whereas “Major Delay” is interpreted as a delay greater than 45 minutes. A similar study in England attempted to determine driver response to DMS; English drivers reported they interpreted “Long Delays” as being between 35 and 47 minutes, whereas “Delays Likely” indicated a 10 to 31 minute delay. The Minnesota Department of Transportation’s Guidelines for Changeable Message Sign Use specifies a “Major Delay” is not indicative of an amount of time but rather an incident causing more than 2 miles of traffic backup. These conflicting definitions demonstrate the need for an evaluation of DMS messages and the conditions to which they correspond (Fish et al., 2012).

2.6.3. Queue Warning Messages

Queue warning messages have been employed on several German motorways. Queue warning messages vary in appearance, scope and complexity. A queue warning system uses a small roadside DMS with flashers to indicate the length and location of the queue.

Germany Transportation Policy strongly emphasizes the comprehensive communication of the queue warning on the message signs by using minimal wording and simple imagery. The German queue warning system yielded benefits including fewer incidents, reduced incident severity, closer headways, greater uniformity on all driver speeds and a slight increase in capacity (Bolte, 2006). Figure 2.2 depicts a dynamic queue warning message sign.

Figure 10: Small DMS Sign for Queue Warning System (Source: ITS Magazine).

Figure 2.2. A Queue Warning Message

2.6.4. Weather-Related Messages

One of most common uses of DMS is to display weather information that affects traffic. DMS advise motorists of severe weather or environmental conditions in the area, especially situations that require a change in their driving behavior (NCDOT, 1996; ORDOT, 2000).

2.6.5. Railroad Crossing Messages

DMS may also be applied where roadways and railroads meet. Finely et al. (2001) argued that because traffic conditions can also be affected by rail systems, railroad grade crossing information should be available via DMS. An example of application of DMS in railroad crossing area is in San Antonio, where displaying real-time information on these messages allows drivers to alter their routes to avoid a lengthy wait for a crossing train.

2.7. Regulatory/Non-Traffic Related Messages

2.7.1. Public Service Announcement Messages

The use of DMS for Public Service Announcements (PSA) is allowed by some agencies. The types of PSAs permitted depend on the jurisdiction. PSAs may include brief messages that do not require an immediate response but encourage drivers to alter future driving behavior. Because PSAs do not provide drivers with real-time safety or travel efficiency information and are not usually associated with any urgent response, these messages are generally given low priority. PSAs provide motorists with information that can be given more effectively through other methods such as media campaigns or pamphlets (NCHRP, 2008). Another argument against displaying PSA messages focuses on the concern that motorists who continually travel a specific route will become accustomed to messages and will begin to ignore all DMS. For example, in State of Oregon Department of Transportation the very lowest priority is given to PSAs. Oregon's DOT allows DMS to display PSAs only in off-peak periods for a maximum of five hours a day and five days a month. In addition, these messages are generally restricted to permanent DMS and not permitted on portable DMS (ORDOT, 2000).

2.7.2. AMBER Alerts

AMBER alerts are notification programs to help locate missing children who authorities believe have been abducted. The Emergency Alert System (formerly known as the Emergency Broadcast System) alerts the public about these children's abductions by means of television and radio (NCHRP, 2008). America's AMBER Plan Program, through which emergency alerts are issued to notify the public, is voluntary. The Federal Highway Administration notes DMS are not always the safest or most effective methods of disseminating information about child abductions because only a limited amount of information can be conveyed on DMS. When there is a need to provide extensive information to motorists, the Federal Highway Administration specifies that other types of traveler information media (e.g., 511, HAR, informative Web sites or commercial radio) should be used and that DMS should only supplement those media.

2.8.Inappropriate uses of DMS

A national policy specifying DMS use and message design does not exist. Transportation authorities are responsible for creating and implementing their own guidelines on the use, location, operation and evaluation of DMS in their jurisdictions. Mounce et al. (2007) assessed current DMS applications and practices based on a national literature reviews and agency surveys. They found the majority of respondents in the survey believed one major benefit of DMS was to provide timely and important information about travel routes. The survey revealed that although most DMS applications are considered effective, respondents indicated some concerns including information overload, adverse traffic effects and lost motorist confidence. The results of the survey also indicated that although DMS evaluations are generally conducted in conjunction with an entire ITS evaluation, very little has been done to evaluate DMS. Additionally, special considerations should be given to DMS' unique capabilities as well as the message content, location and evaluation of DMS to aid in creating successful DMS systems.

According to Mounce et al. (2007) DMS messages should be prioritized in the following order:

*1. Safety-related***:** messages that are directly related to safety are given first priority for display. Examples of this type of messages include winter traction device requirements, mountain pass information and flammable restrictions.

*2. Roadway closures***:** DMS are used to display road or ramp closures, regardless of the reason for the closures (accident, construction, weather, etc.).

*3. Minor traffic effects***:** DMS are used to display information about minor traffic effects such as construction lane closures, blocking incidents and delay information.

4. Public text messages: As mentioned in the previous section, the lowest priority messages are transportation-related PSAs. These messages do not directly affect motorists and therefore are not critical to the safe and efficient operation of the transportation system. Examples of these messages are Click It or Ticket, Rideshare information and announcements about traveler information phone numbers like 511.

5. Test messages: These types of messages are used to perform sign operation or maintenance checks and to ensure proper operation of new DMS.

2.8.1. Traffic-Related Messages

The Kentucky Transportation Center notes several inappropriate ways to use DMS (Walton et al., 2001). A notable inappropriate application is using DMS to restate or replace required permanent signage. This could result in serious problems of information overload and driver inattention to DMS. Specifically, DMS messages should not replace static signs, regulatory signs, pavement markings, standard traffic control devices, conventional warnings or guide signs.

2.8.2. Non Traffic Related Messages

Policies governing the display of non-traffic-related messages on DMS are not consistent. The Manual on Uniform Traffic Control Devices indicates DMS should not be used to display information other than regulatory, warning and guidance information related to traffic control. Some policies state messages displayed on DMS must require motorists to take an action or alter their driving behavior (Johnson, 2001; NCDOT, 1996). There is a consensus that DMS should not be used to advertise commercial events or entities. Additionally, DMS should not display tourist information (Jones et al., 2003; NCDOT, 1996; ORDOT, 2000; Walton, 2001).

2.8.3. Reasons Motorists Disregard the DMS

Dudek (2008) identified problematic uses of DMS that erode motorists' confidence:

- Displaying inaccurate or unreliable information
- Displaying information too late for drivers to take an appropriate response
- Displaying messages drivers do not understand
- Displaying messages too long for drivers to read
- Not informing drivers of major incidents
- Informing drivers of something they already know
- Displaying information not related to environmental, roadway or traffic conditions or routing

- Displaying garbled messages

If DMS operators commit these errors, motorists are likely to disregard DMS. Influencing the decisions of motorists is necessary for DMS to be effective.

2.9. Location of Dynamic Message Signs

DMS locations are generally established through prior experience with local traffic problems. Recently, however, researchers have experimented with computer programs that can place signs more precisely. These methods have not yet been implemented by any local traffic management agency responding to the survey. The locations of DMS are often determined through unwritten historical practices and general policies. Agencies seldom implement methods to ensure specific DMS locations are optimal. Two methods used to optimize DMS locations include genetic algorithms and integer programming. Abbas and McCoy (1999) researched using genetic algorithms. They indicated several factors influenced their decision to implement genetic algorithms, one of which being that genetic algorithms give several solutions instead of one “best” solution. Additionally, the constraints required in genetic algorithms are less than those necessary to find an integer programming solution (Abbas et al., 1999).

Chiu et al. (2001) researched the use of integer programming to optimize DMS locations. With a specified number of DMS, possible locations were determined and analyzed. Optimal locations were chosen so that the long-run expectation of benefits was satisfied under stochastically-occurring incident scenarios. Chiu et al. found the main benefit of correctly locating DMS was reducing total user travel time. Implementing the programming required numerous inputs describing geometry and traffic patterns of the highway network. The problem was simulated using a dynamic traffic assignment algorithm, which aided in determining the effectiveness of DMS locations. Each location needed to have a high probability of capturing the randomly-occurring incidents and then demonstrate it could effectively divert traffic. The final solution generated by the integer-programming model determined the optimal location for all incident scenarios on the system, although given solutions might not be optimal for an individual incident (Chiu et al., 2001).

Chiu and Huynh (2007) combined a mesoscopic dynamic traffic assignment simulation with a tabu search heuristic to optimally locate DMS. Incidents were randomly generated using a Monte Carlo scheme that specified some drivers would switch routes if their path encountered an incident and a DMS sign. Based on the resulting flow patterns, a set of DMS locations was determined to optimize some measure of effectiveness (Chiu et al., 2007).

Huynh et al. (2003) used a similar analysis framework to find the optimal locations of portable DMS in a real-time framework using the G-D heuristic. Although the simulation approach allowed a rich set of traffic and behavioral effects to be modeled, the computational burden associated with many simulation runs on a large network could be troublesome. This limitation was realized by Henderson (2004), who paired a static equilibrium framework for DMS location with a discrete choice model in order to determine the proportion of drivers who were likely to switch routes in response to learning about an incident. Henderson (2004) developed and compared several heuristic techniques, including a genetic algorithm and a greedy approach based on sequential location. While computationally faster, the approach implicitly assumed drivers did not anticipate receiving information. This assumption means drivers' initial route choice was not affected by the DMS locations, so links with a DMS did not "attract" drivers who anticipated benefitting from that information (Hendeson, 2004). Although this distinction may seem subtle, this anticipation effect could lead to radically different route choices for rational drivers, even from the origin (Boyles, 2006).

2.10. DMS Performance Metrics

Tarry (1996) defined performance indicators expressly to evaluate DMS. Table 2.2 presents examples. To produce appropriate driver response, the messages displayed on DMS should be meaningful, accurate, timely and useful. Operators lose credibility if the messages displayed on DMS do not adhere to the guidelines of Dynamic Message Sign Message Design and Display Manual (Dudek, 2006).

2.11. Studies Related to Designs of DMS

Extensive human factors and traffic operations research have been studied to develop fundamental principles and guidelines for DMS message design, including alphanumeric messages, graphics and symbols. Using these fundamental principles, guidelines for effective message design and display for TxDOT were published in Report 0-4023-P3 Dynamic Message Sign Message Design and Display Manual (Dudek, 2006). European countries such as Germany and Spain have used graphics or symbols on DMS, but this practice has not yet gained popularity in the United States.

Nygårdhs (2011) reviewed DMS literature 2006-2009. The literature review reached the following findings about design of DMS:

Table 2.2. Example Performance Indicators for Dynamic Message Signs

Evaluation Category	**Indicators**
Technical Analysis	• Reliability and correctness of information displayed • Appropriateness of plans • Operator interface usability • Sensitivity to errors in inputs • Level of operator intervention needed
Impact Analysis	• Degree of diversion at nodes • Reduction in delays and extent of queuing • Change in travel time on individual routes • Change in total travel times and journey distances in the network • Reduction in the duration of congestion • Reduction in emissions • Driver response to: range of information types, travel cost differences on alternative routes and driver familiarity with the network • Reduction in traffic diversion through urban areas or on the undesirable routes • Number of accidents
Socioeconomic Analysis	• User cost-benefit analysis of performance network • Impact on non-road users
Legal/Institutional Analysis	• Legal/institutional conflicts
Public Acceptance Analysis	• User attitudes to DMSs • Non-user attitudes to DMSs

1. Graphic-aided messages are significantly better than text-only messages (because of motorists' preference, response time and accuracy) and should be used as much as possible.

2. Red is not recommended for DMS messages.
3. Older drivers' performance was significantly improved by graphic-aided messages.
4. Graphic-aided DMS messages enhanced message comprehension time for non-native English speakers.
5. More research is required to determine the proper specifications and design guidelines of graphical images accompanying DMS messages.
6. The number of lines on DMS should be kept to a minimum.
7. Bilingual signs should only be used when absolutely necessary.
8. If bilingual signs are used, different colors or type fonts should separate the languages.
9. The number of information units may be better correlated to DMS reading time than the number of lines displayed.
10. A blank "off-screen" of a short duration may enhance motorists' information processing when successive DMS frames are used.
11. Right-justified text on DMS should be avoided.
12. Abbreviations could decrease understanding of DMS if they are not commonly known.
13. Luminance class L3 is preferable for symbols on DMS.
14. A three-diode symbol thickness leads to better legibility than a symbol of one- or two-diodes' thickness.

Chapter 3: Driver Response Behavior to Messages and Localized Impact of DMS

3.1. Drivers' Response to Displayed Messages

Extant literature evaluating drivers' responses to DMS focus mainly on route-choice guidance, improving road network performance and speed slowdown. It is evident motorists' acceptance of DMS is associated with their perceptions and subjective attitudes about information and how it is presented. Most of the studies found demographic and socio-economic characteristics are important factors in controlling travelers' satisfaction with DMS. Travelers have specific preferences about the format and contents of messages and information posted on the DMS. While most studies show travelers adopt DMS for their traveler information needs, DMS do not necessarily change their travel behavior. Network familiarity, proactive information and advisory information have been found to have different effects at different locations studied (Rogers, 2005). Multinomial and binomial logit models have been predominantly used to model driver diversion behavior under traveler information scenarios with DMS. The effect of DMS has been found to vary at different study sites. Wendelboe (2008) studied driver response to DMS in 2008 by surveying drivers. Table 3.1 shows the results and conclusions of the surveys.

Table 3.1. Results from driver surveys (Wendelboe, 2008)

Respondents who:	Percent
Understood variable speed limits (VSL) correctly	82%
Perceived queue information correctly	88%
Perceived queue information correctly when information about distance to the rear end of the queue was added	61%
Had a generally positive attitude to VSL	84%
Thought VSL had a positive effect on traffic flow	58%
Thought VSL had a negative effect on traffic flow	12%
Thought VSL had a positive effect on traffic safety	33%
Thought VSL had a negative effect on traffic safety	3%
Had a generally positive attitude to queue information	86%
Had a generally negative attitude to queue information	5%

The literature review conducted by Nygårdhs (2011) concluded the following about DMS and drivers' reaction to messages:

1. DMS effectively reroute traffic.
2. Supplementary DMS information may not increase drivers' compliance with the messages.
3. Reading and processing DMS messages lead to speed reductions.
4. Displayed delay times on DMS correlate to diversion patterns.
5. Factors correlating to drivers' unwillingness to divert from the freeway include: driving employer-provided cars, frequency of driving on the freeway and being middle-aged.

There is some concern that more frequent use of non-incident and non-roadwork transportation-related messages can compromise DMS credibility. If DMS distract drivers from more critical tasks while traveling at prevailing speeds or if the messages are erroneous or outdated, driver compliance can be compromised. In addition, if the messages are too long, complex, and/or confusing to read and comprehend, drivers may reduce speed to read the messages, which could result in a safety problem (Dudek, 2008).

3.1.1. Route Diversion in Response to Messages

Many researchers have studied drivers' attention and response to DMS. To evaluate the effectiveness of DMS for route choice guidance, some researchers have tried to estimate a route choice model that predicts how drivers respond to DMS-provided information and whether the drivers will divert to avoid an incident or congestion on road. Many researchers used surveys or simulations to gather the data about motorists' behavior in response to DMS messages. The questionnaires asked motorists to state their preference for actual or hypothetical situations (Abdel-Aty, 2000; Hao et al, 1999; Khattak et al., 1993; Wardman et al., 1998;). Fish (2012) presented an empirical evaluation of the quality and effectiveness of highway DMS. An additional innovation Fish presented was to use Bluetooth sensor technology as a new method for evaluating the accuracy and influence on drivers' travel behavior of DMS messages. The results showed diversion messages are effective in motorists' route choice decisions.

Studies of incident effects on driver behavior focused on changes at the strategic behavior level, particularly changes in their route choice behavior. Incident messages include information about accidents, lane closures and traffic merges. Several researchers have used the stated-preference approach in an attempt to determine the percentage of travelers changing trip decisions in response to information disseminated by ATIS devices such as DMS. The studies concluded the disseminated information could result in up to 60-70 percent of motorists exiting the freeway ahead of a bottleneck, which yielded a 30-40 percent reduction in congestion (Barfield et al., 1989; Benson, 1996; Chatterjee et al., 2002; Madanat et al., 1995). However, limited information is available about actual diversion behavior because traveler information was reflected by revealed preference and not field measurements. A European field study found that DMS compliance rates range between 27 and 44 percent (Tarry et al., 1995). Knopp et al. (2009) found that up to 50 percent of travelers take another route for major incidents. Schroeder et al. (2010) investigated the effects of existing message strategies to determine which messages maximize diversion for specific circumstances and to develop new messages for future deployment.

Ullman et al. (2005) evaluated DMS messages to determine which message drivers found most effective in emergencies. The authors concluded that during emergencies, DMS messages should provide meaningful and straightforward messages that can be read and responded to quickly because their impact on drivers can be great.

In a questionnaire survey, Benson (1996) investigated whether drivers noticed and responded to DMS. Benson found that about 20 percent of respondents ignored active DMS while driving. Interviews conducted by Bonsall (1993) in Paris revealed 97 percent of drivers knew that DMS existed, 84 percent identified DMS as providing very useful information, but only 46 percent had at least once detoured accordingly. Peng et al. (2004) conducted a similar study in Wisconsin with results indicating that 62 percent of drivers responded to DMS messages more than once per week and 66 percent changed their route at least once per month as a result of the posted message. Khattak (1993) suggested diversion behavior was influenced by the accuracy and detail of information including travel times, alternate choices, knowledge of nature of the event and how to avoid incidents.

Roshandeh and Puan (2009) used archival traffic data from a freeway area in Kuala Lumpur to assess the accuracy with which DMS displayed travel-time estimates and driver response to messages of varying lengths and formatting. Results showed DMS reduced the average travel times during the duration of the incident until the clearing of the resulting congestion by a significant amount.

Levinson and Huo (2003) conducted an on-and-off study using data from inductive loop detectors placed on different networks located in Minneapolis and St. Paul, Minn. The purpose was to measure the effectiveness of DMS. Using the traffic flow and occupancy data, a discrete choice model was developed to forecast the percentage of vehicles diverting to an alternate route as a result of the message displayed. Results showed drivers' diversion increased when a warning message about the traffic conditions was displayed, reducing total delay.

Peeta (1991) found the location of an incident and its duration also affected route choice. Virginia drivers' characteristics such as age, education, income and sex had no significant influence on their attitudes about DMS messages (United States Department of Transportation, 2002). In Dallas, 71-85 percent of surveyed drivers used the recommended route. The factors influencing diversion included traffic conditions on the alternate routes, familiarity with the alternate route and confidence in the information (United States Department of Transportation, 2002).

Yang (1993) also found route choice behavior was affected by the characteristics of the alternate routes. The results of this study, based on loop detector data, indicated

DMS could significantly affect drivers' diversion, especially during congested times. DMS had more influence on drivers during morning peak hours than during evening peak hours. According to a survey conducted by Huo and Levinson (2002), drivers are more willing to divert if there were fewer traffic stops on the alternate routes and if they were familiar with the alternate routes. Their study also showed young, male and unmarried drivers were more likely to divert than other drivers.

3.1.2. Speed Reduction in Response to Messages

Benekohal and Shu (1992) evaluated drivers' behavioral responses to speed reduction messages in construction work zone areas. They compared treatment and control conditions when DMS displayed messages and when they were blank. They found displaying the speed limits on DMS was an effective way to reduce average speed. Their study showed displaying messages reduced drivers' speed immediately after passing the sign, but not at a point far from DMS. Cars and trucks reduced their speed by as much as 5 and 4 mph, respectively, near the DMS.

3.2. Effect of DMS Design on Driver Response

Studies show DMS with different formats and designs could have different effects on drivers' behaviors. This section reviews the research comparing drivers' responses to text-based and graphic-aided messages as well as flashing and static messages.

3.2.1. Text-based and Graphic-aided Messages

Wang et al. (2007) studied the use of graphics on DMS. They found most drivers preferred graphics to text and responded faster to graphic-aided messages than to text-only messages. We suggest using graphics in some advisory signs to help enhance drivers' understanding and responses to messages and improve the effectiveness of these signs.

In similar research, Bai et al. (2011) suggested traditional text-based messages have several limitations, such as confusing drivers (which delays their responses), being difficult to read for older drivers and non-English-speaking drivers, and having a short range of legibility. Bai et al. (2011) said using graphic-aided and graphic messages on portable DMS have many advantages over text-based DMS based on a number of previous laboratory simulation experiments. They used field experiments and driver surveys to determine the effectiveness of a graphic-aided and graphic portable DMS on reducing vehicle speed in the upstream of a one-lane, two-way rural highway work zone. They also compared the effectiveness of text, graphic-aided and graphic-portable DMS on reducing vehicle speed in a highway work zone in Kansas using regression models of the relationship between mean vehicle speed and distance under the three conditions. The findings showed that:

1. Text, graphic-aided and graphic-portable DMS resulted in a mean vehicle speed reduction of 13 percent, 10 percent and 17 percent, respectively.
2. Graphic-aided portable DMS reduced mean vehicle speed more effectively than the text one from 1,475 feet to 1,000 feet in the upstream of a work zone.
3. The majority of drivers understood the work zone and flagger graphics and believed the graphics drew their attention more to the work zone traffic conditions.
4. Most drivers preferred the information to be presented in the graphic-aided format.

3.2.2. Flashing and Static Messages

Average reading times for flashing messages were not higher than for static messages (Dudek, 2005). However, results indicate flashing messages may have an adverse effect on message comprehension for drivers unfamiliar with flashing DMS. Average reading times for flashing line messages and two-phase messages with alternating lines were significantly longer than the alternative messages. In addition, message comprehension was negatively affected by flashing line messages.

3.3. Localized Impact of DMS

3.3.1. Traffic Speed Slow Down for Perception of Messages

Oh, Hong, and Park (2009) investigated 20-30-year-old drivers' behavioral responses to DMS when reading and processing the messages in a DMS influence zone. Individual vehicle trajectories were studied via differential global positioning system (DGPS); speed and acceleration rates were used as surrogate measurements to represent driver behavior. DMS influence zones was divided into five sections of 100 meters long. ANOVA results showed drivers' average speed and acceleration were statistically different in each section. Drivers tended to reduce their travel speed while reading and processing DMS messages, and they tended to increase speeds again after they finished reading the messages.

Rama and Kulmala (2000) investigated the effects of two DMS on drivers' car-following behavior. Results showed a sign for slippery road conditions reduced the mean speed by 1-2 km/hour after controlling for the decrease caused by the adverse road conditions.

Wang et al. (2007) studied the effects of DMS messages on traffic approaching and passing the signs. Traffic data gathered by several mobility technology units (MTUs) near DMS along I-95 in Rhode Island were analyzed with the goal of understanding the effects of various DMS messages on the speed variations on traffic approaching and passing the signs. The researchers found a positive correlation between certain posted DMS messages and traffic slow-downs, so the study next explored ways to improve messages' design and display on DMS. Results from a questionnaire indicated DMS were among the top few that caused drivers to slow down, while Danger/Warning messages attracted the most attention from drivers. Results also showed the majority of drivers reduced their speeds when approaching active DMS; lengthy, complex or abbreviated messages caused further slowdowns. Their study also employed a computer-based questionnaire survey and a driving simulation experiment to measure drivers' preferences and responses to various DMS displays and formats. The results showed older drivers exhibit a higher tendency to slow down.

Fish et al. (2012) investigated 2,268 cases of message activation, removal and switching on DMS using RTMS speed data to determine whether DMS messages cause speed slowdown. The study confirmed that in some cases traffic streams decrease speed in response to message activation.

Harder et al. (2003) used a computer-based driving simulation to test various message types to see whether they could detect a slow-down. Results showed 21.7 percent of participants slowed their speed by 13.9 mph as they approached AMBER alert DMS messages. Alternatively, when a Crash alert DMS message was displayed, 13.3 percent of participants slowed their speed by 12.7 mph.

Boyle and Mannering (2004) used a driving simulation to determine the impact of DMS on drivers' speed. Although they found drivers slowed down when approaching active DMS, they also found drivers sped up to compensate for their initial speed reduction. Furthermore, the study demonstrated drivers were more likely to have a larger deviation in speed when encountering a new DMS message. A possible explanation may be that drivers notice a new message and as a result, take more time to process the information when a new DMS message is presented. Moreover, when a DMS displayed the same message for a long period of time, drivers became familiar with the information and thus required less time to read it.

Several studies discussed in section 3.2.1 showed using graphics to convey meaning on roadway signs provided many advantages over text-only messages. Graphic-aided messages could be more easily and quickly identified compared to text-only messages at a greater distance.

DMS including graphic information allowed faster responses than text-only information (e.g., Bruce et al., 2000; Hanowski and Kantowitz, 1997; Staplin et al., 1990). Wang et al. (2007) studied the use of graphics on DMS and found drivers tended to respond faster to graphic-aided messages than text-only messages. All of these studies and practices indicated adding graphics might help enhance drivers' understanding of and responses to DMS and ease slowdowns. Adding graphics to DMS messages could help enhance drivers' understanding of and responses to those messages and reduce their speed variations that occur as a result of reading DMS; it might eventually help ease the slow-downs.

3.3.2. Driver Distraction and Collision Occurrence

Driver distraction plays a significant role in traffic safety. Driver distraction is a factor in one in four car crashes, and of those crashes involving driver distraction, one in four involves distractions outside the vehicle (NHTSA, 2009). Few studies have been conducted on accident rates due to distractions associated with DMS. However, a definite accident rate would be hard to determine. According to the Kiewit Center for Infrastructure and Transportation (2003), accident rates for a section of road can be determined by a ratio of accidents per million vehicle miles of travel. The normalized formula allows for a comparison of various accidents to rates of other stretches of roads that may not be the same length.

Many studies focus on the effects of DMS on driver behavior and the potential benefit of using DMS to reduce downstream accidents. Chamberlain (1995) demonstrated that the use of DMS coupled with a queue detecting system could reduce accidents for upstream drivers who otherwise would be unprepared for queues downstream. According to NHTSA’s Distraction initiative, 20 percent of all accidents are related to some kind of distraction (2010). Many studies indicated that DMS take drivers' attention away from their driving (Wang et al., 2007). Because drivers expect useful information from active DMS, they slow to gain extra time to read and comprehend the messages. To compensate for their speed reduction, drivers speed up after passing DMS. Crashes correlate to driving speed, so this speed variation could pose a threat to other vehicles in the traffic and lead to crashes.

Erke et al. (2007) conducted a field test and video observation study. Their research messages were set to on-and-off in order to compare driver behavior such as route choice, speed and braking behavior when they approached DMS displaying messages and when DMS were left blank. Two DMS were used in this study and displayed road closure and recommendations for alternative routes. Speed measurements of 3,342 vehicles showed large speed reductions; video observations showed large proportions of vehicles braking while approaching the DMS. This research finds speed reductions and braking maneuvers can partly be attributed to attention overload or distraction due to the information on the DMS. In addition, a proportion of the speed reductions was due to chain reactions where one vehicle braked and forced the following vehicles to brake or change lanes in order to avoid collisions. Safety problems may result from distraction or from the reactions of the drivers to the distraction.

3.4.Summary

Many methods have been used to determine drivers' responses when approaching DMS. Data from surveys, simulators, video observations and loop detectors are the most common methods to study these behaviors, and these methods have shown some promising results. Table 3.2 and Table 3.3 present summaries of previous studies of drivers' responses to diversion and speed reduction messages, whereas Table 3.4 summarizes the reviewed literature on the localized effects of the signs. This project uses ground truth data integrated database to evaluate the impact of the signs on occurrence of road accidents.

Table 3.2. Literature Summary on Driver Response to Diversion Messages

Author	**Source**	**Year**	**Country**	**Study Approach**	**Results**
Fish et al.	TRB	2012	US, Maryland	Field Test/ Bluetooth sensors	• diversion messages are effective in route choice decisions.
Chen et al.	IWMSO 2008	2008	China, Beijing,	SP survey	• diversion increases as the traffic speed decreases. (<20 km/h). • 21.45% of drivers divert
Foo & Abdullahi	TRB	2008	Canada, Ontario	Field Test/Loop detector	• occurrence of a message change plays a vital role in influencing downstream diversion
Cheng & Firmin	12th IEE Int. Conf.	2004	U.K., London	SP survey	• more exposure to DMS increases appreciation of the information displayed.
Peng et al.	Trans. Res. Rec.	2004	US, Wisconsin	RP survey combined with logit model	• 75% are positive with usefulness of VMS. • 16% don’t trust VMS information and don’t change their route.

Author	Source	Year	Country	Study Approach	Results
Levinson & Huo	TRB	2003	US, Minnesota	Field Test/ Loop Detector	• a probit model to estimate diversion as a function of message content. • ahead warning is effective for diversion.
Chatterjee et al.	Trans. Res. Part C	2000	U.K., Leeds	Survey, Logistic Regression	• location of incident and message content influence the probability of diversion.

Table 3.3. Literature Summary on Driver Response to Speed Reduction Messages

Author	**Source**	**Year**	**Country**	**Study Approach**	**Results**
Alm & Nilsson	Trans. Human Factors	2000	Sweden	Simulation	• all participants reduced their speed in response to incident warning messages
Luoma et al.	Trans Res. – Part F	2000	Finland	Simulation	• drivers reduced speed 1-2 km/h in response to a DMS warning of slippery condition
Benekohal& Shu	Civil Eng. Studies	1992	US, Illinoise	Treatment control (DMS on and off)/ statistical analysis	• displaying the speed limits is effective in reducing the speed. • speed of cars reduces immediately after passing the DMS, but not at a point far from DMS. • cars and trucks reduced their speed by as much as 5 and 4 mph respectively near the DMS.

Table 3.4. Driver Distraction and Speed Slow Down for Perception of Messages

Author	**Source**	**Year**	**Country**	**Study Approach**	**Results**
Wang et al.	TRB	2009	US, Rhode Island	Survey	• DMS cause slowdown (specially danger warning messages). • lengthy, complex or abbreviated messages caused further slowdowns. • elder drivers exhibit a higher tendency to slow down
Erke et al.	Trans. Res. Part F	2007	Norway, Oslo	Field Test/video observation (messages on/off)	• most of vehicles braked approaching the DMS. • messages causes distraction and leads to speed reduction and chain collisions and safety problem.

Chapter 4: Investigation on Possible Relationship between DMS and Occurrence of Road Accidents

4.1. Problem Statement and Motivation for Research

Although DMS are intended to improve the efficiency and safety of road networks, little has been done to study the effect of these devices on driver safety. In spite of all advantages of DMS, some issues regarding the disadvantages of real-time travel signs have emerged. Reports from WTOP and NBC are examples of the opposing side. These reports claim these devices are expensive adversely affect drivers' concentration, and cause speed slowdown, which may lead to an increase in road crashes (HSM, 2010). The purpose of this research is to investigate the problem and determine if there is any meaningful relationship between occurrence of accidents and proximity of DMS in regards to these accidents.

For this study, accident data and DMS locations in Maryland for 2007 to 2010 were mapped in ArcGIS to determine accident patterns on the state highway network. In order to investigate the above-listed claims, all 184 highway DMS in Maryland were evaluated to their proximity to nearby accident patterns. The purpose of this study is to determine whether DMS on Maryland highways produce significant localized safety issues. The data used and methods of research are described in detail in the following sections.

4.2. Methodology

4.2.1. Data Sources and Preparation

The data used in this research were collected from three major sources: the Center for Advanced Transportation Technology (CATT) Laboratory in the Department of Civil and Environmental Engineering at the University of Maryland, Coordinated Highway Action Response Team (CHART) reports for regions within the District of Columbia in Maryland, and the Maryland Department of Transportation, State Highway Administration (SHA) and DOT archival data. Figure 4.1 shows the databases and sources that are used in the research.

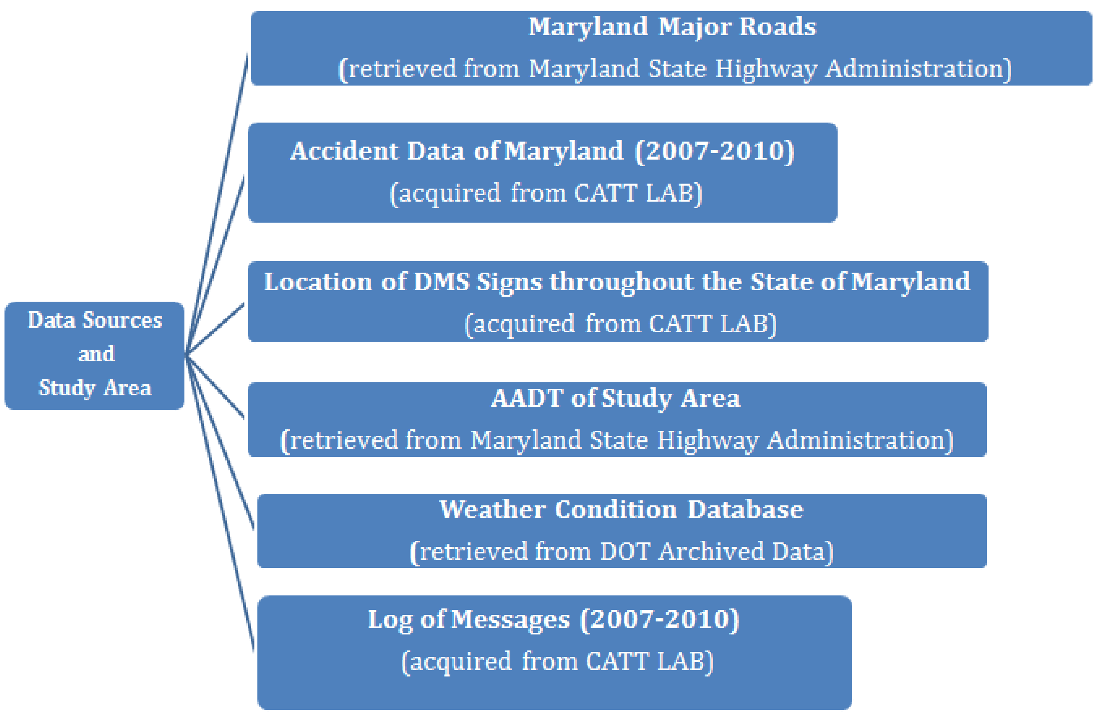


Figure 4.1. The databases and sources of data used in the research

The study area was the roadway network in Maryland. Figure 4.2 depicts the study area in the research.

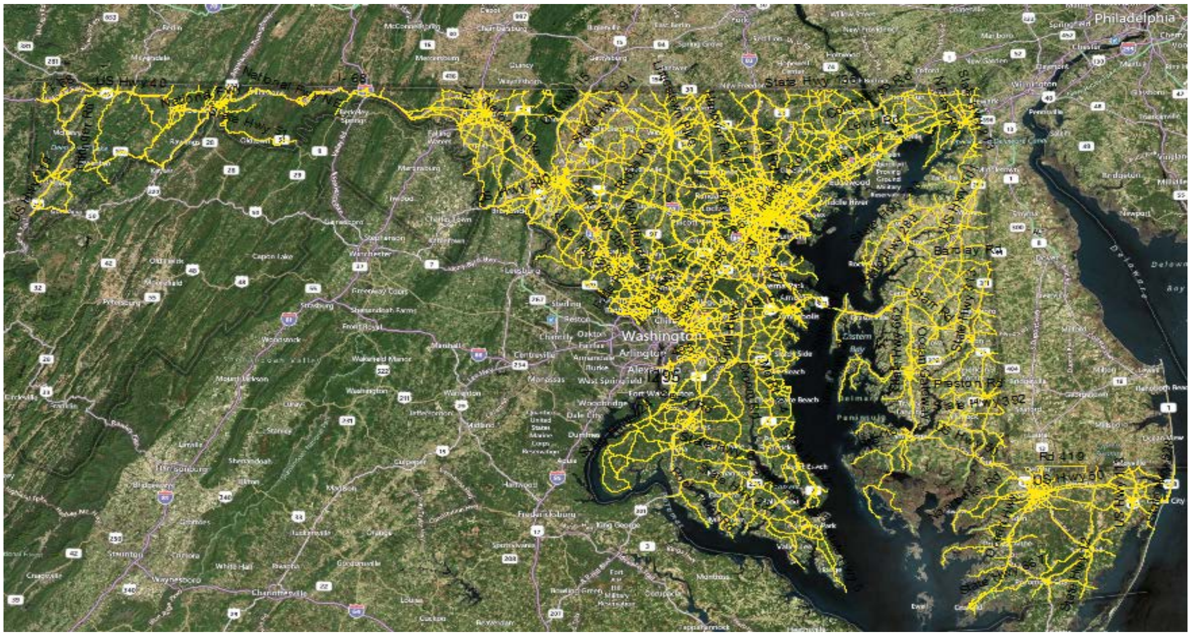
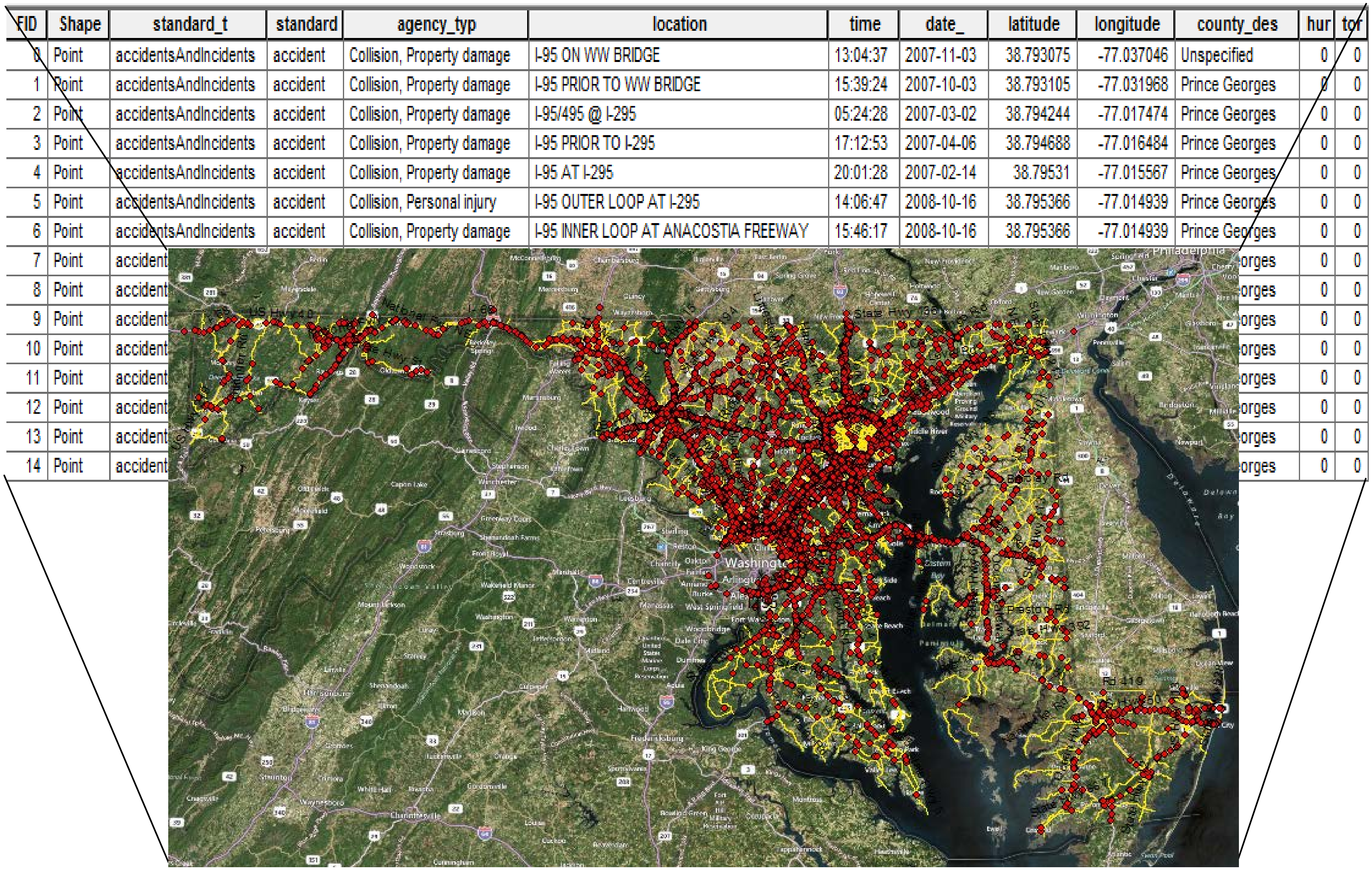


Figure 4.2. Study Area

4.2.2. Accident Database

The accident database included 38,718 records. A data cleansing process was conducted to remove data gaps and outliers, which yielded a data set of 23,842 usable accident records for the period of 2007 to 2010. The data set included accident type (property damage, personal injury and fatality), geographic location, jurisdiction, accident time and other related information. Because of confidentiality concerns, access to police records and accident causes was not possible. Locations of accidents are pinpointed on road network map for further analysis. Figure 4.3 shows the first shape of accident database and the locations of accidents projected on the road map.



FID	Shape	standard_t	standard	agency_typ	location	time	date_	latitude	longitude	county_des	hur	tor
0	Point	accidentsAndIncidents	accident	Collision, Property damage	I-95 ON WW BRIDGE	13:04:37	2007-11-03	38.793075	-77.037046	Unspecified	0	0
1	Point	accidentsAndIncidents	accident	Collision, Property damage	I-95 PRIOR TO WW BRIDGE	15:39:24	2007-10-03	38.793105	-77.031968	Prince Georges	0	0
2	Point	accidentsAndIncidents	accident	Collision, Property damage	I-95/495 @ I-295	05:24:28	2007-03-02	38.794244	-77.017474	Prince Georges	0	0
3	Point	accidentsAndIncidents	accident	Collision, Property damage	I-95 PRIOR TO I-295	17:12:53	2007-04-06	38.794688	-77.016484	Prince Georges	0	0
4	Point	accidentsAndIncidents	accident	Collision, Property damage	I-95 AT I-295	20:01:28	2007-02-14	38.79531	-77.015567	Prince Georges	0	0
5	Point	accidentsAndIncidents	accident	Collision, Personal injury	I-95 OUTER LOOP AT I-295	14:06:47	2008-10-16	38.795366	-77.014939	Prince Georges	0	0
6	Point	accidentsAndIncidents	accident	Collision, Property damage	I-95 INNER LOOP AT ANACOSTIA FREEWAY	15:46:17	2008-10-16	38.795366	-77.014939	Prince Georges	0	0
7	Point	accident								orges	0	0
8	Point	accident								orges	0	0
9	Point	accident								orges	0	0
10	Point	accident								orges	0	0
11	Point	accident								orges	0	0
12	Point	accident								orges	0	0
13	Point	accident								orges	0	0
14	Point	accident								orges	0	0

Figure 4.3. First shape of accident data and pointing location of accidents on road network map

4.2.3. DMS Database

The DMS inventory was acquired from CATT Laboratory. The DMS inventory includes all types of signs, including those permanently mounted overhead, roadside models and portable signs operated by CHART or Maryland Transportation Authority (MTA). The database listing Maryland's 184 DMS includes the signs' identification number, longitude and latitude, address and type. Figure 4.4 shows the first shape of DMS data and its projection onto the road network map. An accident's longitude and latitude were used to join the accident and DMS databases. Figure 4.5 shows a network system is created with the three overlaid layers.

An impact area of 900 feet was defined for each DMS. Accidents that occurred within the 900-foot impact zone were assigned to the relevant sign. The details of how impact areas were defined are presented in next section. Accidents in the 900-foot proximity to DMS were categorized as occurring in an impact area based on location field, visual judgment and direction of DMS.

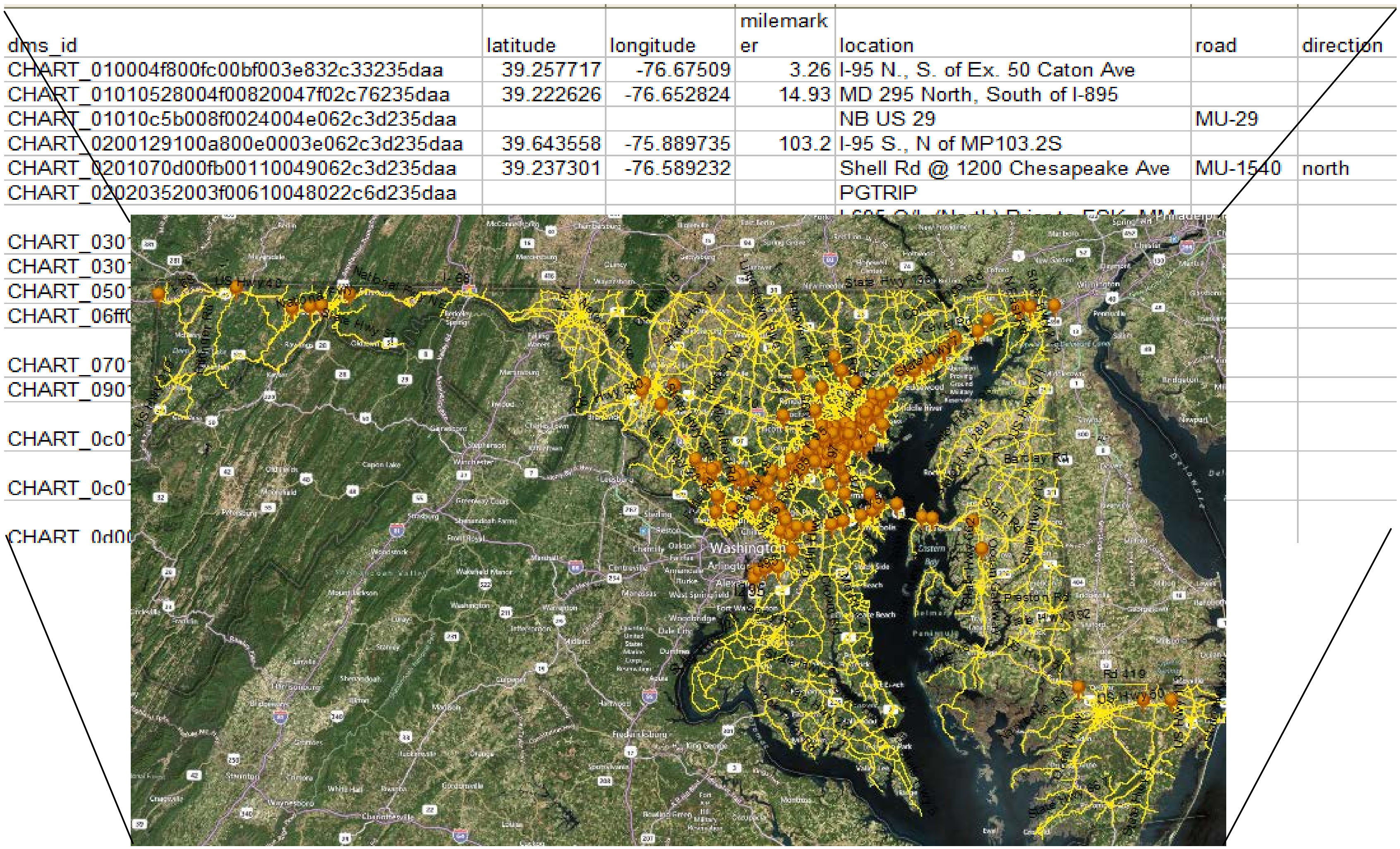


Figure 4.4. First shape of DMS database and projection to road map

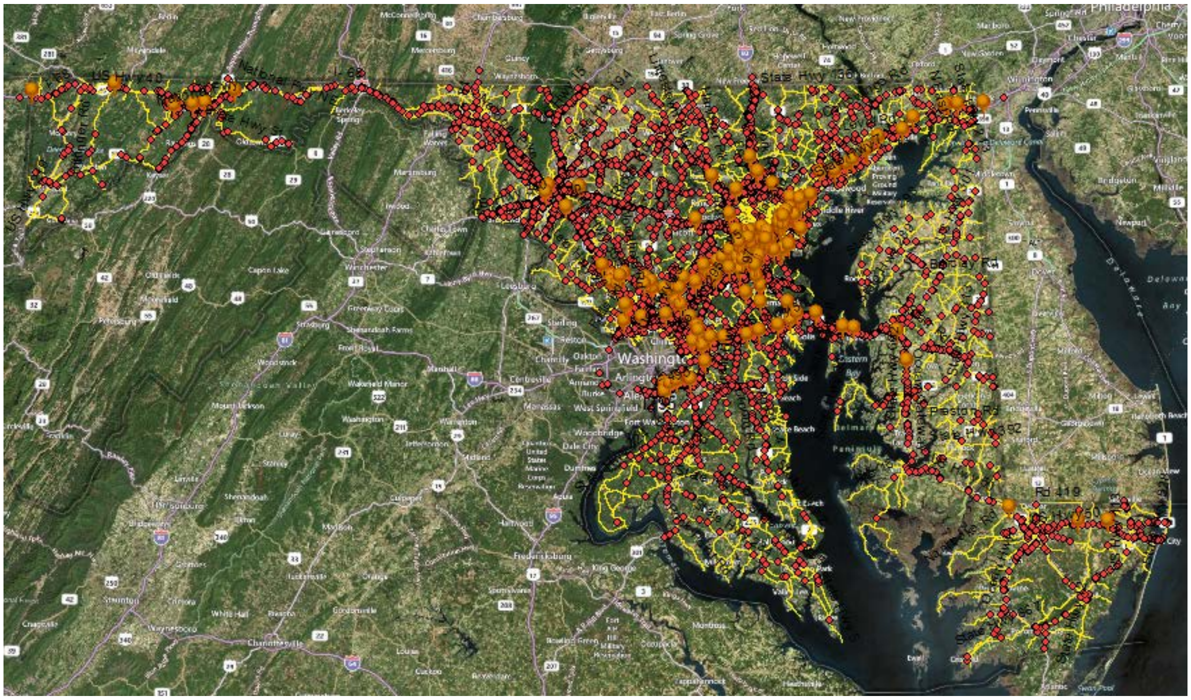


Figure 4.5. Map of accidents and DMS locations

4.2.4. AADT Database

The Highway Safety Manual (2010) specifies traffic flow is one of the most important factors contributing to crashes. This research uses the average annual daily traffic (AADT) of the road segments as an index for traffic flow. The AADT data were retrieved from Maryland's SHA volume maps for the four-year period of study. The AADTs were collected from more than 3,000 program count stations and 79 automatic traffic recorders located throughout Maryland. The shape file of AADT layer is projected onto the road map and the accidents and DMS. An example of the map is shown in Figure 4.6.

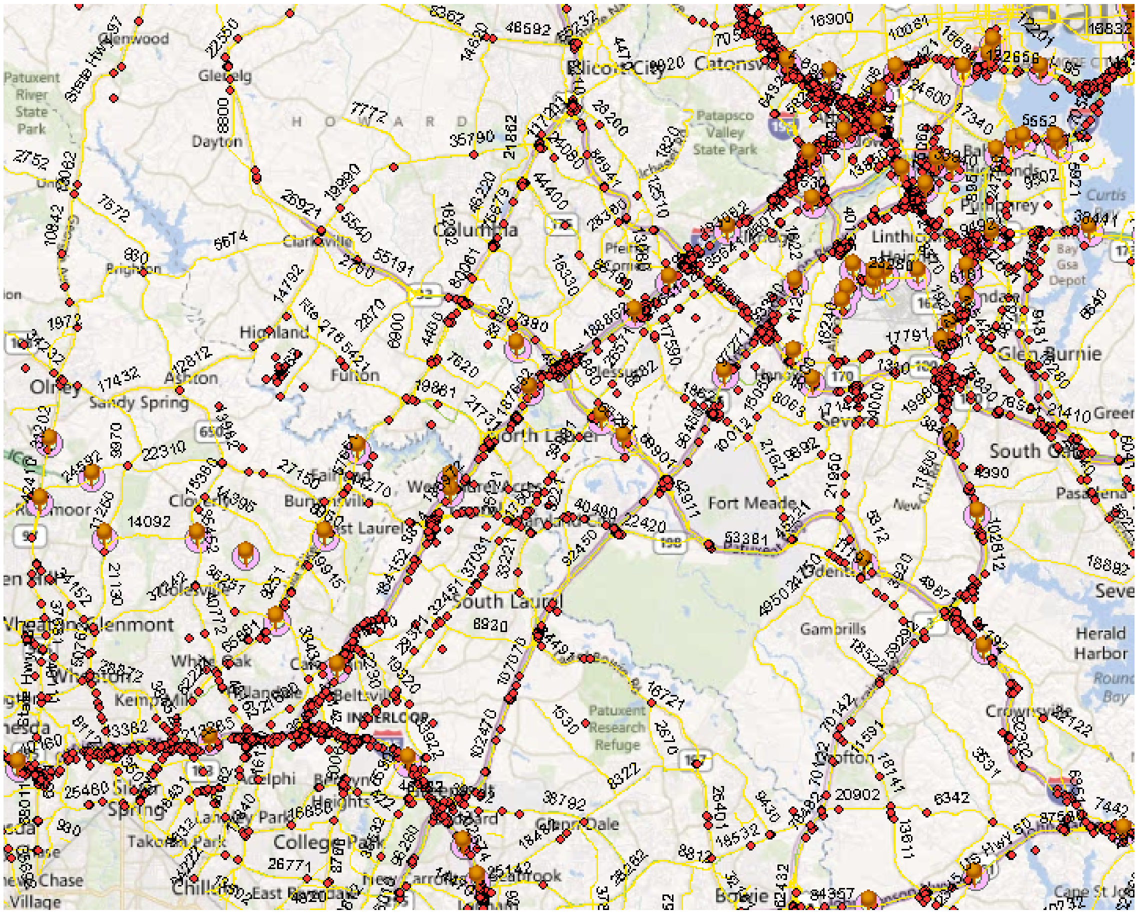


Figure 4.6. An example of the volume map AADT (SHA 2011)

4.3. Data Processing and Preparation Challenges

This study uses a new approach to the problem dealing with several large databases, each with a different data structure and coordination systems. Acquiring data from different sources was another challenge for this project. In addition, some parts of police accident reports, such as causes of the accidents, were not accessible because of confidentiality concerns. In addition to the difficulties in obtaining the necessary data, another issue encountered involved processing data sets that each had more than 10,000 records. That problem was resolved by using a data cleaning process that filtered and removed outliers. Joining the databases by time and location was a challenge that was resolved by pinpointing the locations through GIS tools and matching the time of events through coding in a SQL environment.

4.4. Defining the Impact Area of DMS

The goal of projecting the DMS and accident locations on ArcGIS was to determine the distance within which DMS might affect the occurrence of accidents. The size of characters on electronic signs is the most important factor determining the maximum viewing distance. In order to define the distance within which DMS may affect occurrence of accidents, the visibility distance from DMS needed to be determined. According to Maryland Manual on Uniform Traffic Control Devices (MUTCD), the minimum character size of DMS fonts on major roads (55 mph speed limit) is 18 inches. Based on the information provided by International Sign Association, the maximum viewing distance for 18 inches character size sign is 900 feet. Figure 4.7 illustrates the impact area for research.

4.5.Case Study on I-95

Interstate 95 in Maryland is a major highway that runs diagonally from northeast to southwest, from Maryland's border with Delaware to the Woodrow Wilson Bridge. It briefly enters the District of Columbia before continuing into Virginia. We chose this freeway because the route is one of the most heavily traveled interstate highways in Maryland, especially between Baltimore and Washington, D.C. Figure 4.8 shows I-95 and the DMS located on this highway. The light blue pushpins are DMS on northbound and the dark one are the signs located on southbound.

Figure 4.7. Impact Area

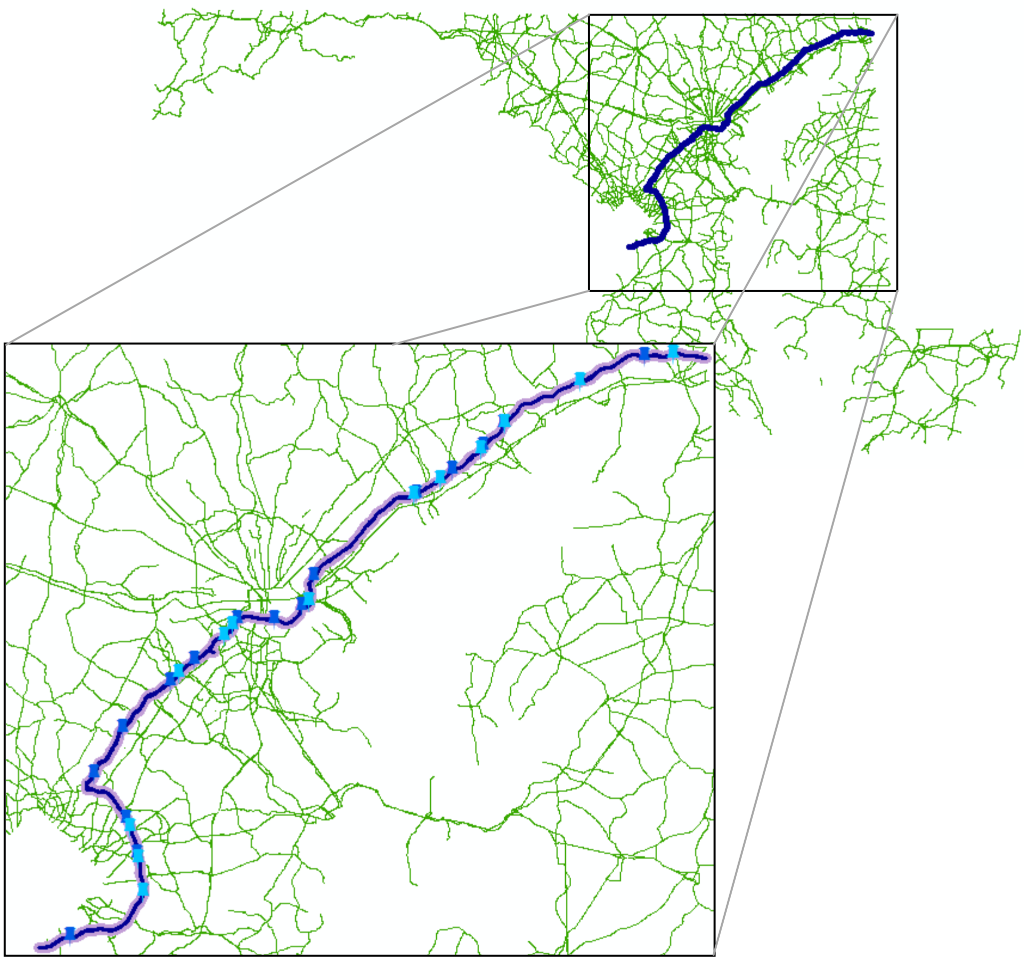


Figure 4.8. I-95 along with the DMSs along this highway

The accidents along I-95 were projected onto the map. Figure 4.9 gives a perspective of the accidents on I-95 and northbound and southbound DMS.

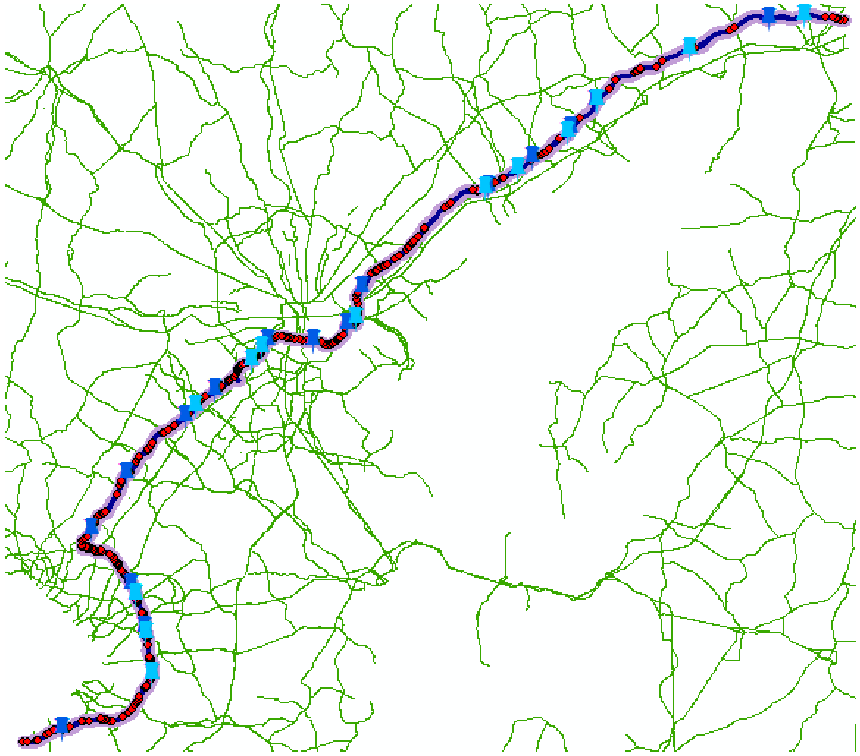


Figure 4.9. Accidents in I-95

Figure 4.10 shows the projected AADTs to road map. Because the impact area of DMS was determined to be 900 feet, multiple ring buffer zones with radius of 900 multiplier-feet (900, 1800, 2700, etc.) radius were performed for each DMS sign along I-95. This is shown in Figure 4.11.

4.5.1. Analysis of Case Study and Preliminary Results

In this step, 70 geometrically homogenous segments with a 900-foot impact zone were selected from Interstate 95. For each segment, accidents were counted and the total number of crashes in each segment was counted for use in regression analysis considering that the segment is an impact area or not as well as the existence of interchange and AADT in the segment. Table 4.1 shows the variable used for the case study.

Table 4.2 shows the 70 segments with their accumulated number of crashes; it also shows the existence of DMS and interchanges in the impact areas. To analyze the data, an unbalanced two-way ANOVA was performed using SAS software. The results show P-value strongly rejects the hypothesis that Interchanges have no impact on the occurrence of accidents. The significance level for the impact of DMS is not high and shows DMS do not significantly contribute to occurrence of accidents. The results are shown in Figure 4.12.

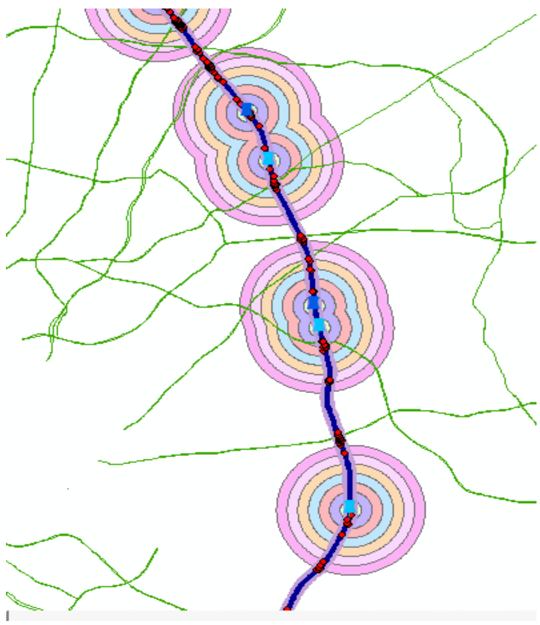


Figure 4.10 . Projection of AADTs to road map

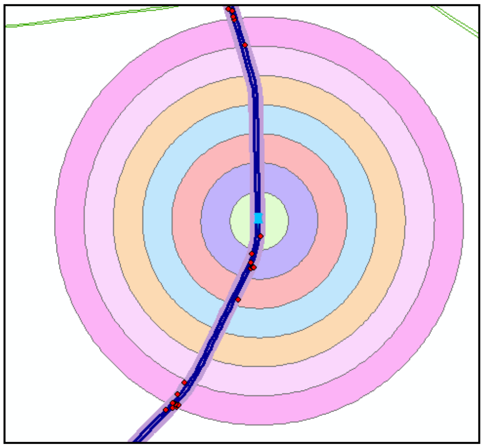


Figure 4.11. Multiple Buffers along I-95

Table 4.1. Variables used in case study

Dependent Variable	Independent Variables		
Number of crashes	Impact Area or not	Existence of Interchange	AADT

Poisson regression analysis was conducted to predict the number of crashes within 900 feet segments given DMS, interchanges and AADT data about the route. The test strongly rejects the hypothesis that interchanges and AADT do not have significant impact on the occurrence of accidents. Regression analysis also shows DMS are not significant contributors in crash occurrence. The results of both methods converge point out that while interchanges and AADT are important factors to accidents, there is no relationship between presence of DMS and occurrence of accidents.

Table 4.2. I-95 Case Study Samples

BufferID	NumberCrash	ImpactArea	Interchange	AADTVMT	SouthORNorthBound
10	1	1	0	147581	S
20	1	1	0	147130	N
30	7	1	0	177981	S
40	1	1	0	206880	N
50	0	1	0	213841	N
60	0	1	0	213841	S
70	1	1	0	205142	N
80	28	1	0	205142	S
90	0	1	0	212261	N
100	0	1	0	188601	S
110	0	1	0	183961	S
120	3	1	0	188671	N
130	0	1	0	194069	N
140	0	1	0	192871	S
150	0	1	0	182473	N
160	40	1	0	182478	S
170	4	1	0	123232	S
180	0	1	0	129021	S
190	3	1	0	119161	N
200	2	1	0	165104	S
210	0	1	0	147341	N
220	1	1	0	147341	S
230	1	1	0	121581	N
240	0	1	0	121581	S
250	0	1	0	96951	N
260	0	1	0	96951	S
270	1	1	0	98941	N
280	2	1	0	98941	S
290	0	1	0	84721	N
300	0	1	0	91711	S
310	0	1	0	91711	N
320	43	0	1	191981	N
330	57	0	1	147581	S
340	2	0	1	147581	N
350	19	0	1	147130	N
360	10	0	1	213841	N
370	81	0	1	213841	S
380	8	0	1	231801	S
390	5	0	1	205142	N
400	15	0	1	221521	N

410	4	0	1	188671	N
420	15	0	1	182473	N
430	3	0	1	123232	N
440	16	0	1	147341	N
450	9	0	1	98941	N
460	5	0	1	80571	N
640	3	1	1	187501	N
650	38	1	1	174051	S
960	18	0	0	147130	S
970	1	0	0	177981	N
980	9	0	0	177981	S
990	1	0	0	177981	N
1000	1	0	0	213841	N
1010	1	0	0	213841	S
1020	1	0	0	205142	S
1030	2	0	0	205142	S
1040	2	0	0	212261	N
1050	2	0	0	183961	N
1060	0	0	0	194069	S
1070	11	0	0	192871	N
1080	1	0	0	192871	N
1090	4	0	0	175027	N
1100	9	0	0	129021	N
1110	17	0	0	129021	S
1120	5	0	0	119151	N
1130	0	0	0	165104	S
1140	1	0	0	161521	S
1150	1	0	0	96951	S
1160	0	0	0	9651	N
1170	0	0	0	98841	N

Dependent Variable: NumberCrash NumberCrash

Source	DF	Sum of Squares	Mean Square	F Value
Model	2	3356.89535	1678.44767	10.43
Error	67	10781.44751	160.91713	
Corrected Total	69	14138.34286		

Source	Pr > F
Model	0.0001
Error	
Corrected Total	

R-Square	Coeff Var	Root MSE	NumberCrash Mean
0.237432	172.0876	12.68531	7.371429

Source	DF	Type I SS	Mean Square	F Value
ImpactArea	1	647.289622	647.289622	4.02
Interchange	1	2709.605723	2709.605723	16.84

Source	Pr > F
ImpactArea	0.0489
Interchange	0.0001

Figure 4.12. SAS outcomes of unbalanced two-way ANOVA for case study in I-95

Recent studies have raised concerns about using a Poisson distribution for accident frequency regression models. They state one characteristic of crash-frequency data is the probability that the variance exceeds the mean of the crash counts (Dominique et al, 2010). A property of the Poisson distribution is the mean and variance are equal; because of this, factor, characteristics of crash-frequency data could be problematic. To validate results, a negative binomial regression was also performed. The results of negative binomial regression also converges Poisson regression. The second analysis strongly rejects the hypothesis that interchanges are not significant contributors, but suggests DMS are not contributing factors to occurrence of accidents. The result for negative binomial regression analysis agrees with the Poisson regression that DMS do not cause accidents. The coding and outcomes are presented in Figure 4.13 and Figure 4.14.

Model Information

Data Set	WORK.AUTO1	
Distribution	Negative Binomial	
Link Function	Log	
Dependent Variable	NumberCrash	NumberCrash

Number of Observations Read	70
Number of Observations Used	70

Class Level Information

Class	Levels	Values
ImpactArea	2	0 1
Interchange	2	0 1

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	66	74.7226	1.1322
Scaled Deviance	66	74.7226	1.1322
Pearson Chi-Square	66	105.3643	1.5964
Scaled Pearson X2	66	105.3643	1.5964
Log Likelihood		993.4624	

Algorithm converged.

Figure 4.13. SAS outcomes of Poisson regression for case study in I-95

Analysis Of Parameter Estimates

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square
Intercept		1	0.8597	1.0341	-1.1672	2.8865	0.69
AADTVMT		1	0.0000	0.0000	0.0000	0.0000	4.17
ImpactArea	0	1	0.3691	0.3878	-0.3909	1.1290	0.91
ImpactArea	1	0	0.0000	0.0000	0.0000	0.0000	.

Analysis Of Parameter Estimates

Parameter		Pr > ChiSq
Intercept		0.4058
AADTVMT		0.0412
ImpactArea	0	0.3412
ImpactArea	1	.

Analysis Of Parameter Estimates

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square
Interchange	0	1	-1.4819	0.4315	-2.3276	-0.6361	11.79
Interchange	1	0	0.0000	0.0000	0.0000	0.0000	.
Dispersion		1	1.9123	0.3831	1.1613	2.6632	

Analysis Of Parameter Estimates

Parameter		Pr > ChiSq
Interchange	0	0.0006
Interchange	1	.
Dispersion		

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

Figure 4.13 (Continued). SAS outcomes of Poisson regression for case study in I-95

Model Information

Data Set	WORK.AUTO1	
Distribution	Negative Binomial	
Link Function	Log	
Dependent Variable	NumberCrash	NumberCrash

Number of Observations Read	70
Number of Observations Used	70

Class Level Information

Class	Levels	Values
ImpactArea	2	0 1
Interchange	2	0 1

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	66	74.7226	1.1322
Scaled Deviance	66	74.7226	1.1322
Pearson Chi-Square	66	105.3643	1.5964
Scaled Pearson X2	66	105.3643	1.5964
Log Likelihood		993.4624	

lgorithm converged.

Figure 4.14. SAS outcomes of Negative Binomial regression for case study in I-95

Analysis Of Parameter Estimates

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square
Intercept		1	0.8597	1.0341	-1.1672	2.8865	0.69
AADTVMT		1	0.0000	0.0000	0.0000	0.0000	4.17
ImpactArea	0	1	0.3691	0.3878	-0.3909	1.1290	0.91
ImpactArea	1	0	0.0000	0.0000	0.0000	0.0000	.

Analysis Of Parameter Estimates

Parameter		Pr > ChiSq
Intercept		0.4058
AADTVMT		0.0412
ImpactArea	0	0.3412
ImpactArea	1	.

Analysis Of Parameter Estimates

Parameter		DF	Estimate	Standard Error	Wald 95% Confidence Limits		Chi-Square
Interchange	0	1	-1.4819	0.4315	-2.3276	-0.6361	11.79
Interchange	1	0	0.0000	0.0000	0.0000	0.0000	.
Dispersion		1	1.9123	0.3831	1.1613	2.6632	

Analysis Of Parameter Estimates

Parameter		Pr > ChiSq
Interchange	0	0.0006
Interchange	1	.
Dispersion		

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

Figure 4.14 (Continued). SAS outcomes of Negative Binomial regression for case study in I-95

4.6.Weather Conditions Database

An important factor that contributes to driver distraction is visibility. Because precipitation, wind gusts and severe weather may have adverse effects on message visibility, another factor that should be considered as contributing to accidents is climate status. The factors analyzed for weather conditions include precipitation, wind gusts and visibility factors. The weather data for this research were retrieved from DOT archival databases. The data initially were formatted as month-to-month archival data from 49 weather tower stations. The initial data files contained the following fields: Date, time, air temperature, humidity, average wind speed, wind gust, wind direction, precipitation type, precipitation intensity (light, medium, heavy), precipitation accumulation, rate (rate per hour in inches), visibility (miles) and surface temperature.

For simplicity, the area of research was divided into north, south, west, east and Washington, D.C. regions. The nearest central weather tower in each region was designated to represent weather conditions in that region. Table 4.3 shows these regions. The data set covered the four-year period from 2007 to 2010. Figure 4.15 shows the format of weather database.

Table 4.3. Tower stations assigned to each weather region

Weather Station	Region	Latitude	Longitude
I-68 @ Cumberland	West	39.70302	-78.63177
US 50 Kent Narrow Bridge	East	38.97203	-76.25391
I-895 @ Levering Ave	North	39.21854	-76.71071
US-301 at Potomac River	South	38.36366	-76.983
I-270 @ I-370	Washington, DC	39.11946	-77.19593

If an accident in the database occurred within 900 feet of approach a DMS, the accident is joined with the DMS and AADT associated with that accident. As a result, the main database was integrated with the weather stations' data by proximity to the closest weather tower station and occurrence time of accident.

In order to integrate the weather database and the main database, the weather database was imported into a SQL server and each accident was matched with the closest weather tower and weather condition at the time of accident. The matching process is performed using SQL queries coded in C++.

1	Date / Time reported (GMT)	Air Temperature	Relative Humidity	Dew Point Temperature	Average Wind Speed	Wind Gust	Wind Direction	Precipitation Type	Precipitation Intensity	Rate	Visibility	Surface Tepmerature
328528	1/1/2007 3:26	44	99	44	0	3	NW	None	None	0		44 - 45
328529	1/1/2007 3:24	44	99	44	0	2	N	None	None	0		44 - 45
328530	1/1/2007 3:13	44	99	44	0	2	W	Rain	Slight	0		44 - 45
328531	1/1/2007 3:03	44	99	44	0	0	W	None	None	0		44 - 45
328532	1/1/2007 3:01	44	99	44	0	0	W	None	None	0		44 - 45
328533	1/1/2007 2:50	44	99	44	0	2	W	None	None	0		44 - 45
328534	1/1/2007 2:44	44	99	44	0	2	N	None	None	0		44 - 45
328535	1/1/2007 2:40	44	99	44	0	2	NE	Rain	Slight	0		44 - 45
328536	1/1/2007 2:30	44	99	44	0	0	NW	Rain	Slight	0		44 - 45
328537	1/1/2007 2:24	44	99	44	0	2	W	Rain	Slight	0.1		44 - 45
328538	1/1/2007 2:20	44	99	44	0	2	N	Rain	Slight	0		44 - 45
328539	1/1/2007 2:08	44	99	44	0	0	W	Rain	Slight	0		44 - 45
328540	1/1/2007 2:03	44	99	44	0	1	NW	Rain	Slight	0.1		44 - 45
328541	1/1/2007 1:57	44	99	44	0	1	NW	Rain	Slight	0.1		44 - 45
328542	1/1/2007 1:46	44	99	44	2	4	NW	Rain	Slight	0.1		44 - 45
328543	1/1/2007 1:43	44	99	44	1	3	NW	Rain	Slight	0		44 - 45
328544	1/1/2007 1:35	44	99	44	1	3	NW	Rain	Slight	0		44 - 45
328545	1/1/2007 1:25	44	99	44	0	1	W	Rain	Slight	0		44 - 45
328546	1/1/2007 1:23	44	99	44	0	0	W	Rain	Slight	0		44 - 45
328547	1/1/2007 1:12	44	99	44	0	0	NW	Rain	Slight	0		44 - 45
328548	1/1/2007 1:04	44	99	44	0	1	SE	Rain	Moderate	0.2		44 - 45
328549	1/1/2007 1:02	44	99	44	0	2	SE	Rain	Slight	0.1		44 - 45
328550	1/1/2007 0:51	44	99	44	1	2	SE	Rain	Moderate	0.1		44 - 45
328551	1/1/2007 0:43	44	99	44	0	2	E	Rain	Slight	0		44 - 45

Figure 4.15. Weather Database Format

4.7. Log of Messages Database

The database containing the message logs was acquired from the CATT Laboratory in the Department of Civil and Environmental Engineering at the University of Maryland. This database contains entire messages displayed on all DMS in Maryland during the time period from 2007 to 2010. This database includes 1,047,586 records of messages, their DMS identification number, time messages were displayed and beacon data fields. The beacon data field shows whether the beacon was on or off. Figure 4.16 shows an example of the messages database.

The syntax for message data field is based on the definitions in National Transportation Communications for ITS Protocol, Object Definitions for Dynamic Message Signs Version 02 (2007). The number of panes can be determined by interpreting the system of coding that comes with each message. The main codes of messages are:

- [PT##O#]: This code is interpreted as Panel Time, ## in tenths of seconds on, # in tenths of seconds off (normally this # is 0, otherwise the panel would be flashing)
- [JL#]: This code is for text justification. The number corresponds to various justifications (i.e. 2 left, 3 center, 4 right)
- [NL] - New Line
- [NP] - New Pane

1	dms_id	start_tstamp	message	beacon
109	CHART_010004f800fc00bf003e832c33235daa	12/24/2008 15:15	[PT25O0][JL3]I-95 TUNNEL[NL][JL3]MAJOR DELAYS[NL][JL3]STAY ALERT	on
110	CHART_010004f800fc00bf003e832c33235daa	12/24/2008 15:20	[PT25O0][JL3]I-95 TUNNEL[NL][JL3]MAJOR DELAYS[NL][JL3]STAY ALERT	on
111	CHART_010004f800fc00bf003e832c33235daa	12/24/2008 15:24	[PT25O0][JL3]I-95 TUNNEL[NL][JL3]MAJOR DELAYS[NL][JL3]STAY ALERT	on
112	CHART_010004f800fc00bf003e832c33235daa	12/24/2008 17:51	[PT25O0][JL3]I-95 TUNNEL[NL][JL3]MAJOR DELAYS[NL][JL3]STAY ALERT	on
113	CHART_010004f800fc00bf003e832c33235daa	12/24/2008 17:52	[PT25O0][JL3]I-95 TUNNEL[NL][JL3]MAJOR DELAYS[NL][JL3]STAY ALERT	on
114	CHART_010004f800fc00bf003e832c33235daa	12/24/2008 23:51		off
115	CHART_010004f800fc00bf003e832c33235daa	12/24/2008 23:55		off
116	CHART_010004f800fc00bf003e832c33235daa	12/25/2008 0:52	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
117	CHART_010004f800fc00bf003e832c33235daa	12/25/2008 6:56	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
118	CHART_010004f800fc00bf003e832c33235daa	12/25/2008 7:00	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
119	CHART_010004f800fc00bf003e832c33235daa	12/25/2008 8:31	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
120	CHART_010004f800fc00bf003e832c33235daa	12/25/2008 8:35	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
121	CHART_010004f800fc00bf003e832c33235daa	12/25/2008 14:04	[PT25O0][JL3]ACCIDENT AHEAD[NL][JL3]PAST EXIT 51[NL][JL3]2 LEFT LANES BLOCKEI	on
122	CHART_010004f800fc00bf003e832c33235daa	12/25/2008 14:39	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
123	CHART_010004f800fc00bf003e832c33235daa	12/26/2008 8:17	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
124	CHART_010004f800fc00bf003e832c33235daa	12/26/2008 8:21	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
125	CHART_010004f800fc00bf003e832c33235daa	12/26/2008 12:48	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT[NP]	off
126	CHART_010004f800fc00bf003e832c33235daa	12/26/2008 13:06	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
127	CHART_010004f800fc00bf003e832c33235daa	12/26/2008 15:16	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
128	CHART_010004f800fc00bf003e832c33235daa	12/26/2008 15:20	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
129	CHART_010004f800fc00bf003e832c33235daa	12/27/2008 1:41	[PT25O0][JL3]DISABLED VEHICLE[NL][JL3]PAST EXIT 55[NL][JL3]RIGHT LANE BLOCKED	off
130	CHART_010004f800fc00bf003e832c33235daa	12/27/2008 1:45	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
131	CHART_010004f800fc00bf003e832c33235daa	12/27/2008 6:31	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off
132	CHART_010004f800fc00bf003e832c33235daa	12/27/2008 6:35	[PT25O0][JL3]ROADWORK [NL][JL3]AT TUNNEL TOLL PLAZA[NL][JL3]STAY ALERT	off

Figure 4.16. Log of Messages Database

The following example illustrates the message syntax:

[PT25O0][JL3]ACCIDENT AHEAD[NL][JL3][NL][JL3]PAST EXIT 51[NP][PT25O0][JL3] 2 LEFT LANES BLOCKED[NL][JL3][NL][JL3] EXPECT DELAYS

This message has 2 panes, alternating appearances for 2.5 seconds, with all lines center-justified. It would appear as:

PANE 1:
ACCIDENT AHEAD

PAST EXIT 51

PANE 2:
2 LEFT LANES BLOCKED

EXPECT DELAYS

The message log database was imported into SQL server and the main database. If an accident was in impact area, the assigned DMS was matched with the message displayed at the occurrence time of accident. The same process matched weather data sets to messages using SQL queries coded in C++.

4.8. Analysis and Results

The integrated database consisted of the integrated data for each accident. Every record of an accident contains was associated with the following information: time and date of accident, location (longitude and latitude) of accident, type of accident, AADT of the roadway and weather condition at the time of accident (including air temperature, humidity, average wind speed, wind gust, wind direction, precipitation type and rate, and visibility). If the accident occurred in a DMS impact area, the following information is also present: the assigned DMS and the message DMS displayed at the time of accident.. Figure 4.17 depicts the projection of integrated database for the entire study area in ArcGIS and Figure 4.18 illustrate the close-up shot of the projected map.

The integrated database consisted of 23,842 records for accident during the period from 2007 to 2010. There were 298 accidents within 900 feet of a DMS. Drivers of 50 accidents were exposed to active DMS that displayed messages. For other 248 accidents, the DMS were blank. As the following sections present, multiple approaches were employed to analyze different aspects of the data. A paired *t*-test analysis at a significant level of 95 percent compared accident rate in impact areas with their onward 900-foot segment. In addition, an on-and-off study was conducted to compare accident rates of 15 DMS with on-and-off display messages. Statistical analyses investigated the effects of weather conditions, visibility and type of messages on accidents in impact areas.

4.9. Analysis on Impact Areas and Following Segment

To investigate the effects of DMSs on occurrence of road accidents, a paired t-tests statistical analysis at 95 percent confidence level was used to compare accident rates for the 50 accidents in impact areas of active DMSs with their subsequent 900 feet segment. The null hypothesis states the difference in mean accident rate between two consecutive 900 feet segments is equal to zero. On the other hand, the alternative hypothesis suggests difference between the means is not equal to zero:

$$H_0 : \mu_2 - \mu_1 = 0$$
$$H_1 : \mu_2 - \mu_1 \neq 0$$

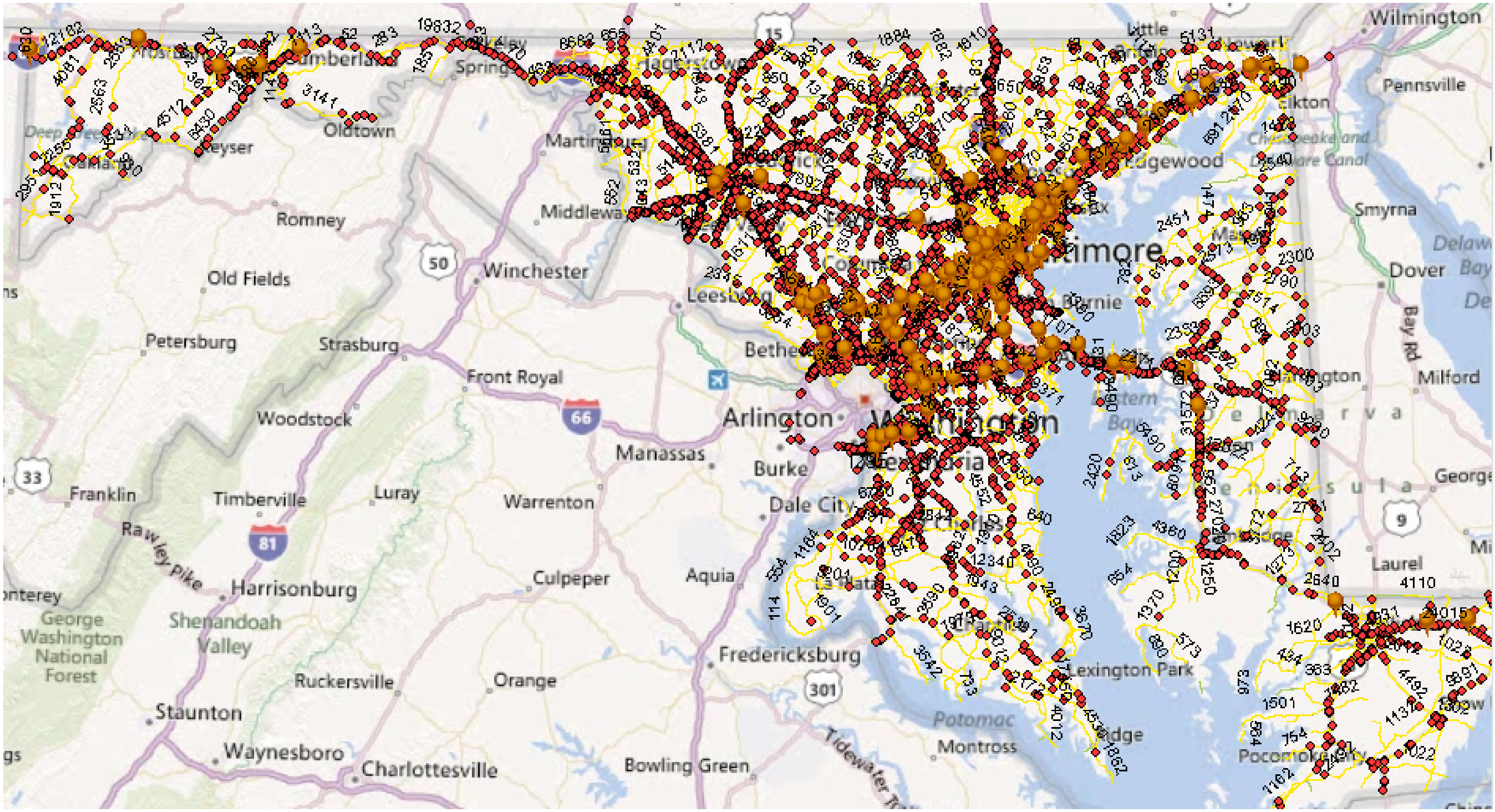


Figure 4.17. Projection of Integrated Database

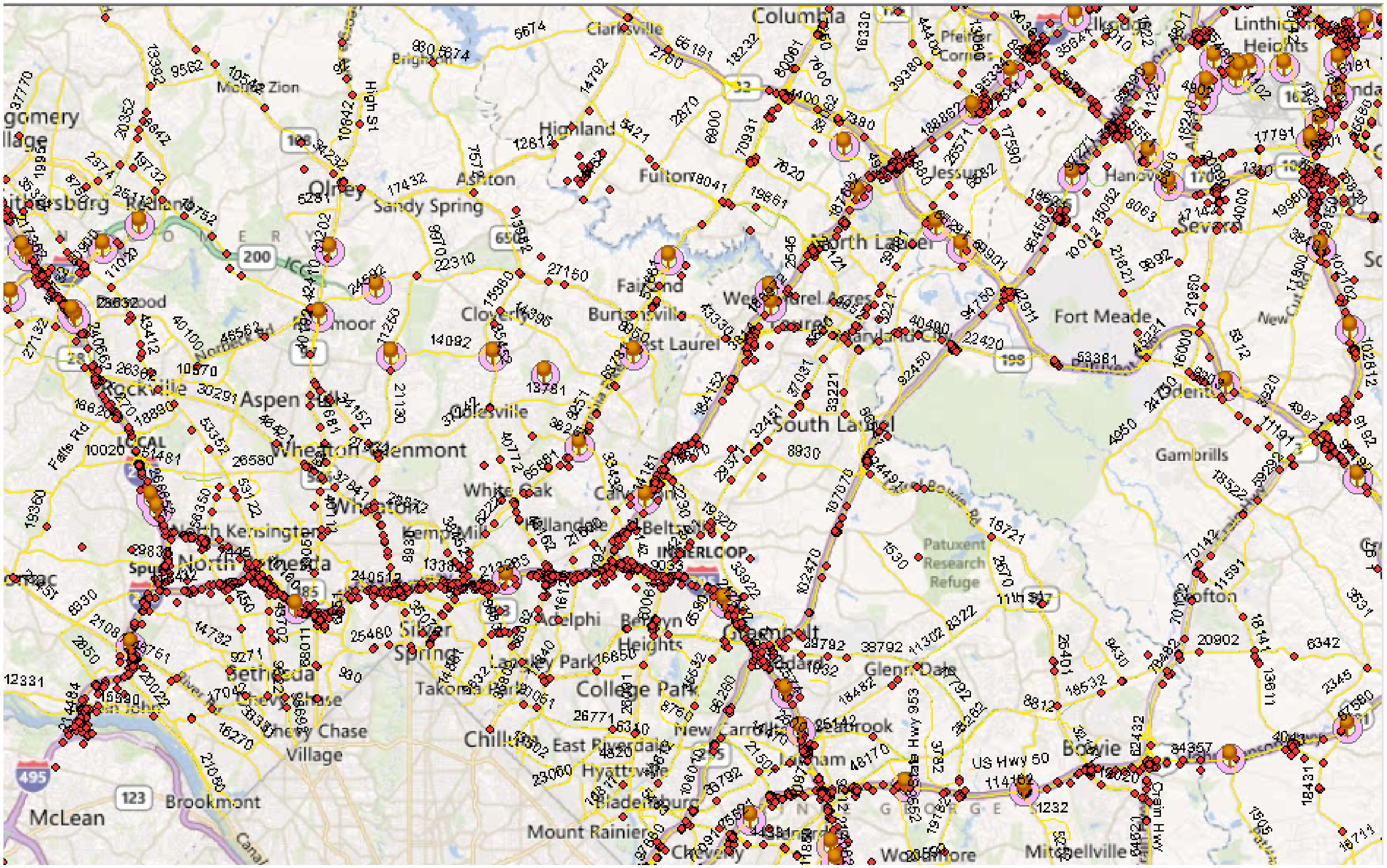


Figure 4.18. Close up shot of projected map

The accident rates for the segments were calculated using the spot accident rate formula recommended by both the FHWA Safety Program guidance and the Kiewit Center at Oregon State University (2003). According to the formula, the accident rate for a spot of a road is calculated by a ratio of accidents per million vehicles. A spot location is generally defined as a location 0.3 miles or less in length. Because the segments compared in this study were 900 feet length (0.17 miles), this formula was appropriate for calculating the accident rate (Kiewit, 2003). The formula allows comparison of various accidents rates. The equation for computing accident rate for a spot location is as follows:

$$Rsp = A/Exposure\ [\text{million entering vehicles}] \qquad \text{(Equation 1)}$$

or

$$Rsp = (C)\ (1{,}000{,}000)/AADT\ (365)(N)$$

Where:

Rsp = Accident rate at a spot in accidents per million vehicles,

C = Number of crashes for the study period,

N = Period of study (years or fraction of years),

AADT = Average Annual Daily Traffic (AADT) during the study period.

Figure 4.19 shows the accident rates for impact areas compared to their subsequent 900 feet segment.

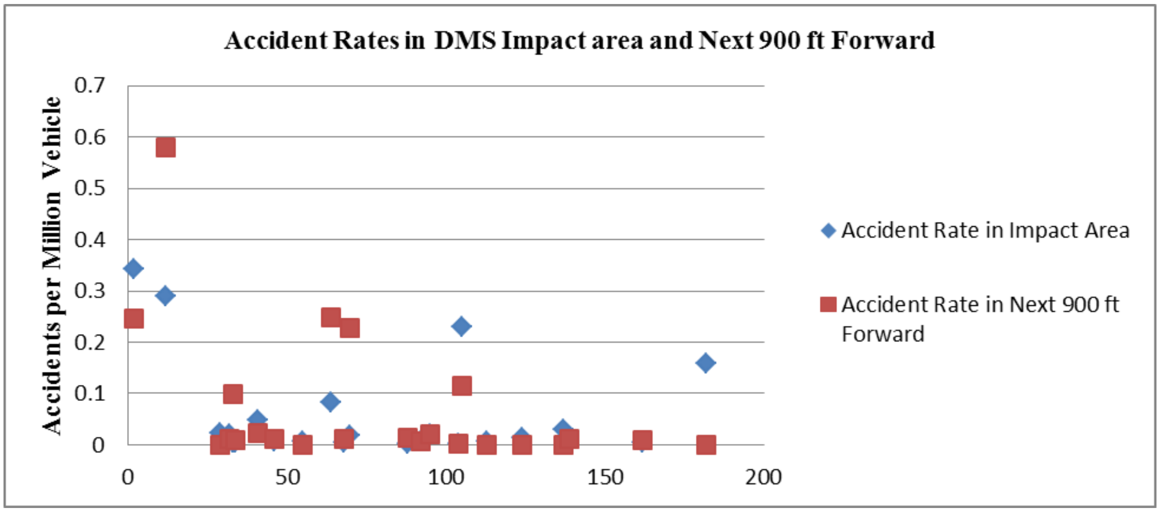


Figure 4.19. Accident rate for impact area of 900 feet compared to their subsequent900 feet segment

Table 4.4 shows the tabulated facts for the accident rates in both segments compiled in a table including DMS identification number, AADT of segment, number of accidents in segment and accident rates in segments.

Table 4.4. Tabulated facts of impact areas and forwarding segments

Impact Area	DMS_id	AADT	# accidents in 900 feet	900ft Accident Rate	# accidents in Forward 900 feet	Forward 900ft Accident Rate	DMS
2	CHART_01010528004f00820047f02c76235daa	13974	7	0.343102945	5	0.245073532	0.098029
12	CHART_0c011090002d0067003f062c3d235daa	2364	1	0.28973414	2	0.57946828	-0.28973
29	CHART_19011709000500020003d242c3b235daa	61273	2	0.022356715	0	0	0.022357
32	CHART_1b010c38005200820047f02c76235daa	65821	2	0.020811945	1	0.010405972	0.010406
33	CHART_1b01212600da0008003d242c3b235daa	187920	1	0.003644804	27	0.098409699	-0.09476
34	CHART_1c000b26004c00820047e22c9e235daa	145780	1	0.004698391	2	0.009396783	-0.0047
41	CHART_1e01133800d90008003d242c3b235daa	57512	4	0.047637467	2	0.023818734	0.023819
46	CHART_2c00083a004b00820047e22c9e235daa	444336	5	0.00770736	7	0.010790304	-0.00308
55	CHART_39010a59005100820047f02c76235daa	88882	1	0.007706077	0	0	0.007706
64	CHART_40ff12d400c200820047e32c96235daa	8282	1	0.08270122	3	0.248103661	-0.1654
68	CHART_46010ade0036005a0039fc442f1f5daa	190391	1	0.003597499	3	0.010792498	-0.00719
70	CHART_4701165e00d90008003d242c3b235daa	74887	2	0.018292401	25	0.228655009	-0.21036
88	CHART_5f00077a004600820047e32c96235daa	245421	1	0.002790843	5	0.013954216	-0.01116
92	CHART_62000ff900a300e0003e062c3d235daa	121581	1	0.005633541	1	0.005633541	0
95	CHART_650113d6003d0067003f062c3d235daa	65214	2	0.021005659	2	0.021005659	0
104	CHART_6dff058b004500820047e32c96235daa	255882	1	0.002676748	1	0.002676748	0
105	CHART_6e00069600af0054003afc442f1f5daa	23726	8	0.230947149	4	0.115473574	0.115474
113	CHART_74000733009000d3003e062c3d235daa	98941	1	0.006922626	0	0	0.006923
124	CHART_89000cab00d80008003d242c3b235daa	147130	3	0.013965843	0	0	0.013966
137	CHART_aa01033e000c00630045152cea235d0a	23741	1	0.028850154	0	0	0.02885
139	CHART_ac0064d1002f00ae003ac7442f1f5daa	66761	1	0.010259455	1	0.010259455	0
162	CHART_d8ff030400b800c60047832c33235daa	153481	1	0.004462647	2	0.008925294	-0.00446
182	CHART_fdff03d9008000c80040062c3d235daa	8600	2	0.159286397	0	0	0.159286
			50				

The graph shows for the majority of impact areas, rate of accidents is lower than their onward adjacent segment. Figure 4.20 shows the difference of the accidents rates for the two segments.

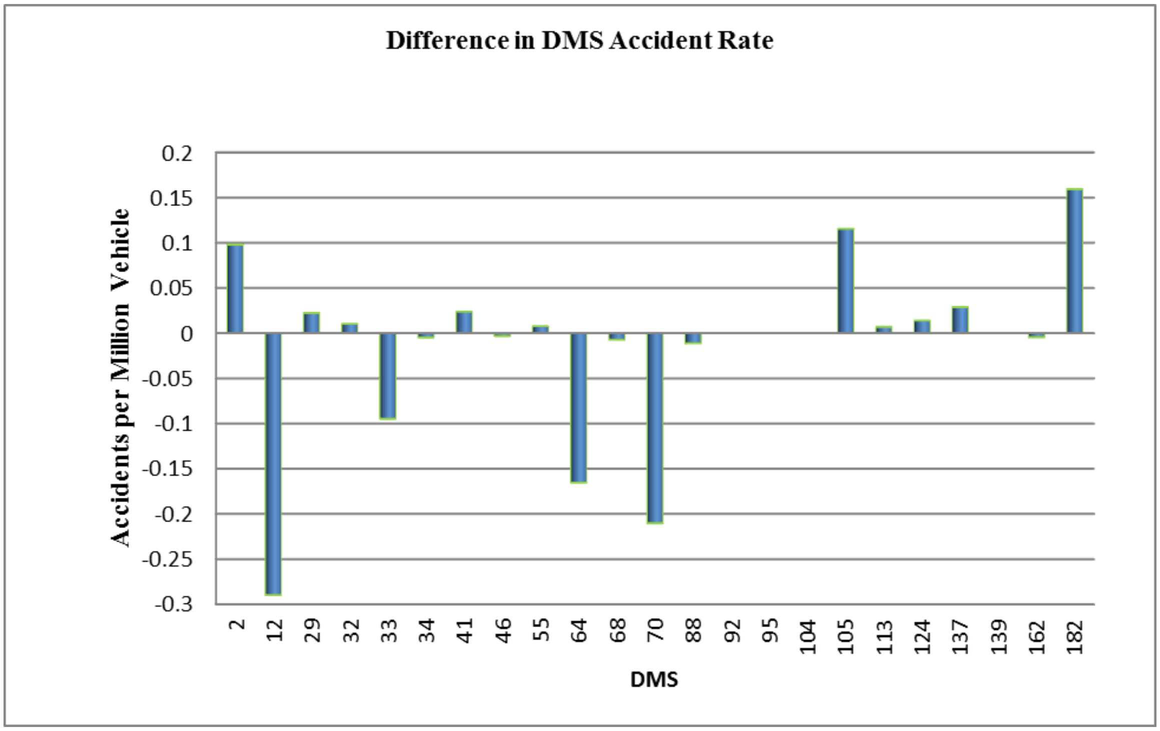


Figure 4.20. Difference of the accidents rates between the impact area and its subsequent segment

The analysis of difference between the accident rates show 70 percent of the impact areas have lower or equal accident rates compared to the 900 feet segments that follow them. This finding indicates DMS do not have significant effects on increasing the accident rate. The remaining 30 percent, or 7 impact areas, show a positive difference between the accident rates. The case study of Interstate 95 supported the fact that interchanges are contributing factor to accidents. Therefore, a simple qualitative analysis of the locations of the DMS with the highest accidents rates showed they tended to occur within short distances of interchanges. Additionally, those with lower rates tended to occur further away from interchanges. The reason for positive accident rates could be attributed to external factors such as existence of interchanges in DMS buffer zones and roadway geometry that increase accident rates in these segments.

4.9.1. Findings

A paired *t*-test on the accident rates was performed to compare accident rates in the two segments. Results suggest DMS do not increase accident occurrence. The mean difference of the two accident rates is -0.013. The coding in SAS software and the results are presented in Figure 4.21.

Obs	Impact Area	DMS
1	2	0.09803
2	12	-0.28973
3	29	0.02236
4	32	0.01041
5	33	-0.09476
6	34	-0.00470
7	41	0.02382
8	46	-0.00308
9	55	0.00771
10	64	-0.16540
11	68	-0.00719
12	70	-0.21036
13	88	-0.01116
14	92	0.00000
15	95	0.00000
16	104	0.00000
17	105	0.11547
18	113	0.00692
19	124	0.01397
20	137	0.02885
21	139	0.00000
22	162	-0.00446
23	182	0.15929

Figure 4.21. SAS outcomes for comparison of impact areas and following section

The TTEST Procedure

Statistics

Variable	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev
DMS	23	-0.056	-0.013	0.0292	0.0758	0.098

Statistics

Variable	Upper CL Std Dev	Std Err	Minimum	Maximum
DMS	0.1387	0.0204	-0.29	0.1593

T-Tests

Variable	DF	t Value	Pr > |t|
DMS	22	-0.65	0.5245

Figure 4.21 (Continued). SAS outcomes for comparison of impact areas and following section

4.10. On-and-off Analysis

An on-and-off study compared results obtained from the previous section. The data were inputted into a table. Total numbers of accidents for 15 signs were counted for periods when DMS displayed messages and when they were blank. The accident rates for both situations were calculated using the formula articulated in the previous section. A one-way ANOVA with pairwise comparisons assessed accident rates in impact area when DMS were on and when they were off. Table 4.5 shows data used in the on-and-off analysis, including DMS identification number, number of accidents in impact areas, and AADT of segment and accident rates in segments.

Figure 4.22 depicts the comparison of accident rates when messages are displaying on DMS and when these signs are blank.

To better determine how different the accidents rates are for on and off DMS, the graph of the difference between the rates of the two conditions is shown in Figure 4.23. As this graph shows, in all DMS impact areas the accident rate is lower when the sign shows a message.

Table 4.5. Tabulated facts of on and off study

Impact Area	DMS_id	# accidents in impact area	With DMS Message Accident Rate	AADT	DMS blank before	DMS Blank Accident Rate	DMS Effect
2	CHART_01010528004f00820047f02c76235daa	7	0.343102945	13974	11	0.53916177	-0.196059
29	CHART_19011709000050002003d242c3b235daa	2	0.022356715	61273	7	0.078248503	-0.055892
32	CHART_1b010c38005200820047f02c76235daa	2	0.020811945	65821	8	0.083247779	-0.062436
33	CHART_1b01212600da0008003d242c3b235daa	1	0.003644804	187920	4	0.014579215	-0.010934
34	CHART_1c000b26004c00820047e22c9e235daa	1	0.004698391	145780	1	0.004698391	0
41	CHART_1e01133800d90008003d242c3b235daa	4	0.047637467	57512	19	0.22627797	-0.178641
46	CHART_2c00083a004b00820047e22c9e235daa	5	0.00770736	444336	16	0.024663552	-0.016956
55	CHART_39010a59005100820047f02c76235daa	1	0.007706077	88882	1	0.007706077	0
64	CHART_40ff12d400c200820047e32c96235daa	1	0.08270122	8282	6	0.496207322	-0.413506
68	CHART_46010ade0036005a0039fc442f1f5daa	1	0.003597499	190391	2	0.007194999	-0.003597
70	CHART_4701165e00d90008003d242c3b235daa	2	0.018292401	74887	7	0.064023403	-0.045731
105	CHART_6e00069600af0054003afc442f1f5daa	8	0.230947149	23726	21	0.606236266	-0.375289
113	CHART_74000733009000d3003e062c3d235daa	1	0.006922626	98941	1	0.006922626	0
124	CHART_89000cab00d80008003d242c3b235daa	3	0.013965843	147130	8	0.037242249	-0.023276
162	CHART_d8ff030400b800c60047832c33235daa	1	0.004462647	153481	1	0.004462647	0

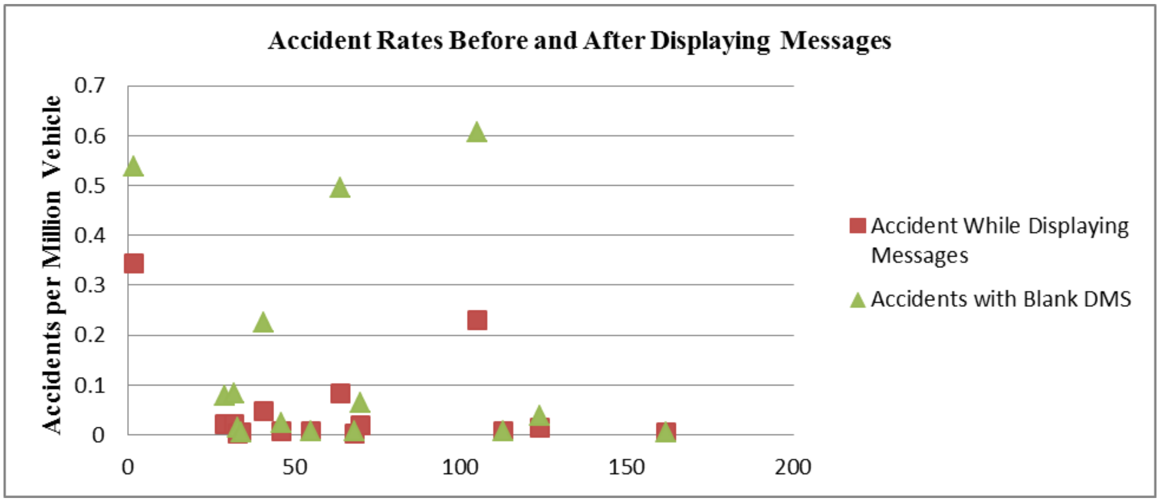


Figure 4.22. Comparison of accident rates while DMS are on and while blank

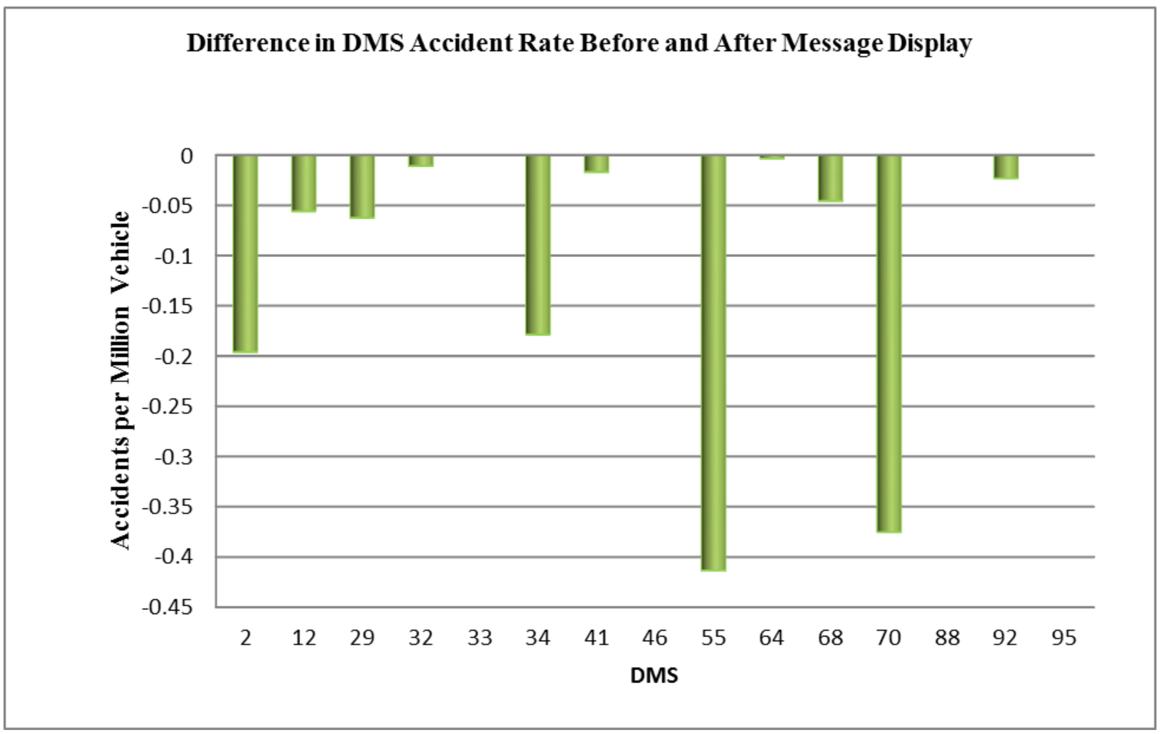


Figure 4.23. Difference of the accidents rates in on and off study

The results show accident rates for DMS displaying messages were less than or equal to blank DMS for all cases analyzed. The results of this on-and-off study support the outcomes of the previous sections – DMS are not contributing factors to accidents.

4.10.1. Findings

A Repeated Measures Analysis of Variance was conducted to compare the mean accident rates in two conditions. The F-value of 6.73 and P(F < 6.73) of 0.0212 for the one-way ANOVA with paired comparison suggests null hypothesis is rejected with 98 percent level of confidence in favor of supporting the fact that the mean accident rate for active DMSs was lower than the rate of accidents for inactive DMSs. The SAS coding and the outcomes are presented in Figure 4.24.

Obs	Impact Area	DMSEffect
1	2	-0.19606
2	29	-0.05589
3	32	-0.06244
4	33	-0.01093
5	34	0.00000
6	41	-0.17864
7	46	-0.01696
8	55	0.00000
9	64	-0.41351
10	68	-0.00360
11	70	-0.04573
12	105	-0.37529
13	113	0.00000
14	124	-0.02328
15	162	0.00000

Figure 4.24. SAS outcomes for on and off study

The ANOVA Procedure

Number of Observations Read	15
Number of Observations Used	15

The ANOVA Procedure
Repeated Measures Analysis of Variance

Repeated Measures Level Information

Dependent Variable	DMSOn	DMSOff
Level of WorNoDMS	1	2

The ANOVA Procedure
Repeated Measures Analysis of Variance
Univariate Tests of Hypotheses for Within Subject Effects

Source	DF	Anova SS	Mean Square	F Value
WorNoDMS	1	0.06369341	0.06369341	6.73
Error(WorNoDMS)	14	0.13243458	0.00945961	

Source	Pr > F
WorNoDMS	0.0212
Error(WorNoDMS)	

Figure 4.24 (Continued). SAS outcomes for on and off study

4.11. Accidents in DMS Impact Areas and Weather Conditions

This section summarizes and categorizes accident characteristics in DMS areas. As mentioned before, weather conditions can contribute to accidents by reducing drivers' visibility. According to FHWA Road Weather Management Program, visibility impairments, precipitation, high winds and temperature extremes affect driver capabilities and operational decisions, traffic flow, and crash risk. This research project concerns driver response to DMS messages, which is known to have environmental factors, so it was necessary to investigate the accident in conjunction with weather conditions at the time of accident for active DMS. As Table 4.6 and Figure 4.25 show, there are only four accidents in the entire set of accidents within the impact area that happened in rainy and snowy conditions.

Table 4.6. Accidents in DMS areas and precipitation

Precipitation	Accidents in Impact Area #
Rain	2
Snow	2
None	45
other	1
Total	50

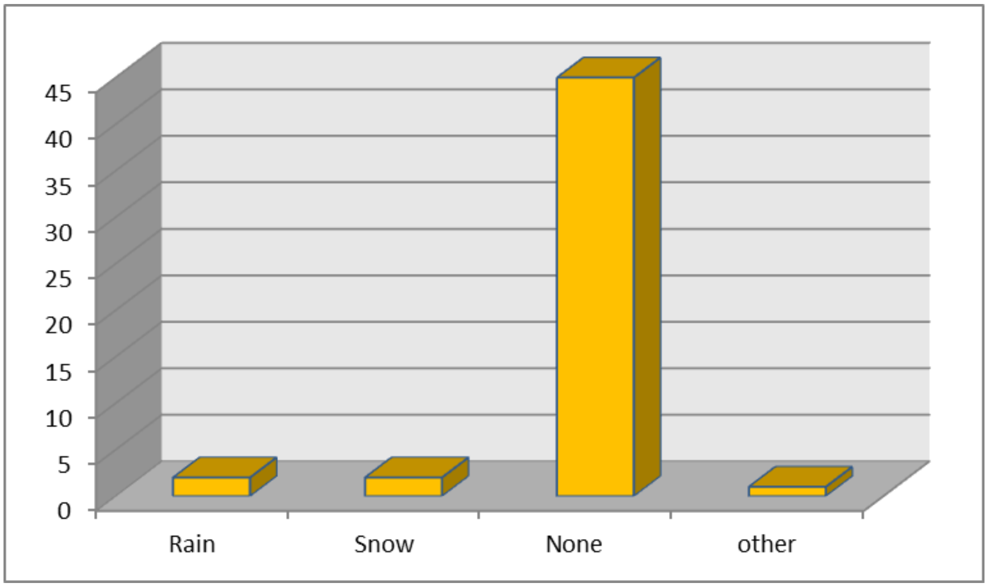


Figure 4.25. Frequency of accidents in different precipitation conditions

Despite the concerns about lack of visibility of messages during wind gust condition, as shown in Table 4.7 and Figure 4.26, the statistical analysis regarding 43 accidents in impact area indicates there was not a significant number of accidents in these adverse conditions.

Table 4.7. DMS accidents and wind gust

Wind Gust (mph)	Accidents in Impact Area #
0-10	32
10-20	9
20-30	2
Total	43

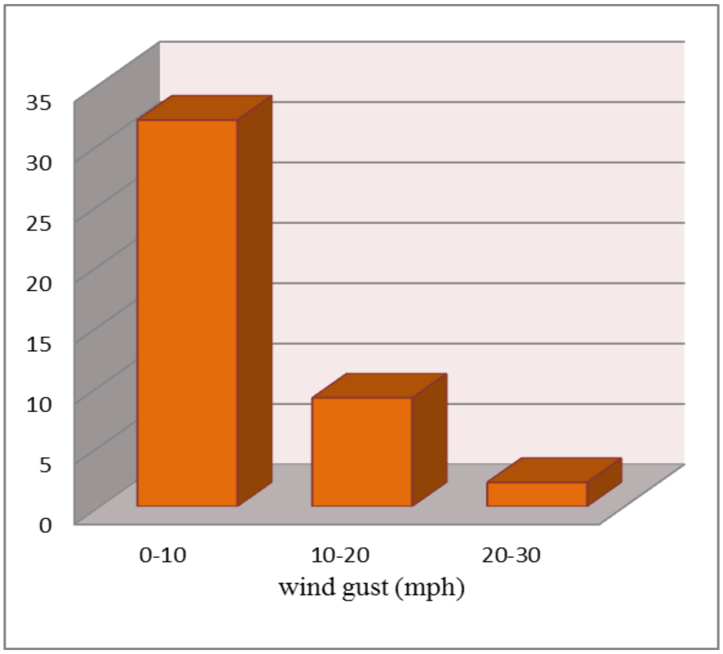


Figure 4.26. DMS accidents and wind gust

4.12. Accidents in DMS Impact Areas and DMS Characteristics

This section details statistical analysis of accident types in DMS impact area, the type of messages and beacon operational status (on/ off) of DMS. Figure 4.27 shows of the 50 accidents in DMS impact areas, 35 collisions were property damage and 15 were personal injury.

Researchers and laypersons have expressed concerns that flashing beacons could distract drivers and negatively affect driving performance. As Figure 4.28 shows, 10 accidents (20 percent) occurred when beacons were on.

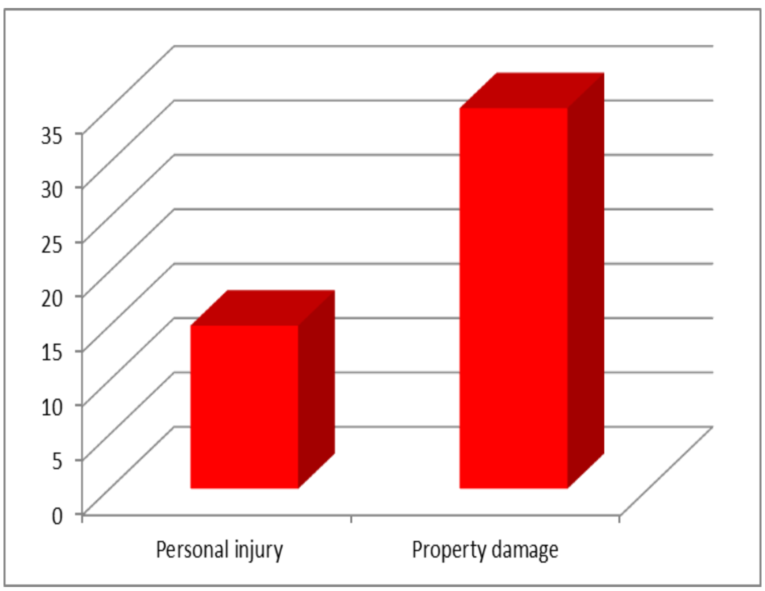


Figure 4.27. Type of accidents in DMS area #

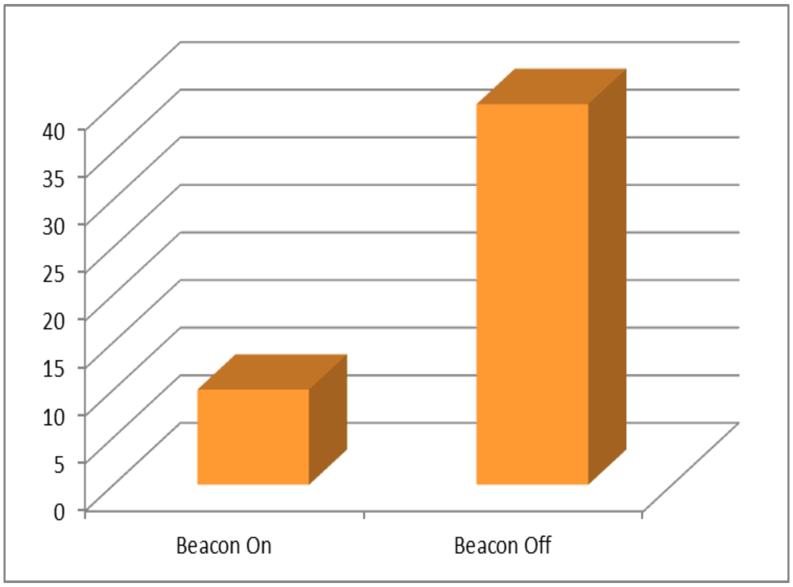


Figure 4.28. Number of accidents versus Beacon status

Analysis of displayed messages showed 11 accidents occurred when Danger/Warning messages were displayed: 22 during Informative/Common Road Condition messages and 17 during Regulatory/Non-Traffic-Related Messages. Although concerns that accident-warning messages attract more attention from drivers than the other types (Wang et al, 2007) and are thus more dangerous, the fewest number of accidents happened during displays of Danger/Warning messages (see Figure 4.29).

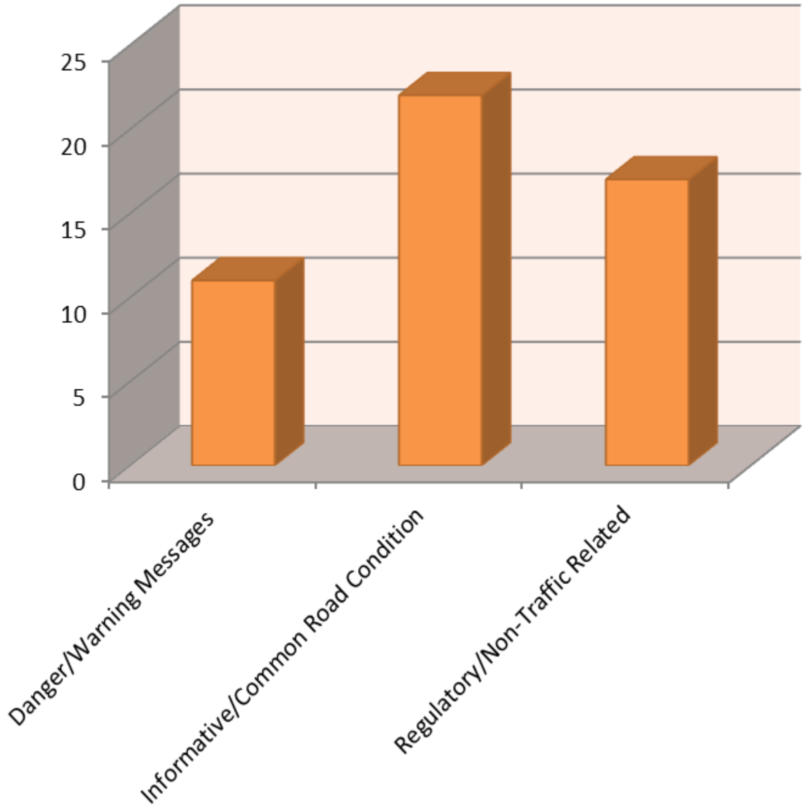


Figure 4.29. Number of accidents for DMS message types

Chapter 5: Conclusions and Directions for Further Research

5.1. Summary and Conclusions

This project evaluated localized safety effects of highway Dynamic Message Signs (DMS). Accident data from 2007 to 2010 was the basis for the analysis of road collisions in Maryland. Accidents and message data in the study period were collected from the Center for Advanced Transportation Technology (CATT) Laboratory in the Department of Civil and Environmental Engineering at the University of Maryland and Coordinated Highway Action Response Team (CHART) reports for regions within the District of Columbia and Maryland. The roadway network map and AADT of roadway segments were obtained from Maryland Department of Transportation State Highway Administration (SHA), and weather conditions databases were gathered from DOT archival data. This research project faced numerous challenges, including managing and joining large databases with different data structures based on only time and location, coordinating systems and working within confidentiality required of police accident reports. Each was successfully overcome.

The accident database included 38,718 records, which were filtered and cleaned and from which data gaps and outliers were removed. After cleaning, the number of accidents decreased to 23,842 records for the four-year study period. The accident database consisted of accident type (property damage, personal injury and fatality), address location and county, time and date of accident and coordinates of accident location. Due to confidentiality concerns, access to police records and accident causes was not possible.

The DMS types, obtained from CATT Laboratory, included permanently mounted overhead, roadside models and portable signs operated by CHART or Maryland Transportation Authority (MTA). The DMS database has 184 signs and the following information associated with each: DMS ID, longitude and latitude, address location and DMS type fields.

Traffic flow is another important contributing factor to crashes, so the AADT of road segments was another factor this analysis accounted for. The AADT data was obtained from Maryland SHA volume maps of the state of Maryland for study period.

The accidents, DMS locations and AADT database were projected onto a Maryland roadway map to perform spot analysis in order to evaluate the influence of DMS on drivers' performance. An impact area of 900 feet was defined for each DMS based on the average size of electronic signs character and maximum visibility distance for the signs. A DMS was assigned to accidents within 900 feet of each DMS based on location and direction of DMS.

A case study was performed on Interstate 95 in Maryland, a major highway. 70 samples of 900 feet segments along I-95 highway were chosen based on the homogeneity of their geometry. The number of accidents were counted for each segment and aggregated for use in regression analysis. Independent variables included whether the segment was in an impact area or not, the existence of interchange in the segment and the AADT of the segment. The results of unbalanced two-way ANOVA showed that interchanges affect occurrence of accidents, whereas DMS do not. Results from Poisson regressions supported this conclusion as well. The results for both methods converged on the idea that interchanges and AADT are important factors on accidents, whereas DMS are not.

Another main factor that contributes to accidents is lack of visibility due to adverse weather conditions. This project sought to determine whether adverse weather conditions such as precipitation, wind gusts and severe weather negatively affected driver performance by impairing visibility. For simplicity, the area of research was divided into five regions: north, south, west, east, and Washington, DC. The nearest central weather tower station in each region was assigned to represent the weather condition in each region. The database was accumulated for the study period from 2007 to 2010. Each accident was joined with its associated weather station. This weather database was joined to the main database by the proximity of the closest weather tower station and the time and location of each accident. The matching process was performed using SQL queries coded in C++.

The database of messages was acquired from the CATT laboratory. This database contained all the messages displayed on DMS in Maryland during the period study. The database contained 1,047,586 records of messages, including their DMS ID, time of displaying the message, the message text and beacon data fields.

The message log database was imported in SQL server and the main database. If a record was located in impact area, the assigned DMS was matched with the message displayed at the time of occurrence of accident. The same was done to match records with weather data. The matching process was conducted using SQL queries coded in C++. The integrated database consisted of 23,842 accident records during the study period. There were 298 accidents within 900 feet of a DMS. 50 accidents occurred during times when the DMS displayed messages. For the remaining accidents, the DMS were blank. The data were analyzed in several aspects.

The paired *t*-test analysis showed DMS do not increase the likelihood of accidents occurring. The mean of the difference of the two accident rates was -0.013.

A one-way ANOVA using pairwise comparisons was used in an on-and-off analysis for 15 DMS. The results of this analysis showed the mean accident rate associated with active DMS is lower than the inactive DMS.

The statistical analysis of accidents in conjunctions with weather conditions showed that there are only four that occurred in rainy and snowy conditions. Thirty-twoof 43 accidents were in wind gusts of 0-10 mph condition, nine were in gusts of 10-20 mph, and two were in wind gusts of 20-30 mph.

A statistical analysis of accidents revealed 35 of the 50 total collisions resulted in property damage, and 15 in personal injury. There were no fatalities.

Ten accidents (20 percent) occurred while beacons were on. Analysis on displayed messages showed 11 accidents occurred while Danger/Warning messages were displayed, 22 occurred during Informative/Common Road Condition messages and 11 occurred during Regulatory/Non-Traffic-Related messages. Although some concerns exist that accident-warning messages attract more attention from drivers, the fewest accidents in DMS areas occurred when DMS displayed such messages.

In summary, the findings from all evaluations converge to indicate DMS are a safe tool for disseminating real-time travel information to motorists because these signs largely do not cause accidents by diverting drivers’ attention. This project focused on DMS operations in Maryland, although the methods employed for evaluation can be extended to other locations if suitable data are available.

5.2. Future Research

The broad range of subjects for future study provides opportunities and challenges for researchers. The research could be further extended if future study areas include several states. Future research in this area may be improved through investigating the issue through simulation and site-human factor analysis. Also, it would be of interest to improve DMS design (e.g., message design, size, color, length and number of panes and speed of switching between messages) to enable drivers (especially older and bilingual drivers) to more easily understand the content of DMS messages. Topics for future research include investigations about the effects of displaying messages on newly installed DMS as well as DMS on road curves. It would also be of interest to investigate differences in daytime and nighttime situations. Another direction for future research concerns the extension of this project to investigate the effect of incident messages and to provide motorists with information about tailgating and secondary accidents close to the incident location. Moreover, the integrated database could be used to investigate the impact of weather conditions on occurrence of road accidents.

Finally, optimizing displayed messages and DMS location while accounting for traffic flow, roadway geometry, and proximity to interchanges; and how to reduce drivers' mental processing time to perceive environmental factors and speed up drivers' response could be other topics for future study. A cost-benefit analysis of installing DMS could clarify concerns about expenses and values associated with the signs. These directions for future studies would help transportation engineers and planners improve DMS operations and eventually improve transportation network management and yield smoother traffic flow.

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