ABSTRACT

Title of Document: EMPIRICAL ANALYSIS OF THE QUALITY, EFFECTIVNESS, AND LOCALIZED IMPACTS OF HIGHWAY DYNAMIC MESSAGE SIGN MESSAGES

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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). Though utilized for over 50 years, the quality of messages used, their effectiveness in influencing traffic, and the localized impacts they have are not well documented. This thesis introduces Bluetooth traffic detection sensors as a new tool for evaluation of DMS message quality and resulting route choice decisions. In addition, highway speed sensors are used to determine whether DMS influence changes in local traffic speeds. The findings indicate DMS messages are generally accurate in communicating prevailing conditions and can influence the route choice behavior of drivers. The speed analysis indicated that certain messages have more influence on traffic than others, though the majority of messages do not negatively affect traffic speeds.

EMPIRICAL ANALYSIS OF THE QUALITY, EFFECTIVNESS, AND LOCALIZED IMPACTS OF HIGHWAY DYNAMIC MESSAGE SIGN MESSAGES

By

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Thesis submitted to the Faculty of the Graduate School of the
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Advisory Committee:
Professor Ali Haghani, Chair
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Professor Lei Zhang

Dedication

This thesis is dedicated to my mother.

Acknowledgement

The completion of this work is a result of the assistance of the brilliant and supportive people with whom I have had the privilege to work with throughout my education.

Foremost, I would like to thank my advisor, Dr. Ali Haghani, for giving me the opportunity, motivation, and guidance needed to succeed as a graduate student. His accessibility and advice made my studies pleasant and rewarding. A better advisor cannot be imagined.

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Throughout my studies, my friends and classmates have both suffered and triumphed with me. Their support has allowed me to maintain my sanity and excel both personally and academically. For this, I am forever thankful.

Finally, I want to thank my father and brothers for their love and support. Their encouragement has motivated me to put forth my best efforts in all endeavors.

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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 in recent years as traffic volumes have increased and the ability to supply additional capacity is limited. Knowledge of rapidly changing traffic conditions gives road users 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) in order to help provide this information. Also known as Variable Message Signs (VMS) and Changeable Message Signs (CMS), these electronic signs have the capability to display various unique messages which can be specified by a remote operator or updated automatically. Among others, this capability allows the roadway administrator to communicate with users about accidents, delays, and, in some jurisdictions, travel time.

An important measure of the value of a DMS message is its credibility. It is vitally important that travelers believe that a message displayed on a DMS is based on fact and accurately describes present roadway conditions. Without consistently valid information, road users will begin to ignore DMS messages altogether.

In Maryland, the State Highway Administration's (SHA) Coordinated Highways Action Response Team (CHART) operates nearly 80 Dynamic Message Signs. The signs are located on major highways and their arterials and are often used to inform motorists of delays, incidents, road closings, and recently real-time travel times. In the case of travel delays, terms such as "Major Delays," "Heavy Delays," and “Expect Congestion” are being used to describe the prevailing conditions. Ambiguous descriptions such as these do little to inspire confidence in the DMS system, unless their meanings are consistent and appropriate for the given road conditions.

In order to determine the meaning and accuracy of such messages, the road conditions under which they are displayed are examined. Specifically, Bluetooth travel time data is collected and analyzed during the periods of time that certain DMS messages are displayed on the I-95 and I-895 corridors in Maryland. This thesis presents the first attempts to utilize Bluetooth ground truth data to determine the timeliness and accuracy of the DMS messages.

Another important aspect of Dynamic Message Signs is their effectiveness. In addition to accurately informing users of road conditions, the messages should, if necessary, induce changes in travel behavior. A good measure of whether or not a message is influencing such a change is if users divert or change routes during a period in which a message suggests as much. The unique identification and re-identification capability of Bluetooth sensors allows for an approximation of these diversion rates. By comparing detection rates among the current and suggested routes during the periods studied, the effectiveness of the messages is determined.

While the quality and effectiveness of messages are incredibly important for the DMS system, there has been historical concern that the display of messages causes localized speed reductions, congestion, and possible safety impacts. To investigate this, DMS 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 impacts of Dynamic Message Signs 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 Dynamic Message signs. Study of existing publications will give insight into the previous methods, their findings, and any benefits or shortcomings.

1.2.1: Message Quality

Dynamic Message Signs are a relatively new and frequently changing technology and, 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 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 confines of the DMS. The MUTCD specifies that a message should be readable at least twice while traveling at the posted speed limit (2). This translates to an upper limit of about 8 seconds of reading time under normal weather and roadway conditions (3). These restrictions can be complicated by the occurrence of multiple incidents or rapidly changing conditions.

Several states have developed message hierarchies ranking the relative importance of various message categories should a conflict arise. In general, messages requiring a change in behavior on the part of the motorist such as emergencies, incidents, and roadway closures sit near the top of these hierarchies *(*1, 4, *5).* The messages of moderate importance in the rankings tend to be congestion, travel time, or weather related. In lieu of any of the preceding messages, some jurisdictions choose to display public service or safety related messages while others leave the signs blank. These three levels were defined into the categories of [1] Danger & Warning Messages, [2] Informative Messages, and [3] Regulatory Messages (6).

In jurisdictions where quantitative travel time information is not available, terms such as “Heavy Delay” and “Major Delay” are often used. Little information or guidance exists on how these terms are defined, however according to the *Dynamic Message Sign Message Design and Display Manual* the average motorist in Texas interprets “Heavy Delay” as being between 25 and 45 minutes while a “Major Delay” is interpreted as a delay greater than 45 minutes (7). Similarly, a study in England to determine driver response to Dynamic Message Signs found that “Long Delays” were interpreted as between 35 and 47 minutes, while “Delays Likely” indicated a 10 to 31 minute delay (8). In contrast, the Minnesota Department of Transportation’s *Guidelines for Changeable Message Sign (CMS) Use* specifies that a “Major Delay” is not indicative of an amount of time but rather an incident causing more than 2 miles of traffic backup (4). These conflicting definitions alone demonstrate the need for high quality evaluation of DMS messages and the conditions to which they correspond.

Since state transportation agencies introduced travel time messages on DMS, there have been attempts to validate 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 that the travel times were accurate in many cases but suffered from deficiencies during incidents or when detectors were placed poorly (9). After designing a model to predict and automatically display travel times on DMS using loop detector data, researchers in California used probe vehicles to validate the travel times. A total of 88 probe vehicle runs were made on two different roads. The authors found good agreement between travel times and probe data when sufficient data existed. From this finding they concluded that it is important to validate travel times using probe data prior to deployment of travel time messages on DMS (*10*). These studies demonstrate previous attempts to validate DMS travel time message through the use of probe vehicle data. While the collected data was of high quality, neither attempt produced more than 100 samples. This thesis utilizes Bluetooth travel time collection for the validation of DMS travel times, which is capable of collecting many times the number of samples, allowing for higher quality evaluation.

1.2.2: Driver Response and Diversion

Revealed (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% of drivers say they will divert whereas when traffic is moving between 20-35 km/h (common congestion) a mere 7.02% 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 that more exposure to DMS leads to an increase in appreciation of the information displayed (*13*). A combined SP & 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 was 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 was 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 that the initial diversion reaction to a change in DMS message is significant and that 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 that 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 that DMS can potentially impact diversion. One caveat to these findings is that loop detector data is unable to identify individual vehicles, so their individual paths are unable to be determined with any certainty.

1.2.3: Speed Impacts

Several researchers have investigated the effect of DMS on traffic speed using various methods. At the University of Iowa, researchers used a full size traffic simulator to investigate travelers speed behavior in response to DMS and other in vehicle information systems. They found that users seeing DMS messages slow 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 that all participants reduced their speeds in response to Incident Warning Systems in the simulation (*20*). Researchers in Finland found that 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 that vehicles showed "large speed reductions." They also observed through video recording that "large proportions" of the traffic stream braked in advance of the DMS (*22*). To determine the effects of DMS on traffic slow downs, researchers at the University of Rhode Island used 5 minute interval speed data during the nearest periods when messages switched from off to on and from on to off. They found that slowdowns occurred in more than half of the cases examined, and particularly during cases of danger messages, although not all 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 characterize their true nature.

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 utilized in an effort 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 some promising results. This thesis presents Bluetooth detection as a new and emerging method for DMS evaluation. The ability to anonymously indentify and re-identify individual vehicles and users to track travel time and diversion was previously unavailable or prohibitively expensive. This method should provide a higher quality analysis method than previously available. In addition, the use of high quality 1-minute interval speed data for analysis of localized impacts will provide finer results than previous attempts.

1.3: Scope

This thesis covers the Bluetooth analysis of two separate DMS case studies on the same segments as well as 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, while due to technical difficulties only 19 were available for the second. For both deployments, several specific message cases are selected for examination and analysis of timeliness and accuracy. In addition, for cases that suggested diversions, an analysis of the diversion rates as represented by Bluetooth detection sampling is performed. Finally, the localized impacts of the DMS are studied through analysis of highway speed data. Two specific analyses are undertaken: the first investigates the effects of message display on speed in two consecutive 5-minute periods, while the second investigates the speeds over several two-week periods.

1.4: Organization

The organization of the thesis is as follows: Chapter 2 will provide a brief review of Bluetooth technology, the specific sensors used in this study, and the data used in the analysis efforts. Chapter 3 will present the efforts and results of the quality and effectiveness analyses resulting from Bluetooth analysis. Chapter 4 examines the localized speed impacts of DMS message display. Finally, Chapter 5 will provide some overarching conclusions as well as recommendations for future work.

Chapter 2: Detection Technology and Data

2.1: Bluetooth Technology

The primary data for this study is derived from Bluetooth device detection. Bluetooth is a short-distance wireless networking protocol that is found in many modern electronic devices including vehicles, cell phones, laptops, and earpieces. Depending on the power rating of the device, the transmission distances range from approximately 1 meter 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 in an effort to locate other devices with which to pair and communicate. This transmission forms the basis for Bluetooth traffic detection technology as it allows anonymous identification and re-identification of individual devices. More detailed information regarding Bluetooth technology can be found through the Bluetooth Special Interest Group.

2.2: Bluetooth Detectors and Data

In order to take advantage of the potential traffic information that can be derived from Bluetooth devices, a specialized detector must be used. For this study, detectors developed by the University of Maryland were utilized for data collection. The detectors are considered “off-line” since they do not transmit the data collected 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 along with detection times on the memory card. When the sensors are retrieved, the memory cards are removed and the data retrieved.

Figure 2.1. Bluetooth Detector Internals

The main processing effort, in simplest terms, consists of matching the MAC addresses from detector to detector and calculating the elapsed time (Figure 2.2). Since the locations of the detectors are known, the distance between them can be calculated. These data are 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*). In addition, the specific processing efforts for this thesis will be discussed in Chapter 3.

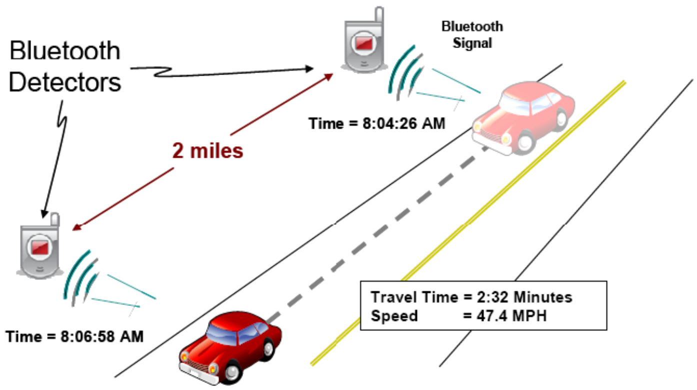


Figure 2.2. Bluetooth Detection Concept of Operation

2.3: Dynamic Message Sign Data

The Dynamic Message sign data used in this study is provided by the state of Maryland 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 timestamps for start and end times, and indication of beacon status. MULTI tags allow for determination of the formatting, number of lines, and number of panes of the messages when 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 impacts of message display on traffic speeds, high quality speed data was required. The data used to complete this analysis was collected from the Center for Advanced Transportation Technology (CATT) lab and consisted of 1-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

<u>*3.1: Deployments and Study Area*</u>

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

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 commonly utilized Dynamic Message Sign. In addition, the roadway should have relatively high traffic volumes, available alternative 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).

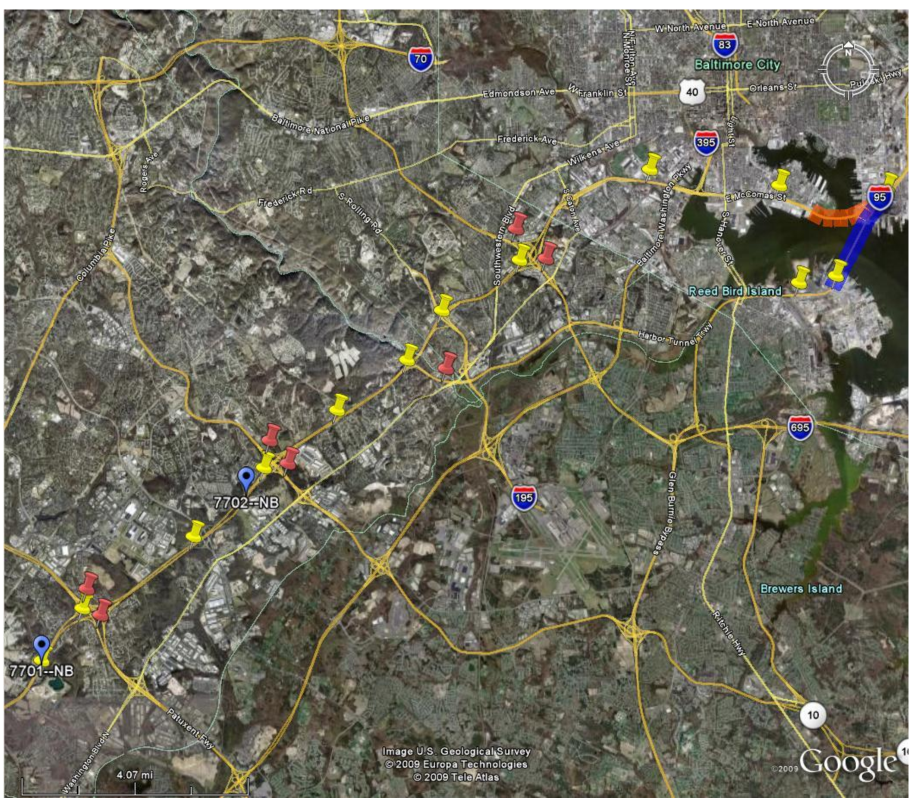


Figure 3.1. Study Area: I-95 and I-895

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 3 major parallel routes through and around Baltimore, namely 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. As of the second deployment, the signs had 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. Since the sensors are deployed manually, there must be a shoulder where a vehicle can stop and the sensors can be safely activated and locked to a permanent object. The next consideration is the distance between sensors. Due to the 300 foot sensing buffer of the sensors, an error of up to 600 feet may be induced. In order to reduce overall errors in travel time and space mean speed, it is desirable to place travel time detection sensors at least 1 mile apart. More information on this error can be found in (*26*). Sensors must also be placed on the major diversion routes such that any vehicles exiting from the main road can be detected. This entails placing the sensors on the diversion routes such that they are as close to the main road as possible without being able 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 prior to MD Route 32 to rendezvous with a Maryland State Highway Administration (SHA) vehicle. The sensors were transferred to the SHA vehicle and the driver was briefed on the general deployment plan. The deployment team gave the driver sufficient warning prior to each deployment site which allowed for safe exiting from the main travel lanes. At the deployment sites the Bluetooth sensors were powered on. 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).

Retrieval of the Bluetooth sensors again required collaboration with SHA. On July 7, 2009, at around 9 AM, the deployment crew met with an SHA vehicle at the 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, power 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 the 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 2-minute intervals, 362,901 samples were available for analysis.

In March 2011, an identical deployment was undertaken. As in the first deployment, the team met with an SHA vehicle to transfer and place sensors. Deployment began on the morning of March 29, 2011. Sensors were placed as closely as possible to the locations used in the previous deployment in order for comparisons to be made and to simplify post processing (Figure 3.4). Unfortunately, one of the sensors malfunctioned prior to deployment and was unavailable. As a result, only 19 sensors were deployed. The sensors were retrieved on April 12, 2011. 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 utilized.

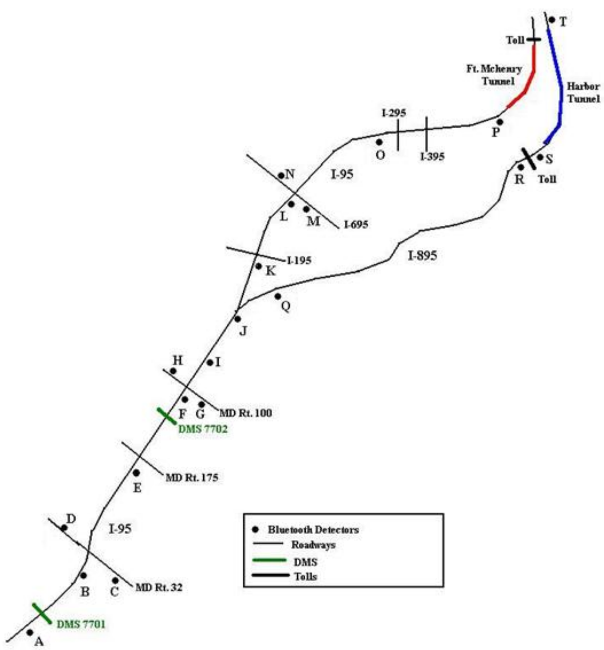


Figure 3.3. Sketch of Sensor Deployments labeled with TMC letter designations

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

Analysis of message quality and timeliness for selected message cases for deployments 1 and 2 are presented in the following sections.

3.2.1: Deployment 1

After collection and examination of the message logs, three interesting cases from the first deployment were selected for evaluation (Table 3.1). In all cases, the messages were identical among the two DMS and persisted 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

The first case indicates “Major Delays” on I-95 for approximately one hour during the afternoon peak 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 evoked the message. In addition, it will be interesting to learn what conditions lead to the removal of 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 & 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 3.5). 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.

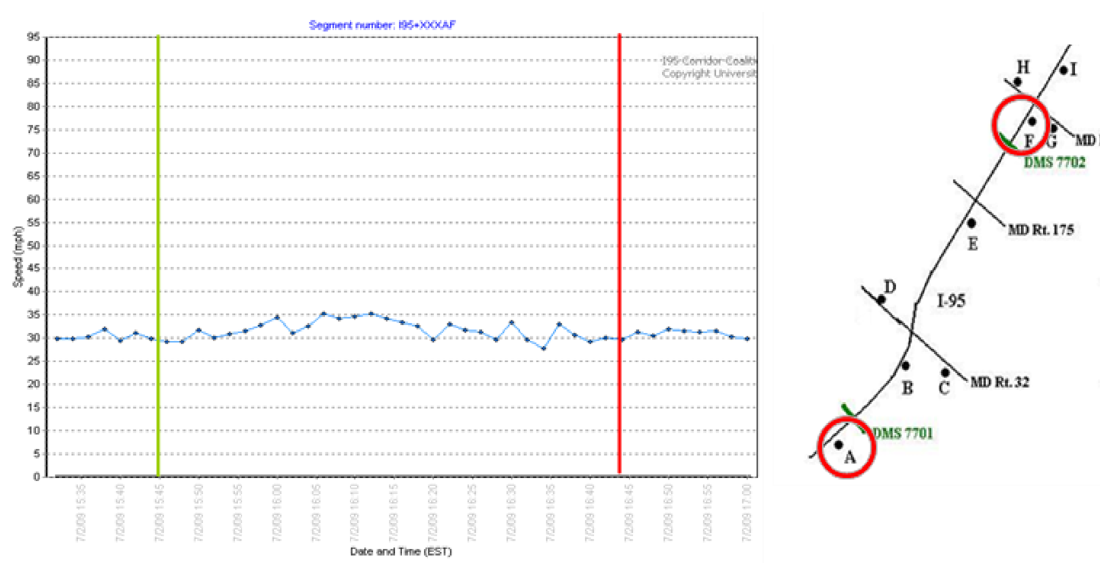


Figure 3.5. Deployment 1, Case I Speed Data for Link AF

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 3.6). Similarly, links FI, IJ, JK, KL, & 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).

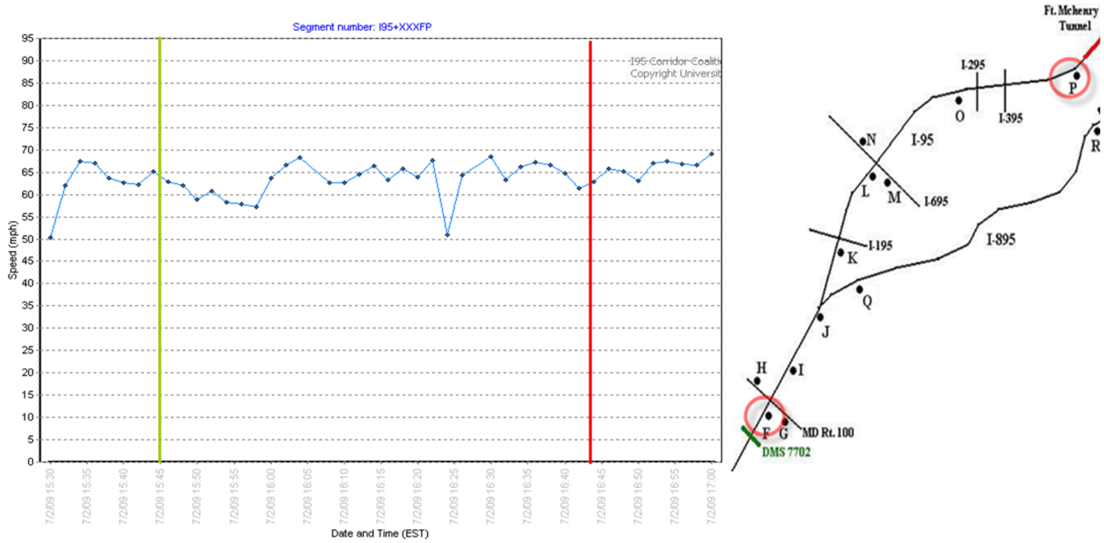


Figure 3.6. Deployment 1, Case I Speed data for Link FP

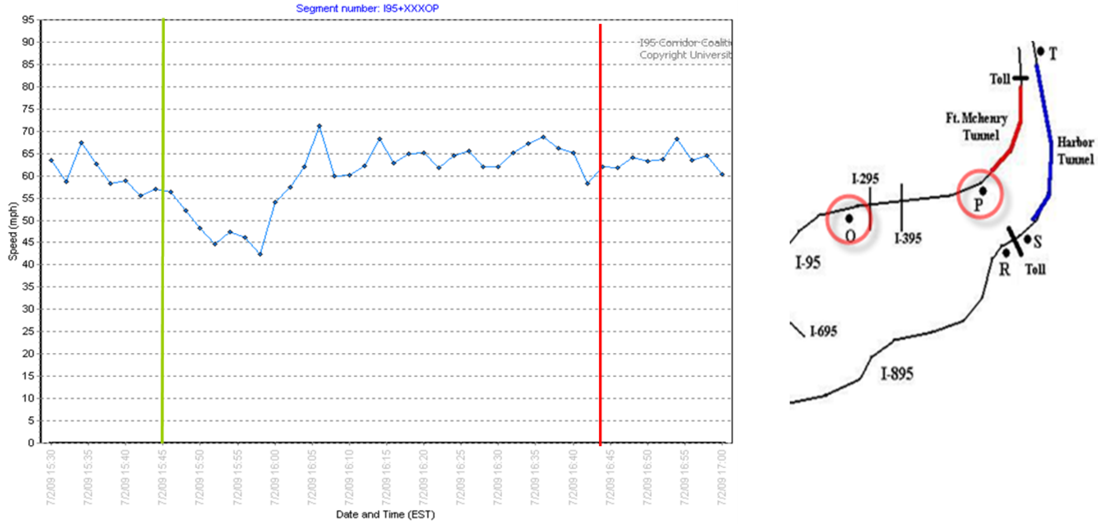


Figure 3.7. Deployment 1, Case I Speed Data for Link OP

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 2 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.

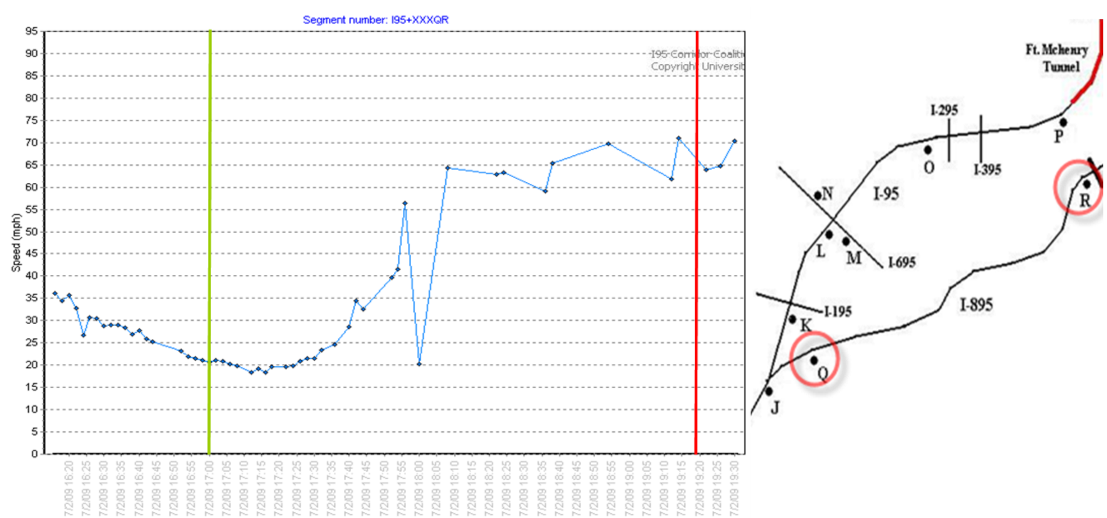


Figure 3.8. Deployment 1, Case II Speed Data for Link QR

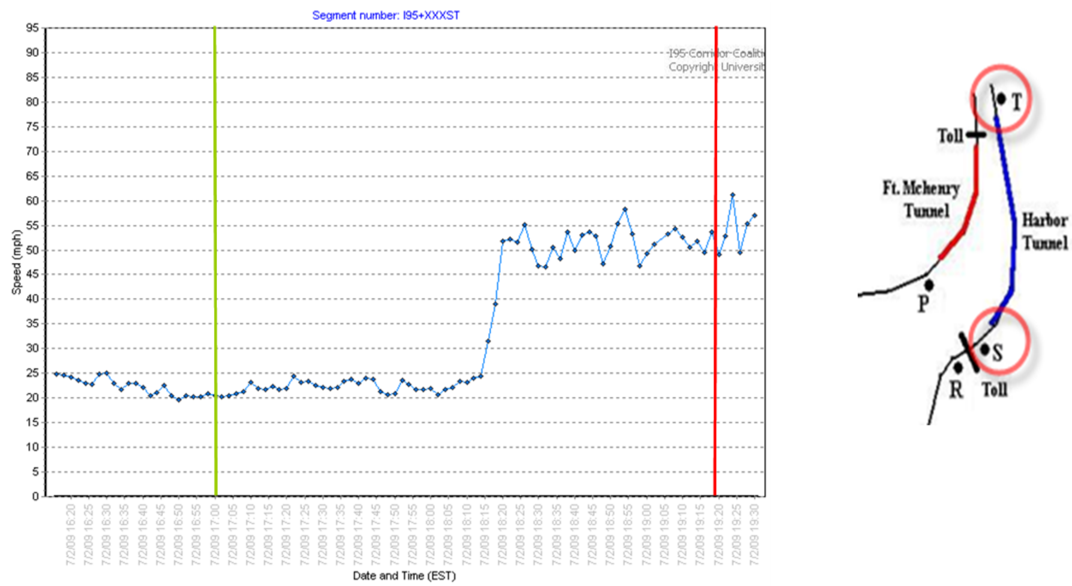


Figure 3.9. Deployment 1, Case II Speed Data for Link ST

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 reveals that 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 likely 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 was 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 twenty 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 ten 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.

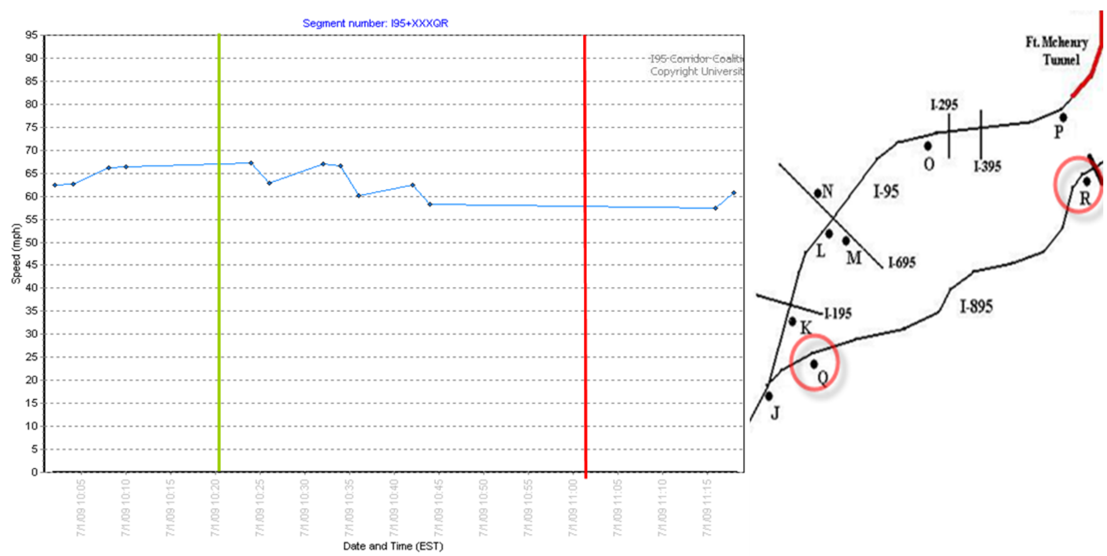


Figure 3.10. Deployment 1, Case III Speed Data for Link QR

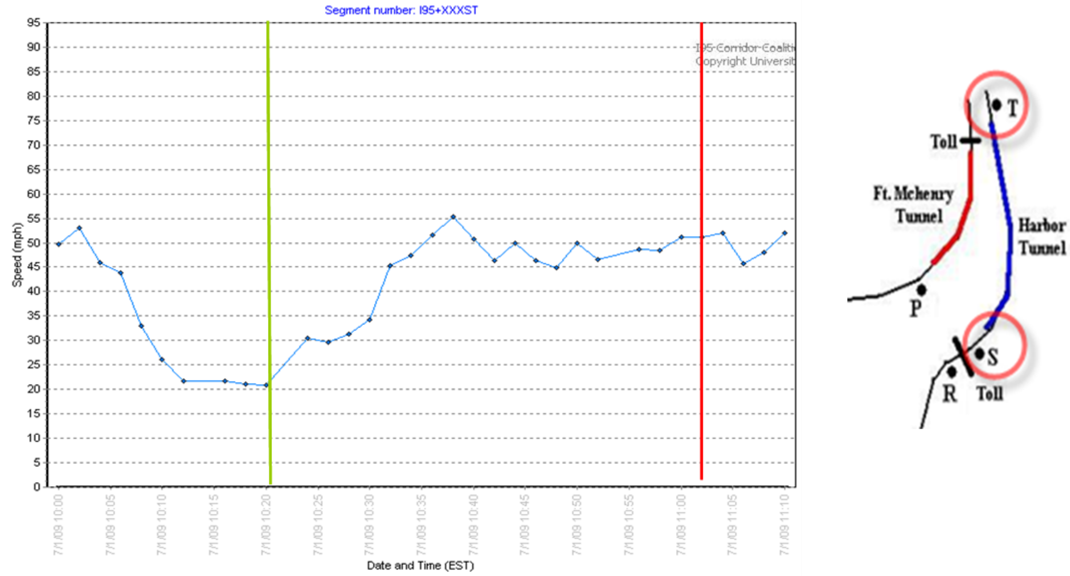


Figure 3.11. Deployment 1, Case III Speed Data for Link ST

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. While all of the messages were warranted by the prevailing traffic conditions and would provide some benefit to drivers, they were somewhat 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 late removed message 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, in addition to the affected roadway, a specific description of the location of delays.

3.2.2: Deployment 2

In the second deployment, the message signs 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 #. Several of these cases are analyzed using the techniques in the previous deployment. In addition, some periods in which travel time messages were displayed are analyzed to assess the accuracy of these messages.

In the first case, the sequence of messages begins at 16:33 PM and ends at 18:45 PM on March 31st, 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 which 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, & 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 as well. Speeds on link QR during the same time show that the delays do not extend below the tunnel (Figure 3.13).

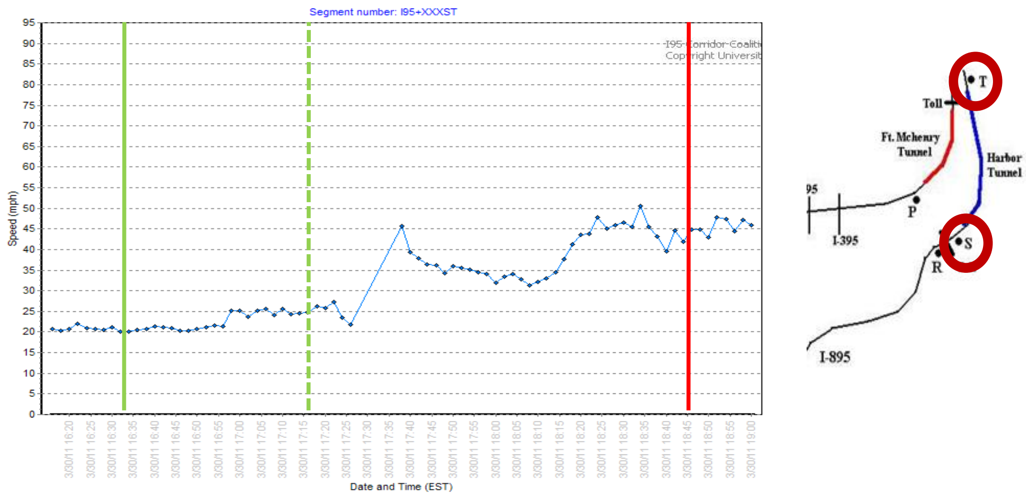


Figure 3.12. Deployment 2, Case I Speed Data for Link ST

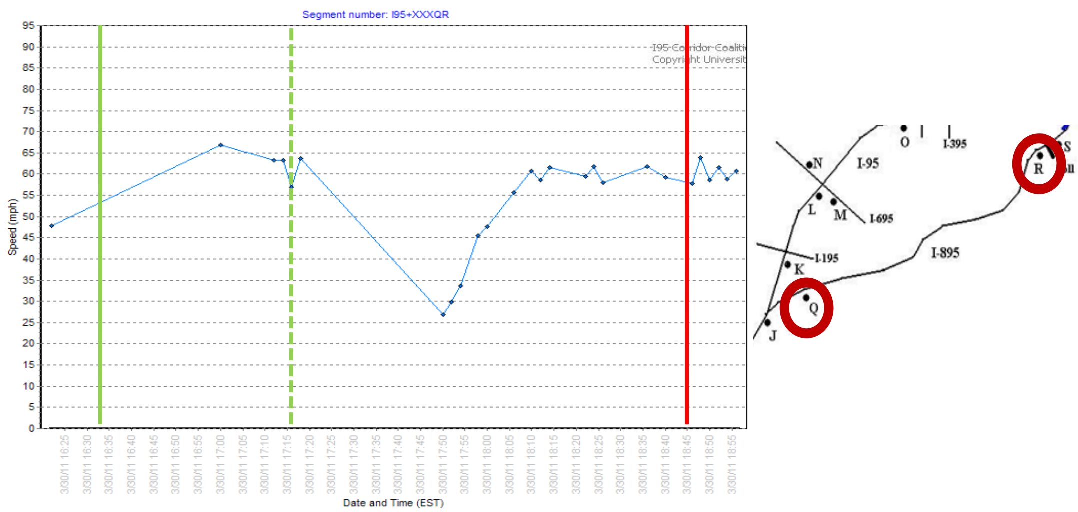


Figure 3.13. Deployment 2, Case I Speed Data for Link QR

At 16:50, both signs begin warning of delays on I-95 prior to the tunnel. On link AF, speeds are observed to be decreasing as the message is deployed (Figure 3.14), though 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 #7702, however, there is no indication that the message is yet necessary as the links after it remain unaffected.

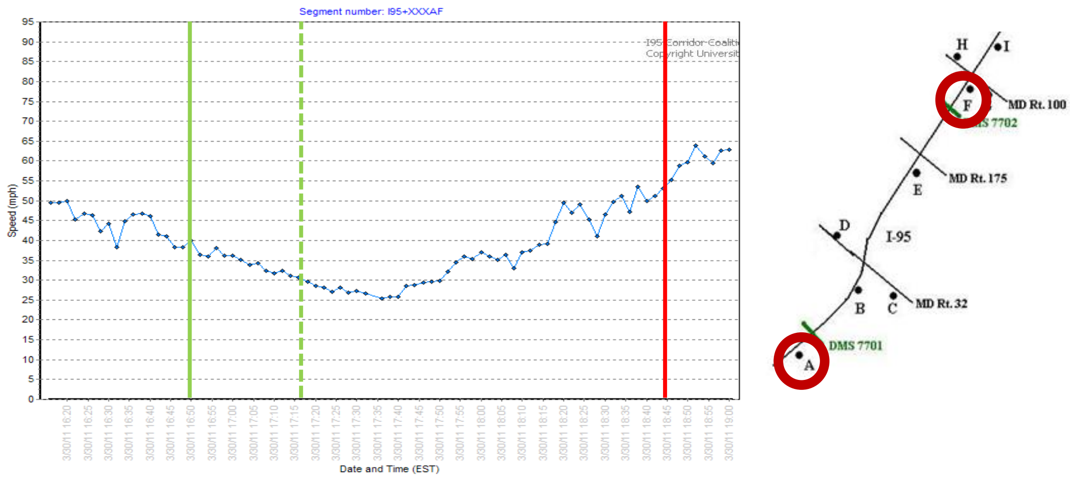


Figure 3.14. Deployment 2, Case I Speed Data for Link AF

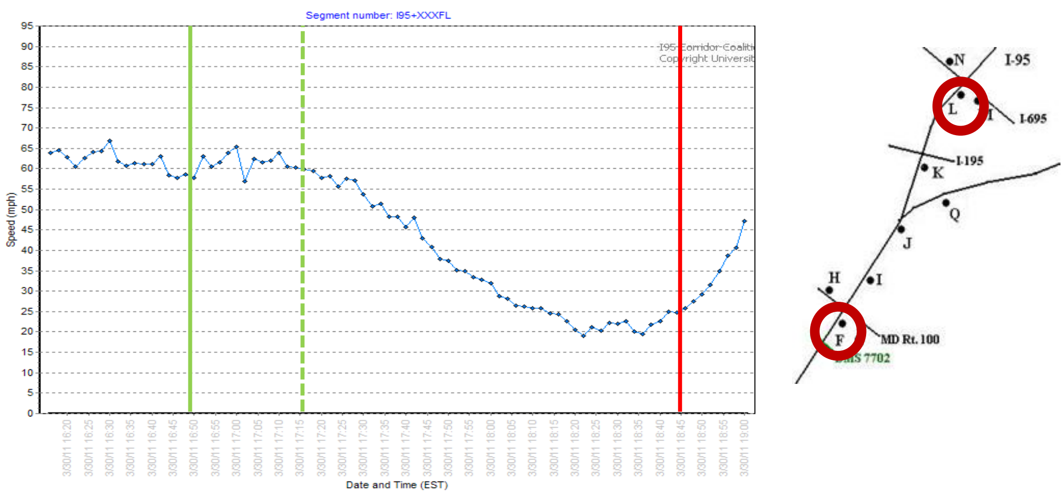


Figure 3.15. Deployment 2, Case I Speed Data for Link FL

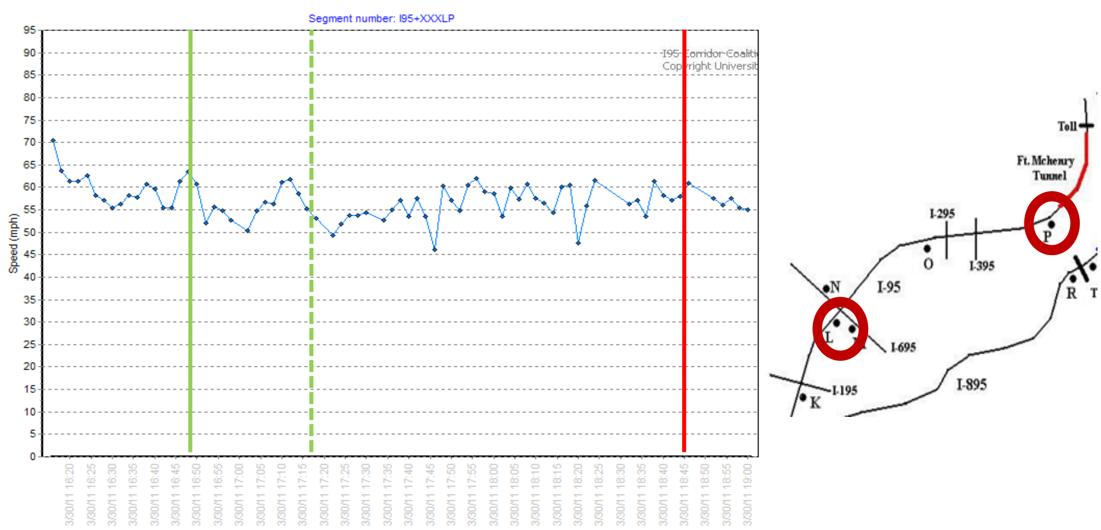


Figure 3.16. Deployment 2, Case I Speed Data for Link LP

For approximately 90 minutes beginning at 17:16, both signs display a message relating to delays on I-95 and I-895 North. In addition, they suggest 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 be decreasing or already low at the onset of the message, validating 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.

In terms of timeliness, the messages relating to delay on I-95 North are activated just as delays are beginning and are removed as conditions are recovering, except in the case of link LP where no delays are observed during the period. The first message displayed relating to I-895 North appears after speeds are already low on link ST. At the time of removal, speeds on I-895 had been at normal levels for 20 minutes on link ST and 30 minutes on link QR. It appears that the message was 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 case attempted to inform users of delays on I-95 and I-895 North. All of the messages displayed were at least partially warranted and for the most part were displayed and removed in a timely fashion. The speed data suggests that diversion onto I-695 East was unnecessary; though 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 1st, 2011 (Table 3.3). At 16:27 a message is 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 persists until 19:14. The message on DMS #7702 is updated at 16:57 with a second pane that notes Major Delays prior to the I-895 tunnel in addition to the delays north of the tunnel. This two-pane message continues until 19:13 when the message reverts to the original one-pane message for one minute. At 19:14, both signs begin 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 had 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 which indicated higher than normal travel times.

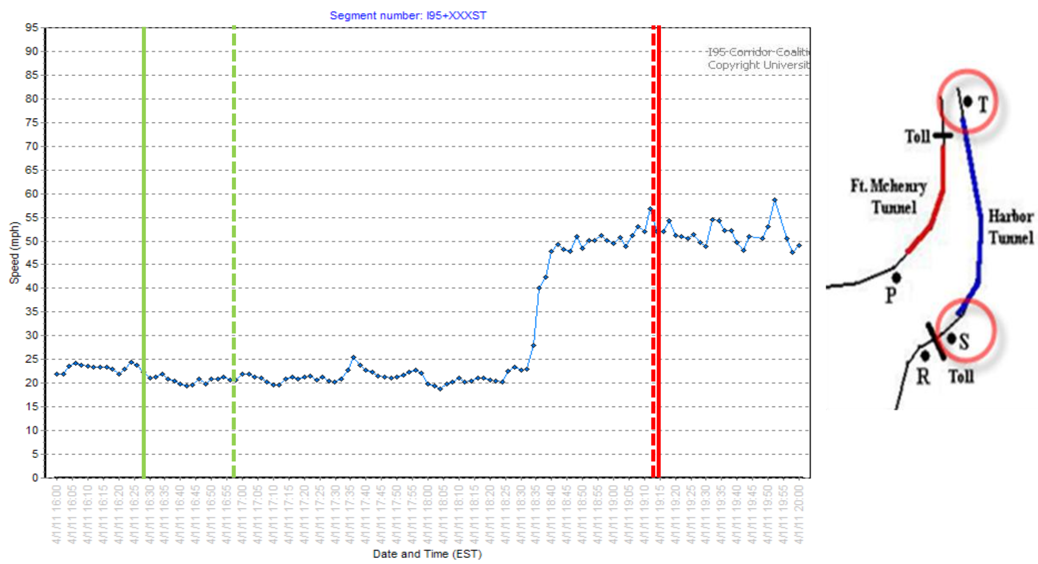


Figure 3.17. Deployment 2, Case II Speed Data for Link ST

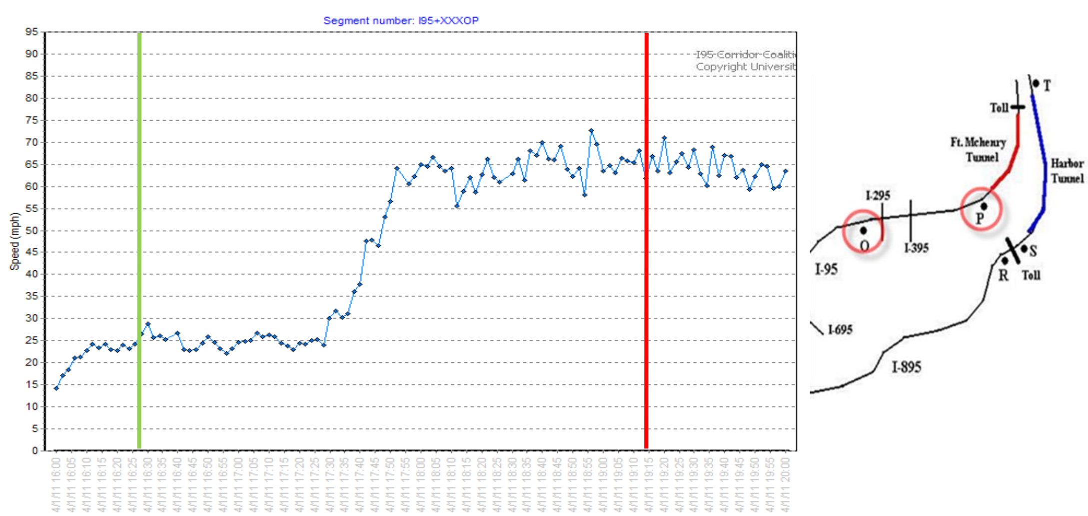
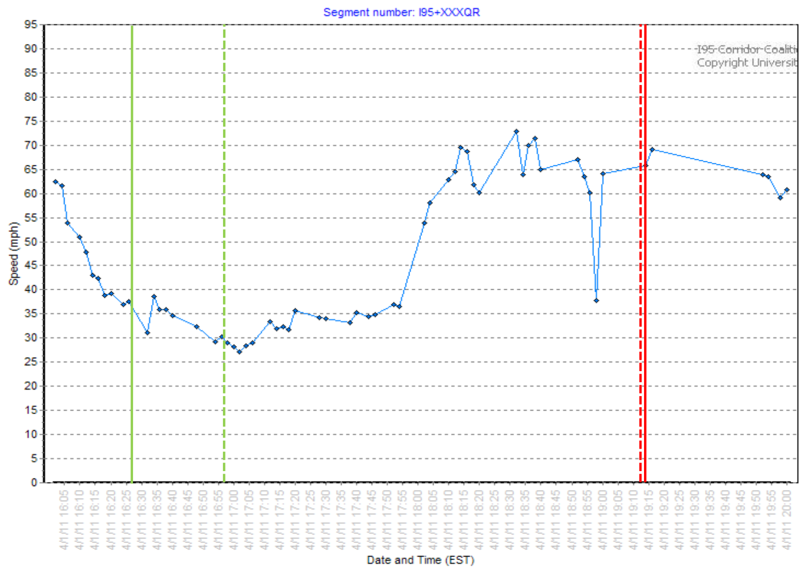


Figure 3.18. Deployment 2, Case II Speed Data for Link OP

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



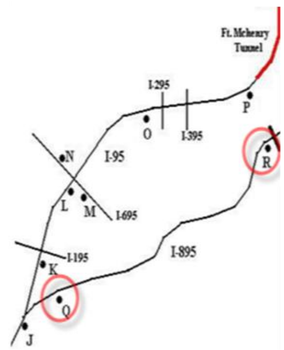


Figure 3.19. Deployment 2, Case II Speed Data for Link QR

By examining link FO (Figure 3.20) it is observed that there were no apparent delays on I-95 between DMS #7702 and the interchanges just prior to the Ft. McHenry tunnel. This shows that the delays north of the tunnel on I-95 had not spilled 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 users chose to avoid I-895 by remaining on I-95 as a result of the DMS message, they would not experience unexpected delays.

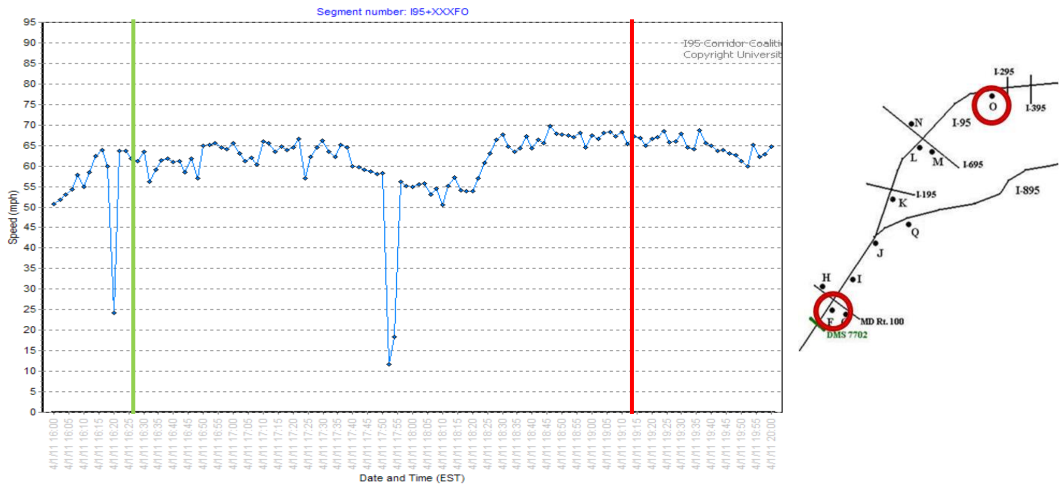


Figure 3.20. Deployment 2, Case II Speed Data for Link FO

On DMS #7701, the message warned only of the delays north of the tunnels for the entire period. While accurately describing those conditions, the message sign 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.

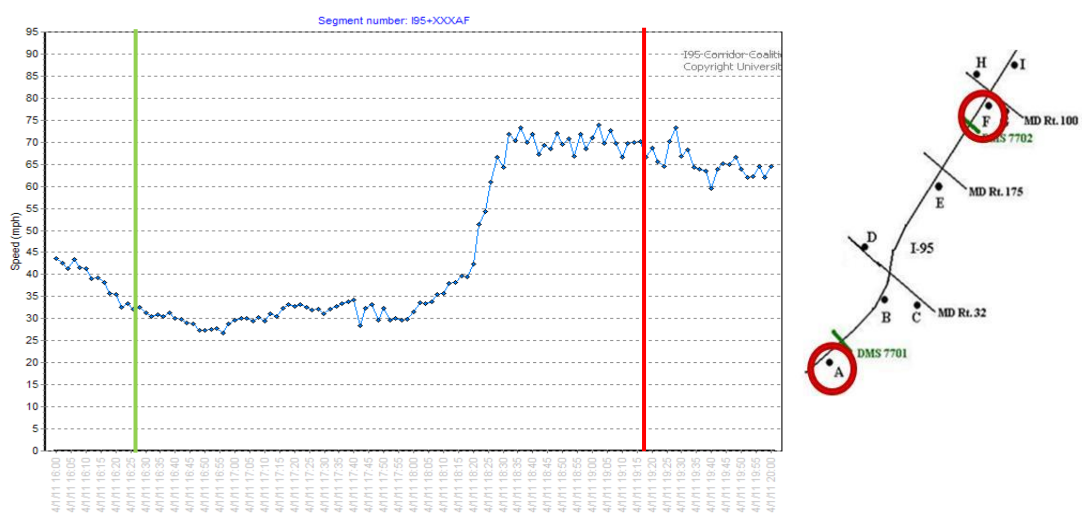


Figure 3.21. Deployment 2, Case II Speed Data for Link AF

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

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

The third case is 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 AM 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 is removed and both signs display their respective travel time messages until 9:32 AM. At this time, both signs display a message that informs users to expect congestion and delays on I-895 North. After approximately 3 hours, this message is removed from both signs. DMS #7701 resumes displaying travel time messages while DMS #7702 warns of Major Delays on I-895 and suggests the same alternate routes as in the morning message. This message persists on DMS #7702 for approximately 6 hours, finally being removed at 18:23 PM.

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 ALTERNATE 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

At the time of the initial message deployment, link ST is observed to be near free flow (Figure 3.22). For the next 15 minutes there is no Bluetooth data available, indicating that no traffic is passing through the tunnel. This finding corresponds with the tunnel closure message. During the following 15 minutes, traffic speeds rapidly drop, stabilizing around 20 mph. At the same time, link QR appears to be unaffected by the tunnel closure (Figure 3.23). In addition, the recommendation to use I-95 North as an alternate route appears to be sound as there are no apparent delays on links AF, FO, or OP (Figure 3.24, Figure 3.25, Figure 3.26).

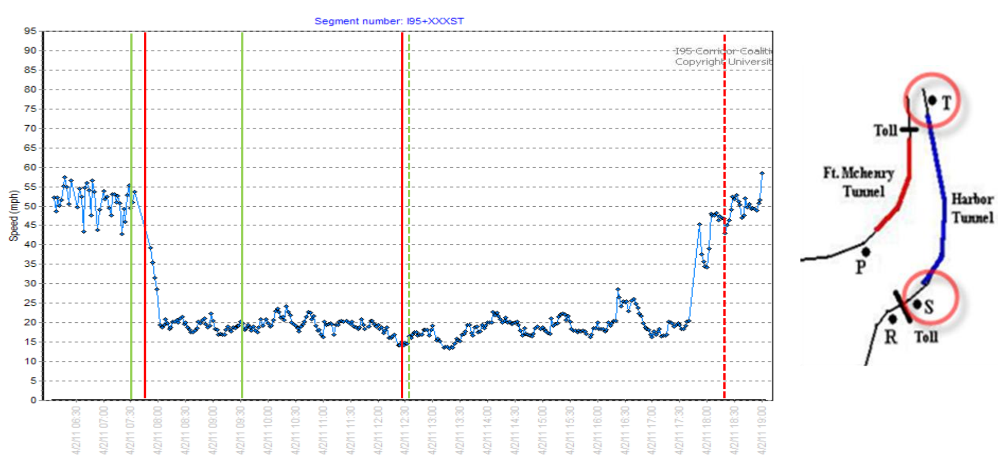


Figure 3.22. Deployment 2, Case III Speed Data for Link ST

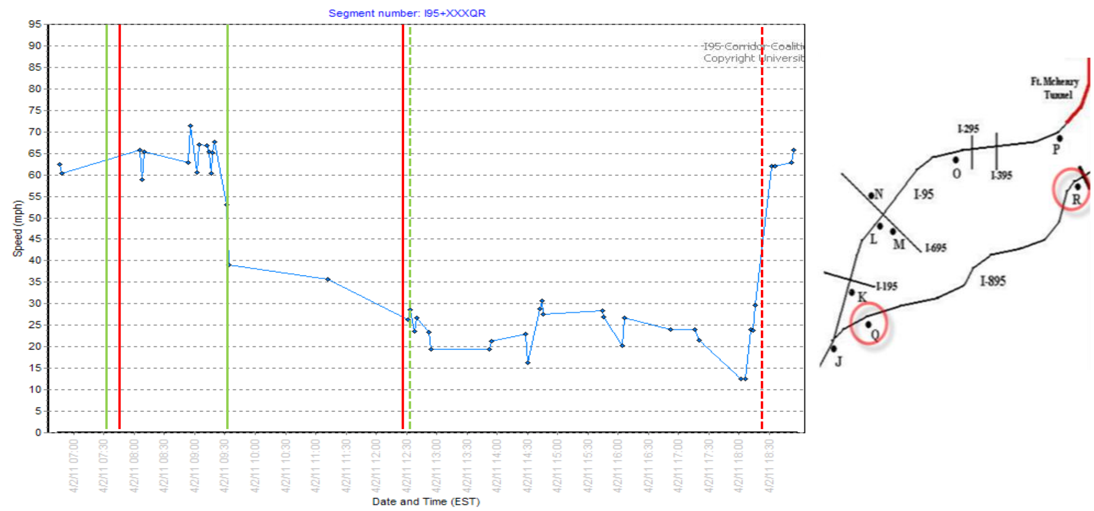


Figure 3.23. Deployment 2, Case III Speed Data for Link QR

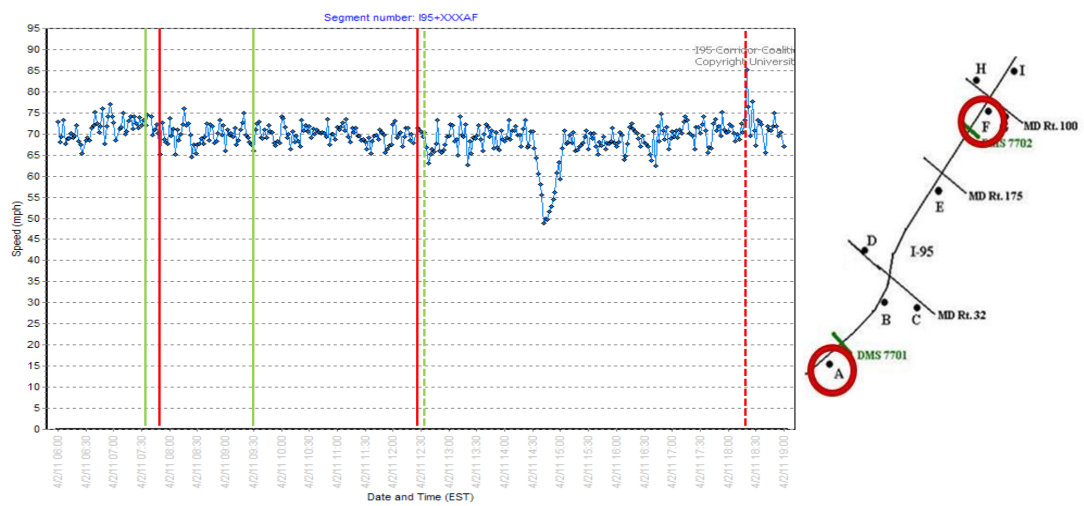


Figure 3.24. Deployment 2, Case III Speed Data for Link AF

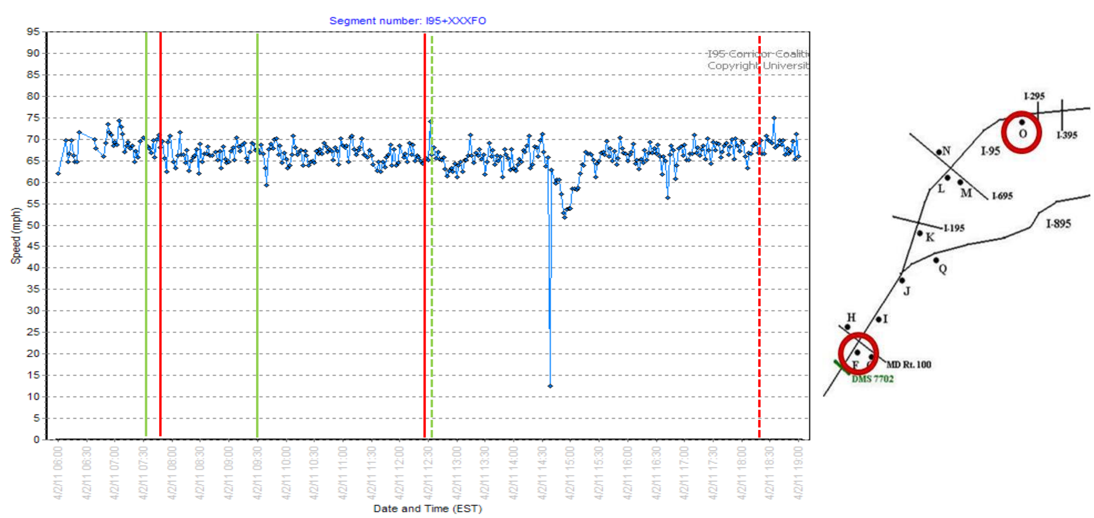


Figure 3.25. Deployment 2, Case III Speed Data for Link FO

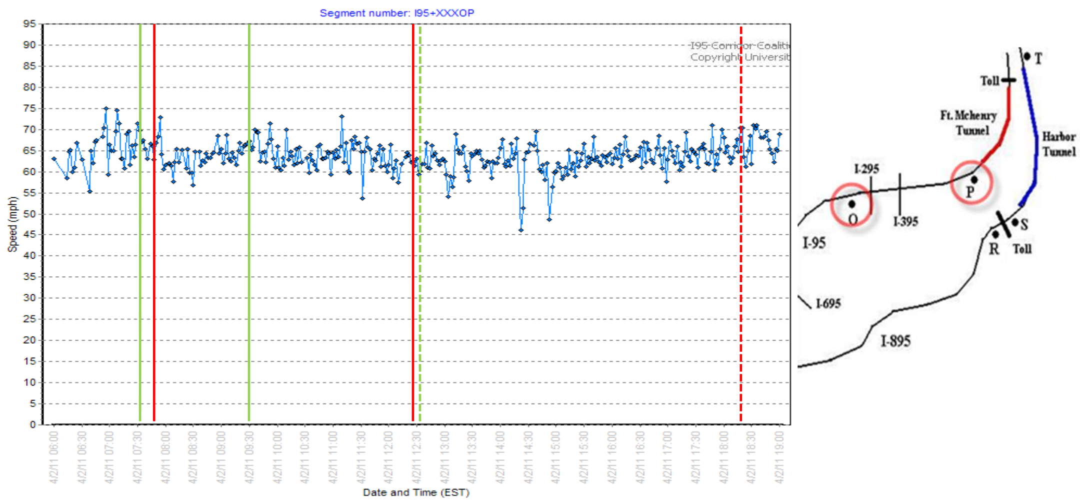


Figure 3.26. Deployment 2, Case III Speed Data for Link OP

Between 7:46 and 9:32 AM, both signs resume display of travel time messages. All links on I-95 North and I-895 North prior to the tunnel remain unaffected by the delays in the tunnel and thus the signs display free flow speed-limited travel times. Unfortunately, no warning is given during this time of the delays occurring in the Harbor Tunnel. At 9:32 AM, the congestion in the Harbor Tunnel appears to have backed up onto link QR resulting in speeds dropping to 40 mph. This prompts the display of the message warning of “congestion and delays” for the next 3 hours on both signs. During those 3 hours, speeds appear to steadily drop on link QR, eventually falling to approximately 25 mph.

At 12:28 PM, the message is removed from both signs and replaced with travel time messages. DMS #7701 continues displaying travel time messages for the remainder of the case period. At 12:32 PM, DMS #7702 replaces 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 continues for approximately 6 hours, ultimately being removed at 18:23 PM. The delays are seen to clear on both links QR and ST about 15 minutes before the removal, indicating a timely reaction to traffic conditions. During the same period, the traffic conditions are near free flow and 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 case, the DMS are being used to communicate changing conditions through an entire day. At each change of message, the conditions observed through the data match the descriptions posted. The messages are also updated and removed rapidly with the conditions to which they correspond. One shortfall during this case was the morning period in which both signs reverted to travel time messages, ignoring the delays in the Harbor Tunnel. Since DMS #7702 displayed equal travel times to the Harbor Tunnel and the Ft. McHenry Tunnel during this time, users may have taken I-895 North just to find heavy delays in the tunnel. While the travel time information displayed on the sign was accurate, users would have benefitted by being warned of the delays in the tunnel. Overall, this case demonstrates sound operation of the DMS system through the timely display of high quality messages with useful information.

The cases from second deployment indicate an improvement in the quality and timeliness of DMS messages over the first deployment. In these cases, the messages specifically indicated certain sections (e.g. before or after the tunnels) when necessary and the Bluetooth observed conditions supported the messages. In some instances, certain messages were left on longer than necessary, which meant users experiencing no delays though they were warned of them. On the other side, travel time messages displayed by default alleviated some of the issues with messages being activated 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 second deployment, the Dynamic Message Signs were utilized 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, is utilized.

Figure 3.27. Sample Travel Time Message for DMS #7701

The timestamps from the Bluetooth data are matched to the timestamps from the DMS message log and the displayed travel time is then extracted from each message. The Bluetooth travel times are matched in raw format to these displayed travel times and converted to minutes. The average difference between these two data sets as well as the standard deviations can be determined.

In addition, a comparison to the rounded and capped Bluetooth travel times is made. The rounded and capped data is differentiated from the raw data by taking into account the speed limit as well as the integer restriction on the signs. On a segment 11 miles in length, with a speed limit of 65 mph, the minimum 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. In both cases, the messages begin display in the morning with free flow travel times indicated and change the displayed travel times as conditions begin to deteriorate. The first case begins at 8:32 AM on 3/30/2011 and ends at 19:52 PM on the same day. Travel times remain at or above free flow until approximately 16:22 PM. At this time, travel time on the segment begins to increase, with the first sign update occurring at 16:30 PM. Travel time continues to increase until approximately 18:30 PM, where it levels off and then returns to free flow conditions by 19:08 PM (Figure 3.28).

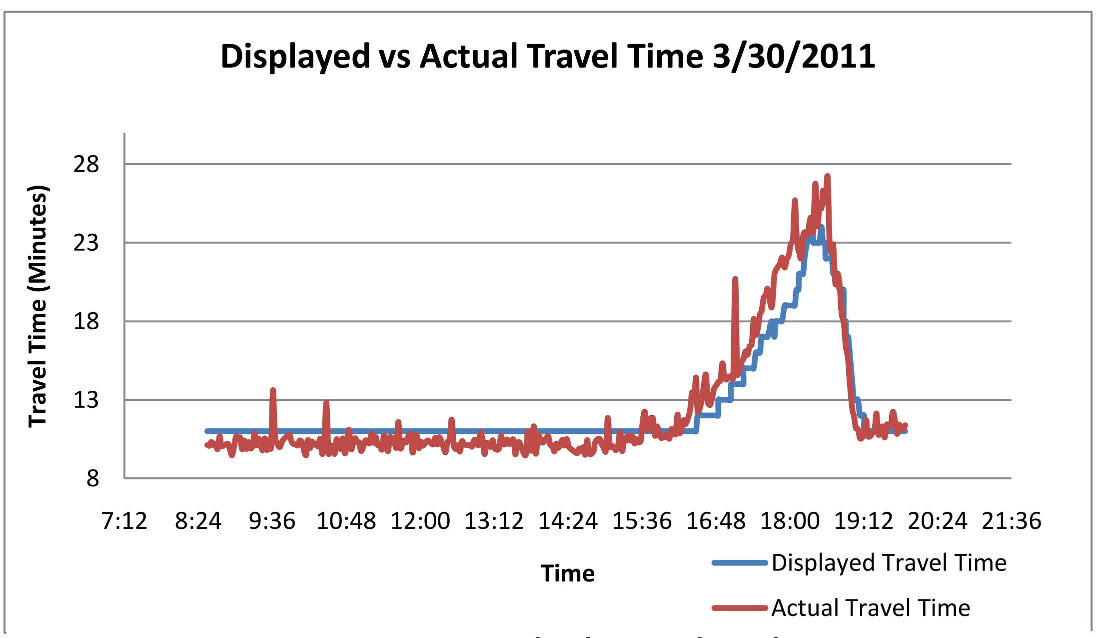


Figure 3.28. Case I, Displayed vs. Actual Travel Time

From the graph, it can be seen that the displayed travel time follows very closely with 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. It is speculated that these outliers are caused by detections of vehicles that make stops or diversions between the matched detectors. As previously mentioned, much of the data during free-flow conditions is below the displayed travel time due to 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).

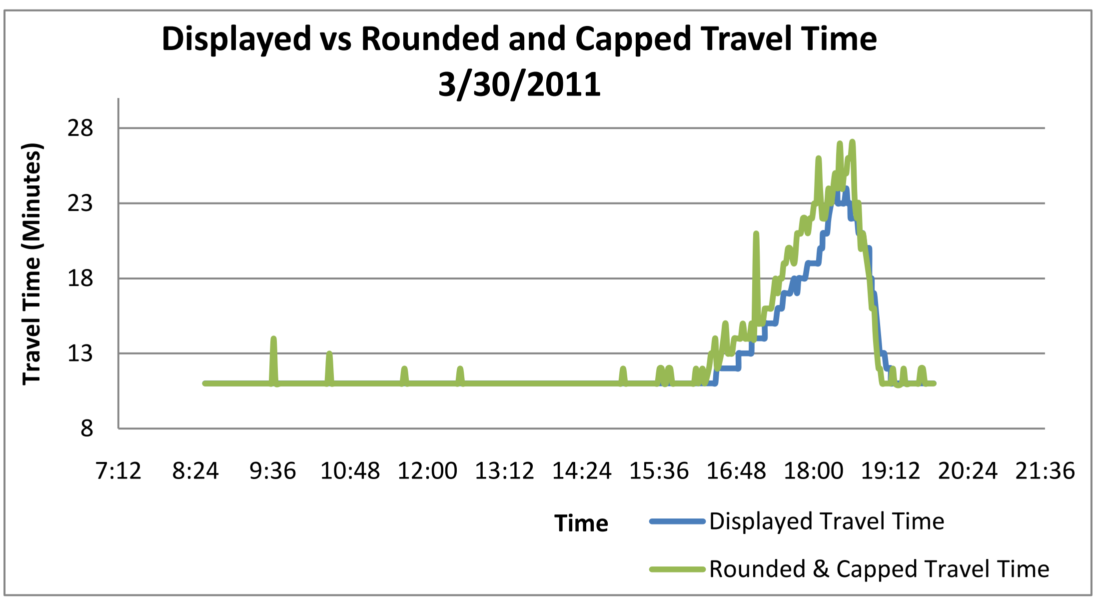


Figure 3.29. Case I, Displayed vs. Rounded and Capped Travel Time

With this manipulation it is clear that during free flow conditions the travel times displayed 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 that actual travel times are slightly higher than the displayed travel times. In the capped case, the higher average value is likely a result of all of the free flow times being rounded up. The standard deviations are relatively high, though this is certainly a result of the outliers during the free flow period. With the outliers removed, the results are dramatically changed (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, 3/31/2011, between 5:00 AM and 16:48 PM. The period primarily consists of free flow conditions, with increases in travel time beginning to occur at 15:12 PM (Figure 3.30). At the end of the period, the message is switched to a non-travel time message.

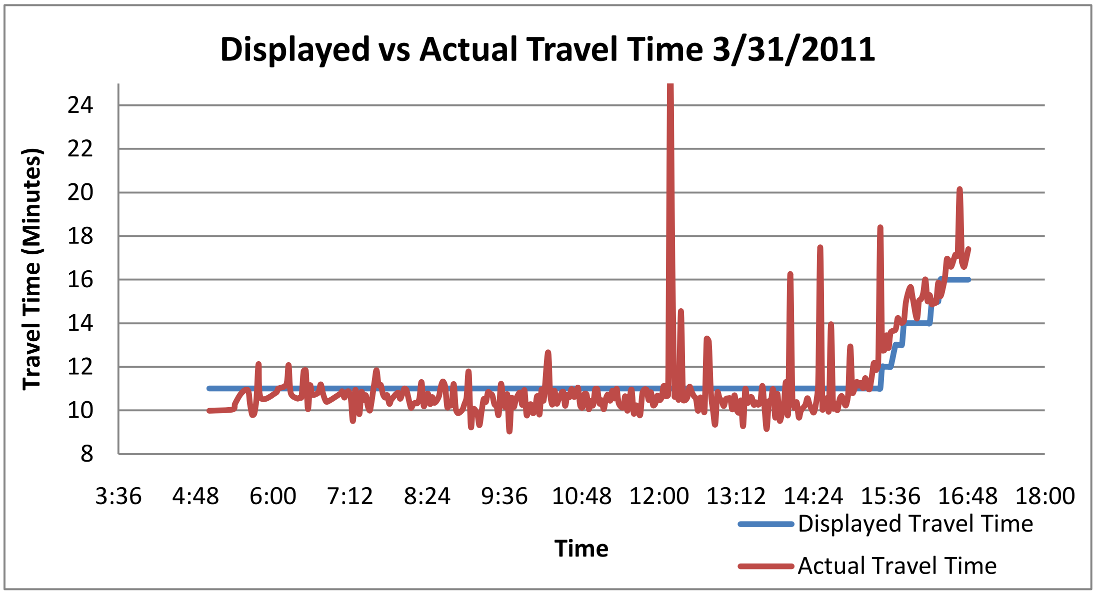


Figure 3.30. Case II, Displayed vs. Actual Travel Time

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

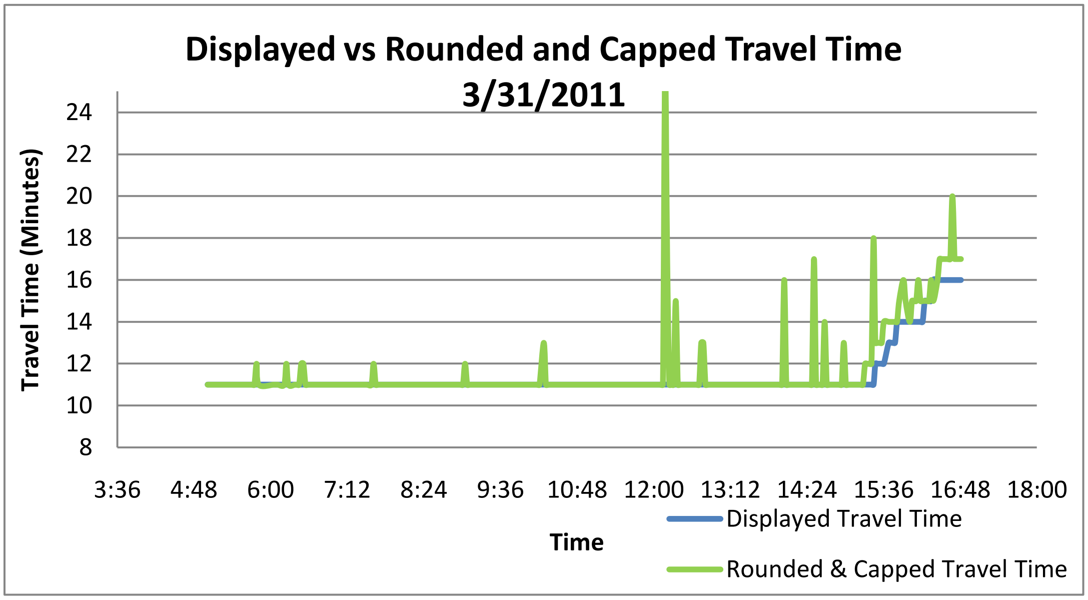


Figure 3.31. Case II, Displayed vs. Rounded and Capped Travel Time

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 were 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 the speed limit capped travel time. When compared with the actual travel time, the displayed times are slightly higher as expected. By removing the influence from the speed limit, the average difference shows that the displayed travel times during congested periods are lower than the actual travel times. The standard deviations in both cases are relatively low, indicating a tight spread in travel time differences.

Overall, these cases show that the data and updating system used for DMS travel time messages are providing accurate and relatively timely information to motorists. On average, the difference between the actual travel time and the displayed travel time is less than one minute, with standard deviations, outliers removed, less than 2 minutes. These cases also demonstrate that Bluetooth sensors are capable of high quality analysis 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 detail the efforts and findings from the utilization of Bluetooth sensors for the evaluation of 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 utilized loop detector data. This type of data gives only traffic counts and 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. By analyzing Bluetooth origin destination data, as a proxy for the actual origin destination data, before and after message display, the response of drivers to the messages can be studied. The downside of this approach is that Bluetooth is only a sampling technology with an average 3.5% penetration rate (*26*).

During the Bluetooth sensor deployments, 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 is I-895 North. To determine the share of traffic on these alternative routes, detections are 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).

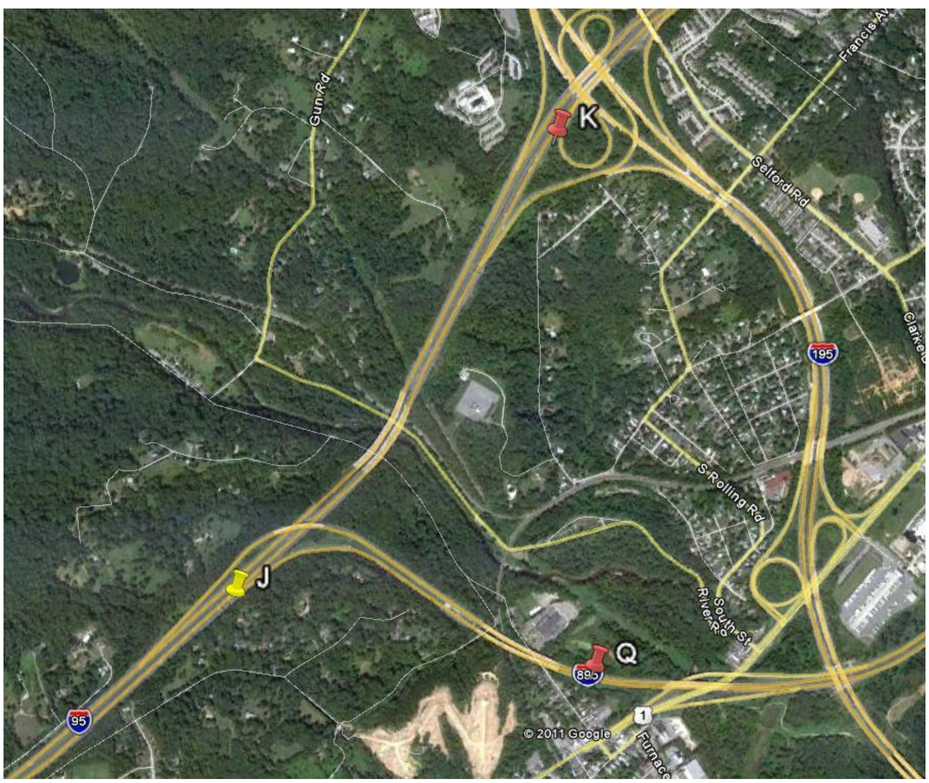


Figure 3.32. I-95 and I-895 North Diversion Point

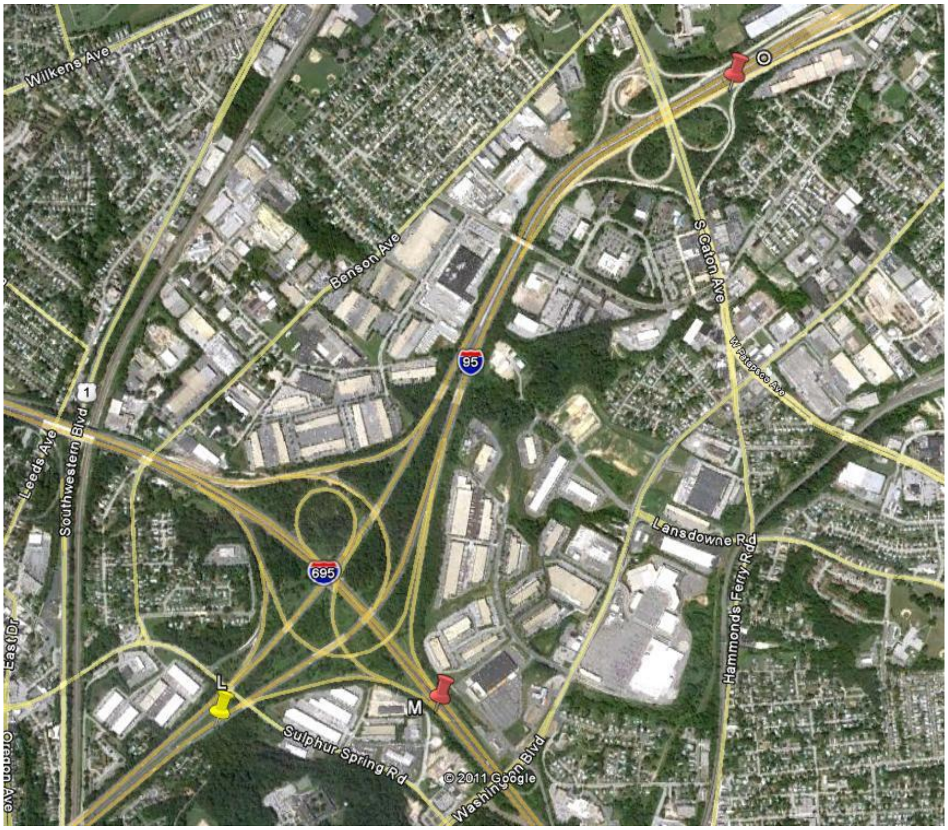


Figure 3.33. I-95 and I-695 Diversion Point

3.3.2: Diversion Analysis

In the first deployment, Cases I and II both contained messages recommending diversion. Case I recommends utilization of I-895 for 58 minutes. After being blank for 15 minutes, Case II recommends utilization of 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).

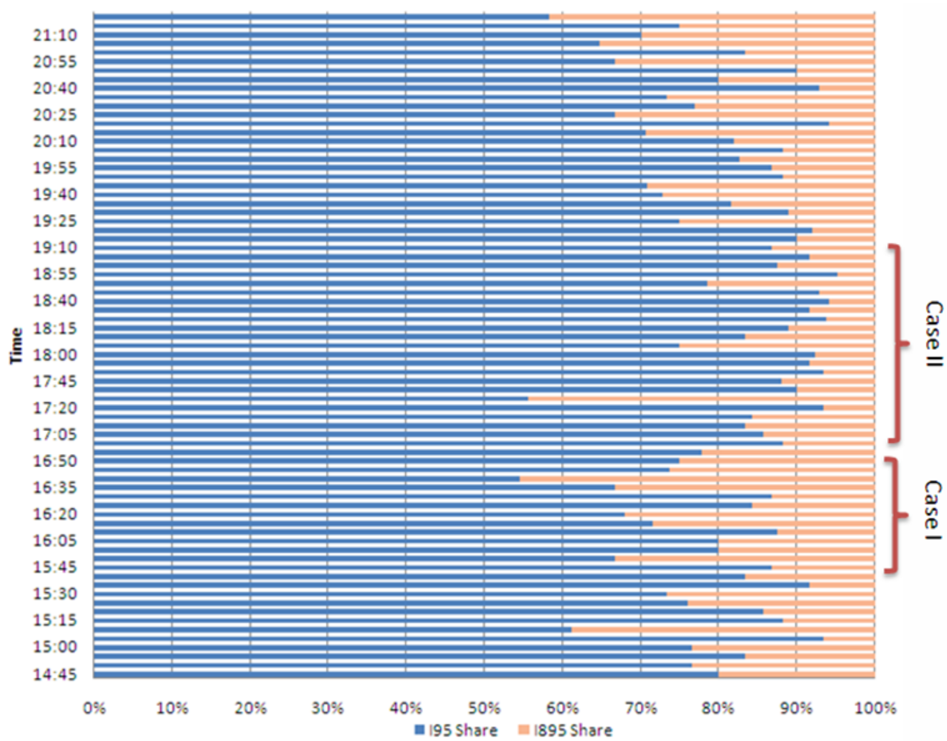


Figure 3.34. Traffic Share During Message Cases Deployment 1

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 recommends diversion onto I-895, it is observed that the share of traffic continuing on I-95 North drops by 5%. Similarly, when Case II suggests use of I-95 instead of I-895, there is a 7% 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 posts 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 are calculated during periods of diversion message display (Figure 3.35).

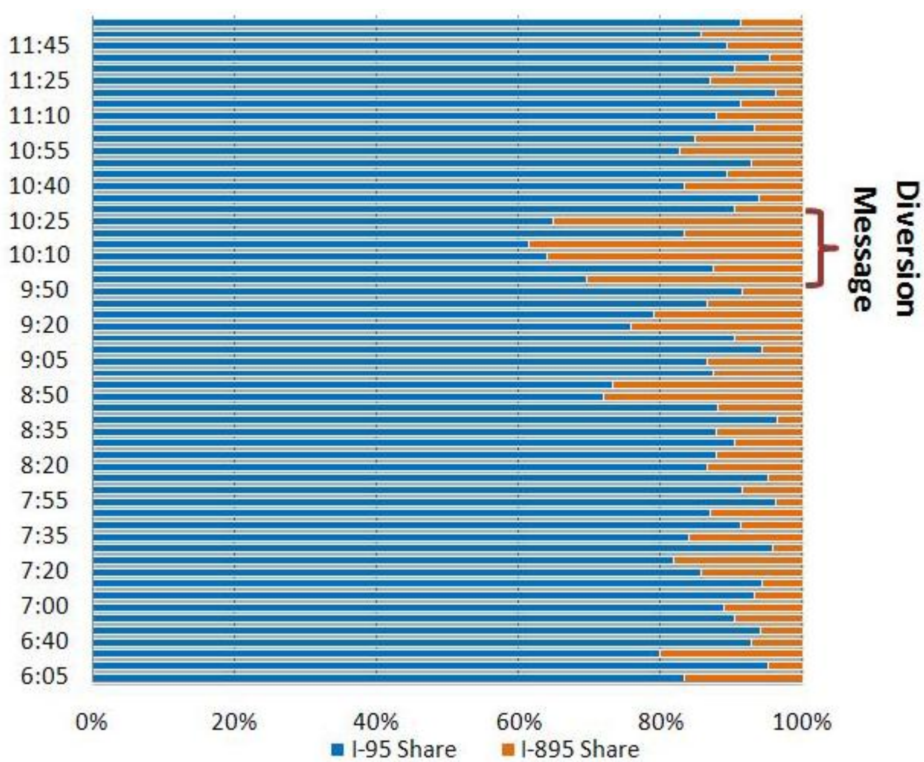


Figure 3.35. Traffic Share During Message Case Deployment 2

During the times the signs indicated free flow travel times, the share of traffic using I-95 over I-895 was approximately 89%. The fraction choosing I-95 over I-695 East during the same periods was approximately 80%. When diversion messages were posted, the average share of traffic utilizing I-95 over I-895 dropped approximately 10% (Table 3.9). Similarly, those choosing I-95 over I-695 East dropped nearly 18% (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 indicate that Dynamic Message Signs have an impact on drivers' en route diversion decisions. When the messages suggested certain 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 driver's response since only a fraction of the traffic is detected using Bluetooth sensors. Although one cannot certainly conclude that the drivers have changed their original route due to the DMS recommendation, 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 near real-time travel time information to motorists via DMS in January, 2010. Although much of the public response to these messages was very positive, some users and media outlets renewed complaints that DMS messages were causing vehicles to slow down, resulting in congestion and safety issues. In order to investigate these claims, several highway DMS were selected for evaluation based on their proximity to one-minute interval RTMS speed detectors. In total, 6 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 separate analyses. The first compared average traffic speeds of vehicles in consecutive five minute periods in which the DMS operational condition changed. In the second, 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 the use of DMS on Maryland highways presents significant localized safety 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 to complete this analysis was collected from the University of Maryland Center for Advanced Transportation Technology (CATT) and consisted of DMS message logs for each DMS as well as 1-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 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 included in that 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

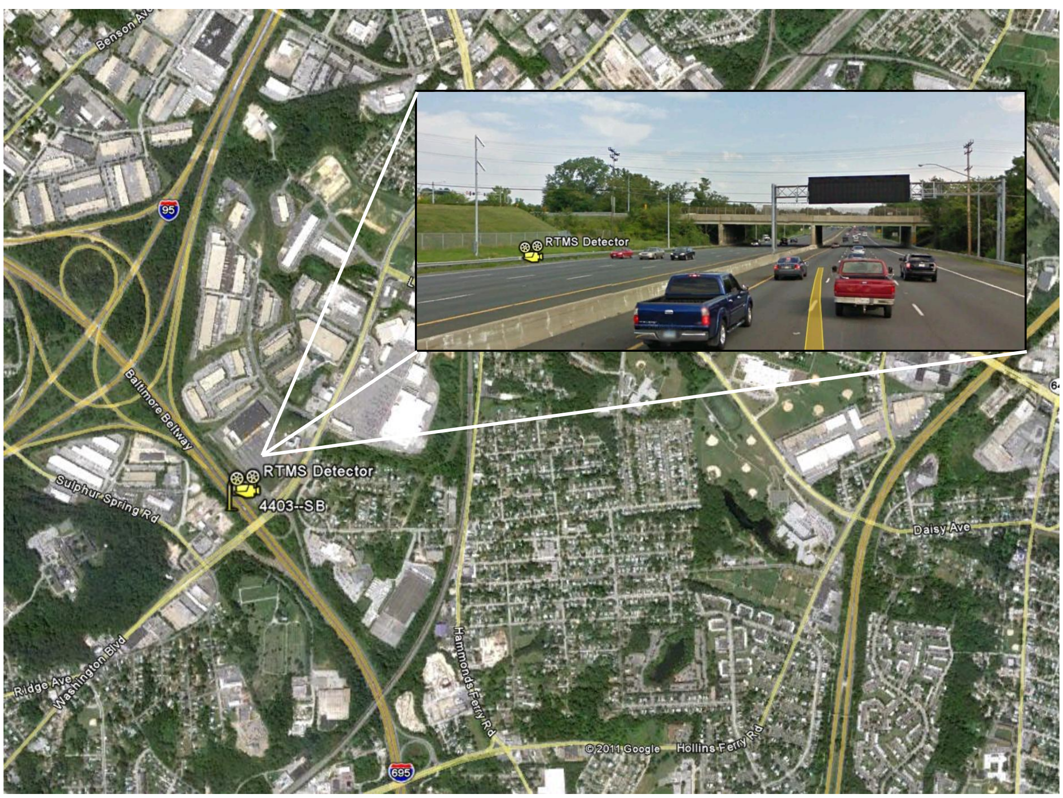


Figure 4.1. Sample DMS-RTMS Pair

In order for analysis to proceed, the DMS and RTMS data needed to be combined in the same time units. The raw DMS data was provided in inconsistent time intervals related to the times 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 along with the corresponding quality scores. Speed data receiving quality scores other than zero (valid) were discarded. Due to observed inconsistencies in the data as well as low traffic volumes, the data was filtered to remove observations between the hours of 7pm and 6am. 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 upon 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 and displaying a message in the following five minutes. The on-off condition is the exact opposite (i.e. on for 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 instances in which the DMS operational condition was observed to have changed. Each case was then sorted and stored into one of the three operational conditions (off-on, on-off, or switching). When congestion was observed to have been occurring throughout the period, as indicated by low traffic speeds, the cases were not included for analysis.

To determine the effects of the changes in 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% confidence level. The null hypothesis states that the difference in mean speeds between consecutive periods is equal to zero. 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 for comparison purposes. Each case is then assigned a category per the 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 message display on absolute travel speed over longer periods, two fourteen day periods were selected for analysis for each DMS. Each message was assigned into either category 1, 2, or 3. 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 that speeds will have a tendency to decrease due to the added task of message comprehension. Conversely, we would anticipate that speeds would tend to increase 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

Over all DMS, 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% and 12.0% 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 tend 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%

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

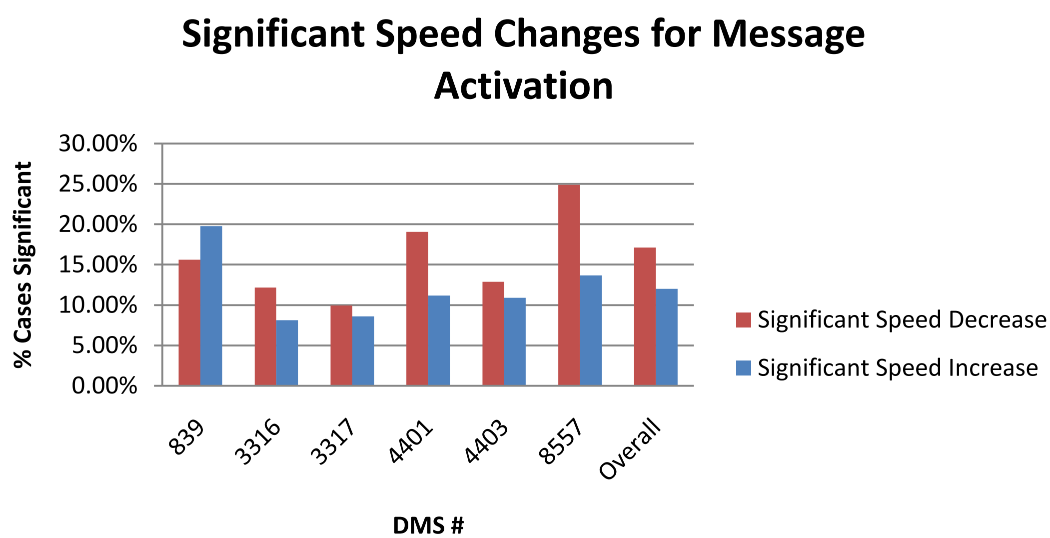


Figure 4.2. Graph of Off-On Summary by DMS

Since 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 shows 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 %**

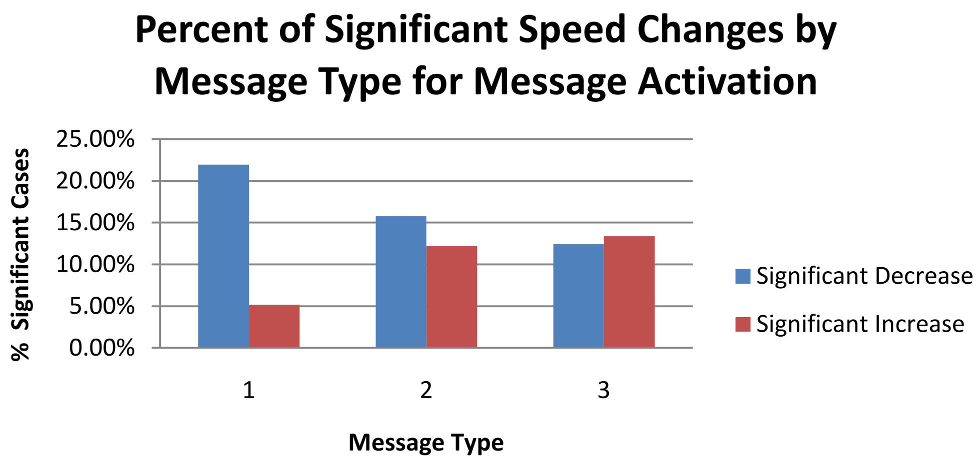


Figure 4.3. Graph of Off-On Summary by Message Type

When grouped in this way, the data shows that the message type that causes significant decreases in speed most often, in terms of percentage, is Type 1, followed by Type 2, and then Type 3. This hierarchy is as expected since Type 1 messages are commonly urgent and should tend to draw the most attention. Additionally, Type 1 messages usually indicate an incident that would create congestion downstream such as road closures or accidents. Type 2 messages, which include travel time messages on the signs that show them, are usually less urgent and as expected cause a lower fraction of disruptions than Type 1 messages. Interestingly, the two DMS in the study that display travel time messages, 839 and 3317, do not show a relative increase in the percentage of significant cases of speed decrease. In fact, they are both lower than the average, and 839 is the only DMS that shows a higher percentage of significant increases than significant decreases for Type 2 messages. The numbers for Type 3 messages indicate that these messages either go unnoticed or users interpret them to mean that there are no disruptions ahead resulting in increased speeds. This may be as a result of Type 3 messages including information that drivers already know such as 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 a message appears on a DMS. When traffic does respond negatively to the messages, the average decrease in speed is just over 3 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% of cases and increases significantly in 19.69% 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 4 of the 6 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 the others.

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

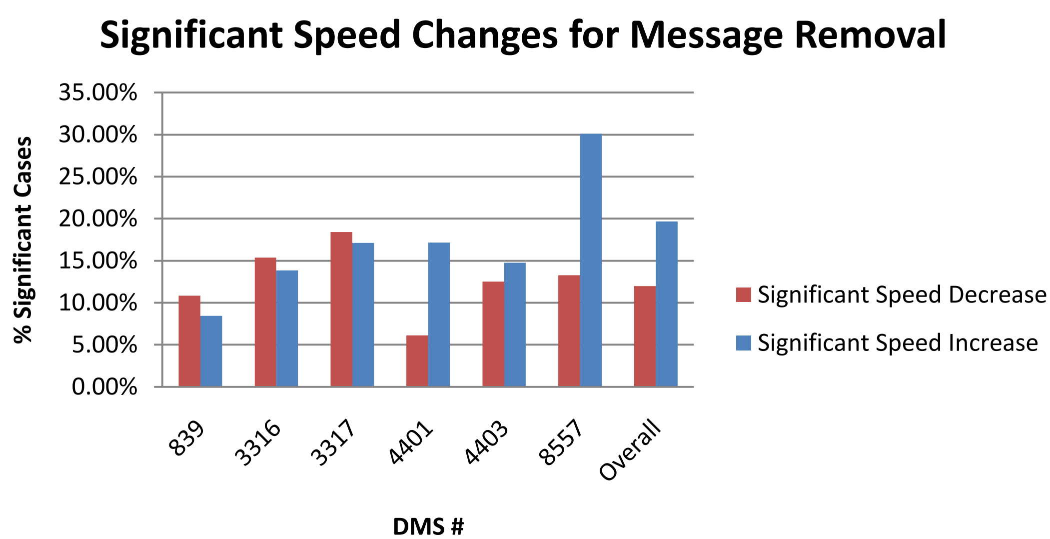


Figure 4.4. Graph of Off-On Summary by DMS

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 %**

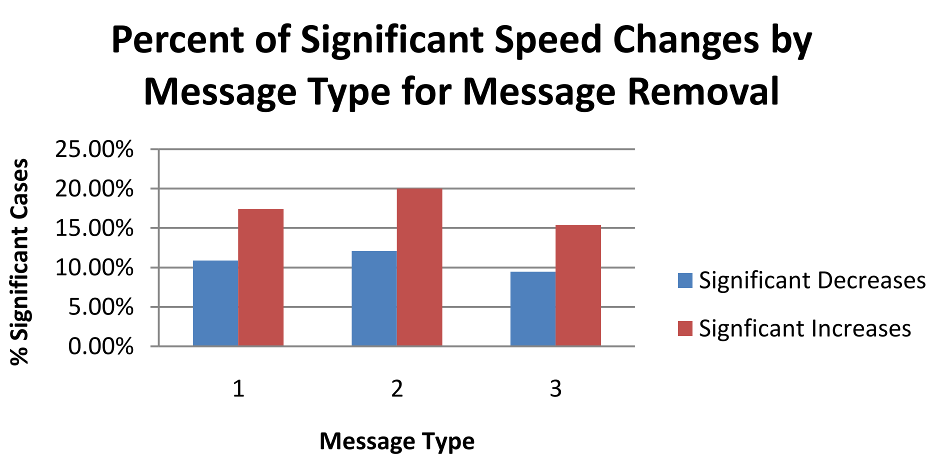


Figure 4.5. Graph of On-Off Summary by Message Type

The findings in this case are less clear. While all three message types show a higher percentage of cases of significant increase than significant decrease, the interpretation of the differences among message types is unclear. Type 2 messages show the highest rate of significant increase, followed by Type 1 and Type 3. This may indicate that removal of Type 2 messages reduces the load of drivers the most. Conversely, it could be interpreted that Type 2 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 valid. Similar arguments could be made for Type 1 messages. In the case of Type 3 messages, the relatively low percentage of significant increases is expected due to the low percentage of significant decreases found in the previous analysis.

In general, the findings from the on-off analysis indicate that average traffic speeds increase in approximately 1 in 5 cases of message removal. The average increase across these cases was 2.7 mph. Again, these results indicate that 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 later reverted from an urgent message to the default message. Analysis of these cases revealed a 13.52% rate of significant speed decreases and an 11.72% rate of significant speed increases. The corresponding changes in speed were -3.14 and 2.44 mph. The similar rates indicate that 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 4 of the 6 cases, the rates of significant increase and decrease are either identical or nearly so. The other 2 cases show a tendency of traffic 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

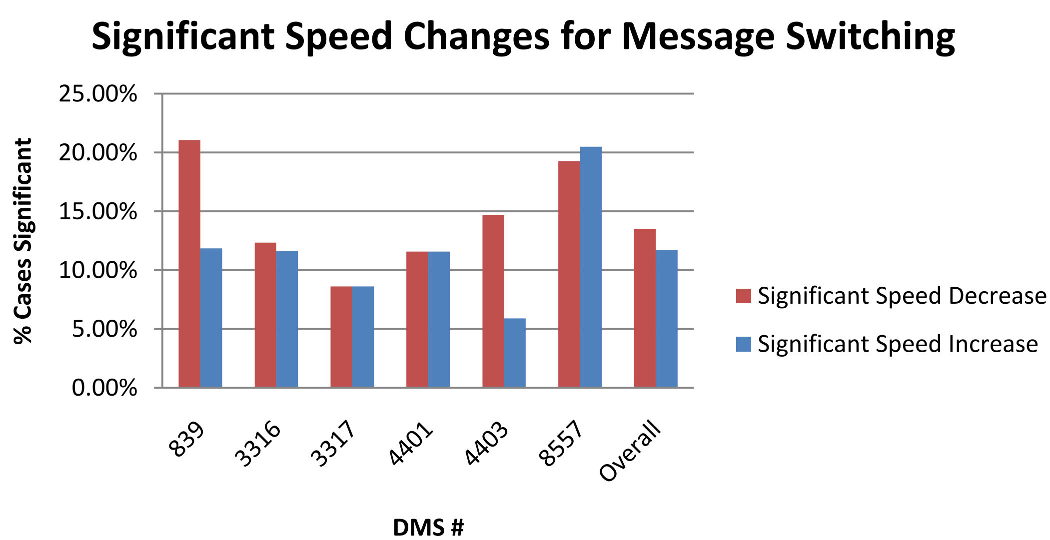


Figure 4.6. Graph of Switching Summary by DMS

In the switching condition, there are nine sub-conditions that can occur; namely, 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 does not appear to be any appreciable patterns within the data. This is likely due to the low number of cases for each switching condition.

Overall, the findings from examination of 2,268 cases indicate that the majority of traffic streams are unaffected by display, removal, or change of a DMS message. In the cases that the initiation of messages influenced a significant decrease in speed, traffic was most sensitive to Type 1 Danger/Warning messages followed in order by Type 2 and Type 3 messages. 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 as a result of message removal or of dissipation of the conditions which the message described. The switching analysis indicated more evenly split results, indicating that a change from one message to another has no appreciable bias in speed impacts.

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 5 minute analysis, two 2-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 twelve 2-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, Type 1 messages accounted for 1.5% of the total study times, Type 2 for 34%, and Type 3 for 12.5%. In the remaining time, the signs were blank. The low fraction of time Type 1 messages were displayed indicates that they are unlikely to appear on a daily basis. Therefore, drivers would not be used to the messages and may reduce speeds more to comprehend them. In two cases (3316 & 3317 Jan '11), Type 3 messages seem to have had a significant impact on traffic speeds. However, in both cases these messages were displayed for less than 1% of the overall 2-week period, approximately 1.5 hours each. This indicates that the messages in these cases could not have caused recurring congestion.

Type 2 messages, due to the large fraction of time they are displayed, have the largest potential to create congestion. The findings show that speeds during Type 2 messages range on average from 4 mph below to 1 mph above the speeds found during the no message display. These speeds indicate either none or light congestion during the message displays. Also, in only 3 of the 12 cases are speeds more than 1 mph below the posted speed limit during Type 2 message display. In 2 of these 3 cases, the overall average speeds were already below the speed limit.

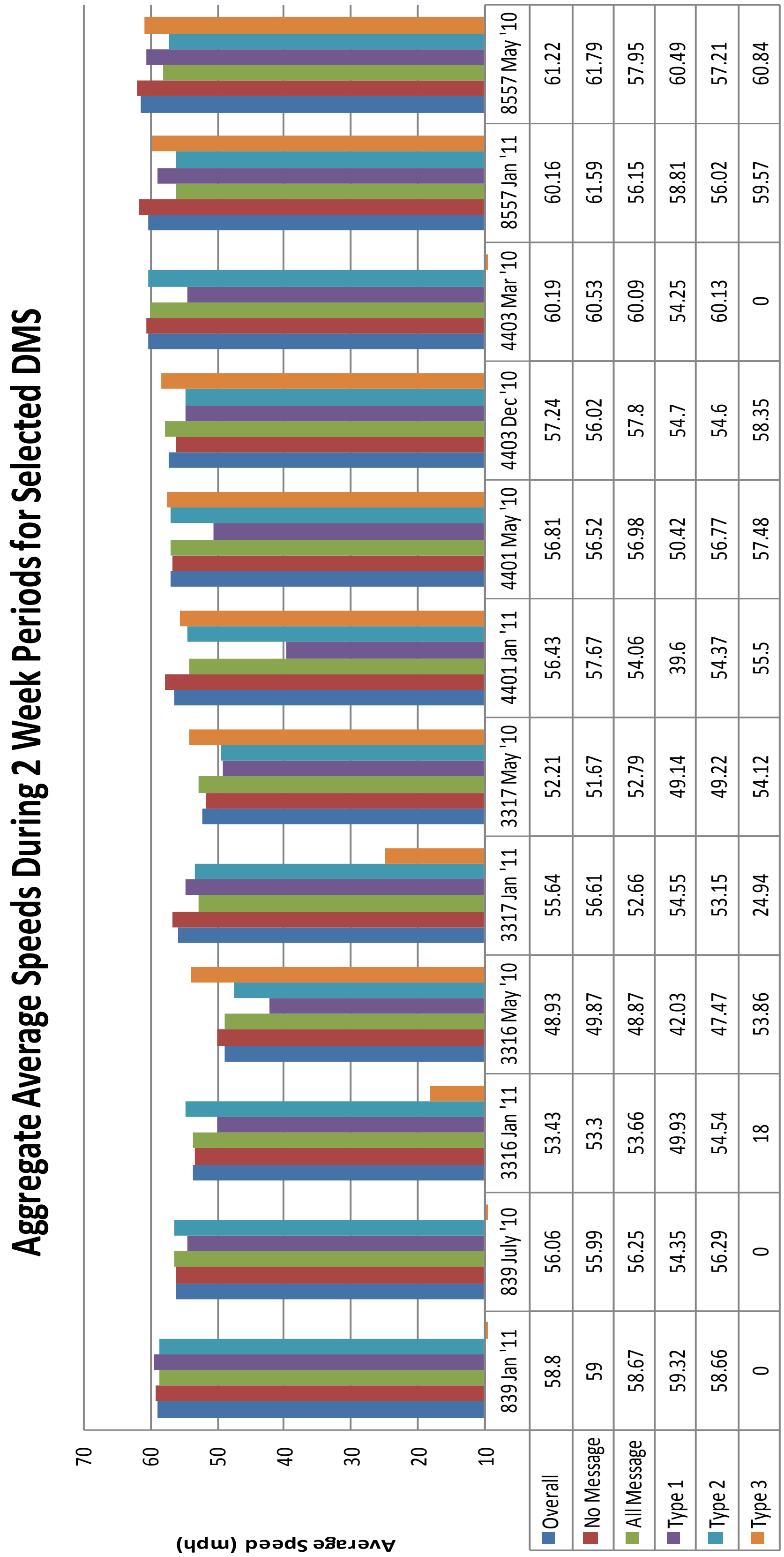


Figure 4.7. Aggregate Average Speeds for Two Week Analysis

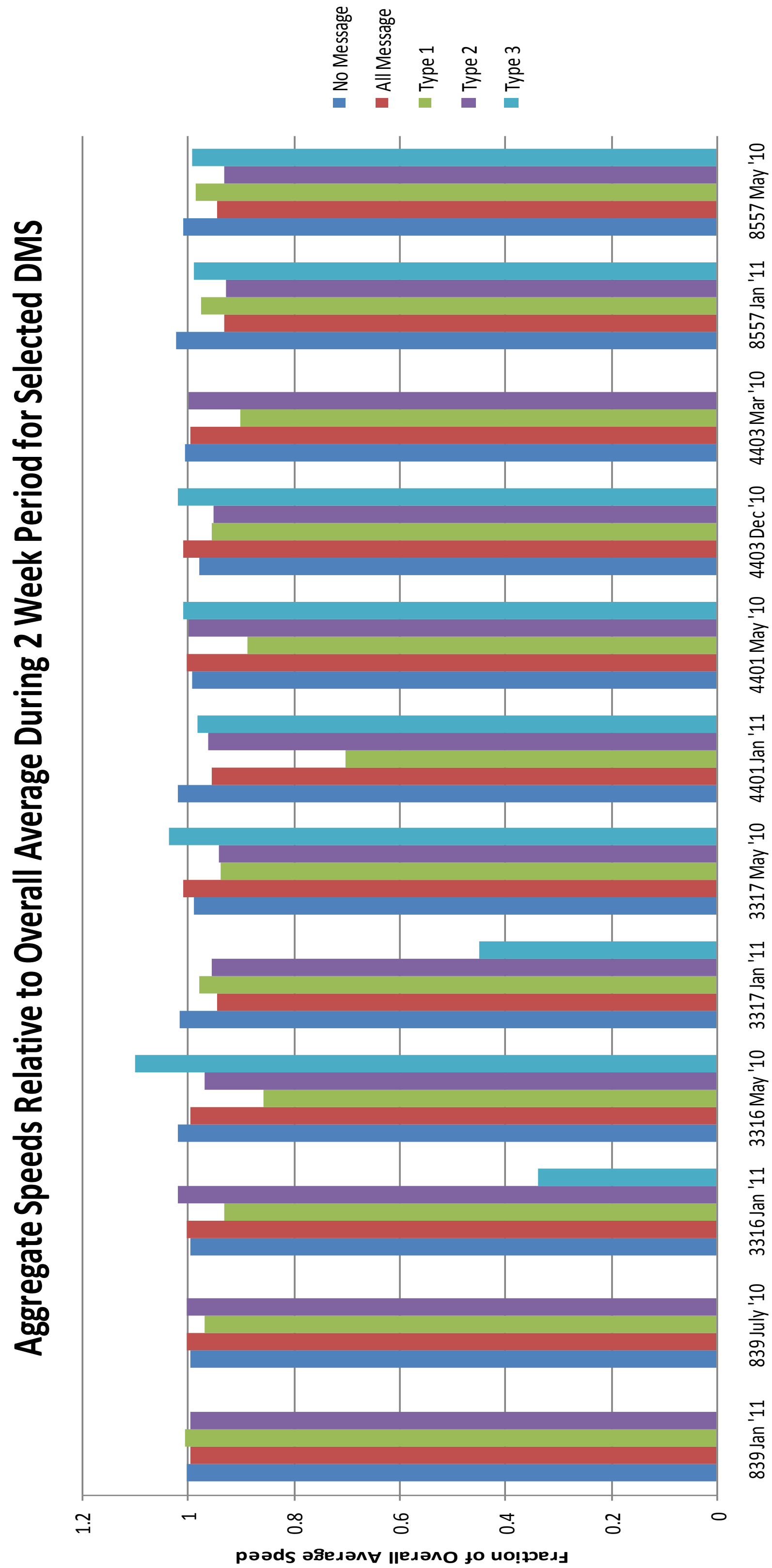


Figure 4.8. Aggregate Speeds Normalized by Overall Average Speeds

In summary, the aggregate analysis shows that average speeds during Type 1 message display are generally lower than the speeds during blank sign conditions. However, the occurrence of these messages is relatively rare and would not cause recurring congestion. Type 2 messages are displayed more often, and in some cases result in lowered traffic speeds. In the majority of the cases, though, the speeds are not below the posted speed limit. Speeds during Type 3 messages are usually higher than the other message types. In the cases where they were much lower, they accounted for less than 1% of the overall study time.

Chapter 5: Conclusions and Future Work

This thesis presented empirical evaluations of the quality, effectiveness, and localized impacts of highway Dynamic Message Signs (DMS). Bluetooth sensor technology was introduced as new method for evaluating messages posted on DMS for both the accuracy of the content as well as the influence they may have on travel 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 impacts (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 evaluation of DMS messages. It was determined that the messages being displayed were accurate in describing many of the prevailing conditions, though 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 DMS evaluation tool. In these cases, the DMS system had improved, utilizing more specific terms to describe congestion locations as well as having the ability to provide travel time messages. The travel time messages alleviated some of the concerns with late display of messages since the travel times would be seen to increase if there was congestion. In some cases, messages were left on longer than necessary, though 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. Analysis of two travel time cases, totaling nearly 24 hours of data, revealed that the average difference between the displayed and true travel times was less than 1 mile per hour. This shows that the source data and updating system utilized on DMS in Maryland is of 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. Analysis of three cases showed that traffic diversion rates on alternate routes increased between 5-20% during periods in which DMS messages recommend those routes. It can be inferred that DMS messages are effective in influencing route choice decisions, though due to the sampling rate of Bluetooth detectors, it cannot be concluded with complete certainty. 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. Type 1 message display indicated the highest percentage of speed decreases overall. Similar analyses on message removal and switching were performed. Overall, the majority of traffic streams either increased speed or did not change speed in response to DMS messages. An aggregate analysis showed that overall traffic speeds were slower during Type 1 messages, although they appeared infrequently. The most frequently appearing, Type 2 messages, corresponded generally with lower traffic speeds than periods with blank signs. These findings indicate that, in some cases, traffic speeds are reduced during periods of message display. It is not clear if these reduced traffic speeds are as 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 that DMS can be an accurate, effective, and safe tool for disseminating real-time travel information to motorists. This thesis 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 as well as other states. More deployments should serve to strengthen the reputation of Bluetooth as a DMS evaluation tool as well as building broader knowledge about DMS operations. In order to validate the 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 is any indication that the existence of a DMS results in higher accident rates.

The methods employed in this thesis are extendable to any DMS operation and could be used to evaluation locations before and after installation of DMS. It would be interesting to learn what effect the installation of a DMS has on a traffic stream in terms of travel time and diversion patterns.

Ultimately, the findings from future studies in this area 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.

Bibliography

1. Agah, M. (2002). *Guidelines on the Use of Permanent Variable Message Signs.* Arizona Department of Transportation, Transportation Technology Group. Retrieved June 22, 2009, from TMC Pooled Fund Study Web Page: http://tmcpfs.ops.fhwa.dot.gov/cfprojects/new_detail.cfm?id=25&new=2

2. Federal Highway Administration. (2003). *Manual on Uniform Traffic Control Devices (MUTCD).* Sec. 6F.55

3. Dudek, C. L. (2004a). *Changeable Message Sign Operation and Messaging Handbook.* Report No. FHWA-OP-03-070, FHWA, United States Department of Transportation, pp. 2-3.

4. Minnesota Department of Transportation. (2000). *Guidelines for Changeable Message Sign (CMS) Use*. Retrieved June 9, 2009, from MnDOT publications web site: http://www.dot.state.mn.us/trafficeng/otepubl/index.html

5. Miller, J., Smith, B., Newman, B, Demetsky, M. (1995). *Development of Manuals for the Effective Use of Variable Message Signs.* Virginia Transportation Research Council Report # VTRC 95-R15, Charlottesville, Virginia.

6. Ridgeway, R. Framework for harmonized Implementation of Variable MessageSigns in Europe. *Rijkswaterstaat*, The Netherlands, 2003.

7. Dudek, C. L. (2004b). *Dynamic Message Sign Design and Display Manual.* Report No. FHWA/TX-04/0-4023-P1, Texas Department of Transportation, pp. 4-11.

8. Wardman, M., Bonsall, P. W., Shires, J. D. (1997). *Driver Response to Variable Message Signs: A Stated Preference Investigation.* Transportation Research-C, Vol. 5, No. 6, pp. 389-405.

9. Monsere, C., Breakstone, A., Bertini, R., Deeter, D., McGill, G. (2007). *Validating Dynamic Message Sign Freeway Travel Times with Ground Truth Geospatial Data.* Transportation Research Record 1959, TRB, National Research Council, Washington, D.C., pp. 19-27.

10. Chen, C., Skabardonis, A., Varaiya, P. (2003). *A System for Displaying Travel Times on Changeable Message Signs.* 83rd Annual Meeting of the Transportation Research Board, Washington, D.C.

11. Peng, Z. R., Guequierre, N, Blakeman, J. C. (2004) *Motorist Response to Arterial Variable Message Signs.* Transportation Research Record 1899, TRB, National Research Council, Washington, D.C., pp. 55-63.

12. Chen, S., Liu, M, Gao, L, Meng, C., Li, W., Zheng, J. (2008) *Effects of Variable Message Signs (VMS) for Improving Congestions.* IEEE International Workshop on Modeling, Simulation and Optimization. Paper # 978-0-7695-3484-8/08, pp. 416-419

13. Cheng, J. J., Firmin, P. E. (2004) *Perception of VMS Effectiveness: A British and Canadian Perspective.* 12th IEE International Conference on Road Transport Information and Control 20th-22nd April 2004, The IEE, Savoy Place, London.

14. Polydoropoulou, A., Ben-Akiva, M., Khattak, A., Lauprete, G. (1996) *Commuters' Normal and Shift Decisions in Unexpected Congestion: En Route Responses to Advanced Traveler Information Systems Volume 2.* California PATH Research Report UCB-ITS-PRR-96-21, Institute of Transportation Studies, University of California, Berkeley.

15. Peeta, S., Ramos, J. L., Pasupathy, R. (2000) *Content of Variable Message Signs and On-Line Driver Behavior.* Transportation Research Record 1725, TRB, National Research Council, Washington, D.C., paper no. 00-0970

16. Schiesel, R., Demetsky, R. J. (2000) *Evaluation of Traveler Diversion Due to En-Route Information.* Center for Transportation Studies Report UVA/29472/CE00/103, University of Virginia, Charlottesville, Virginia

17. Foo, S., Abdulhai, B., Hall, F. L. (2008) *Impact on Traffic Diversion Rates of Changed Message on Changeable Message Sign.* Transportation Research Record: Journal of the Transportation Research Board, *No. 2047,* Transportation Research Board of the National Academies, Washington, DC

18. Levinson, D and Huo, Hong (2003), Effectiveness of VMS Using Empirical Loop Detector Data presented at Transportation Research Board Conference, January 12 – 16 2003 Washington DC (Session 565).

19. Boyle, L.N., and F. Mannering (2003). Impact of Traveler Advisory Systems on DrivingSpeed: Some New Evidence, *Transportation Research – C*, Vol.12, pp. 57-72.

20. Alm, H. and L. Nilsson. Incident Warning systems and traffic safety: a comparison between the PORTICO and MELYSSA test site systems. *Transportation Human Factors*, Vol.2, No.1, 2000, pp. 77-93.

21. Luoma, J., Rama, P., Penttinen, M., Anttila, V. (2000), Effects of variable message signs for slippery road conditions on reported driver behavior. *Transportation Research – F*, Vol. 3, pp. 75-84.

22. Erke, A., Sagberg, F., and R. Hagman (2007), Effects of route guidance variable message signs (VMS) on driver behavior. *Transportation Research – F*, Vol. 10, pp. 447-457.

23. Wang, J.H., Keceli, M., and V. Maier-Speredelozzi (2009), Effect of Dynamic Message Sign Messages on Traffic Slowdowns. *Transportation Research Board Annual Meeting* 2009, Paper #09-1964.

24. Traffic Technology Today, Traffax deploys its BluFax real-time traffic monitoring systems in Arizona and Maryland (2011), *http://cms.ukintpress.com/UserFiles/Image/TTT%20images/BluFax-unit.jpg*

25. University of Maryland Center for Advanced Transportation Technology, Bluetooth Traffic Monitoring Technology – Concept of Operation and Deployment Guidelines (2008), *http://www.catt.umd.edu/documents/UMD-BT-Brochure_REV3.pdf*

26. Haghani, A., M. Hamedi, K.F. Sadabadi, S. Young, and P. Tarnoff (2010) *Freeway Travel Time Ground Truth Data Collection Using Bluetooth Sensors*. Transportation Research Board of the National Academies, Annual Meeting, Washington, D.C.,