EVALUATION OF A MOBILE WORK ZONE BARRIER SYSTEM

Final Report

SPR 746

Oregon Department of Transportation

EVALUATION OF A MOBILE WORK ZONE BARRIER SYSTEM

Final Report

SPR 746

by

John A. Gambatese and Nicholas Tymvios
School of Civil and Construction Engineering
Oregon State University
220 Owen Hall
Corvallis, OR 97331

for

Oregon Department of Transportation
Research Section
555 13th Street NE, Suite 1
Salem OR 97301-5192

and

Federal Highway Administration
400 Seventh Street, SW
Washington, DC 20590-0003

August 2013

Technical Report Documentation Page

1. Report No. FHWA-OR-RD-14-05	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation Of A Mobile Work Zone Barrier System		5. Report Date August 2013 6. Performing Organization Code
7. Author(s) John A. Gambatese and Nicholas Tymvios School of Civil and Construction Engineering, Oregon State University		8. Performing Organization Report No. SPR 746
9. Performing Organization Name and Address Oregon Department of Transportation Research Section 555 13th Street NE, Suite 1 Salem, OR 97301		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Oregon Department of Transportation Research Section and Federal Highway Administration 555 13th Street NE, Suite 1 400 Seventh Street, SW Salem, OR 97301-5192 Washington, DC 20590-0003		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A high percentage of highway maintenance activities and some construction activities are performed in a travel lane, median, or shoulder while the public travels by at relatively high speeds in very close proximity to the workers. Work zone traffic control efforts include safety measures for the workers, but current capabilities for short duration work zones can be improved in order to increase the protection of the workers. A recent advancement in work zone safety is a mobile barrier system that consists of a motorized tractor/trailer combination, and can provide complete isolation of the work area for a distance of up to 100 feet. The research presented in this report involved evaluating a mobile barrier in a variety of work zone environments, leading to a determination of its benefits and limitations to guide ODOT in future work zone safety strategies/investments. A benefit of using a mobile barrier system is the added safety provided by the isolation of workers from errant vehicles. Anticipated benefits also include: improved efficiency of work zone setup and removal; improved efficiency of the work activity as the mobile barrier can be equipped with lights, generators, variable message signs, and TMAs; and improved mobility of the work zone where multiple finite work areas are involved.

17. Key Words WORK ZONE, SAFETY, CONSTRUCTION, MOBILE BARRIER SYSTEM, ROAD MAINTENANCE	18. Distribution Statement Copies available from NTIS, and online at http://www.oregon.gov/ODOT/TD/TP_RES/

19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 186	22. Price

Technical Report Form DOT F 1700.7 (8-72) Reproduction of completed page authorized Printed on recycled paper

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
	NOTE: Volumes greater than 1000 L shall be shown in m^3.			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

ACKNOWLEDGEMENTS

The authors would like to acknowledge the input of the ODOT Research Unit and Technical Advisory Committee. The Technical Advisory Committee members are:

Jon Lazarus, ODOT Research Unit, Research Coordinator
Mike Gehring, ODOT Maintenance Supervisor Bridge Crew
Eric Leaming, ODOT Work Zone Traffic Analyst
Martin Ebner, ODOT Assistant PM, Portland Area
Nick Fortey, FHWA Safety Engineer
Scott Vogel, Wildish Construction
Bob Ebeling, ODOT Assistant District 2B Manager

The authors would also like to thank the members of the ODOT Project and Maintenance crews and contractor personnel who assisted with the case study projects and implementation of the mobile barrier. Without their assistance and support, the study activities described in this report would not be possible.

The authors would also like to recognize Dr. David Hurwitz, Assistant Professor at Oregon State University, Joshua Swake, graduate student at Oregon State University, and Isaac Talley, undergraduate student at Oregon State University, who conducted the driving simulator study of the mobile barrier. The voluntary contribution of time and effort by these researchers to the overall study is appreciated and an enhancement to the study.

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Workers conducting highway construction and maintenance operations commonly work in areas where high speed traffic passes a few feet away from the construction area. Exposure to this hazard is ever-present and evident in the number of work zone crashes that occur on Oregon and US roads annually. Work zone traffic control efforts currently consist of a variety of measures to enhance worker and motorist safety, such as concrete barriers, variable message signs (VMS), and flaggers. A recent advancement in work zone safety for short-term work activities in a finite area, such as maintenance activities, is the use of a mobile barrier system (MBS). Mobile barriers consist of a highly mobile, motorized tractor/trailer combination that provides positive protection and complete isolation of the work area. The National Cooperative Highway Research Program (NCHRP) Report 350 outlines crash testing procedures for use of mobile barriers on the road.

To date, commercially available mobile barriers have seen limited use in a number of states, as well as internationally. The device is still new to many state Departments of Transportation (DOTs) and roadway agencies. Some agencies have acquired mobile barriers and have reported favorably on their use and benefit to safety. However, only limited academic research on mobile barriers is available. As part of the decision to invest in one or more of these systems, ODOT elected to conduct a research study to assess and demonstrate the safety benefit, flexibility of use, and increased efficiency of work activities compared to traditional means of protection. Accordingly, the research conducted involves testing and evaluating an MBS when used for maintenance and construction activities within a variety of work zone environments.

ODOT purchased an MBT-1® mobile barrier from Mobile Barriers LLC to include in the study and for future ODOT use. ODOT then contracted with Oregon State University (OSU) to conduct the study. The overall goal of the investigation was to assist ODOT in evaluating the benefits and limitations of using a mobile barrier system. Rather than repeating the already approved crash tests that have been completed on the MBT-1®, the research plan included the following objectives:

1. Evaluate the MBT-1® when used during representative ODOT maintenance activities (case study projects). The performance metrics evaluated were: (a) time required to set up and break down the system; (b) limitations and enhancements to the work operations; (c) worker safety and safety perception; (d) worker productivity; (e) motorist safety and safety perception; and (f) system performance based on project/worksite attributes.
2. Determine transportation process and any limitations of transporting the MBT-1® to/from a work zone.
3. Evaluate the same performance metrics of traditional work zone protection practice when used during representative ODOT maintenance activities (comparison projects).
4. Compare the performance of the MBT-1® to that of traditional work zone protection practice based on the identified performance metrics.
5. Develop guidance for ODOT and construction contractors for planning and using an MBS for maintenance activities and potential use on ODOT construction projects.

The research study was conducted using a case study approach. Six ODOT maintenance activities were selected on which to implement and evaluate the MBT-1®. The case studies were as follows: (1) joint repair on the I-405 northbound approach to the Fremont Bridge; (2) concrete pavement repair on I-5 northbound and southbound lanes near Brownsville, OR; (3) electrical work on I-5 Interstate Bridge lighting in southbound lanes; (4) installation of drilled shaft on roadway shoulder for overhead signage on US 26; (5) placement of multiple high occupancy vehicle pavement markers in northbound direction on I-5; and (6) repair of seal joint in northbound lanes on I-205 over the Tualatin River. On each case study project, the researchers placed sensors to monitor traffic speed, volume, and types of vehicles, conducted interviews and surveys of workers to obtain their input on the MBT-1®, worker safety and productivity, and recorded observations of the impacts of the MBT-1® on the worksite conditions and work operations.

Based on the research results and analysis, the MBT-1® was found to be an effective and beneficial tool for ODOT maintenance crews. This is especially true in regards to worker safety. The MBT-1® showed that it is able to provide enhanced protection of workers, by both reducing and eliminating safety concerns. In addition, the workers' general response was that they felt safer with the MBT-1® present. Some factors that attribute to this positive safety view are:

- The MBT-1® provides a hard barrier between the work area and passing traffic.
- The presence of the MBT-1® allows the workers to perform their tasks without paying as much attention to the adjacent traffic or needing a spotter.
- Noise from the adjacent traffic is significantly reduced when using the MBT-1®.
- The MBT-1® facilitates the installation of lighting and the work zone can be illuminated to a very comfortable level, reducing the need for additional lighting equipment.

With regards to mobility through the work zone (as measured by vehicle speed), the study reveals that the MBT-1® is beneficial to the travelling public. As vehicles pass through the work zone, speed reductions next to the maintenance work zones were less with the MBT-1® present than with traditional safety measures.

Additionally, the MBT-1® has a variety of options that help to increase worker efficiency, such as storage compartments to carry materials and tools inside the MBT-1® eliminating the need for additional vehicles for that purpose.

The researchers found that there is a need for training ODOT employees who operate the MBT-1® to practice positioning the MBT-1® on construction sites, switching the direction of the MBT-1® (from left-hand to right-hand, and vice versa), and adding/removing wall sections. Sufficient space is also needed on the roadway to place the MBT-1® without obstructing traffic, creating an obstacle for passing traffic to maneuver around or avoid, or interfering with the work operations. In states with over length permit requirements, additional planning may be required to transport the MBT-1® to work sites given its long length. The MBT-1® is expected to be applicable to many different types of maintenance activities, and mostly beneficially to the work performed by electric crews and sign crews, which have high annual expenditures.

1.0 INTRODUCTION

A large portion of highway maintenance activities and construction activities are performed in a travel lane or adjacent shoulder while motorists travel by at relatively high speeds and in close proximity to the workers. Work zone traffic control efforts currently consist of a variety of measures to ensure worker and motorist safety, such as concrete barriers, variable message signs, and flaggers. Current accepted practices for short duration work zones provide limited protection to workers and minimum physical separation from errant vehicles passing through the work zone. Additionally, current safety measures such as truck mounted attenuators (TMAs) and spotters typically require additional personnel to be exposed to the hazards simply to provide safety measures to the work crews. Even with TMAs and spotters, the immediate work area may remain unprotected adjacent to the functioning travel lanes, allowing errant vehicles and distracted drivers to enter this vulnerable work area. Lastly, in many locations, a high percentage of work activities must be performed at night, increasing the risk to the workers and motorists.

A recent advancement in work zone safety for finite area work activities, such as maintenance activities, is the use of a mobile barrier system (MBS). An example of an MBS is the MBT-1® provided by Mobile Barriers (http://www.mobilebarriers.com/). An MBT-1® is a highly mobile, motorized tractor/trailer combination that provides positive protection and complete isolation of the work area for a distance of up to 100 feet. Mobile barriers have parameters for crash testing and acceptance for use on the National Highway System (*Gomez-Leon 2008*). MBSs have seen limited use in a number of states, as well as internationally. These devices are still new to many state Departments of Transportation (DOTs) and roadway agencies. Some agencies have acquired mobile barriers and have reported favorably on their use as positive protection barriers and associated benefits to safety (see Section 2.5.1). Positive protection barriers are defined as "a device which contains and redirects vehicles in accordance with National Cooperative Highway Research Program (NCHRP) Report 350, preventing their intrusion into the workspace." (*FHWA, 2003a*).

However, as part of the decision to invest in one or more of these safety systems, research is needed to assess and demonstrate the safety benefit, flexibility of use, and increased efficiency of work activities compared to traditional means of protection. Accordingly, the research presented in this report involves testing and evaluating an MBS when used for maintenance and construction activities within a variety of work zone environments.

ODOT entered into a contract with Oregon State University (OSU) to study the implementation of an MBS on maintenance and construction worksites and to develop guidelines for its optimal implementation for ODOT activities. This final research report for the study provides a detailed description of the: (1) activities conducted to document and review previous research, regulatory requirements, current industry practice, and available resources; (2) identification and implementation of case study projects for the research; (3) analysis of the case study data; (4) conclusions drawn from the case studies; and (5) recommendations for future implementation of the mobile barrier on ODOT maintenance and construction activities.

1.1 BACKGROUND

Workers conducting highway construction and maintenance operations experience a hazard that is absent on many other types of construction sites: high speed traffic flowing just a few feet away from the construction area. This hazard is ever-present and evident by the number of work zone crashes that occur on Oregon and US roads. Specifically, from 2001 to 2011, there was an average of 489 work zone-related crashes each year in Oregon *(ODOT 2012*).The number of fatalities associated with the work zone crashes in Oregon from 2005 through 2010 amounted to 9 in 2010, 18 in 2009, 5 in 2008, 11 in 2007, 5 in 2006 and 20 in 2005 (*ODOT 2011a*). In Oregon, approximately 40% of work zone crashes occur in the transition zone prior to the work area (*ODOT 2012*). Lastly, ODOT (*2012*) reports that, compared to other occupations, the risk of death is seven times higher for roadway workers than for an average worker.

The National Highway Traffic Safety Administration (NHTSA) maintains a database of all of the fatal crashes that occur on US roads. This information is available to the general public on the NHTSA website (*NHTSA 2011*) also shows the number of fatalities and incidences with fatalities that occurred within work zones during the same time period. Furthermore, the incidences and fatalities that occurred within work zones are divided into four categories: (1) construction work zones, (2) maintenance work zones, (3) utilities work zones, and (4) work zones that were not identified. [As observed in the table, the total number of incidences and fatalities is decreasing in recent years.] Table 1.1 shows the national values for fatalities, and for incidences with fatalities, that occurred over a period of 12 years (1998 – 2009).

Table 1.1: National Values for Road Crashes with Fatalities (*NHTSA 2011*)

Year	Fatalities						Incidences with Fatalities					
	Total Motor Vehicle Crash Fatalities	Work Zone Type				Total WZ Fatalities	Total Motor Vehicle Crash Incidences	Work Zone Type				Total WZ Incidences
		Constr.	Maint.	Util.	WZ type unknown			Constr.	Maint.	Util.	WZ type unknown	
2010	32,287	413	68	6	89	576	30,196	368	61	6	79	514
2009	33,808	510	60	15	82	667	30,797	441	54	14	73	582
2008	37,423	547	68	13	88	716	34,172	505	60	13	84	662
2007	41,259	639	89	11	92	831	37,435	555	84	9	84	732
2006	42,708	764	106	16	118	1004	38,648	678	92	16	109	895
2005	43,510	859	97	13	89	1058	39,252	750	91	12	84	937
2004	42,836	836	99	16	112	1063	38,444	725	92	15	99	931
2003	42,884	931	77	21	66	1095	38,477	824	74	21	63	982
2002	43,005	1,028	84	12	62	1186	38,491	890	77	11	57	1035
2001	42,196	808	96	8	77	989	37,862	714	86	8	69	877
2000	41,945	873	92	12	49	1026	37,526	775	84	12	43	914
1999	41,717	740	72	10	50	872	37,140	649	65	10	46	770
1998	41,501	654	53	15	50	772	37,107	577	47	10	47	681

Similarly, Table 1.2 shows the same information for the State of Oregon. Once again, the total number of incidences and fatalities has decreased in recent years, while the values for work zone incidences and work zone fatalities have fluctuated.

Table 1.2: Oregon Values for Road Crashes with Fatalities (*NHTSA 2011*)

Year	Fatalities						Incidences with Fatalities					
	Total Motor Vehicle Crash Fatalities	Work Zone Type				WZ Fatalities	Total Motor Vehicle Crash Incidences	Work Zone Type				WZ Incidences
		Constr.	Maint.	Util.	WZ type unknown			Constr.	Maint.	Util.	WZ type unknown	
2010	308	9	0	0	0	9	283	9	0	0	0	9
2009	377	16	2	0	0	18	331	15	2	0	0	17
2008	416	4	1	0	0	5	369	4	1	0	0	5
2007	455	10	1	0	0	11	411	6	1	0	0	7
2006	478	4	1	0	0	5	418	4	1	0	0	5
2005	487	20	0	0	0	20	443	19	0	0	0	19
2004	456	12	0	0	0	12	388	10	0	0	0	10
2003	512	2	0	0	0	2	429	2	0	0	0	2
2002	436	4	0	1	0	5	388	4	0	1	0	5
2001	488	3	1	1	0	5	428	3	1	1	0	5
2000	451	4	1	0	1	6	407	4	1	0	1	6
1999	414	6	2	1	0	9	367	5	2	1	0	8
1998	538	9	0	5	0	14	485	8	0	1	0	9

The impact of the crashes on the State of Oregon goes beyond the social and emotional impact of the loss of life and injured citizens. The cost associated with each fatal crash can amount to millions of dollars. Additional losses to the public due to road closures, decreased mobility, and increased travel times as a result of crashes in work zones have a negative impact to the State's economy.

ODOT is required to follow all applicable rules, regulations, and guidelines for work zone safety, as well as the necessary protective steps to ensure the safety of the maintenance and construction crews on Oregon roads. However, as can be seen in Table 1.2, additional measures are needed to ensure zero fatalities (*FHWA 2009b*, *ATSSA 2008*). This goal may be feasible by providing additional barriers between the hazard of fast flowing traffic and the work crews. Positive barriers, such as the MBT-1® manufactured by Mobile Barriers, can provide the needed additional protection. The MBT-1® provides a wall of steel adjacent to the work zone that prevents vehicles from encroaching into the work area.

1.2 STUDY GOALS AND OBJECTIVES

The overall goal of this investigation is to assist ODOT in evaluating the benefits and limitations of using a mobile barrier system (MBS). The MBS evaluated for this research study is the Mobile Barrier's MBT-1®. The only contemporary barrier design that may be compared to the MBT-1® is the Balsi Beam, which was developed by CalTrans. Both of these alternatives have been tested for their ability to withstand impacting vehicles (*Gomez-Leon 2008, Jewell et al. 2008*), although testing standards were different (see Section 2.2). Rather than repeating these crash tests, the present research aims to evaluate the following:

- Efficiency in deploying and removing the MBS
- Impacts of the MBS on work operations
- Impacts of the MBS on worker safety
- Impacts of the MBS on worker productivity
- Perceptions of safety provided by an MBS compared to traditional work zone protective measures for workers and motorists
- Types of projects for which the MBS is most suitable

The specific objectives of the research study are as follows:

1. Evaluate an MBS when used during representative ODOT maintenance activities (case study projects). The performance metrics to be evaluated are:
    a. time required to set up and break down the system;
    b. limitations and enhancements to the work operations;
    c. worker safety and safety perception;
    d. worker productivity;
    e. motorist safety and safety perception; and
    f. system performance based on project/worksite attributes.

    This objective also includes determining and assessing any limitations to transporting the MBS to/from a work zone.

2. Evaluate the same performance metrics of traditional work zone protection practice when used during representative ODOT maintenance activities (comparison projects).

3. Compare the performance of the MBS to that of traditional work zone protection practice based on the identified performance metrics.

4. Develop guidance for ODOT and construction contractors to reference when planning and using an MBS for maintenance activities and potential use on ODOT construction projects.

1.3 RESEARCH SCOPE AND METHODS

To achieve the research goals and meet the stated objectives, seven primary research activities were planned for the study: (1) Study Initiation; (2) Literature Review; (3) Project Case Study Identification; (4) Site Application and Testing of MBS and Traditional Protective measures; (5) Data analysis and System Evaluation; (6) Development of Guidelines for Implementation; (7) Preparation of Draft and Final Reports. Each of the planned activities is described in detail below.

Task 1:Study Initiation

This task involved the setting up an initial meeting with the ODOT Technical Advisory Committee (TAC) to discuss and affirm the objectives, tasks, and timeline for the study. This meeting took place on July 11, 2011 at the ODOT Research Office in Salem. During the meeting the process for identifying ODOT maintenance and construction projects/activities to investigate was also determined. The study contact persons were identified, as well as the process for getting access to and using the MBS. In addition, the MBS operations and maintenance documents were reviewed. On June 15, 2011, the researchers observed a demonstration of the use of the MBS at the ODOT laydown yard near Portland, OR.

Task 2:Literature Review

For this task, an in-depth review of literature, reports, and procedure manuals used for information related to the use and testing of mobile barrier systems was conducted. Special consideration was given to previous research studies on MBS use and safety, the work operations associated with mobile barriers, recommended uses and limitations to their use, the reported performance metrics for the cases when an MBS has been used and when traditional protective measures are used, as well as the recommended practices for measuring the performance metrics.

Task 3:Project Case Studies Identification

In this task, the desired project attributes (size, location, type, duration, etc.) that are applicable to the use of mobile barriers and are to be included in the study were identified. In addition, the specific ODOT maintenance and construction projects/activities, both case-study projects and comparison projects, to be included in the research study, were identified. The research team contacted the case study participants for assistance with the research tasks. The projects/activities included in the study were identified and set up with assistance from ODOT and the TAC.

Task 4:Site Application and Testing of MBS and Traditional Protective Measures

For this task, the MBS was deployed with the support of ODOT personnel on the case study construction and maintenance projects/activities identified. The MBS was evaluated based on the following performance metrics: 1) time required to set up takedown the system, 2) limitations/enhancements to work operations, 3) worker safety and safety perception, 4) worker productivity, 5) motorist safety and safety perception, 6) system performance based on project/site attributes, and 7) MBS transportation to/from work zone.

At each construction/maintenance site, research activities entailed collecting data related to the performance metrics listed above. These activities included: interviewing workers, observing and timing worker movements, recording worksite conditions and attributes, recording work activities undertaken, observing motorist behaviors, measuring motorist speeds through the work zone, and recording and timing MBS movements and performance levels. Similar evaluations of construction/maintenance sites that utilize traditional protective measures were also conducted. Where logistically possible (at the same project location), evaluations of both traditional protective measures and MBS use for construction/maintenance activities were conducted for a direct comparison.

To solicit input from motorists, the researchers planned to work with ODOT to set up a webpage or distribute an e-mail to ODOT personnel and ODOT contractor personnel to provide input regarding their perceptions of safety when traveling through a work zone that utilizes an MBS. A list of questions was to be used that asked the personnel to comment on the performance of the MBS in comparison to traditional protective measures along with the location(s) in which they observed the MBS in use. The research team discovered this information to be unattainable due to the small pool of participants and lack of opportunities for participants driving through the work zone during deployment of the MBS. Instead, the research team conducted a laboratory simulation using a driving simulator. The study and findings from the driving simulator scenario will be written under a separate cover from this research.

Task 5:Data Analysis and System Evaluation

For Task 5, the data collected from the case study and comparison projects was analyzed to measure the performance metrics with respect to each project. This task was done in stages as data was gathered to verify sound, meaningful metrics and the data collection methods. The results were aggregated to determine how the MBS and the traditional protective measures performed relative to each performance metric. Finally, when possible based on the available data, comparisons were made between the MBS and traditional protective measures in regards to their performance.

Task 6:Develop Guidelines for Implementation

This task involved the development of guidelines for ODOT reference when planning and considering use of a mobile barrier on future construction projects and maintenance activities.

Task 7:Preparation of Draft and Final Reports

This task entailed compiling all of the research findings into this final report to be published by ODOT and FHWA.

1.4 IMPLEMENTATION

The guidance document that is produced by this research project (Objective 4 and Task 6) is the practical output from the research. The document is expected to be used for planning and deployment of the MBT-1® within ODOT Maintenance and for potential construction activities. The document will be implemented by ODOT when developing future work zone safety strategies and planning investments, ODOT Maintenance and Operations, and ODOT Construction activities when considering how to set up and design work zones to incorporate these findings for MBT-1® use.

2.0 LITERATURE REVIEW

An on-line literature search was conducted to uncover information on the implementation and impacts of highly mobile, positive barriers on highways and other roads for short term maintenance operations. Keyword searches of the Compendex article database, on the Transportation Research Information Services (TRIS) website, and the World Wide Web (using Google as a search engine) were used to locate research articles, reports, industry standards, and other documents that address issues related to positive barriers. The literature review also included sources identified by members of the Technical Advisory Committee (TAC). The literature collected from this activity was reviewed for its relevance and application to the study. This section of the report describes the results of the literature review. It presents a summary of previous research on the topic published in documents such as journal articles, research reports, and conference proceedings. Applicable State and Federal standards were also examined as part of the literature review and are presented here.

2.1 PREVIOUS RESEARCH

2.1.1 Work Zone Crashes

In order to determine how to optimize the use and implementation of highly mobile positive barriers for maintenance work zones it is important to have an understanding of the types of vehicle crashes that occur in work zones, whether the work zones are for construction or maintenance. The types of crashes that commonly occur in construction work zones have been investigated in prior research studies. Using crash reports and other resources, researchers have identified rear-end collisions and sideswipes as the most common types of work zone crashes *(Upchurch 2000, Khattak et al. 2002, FHWA 2003b, Tsyganov et al. 2003, Sun et al. 2006, Muttart et al. 2007*). Other common types of work zone accidents include (*Tsyganov et al. 2003*):

- Joint collision of vehicles;
- Vehicles running into materials and equipment;
- Vehicles driving into pits and potholes;
- Vehicles running into road workers;
- Vehicles running into pedestrians; and
- Vehicles colliding with road-building machines or mechanisms.

2.1.2 Safety in Construction Work Zones

A large number of research articles and government reports have been published regarding how to provide safe worksites for work crews on highways. In her article in *Better Roads (Stidger 1990*), Stidger suggests the use of visible manned or unmanned police cars and/or the use of radar as the most effective deterrent to motorists speeding in work zones. This suggestion is also recommended by others (*South 1998*, *Pratt et al. 2001*, *Antonucci et al. 2005*). For the Washington State Department of Transportation (WSDOT), for example, police officer presence is tied to the standard construction operations within WSDOT for all major work zones. It is standard practice for police officers to be present during WSDOT highway projects. Police presence is dependent not only on the standard operations within a state but also on the availability of officers and the amount of funding available to pay for officers working more hours. Additional suggestions for ways to enhance safety in construction work zones include:

- High visibility apparel and signage (*Stidger 1990*, *Upchurch 2000*, *Pratt et al. 2001*, *FHWA 2003b*, *Antonucci et al. 2005*)
- Clear, effective, credible real-time signage indicating when the work zone will start and what is expected of drivers (*Stidger 1990*, *South 1998*, *Upchurch 2000*, *Pratt et al. 2001*)
- Better traffic control systems (*Tsyganov et al. 2003*)
- Employing competent persons for accountability and oversight of the work sites (*Pratt et al. 2001*)
- Public information campaigns to educate the public about upcoming and current traffic construction/maintenance (*Stidger 1990*, *South 1998*, *Upchurch 2000*, *Pratt et al. 2001*, *Antonucci et al. 2005*)
- Full lane closures that significantly reduce risk to workers and reduce project duration (*FHWA 2003b*)

The examples described above are implemented by many DOTs to their full extent. However, as seen in Table 1.1 and Table 1.2 accidents still occur. There is a need for something different and more effective to fully protect construction and maintenance workers. In addition, the reactive nature of maintenance work and the short duration of its presence at any given location, make the implementation of some of the measures listed above expensive and impractical.

2.2 REGULATORY REQUIREMENTS, SPECIFICATIONS, AND STANDARDS

Specifications are an explicit set of requirements detailing an item by size, material, weight, product, and/or service. Standards are drawings approved for use by ODOT (and FHWA) showing pre-approved items required to be installed or implemented during highway construction operations. A Guideline document is a set of statements or examples, citing standards and specifications, to determine a course of action if specific scenarios are not covered by standards. The purpose of a Guideline document is to help streamline practice so actions are more predictable and presumably higher quality. Guidelines are not mandatory. State and Federal agencies provide specifications, standards, and guidelines to ensure the safety of motorists and workers. As part of the literature review, specifications, standards, and guidelines published by State of Oregon and national agencies were examined for content applicable to maintenance operations and the use of temporary mobile barriers. This section of the report describes the applicable regulatory requirements contained in any of those documents.

2.2.1 Manual on Uniform Traffic Control Devices (MUTCD)

The *Manual on Uniform Traffic Control Devices for Streets and Highways* (*FHWA 2009*) is recognized as the national standard for all traffic control devices installed on any street, highway, or bicycle trail open to public travel. Part 6 of the MUTCD discusses the design of temporary traffic control zones and the features included in the control zones. These guidelines address all types of traffic control design requirements including the individual control features and their location and use in work zones.

The MUTCD is directly related to this research study. Traffic control plans (TCPs) must be designed to meet the requirements of the MUTCD. ODOT develops TCPs for the highway construction and maintenance projects it undertakes. The intent of the TCP is to communicate required traffic control measures to the work crews and to control traffic in the work zone in an effort to ensure safe motorist travel through the work zone and a safe worksite for the workers. Discrepancies between a TCP and the MUTCD may negatively impact safety through the work zone.

The current version of the MUTCD does not contain specific provisions relating to the inclusion of an MBS in a temporary work zone. Illustrations for placement of an MBS in the worksite have been developed by the MBT-1® manufacturer, Mobile Barriers LLC, and can be viewed on the Mobile Barriers website (*Mobile Barriers 2009*). The manufacturer's illustrations have not been approved by FHWA, however, they typically do not approve individual placement documents. The illustrations are available to support DOT operators when using an MBS.

2.2.2 NCHRP Report 350: "Recommended Procedures for the Safety Performance Evaluation of Highway Features"

NCHRP Report 350 provides guidance for the evaluation and testing of roadside devices for use on the National Highway System (*NCHRP 2004*). FHWA policy requires that only crashworthy devices be used within the clear zone on all projects on the national highway system. "Crashworthy" means that the devices have met the test and evaluation criteria of Report 350 and/or have received a Letter of Acceptance from FHWA (*Artimovich 2004*).

Report 350 addresses four categories of devices: (1) Cones, barrels, delineators; (2) Barricades, sign stands; (3) Barriers, crash cushions, TMA; and (4) Trailer mounted devices. Mobile barriers are included within Category 3, which are subject to the full crash testing requirements of NCHRP Report 350 (*Artimovich 2004, Ross et al. 1993*).

According to NCHRP Report 350 (*Ross et al. 1993*), there are up to six levels of testing (TL-1 – TL-6) that can be selected to gain approval for using a device on the national highway system.

The higher test levels are applicable for evaluating features to be used on higher service level roadways or at locations that demand a special, high-performance safety feature. Test Level 1 (TL-1) is acceptable for some work zones and very low-volume, low-speed, local streets and highways. TL-2 is acceptable for most local and collector roads and many work zones. TL-3 is the basic level of testing for roadside devices and for which most crash-tested safety features in use on highways have been qualified. TL-3 is acceptable for a wide range of high-speed arterial highways. Test Levels 4-6 (TL-4 – TL-6) are applicable to longitudinal barriers only except under very unusual conditions, a temporary barrier would not normally be designed for impact conditions greater than TL-3. For TL-3, the device must withstand an impact by a 2,000 kg (4,410 lbs.) vehicle (pickup truck) traveling at 100 km/hour (62 mph) and striking the barrier at an angle of 25 degrees. In addition, the barrier must withstand a 20 degree hit with an 820 kg (1,810 lbs.) vehicle (small car) traveling at 100 km/hour (62 mph).

2.2.3 AASHTO Manual for Assessing Safety Hardware (MASH)

The AASHTO "Manual for Assessing Safety Hardware" (MASH) is used for crash testing safety hardware devices for use on the national highway system, and updates and replaces NCHRP 350 (*MASH 2013*). As of January 1, 2011, all new testing is conducted using the MASH evaluation techniques. Devices previously accepted under NCHRP Report 350 are appropriate for replacement and new installation; retesting is not required.

Under the MASH testing requirements, tests similar to NCHRP Report 350 TL-3 are conducted for temporary barriers similar to the mobile barrier. However, the test conditions are slightly different (*AASHTO 2013*). For the tests involving a small car, the device must withstand an impact by a 1,100 kg (2,420 lbs.) vehicle traveling at 100 km/hour (62 mph) at an angle of 25 degrees. For the tests involving a light truck, the device must withstand a 25 degree impact with a 2,270 kg (5,000 lbs.) vehicle traveling at 100 km/hour (62 mph). No increase in the 100 km/hour test speed was made for the MASH testing because crash data shows that, regardless of posted speeds, most impacts with fixed objects occurred at somewhat reduced speeds, likely due to pre-crash application of brakes (*MASH 2013*).

The Balsi Beam was tested under NCHRP Report 350, TL-2, whereas the MBT-1® was tested under NCHRP Report 350, TL-3 prior to MASH standards being implemented. In a letter dated June 5, 2008, FHWA approved the MBT-1®'s NCHRP Report 350, TL-3 test results as compliant with the then proposed MASH standards (*Nicol 2008*) and accepted the device for use on the national highway system.

2.2.4 2011 Oregon Temporary Traffic Control Handbook (OTTCH)

The *2011 Oregon Temporary Traffic Control Handbook* (*ODOT 2011b*) provides a reference describing the principles and standards for temporary traffic control zones in place continuously for three days or less on public roads in Oregon. The handbook is based on the principles set forth in Part 6 of the MUTCD published by the Federal Highway Administration (FHWA) and is an Oregon Supplement to the 2009 MUTCD. For work requiring devices in place longer than three days, a site specific traffic control plan based on the principles in Part 6 of the MUTCD is required.

The OTTCH presents extensive guidelines for how to provide temporary traffic control measures, including guidance on flagging and portable signals, signs, pavement markings, and other traffic control devices. Diagrams are provided to indicate how to apply the traffic control measures under specific work zone conditions.

The guidelines contained in this handbook provide guidance applicable to construction and maintenance work zones. Maintenance operations commonly do not extend beyond three days. Therefore, this handbook would be referenced for maintenance operations utilizing the MBS in Oregon. However, guidelines for use of an MBS, such as the MBT-1®, are currently not included in the OTTCH.

2.2.5 2011 Traffic Control Plans Design Manual (TCP Design Manual)

The *2011 Traffic Control Plans Design Manual* (*ODOT 2011c*) provides an organized collection of traffic control plan design standards, guidelines, policies, and procedures to apply in designs for Traffic Control Plan (TCP) Designers. Unlike the OTTCH, the TCP Design manual is for longer duration construction (greater than three days). The TCP Design Manual is intended to be utilized by ODOT TCP Designers, by members of City or County Public Works offices, and by private consulting engineering firms responsible for the development of temporary traffic control and highway construction staging plans. The TCP Design Manual is critical to ensuring consistent and high quality traffic control through work zones around the state.

The manual discusses traffic control plans design in general (job description, design processes, etc.) and the specific TCP design elements (traffic control devices, standard drawings, bid estimates, specifications, etc.). Accompanying the design manual are standard drawings for temporary traffic control. These drawings provide TCP Designers examples of traffic control drawings. The drawings are designed to help maintain consistency and quality of TCPs between projects. There currently are no guidelines for the inclusion of a mobile barrier such as the MBT-1® within the TCP Design Manual.

2.2.6 ODOT Sign Policy and Guidelines

The ODOT *Sign Policy and Guidelines* (*ODOT 2011d*) is a combination of State of Oregon Revised Statutes, Administrative Rules, Federal Highway Administration rules and guidelines, and engineering practice. Since the MUTCD has been adopted by ODOT as policy, the *Sign Policy and Guidelines* deal exclusively with items not included in the MUTCD or items that need further clarification as they are used on the state highway system. Chapter 6 of the guidelines addresses construction and maintenance signs. This chapter provides guidance on the size, layout, color, location, and other features of signs to be used in construction work zones. The maintenance crews are using these signs during maintenance activities. No content is currently provided in this document regarding the use of signs with respect to mobile barriers.

2.2.7 FHWA Standard Highway Signs Manual

The *Standard Highway Signs* manual (*FHWA 2004*) provides specifications for signs described in the MUTCD. The *Signs* manual is designed for use by all traffic authorities, agencies, jurisdictions, and persons involved in the fabrication, installation, and maintenance of traffic signs on streets and highways. The specifications for signs used to control traffic in construction work zones are provided in this FHWA manual. No content is currently provided in this manual regarding the use of signs with respect to mobile barriers.

2.2.8 OR-OSHA Construction Safety and Health Manual

The Oregon Occupational Safety and Health Division (OR-OSHA) publishes safety and health standards for employees. Division 3 of the standards applies specifically to the safety of workers on construction sites, including maintenance workers (*OR-OSHA 2011*).The purpose of the Division 3 rules is to prescribe minimum safety and health requirements for employees engaged in construction work, including demolition, blasting and use of explosives, and power transmission distribution and maintenance work. Within Division 3, standards are provided that cover safety and health measures applicable to all types of construction. No requirements are currently included in this manual that *specifically* address safety and health in highway construction work zones, or the use of mobile barriers. However, constructors involved in highway construction projects must abide by the requirements set forth in the OR-OSHA standards.

2.2.9 Guidelines for Portable Maintenance Barriers

Positive protection measures are becoming more common in highway maintenance and construction. FHWA has federal regulations on positive protection barriers (23 CFR 660.1102 to 630.1110). As a result, state DOTs are developing guidelines following FHWA's framework to facilitate and standardize their use. One set of guidelines was developed by the Colorado Department of Transportation (CDOT). Included in the CDOT guidelines are suggestions regarding when to use positive protection measures on projects and factors to consider when implementing these measures. The factors identified in the report are separated into three categories which are: Primary Factors, Special Factors, and Secondary Factors (*CDOT 2010*). The Primary Factors are the following:

- Clear Zone Distances,
- Roadside Geometry,
- Anticipated Traffic Volumes,
- Work Zone Speeds,
- Roadway Geometry, and
- Duration.

The following is the list of Special Factors included in the CDOT guidelines (*CDOT 2010*):

- Worker Safety,
- Pedestrian Safety,
- Separating Opposing Traffic, and
- Law Enforcement.

Lastly, CDOT lists the following Secondary Factors to consider (*CDOT 2010*):

- Crash History,
- Impacts on Project Cost and Duration,
- Impacts on Available Lane Width,
- Roadway Classification,
- Work Area Restrictions, and
- Bridge Construction.

The CDOT report concludes that there are great benefits in using positive protection measures in the appropriate situations where the measures can improve safety for the workers and motorists. The report also stresses that the guidelines should be used in conjunction with engineering judgment to determine the best use of these measures. Finally, the report also lists the MBT-1® as a positive protection device that can be implemented.

A similar report providing guidelines for positive protection was developed by the Texas Department of Transportation (TXDOT) (*Ullman et al. 2010*). The report aimed at developing guidelines that TXDOT can use in making better decisions regarding positive protection use in work zones. The report authors examined the national and statewide practices for positive protection use in work zones, and also implemented the Roadside Safety Analysis program (RSAP) to examine crash cost reduction potential for a portable concrete barrier. Regarding steel or mobile barrier technologies, such as the MBT-1®, the report authors concluded that the technologies are currently very expensive relative to the "intrusion crash cost reductions that are possible". They also added that such technologies would only be justifiable for "high volume" and "high speed facilities," where they are capable of recouping their initial high investment after several years (*Ullman et al. 2010*).

2.3 POSITIVE BARRIER SYSTEMS USED IN HIGHWAY CONSTRUCTION AND MAINTENANCE

Several commercial barrier systems are available that can provide protection to highway construction and maintenance workers from passing traffic, as well as protecting motorists from construction and maintenance hazards. The list of barrier systems included in this section provides brief descriptions of the barrier systems that are commonly used by DOTs.

Barrier systems can be separated into two categories: systems for long term construction/maintenance projects, and systems for short term construction/maintenance projects. The distinction between the two categories of systems is made based on the ease of mobility of each available system. Unless otherwise indicated, the barrier systems discussed here have been approved for highway use and passed the criteria set forth in the National Cooperative Highway Research Program (NCHRP) Report 350 and/or AASHTO MASH requirements which provides guidelines and recommended procedures for evaluating safety performance of highway features (*NCHRP 1993, AASHTO 2013*).

2.3.1 Positive Barrier Systems for Long-term Construction/Maintenance

This section describes positive barrier systems which are put in place for long-term construction operations. Long-term operations are considered to be those in which the work zone is kept in place for more than one or two days at a time. Short-term operations consist of nightly maintenance work and construction work in which the duration of road closure is no more than one or two days (crew shifts). Positive barrier systems are not typically utilized for short-term maintenance tasks; however they may be employed for shorter duration tasks in some instances. FHWA categorizes and maintains a list of movable longitudinal barriers which it has found to be crashworthy and eligible for use on the highway system. Longitudinal barriers are those able to be installed in parallel, or lengthwise, with traffic. Since these are not permanent barriers, they are described in the research as “movable” barriers. This term was chosen since the barriers can be transported from one location to another, but due to logistical issues, they lack the ability to be implemented for short periods of time. A short period of time is defined as one or two crew shifts. It is important to note that one type of “movable” barrier is a “mobile” barrier, denoting its ability to accommodate shorter period deployments. Mobile barriers are described in Section 2.3.2.3 of this report.

2.3.1.1 Quickchange® Moveable Barrier System (QMBS)

The *Quickchange Moveable Barrier System* (QMBS) is produced by Barrier Systems, a company located in Rio Vista, California. The QMBS consists of a specialized vehicle, the Barrier Transfer Machine (BTM), which is used to transfer concrete or steel road barrier blocks from one side of the road lane to the other side. This process allows for efficiently opening or closing a lane to traffic. The blocks are interlocked and create a safe barrier through a Reactive Tension System (RTS) (*Barrier Systems 2008*).

The blocks within the concrete block system (CRTS) have a width of 18 inches and length of 39 inches. According to the manufacturer, the CRTS is preferred where low deflections are required when a vehicle collides with the barrier. The blocks within the steel block system (SRTS) have the same length as the concrete blocks, but their width is only 13 inches. The SRTS is ideal for locations that have reduced lane widths and require low deflections in the case of an impact (*Barrier Systems 2008*).

According to the manufacturer, the BTM can transfer the blocks at a traveling speed of 10 mph. The system can be used in permanent and construction applications, on highways with high traffic volume, and at locations where right-of-way is not available. Figure 2.1 shows a picture of a QBMS at work on a construction site. The picture was obtained from the Barrier Systems website (*Barrier Systems 2008*).

Figure 2.1: QMBS in Operation on a Construction Project (*Barrier Systems 2008*)

2.3.1.2 Triton TL-2 & TL-3 Barriers

The Triton TL-2 Barrier system is a water-filled positive protection system that is manufactured by Energy Absorption Systems, Inc. in Chicago, Illinois. This barrier system consists of interlocking 78-inchlong polyethylene sections supported by an internal steel frame. The height of each section is 32inches, and their width is 21 inches (*EAS 2012a*, *2012b*).

The Triton system manufacturer claims that 600 feet of the system can be deployed in under one hour by three workers. This high productivity rate is due to the low weight of each section, approximately 140 lbs. when not filled with water. Water-filled sections have a weight of 1,350lbs, and have a capacity of 145 gallons. A picture of the system, obtained from the manufacturer's website, is shown in Figure 2.2 (*EAS 2012a*, *2012b*).

The Triton TL-3 is similar to the TL-2, with the difference being that the TL-3 sections are supported by pedestals (*EAS 2012a*, *2012b*).

Figure 2.2: Triton TL-2 Barrier (*EAS 2012a*)

2.3.1.3 Vulcan Barrier

The Vulcan Barrier is also manufactured by Energy Absorption Systems, Inc. This barrier system consists of portable steel longitudinal sections that are pinned to each other to create a continuous barrier. Each section has a length of 13.5 feet, height of 32 inches, and width of 21.5 inches. The weight of each section is 871 lbs. (*EAS 2012c*). Due to the weight of the sections, their installation requires a forklift, crane, or other type of hoisting equipment to be available at the worksite. A picture of the barrier is shown in Figure 2.3. The image was obtained from the manufacturer's website (*EAS 2012c*).

Figure 2.3: Vulcan Barrier (*EAS 2012c*)

2.3.1.4 Armor Guard Barrier

The Armor Guard Barrier system is produced by Barrier Systems and is comparable to the Vulcan Barrier produced by Energy Absorption Systems, Inc. The Armor Guard Barrier also consists of steel sections. Each steel section has a length of 28 feet, height of 32 inches, and width of 28 inches. Each segment weighs 3,700 lbs., and their installation also requires a forklift, crane, or other hoisting equipment. A picture of the Armor Guard System, obtained from the manufacturer's website, is shown in Figure 2.4.

Figure 2.4: Armor Guard Barrier (*Barrier System 2008*)

2.3.2 Positive Barrier Systems for Short-term Construction/Maintenance

The systems discussed in the previous section requires more time to be installed than mobile barriers and are not suitable for maintenance operations where there are short-term time constraints. For short-term construction/maintenance operations the systems discussed in this section provide more desirable alternatives. As mentioned previously, these positive protection systems are referred to in this research study as "mobile" barriers. Mobile barriers have the ability to be transported, or travel on their own, from one work location to another in short periods of time, without excessive logistical effort.

2.3.2.1 Historical Mobile Positive Protection Barriers

According to literature there have been attempts to create highly mobile positive barriers in the past. Two types of such systems are on record and both were developed by the Texas Transportation Institute (TTI) for the Texas Department of Transportation (TXDOT). Their use, however, never went beyond the initial trials (*Jewell and Caldwell 2008*).

The first system that was developed consisted of a series of station wagons connected together with a system of tow bars as shown on Figure 2.5. A thrie beam was attached to the vehicles and provided a continuous smooth surface preventing impacting vehicles from snagging on the barrier. The leading car was the only one maintained in operating condition and it was used to tow the other 4 vehicles in the assembly. The assembly had a turning radius about double that of a normal vehicle, and its total length was 100 feet (*Sicking et al. 1982*).

Figure 2.5: TTI Portable Traffic Barrier (*Jewell and Caldwell 2008*)

Two crash-tests were conducted on the assembly using a vehicle weighing 4,500 lbs. and with impact angles of 7 and 15 degrees resulting to deformations of 2.5 inches and 8.4 inches, respectively. In both cases there was minor damage on the thrie beam, but the barrier was driven from the test site without need of repair (*Sicking et al. 1982*).

The second system that was developed was a “Truck-mounted Portable Maintenance Barrier” which consisted of a steel barrier section carried from both ends by two trucks as shown in Figure 2.6. This barrier was developed for use in short-term maintenance operations that last less than a day, and provided positive protection to workers from in-lane impacts and lateral impacts at the same time. In contrast to the previous system, this barrier did not require the use of an additional lane to create the “Ring of Steel” to protect workers during maintenance operations (*Beason 1985*).

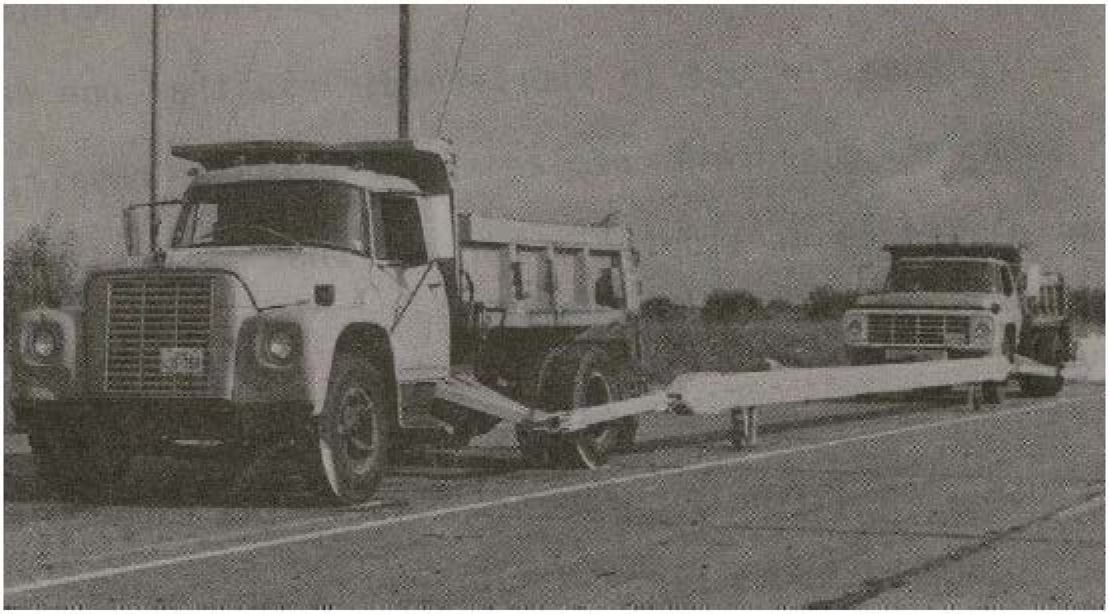

Figure 2.6: Truck-Mounted Portable Maintenance Barrier (*Jewell and Caldwell 2008*)

The prototype that was developed used two 5.0 cubic-yards dump trucks with an additional frame installed to increase their in-plane stiffness in order to withstand impacts without damage. The steel barrier was carried by the front truck, and was hitched to the back truck when it was used in the field. When the system needed to be moved, a detachable transport dolly was used (*Beason1985*).

The barrier was designed to redirect a 4,500 lbs. vehicle traveling at a speed of 50 mph with an impact angle of 15 degrees. Three full-scale crash tests were conducted on the barrier, and in all three tests the barrier sustained permanent deformation ranging from 1.5 to 3 inches. The tests were conducted on only one barrier with no intermediate repairs or strengthening between tests (*Beason 1985*).

2.3.2.2 Balsi Beam

The Balsi Beam is named after Mark Balsi, a CalTrans maintenance employee who was injured in January 2001 when a motorist crashed into a work zone where he and other workers were collecting trash along the I-280 highway in Santa Clara County, CA. As a result of the accident, the CalTrans Division Chief of Maintenance ordered a research project to solve the problem of errant vehicles entering work zones. The CalTrans Division of Equipment was assigned with the design and fabrication of a system that would protect workers from lateral impacts. They named their design the Balsi Beam in honor of Mark Balsi (*Caltrans DRI 2007*).The Balsi Beam was developed, patented, and internally tested by CalTrans.

As shown in Figure 2.7, a Balsi Beam trailer system consists of a semi-truck tractor and a trailer. The trailer has two telescoping expandable steel beams along each side of the trailer that rotate to provide a stackable two beam protection barrier on either side of the trailer. The beams can be rotated to either side depending on the location of the work that needs to be performed. Approximately 20-30 feet of work space is available behind the beams. The first working prototype of the Balsi Beam was completed in 2003 and the trailer passed the NCHRP Report 350 test, Level 2 (*Caltrans DRI 2007, Caldwell 2008*).

Figure 2.7: Balsi Beam Mobile Barrier (*www.dot.ca.gov*)

2.3.2.3 Mobile BarriersMBT-1®

The MBT-1® is a mobile positive protection system that is a patented product manufactured by Mobile Barriers, LLC, in Golden, Colorado. The MBT-1® consists of an “integrated, rigid wall, semi-trailer” pulled by an ordinary semi-tractor to provide protection in a variety of settings such as highway construction, maintenance, and security. The wall is approximately five feet tall and helps to provide both a physical and visual barrier. Due to its rigid steel wall, the MBT-1® can eliminate work zone incursions from passing traffic (*MobileBarriers 2010*).The MBT-1® was tested and passed the NCHRP Report 350 TL-2 and TL-3 requirements, and is approved by FHWA for use on the national highway system (*Nicol, 2008*).

In addition to protection of the workers, the trailer can provide worksites with a variety of amenities. Such amenities include light sources, storage containers, integrated power, and a truck mounted attenuator (*Mobile Barriers 2010*). The presence of these amenities reduces the number of collateral vehicles that need to be mobilized and located in the work area and provides the amenities in close proximity to the workers.

The length of the MBT-1® trailer can be modified in the field. Starting from the two wheeled platforms and a length of about 40 feet, the trailer can be expanded to a maximum length of 100 feet by adding three 20-foot wall sections. The trailer can be towed from either end, allowing it to be used for protection on either side (*Mobile*

Barriers 2010). A picture of the MBT-1® at the ODOT laydown yard is shown in Figure 2.8.

Figure 2.8: MBT-1®® at the ODOT Laydown Site

2.4 CURRENT ODOT MAINTENANCE PRACTICES

Similar to other organizations, ODOT has a command structure to facilitate and expedite operations and activities taking place within the state. Within that command structure, maintenance activities are carried out by various individuals at the Region and District levels. This section of the report identifies these Regions, Districts, individuals, their roles, and the types of actions they undertake. In addition, this section discusses the activities maintenance crews undertake within the state and the equipment they have at their disposal to complete their tasks. This information is included in the report in order to understand current ODOT maintenance practices as a starting point for making recommendations for integrating an MBS within the practices.

2.4.1 ODOT Maintenance Program and Structure

(Note: This section of the report does not reflect the recent organization and personnel changes in the ODOT structure that took place in summer 2011).

Maintenance for State of Oregon roadways falls under the jurisdiction of multiple entities within ODOT. These entities are: a) Office of Maintenance and Operations – State Maintenance Engineer, b) Region Managers, c) Region Maintenance and Operations Managers, d) District Managers, and e) Transportation Maintenance Manager. An organizational chart of all of the entities that participate in maintenance operations decisions and support is shown in entities that participate in maintenance operations decisions and support is shown in Figure 2.9. Descriptions of all of the entities depicted and their corresponding duties are provided below.

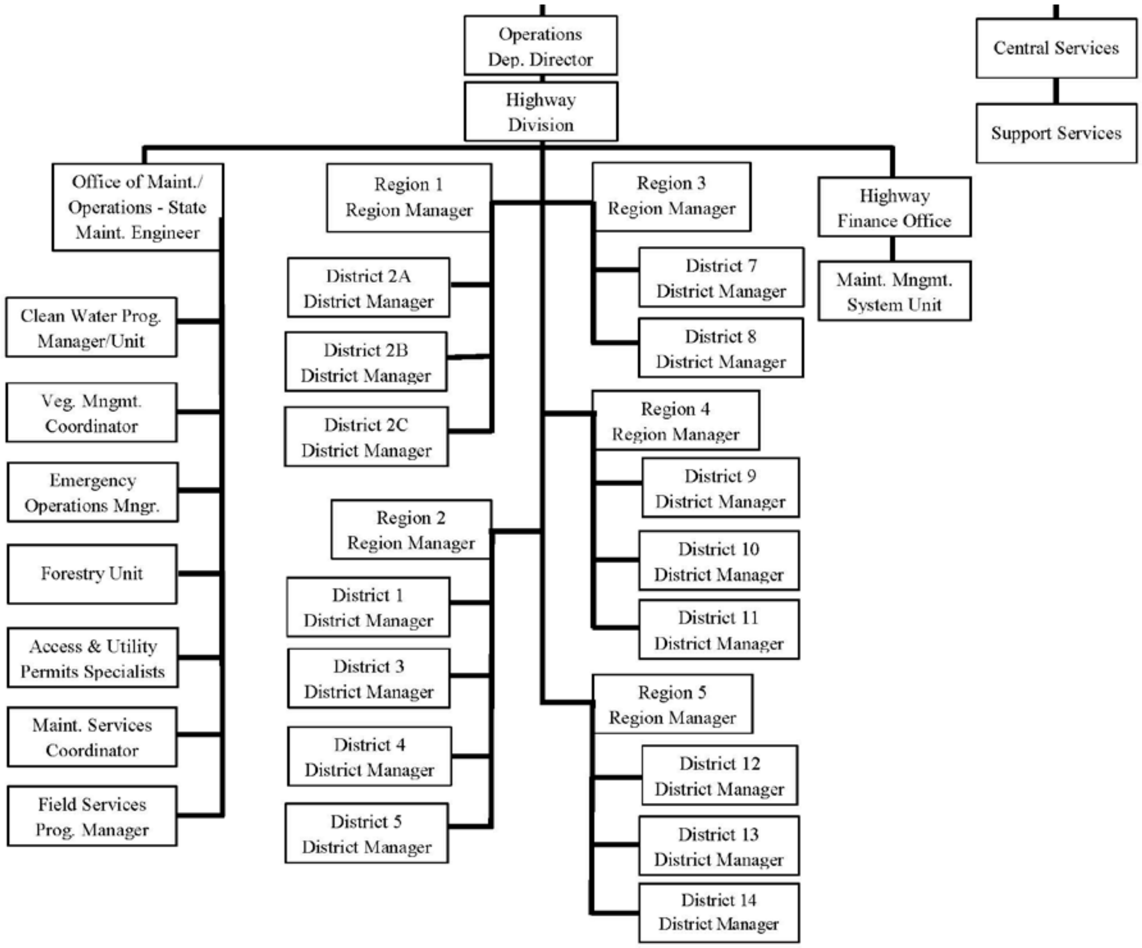

Figure 2.9: ODOT Organizational Chart for Maintenance Activities

2.4.1.1 Office of Maintenance and Operations – State Maintenance Engineer

The Office of Maintenance and Operations is responsible for policy and staff-level functions related to the State's maintenance program. These responsibilities include (*ODOT 2004*):

- Assurance that ODOT maintains and operates the State Highway System uniformly
- Development of appropriate policies and procedures to maintain the State Highway System
- Development and assurance of overall implementation of maintenance and performance budgets
- Provision for staff level support of the maintenance program
- Promotion of the efficient administration of the maintenance program
- Update of the maintenance district map

The staff in the Office of Maintenance specializes in activities in the following subject areas (*ODOT 2004*):

- Access and Utility Permits – The Office of Maintenance provides guidance, advice, and administrative support for obtaining permits for right-of-way and utility work. The Office also provides guidance and advice to district managers for insurance and bond needs, helps in interpretation of the permits for banking responsibilities for fees or payments for permits.

- Clean Water Program – The Office of Maintenance provides to district managers: 1) guidance, advice, and assistance for erosion control sedimentation and pollutants/contaminants resulting from maintenance activities, 2) guidance and advice in developing and implementing an Integrated Vegetation Management plan, and 3) guidance and expertise regarding management and maintenance of trees and timber resources.

- Emergency Response Program – The Office of Maintenance, through the Emergency Operations Manager, provides guidance, advice, and assistance to the district managers on: 1) emergency response, 2) incidence response and management, 3) the emergency highway traffic regulation plan, and iv) the FHWA emergency relief program for federal highways.

- Field Services Program – Through the Field Services Program Manager, the Office of Maintenance: 1) provides assistance to the state maintenance engineer in coordinating ODOT activities related to needs and requests of the Legislature, 2) provides support for maintenance personnel performing signing, traffic line, or legend work in the form of training, acquiring materials/equipment, etc., and 3) develops, provides, and facilitates training for maintenance personnel as needed.

- Maintenance Services Program – Through the Maintenance Services Coordinator, the Maintenance Office assists in developing, interpreting, and applying laws, rules, and policies for highway maintenance activities.

2.4.1.2 Maintenance Management System Unit

The Maintenance Management System Unit of the ODOT Highway Finance Office assists the Office of Maintenance, the Region Managers, and the District Managers in the following functions (*ODOT 2004*):

- Preparing the annual performance budget for maintenance activities

- Recording and reporting costs and accomplishments of the maintenance program

- Maintaining the features and stockpile inventory programs

2.4.1.3 Support Services Branch

The Support Services Branch assists the Office of Maintenance and Operations, the Region Managers, and the District Managers through the following (*ODOT 2004*):

- Business Services –provides management of ODOT information through a variety of services
- Facilities Management – manages all ODOT-owned and occupied buildings and properties
- Fleet Services – manages ODOT's fleet of equipment
- Purchasing and Contract Management – provides purchasing services

2.4.1.4 Regions and Region Managers

ODOT is separated into five distinct regions located across Oregon. These regions are shown in Figure 2.10. The Portland Metro Area makes up Region 1. Region 2 is located in the northwestern portion of the state. The southwestern portion of the state makes up Region 3.Central Oregon makes up Region 4, and Region 5 contains all of eastern Oregon.

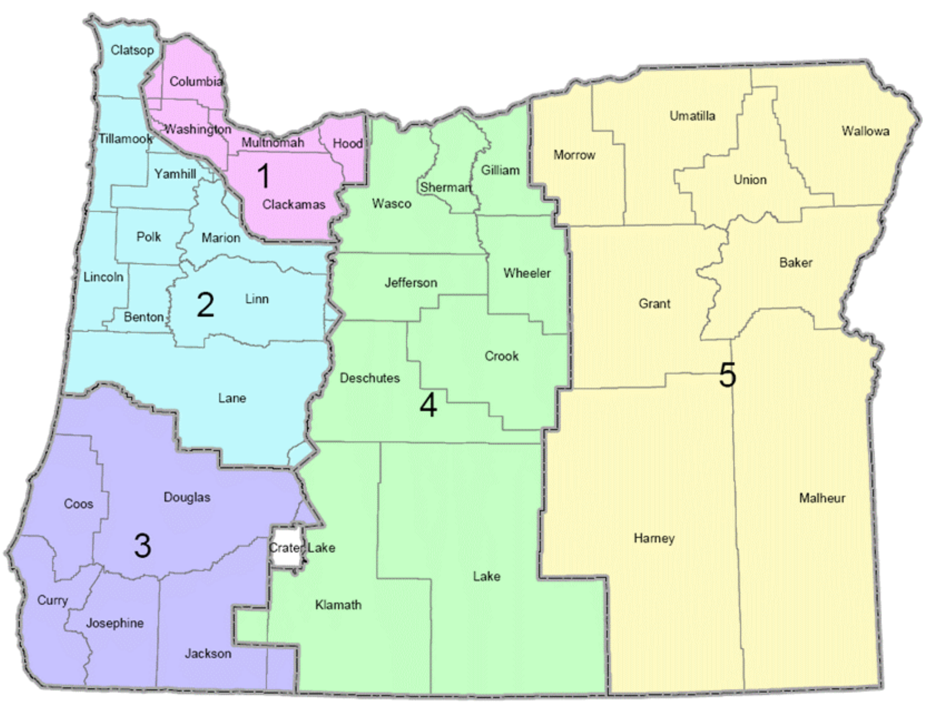

Figure 2.10: Regional Map of Oregon

Each region has a Region Manager who is responsible for all ODOT work performed under their managed area. The responsibilities of the Region Managers in regards to maintenance include the following (*ODOT 2004*):

- Assigning personnel to perform the maintenance activities in their region, according to the needs of the maintenance program
- Providing guidance, assistance, and advice to the District Managers in their Region
- Provide administrative support and guidance for the Maintenance Program in the form of safety, training, and purchasing
- Coordinating the parties involved in their Region in project delivery of maintenance activities
- Assuring that the necessary resources are available for ODOT Emergency Operations Plan needs

2.4.1.5 Districts and District Managers

Prior to August of 2011, ODOT separated Oregon in 15 districts, shown in Figure 2.11.The Districts are allocated to the Regions in which they preside and handle primarily maintenance operations. Districts 2A, 2B, and 2C constitute Region 1. Districts 1, 3, 4, and 5 make up Region 2. Region 3 consists of Districts 7 and 8. Districts 9, 10, and 11 constitute Region 4, and Districts 12, 13, and 14 constitute Region 5.

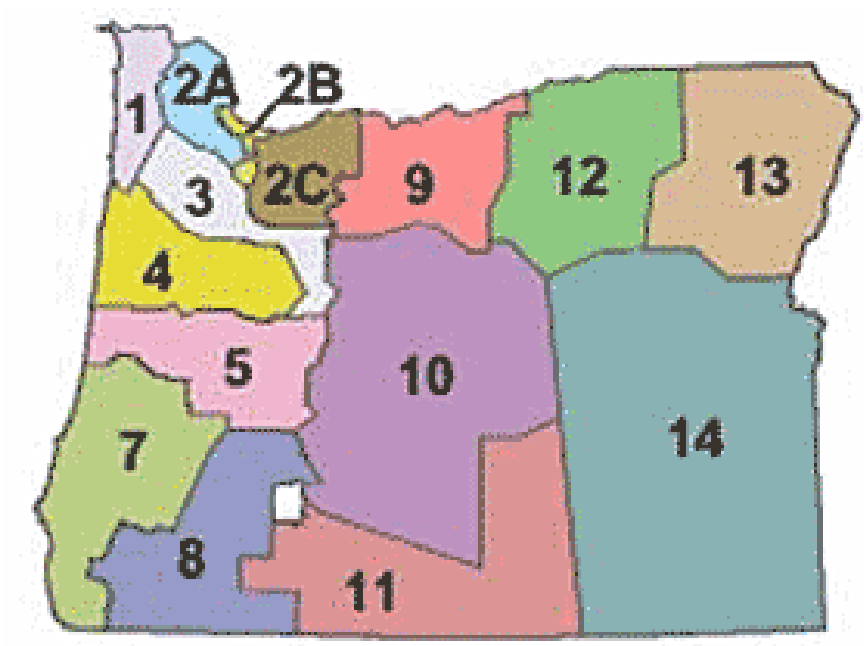

Figure 2.11: District Map of Oregon (prior to August 2011)

As of August 2011, restructuring of the districts resulted in the removal of District 2A.Other districts, namely Districts 1 and 2B, have expanded to cover maintenance control of the area formerly belonging to District 2A as shown in Figure 2.12.

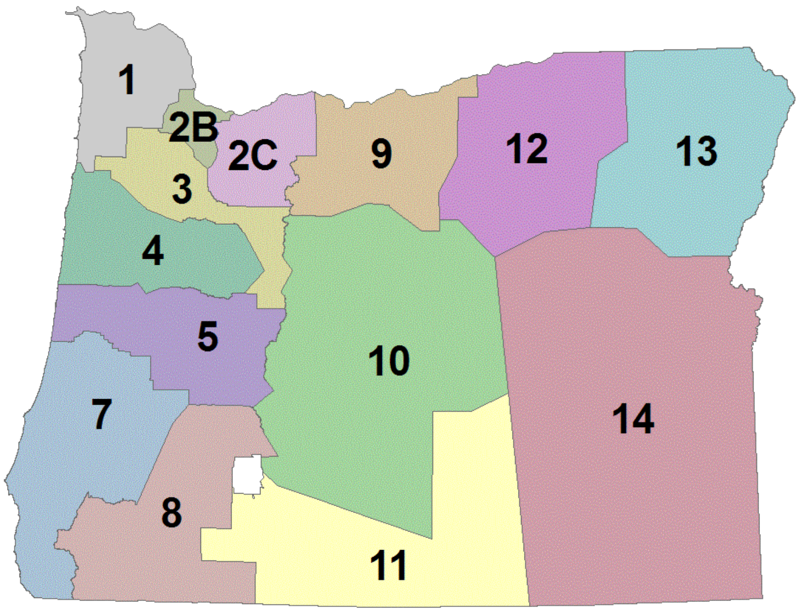

Figure 2.12: District Map of Oregon (after August 2011)

Each district has a District Manager who is responsible for the performance of all activities in the district, including maintenance operations. The duties of the District Manager include the following (*ODOT 2004*):

- Organize all of the individuals in the District who are involved in implementing the Maintenance Program
- Develop an annual performance budget for the District identifying maintenance activities to maintain the level of service of the roads in their jurisdiction.
- Acquire and assign equipment, resources, and personnel to accomplish the maintenance program operations
- Assure that the budget for the District is not exceeded
- Provide mentoring, guidance, and assistance to each Transportation Manager in the District
- Assure that the necessary training is provided for all employees in the District
- Maintain emergency contact lists for all employees in the District
- Review serious fatal crashes with the Region Traffic Engineer to determine if highway conditions were the cause

Within each district, several other personnel have responsibilities for road maintenance. These include the Transportation Maintenance Managers and the Transportation Maintenance Coordinators. The Transportation Maintenance Managers are responsible for the daily operations of the District for matters regarding maintenance, and assist the District Managers in their duties. The Transportation Maintenance Coordinators assist the Transportation Maintenance Managers in their duties, and are also involved in the daily maintenance operation in their district (*ODOT 2004*).

2.4.2 Maintenance Activities

Maintenance crews participate in a number of activities that vary greatly in type of work performed, duration, crew composition, and equipment used. According to the Oregon Department of Transportation Maintenance Guide (*ODOT 2004*), the activities that the maintenance crews participate in are divided into 11 distinct categories. These are:

1. Surface – minor and major road surface repair, deep base repair, pavement sealing, concrete repair and crack sealing

2. Shoulder – shoulder rebuilding/blading and erosion repair, and sweeping/flushing

3. Drainage – ditch cleaning and reshaping, culvert and inlet cleaning/repair, channel maintenance, water quality facilities, and horizontal/vertical drains

4. Roadside and Vegetation – mowing, spraying, brush mowing/cutting, litter pickup, and landscape maintenance

5. Traffic Services – stripping, pavement legend marking, sign installation and maintenance, traffic signal/illumination/flasher/beacon/delineator/attenuatormaintenance, accident cleanup and repair, guardrail/barrier maintenance/repair

6. Structures – bridge maintenance/repair, structure painting, drawbridge operations, and graffiti removal

7. Snow and Ice – snow removal, sanding, winter road patrol, anti-icing, and de-icing

8. Extraordinary Maintenance – emergency maintenance, slide and rock fall, sinks and settlements

9. Other Direct Maintenance – snow-pack maintenance, road patrol, contract maintenance

10. Non-Direct – agreements, training, etc.

11. Operations and Other Special Programs – miscellaneous permits, locate facilities, roadside cameras/weather stations, etc.

A more detailed list of the categories is provided in Appendix A.

2.4.2.1 Use of Mobile Barrier on ODOT Maintenance Activities

In discussions with ODOT Maintenance Managers, the maintenance activities in which the managers perceive that the MBT-1® would be most applicable are in the following categories: Surface, Drainage, Traffic Services, and Structures. The identified activities are summarized in Table 2.1.When asked about the amount of time, equipment, and personnel needed for each activity, ODOT managers reported that the type of work they perform is "highly reactionary", and that the amount of equipment and personnel needed differs depending on the level of repair or work needed. Additional study results providing information about the extent to which each maintenance activity is undertaken by ODOT and an analysis of the extent to which the MBT-1® might be utilized are provided later in this report.

Table 2.1: Anticipated ODOT Activities for MBT-1® Implementation

Category	Activity
Surface	Minor/Major Surface Repair Deep Base Repair Concrete Repair Crack Sealing
Drainage	Minor Culvert and Inlet Cleaning Minor Culvert and Inlet Repair
Traffic Services	Pavement Legend Marking Major/Minor Sign Installation Maintenance Traffic Signal Maintenance Illumination Maintenance Flasher/Beacon Maintenance Guardrail/Barrier Maintenance/Repair/Clean Attenuator Maintenance
Structures	Bridge Maintenance Bridge Repair Structure Painting

An analysis of the typical amount of annual expenditures for each activity listed in Table 2.1 is provided in Section 4.7 of this report. The benefit of the MBT-1® to ODOT will be greater if the activities for which the MBT-1® is particularly suited are activities which ODOT undertakes to a great extent. An analysis of the annual amount of expenditures for each activity, provided in the Analysis section of this report, will allow for making such an evaluation.

2.4.3 Road Construction Safety Equipment used by ODOT

In addition to the traditional equipment and tools that are available and required by the rules and guidelines discussed in Section 2.2 of this report, ODOT currently owns and operates a Quickchange Moveable Barrier System that uses Concrete Reactive Tension System (CRTS) blocks. The system was purchased about 10 years ago, and has been successfully used on a number of ODOT construction projects in the Portland area. A brief description of a CRTS system is provided above in Section 2.3.1.1 of this report.

2.5 CURRENT PRACTICES OF STATE AGENCIES

As part of the review of current practice, the research also aimed to determine the types of barrier systems currently used by other state DOTs across the country. To do so, an on-line survey was prepared and conducted from September to November 2011 (See Appendix B). The survey form asked questions on the following topics:

- The types of barrier systems, including mobile barriers, utilized by the DOTs for maintenance and construction work zones. A list of common types of barrier systems was provided from which the respondents could select those which they use. The aim of this question was to identify which agencies use the various types of MBS, including the MBT-1® and the Balsi beam.

- The current experiences with the MBT-1® Agencies that responded that they use the MBT-1® were asked to comment on the impacts of the MBT-1® on work zone safety, worker productivity, and worker supervision. In addition, respondents were asked to identify on which types of projects the MBT-1® is typically used, as well as comment on what worksite features (physical geometry, weather conditions, type of work, etc.) limit or enhance the use of the MBT-1®.

- The current experiences with the Balsi Beam. The questions asked about the Balsi Beam were the same as those asked regarding the MBT-1®

A copy of the survey form is provided in Appendix B. The survey was distributed by the ODOT Research Office using the AASHTO Research Advisory Committee listserv which includes all 50 state DOTs, Canadian Provinces, and Washington DC DOT. Participation in the survey was voluntary. DOT employees from 17 states, shown in Figure 2.13, and the Canadian province of Saskatchewan, responded to the survey.

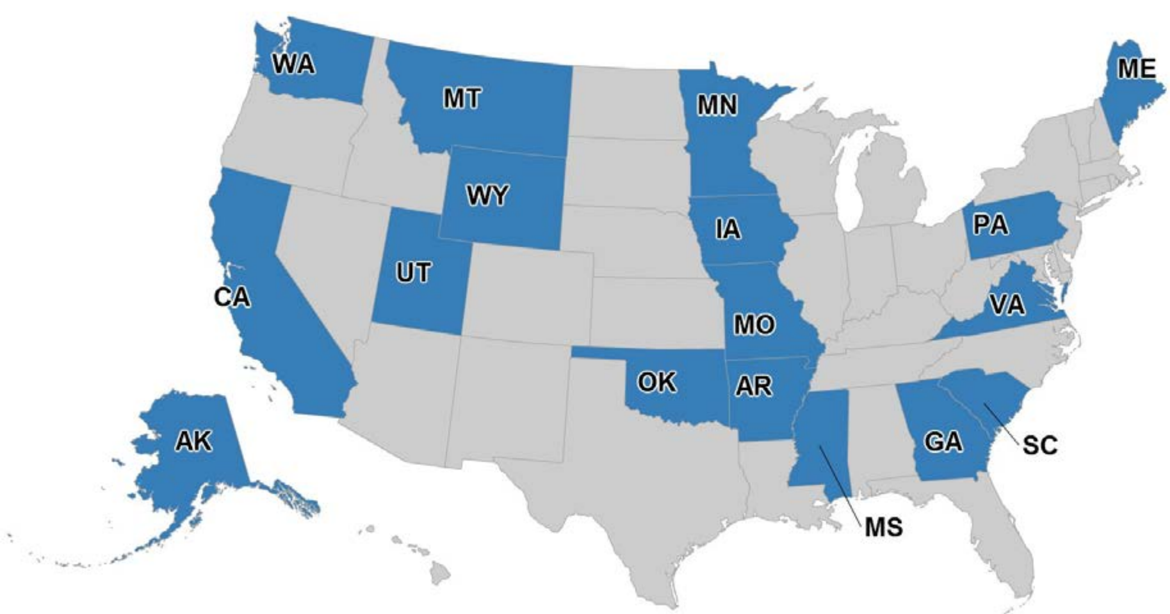

Figure 2.13: Map of State DOTs that Responded to Survey

The types of barriers used by the various state DOTs differ across the country, and a summary of the results is provided in Table 2.2. As observed in the table, only one state (California) is using the Balsi Beam, while the MBT-1® is not used in any of the 17 states that responded. However, as described later in the report, further contact with state agencies confirmed that MBT-1®s were purchased and are currently used in four states and a Canadian Province. Water filled barriers are widely used, while other barriers such as Barrier Guard, CRTS, SRTS, and K-Rail, are also used to a lesser extent.

Table 2.2: Survey Responses – Barrier Types Used by US state DOT's

Use the barrier system?	Balsi Beam	MBT-1®	Armor Guard	Barrier Guard	Vulcan Barrier	CRTS	SRTS	K-Rail	Water Filled
Yes	1	0	0	1	0	2	1	5	9
Uncertain	2	3	3	4	4	3	4	4	2
No	13	12	12	10	11	10	9	4	4
Total	16	15	15	15	15	15	14	13	15

The results of this survey cannot be generalized for the whole country since the response to this survey was entirely voluntary and the response rate was relatively low (17 out of 50 states, and 1 out of the 13 Canadian Provinces and Territories). In addition, as observed by the large percentage of "Uncertain" responses, the participants in the survey were to a great extent unaware of the barriers used in their own states/provinces/territories.

The participant from California did not provide any additional information regarding the use of the Balsi Beam by the state.

2.5.1 Follow-up Survey of Current Practices of State Agencies

The previously discussed survey did not provide any additional information regarding the use of the Balsi Beam and the MBT-1® in other states. For that reason the researchers decided to contact MBT-1® users directly in the states and transportation agencies which were known to have one or more MBT-1®. Through the MBT-1® manufacturer's website (*Mobile Barriers 2012*), input from Mobile Barriers, LLC (*Stockton 2011*), and through an internet search using keywords "mobile" and "barrier" on www.google.com, the researchers identified MBT-1®'s in use and current users of MBT-1®'s in the US and Canada. Specifically MBT-1® mobile barriers are present in the following US states and Canadian provinces:

- Colorado: Colorado DOT operates three MBT-1®s.
- Texas: MBT-1®s are operated in Texas by the North Texas Tollway Authority (NTTA). NTTA owns and operates three MBT-1®s for its maintenance and construction operations.
- New York/New Jersey: There are three MBT-1®s in the NY/NJ area. The MBT-1® trailers are owned by a private company, Impact Absorption, which leases the barriers to contractors in the area.

- Oregon: In Oregon, one MBT-1® was purchased by ODOT and it is the subject of this research study.

- Ontario: Three MBT-1®s are located in Toronto. The MBT-1® trailers are owned by a private company, Powell Mobile Barriers, which leases the barriers to contractors in Ontario.

Attempts were made to contact personnel in the various locations where the MBT-1® are operating. The researchers contacted the personnel via the telephone to conduct an interview using the same survey questions asked as part of the State DOT on-line survey described above. The intent of the interviews was to identify the types of MBT-1® barriers used in the other states and their effects on safety, supervision of work, and productivity. Those contacted and interviewed were personnel involved in the deployment and operation of the MBT-1® in each agency/organization. A total of three interviews were conducted. A summary of the responses from those contacted and interviewed is provided below:

- Types of work activities: The MBT-1® is used by the agencies in a variety of work activities. Some of the work activities that were mentioned by the contacted agencies included:
    - Pot hole filling
    - Overnight slab replacement
    - Light bulb changes on highways
    - Joint seal replacements
    - Work required on medians
    - Bridge rehabilitation
    - Culvert replacements
    - Guard rail replacement
    - Pavement distress surveys

- Work zone safety: The researchers asked MBT-1® users to describe the effects of the MBT-1® on worker safety. Those interviewed mentioned that the barriers have a positive impact on safety, while at the same time traffic flows at normal speeds next to the workers. The interviewees also stated that their workers felt comfortable working behind the barrier without having to always be “looking over their shoulders”.

- Worker productivity: Regarding productivity, one of the agency representatives stated that even though there has not been an official study on productivity relative to the use of the barrier, workers are able to focus more on their work, suggesting increased productivity among the work crews. Another agency representative stated that productivity for their crews increased since the MBT-1® allowed them to be more flexible, and the agency has managed to complete more work in the time allocated for their projects. The interviewees also stated that the MBT-1® allowed them to save time in the implementation of the Traffic Control Plans.

- Worker supervision: When asked to comment on the ability to supervise the work crews, the agency representatives indicated that there was no impact, positive or negative.

- Limitations to work: The users of the MBT-1® mentioned some limitations experienced when using the MBT-1®. One limitation, given the barrier's long length, was the need to have additional access to the worksite, especially when more than one additional wall section is used on the trailer. Also "off-tracking" requirements (the efforts required to situate the MBT-1® at the desired location) can be inhibited by the work area, especially if the work area is small or crowded. Additionally, in some locations special permissions need to be obtained to move the trailer on public roadways with additional sections due to its long length. The increased length of the trailer also creates access issues at some on and off ramps, requiring police presence for its transportation.

- Enhancements to work: The users of the MBT-1® stated that the barrier works great for guardrail repair. Those interviewed also stated that the additional features present on the trailer, such as generators and additional lights, are beneficial for their crews.

2.5.2 Research Reports on MBT-1®

2.5.2.1 Evaluation of MBT-1® Deployment and Use in New Jersey

The deployment of an MBT-1® was evaluated in a study conducted for the New Jersey Department of Transportation (NJDOT) by researchers from the City College of New York and the New Jersey Institute of Technology (*Kamga and Washington 2009*). The researchers made recommendations regarding the maintenance of the MBT-1®, its functionality and safety, the design components, and the issues that arise when the MBT-1® is deployed at a work zone. The findings of the study are summarized below:

- Maintenance: The researchers suggested that maintenance of the MBT-1® can be improved by allowing adequate drainage from its platform to the area over the tires. The placement of the drainage holes over the cargo area and the mechanical connections increases the need of maintenance of those areas.

- Functionality: The researchers were skeptical about the ability of the MBT-1® to be transported with all three 20-foot sections installed. With all three sections, the total length of the barrier and cab is approximately 120 feet. The researchers admitted that the capability was not tested, but they made the claim from assessing the opinions of drivers and NJDOT personnel. The study included testing the MBT-1® with two 20-foot long wall sections, from which the researchers concluded that it was still difficult to maneuver, especially at turns and intersections. The researchers recommended the installation of a transverse beam assembly in the rear at the caboose for improved maneuverability (note: Mobile Barriers, LLC has now made this option available when purchasing a new MBT-1®).

- Safety: The researchers recommended the installation of additional lighting on the rear and sides of the trailer for ease in “backing-up” the long trailer in the dark. They also recommended providing escort vehicles when transporting the MBT-1® to help the safe transportation of the trailer to and from work zones.

- Design and components: The researchers recommended that future MBT-1® owners order the trailers with all of the additional functionalities available for the vehicle (integrated power, speed radar, message/arrow board, safety lighting, work lighting, storage and supply areas, etc.) in order to reduce the number of secondary and support vehicles that need to be transported to the work site.

- Work zone issues: The researchers hypothesized that some maintenance activities can possibly encroach into the adjacent travel lane when the MBT-1® is used. They suggest that the trailer be deployed in areas where there is enough space to allow access to materials and equipment by workers. The researchers also commented that the use of the MBT-1® should not be a problem on multi-lane highways, nor on roads with wide shoulders.

The researchers also made some general conclusions regarding the MBT-1® (*Kamga and Washington 2009*). They concluded that the deployment of the trailer requires a substantial amount of planning because of the need to pre-assemble the barrier into the desired length off-site. Inserting or removing sections requires additional space, and can take a substantial amount of time (2-3 hours). The needed space is typically not available at the work zones, and the time required often conflicts with the short duration of the work period. The researchers also concluded that the best application of the MBT-1® is at straight road sections, and that the trailer should not be placed on ramps, clover leafs, and intersections.

2.5.2.2 Work Site Illumination using the MBT-1®

As discussed previously, the MBT-1® is designed to facilitate roadway construction under a variety of road and weather conditions, including nighttime work. In a recent study conducted at the University of Colorado at Boulder (*Hallowell et al. 2010*), the worksite lighting capabilities of the MBT-1® were evaluated. Specifically the study investigated the quality of the lighting on the MBT-1®, and provided recommendations for future uses of the barrier. The quality of the lighting schemes was evaluated for illuminance, glare, and shadowing relationships. The researchers used one, two, and three light pole configurations, and the light poles had heights of 9 and 12 feet.

The researchers concluded that the MBT-1® could have a significant positive impact on worksite safety. In addition to providing a solid 100-foot barrier between workers and traffic, the fully illuminated barrier helps workers to be visible to operators of other pieces of mobile equipment. The MBT-1® has multiple light source layout possibilities. The possibility of installing multiple posts on the trailer reduces shadowing, providing light to the whole work zone even when one source is obstructed by heavy equipment.

The researchers provide the following recommendations for future users of the MBT-1® (*Hallowell et al. 2010*):

- Utilize the maximum number of light poles available for the MBT-1® setup deployed.
- Conduct the most difficult work tasks as close to the barrier system as possible for "maximum brightness and minimum glare".
- Fully extending the telescoping poles to 12 feet (from a mid-height of 9 feet) to achieve "the greatest shadow reduction".

2.6 SUMMARY

Providing safe work zones during maintenance work is imperative for DOTs around the country and for ODOT as well. Extensive documentation is available that provides guidelines, regulations, and recommendations for safe maintenance operations on highways. While Mobile Barrier Systems (MBSs) are being increasingly deployed, current independent guidelines and standards provide limited information on the use of a mobile positive barrier systems. As a result, DOTs that purchased MBSs for the protection of their work crews must use their own judgment or conduct their own investigations to determine how and where it is best to deploy the barriers.

Anecdotal evidence from practical implementation finds MBSs to be suitable for short-term and moving work zones. User reports suggest MBSs offer a promising alternative to traditional barriers and, in many cases, provide positive protection where previously impractical and at the same time improving efficiency and traffic flows in and around work zones. Initial reports and user feedback indicate that MBSs enable smooth flow of traffic through work zones without slowing down vehicles.

However, minimal literature is available that describes academically rigorous investigations of the use and outcomes of using MBSs in short-term work zones. Specifically, quantitative data on the use and outcomes of passing vehicles with an MBS at various speeds is needed. The speed with which vehicles pass through the work zone with and without a MBS present provides an indication of worker and driver safety as well as mobility of the traveling public. Vehicle speed is one indicator of mobility along with a variety of other factors such as travel distance, weather conditions, roadway type and design, route connectivity, and congestion (*Zhu et al. 2010, Schrank and Lomax 2007*).

Additionally, data is needed on whether a MBS impacts, positively or negatively, worker productivity. The time it takes to perform the construction/maintenance work with and without a MBS present is of interest to state agencies. Assessing worker productivity can be accomplished through various means including periodic work sampling and time observations *(Oglesby et al. 1989*). An understanding of the ease in which a MBS can be deployed is of interest as well. The typical amount of time required for an agency's workforce to set up, locate, and position a MBS is a consideration when deciding whether and when to deploy a MBS.

The extent to which a mobile barrier can be used within an agency's slate of work activities is also of concern. This requires an analysis of the agency's work distribution in comparison with the activities on which a mobile barrier is particularly suitable. For this study, determining and characterizing work distribution was performed by quantifying the amount of expenditures the agency has for each type of work activity on a regular basis. To get the most value it can out of the equipment, state agencies want to make sure that a mobile barrier can be used on as much of its typical work as possible.

Based on the gaps in relevant academic literature, further research is needed that investigates and measures the actual implementation of mobile barriers, their interaction with and effect on the work crews, and the types of work for which mobile barriers are best suited. In addition, formal guidelines need to be developed to provide ODOT with recommendations on how to put mobile barriers to work as efficiently as possible within Oregon and to minimize the time expended learning how to best implement the barrier.

3.0 CASE STUDIES

3.1 INTRODUCTION

Tasks 3 and 4 of the research study entail identifying and conducting case studies for application and evaluation of the mobile barrier. As described previously, in these tasks the desired project attributes (size, location, type, duration, etc.) that are applicable to the use of mobile barriers and are to be included in the study are identified. In addition, the specific ODOT maintenance and construction projects/activities, both case-study projects and comparison projects, to be included in the research study, are identified. The results of the research efforts related to these tasks are described below.

Summaries of each of the case study projects are also provided. For each case study, this section presents a description of the work performed, research activities, hazards observed, and responses to the worker and supervisor surveys. The vehicle speed data recorded as part of the case studies is presented and analyzed in Section 4.0 of this report.

3.2 VARIABLES INVESTIGATED

Prior to selecting the case study projects to include in the research, the researchers first identified variables to be measured or observed in order to satisfy the study objectives. The study objectives, discussed in Section 1.2 of this report, are:

1. Investigate the time to setup/breakdown a mobile barrier system
2. Investigate the possible limitations and enhancements to work operations due to using a mobile barrier
3. Investigate the effects of a mobile barrier on worker safety
4. Investigate worker safety perceptions when using a mobile barrier
5. Investigate the impacts of a mobile barrier on worker productivity
6. Evaluate motorist safety when using a mobile barrier
7. Determine motorist safety perception when a mobile barrier is used
8. Investigate the worksite attributes that impact and facilitate use of a mobile barrier
9. Investigate the ability to transport a mobile barrier to/from a work site and the associated transportation duration required

Using the study objectives as a starting point, the researchers identified the following measurements and data collection activities. Each is selected to provide requisite data to meet the study objectives.

A. Time measurements: Time measurements are recorded to determine the typical amount of time it takes to setup and breakdown the worksite, to measure worker productivity, and to measure the time to transport the MBT-1® to and from the worksite.

B. Recording of prep work requirements: This effort involves the identification and timing of all of the work that is needed to setup the work site, and identification of differences between sites on which the MBT-1® was used with sites that did not use the MBT-1®.

C. Survey of workers: Workers are surveyed in order to identify possible limitations and enhancements to work operations, their perceptions on safety, their productivity, and how they perceive the project site attributes affect the use of the MBT-1®.To gain worker input, a survey was prepared and is distributed to the workers at the end of their work shift at each investigated site. A copy of the survey is shown in Appendix C.

D. Survey of supervisors: Supervisors of the work performed are surveyed in order to identify any limitations and enhancements to work operations, identity their perceptions of worker safety and productivity, and record how they perceive the project site attributes affect the use of the MBT-1®. To gain supervisor input, a survey was prepared and is distributed to all supervisors at the end of their work shift at each investigated site. A copy of the survey is shown in Appendix D.

E. Survey of ODOT personnel: To gather information about motorist safety, ODOT personnel are asked to comment on their perception of safety while driving by the work sites during the MBT-1® deployment. To collect their opinions, an on-line survey questionnaire and link to the survey was planned for distribution to ODOT personnel. A copy of the survey is shown in Appendix E. This survey was not conducted due to the time and resources available for conducting the survey.

F. ODOT focus panel: In order to get additional views and perceptions on motorist safety while the mobile barrier is in use, a focus panel of ODOT personnel was planned. It was planned to have the focus panel drive through the work zone and record their perceptions of motorist safety compared to work zones with traditional safety measures. This effort was not conducted during the research due to the time and resources available for conducting the focus panel.

G. Researcher evaluation of site: As they visit each work site, the researchers prepare a personal evaluation using a worksheet (shown in Appendix F).This evaluation helps to determine if the project site attributes have any impact on the work performed.

H. Record site characteristics: As they visit each work site, the researchers prepare a diagram of the site and record any special site features that impact use of the mobile barrier and the work that is performed. The researchers record the site data on the worksheet shown in Appendix F.

I. Record of travel route characteristics: The researchers communicate with the ODOT personnel in charge of transporting the MBT-1® to and from the worksite and record the route and time taken to reach the worksite and return to the ODOT laydown yard.

J. Record crashes/injuries: The researchers record any accidents that occur in the work zone when the mobile barrier is used and whether the crashes involve motorists and/or workers. This process is intended to evaluate both worker and motorist safety.

K. Gather historical data from ODOT/OSHA: The researchers obtain historical accident information from various sources to help evaluate worker and motorist safety both with and without use of the MBT-1®.

L. 5-minute sample survey of site: The researchers conduct periodic 5-minute safety surveys of the sites to evaluate worker and motorist safety. A copy of the form developed to record the results of the 5-minute surveys is shown in Appendix G.

M. Speed measurements: Speed measuring devices are placed on the roadway pavement at the location of the worksites to record vehicle speeds as they pass by. Further discussion of the equipment used during the on-site data collection is provided later in the equipment section of this report. The vehicle speed measurements are used as an indication of worker and motorist safety. For this study, lower speeds and less speed variability within the passing traffic are assumed to be indicators of better safety performance in the work zone. In addition, for this study, vehicle speed through the work zone is used as an indicator of the mobility of the travelling public through the work zone (i.e., higher speeds suggesting greater mobility).

N. Survey of other DOTs and mobile barrier owners: Experience from the use of an MBT-1® or similar mobile barrier by other agencies is sampled, initially by conducting the DOT survey that was discussed in Section 2.6.1 of this report. This survey and follow up investigation help evaluate the MBT-1® in regards to several of the study objectives.

A summary of the objectives and the measurements/observations recorded during the research study is shown in Table 3.1.

Table 3.1: Data Collection Matrix

Measurements/Observations Recorded		Study Objectives								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
		Time to setup / breakdown system	**Limitations / enhancements to work operations**	**Worker safety**	**Worker safety perception**	**Worker productivity**	**Motorist safety**	**Motorist safety perception**	**Impact of project site attributes**	**MBS transportation to/from worksite**
A	Time measurements	X				X				X
B	Record prep work requirements	X								
C	Survey of workers		X		X	X			X	
D	Survey of supervisors		X		X	X			X	
G	Researcher evaluation of site								X	
H	Record site characteristics								X	
I	Record travel route characteristics									X
J	Record crashes/injuries:									
	i. With motorists			X			X			
	ii. Not involving motorists (workers only)			X						
K	Gather historical crash and injury data from ODOT:									
	i. With motorists			X			X			
	ii. Not involving motorists (workers only)			X						
L	5-min. sample survey of site			X			X			
M	Speed measurements			X			X			
N	Survey of other DOTs and mobile barrier owners	X	X	X		X	X		X	X

3.3 EQUIPMENT USED

This section describes the equipment used during data collection on the case study sites. The primary data collection equipment was the traffic analyzers described below. The researchers also used standard still and video cameras, computers, and checklists and forms as described above.

3.3.1 Portable Traffic Analyzer NC-200 (PTA)

The speed of passing vehicles was measured using NC-200 Portable Traffic Analyzers (PTAs) that are produced by Vaisala Nu-metrics. The devices are programmable and can detect vehicles traveling from 8 to 120 mph using Vehicle Magnetic Imaging technology. The NC-200s are battery powered and designed to capture up to 300,000 vehicles or 21 days of data before recharging, whichever occurs first (*Vaisala 2010*). The data collected is exported using Highway Data Management (HDM) software provided by the PTA manufacturer. The analyzers are calibrated by the manufacturer at the time of purchase. For this study, the data collected was downloaded from the analyzers, and the PTA reprogrammed for the next use, after every work shift (approximately 6-8 hours of data collection). The PTA analyzers are placed on the roadway and covered by an adhesive tape for protection and to attach them to the roadway surface. A picture showing an NC-200 device on a roadway is shown in Figure 3.1 (*Vaisala 2010*). The same NC-200 devices were used in all but one case study. Case study #4 (see Section 3.9) on US 26 used a Wavetronix SmartSensor HD device.

Figure 3.1:NC-200 Portable Traffic Analyzer (*Vaisala 2010*)

3.3.2 Wavetronix SmartSensor HD (Wavetronix)

The Wavetronix SmartSensor HD (Model 125, software version 1.3) device uses radio frequencies to detect and measure up to 10 lanes of traffic. The device is mounted to a light pole and is capable of measuring traffic count, classification, average speed, and individual vehicle speed. Unlike the NC-200s, the Wavetronix device requires a power source. The Wavetronix device is used when higher amounts of daily traffic on the road prohibit safe installation of the NC-200s, when there are more than two lanes of traffic to be analyzed, or when a longer duration of analysis is needed.

3.4 PILOT INVESTIGATION

Following a demonstration of the MBT-1® for ODOT Maintenance employees at an ODOT laydown site, the MBT-1® was used for the first time by ODOT crew members at a worksite on August 24, 2011. The worksite selected for the pilot test involved taking core samples from the roadway pavement as part of a different research study. The coring took place on I-5 southbound at Mile Post 285.7.The work crew was at the site from 3:00 a.m. to 4:40 a.m., at a time of low traffic volume on the roadway.

In addition to the mobile barrier, four additional trucks were deployed at the site. The coring truck was used to collect the core sample, while two trucks were used to block the work zone from the oncoming traffic. The last truck was used to carry the ODOT personnel and researchers to the site. The MBT-1® was extended to include one additional 20 foot segment attached to its trailer body. One light source from the MBT-1® was used and positioned at the midpoint of the trailer. The researchers did not use the PTAs during this pilot study to record traffic speeds through the work zone.

The crews and work vehicles occupied the rightmost lane (C-lane) of the southbound traffic, as well as the shoulder in that road segment. Two adjacent lanes of traffic in the southbound direction (A- and B-lanes) were open for public use.

The coring was completed successfully with no incidents. The researchers at the site commented that the presence of the MBT-1® restricted the work area and required the coring vehicle to be parked at an angle to the roadway, using a portion of the shoulder, in order to collect the core sample. This positioning of the coring vehicle was due to the reduced amount of space available at the site because of the small right-of-way and the presence of the MBT-1®.

While the work took place, the researchers conducted 5-minute sample safety surveys using the form shown in Appendix G. During the 5-minute surveys, the researchers noted the high speeds close to the barrier and work zone, creating safety hazards for the workers.

Surveys of the work crew members were also conducted to obtain their perspective on the MBT-1®. The surveys revealed that the workers were very content with the MBT-1®.The workers commented that they felt safer than when traditional safety measures are used. The workers also indicated that they had more room to work and were able to concentrate more on their work without thinking as much about their safety.

The work site supervisors were also pleased with the MBT-1®.The supervisors noted in their survey responses that safety from ongoing traffic was not an issue, and that the barrier eliminated the use of a spotter watching for rogue vehicles. The supervisors also felt that the presence of the MBT-1® allowed them to concentrate more on their work than worry about the hazards from passing vehicles. One of the supervisors was also impressed with the features of the MBT-1® that were available to the workers, such as a generator, lights, and storage space.

3.5 IDENTIFICATION OF CASE STUDIES

At the initial TAC meeting for the research study, the TAC members discussed the process for selecting case studies for the research. The intent of the case studies is to provide multiple opportunities to collect data regarding implementation of the mobile barrier. Multiple case studies are desired in order to study the impacts of the mobile barrier based on different site and work conditions, such as daytime/nighttime, shoulder work or in-lane work, rural and urban settings, and so forth.

The nature of maintenance work is such that the work can vary from one day to the next in terms of location, type of work activity, work zone equipment needed, and duration of the work. In addition, maintenance work is often reactionary; that is, maintenance crews respond to conditions on the roadway as a result of severe weather, crashes, and other roadway impacts. As a result, during the first TAC meeting, maintenance personnel indicated that determining the exact timing of when the mobile barrier could be used would be difficult. Therefore, for the first portion of testing, the Maintenance Office implemented the mobile barrier whenever it could, rather than on sites picked specifically to meet the research protocol. After that, the TAC indicated that specific work sites would be selected in order to collect data on a representative sample of sites for the different test variables.

Much of the maintenance work in District 2A at that time was located in and adjacent to waterways. Hence, opportunities to utilize the mobile barrier on maintenance work have been minimal. Besides the pilot test, the mobile barrier had not yet been used on any maintenance sites. As the waterway work wound down, and other types of work increased, there were more opportunities to use the mobile barrier.

When a worksite was identified for application of the mobile barrier, the researchers discussed the work plan with the maintenance supervisor to determine how the mobile barrier was to be used during the work and how best to collect data. The researchers accompanied the maintenance crews to observe the mobile barrier and collect data. The data collection process to be followed, and the research activities to be conducted, on each test site were communicated to the maintenance crews beforehand so that it is clear what the research activities will entail. The research activities are listed below. The list was given to the maintenance supervisor prior to the testing.

<u>Site Investigation Procedures:</u>

- Prior to site visit:

    1. Coordinate with ODOT on location, time, and type of work
    2. Coordinate with ODOT on meeting time and access point at the site
    3. Coordinate with crew/State Patrol for assistance in placing the speed measuring devices
    4. Inform crews that the researchers will be taking a few minutes to complete the worker and supervisor surveys when work is done

- Prior to mobilizing to site:

    1. Meet with crew for placing the measuring devices

    2. Place speed measuring devices (this is done prior to the work site operations to record speeds on the road prior to maintenance operations)

- During mobilization to site:

    1. The investigating team needs to know the:
        a. Time the traffic control crew starts setting up
        b. Time the traffic control crew finishes setting up
        c. Time the mobile barrier departs from the laydown yard
        d. Time of arrival of the mobile barrier at the work site
        e. Route that the mobile barrier took to reach work site
        f. Time of work start
    2. Any issues/problems that occurred during mobilization of the mobile barrier were communicated to the research team.

- During the work operations:

    1. The investigating team collected data by:
        a. Taking 5-minute safety surveys by observing the maintenance operations (this involves observing the site from some distance and noting any hazards that appear around the work site)
        b. Sketching diagrams of the work site and filling out a data collection sheet with the site information
        c. Taking pictures/video of the site
    2. The investigating team also recorded composition and makeup of the work crews involved with the maintenance operations and the transportation of the equipment.

- During departure:

    1. The investigating team needs to know the:

    2. Any issues/problems that occurred during the return of the equipment were communicated to the investigating team.
        a. Time the work finished
        b. Time of mobile barrier departure from the site
        c. Time the traffic maintenance crew started picking up equipment
        d. Time the traffic crew finished picking up equipment
        e. Time the mobile barrier arrived at the laydown yard or next work location
        f. Route that the mobile barrier took to reach lay down yard or next work location

3. The investigating team distributed worker and supervisor surveys, and asked that they be completed either when the crew returns to base or, with the assistance of the supervisors, to be e-mailed to the investigators.
    a. Time the work finished
    b. Time of mobile barrier departure from the site
    c. Time the traffic maintenance crew started picking up equipment
    d. Time the traffic crew finished picking up equipment
    e. Time the mobile barrier arrived at the laydown yard or next work location
    f. Route that the mobile barrier took to reach lay down yard or next work location
4. Any issues/problems that occurred during the return of the equipment were communicated to the investigating team.
5. The investigating team distributed worker and supervisor surveys, and asked that they be completed either when the crew returns to base or, with the assistance of the supervisors, to be e-mailed to the investigators.

- After investigation is complete:
    1. Meet with crew/State Patrol to pick up the measuring devices (assistance with work zone control may be needed)
    2. Pick up the speed measuring devices

3.6 CASE STUDY #1 – FREMONT BRIDGE

The site selected for the first case study was the Fremont Bridge in Portland (I-405 Northbound) where one of the Portland area bridge crews needed to replace and repair several expansion joints on the bridge. The work took place during the nights of December 2 and 3, 2011 (Friday and Saturday nights). The MBT-1® was used the first night (December 2), while traditional safety measures were used the following night (December 3).

3.6.1 Case Study Narrative

<u>Day 1 – With Mobile Barrier</u>

The research team met with the ODOT traffic control crew near the on-ramp to I-405 at Glisan Street in Portland at 9:00 p.m. The traffic control crew assisted the researchers with placing the speed sensor devices (PTAs) to measure traffic volume and speeds, at the same time that the traffic control crew was setting up signs for the work zone traffic control. The traffic control operations started at 9:41 p.m.

Two speed measuring devices were placed on the A- and B-lanes at marker 81 on I-405 northbound. Marker 81 is located under the bridge where Yamhill Street passes over I-405. The traffic control crew placed signs warning drivers that there is “Road Work Ahead” (RWA), and their location is shown on Figure 3.2 marked with RWA.

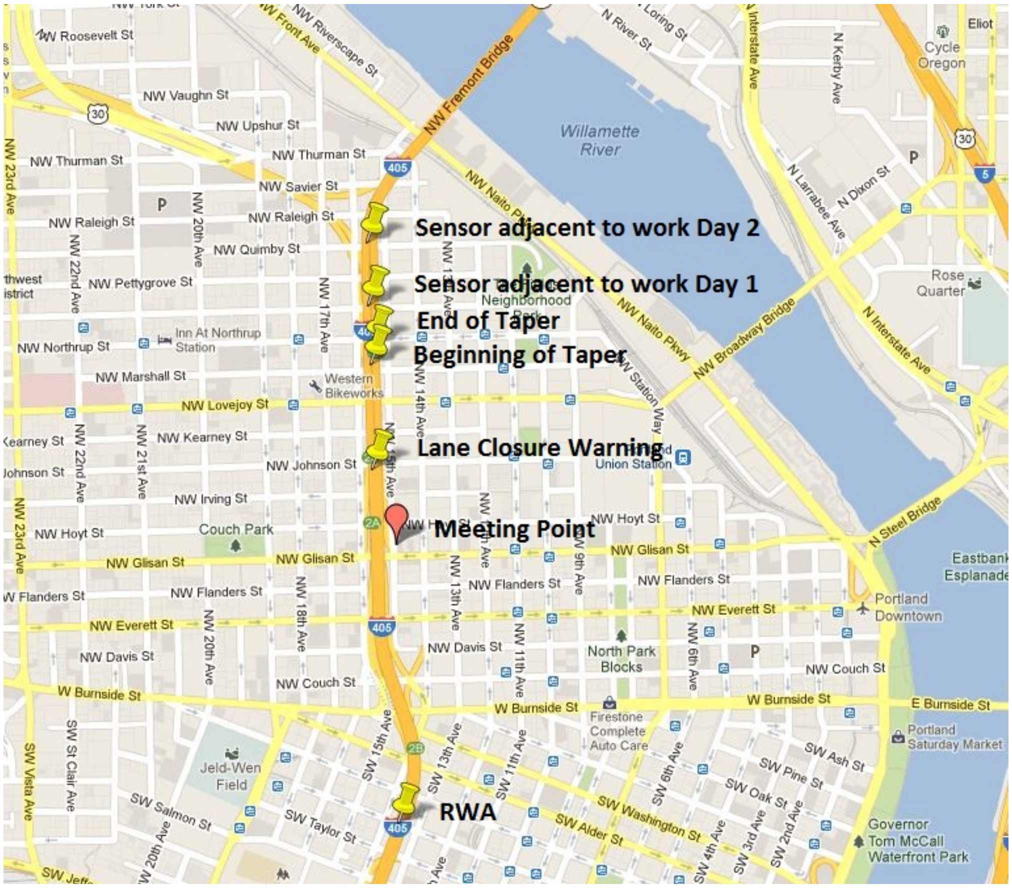

Figure 3.2: Image Showing Locations of the Speed Measuring Devices (Case Study #1)

Two additional speed measuring devices were placed on the B- and C-lanes, close to marker 75, approximately 2,000 feet after the first two devices. No speed measuring devices were placed in the A-lane at this location because the A-lane exited to the west just prior to the work zone. At that location, the traffic control crew placed a sign informing the motorists that the A-lane was going to be closed ahead. That point is marked on Figure 3.2 with "Lane Closure Warning".

At a distance of 700 feet from marker 75, a fifth device was placed on the B-lane adjacent to the end of the cone taper that closed the A-lane. This speed sensor location is marked with "End of Taper" in Figure 3.2. At approximately 300 feet north of the fifth device, the researchers placed a sixth device on the B-lane adjacent to the bridge joint the Bridge crew was schedule to work. That point is marked on Figure 3.2 with "Sensor Adjacent to work Day 1".

With the end of the traffic control placement, the bridge crew was called, and a few minutes later at 10:17 p.m. the mobile barrier entered the work zone, along with the bridge crew and the support vehicles. The mobile barrier required some time to be situated at the precise point where the work was to take place. Once it was in place, the work crew observed that the barrier's attenuator was not lowering to its work position. An additional vehicle with an attenuator attached to it was called in and parked behind the mobile barrier. Work on the bridge joint started at 10:28 p.m. To conduct the work, the bridge maintenance crew required two additional vehicles, a welding truck, and a tool van. These vehicles were parked within the work zone on the A-lane and the A-lane shoulder (Figure 3.3). Present at the worksite were five members of the traffic control crew and eight members of the bridge repair crew, as well as the ODOT regional safety manager.

Figure 3.3: ODOT Bridge Crew Working on Repair of Fremont Bridge Joint with the MBT-1® (Case Study #1)

The researchers completed the work site worksheet, noting down the layout of the site and information regarding the work performed and the site conditions. During the work operations, the researchers performed 5-minute safety surveys at 11:20 p.m., 12:10 p m., and 1:10 a.m. The worksite was busy, and there was enough room for all of the workers to move around.

The researchers also noted the following during their observations of the work performed:

- There was a need for additional traffic control personnel to help situate the mobile barrier at the correct spot within the work zone.
- The mobile barrier crash attenuator could not be lowered, and an additional truck with an attenuator was brought in and placed behind the mobile barrier.
- Prior to driving it to the work area, it took the bridge crew 3-4 hours to switch the mobile barrier direction at the laydown yard.
- There was very little noise from adjacent traffic within the area protected by the mobile barrier.
- Flares were used along with cones to mark the work zone.

The research team also placed two additional speed measuring devices on the roadway within the A-lane in order to measure vehicle speeds during the daytime and during work that was going to be performed the following night on the B-lane. These points are marked on Figure 3.2 as "Sensor adjacent to work Day 1", and "Sensor adjacent to work Day 2".

The bridge crew finished work on the particular joint on the bridge at 3:09 a.m., and at that time the workers started to clear the work zone and return the A-lane back to the traveling public.

Day 2 – Without Mobile Barrier

The research team met with the ODOT traffic control crew at the same location as the previous night to implement the traffic control plan (without MBT-1®). Traffic control operations started at 9:00 p.m. and finished at 9:35 p.m. The bridge crew arrived at 9:35 p.m. and work started on the bridge joint at 9:40 p.m. The first part of the work took place in the A-lane on the joint immediately following the joint that was repaired the night before; a distance of about 495 feet. The location is marked on Figure 3.2 as "Sensor adjacent to work Day 2".

Present at the worksite were five members of the traffic control crew and eight members of the bridge repair crew. The bridge crew required three additional vehicles: the work van, welding truck, and a support truck with compressor (Figure 3.4).

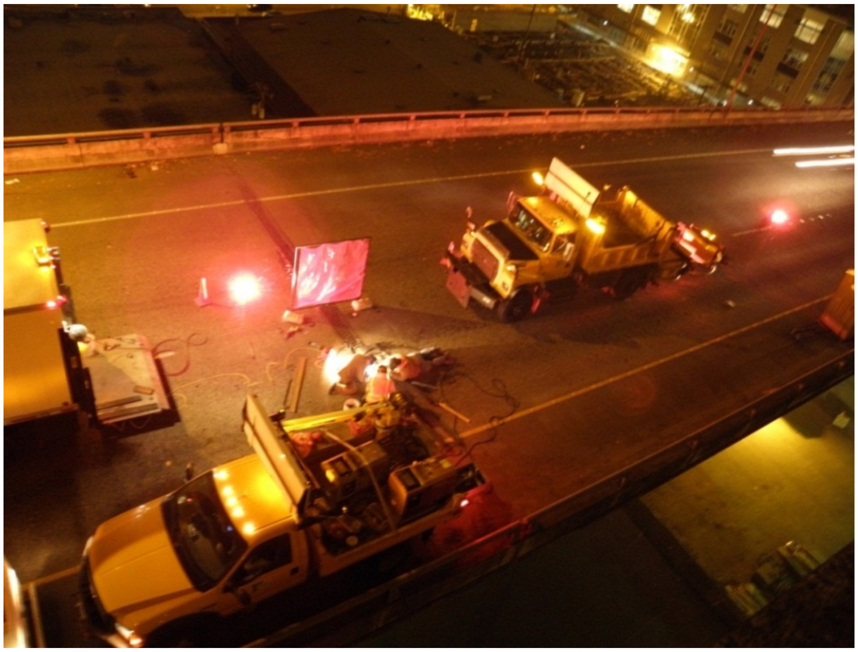

Figure 3.4: ODOT Bridge Crew Working on Repair of Fremont Bridge Joint without the MBT-1® (Case Study #1)

The researchers completed the work site worksheet, noting down the layout of the site and information regarding the work performed and the site conditions. During the work operations, the researchers performed 5-minute safety surveys at 10:20 p.m., 11:11 p.m., and 12:07a.m. The hazards that were recorded were:

- Vehicle traffic bottlenecks close to the work zone
- Vehicle traffic bottlenecks beyond warning signs
- High vehicle speeds close to work zone

The researchers also noted the following during their observations of the work performed:

- There was considerably more noise from traffic within the work zone compared to when the mobile barrier was used.
- Workers were performing tasks less than 8 feet away from the passing traffic.
- There was considerable wind from the passing traffic within the work area.
- There was a need for temporary lighting close to the work tasks.
- The welding screen blew over into traffic.
- Near the beginning of the work period, eight out of 20 drivers turned and looked at the work operations when they were passing by the work zone. Later on in the night when there was less traffic on the roadway and vehicles were driving faster, two out of 20 drivers turned and looked at the workers as they drove past.

The bridge crew finished work on that particular joint on the bridge at 1:20 a.m., and at that time the workers started to clear the work zone. Preparations were made to move the work zone to the B-lane and continue repairing the joint. Traffic control for switching lanes took about 26 minutes, and at 1:46 a.m. work started on the B-lane of the same joint.

The researchers completed the work site worksheet for the second part of the work, noting down the layout of the site and information regarding the work performed and the site conditions. Work on the joint in the B-lane finished at 2:55 a.m. The bridge crew departed, and the researchers joined the traffic control crew to begin the release of the lanes to the public and to collect the traffic measuring devices. The complete operation finished at 3:30 a.m.

3.6.2 Observations

The researchers made periodic observations of the work as it progressed on the case study project. While observing the work, the researchers noted any worksite conditions and operations that appeared to impact (either positively or negatively) the safety of the workers and motorists that were present on the site. A summary list of the researcher observations on each day of the testing is provided below.

- Day 1 – With Mobile Barrier:
    - Due to apparent difficulties in lowering the attenuator on the rear of the MBT-1®, some workers stepped outside the controlled work zone to try to determine the reason for it not lowering. The attenuator's hydraulic lines were adjusted and it eventually lowered. The cause of these difficulties was not identified to the researchers.

- Day 2 – Without Mobile Barrier:
    - Continuous high noise level from the passing traffic
    - High vehicle speeds close to work zone
    - Wind blowing in the work zone from traffic
    - Welding screen in danger of blowing into traffic

3.6.3 Summary of Survey Responses

The researchers collected a total of 12 surveys from the workers on site. Six surveys were completed by the bridge crew workers, two from bridge crew supervisors, four from traffic control crew workers, and one from the traffic control crew supervisor. The responses are summarized in Table 3.2. For each question shown in the table, the survey asked the respondents to indicate which is better, the mobile barrier or traditional traffic control measures, or if there is no difference.

Table 3.2: Summary of Worker and Supervisor Survey Responses (Case Study #1)

	Which is better: mobile barrier or traditional traffic control measures?	**ODOT Bridge Crew**			**ODOT Traffic Control Crew**		
		MB	**Both**	**Traditional**	**MB**	**Both**	**Traditional**
Q1	Ease of movement	5	2	0	2	3	0
Q2	Access to equipment	1	5	1	0	4	1
Q3	Ability to see worksite	4	3	0	1	4	0
Q4	Ability to complete work tasks with high quality	5	2	0	2	3	0
Q5	Ability to complete work tasks efficiently	3	4	0	1	2	2
Q6	Worker safety	7	0	0	4	1	0
Q8	Worker productivity	5	2	0	1	3	0
	Total responses	30	18	1	11	20	3

In Question #7 (Q7), the respondents were asked to explain why they felt safer. The most common responses were that with the mobile barrier, they did not notice the traffic, had better lighting, and could focus on their tasks better. In response to their opinion about productivity (Q8), the respondents were also asked to further explain their answer. They commented that with the mobile barrier they did not have to pay attention to the traffic, a spotter was not needed so more workers were available to do the work, and they could move freely within the worksite. The supervisors who submitted responses commented that the supervision of the work was easier with the mobile barrier since they could better focus on the work at hand.

The workers and supervisors were also asked to comment on any limitations of the site for mobile barrier use. In response to this question they commented that in their opinion the mobile barrier would not be good for sites that are very spread out. The respondents were also unsure about the barrier's use on a 4-lane highway when work needed to be performed in the middle lanes. Lastly, they added that use of the barrier might be difficult on blind corners and on hills due to its length.

In regards to factors that would enhance the use of the mobile barrier, the survey respondents commented that the mobile barrier would work great for localized projects and at locations with wide shoulders.

3.7 CASE STUDY #2 – I-5 NEAR BROWNSVILLE

The site that was selected for the second case study was on I-5 near Brownsville, OR (close to Mile Post 220). The work being conducted involved emergency repairs of sections of the concrete pavement in the northbound and southbound directions. The scope of work was completed during the weeks of March 6 – March 17, but the mobile barrier was requested for only two days, March 12 and March 13.

3.7.1 Case Study Narrative

The research team met the construction personnel and ODOT staff at the jobsite to discuss the logistics of implementing the MBT-1® on the site. The initial traffic control plan for the jobsite was obtained from ODOT personnel at this time. To utilize the mobile barrier on the project, the MBT-1® needed one additional 20-foot section installed on the trailer for a total trailer length of 80 feet (two 20-foot sections total on barrier). In addition, the barrier needed to be switched from one side to the other. The procedure for adding the sections and rotating the trailer from A-lane configuration to B-lane configuration took place at the ODOT laydown yard on I-205 near the 10th Street exit in Portland. The research team observed the operations, and the processes were filmed and timed (see Figure 3.5)

Figure 3.5: Adding a 20-footExtension on the MBT-1® (Case Study #2)

Due to the increased length of the trailer, a special permit needed to be obtained for the trailer to be transported to Brownsville (*ODOT 2013*). This type of permit may not be required in other states.

The trailer was transported from the laydown yard and placed in the median near MP 220 on I-5 southbound. When the MBT-1® arrived on the site, the contractor responsible for the work had already completed work on the A-lanes (northbound and southbound). The case study involved investigating work taking place on the B-lanes of the highway, both northbound and southbound.

The research team met with the contractor and ODOT personnel to place the speed sensor devices to measure traffic volume and speeds on the northbound and southbound lanes of I-5 near the construction zones.

On the southbound lane, sensors were placed on the A-lane next to the work zone, and on both lanes at a distance of 2,325 feet away from and prior to the work zone. On the northbound lane, one sensor was placed at the work zone on the A-lane, one at the end of the tapering of the cones on the A-lane (325 feet from the work zone), and on both the A- and the B-lanes at a distance 2,325 feet away from and prior to the work zone. All of the sensors were programmed to start recording at 2:00 a.m. Monday morning (March 12) and record traffic for 24 hours.

On Monday, March 12, at approximately 1:50 p.m., the MBT-1® was moved from the southbound median and was placed at the northbound work zone, at the location that was specified by the contractor's personnel. The MBT-1® was to remain there until work was completed. On Monday no work was performed on the northbound lanes while the MBT-1® was at the site.

The devices were removed from the road and the data collected was downloaded onto a computer to be analyzed. The research team noted that in future site investigations:

- The sensors should not be placed when adverse weather conditions are expected especially during wet site conditions and heavy rainfall. Four of the sensors that were placed were displaced from their initial location due to a combination of inadequate bonding of the tape with the ground and heavy impact from vehicles. The data from three of the four displaced monitors was irretrievable on this case study.

- Sensors placed on the lanes adjacent to barrels and the work zone should not be placed in the middle of the lane, but closer to the edge of the lane away from the work zone in order to avoid heavy impact from vehicles. Passing vehicles tend to shift over in the lane, away from the line of cones or barrels.

- At times, traffic backed-up past the first set of speed monitoring devices placed to record the "steady state" speed on the roadway. As a result, the traffic came to a stand-still prior to the first signage indicating construction work ahead. On future case studies, it is important to ensure that those devices placed to measure the steady state speeds are far enough away from the work zone such that they are not impacted by slow-downs and queues due to heavy traffic volumes.

The next day workers started to remove the concrete pavement in the northbound work zone (see Figure 3.6). The research team visited the site to conduct additional investigations. Present at the site were five workers from the construction firm, and two ODOT personnel. The contractor had two jackhammers, an excavator, and two generators for the jackhammers. In addition, there was a tool van that has hitched to a truck. Parked on the shoulder and within the closed section of the B-lane were the workers' personal vehicles and the two trucks belonging to ODOT. At a distance of about 325 feet south of the northbound work zone on the B-lane there was a truck with an attenuator attached to it inside the taper.

Figure 3.6: Workers Removing Concrete Pavement (Case Study #2)

The researchers completed the work site worksheet, noting down the layout of the site and information regarding the work performed and the site conditions. During the work operations, the researchers performed a 5-minute survey at 11:00 a.m. The worksite was not crowded and there was enough room for all of the workers and ODOT personnel to move around freely. The researchers also noted the following during their observations of the work performed:

- While the MBT-1® was parked at the site overnight, its left, side view mirror on the driver's side was impacted by a passing vehicle. The same, or another vehicle, also hit the flashing light on the top, left-hand corner of the MBT-1® near the cab. Another vehicle scraped the side of the MBT-1®, and was stopped by an OSP patrol officer. No other damage was observed on the MBT-1®.

- The message board on the MBT-1® was working properly, but the operator could not show the message indicating the vehicle's speed generated from the radar. This may have been due to the operator not having enough experience using the system.

3.7.2 Observations

The researchers recorded the following observations on case study #2 while viewing the worksite conditions and work practices with the mobile barrier present:

- The ODOT crew evaluated the space the contractor needed to excavate. They elected to park the MBT-1® over the skip line, where it encroached on the A-lane, making the width of the driving lane narrower than normal. The size of the work area and safe distance to operate the equipment required the MBT-1® to be situated into the travel lane. It was noted that the encroachment into the A-lane was not greater than a barrel, therefore ODOT agreed to its placement. Additionally, approximately 50 feet ahead of the work was the start of a guardrail in the median. The guardrail edge had a reflective marker indicating where it started. The passing vehicles needed to drive partly on the A-lane and partly on a narrow strip of paved area in the median. The combination of encroached lane and start of guardrail may be the reasons for the mobile barrier getting struck by passing vehicles.

3.7.3 Summary of Survey Responses

The researchers collected a total of five completed worker and supervisor surveys from those on the site. Two surveys were completed by ODOT personnel (supervisor surveys), and three from the contractor's crew (1 supervisor, 2 workers).The responses are summarized in Table 3.3.

Table 3.3: Summary of Worker and Supervisor Survey Responses (Case Study #2)

	Which is better: mobile barrier or traditional traffic control measures?	ODOT Crew			Contractor Crew		
		MB	Both	Traditional	MB	Both	Traditional
Q1	Ease of movement	1	1	0	0	3	0
Q2	Access to equipment		1	1	0	3	0
Q3	Ability to see worksite	1	1	0	1	2	0
Q4	Ability to complete work tasks with high quality	2		0	0	3	0
Q5	Ability to complete work tasks efficiently	1	1	0	0	3	0
Q6	Worker safety	2	0	0	1	2	0
Q8	Worker productivity	1	1	0	0	3	0
	Total responses	8	5	1	2	19	0

The respondents were asked to explain why they felt safer in either case (Q7). The ODOT crews were happy with the MBT-1® since they felt that traffic could not hit them, and that they did not need a spotter to look at oncoming traffic. From the contractor crew's perspective, one worker stated that he felt safer, another stated that they are both equally safe, and a third stated an opinion that the MBT-1® gives a false sense of safety (although the third indicated "Both" in response to Q6 as shown above.

The respondents were also asked to explain further their answer on productivity. From the statements provided, the majority of the crews believe that productivity is the same for both safety measures (with and without the MBT-1®).

The contractor supervisor stated that their ability to supervise the work is the same for both conditions, while the ODOT supervisors commented that supervision is better with the MBT-1® since it allows them to concentrate more on the workers.

The workers and supervisors were also asked to comment on any site conditions that limit use of the mobile barrier. Similar to case study #1, the respondents commented that use of the mobile barrier would likely be limited on sites that are really spread out or sites with narrow shoulders and lanes. The ODOT supervisors also added that they think the work might be more difficult in work zones with super-elevation.

In regards to enhancements provided by the MBT-1®, the survey responders commented that the MBT-1® with the arrow board, generators, and work lights is a great addition to the work zone. Additionally, those surveyed indicated that site conditions with no elevation changes and no turns would enhance use of the MBT-1®.

3.8 CASE STUDY #3 – I-5 INTERSTATE BRIDGE

The site that was selected for the third case study was the repair of light circuits, lights, and cameras on the southbound lanes of the I-5 Interstate Bridge. The work took place during the nights of March 16 and 17 (Friday and Saturday nights). Traditional safety measures were used on the first night (March 16) while the MBT-1® was used on the second night (March 17).

3.8.1 Case Study Narrative

Day 1 – Without Mobile Barrier

On the first night of data collection, the research team met with the traffic control crew for a safety meeting at approximately 8:45 p.m. at the ODOT Permit Office near Exit #308 on I-5. At the meeting the head of the traffic control crew informed the Washington State Trooper and the District 2B Bridge Supervisor who were present of the necessary lane closures. The District 2B Bridge Supervisor handed out a list of the work that was to take place during the night and informed the traffic control crew of expected hazards. The research team decided not to place traffic sensors on the roadway due to the heavy rain that was expected, and informed the traffic control crew accordingly.

At approximately 9:15 p.m. the traffic control crew headed out to implement their plan, and the research team went along with them to observe their operations. At approximately 10:15 p.m., the research crew met with the District 2B Bridge Supervisor, who was conducting a safety meeting with the work crews working on the bridge that night.

Following the meeting at approximately 11:00 p.m., the crews headed to their predetermined locations and followed the traffic control crew which was closing the B- and C-lanes on the southbound direction of the bridge. The research team walked towards the bridge and through the Bridge Control Office to gain access to the work zone. Lanes A- and B were closed to traffic. Lane C was open to traffic.

The work that was performed included the repair of lights and their wiring on the bridge. The electrical contractor performed the work with two boom trucks and six workers (see Figure 3.7).

Figure 3.7: Crew Repairing Lights on I-5 Interstate Bridge without the MBT-1® (Case Study #3)

During the work operations observed on the case study, the researchers completed the work site worksheet, noting down the layout of the site and information regarding the work performed and site conditions. The researchers also performed two 5-minute surveys, one at 11:46 p.m. and the other at 12:19 a.m.

Day 2 – With Mobile Barrier

On the following night, the research team met with the traffic control crew for a safety meeting at approximately 8:45 p.m. at the ODOT Permit Office near Exit #308 on I-5. Following the meeting at approximately 9:15p.m., the research team joined the traffic control crew in their work to implement the traffic control plan. At a distance of about 2 miles away from and prior to the bridge, the traffic control crew placed their first signs ("Road Work Ahead" or "RWA") and the research team placed two speed sensors on the road, one in the A-lane and one in the B-lane.

Closer to the Interstate Bridge and at a distance of 10,975 feet from the RWA sign, the traffic control tapered the traffic to one lane (A-lane) and the research team placed one speed measuring device on the road in the A-lane.

Three more devices were placed on the I-5 bridge. The first was placed prior to the drawbridge at a distance of about 600 feet beyond the end of the taper. The second sensor on the bridge was placed a distance of about 1,370 feet away from the first device at approximately the location of the State line. The third sensor on the bridge was placed at approximately 1,800 feet away from the 2nd device, close to the end of the bridge. The approximate placement of the sensors in relation to the roadway is shown in Figure 3.8.

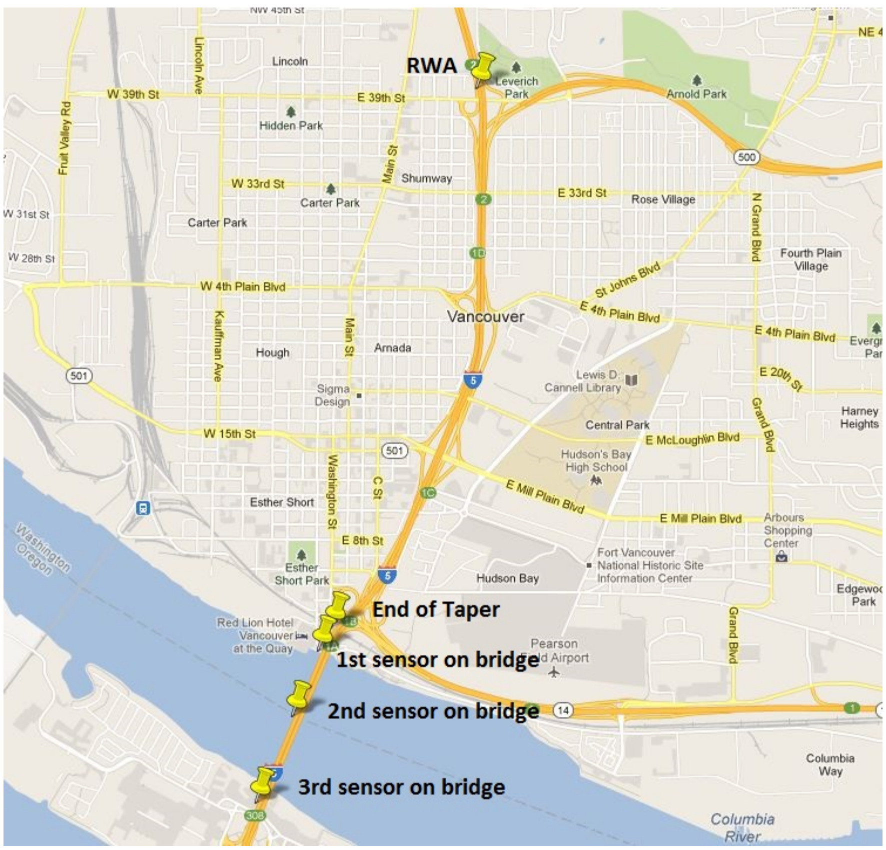

Figure 3.8: Location of Speed Sensors on Southbound I-5 (Case Study #3)

After placement of the devices, the research team met with the District 2B Bridge Supervisor, who was conducting a safety meeting with the work crews working on the bridge that night. The crews were informed of the research and the needs of the research and were asked to complete a survey at some point during the night. The crews were also informed that there were going to be visitors at the worksite. These visitors were supervisors from WSDOT, and a representative from Mobile Barriers.

At approximately 11:00 p.m., the crews headed to their predetermined locations and followed the traffic control crew which was closing the B- and C-lanes on the southbound direction of the bridge. One of the contractor crews was designated to work with the mobile barrier. The crew with their vehicle (boom truck) and the mobile barrier took their place on the bridge, and at approximately 11:15 p.m. they were ready to start work. Work was performed throughout the night at various locations along the bridge. The approximate work locations on the bridge where the MBT-1® was used are shown in Figure 3.9. The locations of the sensors are shown with a yellow marker, and the work locations are indicated with a red marker.

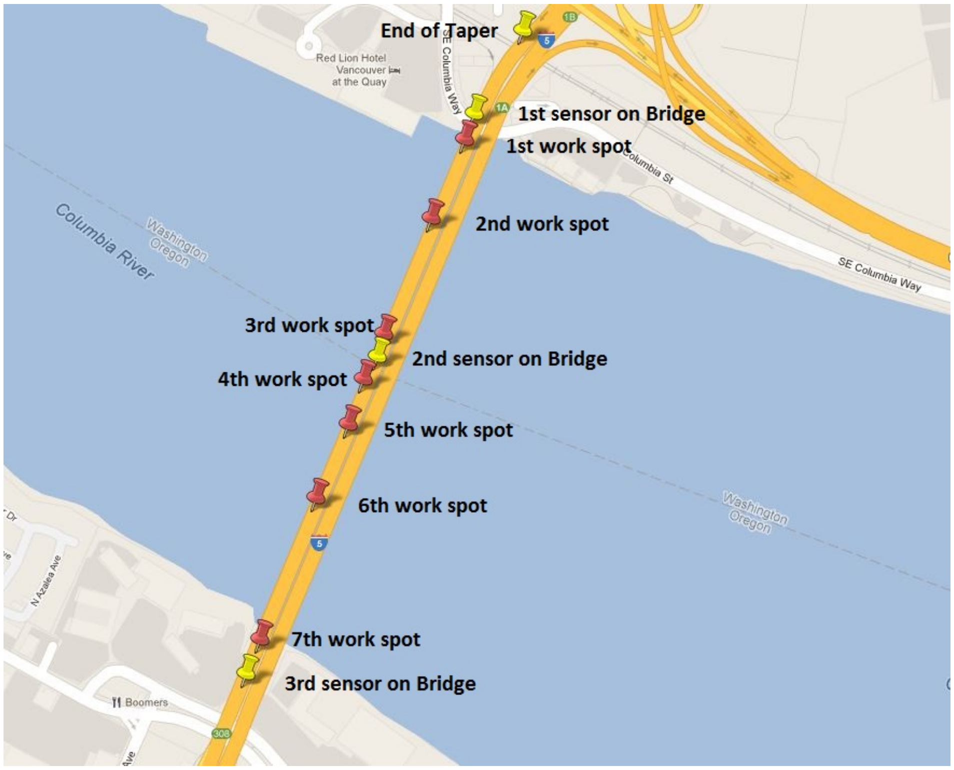

Figure 3.9: Locations of Speed Sensors and Work on Bridge (Case Study #3)

During the work operations observed on the I-5 Interstate Bridge, the researchers completed the work site worksheet, noting down the layout of the site and information regarding the work performed and site conditions. The researchers also performed two 5-minute surveys, at 11:50 p.m. and at 2:33 a.m. The researchers observed that the first work site location was crowded at the beginning of the work due to the large number of personnel and visitors who were present. The visitors were guests invited by the vendor from the Washington State Department of Transportation to observe operations. The presence of additional visitors is not expected or typical. The visitors left shortly after midnight and as a result the work site was less crowded.

As indicated above, work was performed throughout the night at various locations along the bridge. Figure 3.10 shows one of the work site locations. Below are summary descriptions of the work performed at each location:

- 1st work location: Light and wiring repair.
  - Work started at 11:15 p.m. and finished at 12:05 a.m.
  - Work crew: Three construction personnel with a boom truck; two MBT-1® operators (driver and co-driver).
  - Travel to next location – The MBT-1® co-driver guided both vehicles along the bridge towards the next location. Distance to next location 474 feet.
- 2nd work location: Light and wiring repair.
  - Work started at 12:39 a.m. and finished at 1:30 a.m.
  - Work crew: Three construction personnel with a boom truck; two MBT-1® operators (driver and co-driver).
  - Travel to next location – The MBT-1® co-driver guided both vehicles along the bridge towards the next location. Distance to next location 687 feet.
- 3rd work location: Installation of clamps to protect wiring on bridge frame.
  - Work started at 1:50 a.m. and finished at 2:27 a.m.
  - Work crew: Three construction personnel with a boom truck; two MBT-1® operators (driver and co-driver).
  - Travel to next location – The MBT-1® co-driver guided both vehicles along the bridge towards the next location. Distance to next location 215 feet.
- 4th work location: Installation of clamps to protect wiring on bridge frame.
  - Work started at 02:33 a.m. and finished at 3:05 a.m.
  - Work crew: Three construction personnel with a boom truck; two MBT-1® operators (driver and co-driver).
  - The contractor's crew moved on to their next location. The MBT-1® remained at the same location and waited for an ODOT crew that was to repair traffic cameras attached to the bridge frame. The ODOT crew composed of two people and a boom truck entered the work zone that the MBT-1® was protecting.
  - Contractor crew left work area at 3:05 a.m., and ODOT crew entered at 3:10 a.m. ODOT crew finished at 3:20 a.m.
  - Travel to next location – The MBT-1® co-driver guided the MBT-1® to the next location to cover the same contractor crew again. Distance to next location 221 feet.

- 5th work location: Installation of clamps to protect wiring on bridge frame.
  - Work started at approximately 3:25 a.m. and finished at 3:43 a.m.
  - Work crew: Three construction personnel with a boom truck; two MBT-1® operators (driver and co-driver).
  - Travel to next location – The MBT-1® co-driver guided both vehicles along the bridge towards the next location. Distance to next location 413 feet.
- 6th work location: Installation of clamps to protect wiring on bridge frame.
  - Work started at 3:48 a.m. and finished at 4:09 a.m.
  - Work crew: Three construction personnel with a boom truck; two MBT-1® operators (driver and co-driver).
  - Travel to next location – The MBT-1® co-driver guided both vehicles along the bridge towards the next location. Distance to next location 650 feet.
- 7th work location: Installation of clamps to protect wiring on bridge frame.
  - Work started at 4:16 a.m. and finished at 4:30 a.m.
  - Work crew: Three construction personnel with a boom truck; two MBT-1® operators (driver and co-driver).
  - This was the last work location for the construction crew.

At approximately 4:30 a.m., the research team met with the traffic control crew to collect the speed measuring devices from the roadway. All of the devices were removed by approximately 5:15 a.m., at which time the research team left the site.

Figure 3.10: Workers Repairing Electrical Circuits on I-5 Interstate Bridge with MBT-1® (Case Study #3)

3.8.2 Observations

The researchers observed the following impacts to the work site conditions and work operations on this case study:

- Day 1 – Without Mobile Barrier:
    - There was not enough illumination within the work zone. Workers were wearing head lamps, and there was need for a spotter on the ground for each boom truck.
    - The workers and the trucks were exposed to potentially errant traffic. While no vehicles were observed entering the work zone, the cones were set far apart and vehicles could easily enter the work zone between the cones.
- Day 2 – With Mobile Barrier:
    - The worksite was crowded from the visitors at the beginning of the work. This impact would not be present on a typical work site.

3.8.3 Summary of Survey Responses

During the work period, several crew members answered the survey questionnaire that was submitted to them by the research team. There were a total of nine surveys collected from the workers on site. Five surveys were completed by ODOT personnel (1 supervisor, 2 MBT-1® drivers, and 2 work crew members), and four were collected from the contractor personnel (1 supervisor, 3 workers).The responses are summarized in

Table 3.4: Summary of Worker and Supervisor Survey Responses (Case Study #3)

	Which is better: mobile barrier or traditional traffic control measures?	ODOT Crew			Contractor Crew		
		MB	Both	Traditional	MB	Both	Traditional
Q1	Ease of movement	3	1	1	1	3	0
Q2	Access to equipment	2	2	1	0	4	0
Q3	Ability to see worksite	3	2	0	4	0	0
Q4	Ability to complete work tasks with high quality	4	1	0	1	3	0
Q5	Ability to complete work tasks efficiently	5	0	0	1	3	0
Q6	Worker safety	5	0	0	4	0	0
Q8	Worker productivity	2	1	0	1	2	0
	Total responses	24	7	2	12	15	0

Similar to previous case studies, the survey respondents were asked to explain why they felt safer (Q7).The ODOT crews commented that the MBT was a good safety practice, they liked the additional lighting and storage, and that they did not feel the live traffic on the other side of the barrier. The contractor crews commented that the MBT provided a visual barrier from vehicle headlights, and said that they did not have to worry about traffic and vehicles running them over.

In regards to worker productivity, the ODOT crew commented that because they did not have to look over their shoulders, their productivity was better with the MBT. On this project, the MBT-1® was protecting a bucket truck and crews needed some time to coordinate the movement of the two pieces of equipment. Most of the contractor crew respondents commented that their productivity was the same, but one contractor employee indicated that productivity was better with the MBT-1® because he did not have to look over his shoulder to conduct his work. The contractor supervisor stated that the ability to supervise is the same for each condition.

With respect to limitations for mobile barrier use, the workers and supervisors responded that there might be limitations on lanes with slopes and on locations where there is not adequate space to locate the mobile barrier. The ODOT crew said that having two lanes closed to traffic helped (only the A-lane was open to traffic), and the supervisors were very pleased with the additional lighting and the VMA sign on the mobile barrier. An additional comment included: "The mobile barrier is definitely needed for work that requires folks to work on hands and knees on the road surface for long periods of time".

3.9 CASE STUDY #4 – US 26 CLOSE TO ZOO EXIT

The fourth case study that was selected was on US 26 near the Zoo exit (Mile Post 73). The construction work involved the installation of a drilled shaft on the side of the road on the westbound direction as shown on Figure 3.11. The scope of work was part of an ongoing ODOT project performed by an independent contractor headquartered in Eugene, Oregon. The work took place from September 10–13, 2012.

Figure 3.11: Location of Work for Case Study #4

3.9.1 Case Study Narrative

As part of the general upgrades and improvements on US 26, ODOT requested the installation of a bridge sign structure near MP 73. US 26 is a busy highway with multiple lanes in each direction. Near MP 73, there are four lanes of traffic in the westbound direction and three lanes in the eastbound direction.

Work at the site started in the morning of September 10. The MBT-1® was moved and parked close to the site but was not involved in the protection of either the worksite or the workers performing the work. The MBT-1® was to be used only for the protection of the drilled shaft after all drilling work was completed. Traditional protection measures were used at all other times.

On the afternoon of the first day of work, a Wavetronix speed sensor was installed on a light post located at approximately 100 feet prior to the worksite. The sensor has the capability of measuring speeds and vehicle lengths on up to 10 lanes of traffic at the same time. The speed sensor was installed according to the manual requirements and was powered by a generator that was refueled at regular intervals by the District 2A bridge crew personnel. The NC-200 speed sensors used for the other case studies were not used for this case study due to the long duration of the work and the number of lanes of traffic.

3.9.2 Days 1 and 2 without Mobile Barrier

On the first two days of the case study, the MBT-1® was on the site but was not used for the protection of the work nor the worksite and it was parked some distance away from the worksite. On the second day, after work on the drilled shaft was completed, the MBT-1® was moved and parked in front of the completed shaft for two days after which it was then moved back to the ODOT laydown yard on I-205. A permanent guard rail was put in place at the site that morning after the MBT-1® was removed.

The research team visited the worksite on three different occasions. On the first day of the case study, the Wavetronix sensor was installed and the research team took pictures of the work performed, conducted a 5-minute safety survey, and completed the data collection worksheet.

There was a crew of four workers working at the site who were preoccupied with drilling the shaft. Present also were a forklift, a drill, and a wheel loader. Traditional safety measures were used, and the only hazard that was observed was the high speed vehicles traveling next to the work zone. Workers were moving on the shoulder (as shown in Figure 3.12) but they were within the area marked with barrels and cones. The controlled work area was on the shoulder and far enough from the passing traffic that the work was not affected by the traffic.

Figure 3.12: Workers Working on the Site, September 10 (Case Study #4)

On the second day, the research team downloaded information from the Wavetronix sensor, took pictures of the site, and conducted a 5-minute survey of the area. There was a crew of four workers working at the site who were preoccupied with drilling the second shaft at the site, and with the placement of the concrete that was arriving via concrete trucks. Present also were a forklift, a drill, a wheel loader, and several concrete trucks (Figure 3.13). Traditional safety measures were used, and the only hazard that was observed again was the high speed vehicles traveling next to the work zone.

Figure 3.13: Worksite, September 11 (Case Study #4)

3.9.3 Days 3 and 4 with Mobile Barrier

After work was completed on the second day, the MBT-1® was moved and parked in front of the completed drilled shaft for two days after which it was then moved back to the ODOT laydown yard on I-205. There were no workers on site and the MBT-1® was parked as shown in Figure 3.14. On the third day, the research team downloaded information from the Wavetronix sensor, took pictures of the work zone, and completed the data collection worksheet.

Figure 3.14: MBT-1® Parked Next to Drill Shaft

3.9.4 Observations

As the researchers conducted the case study they observed high vehicle speeds next to the work zone and the MBT-1®. No lane closures were needed to conduct the work, so the passing traffic could travel at normal speeds.

3.9.5 Summary of Survey Responses

The research team sent surveys to two supervisors working for the contractor and an ODOT employee who was present at the site. The responses from the three participants are summarized in Table 3.5.

Table 3.5: Summary of Worker and Supervisor Survey Responses (Case Study #4)

	Which is better: mobile barrier or traditional traffic control measures?	**ODOT Supervisor**			**Contractor Supervisor**		
		MB	**Both**	**Traditional**	**MB**	**Both**	**Traditional**
Q1	Ease of movement	0	0	1	2	0	0
Q2	Access to equipment	0	0	1	2	0	0
Q3	Ability to see worksite	0	0	1	0	2	0
Q4	Ability to complete work tasks with high quality	0	0	1	1	1	0
Q5	Ability to complete work tasks efficiently	0	0	1	1	1	0
Q6	Worker safety	0	0	1	2	0	0
Q8	Worker productivity	0	0	1	2	0	0
	Total responses	0	0	7	10	4	0

The three respondents provided the following responses to the open-ended survey questions (Q7, Q9-Q13):

- Q7: Why do you feel safer? (Explain your answer to Q6)
    - The contractor employees commented that they feel safer working behind the mobile barrier especially in situations such as the one next to US 26 due to the high vehicle speeds present.
- Q9: Why is there higher/lower productivity? (Explain your answer to Q8)
    - The contractor employees commented that workers can concentrate more on their work and not be distracted by traffic.
- Q10: Supervision
    - The contractor employees commented that their supervision is easier with the mobile barrier.
- Q11: Limitations
    - The contractor employees commented that there is a need for a wider shoulder in order to have better access to the work zone and for large equipment to move freely within the area behind the mobile barrier. The ODOT employee commented that if there is only one lane of travel in each direction, traffic access within the work zone would be difficult.
- Q12: Enhancements (no comments provided)
- Q13: Other comments
    - The respondents indicated that it is great for safety and should be used more often. Suggestions for its use included: (1) the direction switch could be performed more easily during daylight; (2) provide a dedicated tractor for the MBT-1®; (3) provide training on using the MBT-1® for multiple crews; and (4) the cone truck and crash truck could follow the mobile barrier into the worksite.

3.10 CASE STUDY #5 – I-5 MP 304 – 307.5

The work under investigation in this case study involved the placement of high occupancy vehicle (HOV) markers on a northbound section of I-5 Interstate in Portland between MP 304 to MP 307.5. This work utilized a rolling work zone where a convoy of maintenance vehicles closes a lane of the intestate to perform the installation work and then moves further down that lane for the next installation. The work took place on September 27, 2012. The MBT-1® was used for the work with a driver from the Portland Bridge Crew, and the striping crew from the Milwaukie maintenance crew performed the installation of the HOV markers.

3.10.1 Case Study Narrative

The research team met with the ODOT striping crew at their Milwaukie office at 8:00 p.m. for the safety meeting that took place prior to the night's work. The crew was informed that the research required the placement of speed sensors on the road, and set up a plan to install them prior to the beginning of the work. The driver for the MBT-1® met the striping crew and headed to the I-205 laydown yard to place the equipment required for the night's work onto the mobile barrier.

At 9:15 p.m., the crew responsible for traffic control and operations for the installation of the speed sensors headed towards I-5. Installation of the sensors started at 9:40 p.m.. The research team was in an ODOT truck followed and protected by three crash trucks. Seven sensors in total were placed on the road. Two were placed in the B- and C-lanes near MP 304 (N45^o 33.362$'$, W122^o 40.710$'$), two in the B- and C-lanes near MP 304.5 (N45^o 33.737$'$, W122^o 40.708$'$), two in the B- and C-lanes near MP 305 (N45^o 34.235$'$, W122^o 40.710$'$) and one on the B-lane near MP 305.5 (N45^o 34.722$'$, W122^o 40.707$'$). Placement of the sensors finished at 10:00 p.m. At 10:10 p.m. the whole team (crush trucks, research team truck, work crews) met on I-405 on the shoulder right before the Fremont Bridge to regroup and assemble all the vehicles in a convoy to head to the locations where work needed to take place. The first vehicle in the convoy was the truck carrying the three striping crew workers, followed by the MBT-1®, the truck carrying the research team, and then by the three crash trucks. At 10:20 p.m. the convoy headed towards I-5 and at 10:26 p.m. the convoy reached the first work location.

The typical work process at each marker location included the following activities:

1. Upon arrival at each HOV marker, the work crew dropped a cone from their truck to indicate the location of the marker for the MBT-1® driver. The MBT-1® driver, using the cone as a guide, would stop at the marker location with the marker enclosed within the opening of the MBT-1®.

2. Once at a stop, the workers would step out of their vehicles and head inside the MBT-1® enclosure. The workers would open the compartments on the barrier to retrieve their equipment and start the work.

3. The HOV shape was placed on the road at the desired location and then two of the workers using blowtorches stuck the diamond shape on the road. A third worker added a powder on the blowtorched shape to reduce the cooling time and reduce the waiting time.

4. As the shape was cooling down, the workers would place their equipment back in the MBT-1® compartments. Once the shape was cool enough, the workers would get back in their vehicle and the convoy would proceed to the next work location.

Figure 3.15 shows the workers placing one of the HOV markers.

Figure 3.15: Installation of HOV Markers on I-5 Northbound (Case Study #5)

At each work location the work time at each location was recorded along with the GPS coordinates of the location.

Table 3.6 shows the time of work at each location and the approximate GPS coordinates. The letters (A – N) represent the time segment associated with the work performed at each particular location. These time segments are later used in the analysis portion of this report (4.5), to make comparisons between the speeds of the vehicles.

Table 3.6: Time and GPS Coordinates at Each Work Location (Case Study #5)

Work Location	Latitude	Longitude	Start Time	End Time	Work Duration	Transition time to next location
1 – A	N 45° 33.342’	W 122° 40.716’	10:26pm	10:36pm	10 min	1 min
2 – B	N 45° 33.428’	W 122° 40.713’	10:37pm	10:46pm	9 min	2 min
3 – C	N 45° 33.504’	W 122° 40.719’	10:48pm	10:55pm	8 min	1 min
4 – D	N 45° 33.593’	W 122° 40.711’	10:56pm	11:05pm	9 min	1 min
5 – E	N 45° 33.683’	W 122° 40.710’	11:06pm	11:14pm	8 min	1 min
6 – F	N 45° 33.753’	W 122° 40.713’	11:15pm	11:22pm	7 min	1 min
7 – G	N 45° 33.832’	W 122° 40.721’	11:23pm	11:33pm	10 min	1 min
8 – H	N 45° 33.911’	W 122° 40.718’	11:32pm	11:39pm	7 min	1 min
9 – I	N 45° 34.000’	W 122° 40.715’	11:40pm	11:47pm	7 min	2 min
10 – J	N 45° 34.072’	W 122° 40.711’	11:49pm	11:58pm	9 min	1 min
11 – K	N 45° 34.156’	W 122° 40.718’	11:59pm	00:11am	12 min	1 min
12 – L	N 45° 34.239’	W 122° 40.719’	00:12am	00:20am	8 min	1 min
13 – M	N 45° 34.320’	W 122° 40.719’	00:21am	00:31am	10 min	1 min
14 – N	N 45° 34.407’	W 122° 40.717’	00:32am	00:42am	10 min	1 min
15	N 45° 34.482’	W 122° 40.718’	00:43am			

The research team observed 14 placements of the HOV markers. There were a total of 21 placements. During that time period the research team conducted 5-minute safety surveys, took pictures, and completed the data collection worksheet. A map showing the approximate locations of the HOV placements relative to the sensors is shown in Figure 3.16.

Figure 3.16: Location of the HOV Placements Relative to the Locations of Speed Sensors (Case Study #5)

Table 3.7 shows the relative distances between the sensors and the work locations. Work ended at approximately 2:00 a.m., and the crews proceeded to their bases (Milwaukie and I-205 laydown yard). The three crash trucks followed the research team to collect the sensors and at 2:35 a.m. the research team returned to the striping crew office in Milwaukie.

Table 3.7: Distance between Work Locations and Sensor Placement (Case Study #5)

Work Location	Distance to Work Location (miles)			
	Sensor 1	Sensor 2	Sensor 3	Sensor 4
WZ1	0	-0.4	-0.95	-1.7
WZ2	0.1	-0.3	-0.85	-1.6
WZ3	0.19	-0.21	-0.76	-1.51
WZ4	0.28	-0.12	-0.67	-1.42
WZ5	0.37	-0.03	-0.58	-1.33
WZ6	0.47	0.07	-0.48	-1.23
WZ7	0.56	0.16	-0.39	-1.14
WZ8	0.65	0.25	-0.3	-1.05
WZ9	0.75	0.35	-0.2	-0.95
WZ10	0.84	0.44	-0.11	-0.86
WZ11	0.95	0.55	0	-0.75
WZ12	1.02	0.62	0.07	-0.68
WZ13	1.12	0.72	0.17	-0.58
WZ14	1.21	0.81	0.26	-0.49
WZ15	1.3	0.9	0.35	-0.4

3.10.2 Observations

The researchers observed normal traffic speeds for that section of freeway on the B- and C-lanes next to the MBT-1®.

3.10.3 Summary of Survey Responses

There were a total of six surveys completed by the supervisors and crews. Three supervisor surveys were completed: two from the supervisors present from the striping crews and one from the Region 1 Safety supervisor. Three worker surveys were completed. (Note: Two of the worker surveys were not scanned clearly and a hardcopy was requested but not received. The responses from the supervisors and only one worker survey are included in the research data). Table 3.8 provides a summary of the responses to each question in regards to which condition is better (or no difference).

Table 3.8: Summary of Worker and Supervisor Survey Responses (Case Study #5)

	Which is better: mobile barrier or traditional traffic control measures?	Supervisor Survey			Worker Survey		
		MB	Both	Traditional	MB	Both	Traditional
Q1	Ease of movement	1	1	1	0	0	1
Q2	Access to equipment	1	1	1	0	0	1
Q3	Ability to see worksite	1	1	1	0	0	1
Q4	Ability to complete work tasks with high quality	2	1	0	0	0	1
Q5	Ability to complete work tasks efficiently	1	1	1	0	0	1
Q6	Worker safety	2	0	0	0	0	1
Q8	Worker productivity	2	0	1	0	0	1
	Total responses	10	5	5	0	0	1

The four respondents provided the following responses to the open-ended survey questions (Q7, Q9-Q13):

- Q7: Why do you feel safer? (Explain your answer to Q6)
    - The supervisors stated that the workers feel safer, traffic noise is baffled, and workers do not step into traffic accidentally.

- Q9: Why is there higher/lower productivity? (Explain your answer to Q8)
    - One comment recorded a perception that the MBT-1® is big and the crews can move faster without it. The respondent felt that even though the mobile barrier is safer, productivity would be fine without it.
    - Two respondents stated that the workers can focus on work tasks better with the barrier and therefore are more productive.
- Q10: Supervision
    - One response stated that there is a higher need for preplanning, but during the work, supervision is better with the barrier.
- Q11: Limitations
    - One respondent felt that in one lane operations, there might be difficulty in moving equipment in the work area.
- Q12: Enhancements
    - Wider lanes enhance the use of the mobile barrier.
- Q13: Other comments
    - One respondent felt that the size of the barrier limits some of its uses, but it provides great protection for workers especially next to traffic.
    - One respondent suggested that there should be a camera facing the work zone inside the barrier so that the driver would not have to step out of the truck and to position the barrier easier in situations such as those observed.

3.11 CASE STUDY #6 – I-205 MP3

The site that was selected for the sixth case study was the repair of a seal joint on the northbound lane on I-205 near MP 3 over the Tualatin River. The work took place during the nights of September 28 and 29, 2012 (Friday and Saturday nights). Traditional safety measures were used on the first night (September 28) while the MBT-1® was used the second night (September 29).

3.11.1 Case Study Narrative

Day 1 – Without Mobile Barrier

The research team met at 9:00 p.m. with a person from the ODOT District 2B Bridge crew and two crash trucks on the southbound Exit #3 on-ramp of I-205. After a brief talk and an explanation of where the speed measuring devices needed to be placed, the research team with the ODOT personnel started the installation of the sensors at 9:25 p.m.

Two sensors were placed on the A- and B-lanes next to the Exit #3 off-ramp on I-205 northbound (N45^{o} 22.290’, W122^{o} 42.713’). Two additional sensors were placed on the A- and B-lanes next to the Exit #3 on-ramp on I-205 (N45^{o} 22.125’, W122^{o} 42.122’). One sensor was placed on the A-lane at the end of the traffic control barrel taper prior to the work zone (N45^{o} 22.036’, W122^{o} 41.694’), and a final sensor was placed on the A-lane next to the location of the work (N45^{o} 21.981’, W122^{o} 41.254’).

The distance between the first and second sets of sensors was approximately 2,700 feet. The distance between the second set of sensors and the sensor next to the taper was approximately 1,900 feet. The distance between the sensor at the end of the taper and the sensor next to the work site was approximately 1,900 feet. A map showing the location of the sensors relative to the worksite is shown below in Figure 3.17.

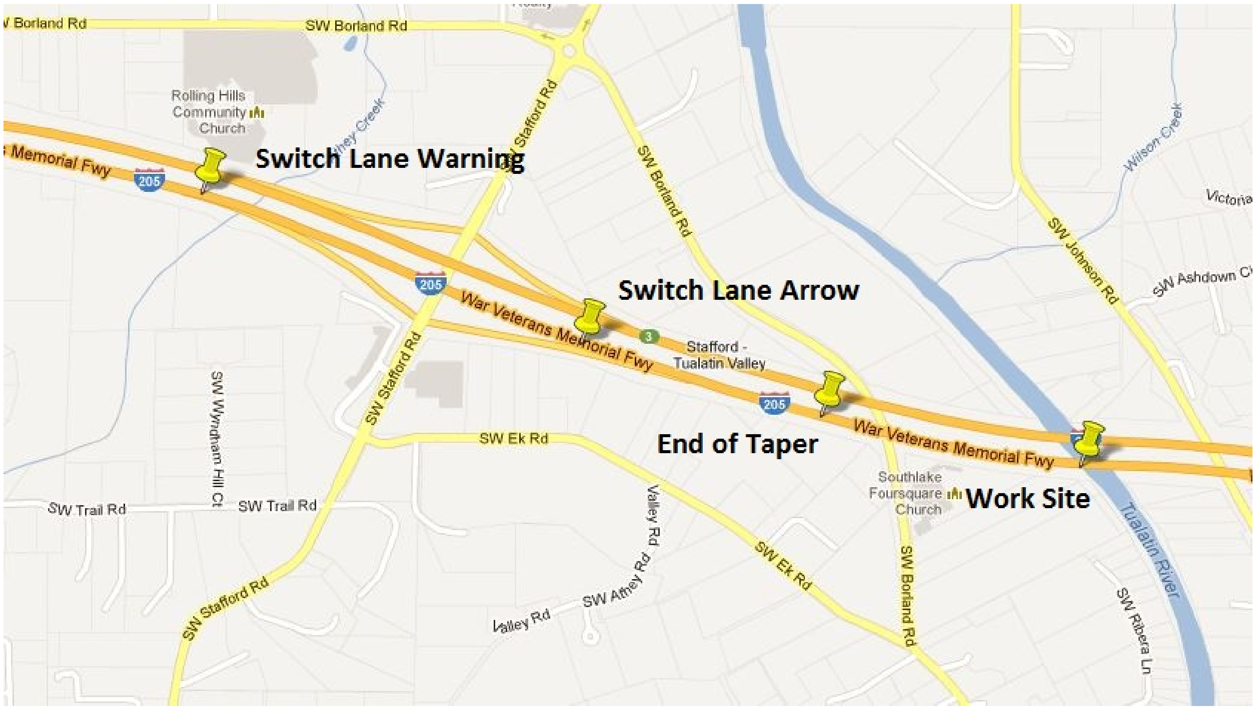

Figure 3.17: Location of Speed Sensors relative to the Work Site (Case Study #6)

The traffic control cone placement started at 9:50 p.m. and finished at approximately 10:05 p.m. The installation of the sensors ended at 9:55 p.m. and the research team headed to the worksite at 10:15 p.m. The bridge crew was already at the site and work started at about that time (10:15 p.m.).

Present at the worksite were seven members of the bridge crew, along with several vehicles. All vehicles were parked in the B-lane and the shoulder. The following vehicles were present:

- 1 pickup truck with a generator hitched to the back
- 1 work van
- 1 pickup truck with a trailer carrying materials and equipment
- 1 portable light post with its generator
- 1 truck carrying the sand blasting material needed for the work
- 1 truck belonging to the ODOT personnel that helped the researchers place the sensors
- 1 truck carrying the portable toilet
- 2 crash trucks (parked on the B-lane further back from the site as per traffic control plan)

The following work operations took place during the repair of the joint seal:

- Cut existing concrete using concrete saw
- Jackhammer out the concrete and remove debris and existing joint
- Sandblast exposed concrete
- Prepare and install new joint
- Prepare and install new fast-setting concrete

Pictures from the night's work are shown in Figure 3.18 (jackhammering), Figure 3.19 (sandblasting and sealing), and Figure 3.20 (welding & placement of mortar).

Figure 3.18: Jackhammering and Concrete Cutting (left); Dust from Concrete Cutter 'Fogging' Work Area (right) (Case Study #6)

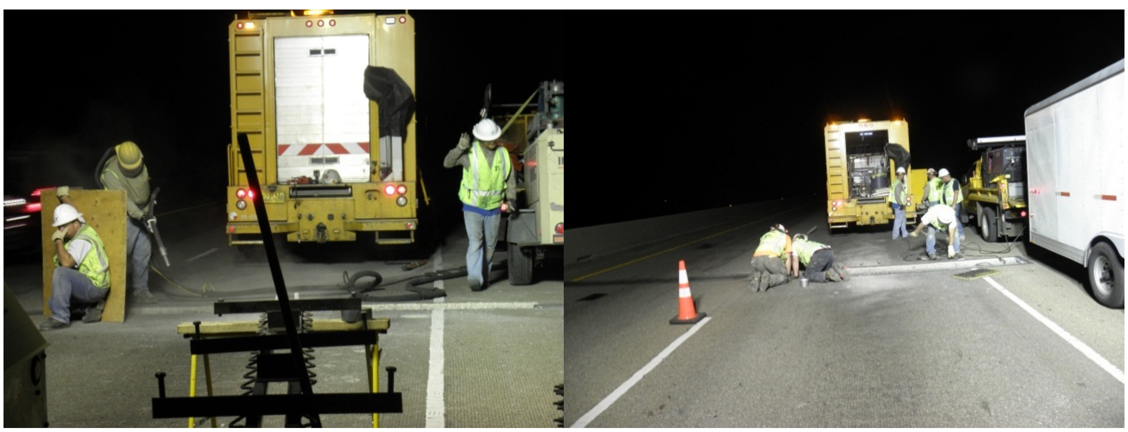

Figure 3.19: Sandblasting (left);Workers Working on Joint (right) (Case Study #6)

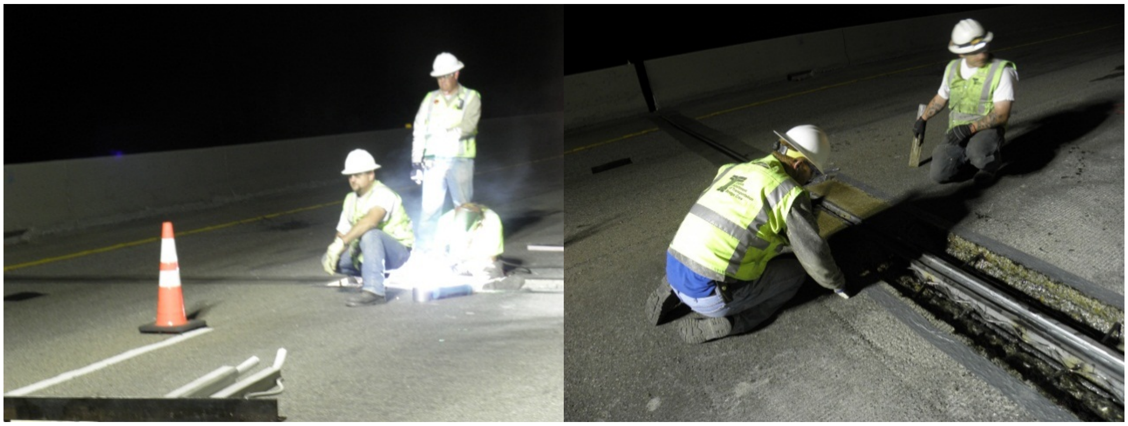

Figure 3.20: Welding of the Joint (left); Placing Concrete (right) (Case Study #6)

The bridge crew finished work on the B-lane joint at 3:52 a.m. Afterwards the research team headed with the ODOT personnel and the crash trucks out of the work zone to collect the sensors from the road. Collection of the sensors and removal of traffic control ended at 4:37 a.m. During the night the researchers completed the work site worksheet, noting down the layout of the site and information regarding the work performed and the site conditions.

Day 2 – With Mobile Barrier

The research team met at 9:00 p.m. with a person from the ODOT District 2B Bridge crew. Since the placement of the sensors was to take place at the exact locations as the night before, there was no need for much discussion of their placement with the traffic control crash trucks, and the research team met the trucks on northbound I-205 at about 9:15 p.m. and started with the placement of the sensors.

Two sensors were placed on the A- and B-lanes next to the Exit #3 off-ramp on I-205 northbound (N45^{o} 22.294’, W122^{o} 42.716’). Two additional sensors were placed on the A- and B-lanes next to Exit #3 on-ramp on I-205 (N45^{o} 22.156’, W122^{o} 42.233’). One sensor was placed on the B-lane at the end of the traffic control barrel taper prior to the work zone (N45^{o} 22.031’, W122^{o} 41.681’), and a final sensor was placed on the B-lane next to the location of the work (N45^{o} 21.980’, W122^{o} 41.257’).

The distance between the first and second sets of sensors was approximately 2,700 feet. The distance between the second set of sensors and the sensor next to the taper was approximately 1,900 feet. The distance between the sensor at the end of the taper and the sensor next to the work site was approximately 1,900 feet.

The traffic control cone placement started at 9:50 p.m. and finished at about 10:00 p.m. The installation of the sensors ended at 9:55 p.m. The mobile barrier departed from the I-205 laydown yard at 9:50 p.m. and arrived at the site at 10:00 p.m. along with all the vehicles that needed to be at the worksite. The research team headed to the worksite at 10:15 p.m. The bridge crew was already at the site and work had started at about 10:00 p.m.

Present at the worksite were seven members of the bridge crew, along with several vehicles. All vehicles were parked on the A-lane and the shoulder. The following vehicles were present:

- 1 pickup truck with a generator hitched to the back
- 1 MBT-1®
- 1 work van
- 1 pickup truck with a trailer carrying materials and equipment
- 1 truck carrying the sand blasting material needed for the work
- 1 truck belonging to the ODOT personnel that helped the researchers place the sensors
- 1 truck carrying the portable toilet
- 2 crash trucks (parked on the B-lane further back from the site as per traffic control plan)

The researchers completed the work site worksheet, noting down the layout of the site and information regarding the work performed and the site conditions. The work that took place was identical as the previous night with the only difference being that the work was performed on the A-lane instead of the B-lane. Pictures from the night's work are shown in Figure 3.21 (saw cutting and jackhammering of concrete), and Figure 3.22 (placement of steel joint and removal of wrong concrete mix).

Figure 3.21: Workers Cutting Concrete (left); Workers Jackhammering Concrete (right) (Case Study #6)

Figure 3.22: Workers Placing Joint (left); Workers Removing Concrete (right) (Case Study #6)

The bridge crew saw about 45 minutes of productivity increase over the course of the night. At the final stage though when they were placing the concrete, they discovered that for one batch of concrete they did not add the accelerator, and the workers had to remove the concrete and mix another batch. That removal and remixing of the concrete eliminated all the time gains they had accumulated.

The productivity increases were due to the availability of all the crew to work. During the previous night, one person spent time as a "spotter" for people working close to the active lane. A spotter was not needed with the mobile barrier.

The bridge crew finished work on the B-lane joint at 4:06 a.m. and right after the research team headed with the ODOT personnel and the crash trucks out of the work zone to collect the sensors from the road. Collection of the sensors and removal of traffic control ended at 4:46 a.m.

3.11.2 Observations

Day 1 –Without Mobile Barrier:

During the work operations, the researchers performed 5-minute safety surveys at 11:00 p.m., 12:07 a.m., 12:58 a.m., and 1:58 a.m. The worksite was busy, but there was enough room for all of the workers to move around safely. The researchers observed the following worksite conditions and work operations during their 5-minute surveys:

- The speeds of the vehicles close to the work zone were very high.
- Debris from the work zone was 'flying around' inside the A-lane.
- Workers would step into the A-lane to retrieve debris.
- The work location forced workers to step into the A-lane past the coned section.
- Dust from the concrete saw 'fogged' both lanes and the work zone.
- Glare from the welding operations was very bright for drivers.
- On occasions, a person working next to the A-lane was not spotted by other workers.

Day 2 – With Mobile Barrier:

During the work operations, the researchers performed 5-minute safety surveys at 11:25 p.m., 1:05 a.m., and 2:28 a.m. The worksite was busy and crowded, but there was enough room for all of the workers to move around safely. Several observations were noted:

- Debris and dust from the work zone was 'flying around' inside the B-lane from under the mobile barrier.
- Dust from the concrete saw 'fogged' the work zone.
- The work zone was crowded, since there was a smaller shoulder adjacent to the A-lane.

3.11.3 Summary of Survey Responses

There were a total of six surveys collected from the workers on site. Table 3.9 shows the number of responses to each question in regards to which is better (or no difference).The respondents provided the following responses to the open-ended survey questions (Q7, Q9-Q12 for worker survey):

- Q7: Why do you feel safer? (Explain your answer to Q6)
    - The workers said that they did not notice the traffic, did not need to have a spotter, and can focus on tasks better.
- Q9: Why is there higher/lower productivity? (Explain your answer to Q8)
    - The workers indicated that they did not have to pay attention to the traffic; a spotter was not needed so more workers were available to do the work, and they could move freely within the worksite.
- Q10: Limitations
    - The shoulder next to the A-lane was too narrow and was a little crowded (mentioned on two survey responses).
- Q11: Enhancements
    - The MBT-1® is great for multiple lanes and wider shoulders.
- Q12: Other comments
    - The respondents stated that: (1) there was no need to think about traffic; (2) the MBT-1® provides protection for workers and public and provides a high visual presence; and (3) the MBT-1® is great for safety, especially at night.

Table 3.9: Summary of Worker Survey Responses (Case Study #6)

	Which is better: mobile barrier or traditional traffic control measures?	Bridge Crew		
		MB	Both	Traditional
Q1	Ease of movement	6	0	0
Q2	Access to equipment	4	1	1
Q3	Ability to see worksite	3	2	1
Q4	Ability to complete work tasks with high quality	6	0	0
Q5	Ability to complete work tasks efficiently	5	1	0
Q6	Worker safety	6	0	0
Q8	Worker productivity	3	2	0
	Total responses	33	6	2

4.0 ANALYSIS

Following the completion of all of the case studies, the researchers analyzed the case study data to determine the impacts, benefits, and limitations of using the mobile barrier. Where possible based on the case study conditions, comparisons are made between the instances when the mobile barrier was used and when the mobile barrier was not used. This section of the report includes the following analyses of the data:

- Vehicle speed analyses for all case studies. The vehicle speed analyses are performed to determine driver behavior while driving in a lane adjacent to the MBT-1® compared to driving in a lane with a work zone consisting of only traditional safety measures. Vehicle speed, and variability between the speeds of the passing vehicles, are used to assess worker and driver safety, and mobility through the work zone. Higher speeds are assumed to be an indicator of greater mobility.

- Financial analyses of Region 1 Maintenance operations. Financial analyses of ODOT Region 1 Maintenance operations are performed to determine which Region 1 Maintenance operations take place most often. Those most often undertaken were assumed to coincide with the greatest financial expenditure. Some activities were identified as being more suitable for MBT-1® use while others were less suitable. This research scope focuses on ODOT's work practices and this analysis will facilitate determining, according to the volume of work performed, the extent to which ODOT will benefit the most by using the MBT-1®.

- Time analysis for the MBT-1® for switching directions of the MBT-1® and for adding/removing a wall section. The time analyses were performed to determine the expected time for inexperienced crews to perform the work necessary to switch the direction of the MBT-1® and to add/remove a wall section.

4.1 CASE STUDY 1 – I-205 FREMONT BRIDGE

The characteristics of this case study permitted several different analyses. The analysis section for this case study includes the following:

- A discussion on the procedure for the placement of the speed sensors
- A discussion on the data used for the analysis
- Initial descriptive statistics for the data that was collected from each sensor
- Comparisons of speeds between the two nights of the study
- Comparisons of speeds between different locations along the path of the vehicles

4.1.1 Sensor Setup and Data Collection

As described in Section 3.6.1, eight sensors were placed on the northbound lanes of I-205, both on the approach and on the Fremont Bridge, on both nights of the case study investigation. The speed sensors recorded vehicle speeds and lengths for every vehicle that passed over the sensors.

The recorded vehicle data was downloaded from the sensors for the analysis. For each sensor location on each day, the research team created tables and figures showing the variability of the speeds over regular time intervals. The information generated is voluminous and too extensive to include in the body of this report. Therefore, only the tables associated with the sensor that was placed adjacent to the work zone on the first night with the MBT-1® present (sensor #684) are shown below. The vehicle data recorded by the other sensors is shown in Appendix H. The information for all of the other sensors is presented in the Appendix in a fashion similar to that presented for sensor #684 described below.

Table 4.1 shows the time summary of vehicle speeds from sensor #684 that was collected during the period of the investigation. The MBT-1® was present during the first night of the case study (December 2) and not used on the second night (December 3). The speeds are grouped into 5 mph increments and these increments are shown in the first column of the table. The second column labeled "Total" shows the vehicle speed information for the complete duration of the study (all hours combined) for sensor #684. The following columns show the information collected for each half hour of the study period. The values shown represent the percentage of vehicles in each speed increment. In addition, the table shows the total number of vehicles for that day, average speed of all vehicles for that day, standard deviation of the speeds, the 85th percentile of all vehicle speeds, the minimum and maximum speeds for that day and time period, and the range of all vehicle speeds. The yellow bars and red bars provide a graphical view of the distribution of vehicle speeds. The yellow bars show that the speed for all vehicles is approximately normally distributed, with a midpoint in the 45-49 mph range. The red bars reveal that the speed distribution changes from one time period to the next time period (Note: Blank cells in the table indicate time segments in which no or only one vehicle was recorded and a measurable statistic could not be produced).

The total number of vehicles row in the table shows the traffic volume for that day. This information may not be consistent among different traffic sensors placed in sequence, since the vehicles can only be recorded if their drivers pass over each particular sensor. In some cases, depending on the location of each sensor in the lane, some vehicles may not travel over the sensor and therefore not be recorded. The traffic data collected (see Appendix H) shows that this is not a common occurrence. The vehicle counts from one sensor to the next are similar after taking into consideration lane changes.

Table 4.2, Table 4.3 , Table 4.4, and Table 4.5 show similar information to that shown Table 4.1, but the information is separated according to the length (type) of the vehicles being measured. The vehicles are categorized into four length categories. Table 4.2 shows the speed information for vehicles less than 25 feet long, which are normal passenger cars and small pick-ups without a trailer. Table 4.3 shows speeds for vehicles between 25 and 50 feet long, which are mostly long vans, one trailer pick-ups, and small trucks. Table 4.4 shows the speeds for vehicles from 50 to 75 feet in length, which are mid-size, semi-trucks with trailers. Table 4.5 shows the speeds for vehicles longer than 75 feet, which are long trucks. The tables described above and their interpretation are an example of how to understand the additional sensor tables provided in Appendix H (Note: Similar to Table 4.1, blank cells in the tables indicate time segments in which no or only one vehicle was recorded and a measurable statistic could not be produced).

Table 4.1: Time Summary of Vehicle Speed (Sensor #684 WZ December 2)

Vehicle Speed (all vehicles)	Total	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430	0430-0630	0630-0830	0830-1030	1030-1230	1230-1430	1430-1630	1630-1830	1830-1930	1930-2030	2030-2130	2130-2230	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430
MPH																								
< 10	4.3%	2.8%	1.7%	2.3%	2.7%	2.0%	4.8%	2.2%	9.8%	9.0%	7.3%	8.7%	5.7%	6.0%	7.8%	5.3%	2.6%	3.0%	3.6%	3.6%	5.8%	25.0%	100.0%	20.0%
10-14	1.7%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.9%	8.5%	2.2%	0.3%	0.3%	0.0%	0.0%	0.0%
15-19	6.7%	0.3%	0.1%	0.6%	0.0%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	18.1%	33.5%	9.2%	0.2%	0.7%	20.8%	0.0%	0.0%
20-24	7.5%	2.0%	0.1%	0.0%	0.0%	1.0%	0.0%	0.0%	0.8%	0.0%	0.0%	0.2%	0.2%	0.0%	0.0%	0.8%	16.8%	38.0%	8.0%	1.4%	1.4%	4.2%	0.0%	0.0%
25-29	4.4%	4.9%	0.3%	0.4%	0.3%	1.0%	0.0%	0.0%	1.6%	0.4%	0.0%	0.2%	1.1%	0.5%	0.6%	0.0%	15.2%	13.6%	6.5%	5.1%	1.7%	0.0%	0.0%	0.0%
30-34	3.6%	11.6%	0.8%	1.6%	0.8%	1.5%	0.0%	0.0%	0.8%	0.0%	0.2%	0.0%	1.0%	0.5%	0.6%	1.5%	2.9%	2.7%	8.7%	6.9%	2.7%	12.5%	0.0%	0.0%
35-39	6.0%	16.8%	6.3%	4.5%	1.6%	5.1%	0.0%	0.0%	0.8%	0.7%	0.2%	0.0%	1.1%	1.2%	1.7%	0.8%	4.5%	0.4%	15.2%	14.0%	8.2%	12.5%	0.0%	10.0%
40-44	9.4%	19.9%	17.1%	11.8%	13.7%	11.7%	4.8%	0.0%	0.8%	1.1%	0.2%	1.2%	1.5%	3.1%	3.4%	0.8%	2.3%	0.2%	17.9%	17.4%	22.0%	8.3%	0.0%	20.0%
45-49	13.1%	19.5%	28.7%	24.3%	24.1%	22.8%	4.8%	15.6%	1.6%	4.3%	3.4%	4.9%	5.0%	11.1%	10.6%	11.5%	5.8%	0.2%	14.1%	22.0%	19.2%	16.7%	0.0%	20.0%
50-54	12.7%	12.2%	25.3%	23.9%	28.7%	23.9%	33.3%	17.8%	15.4%	6.9%	9.6%	6.9%	10.5%	14.2%	22.3%	19.8%	8.7%	0.0%	9.2%	14.0%	16.5%	0.0%	0.0%	0.0%
55-59	12.6%	6.4%	12.9%	20.2%	16.6%	12.7%	14.3%	28.9%	22.8%	21.7%	23.9%	24.4%	23.1%	30.0%	25.1%	26.7%	7.1%	0.0%	2.9%	7.1%	11.0%	0.0%	0.0%	0.0%
60-64	8.0%	2.2%	3.8%	5.6%	8.0%	9.1%	9.5%	17.8%	20.3%	17.0%	23.4%	24.8%	21.0%	15.9%	11.7%	11.5%	4.5%	0.0%	1.5%	5.1%	4.5%	0.0%	0.0%	0.0%
65-69	4.8%	0.6%	1.8%	3.3%	2.1%	2.5%	14.3%	8.9%	16.3%	15.2%	16.1%	13.6%	14.9%	9.4%	4.5%	9.2%	2.9%	0.0%	0.7%	1.7%	2.4%	0.0%	0.0%	20.0%
70-74	2.0%	0.1%	0.6%	1.0%	1.1%	2.5%	0.0%	2.2%	4.1%	6.5%	6.0%	6.9%	5.5%	3.4%	4.5%	3.8%	1.3%	0.0%	0.3%	0.3%	1.7%	0.0%	0.0%	0.0%
>=75	3.1%	0.3%	0.6%	0.4%	0.3%	3.0%	14.3%	6.7%	4.9%	17.3%	9.6%	8.1%	9.2%	4.8%	7.3%	8.4%	3.2%	0.0%	0.0%	0.8%	1.7%	0.0%	0.0%	10.0%
Total # of vehicles	8846	1023	719	485	373	197	21	45	123	277	436	492	523	416	179	131	309	1319	861	591	291	24	1	10
Average speed	43.7	41.5	48.3	49.4	49.8	50.0	57.0	57.1	53.6	58.6	57.8	56.6	57.3	54.2	52.7	54.8	34.7	20.0	35.9	43.4	45.1	24.5	0.0	60.6
St. Dev.	18.9	13.4	9.7	11.1	10.8	12.8	17.0	12.8	20.2	21.5	18.4	19.6	17.7	16.5	18.3	16.6	19.3	5.6	14.0	13.0	15.3	17.2		71.9
85th percentile	61.0	52.0	56.0	57.0	57.0	60.6	68.0	67.0	67.0	76.0	70.0	69.4	69.0	66.0	65.3	66.5	57.8	25.0	49.0	54.5	57.0	43.7	0.0	69.0
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	254.0	254.0	82.0	80.0	80.0	82.0	82.0	86.0	87.0	95.0	94.0	94.0	96.0	90.0	88.0	0.0	92.0	49.0	70.0	80.0	81.0	49.0	0.0	254.0
Range	254.0	254.0	82.0	80.0	80.0	82.0	82.0	86.0	87.0	95.0	94.0	94.0	96.0	90.0	88.0	0.0	92.0	49.0	70.0	80.0	81.0	49.0	0.0	254.0

Table 4.2: Time Summary of Vehicle (0-25 feet long) Speed (Sensor #684 WZ December 2)

Vehicle Speed (0-25 FT Vehicles)	Total	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430	0430-0630	0630-0830	0830-1030	1030-1230	1230-1430	1430-1630	1630-1830	1830-1930	1930-2030	2030-2130	2130-2230	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430
MPH																								
< 10	4.7%	3.0%	1.8%	2.5%	3.0%	2.3%	6.3%	2.8%	10.3%	10.5%	8.0%	9.6%	6.4%	6.6%	8.5%	6.0%	2.8%	3.2%	4.0%	3.9%	6.4%	25.0%	100.0%	40.0%
10-14	1.8%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.2%	8.6%	2.5%	0.4%	0.4%	0.0%	0.0%	0.0%
15-19	7.1%	0.3%	0.1%	0.7%	0.0%	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	19.0%	34.5%	9.7%	0.2%	0.7%	20.8%	0.0%	0.0%
20-24	7.7%	1.9%	0.1%	0.0%	0.0%	1.1%	0.0%	0.0%	0.9%	0.0%	0.0%	0.2%	0.2%	0.0%	0.0%	0.9%	17.0%	38.1%	8.4%	1.3%	1.5%	4.2%	0.0%	0.0%
25-29	4.4%	4.9%	0.1%	0.5%	0.3%	1.1%	0.0%	0.0%	1.7%	0.4%	0.0%	0.2%	1.3%	0.5%	0.6%	0.0%	15.9%	13.0%	6.2%	5.5%	1.9%	0.0%	0.0%	0.0%
30-34	3.7%	11.9%	0.9%	1.8%	0.9%	1.1%	0.0%	0.0%	0.9%	0.0%	0.2%	0.0%	1.1%	0.5%	0.6%	1.7%	2.8%	2.3%	8.7%	7.4%	2.6%	12.5%	0.0%	0.0%
35-39	6.2%	16.7%	6.2%	4.6%	1.8%	5.7%	0.0%	0.0%	0.9%	0.8%	0.2%	0.0%	1.1%	1.3%	1.8%	0.9%	4.2%	0.2%	15.9%	14.5%	8.6%	12.5%	0.0%	0.0%
40-44	9.4%	20.0%	17.1%	11.2%	12.6%	10.3%	0.0%	0.0%	0.9%	1.3%	0.2%	1.3%	1.7%	3.5%	3.6%	0.9%	2.4%	0.0%	17.8%	18.2%	21.7%	8.3%	0.0%	40.0%
45-49	13.1%	19.0%	29.0%	25.3%	25.1%	24.7%	6.3%	19.4%	1.7%	4.6%	3.5%	5.1%	5.1%	12.0%	10.3%	12.1%	6.2%	0.0%	13.3%	20.6%	19.5%	16.7%	0.0%	0.0%
50-54	12.5%	12.5%	24.8%	22.6%	27.8%	24.1%	31.3%	19.4%	15.4%	7.1%	9.2%	7.1%	10.6%	14.9%	21.8%	21.6%	8.7%	0.0%	8.8%	13.8%	16.9%	0.0%	0.0%	0.0%
55-59	12.5%	6.6%	13.1%	20.5%	16.8%	12.1%	18.8%	25.0%	23.1%	20.9%	24.9%	23.8%	23.6%	29.0%	26.7%	23.3%	7.3%	0.0%	2.8%	7.4%	10.9%	0.0%	0.0%	0.0%
60-64	8.0%	1.9%	3.8%	5.9%	8.4%	9.2%	12.5%	19.4%	21.4%	17.2%	23.4%	24.7%	20.4%	16.5%	12.1%	12.9%	4.2%	0.0%	1.6%	5.0%	4.1%	0.0%	0.0%	0.0%
65-69	4.6%	0.5%	1.8%	3.2%	2.1%	2.3%	18.8%	11.1%	16.2%	15.9%	14.9%	14.7%	15.3%	8.0%	4.2%	10.3%	3.1%	0.0%	0.4%	0.9%	2.6%	0.0%	0.0%	0.0%
70-74	1.8%	0.1%	0.6%	1.1%	0.9%	1.7%	0.0%	2.8%	4.3%	7.1%	6.2%	6.7%	5.7%	3.5%	3.6%	2.6%	0.7%	0.0%	0.0%	0.4%	1.1%	0.0%	0.0%	0.0%
>=75	2.4%	0.3%	0.4%	0.2%	0.3%	2.9%	6.3%	0.0%	2.6%	14.2%	9.2%	6.7%	7.4%	3.7%	6.1%	6.9%	1.7%	0.0%	0.0%	0.7%	1.1%	0.0%	0.0%	20.0%
Total # of vehicles	8126	968	677	439	334	174	16	36	117	239	402	450	470	376	165	116	289	1243	774	544	267	24	1	5
Average speed	50.4	41.4	48.3	49.3	49.6	49.5	55.7	54.9	52.8	57.2	57.2	56	56	53	52	54	33	20	35	43	44	25	0	68
St. Dev.	11.7	13.5	9.8	11.4	11.2	12.9	17.2	11.9	20.2	22.3	18.9	20	18	17	18	17	18	5	14	13	15	17		106
85th percentile	61.0	52.0	56.0	57.0	57.1	60.0	66.5	64.0	66.6	74.0	70.0	69	69	65	64	65	56	25	49	54	56	44	0	127
Min	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	254.0	254.0	82.0	80.0	80.0	82.0	82.0	70.0	87.0	95.0	94.0	94.0	95.0	90.0	88.0	0.0	81.0	35.0	70.0	80.0	79.0	49.0	0.0	254.0
Range	243.0	254.0	82.0	80.0	80.0	82.0	82.0	70.0	87.0	95.0	94.0	94.0	95.0	90.0	88.0	0.0	81.0	35.0	70.0	80.0	79.0	49.0	0.0	254.0

Table 4.3: Time Summary of Vehicle (25-50 feet long) Speed (Sensor #684 WZ December 2)

Vehicle Speed (25-50 FT Vehicles)	Total	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430	0430-0630	0630-0830	0830-1030	1030-1230	1230-1430	1430-1630	1630-1830	1830-1930	1930-2030	2030-2130	2130-2230	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430
MPH																								
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			
10-14	0.8%	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.3%	0.0%	0.0%	0.0%			
15-19	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	15.6%	2.6%	0.0%	0.0%			
20-24	4.7%	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	17.6%	31.3%	5.3%	0.0%	0.0%			
25-29	4.7%	6.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.9%	26.6%	9.2%	0.0%	0.0%			
30-34	3.4%	8.3%	0.0%	0.0%	0.0%	5.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.9%	9.4%	7.9%	2.4%	4.8%			
35-39	4.2%	18.8%	2.9%	2.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.5%	0.0%	0.0%	0.0%	5.9%	3.1%	7.9%	7.3%	4.8%			
40-44	9.0%	12.5%	17.6%	14.3%	18.5%	26.3%	20.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.7%	18.4%	7.3%	23.8%			
45-49	13.2%	29.2%	26.5%	14.3%	11.1%	10.5%	0.0%	0.0%	0.0%	4.0%	3.7%	0.0%	2.5%	2.6%	14.3%	7.7%	0.0%	3.1%	22.4%	39.0%	14.3%			
50-54	14.2%	8.3%	32.4%	37.1%	37.0%	15.8%	40.0%	0.0%	33.3%	4.0%	14.8%	5.6%	10.0%	7.9%	28.6%	7.7%	5.9%	0.0%	14.5%	17.1%	9.5%			
55-59	13.5%	2.1%	11.8%	20.0%	18.5%	15.8%	0.0%	50.0%	33.3%	20.0%	7.4%	27.8%	20.0%	36.8%	7.1%	53.8%	5.9%	0.0%	2.6%	4.9%	14.3%			
60-64	9.6%	8.3%	2.9%	2.9%	7.4%	10.5%	0.0%	12.5%	0.0%	24.0%	22.2%	27.8%	27.5%	10.5%	7.1%	0.0%	11.8%	0.0%	1.3%	7.3%	9.5%			
65-69	6.8%	2.1%	2.9%	5.7%	3.7%	5.3%	0.0%	0.0%	0.0%	12.0%	33.3%	2.8%	7.5%	23.7%	7.1%	0.0%	0.0%	0.0%	3.9%	12.2%	0.0%			
70-74	3.4%	0.0%	0.0%	0.0%	3.7%	5.3%	0.0%	0.0%	0.0%	0.0%	3.7%	8.3%	5.0%	2.6%	14.3%	15.4%	11.8%	0.0%	3.9%	0.0%	9.5%			
>=75	10.3%	0.0%	2.9%	2.9%	0.0%	5.3%	40.0%	37.5%	33.3%	36.0%	14.8%	27.8%	25.0%	15.8%	21.4%	15.4%	29.4%	0.0%	0.0%	2.4%	9.5%			
Total # of vehicle	591	48	34	35	27	19	5	8	3	25	27	36	40	38	14	13	17	64	76	41	21	0	0	0
Average speed	53.6	43.2	50.6	51.8	52.3	52.5	61.0	67.5	61.3	67.3	64.6	66.4	65.3	63.8	62.4	61.6	57.2	25.4	43.0	51.2	53.8			
St. Dev.	12.6	10.8	7.5	7.7	7.5	11.5	17.8	13.3	15.5	11.5	9.4	9.6	12.8	10.9	13.9	9.5	25.2	7.8	12.5	9.7	13.9			
85th percentile	66.0	51.9	57.1	56.9	57.3	63.1	79.0	82.0	71.8	79.2	73.5	78.8	82.2	77.2	80.2	73.0	85.6	32.0	54.0	64.0	72.0			
Min	14.0	14.0	37.0	39.0	41.0	32.0	40.0	56.0	50.0	45.0	45.0	53.0	38.0	48.0	45.0	0.0	22.0	12.0	17.0	34.0	34.0			
Max	90.0	69.0	76.0	76.0	70.0	76.0	82.0	86.0	79.0	90.0	86.0	86.0	96.0	90.0	85.0	0.0	92.0	49.0	70.0	77.0	81.0			
Range	76.0	55.0	39.0	37.0	29.0	44.0	42.0	30.0	29.0	45.0	41.0	33.0	58.0	42.0	40.0	0.0	70.0	37.0	53.0	43.0	47.0			

Table 4.4: Time Summary of Vehicle (50-75 feet long) Speed (Sensor #684 WZ December 2)

Vehicle Speed (50-75 FT Vehicles)	Total	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430	0430-0630	0630-0830	0830-1030	1030-1230	1230-1430	1430-1630	1630-1830	1830-1930	1930-2030	2030-2130	2130-2230	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430
MPH																								
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%					0.0%	0.0%	0.0%	0.0%			0.0%
10-14	1.8%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%					12.5%	0.0%	0.0%	0.0%			0.0%
15-19	3.5%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%					12.5%	14.3%	0.0%	0.0%			0.0%
20-24	12.3%	20.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%					75.0%	0.0%	0.0%	0.0%			0.0%
25-29	3.5%	0.0%	33.3%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%					0.0%	14.3%	0.0%	0.0%			0.0%
30-34	1.8%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%					0.0%	14.3%	0.0%	0.0%			0.0%
35-39	8.8%	20.0%	33.3%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%					0.0%	14.3%	50.0%	0.0%			50.0%
40-44	8.8%	40.0%	0.0%	20.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%					0.0%	14.3%	50.0%	0.0%			0.0%
45-49	12.3%	20.0%	0.0%	20.0%	50.0%	0.0%		0.0%	0.0%	0.0%	0.0%	33.3%	50.0%					0.0%	14.3%	0.0%	0.0%			0.0%
50-54	19.3%	0.0%	33.3%	40.0%	50.0%	66.7%		100.0%	0.0%	20.0%	20.0%	0.0%	0.0%					0.0%	0.0%	0.0%	100.0%			0.0%
55-59	14.0%	0.0%	0.0%	20.0%	0.0%	0.0%		0.0%	0.0%	60.0%	20.0%	33.3%	50.0%					0.0%	14.3%	0.0%	0.0%			0.0%
60-64	3.5%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	40.0%	0.0%	0.0%					0.0%	0.0%	0.0%	0.0%			0.0%
65-69	5.3%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	100.0%	0.0%	20.0%	0.0%	0.0%					0.0%	0.0%	0.0%	0.0%			50.0%
70-74	3.5%	0.0%	0.0%	0.0%	0.0%	33.3%		0.0%	0.0%	0.0%	0.0%	33.3%	0.0%					0.0%	0.0%	0.0%	0.0%			0.0%
>=75	1.8%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	20.0%	0.0%	0.0%	0.0%					0.0%	0.0%	0.0%	0.0%			0.0%
Total # of vehicle	57	5	3	5	4	3	0	1	1	5	5	3	2	0	0	0	0	8	7	2	1	0	0	2
Average speed	50.9	38.0	39.3	49.6	49.5	58.0		53.0	69.0	61.6	60.0	59.7	53.0					20.3	37.3	41.0	53.0			52.0
St. Dev.	12.2	9.9	10.5	5.0	4.1	13.0				12.2	4.6	12.9	7.1					3.2	12.1	4.2				24.0
85th percentile	59.0	45.0	46.7	53.8	53.0	66.4		53.0	69.0	68.6	62.8	68.6	56.5					23.0	46.1	43.1	53.0			63.9
Min	22.0	22.0	29.0	43.0	45.0	50.0		53.0	69.0	53.0	54.0	49.0	48.0					14.0	18.0	38.0	53.0			35.0
Max	83.0	48.0	50.0	55.0	53.0	73.0		53.0	69.0	83.0	67.0	74.0	58.0					24.0	56.0	44.0	53.0			69.0
Range	61.0	26.0	21.0	12.0	8.0	23.0		0.0	0.0	30.0	13.0	25.0	10.0					10.0	38.0	6.0	0.0			34.0

Table 4.5: Time Summary of Vehicle (75+ feet long) Speed (Sensor #684 WZ December 2)

Vehicle Speed (+75 FT Vehicles)	Total	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430	0430-0630	0630-0830	0830-1030	1030-1230	1230-1430	1430-1630	1630-1830	1830-1930	1930-2030	2030-2130	2130-2230	2230-2330	2330-0030	0030-0130	0130-0230	0230-0330	0330-0430
MPH																								
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%
15-19	5.6%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	33.3%	50.0%	25.0%	0.0%	0.0%			0.0%
20-24	4.2%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	50.0%	0.0%	25.0%	0.0%			0.0%
25-29	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%
30-34	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	25.0%	0.0%	0.0%			0.0%
35-39	5.6%	0.0%	20.0%	16.7%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	33.3%	0.0%	25.0%	0.0%	0.0%			0.0%
40-44	15.3%	100.0%	20.0%	33.3%	50.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	25.0%	0.0%	50.0%			0.0%
45-49	11.1%	0.0%	20.0%	16.7%	12.5%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	50.0%	50.0%			66.7%
50-54	12.5%	0.0%	40.0%	33.3%	25.0%	0.0%			0.0%	0.0%	0.0%	0.0%	9.1%	0.0%		0.0%	33.3%	0.0%	0.0%	25.0%	0.0%			0.0%
55-59	15.3%	0.0%	0.0%	0.0%	12.5%	100.0%			0.0%	25.0%	50.0%	66.7%	9.1%	100.0%		50.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%
60-64	5.6%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	33.3%	27.3%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%
65-69	6.9%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%	12.5%	0.0%	0.0%	27.3%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			33.3%
70-74	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%	12.5%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%
>=75	15.3%	0.0%	0.0%	0.0%	0.0%	0.0%			100.0%	50.0%	50.0%	0.0%	27.3%	0.0%		50.0%	0.0%	0.0%	0.0%	0.0%	0.0%			0.0%
Total # of vehicle	72	2	5	6	8	1	0	0	2	8	2	3	11	2	0	2	3	4	4	4	2	0	0	3
Average speed	56.5	42.0	46.0	45.5	46.5	59.0			81.0	74.3	74.0	59.0	67.5	57.0		66.0	36.0	19.3	32.8	41.3	43.0			54.7
St. Dev.	16.5	2.8	6.0	5.4	6.2				2.8	12.9	21.2	3.0	10.4	1.4		14.1	16.7	2.5	11.9	13.1	2.8			12.5
85th percentile	79.2	43.4	52.0	51.3	53.0	59.0			82.4	85.0	84.5	61.1	80.0	57.7		73.0	47.4	21.1	41.2	49.2	44.4			63.0
Min	38.0	40.0	38.0	39.0	40.0	59.0			79.0	57.0	59.0	56.0	54.0	56.0		0.0	18.0	16.0	16.0	22.0	41.0			46.0
Max	92.0	44.0	52.0	52.0	56.0	59.0			83.0	92.0	89.0	62.0	86.0	58.0		0.0	51.0	22.0	43.0	51.0	45.0			69.0
Range	54.0	4.0	14.0	13.0	16.0	0.0			4.0	35.0	30.0	6.0	32.0	2.0		0.0	33.0	6.0	27.0	29.0	4.0			23.0

4.1.2 Speed comparisons

Figure 4.1shows the average and 85th percentile speeds as well as the number of vehicles for the duration of the study that were collected by sensor #683 which was the first sensor that was placed on the A-lane in the approach to the work zone. Figure 4.2shows the same information from sensor #687which was the first sensor placed on the B-lane in the approach to the work zone. Both of these figures show a steady flow of traffic during the times they were present on the road, with a few exceptions when there was a very low volume of traffic on the road and vehicles were seen to be speeding.

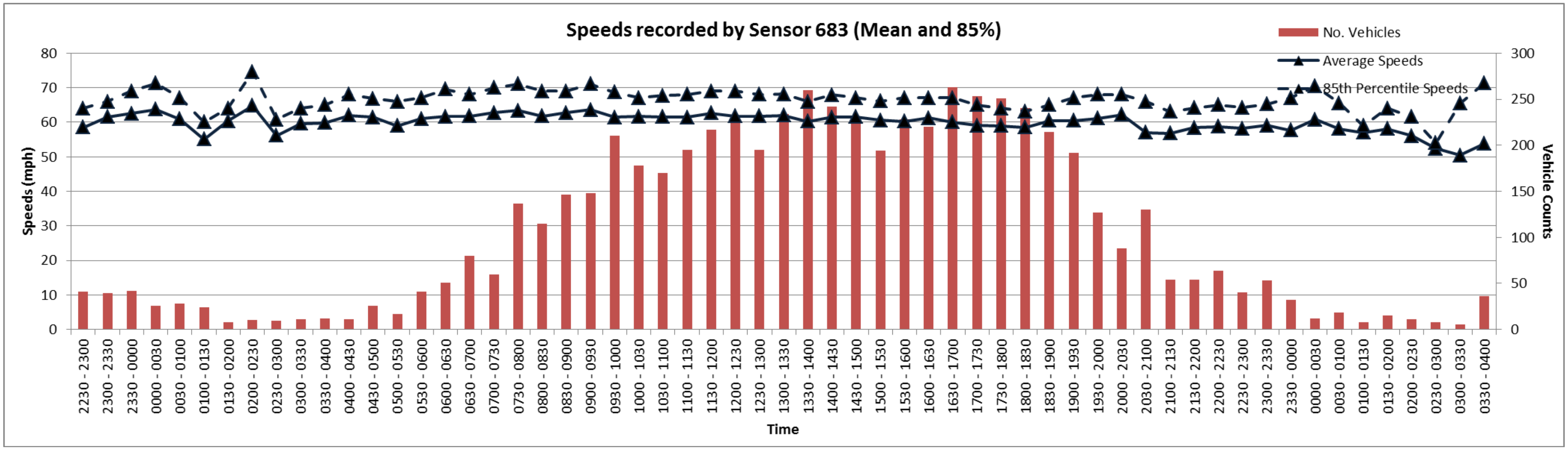

Figure 4.1: Average Speeds, 85th Percentile Speeds, and Vehicle Counts from Sensor #683

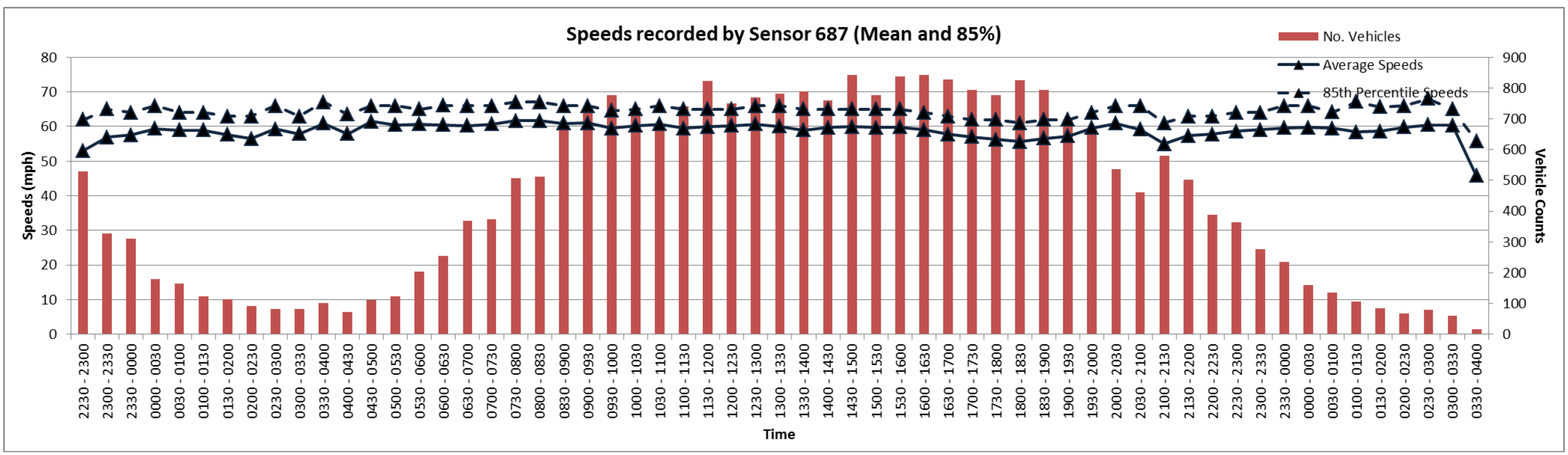

Figure 4.2: Average Speeds, 85th Percentile Speeds, and Vehicle Counts from Sensor #687

Figure 4.3 shows the average and 85th percentile speeds as well as the number of vehicles for the duration of the study that were collected by sensor #688 which was the second sensor that was placed on the B-lane in the approach to the work zone. Figure 4.4 shows the same information from sensor #181 that was the second sensor placed on the C-lane in the approach to the work zone. Both of these figures show a steady flow of traffic during the times they were present on the road, with one exception during the traffic control placement on the second night of the work (December 3) where the traffic was slowed down considerably.

Figure 4.5 and Figure 4.6 show the average and 85th percentile speeds as well as the number of vehicles for the duration of the study that were collected by sensors #685 and #184 respectively. Sensor #685 was placed at the end of the taper on the A-lane during the second night of the study (December 3). As observed in the figure, the sensor only recorded when the work was taking place on the B-lane. Sensor #184 was placed at the end of taper on the B-lane when the work was taking place on the A-lane. The sensor was recording vehicle activity during the whole duration of the study, and as observed when work was taking place on the B-lane, there were no vehicles passing over the sensor. During the traffic control procedures sensor #184 also recorded vehicle speeds that were much slower than all the other times in the study period.

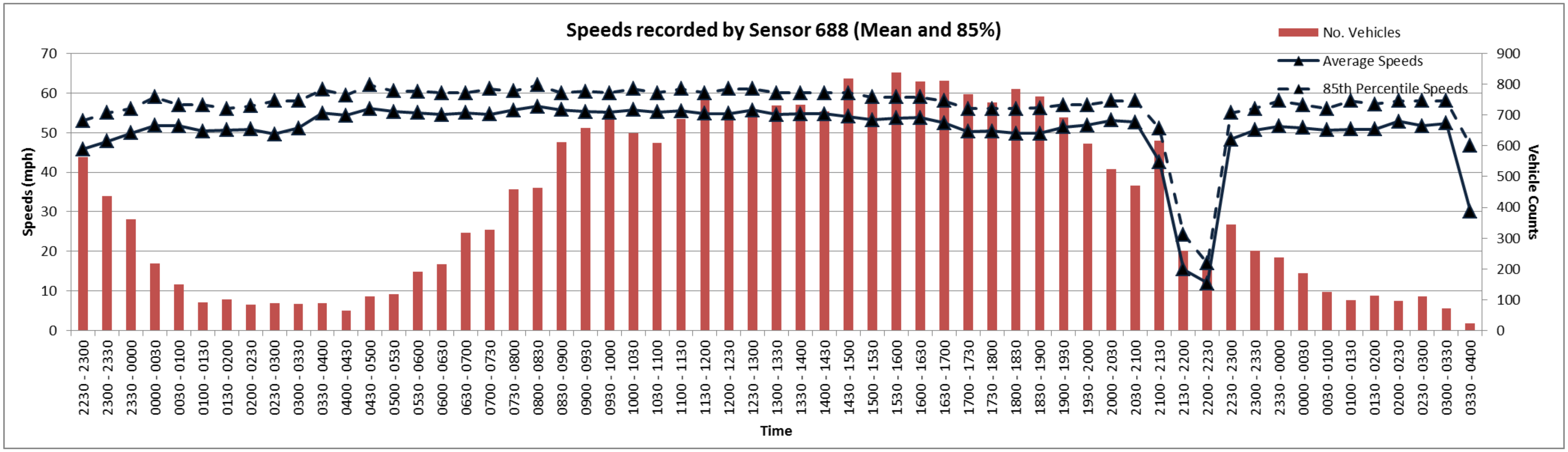

Figure 4.3: Average Speeds, 85th Percentile Speeds, and Vehicle Counts from Sensor #688

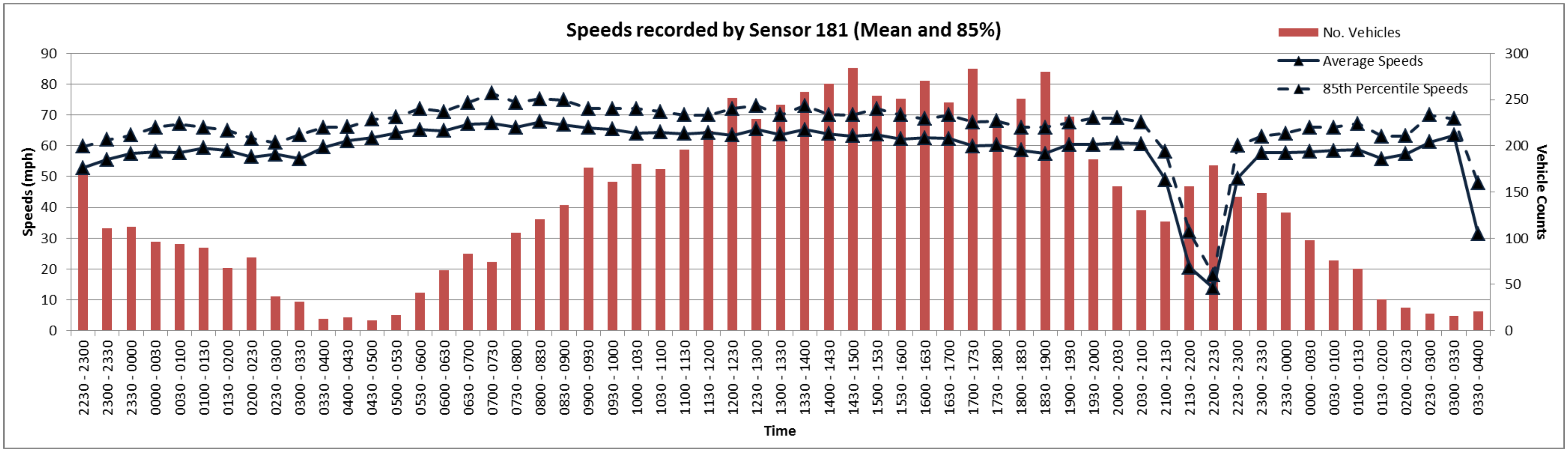

Figure 4.4: Average Speeds, 85th Percentile Speeds, and Vehicle Counts from Sensor #181

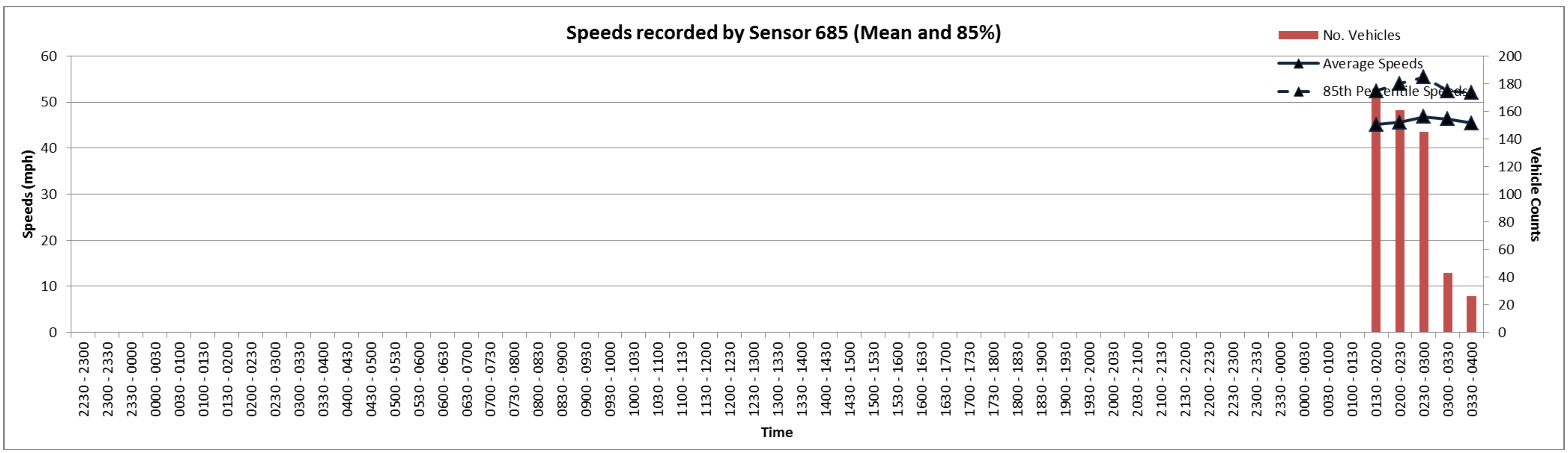

Figure 4.5: Average Speeds, 85th Percentile Speeds, and Vehicle Counts from Sensor #685

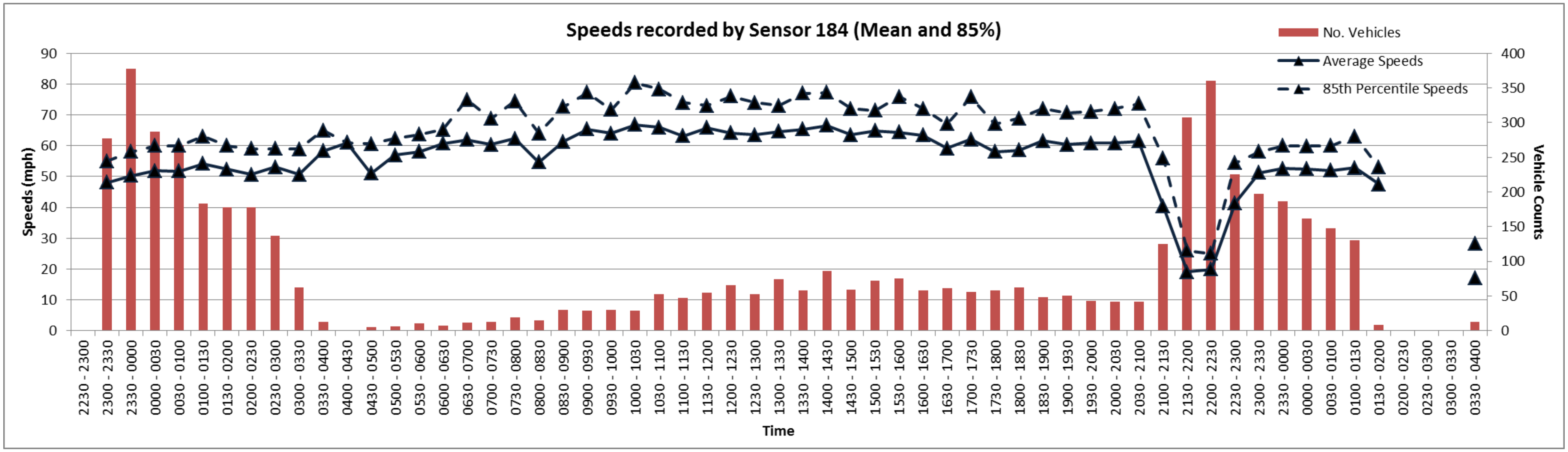

Figure 4.6: Average Speeds, 85th Percentile Speeds, and Vehicle Counts from Sensor #184

Figure 4.7 shows the average and 85th percentile speeds as well as the number of vehicles for the duration of the study that were collected by sensor #684 which was the sensor that was placed on the B-lane adjacent to the work zone during the first night of the study (December 2). Figure 4.8 shows the same information from sensor #686 which was the sensor that was placed on the A-lane adjacent to the work zone. That sensor was damaged during the study period and stopped recording sometime in the afternoon of December 3. As observed in the figure, there is a sudden decrease in the recorded speeds at approximately 11:00 a.m. of December 3, and the sensor eventually stopped recording at approximately 3:00 p.m. of the same day.

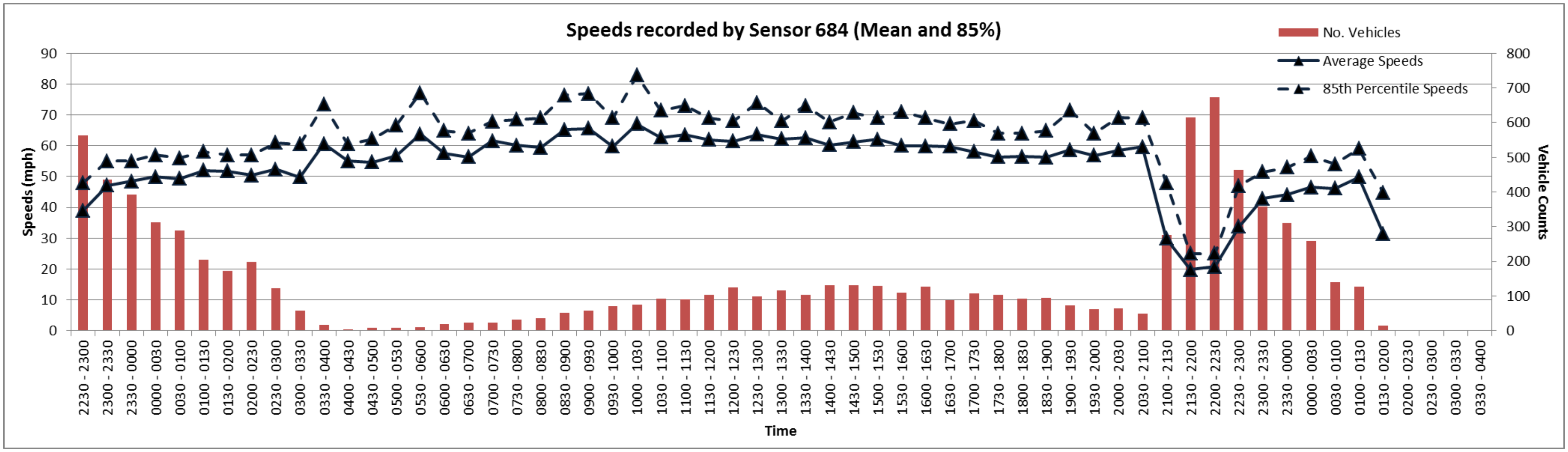

Figure 4.7: Average Speeds, 85th Percentile Speeds, and Vehicle Counts from Sensor #684

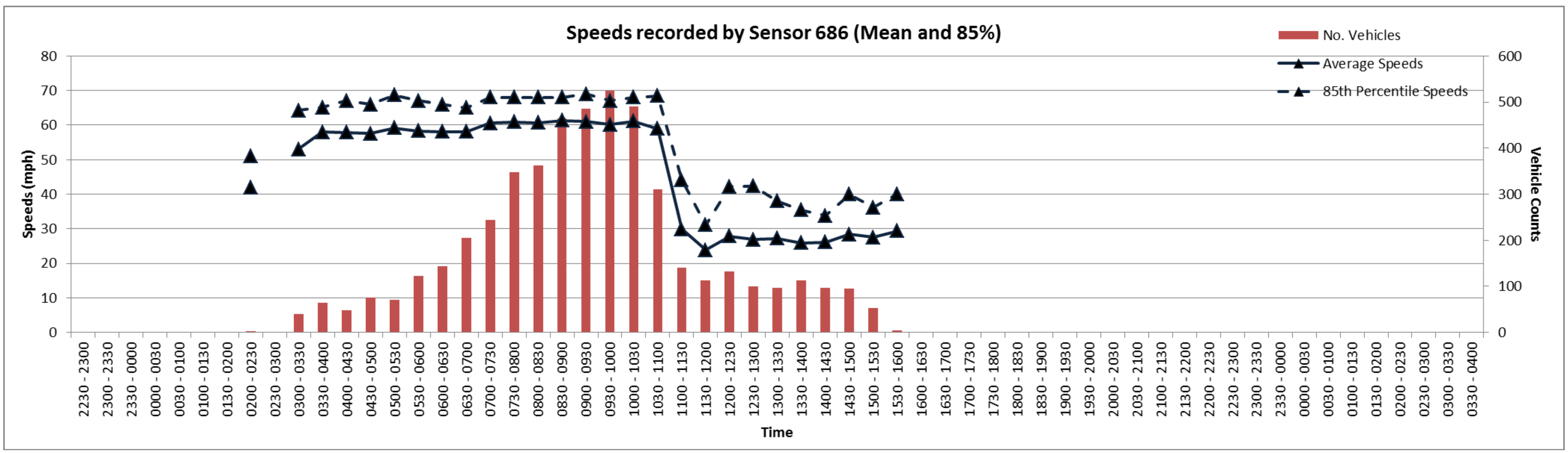

Figure 4.8: Average Speeds, 85th Percentile Speeds, and Vehicle Counts from Sensor #684

To facilitate a comparison of the vehicles speeds, the recorded times were separated into time segments. As observed in Figure 4.9, times marked in red (labeled with a "T") represent the time periods when traffic control measures were being implemented and the speeds of the vehicles were greatly affected by the implementation of the measures. Even though traffic control measures were not in place between 1:00 a.m. and 1:30 a.m. on December 3, the recorded speeds were not used to facilitate the comparison of the observations between days. Traffic control measures were being implemented between 1:00 a.m. and 1:30 a.m. on December 4.

Marked in yellow (labeled with a "P") in Figure 4.9 are the times when there was no work taking place on the road, and these speeds and recordings were not compared. Marked in blue (labeled A, B, C, and D) on the same figure are the time segments that can be compared. Specifically these study periods had the following characteristics:

- A: December 2 – MBT-1® and A-lane closure
- B: December 3 – MBT-1® and A-lane closure
- C: December 3 – Without MBT-1® and A-lane closure
- D: December 4 – Without MBT-1® and B-lane closure

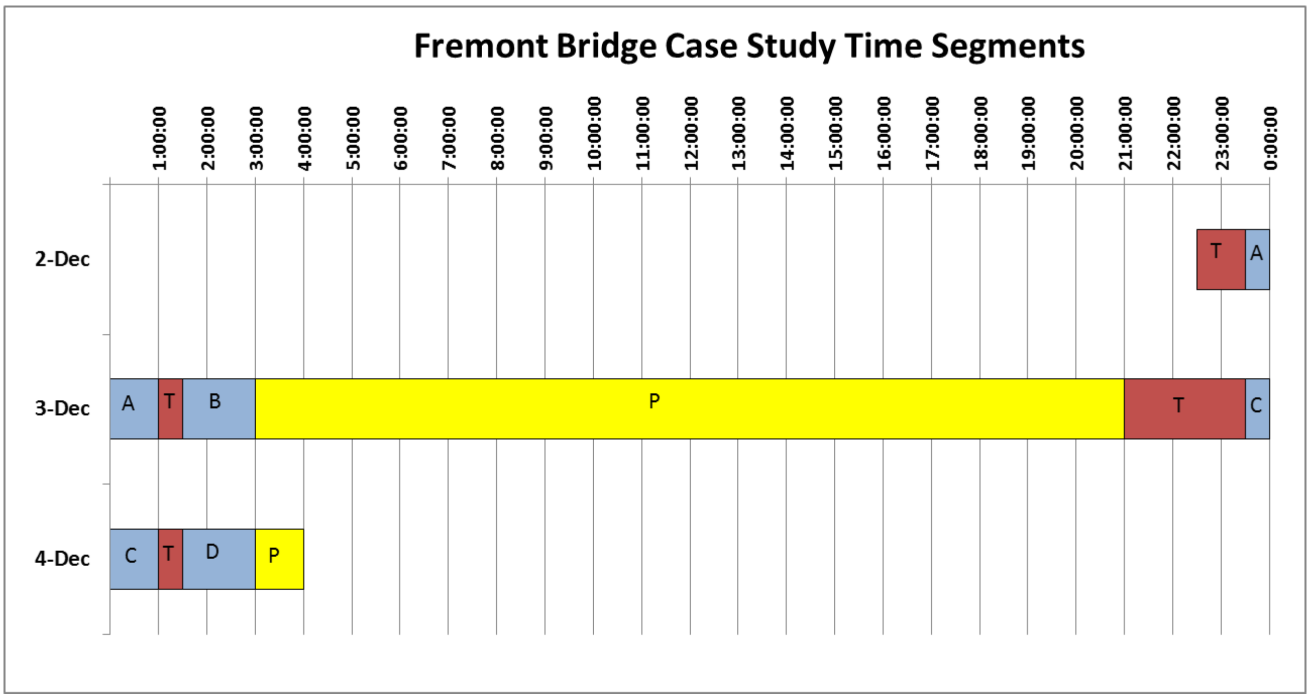

Figure 4.9: Time Segments Used for Comparison of the Speeds (Case Study 1)

The Shapiro-Wilk test, which is commonly used to determine if a data sample came from a normally-distributed population, was performed on the speed measurement to determine whether the recorded speeds are normally distributed (*Shapiro and Wilk 1965*).

Table 4.6 shows the results for the normality of the data for time segments A through D. As observed by the low p-values, all of the data recorded was normally distributed. A p-value below 0.05 suggests that there is less than a 5% probability that the result is due to chance (i.e., the data should be considered as normal and there is not enough information to reject the hypothesis that the data is not normal).

Table 4.6: Shapiro-Wilk Results on Normality of Vehicle Speeds (Case Study 1)

Time Segment	Sensors#683 &#687 1st set on approach	Sensors#688 &#181 2nd set on approach	Sensor #685 End of Taper Lane A	Sensor #184 End of Taper Lane B	Sensor #684 Work Zone Lane B	Sensor #686 Work Zone Lane A
A	W = 0.9812 p = 7.3e-08	W = 0.9825 p = 3.736e-09	NA	W = 0.978 p = 2.381e-11	W = 0.9778 p = 4.28e-11	NA
B	W = 0.9789 p = 0.000149	W = 0.9769 p = 1.797e-05	NA	W = 0.989 p = 0.000916	W = 0.9692 p = 9.964e-09	NA
C	W = 0.9805 p = 6.873e-08	W = 0.9819 p = 8.236e-09	NA	W = 0.9846 p = 4.118e-05	W = 0.9917 p = 0.000455	NA
D	W = 0.9789 p = 0.000575	W = 0.9776 p = 7.431e-06	W = 0.9776 p = 1.009e-06	NA	NA	NA

Figure 4.10, Figure 4.11, Figure 4.12, and Figure 4.13 show histograms of all the vehicle speed data that was recorded at the various locations during each time segment, A through D, respectively. As observed, the speeds appear to be normally distributed.

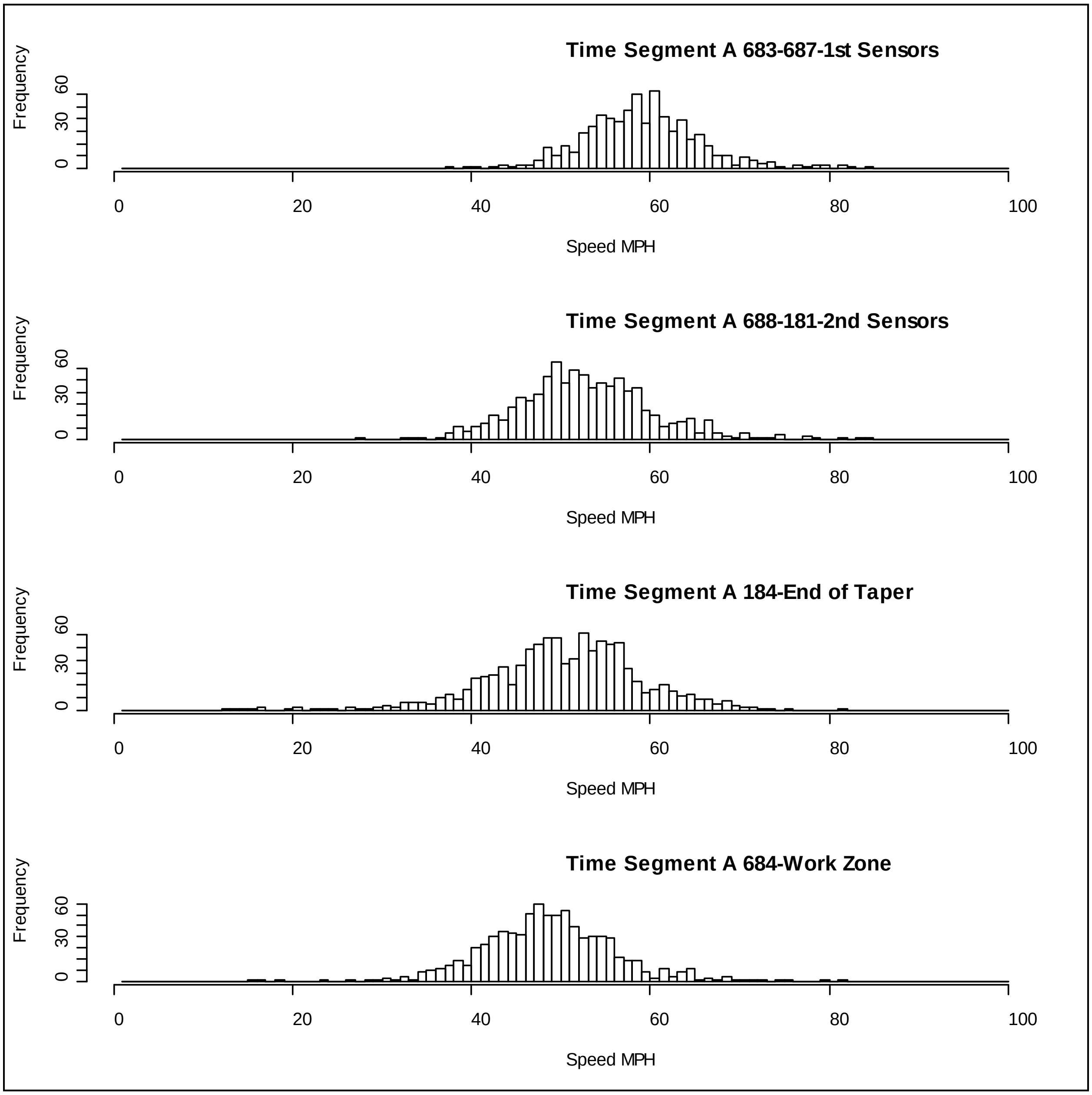

Figure 4.10: Histograms of Speeds Recorded from the Various Sensors with MBT-1® (Time Segment A)

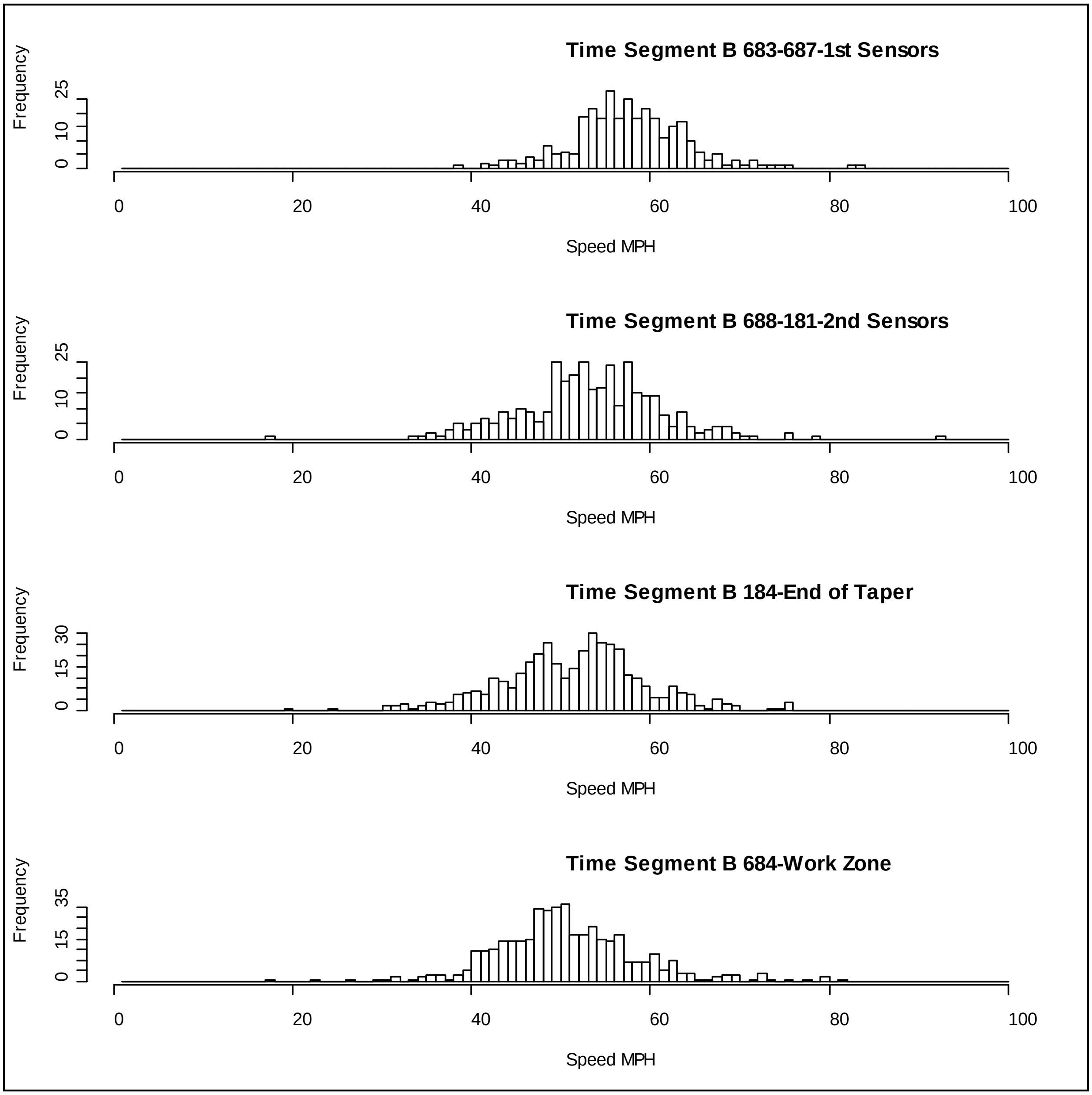

Figure 4.11: Histograms of Speeds Recorded from the Various Sensors with MBT-1® (Time Segment B)

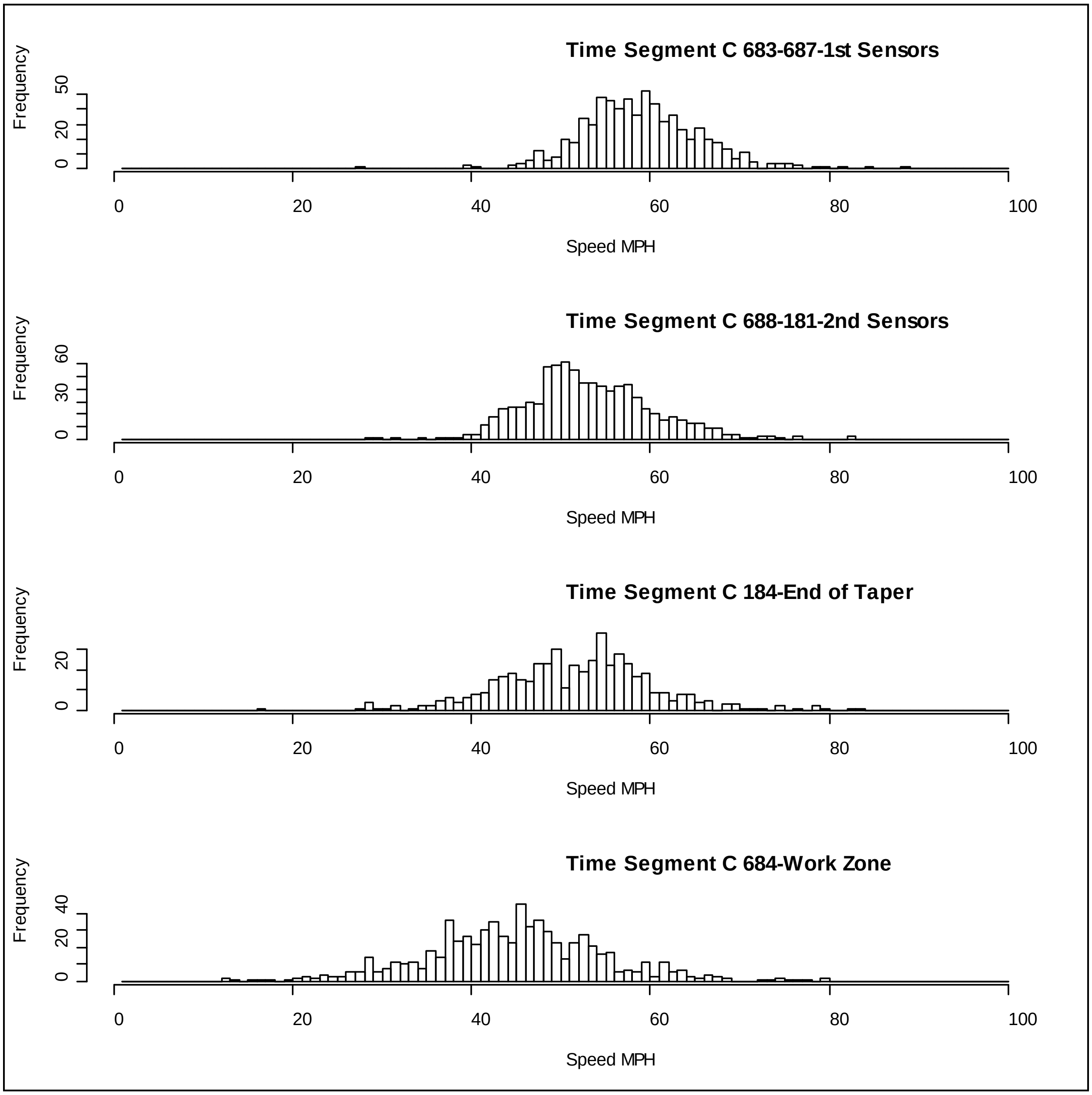

Figure 4.12: Histograms of Speeds Recorded from the Various Sensors without MBT-1® (Time Segment C)

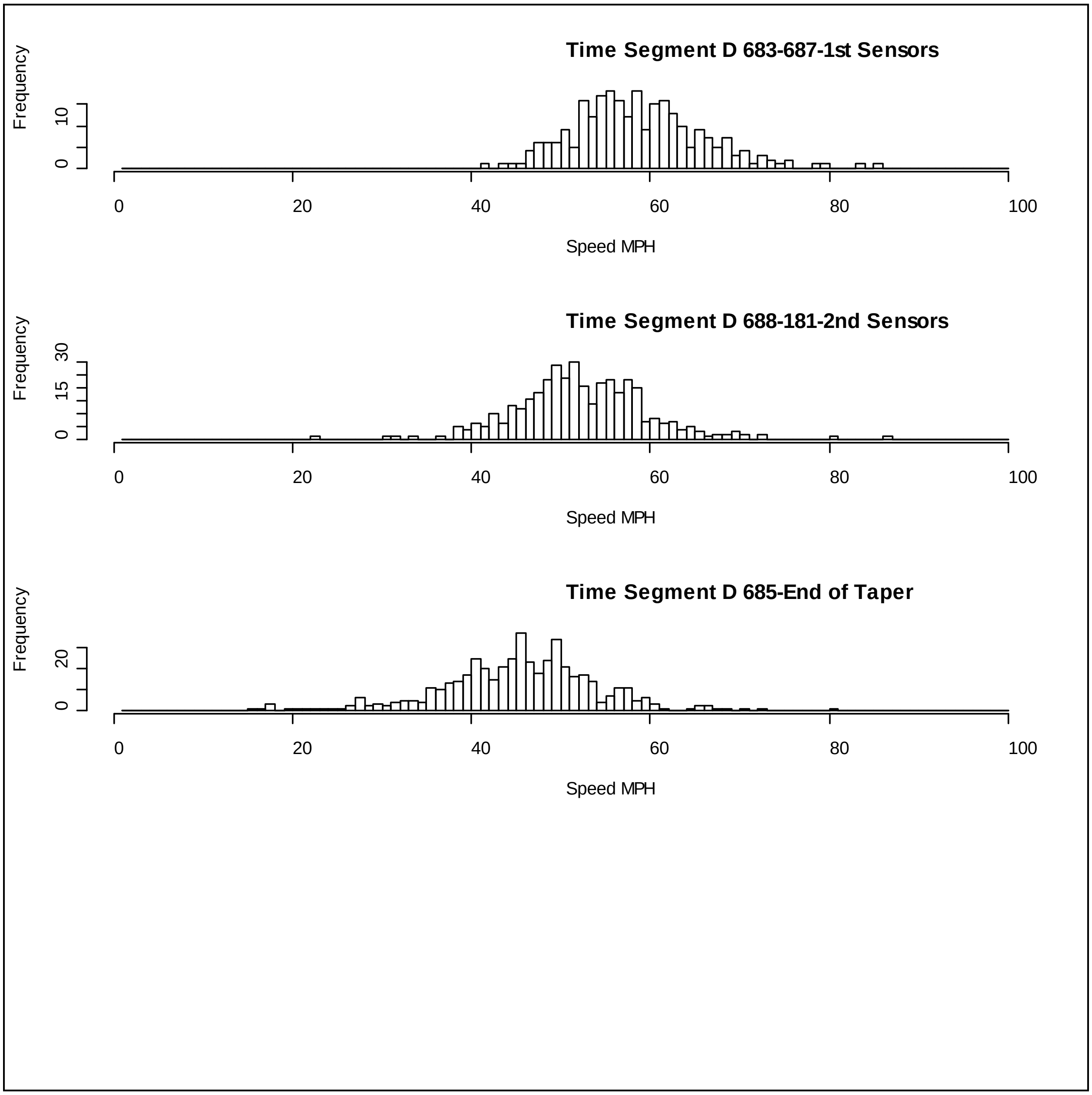

Figure 4.13: Histograms of Speeds Recorded from the Various Sensors without MBT-1® (Time Segment D)

4.1.3 Vehicle Speed Comparisons

The Welch two-sample t-test was performed on the speed data to investigate possible differences in driver behavior. Welch's t-test compares two sets of normally-distributed data that may or may not have the same standard deviation (Ramsey et al. 2002). This test was selected because of the possible difference in speed variances between the data samples. Specifically the following was investigated based on the mean and 85th percentile speeds:

- Differences in the vehicle speeds at all locations for the various time segments

- Differences in the vehicle speeds between the end of the taper and the work zone for the various time segments

4.1.3.1 Differences in speeds between the various time segments

Table 4.7 summarizes the results of the t-tests that were performed on the data for all sensor locations between time segments A (with MBT-1®) and C (without MBT-1®). Both of these time segments had an A-lane (fast lane) closure. As observed in the table, the speeds in the approach sensors do not show any significant variation since the confidence interval for the mean speeds includes the zero value. Specifically, the mean speed in the 1st set of sensors with the MBT-1® (Segment A) was 59.57 mph, while the mean speed without the MBT-1® (Segment C) was 59.39 mph. The p-value for the difference is approximately 0.6071, suggesting that the two groups are identical, and the confidence interval (CI) for their difference in mean speeds is between -0.50 and -0.85 mph.

Table 4.7: Mean Speed Comparisons at all Sensor Locations for Segments A & C (Case Study 1)

	1st Set of Sensors	2nd Set of Sensors	End of Taper	Work Zone
T statistic	0.5143	-0.8797	-3.1332	8.7185
Degrees of freedom	1381.71	1786.38	986.355	1275.27
p-value	0.6071	0.3791	0.00178	2.2e-16
Mean Segment A (with MBT-1®)	59.57 mph	53.40 mph	50.87 mph	49.21 mph
Mean Segment C (without MBT-1®)	59.39 mph	53.70 mph	52.36 mph	45.24 mph
Lower bound C.I.	-0.50	-0.97	-2.42	3.07
Upper Bound C.I.	0.85	0.37	-0.55	4.85

Similarly, the differences in the speed data recorded by the second set of sensors again do not show any significant variations. The mean speeds were 53.4 mph and 53.7 mph for the two segments, respectively. The CI for the mean speed difference was from -0.97 and 0.37 mph, while the p-value was 0.3791.

At the end of the taper, the vehicle speeds on both days showed some variation. The mean speed during time segment A was 50.87 mph, and 52.36 mph during time segment C. The p-value for the difference in the mean speeds was 0.00178 suggesting that the speeds on both days were different, with a CI for that difference being between -2.42 and -0.55 mph. This CI is very small and it is very close to zero.

Adjacent to the work zone, the speeds during the time segment with the MBT-1® present (segment A) were faster compared to the speeds without the MBT-1® (segment C). Specifically, the mean speeds were 49.21 mph and 45.24 mph respectively. The p-value for that difference was approximately zero, while the CI was between 3.07 and 4.85 mph.

Table 4.8 summarizes the t-test results for the tests that were performed on the data for all sensor locations between time segments B (with MBT-1®) and D (without MBT-1®). During time segment B, there was an A-lane closure while during time segment D, there was a B-lane closure. As observed in the table, the first sensors show some variation, but that variation is very small since the CI is very close to zero (-2.25 and -0.02). The mean speeds of the second set of sensors in the approach do not show any variation. Time segment B had a mean speed of 53.84 mph, while the mean speed for time segment D was 52.84 mph. The p-value for the difference is approximately 0.0733, suggesting that the two groups are identical, and the confidence interval (CI) for their difference in mean speeds is between-0.09 and 2.10 mph.

Table 4.8: Mean Speed Comparisons at all Sensor Locations for Segments B & D (Case Study 1)

	1st Set of Sensors	2nd Set of Sensors	End of Taper	Work Zone
T statistic	-2.0048	1.7936	11.416	NA
Degrees of freedom	533.613	723.107	955.694	NA
p-value	0.04549	0.0733	2.2e-16	NA
Mean Segment B (with MBT-1®)	58.03 mph	53.84 mph	51.93 mph	NA
Mean Segment D (without MBT-1®)	59.17 mph	52.84 mph	45.77 mph	NA
Lower bound C.I.	-2.25	-0.09	5.09	NA
Upper Bound C.I.	-0.02	2.10	7.21	NA

At the end of the taper, the vehicle speeds on both days showed some variation. The mean speed during time segment B was 51.93 mph, and 45.77 mph during time segment D. The p-value for the difference in the mean speeds was close to zero suggesting that the speeds on both days were different, with a CI for that difference being between 5.09 and 7.21 mph and the speeds of time segment B being faster. The speeds adjacent to the work zone cannot be compared since the sensor on the A-lane was damaged.

4.1.3.2 Differences in speeds between End of Taper and WZ

From the previous section (Table 4.7), it was observed that the end-of-taper speeds had very minor differences with and without the MBT-1®, while the work zone speeds were higher with the MBT-1® present. To investigate the amount of reduction in speed between the two time segments, t-tests were conducted on the mean speeds between the end of taper and the WZ. Table 4.9 shows the summary of the tests.

Table 4.9: Mean Speed Comparisons at End of Taper and WZ Speeds for Time Segments A & C (Case Study 1)

	Time Segment A With MBT-1®	Time Segment C Without MBT-1®
T statistic	4.5248	13.03
Degrees of freedom	1992.88	1163.601
p-value	6.4e-06	2.2e-16
Mean End of Taper speed	50.87 mph	52.37 mph
Mean WZ speed	49.21 mph	45.24 mph
Lower bound C.I.	0.94	6.05
Upper Bound C.I.	2.38	8.19

As observed in the table, with the MBT-1® present (time segment A), the reduction in the mean speed between the end of taper and the work zone was between 0.94 mph and 2.38 mph, with a p-value approximately equal to zero. Similarly, without the MBT-1® the reduction in the mean speed between the end of taper and the work zone was between 6.05 mph and 8.19 mph, with a p-value approximately equal to zero. This difference in the speed reduction suggests that drivers slow down more if traditional safety measures are used (without the MBT-1® present). The drivers may slow down for a variety of reasons such as being distracted by the work operations, additional glare from the work zone lighting, and the presence of debris in the roadway. However, the researchers did not record a specific reason during their observations. Using vehicle speed as an indicator of mobility, slower speeds through the work zone indicate reduced mobility.

A comparison of time segments B and D could not be made since the sensor adjacent to the work zone in the A-lane was damaged. Table 4.10 shows the results of the t-test that was performed for time segment B. It shows that there is no difference between the speeds observed at the end of taper and adjacent to the work zone. The CI for the difference in speeds was between -0.29 and 1.70 and that range includes the zero value.

Table 4.10: Mean Speed Comparisons of End of Taper and WZ Speeds for Segments B & D (Case Study 1)

	Time Segment B With MBT-1®	Time Segment D Without MBT-1®
T statistic	1.3763	NA
Degrees of freedom	988.945	NA
p-value	0.1691	NA
Mean End of Taper speed	51.93 mph	NA
Mean WZ speed	51.22 mph	NA
Lower bound C.I.	-0.29	NA
Upper Bound C.I.	1.70	NA

The above tests suggest that vehicles were traveling slower adjacent the work zone when traditional safety measures were implemented. The presence of the MBT-1® showed that there was very little reduction in speeds by the drivers, i.e., greater mobility through the work zone.

4.2 CASE STUDY 2 – I-5 NEAR BROWNSVILLE

During this case study, information from the sensors was not collected at all locations. Due to heavy rain, the adhesive on the tape used to secure the sensors to the pavement failed on some of the sensors and the sensors were displaced from their original location. Figure 4.14 and Figure 4.15 show the placement of the sensors in the southbound and northbound lanes of I-5 near Brownsville. In the southbound lane, sensors #686 and #184 were displaced, while in the northbound lane the sensors that were displaced were #683 and #181. Information from sensor #685 was corrupted due to the increased moisture from the road conditions. Because of the loss of data from the sensors that were displaced, comparison analyses of the speeds between the two lane conditions were not possible.

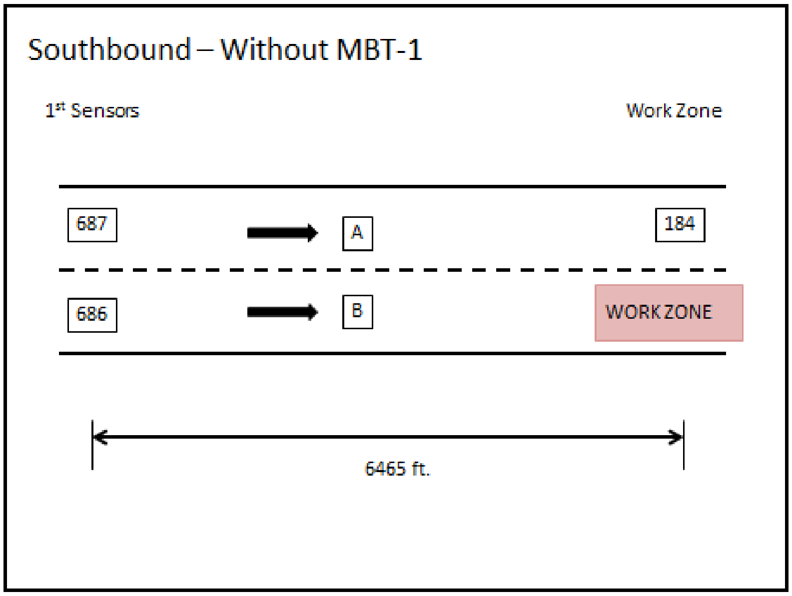

Figure 4.14: Setup of Sensors in Southbound Lane – Case 2

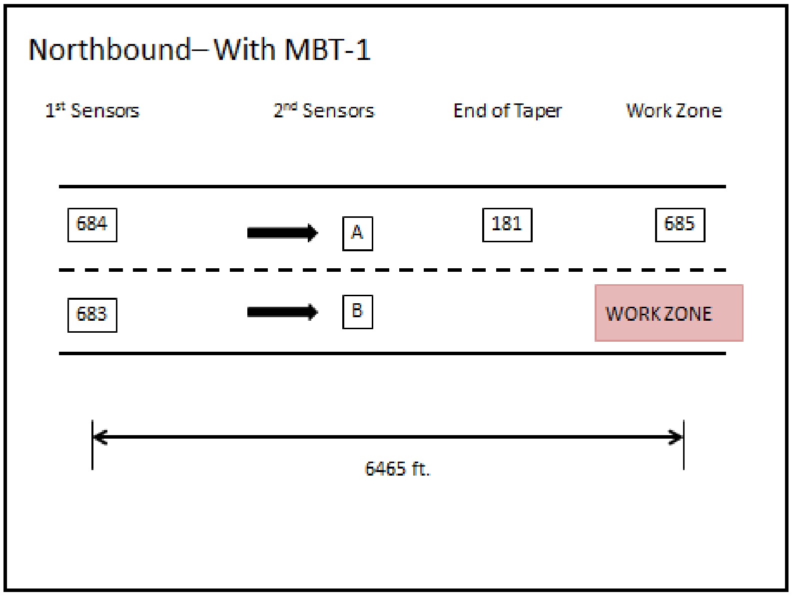

Figure 4.15: Setup of Sensors in Northbound Lane – Case 2

4.3 CASE STUDY 3 – INTESTATE BRIDGE

As described previously, the third case study was conducted on electrical maintenance work on the Interstate Bridge across the Columbia River. The analysis section for this case study includes the following:

- A discussion on the procedure for the placement of the speed sensors
- A discussion on the data used for the analysis
- Initial descriptive statistics for the data that was collected from each sensor
- Comparisons of speeds between different locations along the path of the vehicles

4.3.1 Sensor Setup and Data Collection

As described in Section 3.8.1, six sensors were placed in the southbound lanes of I-5, as shown in Figure 3.8 and Figure 3.9. The speed sensors recorded vehicle speeds and lengths from every vehicle that passed over them and that information was later downloaded and analyzed. For each sensor location the research team created tables and figures showing the variability of the speeds over regular time intervals. The information generated is very extensive and, as a result, only the tables associated with sensor #685are shown below. The remaining tables of speed information are shown in Appendix J. The information for all of the other sensors is presented in a format similar to the information for sensor #685 as described below.

Table 4.11shows the time summary of vehicle speeds recorded by sensor #685 on March17. On that day, the sensors recorded vehicle speeds from 11:00 p.m. until 5:30 a.m. For the analysis, the speeds compared were separated into segments according to the location of the mobile barrier as described in Section 3.8.1 of this report. During that time period, work was taking place on the roadway and the research team monitored the progress of the work. The speeds are grouped into

5 mph increments and these increments are shown in the first column of the table. The second column labeled “Total” shows the vehicle speed information for the duration of the analysis for sensor #685. The following columns show the information collected for each work location. Between 11:00 p.m. and 11:15 p.m., the work vehicles were preparing to approach the work zone. Between 11:15 p.m. and 12:39 a.m., work was performed at the first location on the bridge. Between 12:39 a.m. and 1:30 a.m., work was taking place at the second work location. In total the MBT-1® was at seven work locations on the bridge (note: Blank cells in the table indicate time segments in which no or only one vehicle was recorded and a measurable statistic could not be produced).

Table 4.11: Time Summary of Vehicle Speed for March 17 (Sensor #685, 1st on Bridge)

Vehicle Speed (all vehicles)	Total	2300-2315	2315-0039	0039-0150	0150-0233	0233-0325	0325-0348	0348-0416	0416-0430	0430-0530
MPH										
< 10	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.7%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.1%	0.0%	0.0%	0.4%	0.0%	0.6%	0.0%	0.0%	0.0%	0.5%
25-29	4.0%	5.5%	3.8%	8.1%	3.8%	1.1%	0.0%	1.9%	0.0%	0.0%
30-34	18.5%	11.4%	26.5%	19.6%	9.7%	11.4%	11.5%	10.5%	1.6%	6.8%
35-39	32.2%	18.6%	42.7%	33.4%	24.9%	28.4%	17.2%	15.2%	12.7%	17.7%
40-44	27.5%	41.5%	20.2%	25.1%	32.9%	33.0%	36.8%	32.4%	49.2%	34.4%
45-49	12.3%	14.8%	5.7%	9.8%	22.8%	17.0%	20.7%	26.7%	27.0%	22.4%
50-54	4.2%	5.5%	1.0%	3.1%	5.5%	7.4%	12.6%	11.4%	7.9%	11.5%
55-59	0.6%	1.7%	0.1%	0.2%	0.4%	1.1%	0.0%	1.9%	1.6%	2.1%
60-64	0.1%	0.4%	0.0%	0.0%	0.0%	0.0%	1.1%	0.0%	0.0%	0.0%
65-69	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
70-74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
>=75	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total # of vehicles	2764	236	1159	509	237	176	87	105	63	192
Average speed	38.9	40.8	37.1	37.9	40.9	40.9	42.5	42.6	43.3	41.2
St. Dev.	6.1	6.6	4.6	6.0	5.7	5.8	6.0	6.3	4.7	9.1
85th percentile	45.0	46.0	41.0	44.0	47.0	47.8	49.0	49.0	47.0	49.0
Min	9.0	25.0	25.0	17.0	26.0	24.0	30.0	28.0	33.0	9.0
Max	67.0	67.0	55.0	57.0	55.0	55.0	61.0	59.0	58.0	57.0
Range	58.0	42.0	30.0	40.0	29.0	31.0	31.0	31.0	25.0	48.0

The table also shows the total number of vehicles for that period, average vehicle speed, standard deviation for the average speed, 85th percentile of vehicle speeds, minimum and maximum speeds, and the range of all vehicle speeds. The yellow bars and red bars provide a graphical view of the distribution of vehicle speed. The yellow bars show that the speed for all vehicles is approximately normally distributed, with a center at approximately 50-54 mph. The red bars indicate that the speed distribution changes from time period to time period.

The total number of vehicles row shows the traffic volume for each time period. This information may not be consistent among different traffic sensors placed in sequence, since the vehicles can only be recorded if their drivers pass over each particular sensor. Depending on the location of each sensor in the lane, some vehicles may not travel over it and therefore not be recorded. In addition vehicles could change lanes and enter/exit the highway prior to getting on the bridge.

Table 4.12, Table 4.13, Table 4.14 and Table 4.15 show similar information to that shown in Table 4.11, but the information is separated according to the length of the vehicles being measured. The vehicles are categorized into four length categories. Table 4.12 shows the speed information for vehicles less than 25 feet long, which are normal passenger cars and small pick-ups without a trailer. Table 4.13 shows speeds for vehicles between 25 and 50 feet long, which are mostly long vans, one trailer pick-ups, and small trucks. Table 4.14 shows the speeds for vehicles from 50 to 75 feet in length, which are mid-size, semi-trucks with trailers. Table 4.15 shows the speeds for vehicles longer than 75 feet, which are long trucks. These tables and their interpretation are an example of how to understand the additional tables in Appendix J (note: Blank cells in the tables indicate time segments in which no or only one vehicle was recorded and a measurable statistic could not be produced).

Table 4.12: Time Summary of Vehicle (0-25 feet long) Speed for March 17 (Sensor #685, 1st on Bridge)

Vehicle Speed (0-25 FT Vehicles)	Total	2300-2315	2315-0039	0039-0150	0150-0233	0233-0325	0325-0348	0348-0416	0416-0430	0430-0530
MPH										
< 10	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.9%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.1%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
25-29	3.6%	4.4%	3.3%	7.3%	3.1%	1.2%	0.0%	2.2%	0.0%	0.0%
30-34	18.2%	11.9%	26.1%	19.1%	9.4%	9.9%	12.2%	8.8%	1.9%	6.7%
35-39	32.4%	18.6%	43.1%	33.1%	25.4%	28.0%	15.9%	12.1%	13.0%	17.8%
40-44	27.7%	41.2%	20.5%	25.8%	33.0%	34.8%	37.8%	35.2%	46.3%	32.8%
45-49	12.7%	15.5%	5.9%	10.5%	23.2%	16.8%	20.7%	28.6%	27.8%	23.9%
50-54	4.4%	5.8%	1.0%	3.4%	5.4%	8.1%	12.2%	13.2%	9.3%	12.2%
55-59	0.5%	1.8%	0.1%	0.2%	0.4%	1.2%	0.0%	0.0%	1.9%	2.2%
60-64	0.1%	0.4%	0.0%	0.0%	0.0%	0.0%	1.2%	0.0%	0.0%	0.0%
65-69	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
70-74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
>=75	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total # of vehicles	2603	226	1108	477	224	161	82	91	54	180
Average speed	39.1	41.0	37.2	38.1	41.0	41.2	42.5	42.8	43.5	41.7
St. Dev.	6.0	6.5	4.5	6.0	5.5	5.7	6.1	6.0	4.9	8.7
85th percentile	45.0	46.3	41.9	44.0	47.0	48.0	49.0	49.0	48.1	49.0
Min	9.0	25.0	25.0	17.0	26.0	28.0	30.0	28.0	33.0	9.0
Max	67.0	67.0	55.0	57.0	55.0	55.0	61.0	53.0	58.0	57.0
Range	58.0	42.0	30.0	40.0	29.0	27.0	31.0	25.0	25.0	48.0

Table 4.13: Time Summary of Vehicle (25-50 feet long) Speed for March 17 (Sensor #685, 1st on Bridge)

Vehicle Speed (25-50 FT Vehicles)	Total	2300-2315	2315-0039	0039-0150	0150-0233	0233-0325	0325-0348	0348-0416	0416-0430	0430-0530
MPH										
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	1.1%	0.0%	0.0%	0.0%	0.0%	11.1%	0.0%	0.0%	0.0%	0.0%
25-29	10.6%	12.5%	14.3%	18.2%	11.1%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	17.0%	0.0%	25.0%	27.3%	11.1%	22.2%	0.0%	0.0%	0.0%	0.0%
35-39	29.8%	25.0%	35.7%	36.4%	22.2%	22.2%	33.3%	20.0%	25.0%	16.7%
40-44	28.7%	62.5%	17.9%	18.2%	22.2%	22.2%	0.0%	40.0%	50.0%	83.3%
45-49	8.5%	0.0%	3.6%	0.0%	22.2%	22.2%	33.3%	20.0%	25.0%	0.0%
50-54	3.2%	0.0%	3.6%	0.0%	11.1%	0.0%	33.3%	0.0%	0.0%	0.0%
55-59	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	0.0%	0.0%
60-64	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
65-69	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
70-74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
>=75	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total # of vehicle	94	8	28	22	9	9	3	5	4	6
Average speed	37.8	38.8	36.3	34.8	39.7	37.4	44.7	44.8	41.3	40.5
St. Dev.	6.4	4.9	5.6	5.2	7.9	8.2	5.5	8.9	3.0	2.0
85th percentile	44.0	41.0	41.0	39.7	46.0	44.8	48.5	51.2	43.7	42.0
Min	24.0	28.0	27.0	26.0	26.0	24.0	39.0	35.0	38.0	37.0
Max	59.0	44.0	50.0	44.0	50.0	48.0	50.0	59.0	45.0	42.0
Range	35.0	16.0	23.0	18.0	24.0	24.0	11.0	24.0	7.0	5.0

Table 4.14: Time Summary of Vehicle (50-75 ft. long) Speed for March 17 (Sensor #685, 1st on Bridge)

Vehicle Speed (50-75 FT Vehicles)	Total	2300-2315	2315-0039	0039-0150	0150-0233	0233-0325	0325-0348	0348-0416	0416-0430	0430-0530
MPH										
< 10	6.9%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	66.7%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
25-29	13.8%	100.0%	9.1%	25.0%	25.0%	0.0%		0.0%	0.0%	0.0%
30-34	51.7%	0.0%	72.7%	75.0%	25.0%	50.0%		100.0%	0.0%	33.3%
35-39	6.9%	0.0%	18.2%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
40-44	13.8%	0.0%	0.0%	0.0%	50.0%	0.0%		0.0%	66.7%	0.0%
45-49	6.9%	0.0%	0.0%	0.0%	0.0%	50.0%		0.0%	33.3%	0.0%
50-54	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
55-59	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
60-64	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
65-69	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
70-74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
>=75	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
Total # of vehicle	29	1	11	4	4	2	0	1	3	3
Average speed	32.6	28.0	31.6	31.5	37.0	39.5		34.0	43.0	17.3
St. Dev.	8.5		2.7	2.4	8.1	7.8			2.6	14.4
85th percentile	43.2	28.0	34.5	33.6	44.0	43.4		34.0	44.7	26.5
Min	9.0	28.0	26.0	29.0	29.0	34.0		34.0	40.0	9.0
Max	45.0	28.0	35.0	34.0	44.0	45.0		34.0	45.0	34.0
Range	36.0	0.0	9.0	5.0	15.0	11.0		0.0	5.0	25.0

Table 4.15: Time Summary of Vehicle (75+ ft. long) Speed for March 17 (Sensor #685, 1st on Bridge)

Vehicle Speed (+75 FT Vehicles)	Total	2300-2315	2315-0039	0039-0150	0150-0233	0233-0325	0325-0348	0348-0416	0416-0430	0430-0530
MPH										
< 10	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
25-29	10.5%	100.0%	16.7%	16.7%		0.0%	0.0%	0.0%	0.0%	0.0%
30-34	15.8%	0.0%	25.0%	0.0%		25.0%	0.0%	25.0%	0.0%	0.0%
35-39	47.4%	0.0%	41.7%	66.7%		75.0%	50.0%	50.0%	0.0%	33.3%
40-44	21.1%	0.0%	16.7%	16.7%		0.0%	50.0%	0.0%	100.0%	66.7%
45-49	2.6%	0.0%	0.0%	0.0%		0.0%	0.0%	12.5%	0.0%	0.0%
50-54	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
55-59	2.6%	0.0%	0.0%	0.0%		0.0%	0.0%	12.5%	0.0%	0.0%
60-64	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
65-69	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
70-74	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
>=75	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
Total # of vehicle	38	1	12	6	0	4	2	8	2	3
Average speed	36.8	25.0	34.7	36.7		36.0	38.5	39.4	40.5	39.7
St. Dev.	5.6		4.8	4.7		2.6	2.1	7.6	0.7	4.5
85th percentile	41.0	25.0	39.1	40.0		38.1	39.6	44.7	40.9	42.8
Min	25.0	25.0	28.0	29.0		33.0	37.0	34.0	40.0	35.0
Max	56.0	25.0	42.0	43.0		39.0	40.0	56.0	41.0	44.0
Range	31.0	0.0	14.0	14.0		6.0	3.0	22.0	1.0	9.0

4.3.2 Speed comparisons

Figure 4.16 shows the average and 85th percentile speeds for all vehicles during each work time segment relative to the distance from sensor #684, as recorded by that sensor. Sensor #684 was placed at the end of the taper at the approach to the Interstate Bridge. As observed, the speeds appear to be lower at the beginning of the work period (time segment A). This result may be due to the increased traffic that occurred during the traffic control set up. The mean speeds appear to be leveling off to just over 40 mph during the rest of the night's work.

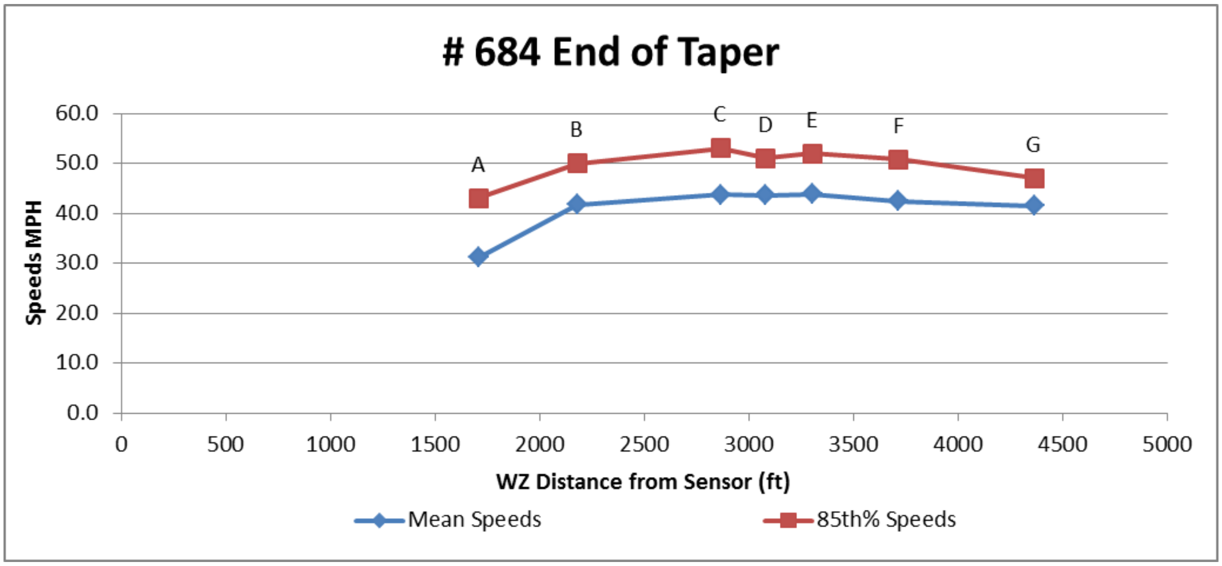

Figure 4.16: Average and 85thPercentileSpeeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #684 (End of Taper)

Figure 4.17 shows the same information as recorded from sensor #685, which was the 1st sensor placed on the bridge. At the location of sensor 685, it is observed that the mean vehicle speeds are just below 40 mph during time segments A and B, and gradually increase during the subsequent time segments to just over 40 mph.

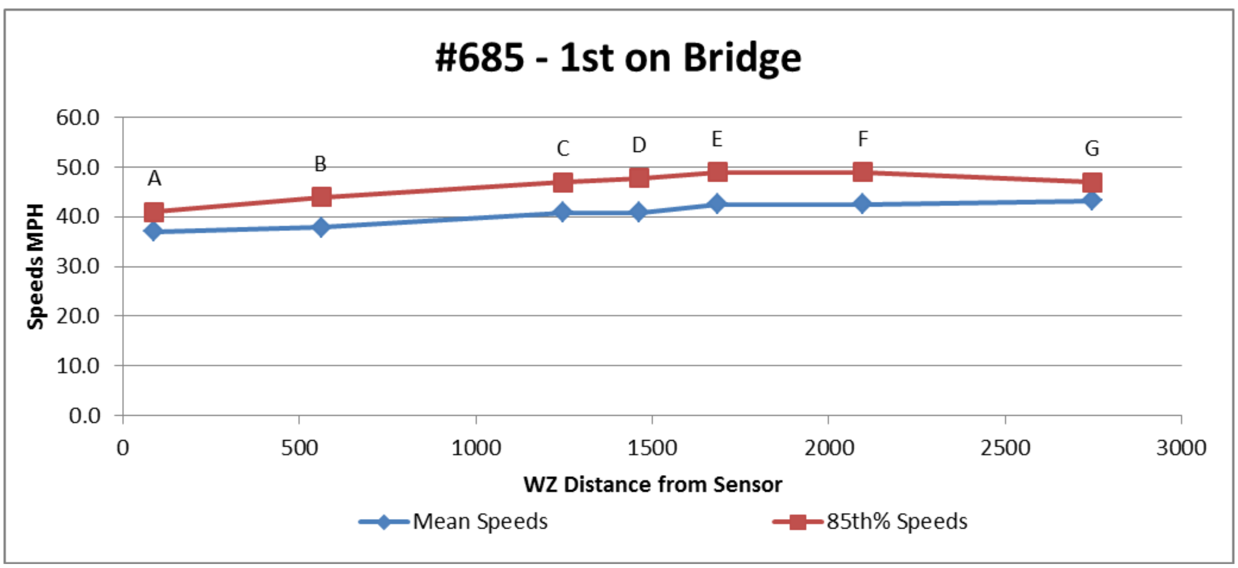

Figure 4.17: Average and 85thPercentileSpeeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #685 (1st Sensor on Bridge)

Figure 4.18 shows the mean and 85th percentile speeds from sensor 687, which was the 2nd sensor that was placed on the bridge. At that location, the average and 85th percentile speeds appear to be lower during time segments C and D. During these time segments the MBT-1® was close to the sensor. Figure 4.19 shows that mean and 85th percentile speeds from sensor #688, which was the 3rd sensor that was placed on the bridge. The speeds show a slight reduction during time segments F and G, which were the time segments when the MBT-1® was close to the sensor.

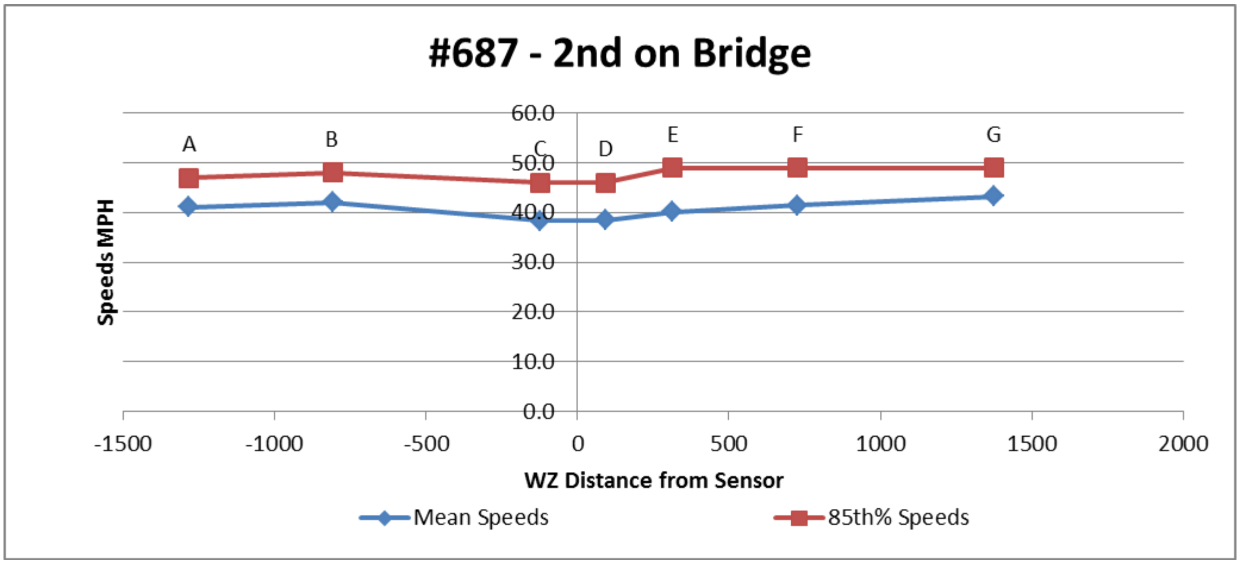

Figure 4.18: Average and 85[th]Percentile Speeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #687 (2nd Sensor on Bridge)

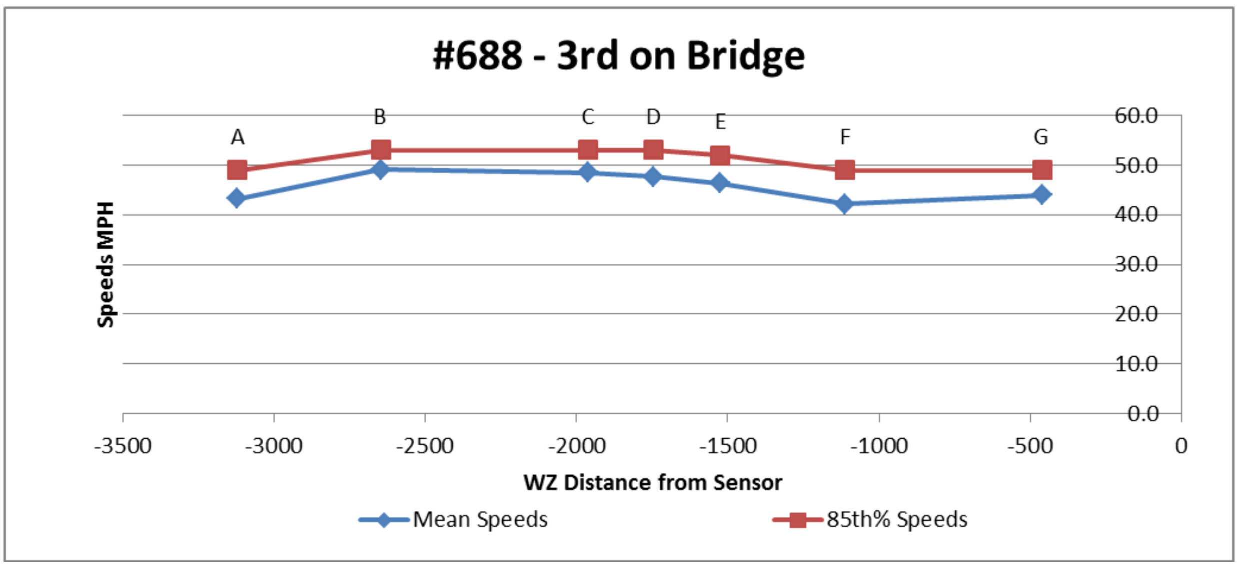

Figure 4.19: Average and 85[th]PercentileSpeeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #688 (3rd Sensor on Bridge)

The Shapiro-Wilk test was again performed on the speed measurements to determine whether the observations were normally distributed.

Table 4.16 shows the results for the normality of the data for each sensor and each time segment. Highlighted with green are the locations and times where the data is normally distributed. Locations where the data is not normal are highlighted in red.

Table 4.16: Shapiro-Wilk Results on Normality of Vehicle Speeds (Case 3)

Time Segment	Segment Time Start	Sensor#684 End of Taper	Sensor#685 1st on Bridge	Sensor#687 2nd on Bridge	Sensor#688 3rd on Bridge
A	11:15 pm	W = 0.9873 p = 2.861e-08	W = 0.9846 p = 1.025e-09	W = 0.99 p = 4.289e-07	W = 0.9922 p = 7.967e-06
B	00:39 am	W = 0.9749 p = 2.277e-07	W = 0.9944 p = 0.05847	W = 0.9836 p = 1.534e-05	W = 0.9481 p = 2.341e-12
C	01:50 am	W = 0.9805 p = 0.00346	W = 0.9867 p = 0.02697	W = 0.994 p = 0.4547	W = 0.986 p = 0.01946
D	02:33 am	W = 0.9646 p = 0.000192	W = 0.9924 p = 0.4855	W = 0.9922 p = 0.4877	W = 0.9509 p = 1.083e-05
E	03:25 am	W = 0.9392 p = 0.000487	W = 0.9843 p = 0.3744	W = 0.9865 p = 0.4731	W = 0.9822 p = 0.2644
F	03:48 am	W = 0.9735 p = 0.03803	W = 0.9841 p = 0.2433	W = 0.9627 p = 0.005034	W = 0.9782 p = 0.08129
G	04:16 am	W = 0.9064 p = 0.000178	W = 0.9595 p = 0.03648	W = 0.9684 p = 0.09019	W = 0.9612 p = 0.03964

Figure 4.20 shows the variability in speeds recorded by the sensor that was placed at the end of the taper on the approach to the Interstate Bridge. Similarly, Figure 4.21 shows the variability in speeds recorded by the 1st sensor that was placed on the bridge. Likewise, Figure 4.22 and Figure 4.23 show the variability in speeds recorded by the 2nd and 3rd sensors that were placed on the bridge. Even though the data is not normal at all locations, it is assumed that the observations are part of a larger population that has normally distributed speeds. This assumption allows the investigation of differences in the speeds using t-tests.

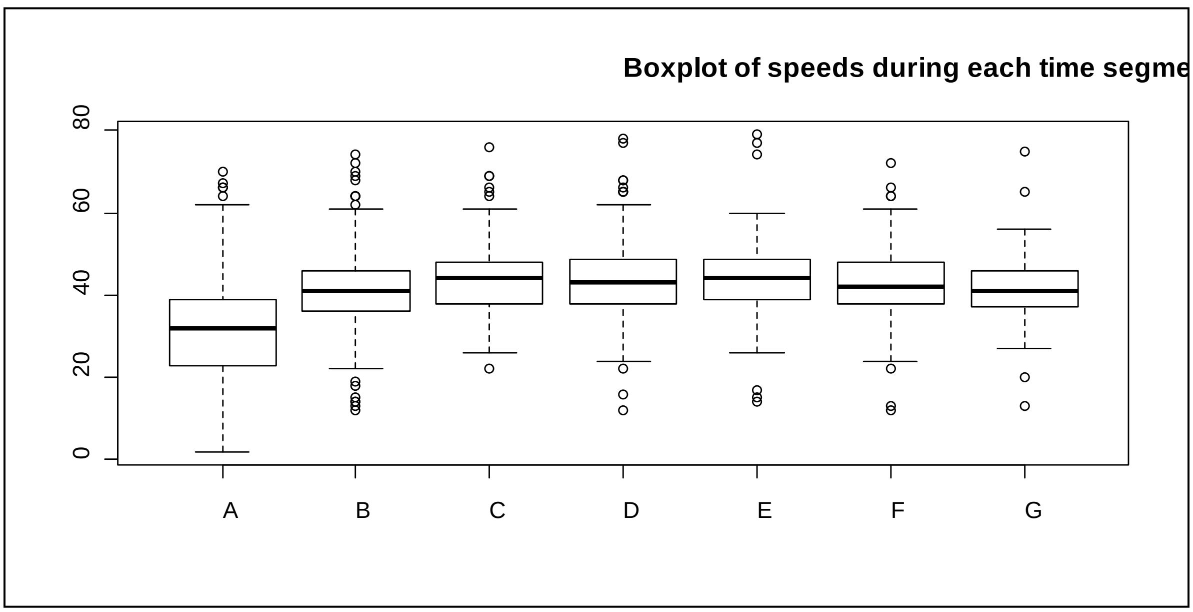

Figure 4.20: Sensor #684 (End of Taper) Speed Measurements per Time Segment

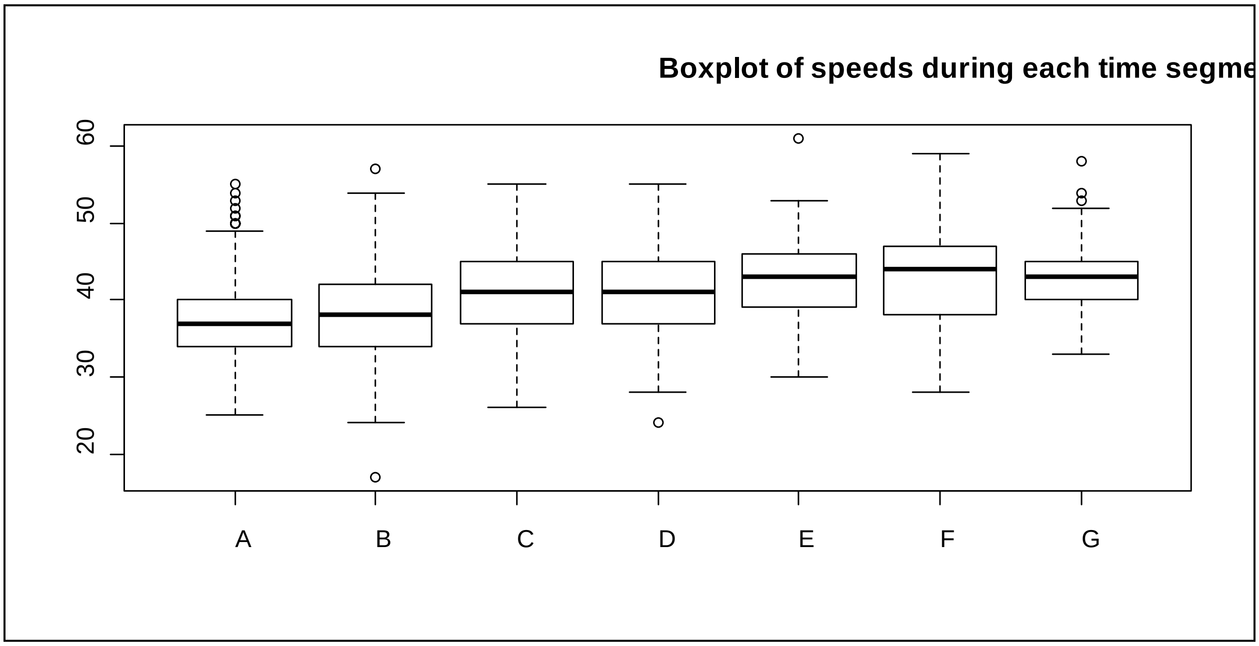

Figure 4.21: Sensor #685 (1st on Bridge) Speed Measurements per Time Segment

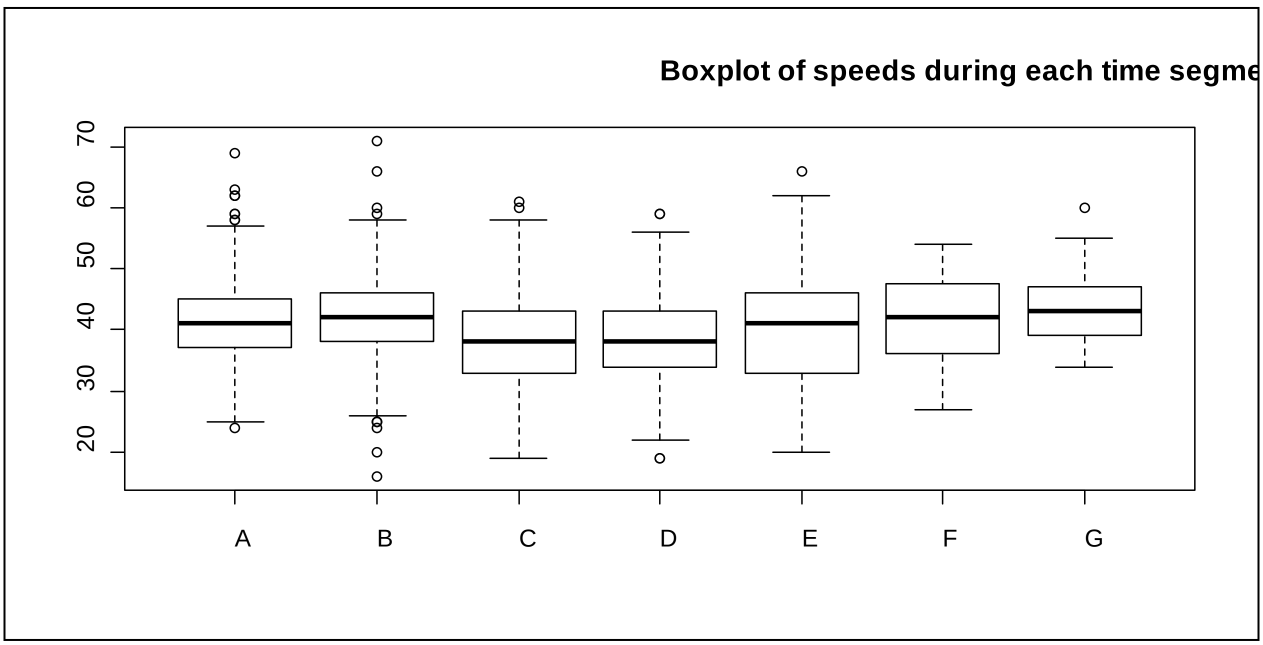

Figure 4.22: Sensor #687 (2nd on Bridge) Speed Measurements per Time Segment

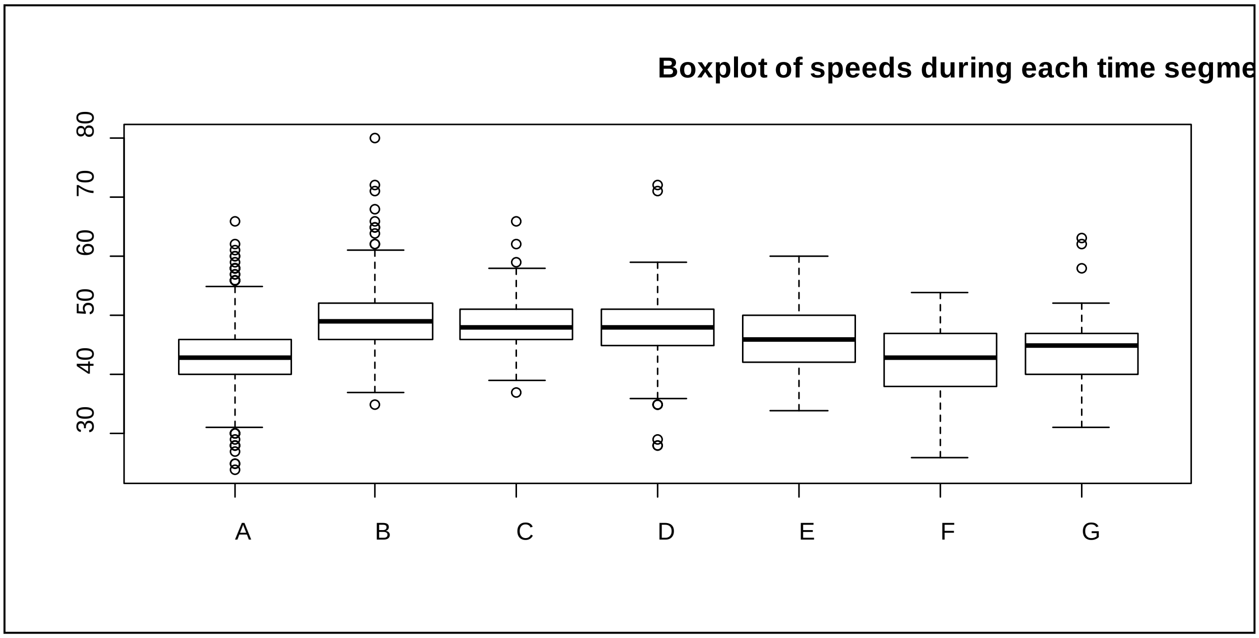

Figure 4.23: Sensor #688 (3rd on Bridge) Speed Measurements per Time Segment

4.3.3 Speed Comparisons

Similar to the analysis for Case Study #1, the Welch two sample t-test was performed on the data to investigate possible differences in driver behavior. Specifically, the mean vehicle speed differences at each time segment between different sensor locations were compared.

During time segment A, work was carried out relatively close to the first sensor that was placed on the bridge. The distance between the work zone and the sensor was 88 feet. The average speeds recorded during time segment A are shown in Table 4.17. The table also presents the differences between the mean speeds recorded along with the p-value and the 95% confidence interval of that comparison. As observed in the table, speeds recorded by the sensor at the end of taper were slower than all the other speeds recorded during time segment A from all the other sensors on the bridge. This result may be due to the presence of the Washington State Police vehicle which was parked near that location. After the vehicles passed the police officer, they started speeding up again with the greatest difference of 11.99 mph between the end of taper location and the 3rd sensor (p-value ~0, with 95% CI from -12.78 mph to -11.27 mph).

Table 4.17: Comparison of Mean Speeds during Time Segment A (Case 3)

			Avg. Speed 1st Sensor on Bridge (mph)	**Avg. Speed 2nd Sensor on Bridge (mph)**	**Avg. Speed 3rd Sensor on Bridge (mph)**
			37.05 mph	**41.08 mph**	**43.23 mph**
Avg. Speed, End of Taper Sensor (mph)	31.24 mph	CI	-5.11,-6.57	-10.63, -9.11	-12.78, -11.27
		P	2.2e-16	2.2e-16	2.2e-16
Avg. Speed, 1st Sensor on Bridge (mph)	37.05 mph	CI		-4.46, -3.59	-6.59, -5.77
		P		2.2e-16	2.2e-16
Avg. Speed, 2nd Sensor on Bridge (mph)	41.08 mph	CI			-2.61, -1.68
		P			2.2e-16

During time segments C and D, work was carried out relatively close to the second sensor that was placed on the bridge. During time segment C, the work zone was located 122 feet before the second sensor (upstream). During time segment D, the work zone was located 93 feet after the second sensor. The average speeds recorded during time segment C shown in Table 4.18. The average speeds recorded during time segment D shown in Table 4.19. The tables also depict the differences between the mean speeds recorded along with the p-values and the 95% confidence interval of all comparisons.

Table 4.18: Comparison of Mean Speeds during Time Segment C (Case 3)

			Avg. Speed 1st Sensor on Bridge (mph)	**Avg. Speed 2nd Sensor on Bridge (mph)**	**Avg. Speed 3rd Sensor on Bridge (mph)**
			40.85 mph	**38.38 mph**	**48.47 mph**
Avg. Speed, End of Taper Sensor (mph)	43.79 mph	CI	4.30, 1.58	3.99, 7.02	-5.96, -3.39
		P	2.734e-05	3.424e-12	5.051e-12
Avg. Speed, 1st Sensor on Bridge (mph)	40.85 mph	CI		1.35, 3.79	-8.53, -6.70
		P		4.157e-05	2.2e-16
Avg. Speed 2nd Sensor on Bridge (mph)	38.28 mph	CI			-11.32,-9.06
		P			2.2e-16

As observed in the tables, the average speeds at the second sensor location are slower than at all of the other locations during both time intervals. During time interval C, the average speed at the second sensor location was 5.41 mph slower than the speed recorded at the end of taper, and 2.47 mph slower than the speeds recorded at the first sensor on the bridge. The difference with the third sensor during the same time interval was 10.19 mph.

During time interval D, the average speed at the second sensor location was 5.23 mph slower than the speed recorded at the end of taper, 2.43 mph slower than the speeds recorded at the first sensor on the bridge, and 9.23 mph slower that the speeds recorded by the third sensor.

Table 4.19: Comparison of Mean Speeds during Time Segment D (Case 3)

			Avg. Speed 1st Sensor on Bridge (mph)	**Avg. Speed 2nd Sensor on Bridge (mph)**	**Avg. Speed 3rd Sensor on Bridge (mph)**
			40.87 mph	**38.44 mph**	**47.67 mph**
Avg. Speed, End of Taper Sensor (mph)	43.67 mph	CI	4.46, 1.12	3.42, 7.03	-5.69, -2.30
		P	0.001116	2.702e-08	5.086e-06
Av. Speed 1st Sensor on Bridge (mph)	40.87 mph	CI		1.03, 3.83	-8.05, -5.54
		P		0.0007233	2.2e-16
Av. Speed 2nd Sensor on Bridge (mph)	38.44 mph	CI			-10.66,-7.79
		P			2.2e-16

During time segment G, work was carried out relatively close to the third sensor that was placed on the bridge. The work zone was approximately 461 feet prior to the sensor. The average speeds recorded during time segment G are shown in Table 4.20. The table also depicts the differences between the mean speeds recorded along with the p-values and the 95% confidence interval of that comparison. As observed, the speeds recorded did not show any significant difference as is evident by the p-values that are above 0.05 and the confidence intervals that contain the ‘0’ value in their range.

Table 4.20: Comparison of Mean Speeds during Time Segment G (Case 3)

			Avg. Speed 1st Sensor on Bridge (mph)	Avg. Speed 2nd Sensor on Bridge (mph)	Avg. Speed 3rd Sensor on Bridge (mph)
			43.25 mph	**43.24 mph**	**44.00 mph**
Avg. Speed End of Taper Sensor (mph)	41.53 mph	CI	-4.23, 0.79	-4.28,0.86	-5.18,0.25
		P	0.1775	0.1905	0.07513
Avg. Speed 1st Sensor on Bridge (mph)	43.25 mph	CI		-1.72,1.75	-2.70, 1.21
		P		0.9895	0.4517
Avg. Speed2nd Sensor on Bridge (mph)	43.24 mph	CI			-2.79,1.27
		P			0.4621

4.4 CASE STUDY 4 – US 26 CLOSE TO ZOO EXIT

This project presented a unique case study for the research that was different than the other case study projects. In addition, as described previously, a different type of equipment was used to record the vehicle speeds. Although, using different equipment between case studies was not ideal, both pieces of equipment were able to produce comparable data sets, but with different formats. The analysis section includes the following:

- Initial descriptive statistics for the data that was collected from the Wavetronix speed sensor
- Comparisons of speeds between various time frames associated with different site conditions

4.4.1 Sensor Setup and Data Collection

As described in Section 3.9.1 of this report, a Wavetronix speed measuring device was placed in close proximity to the work zone. Figure 4.24 depicts the times that the Wavetronix sensor was recording speeds at the site. As observed, there are several gaps in the times the sensor was recording. The gaps occurred because the generator which powered the sensor ran out of fuel. Once ODOT crews refueled the generator, the sensor started recording again. Additionally, in the evening several days later (December 13), the generator was stolen from the site and the sensor stopped recording.

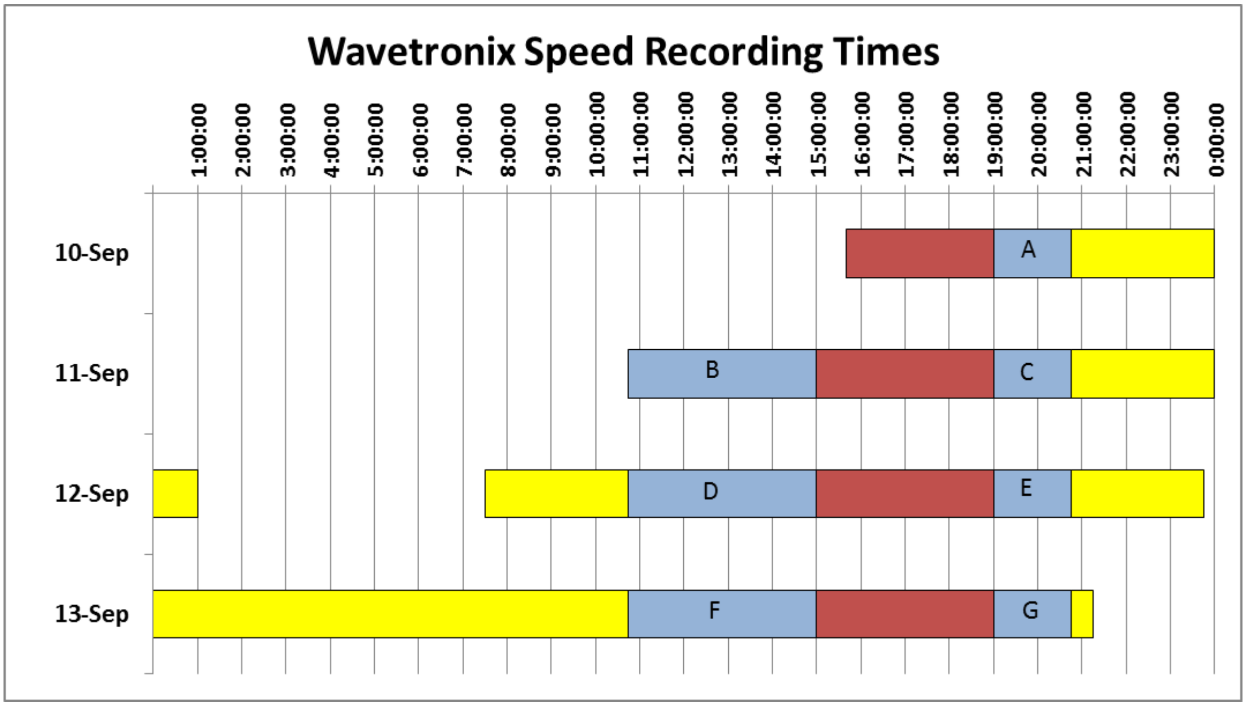

Figure 4.24: Times in which Wavetronix Device was Recording Vehicle Speeds

Figure 4.25 and Figure 4.26 show the recorded mean and 85th percentile speeds of the vehicles in the D-lane adjacent to the work zone during the time frames depicted in Figure 4.24. The recorded speeds from the other three lanes of traffic at the segment of road next to the work zone are shown in Appendix K. The speeds were recorded in 15 minute increments and are indicated with different markers according to the day of recording. An "x" signifies speeds recorded on the first day (September 10), a diamond signifies speeds recorded on day 2 (September 11), a square the speeds for day 3 (September 12), and a triangle the speeds on day 4 (September 13).

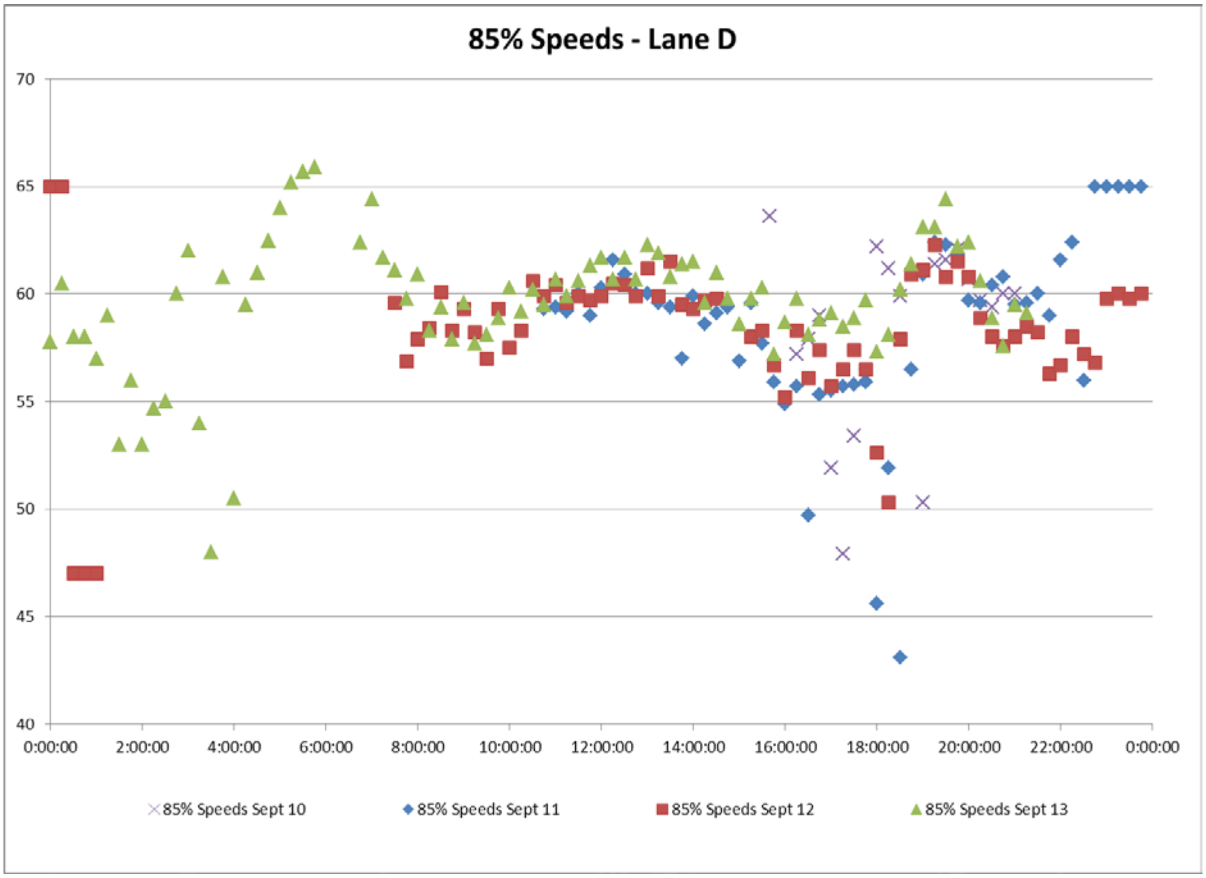

Figure 4.25: Recorded 85th PercentileSpeeds in D-Lane

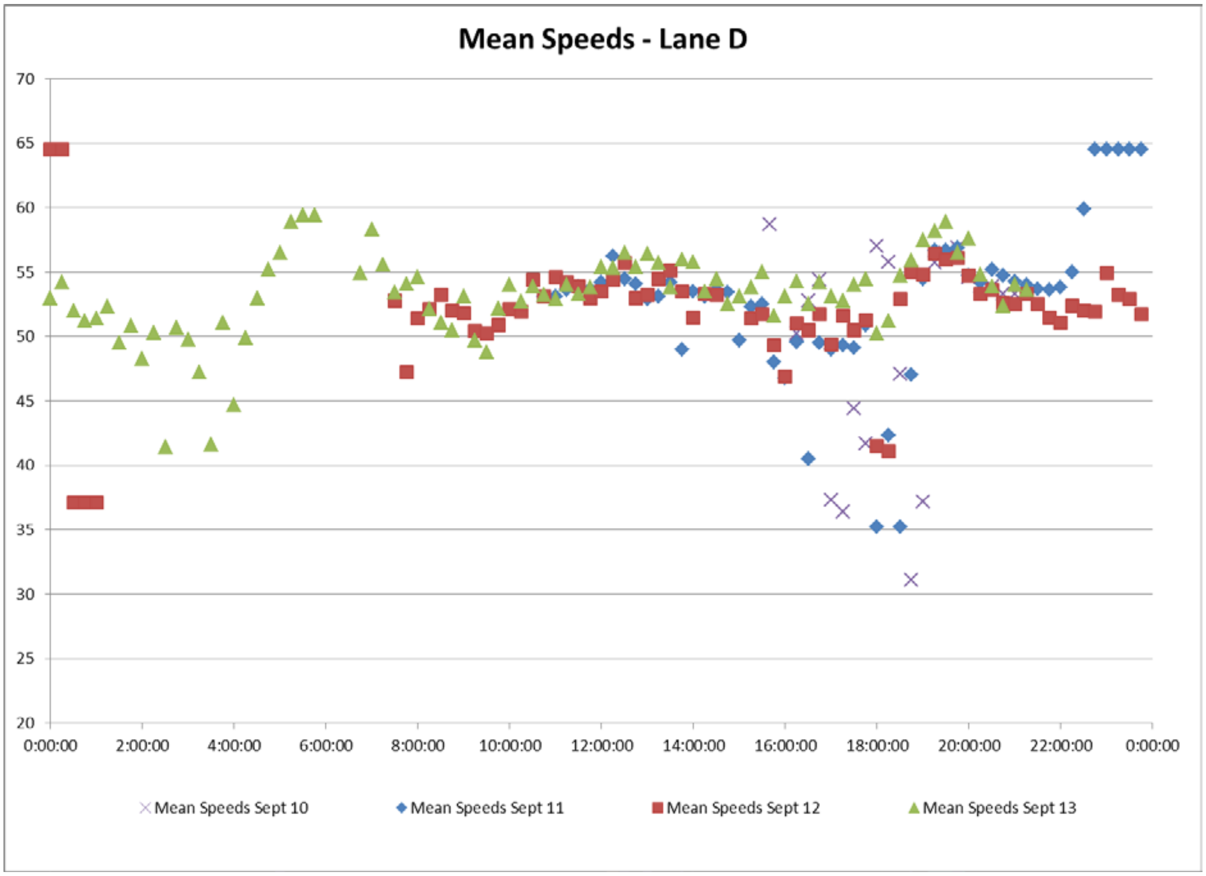

Figure 4.26: Recorded Mean Speeds in D-Lane

As observed in the figures, the speeds were found to be lower between 3:00 p.m. and 7:00 p.m. on all days except on September 13. The reduction in speed was due to increased rush hour traffic each day during that time period. During all other times, the speeds appear to be the same and approximately 55-65 mph for the 85th percentile speeds and between 45 and 57 mph for the mean speeds. The reduction in speed during rush hour is marked with red in Figure 4.24. Marked in blue (segments A-G) are the periods of time that can be compared. Marked in yellow are the times that cannot be compared since there is not enough comparison points or the number of vehicles is too small for comparison purposes. Specifically, the periods of time labeled A-G in Figure 4.24 had the following characteristics:

- Segment A – September 10 (1900 – 2045):No MBT-1®, only traditional safety measures used (cones)
- Segment B – September 11 (1045 – 1500):No MBT-1®, only traditional safety measures work taking place
- Segment C – September 11 (1900 – 2045):MBT-1® parked next to work zone on shoulder; no work taking place
- Segment D – September 12 (1045 – 1500): MBT-1® parked next to work zone on shoulder; no work taking place.
- Segment E – September 12 (1900 – 2045):MBT-1® parked next to work zone on shoulder; no work taking place

- Segment F – September 13 (1045 – 1500):No MBT-1®, installation of a permanent barrier
- Segment G – September 13 (1900 – 2045): No MBT-1®, permanent barrier in place

4.4.2 Speed comparisons

Due to the limited use of the MBT-1® and the problems associated with collecting speed data on the project, this case study provided only minimal data for analysis. The following t-tests were performed to determine if there is a difference between the recorded speeds:

- Time frame A vs. time frame C
- Time frame A vs. time frame E
- Time frame A vs. time frame G
- Time frame C vs. time frame E
- Time frame C vs. time frame G
- Time frame E vs. time frame G
- Time frame B vs. time frame D
- Time frame B vs. time frame F
- Time frame D vs. time frame F

The results of these tests are shown Table 4.21. As observed in the table, only the comparison between time frames B and F showed results that might be deemed significant (p-value < 0.05), but that significance has a 95% confidence interval between -2.23 mph and -0.23 mph. This confidence interval suggests that mean speeds during time frame B are between 2.23 and 0.23 mph slower than mean speeds in time frame F. This lack in significant speed differences suggests that the presence of the mobile barrier did not affect the average speeds in the D-lane.

Table 4.21: Results of Student's t-tests between the Mean Speeds of the Various Time Segments in D-lane– Case Study 4

	Time Frames Compared	P-value	95% CI (mph)
1	A vs. C	0.2773	(-8.082589,2.682589)
2	A vs. E	0.4295	(-7.333678,3.458678)
3	A vs. G	0.1839	(-8.94693,1.99693)
4	C vs. E	0.255	(-0.619033,2.144033)
5	C vs. G	0.4101	(-2.780209,1.230209)
6	E vs. G	0.1333	(-3.6196527,0.5446527)
7	B vs. D	0.2245	(-1.5588541,0.3832986)
8	B vs. F	0.01713	(-2.2326179, -0.2340488)
9	D vs. F	0.1328	(-1.5013823,0.2102712)

4.5 CASE STUDY 5 – I-5 MP 304-307.5

This section of the report provides an analysis of the speed data recorded on case study #5. The analysis section for this case study includes the following:

- A discussion on the procedure for the placement of the speed sensors
- A discussion on the data used for the analysis
- Initial descriptive statistics for the data that was collected from each sensor
- Comparisons of speeds between different locations along the path of the vehicles

4.5.1 Sensor Setup and Data Collection

As described in Section 3.10.1, seven sensors were placed approximately every half mile in the northbound lanes of I-5 between mileposts (MP) 304 and 305.5. The first location of the work was at MP 304, and the relative distance between the work locations was 490 ft. The locations of the work and the speed sensors are shown in Figure 3.16.

The speed sensors recorded vehicle speeds and lengths from every vehicle that passed over the sensors, and that information was later downloaded and analyzed. For each sensor location the research team created tables and figures showing the variability of the speeds over regular time intervals. The information generated is very extensive and as a result only the tables associated with sensor #774 on September 27 is shown below. The remaining tables of speed information are shown in Appendix L. The information for all of the other sensors is presented in a format similar to that shown for sensor #774 below.

Table 4.22 shows the time summary of vehicle speeds from sensor #774 that were collected on September 27. The sensors recorded vehicle speeds from 10:00 p.m. until 2:00 a.m. For the analysis, the speeds compared were recorded between 10:26 p.m. and 12:43a.m. in the time segments A-N shown in

Table 3.6. During that time period, work was taking place on the roadway and the research team was monitoring the progress of the work. The speeds are grouped into 5 mph increments and these increments are shown in the first column of the table. The second column labeled “Total” shows the vehicle speed information for the duration of the analysis for sensor #774. The following columns show the information collected for each work location. Between 10:26 p.m. and 10:37 p.m., work was performed to replace the first HOV marker. Between 10:37 p.m. and 10:48 p.m., work took place at the second HOV marker. In total, 14 HOV markers were installed on the A-lane during that period, and each column represents the time frame for each marker from the time the MBT-1® stopped at the location to the time it reached the next location.

The table also shows the total number of vehicles for that period, average speed, standard deviation of the average speed, the 85th percentile of vehicle speeds, the minimum and maximum speeds, and the range of all vehicle speeds. The yellow bars and red bars provide a graphical view of the distribution of vehicle speed. The yellow bars show that the speed for all vehicles is approximately normally distributed, with a center near 50-54 mph. The red bars indicate that the speed distribution changes from one time period to the next (note: Blank cells in the table indicate time segments in which no or only one vehicle was recorded and a measurable statistic could not be produced).

The total number of vehicles row shows the traffic volume for each time period. This information may not be consistent among different traffic sensors placed in sequence, since the vehicles can only be recorded if their drivers pass over each particular sensor. Depending on the location of each sensor in the lane, some vehicles may not travel over it and therefore not be recorded. In addition vehicles could change lanes and enter/exit the highway.

Table 4.23, Table 4.24, Table 4.25, and Table 4.26 show similar information as that shown in Table 4.22, but the information is separated according to the length of the vehicles being measured. The vehicles are categorized into four length categories. Table 4.23 shows the speed information for vehicles less than 25 feet long, which are normal passenger cars and small pick-ups without a trailer. Table 4.24 shows speeds for vehicles between 25 and 50 feet long, which are mostly long vans, one trailer pick-ups, and small trucks. Table 4.25 shows the speeds for vehicles from 50 to 75 feet in length, which are mid-size, semi-trucks with trailers. Table 4.26 shows the speeds for vehicles longer than 75 feet, which are long trucks. These tables and their interpretation are an example of how to understand the additional tables in Appendix L.

Table 4.22: Time Summary of Vehicle Speed for September 27 (Sensor #774 2nd B-lane)

Vehicle Speed (all vehicles)	Total	2226-2237	2237-2248	2248-2256	2256-2306	2306-2315	2315-2323	2323-2332	2332-2340	2340-2349	2349-2359	2359-0012	0012-0021	0021-0032	0032-0043
MPH															
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.5%	0.0%	0.0%	0.0%	0.0%
20-24	0.1%	0.0%	0.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	0.0%	1.5%	0.0%	0.0%	0.0%	0.0%
30-34	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	3.0%	0.0%	0.0%	2.0%	0.0%	2.4%
35-39	1.3%	4.3%	0.0%	1.4%	1.4%	0.0%	1.1%	0.0%	2.2%	0.0%	2.9%	2.9%	0.0%	0.0%	0.0%
40-44	4.6%	3.5%	1.7%	5.7%	2.7%	9.1%	6.5%	1.5%	8.9%	0.0%	5.9%	7.1%	0.0%	8.1%	0.0%
45-49	16.3%	8.7%	8.7%	5.7%	14.9%	34.1%	40.2%	21.2%	26.7%	15.2%	14.7%	5.7%	10.2%	8.1%	9.5%
50-54	33.0%	32.2%	37.4%	32.9%	40.5%	38.6%	32.6%	34.8%	35.6%	30.3%	32.4%	30.0%	26.5%	24.2%	21.4%
55-59	24.4%	24.3%	34.8%	34.3%	21.6%	14.8%	16.3%	25.8%	15.6%	30.3%	16.2%	28.6%	22.4%	25.8%	31.0%
60-64	12.8%	17.4%	16.5%	14.3%	9.5%	3.4%	2.2%	13.6%	4.4%	15.2%	11.8%	12.9%	24.5%	22.6%	16.7%
65-69	3.6%	5.2%	0.0%	1.4%	5.4%	0.0%	0.0%	0.0%	0.0%	6.1%	10.3%	7.1%	10.2%	4.8%	7.1%
70-74	1.3%	2.6%	0.0%	1.4%	1.4%	0.0%	1.1%	3.0%	0.0%	0.0%	1.5%	2.9%	2.0%	0.0%	2.4%
>=75	1.9%	1.7%	0.0%	2.9%	2.7%	0.0%	0.0%	0.0%	2.2%	0.0%	1.5%	2.9%	2.0%	6.5%	9.5%
Total # of vehicles	989	115	115	70	74	88	92	66	45	33	68	70	49	62	42
Average speed	54.9	55.5	54.5	55.5	54.7	50.4	50.3	54.0	50.0	54.2	53.6	55.8	57.2	56.7	58.2
St. Dev.	7.7	7.9	5.5	7.7	7.9	4.8	5.1	6.1	7.9	6.4	9.7	8.6	7.6	8.5	10.5
85th percentile	61.0	62.0	60.0	60.7	61.0	55.0	55.0	60.0	55.4	60.0	63.0	63.0	64.0	63.0	66.9
Min	16.0	38.0	23.0	35.0	36.0	41.0	38.0	43.0	26.0	33.0	16.0	36.0	31.0	41.0	30.0
Max	88.0	82.0	64.0	82.0	88.0	62.0	70.0	72.0	77.0	67.0	75.0	86.0	75.0	83.0	85.0
Range	72.0	44.0	41.0	47.0	52.0	21.0	32.0	29.0	51.0	34.0	59.0	50.0	44.0	42.0	55.0

Table 4.23: Time Summary of Vehicle (0-25 feet long) Speed for September 27 (Sensor #774 2^{nd} B-lane)

Vehicle Speed (0-25 FT Vehicles)	Total	2226-2237	2237-2248	2248-2256	2256-2306	2306-2315	2315-2323	2323-2332	2332-2340	2340-2349	2349-2359	2359-0012	0012-0021	0021-0032	0032-0043
MPH															
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.5%	0.0%	0.0%	0.0%	0.0%
20-24	0.1%	0.0%	0.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	0.0%	1.5%	0.0%	0.0%	0.0%	0.0%
30-34	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	3.0%	0.0%	0.0%	2.4%	0.0%	2.8%
35-39	1.3%	4.7%	0.0%	1.4%	1.4%	0.0%	1.1%	0.0%	2.2%	0.0%	3.1%	1.6%	0.0%	0.0%	0.0%
40-44	4.3%	2.8%	1.9%	5.7%	2.7%	8.3%	6.7%	1.5%	8.9%	0.0%	3.1%	7.9%	0.0%	7.5%	0.0%
45-49	16.3%	8.5%	7.4%	5.7%	15.1%	33.3%	41.1%	21.5%	26.7%	15.2%	13.8%	4.8%	9.5%	9.4%	8.3%
50-54	32.4%	32.1%	38.0%	32.9%	41.1%	39.3%	31.1%	35.4%	35.6%	30.3%	33.8%	28.6%	21.4%	17.0%	16.7%
55-59	24.7%	23.6%	34.3%	34.3%	20.5%	15.5%	16.7%	24.6%	15.6%	30.3%	16.9%	28.6%	26.2%	30.2%	33.3%
60-64	13.1%	17.9%	17.6%	14.3%	9.6%	3.6%	2.2%	13.8%	4.4%	15.2%	12.3%	14.3%	23.8%	22.6%	19.4%
65-69	3.8%	5.7%	0.0%	1.4%	5.5%	0.0%	0.0%	0.0%	0.0%	6.1%	10.8%	7.9%	11.9%	5.7%	5.6%
70-74	1.4%	2.8%	0.0%	1.4%	1.4%	0.0%	1.1%	3.1%	0.0%	0.0%	1.5%	3.2%	2.4%	0.0%	2.8%
>=75	2.0%	1.9%	0.0%	2.9%	2.7%	0.0%	0.0%	0.0%	2.2%	0.0%	1.5%	3.2%	2.4%	7.5%	11.1%
Total # of vehicles	933	106	108	70	73	84	90	65	45	33	65	63	42	53	36
Average speed	55.1	55.8	54.6	55.5	54.7	50.5	50.3	53.9	50.0	54.2	54.0	56	58	57	59
St. Dev.	7.7	8.0	5.5	7.7	7.9	4.8	5.2	6.2	7.9	6.4	9.7	9	8	9	11
85th percentile	62.0	62.3	60.0	60.7	61.0	55.6	55.0	60.0	55.4	60.0	63.4	64	65	64	67
Min	16.0	38.0	23.0	35.0	36.0	41.0	38.0	43.0	26.0	33.0	16.0	36.0	31.0	41.0	30.0
Max	88.0	82.0	64.0	82.0	88.0	62.0	70.0	72.0	77.0	67.0	75.0	86.0	75.0	83.0	85.0
Range	72.0	44.0	41.0	47.0	52.0	21.0	32.0	29.0	51.0	34.0	59.0	50.0	44.0	42.0	55.0

Table 4.24: Time Summary of Vehicle (25-50 feet long) Speed for September 27 (Sensor #774 2nd B-lane)

Vehicle Speed (25-50 FT Vehicles)	Total	2226-2237	2237-2248	2248-2256	2256-2306	2306-2315	2315-2323	2323-2332	2332-2340	2340-2349	2349-2359	2359-0012	0012-0021	0021-0032	0032-0043
MPH															
< 10	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
30-34	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
35-39	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
40-44	7.9%	11.1%	0.0%		0.0%	0.0%	0.0%	0.0%			100.0%	0.0%	0.0%	16.7%	0.0%
45-49	10.5%	11.1%	16.7%		0.0%	100.0%	0.0%	0.0%			0.0%	20.0%	0.0%	0.0%	0.0%
50-54	44.7%	33.3%	33.3%		0.0%	0.0%	100.0%	0.0%			0.0%	60.0%	66.7%	66.7%	0.0%
55-59	26.3%	33.3%	50.0%		100.0%	0.0%	0.0%	100.0%			0.0%	20.0%	0.0%	0.0%	100.0%
60-64	10.5%	11.1%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	33.3%	16.7%	0.0%
65-69	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
70-74	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
>=75	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%	0.0%	0.0%
Total # of vehicle	38	9	6	0	1	1	1	1	0	0	1	5	6	6	1
Average speed	53.4	52.7	54.2		57.0	47.0	50.0	56.0			44.0	51.4	55.8	52.5	57.0
St. Dev.	6.1	5.0	3.8									3.6	5.0	6.8	
85th percentile	59.0	56.0	56.8		57.0	47.0	50.0	56.0			44.0	54.4	61.0	56.3	57.0
Min	34.0	44.0	48.0		57.0	47.0	50.0	56.0			44.0	46.0	52.0	42.0	57.0
Max	72.0	60.0	59.0		57.0	47.0	50.0	56.0			44.0	55.0	64.0	63.0	57.0
Range	38.0	16.0	11.0		0.0	0.0	0.0	0.0			0.0	9.0	12.0	21.0	0.0

Table 4.25: Time Summary of Vehicle (50-75 feet long) Speed for September 27 (Sensor #774 2nd B-lane)

Vehicle Speed (50-75 FT Vehicles)	Total	2226-2237	2237-2248	2248-2256	2256-2306	2306-2315	2315-2323	2323-2332	2332-2340	2340-2349	2349-2359	2359-0012	0012-0021	0021-0032	0032-0043
MPH															
< 10	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
10-14	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
15-19	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
20-24	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
25-29	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
30-34	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
35-39	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
40-44	18.2%		0.0%			100.0%	0.0%				50.0%		0.0%	0.0%	0.0%
45-49	36.4%		100.0%			0.0%	0.0%				50.0%		100.0%	0.0%	25.0%
50-54	36.4%		0.0%			0.0%	100.0%				0.0%		0.0%	100.0%	50.0%
55-59	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
60-64	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
65-69	9.1%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	25.0%
70-74	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
>=75	0.0%		0.0%			0.0%	0.0%				0.0%		0.0%	0.0%	0.0%
Total # of vehicle	11	0	1	0	0	1	1	0	0	0	2	0	1	1	4
Average speed	51.7		47.0			44.0	50.0				45.5		45.0	51.0	53.5
St. Dev.	6.4										2.1				8.4
85th percentile	58.0		47.0			44.0	50.0				46.6		45.0	51.0	58.8
Min	42.0		47.0			44.0	50.0				44.0		45.0	51.0	48.0
Max	67.0		47.0			44.0	50.0				47.0		45.0	51.0	66.0
Range	25.0		0.0			0.0	0.0				3.0		0.0	0.0	18.0

Table 4.26: Time Summary of Vehicle (75+ feet long) Speed for September 27 (Sensor #774 2nd B-lane)

Vehicle Speed (+75 FT Vehicles)	Total	2226-2237	2237-2248	2248-2256	2256-2306	2306-2315	2315-2323	2323-2332	2332-2340	2340-2349	2349-2359	2359-0012	0012-0021	0021-0032	0032-0043
MPH															
< 10	0.0%					0.0%						0.0%		0.0%	0.0%
10-14	0.0%					0.0%						0.0%		0.0%	0.0%
15-19	0.0%					0.0%						0.0%		0.0%	0.0%
20-24	0.0%					0.0%						0.0%		0.0%	0.0%
25-29	0.0%					0.0%						0.0%		0.0%	0.0%
30-34	0.0%					0.0%						0.0%		0.0%	0.0%
35-39	14.3%					0.0%						50.0%		0.0%	0.0%
40-44	0.0%					0.0%						0.0%		0.0%	0.0%
45-49	14.3%					50.0%						0.0%		0.0%	0.0%
50-54	42.9%					50.0%						0.0%		50.0%	100.0%
55-59	14.3%					0.0%						50.0%		0.0%	0.0%
60-64	14.3%					0.0%						0.0%		50.0%	0.0%
65-69	0.0%					0.0%						0.0%		0.0%	0.0%
70-74	0.0%					0.0%						0.0%		0.0%	0.0%
>=75	0.0%					0.0%						0.0%		0.0%	0.0%
Total # of vehicle	7	0	0	0	0	2	0	0	0	0	0	2	0	2	1
Average speed	50.7					51.5						48.0		57.0	53.0
St. Dev.	9.9					3.5						12.7		7.1	
85th percentile	57.9					53.3						54.3		60.5	53.0
Min	21.0					49.0						39.0		52.0	53.0
Max	65.0					54.0						57.0		62.0	53.0
Range	44.0					5.0						18.0		10.0	0.0

4.5.2 Vehicle Speed Analysis

Figure 4.27 shows the average and 85th percentile speeds of all vehicles during each time segment relative to the distance from sensor #216, which was placed at MP 304 in the B-lane, as recorded by sensor #216. Figure 4.28 shows the same information as recorded from sensor 803, which was placed in the C-lane at MP 304. As mentioned in the previous section, each time segment represents one work zone location where a HOV marker was placed on the roadway. The vehicle speeds appear to be much lower during the installation of the first three HOV markers, but they increase and become more consistent during the rest of the installations. This was due to the increased traffic that occurred as the maintenance crews were preparing and implementing traffic control initially.

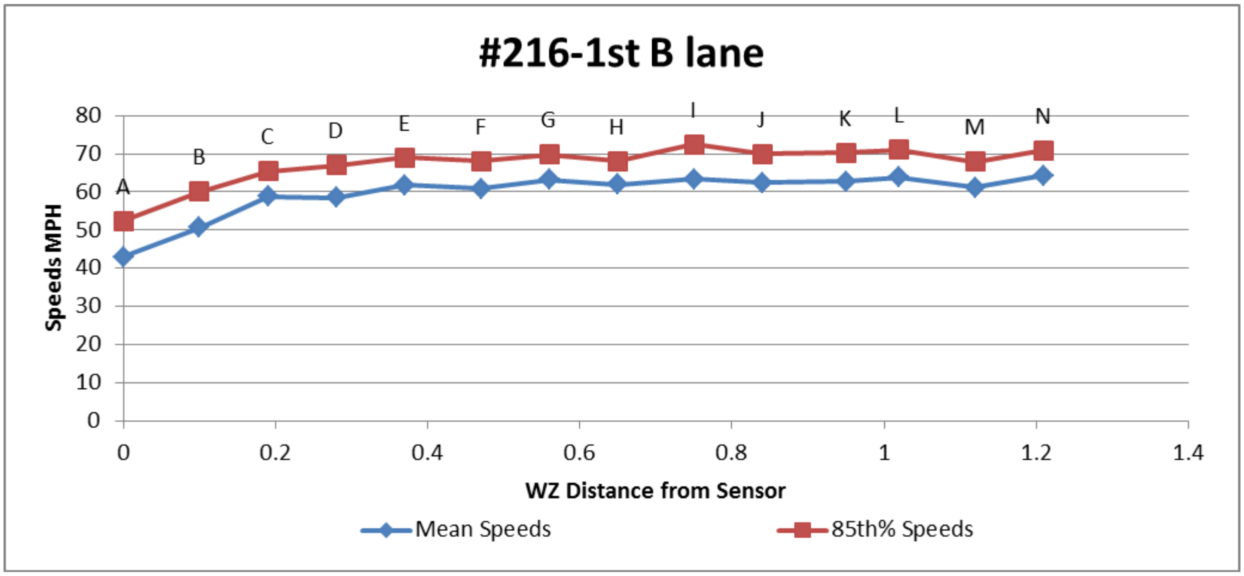

Figure 4.27: Average and 85thPercentileSpeeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #216 (1st sensor MP 304 B-lane)

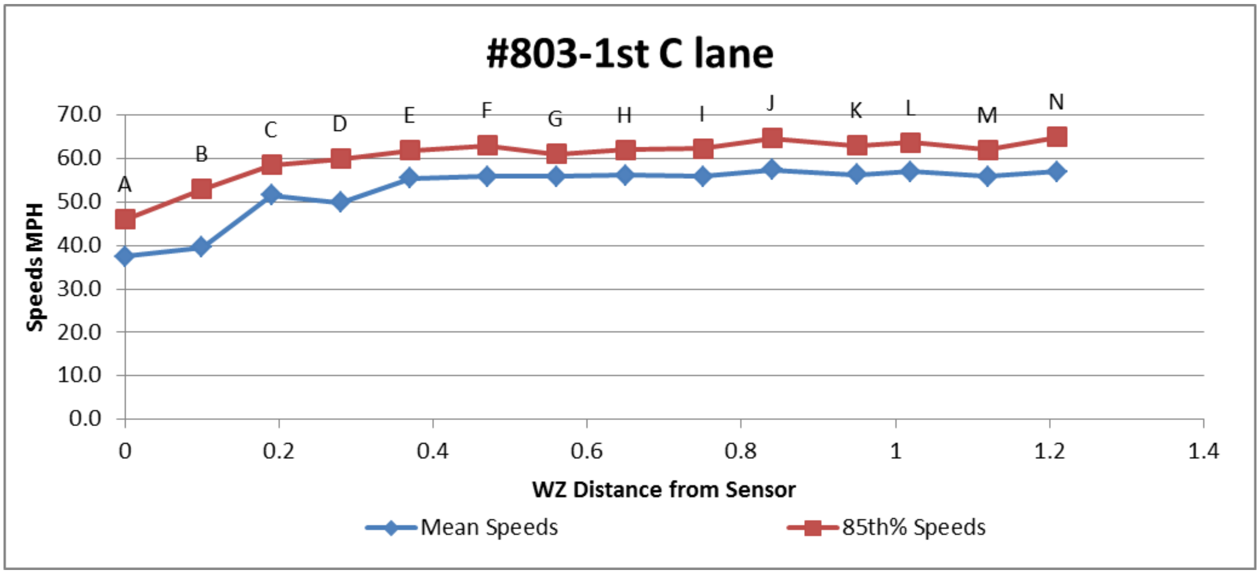

Figure 4.28: Average and 85th Percentile Speeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #803 (1st sensor MP 304C-lane)

Figure 4.29 shows the average and 85th percentile speeds of all vehicles during each time segment relative to the distance from sensor #774, which was placed at MP 304.5 in the B-lane, as recorded by that sensor. Figure 4.29 shows the same information as recorded from sensor #803 which was placed on the C-lane at MP 304.5. The speeds of the vehicles appear to be lower during the installation of the HOV markers close to the sensors, as seen in Figure 4.29. The speeds in the C-lane (Figure 4.30) appear to be unaffected by the presence of the work. Further analysis is performed to quantify the differences in speeds between the sensors during each time period.

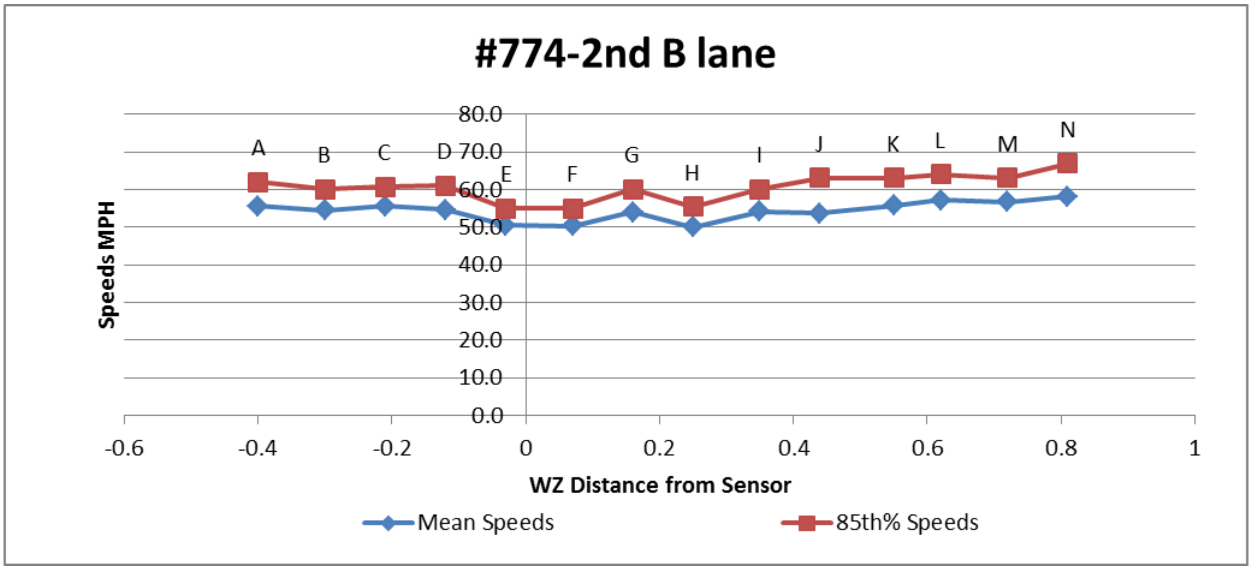

Figure 4.29: Average and 85th Percentile Speeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #774 (2nd sensor MP 304.5 B-lane)

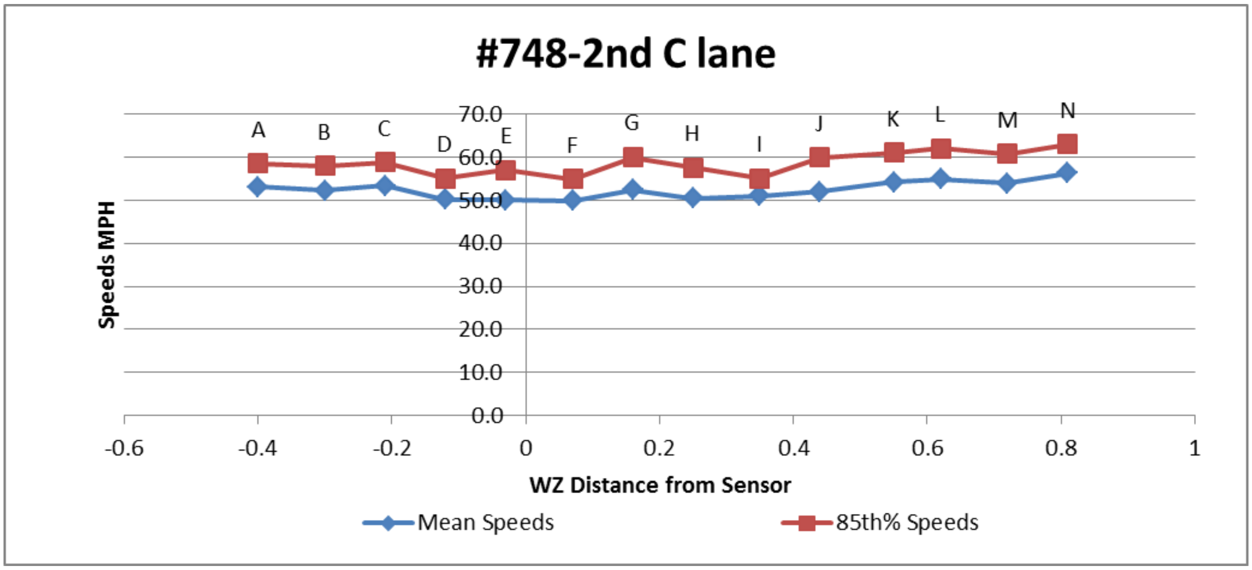

Figure 4.30: Average and 85th Percentile Speeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #748 (2nd sensor MP 304.5 C-lane)

Figure 4.31 shows the average and 85th percentile speeds of all vehicles during each time segment relative to the distance from sensor #816, which was placed at MP 305 in the B-lane, as recorded by that sensor. Figure 4.32 shows the same information as recorded from sensor #379 which was placed in the C-lane at MP 305. Again, as observed previously, the speeds of the vehicles appear to be lower during the installation of the HOV markers close to the sensors, as seen on Figure 4.31. The speeds in the C-lane (Figure 4.32) appear to be unaffected by the presence of the work. Further analysis is performed to quantify the differences in speeds between the sensors during each time period.

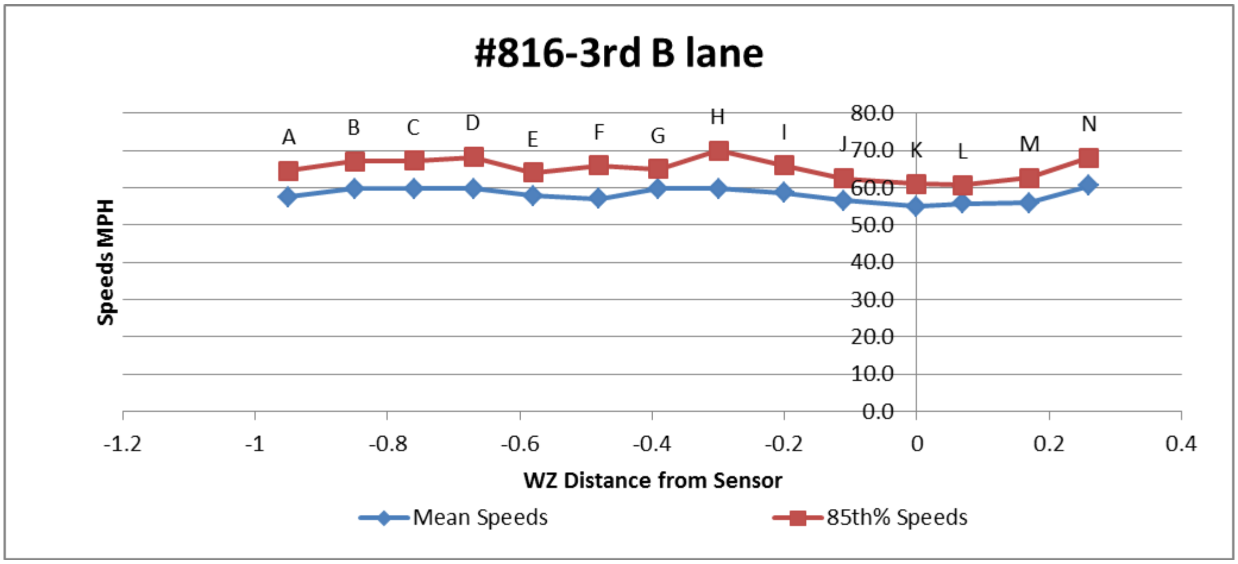

Figure 4.31: Average and 85th Percentile Speeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #816 (3rd sensor MP 305 B-lane)

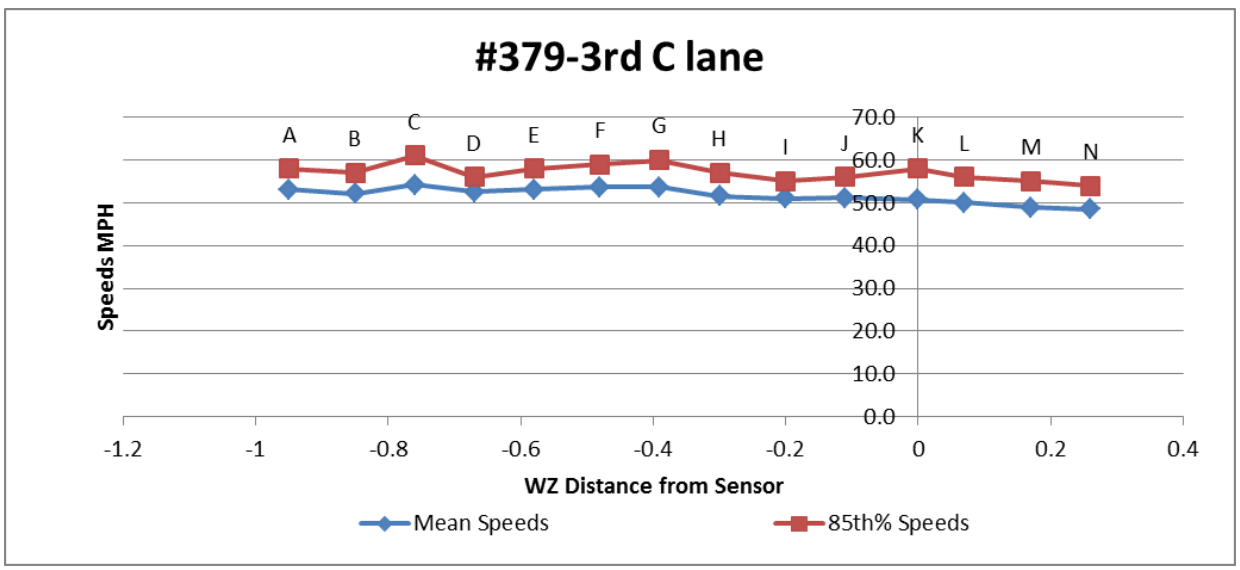

Figure 4.32: Average and 85th Percentile Speeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #379 (3rd sensor MP 305 C-lane)

Figure 4.33 shows the average and 85th percentile speeds of all vehicles during each time segment relative to the distance from sensor #687, which was placed at MP 305.5 in the B-lane, as recorded by that sensor. During the investigated period there were no HOV placements close to that sensor, and as observed in the figure, the speeds appear to be constant with little or no variation between time segments.

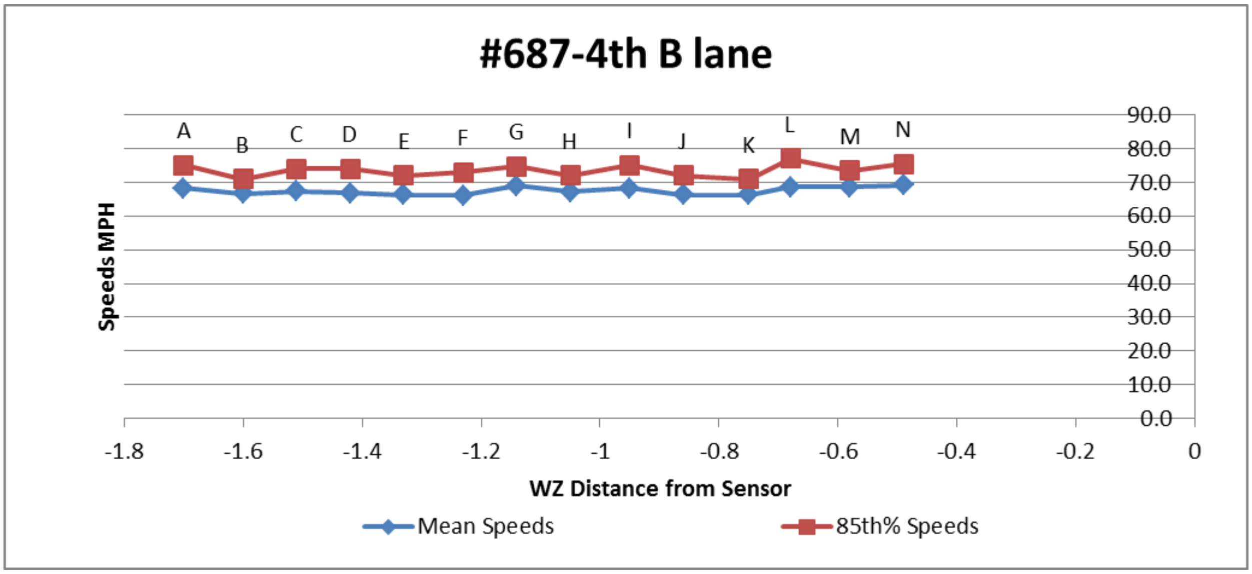

Figure 4.33: Average and 85th Percentile Speeds of Vehicles for Each Time Segment and Relative Distance from Speed Sensor #687 (4th sensor MP 305.5 B-lane)

The Shapiro-Wilk test was performed on the speed measurements to determine whether the observations were normally distributed (*Shapiro and Wilk, 1965).* Table 4.27 shows the test results for the normality of the data for each sensor and each time segment. Highlighted with green are the locations and times where the data is normal. Locations where the data is not normal are highlighted in red.

Table 4.27: Shapiro-Wilk Results on Normality of Vehicle Speeds (Case 5)

Time Segment	Time Segment Start	Sensor #216 1st B-lane	Sensor #803 1st C- lane	Sensor #774 2nd B-lane	Sensor #748 2nd C-lane	Sensor #816 3rd B-lane	Sensor #379 3rd C-lane	Sensor #687 4th B-lane
A	10:26pm	W = 0.958 p = 0.213	W = 0.9922 p = 0.2148	W = 0.9666 p = 0.00573	W = 0.9828 p = 0.03966	W = 0.9824 p = 0.1826	W = 0.9721 p = 0.00594	W = 0.9686 p = 0.00966
B	10:37pm	W = 0.9542 p = 0.02453	W = 0.9678 p = 8.52e-05	W = 0.8824 p = 4.56e-08	W = 0.986 p = 0.1506	W = 0.9227 p = 3.74e-06	W = 0.9829 p = 0.115	W = 0.8918 p = 1.14e-07
C	10:48pm	W = 0.979 p = 0.5795	W = 0.972 p = 0.01493	W = 0.9169 p = 0.00019	W = 0.9471 p = 0.00046	W = 0.9239 p = 0.00058	W = 0.9102 p = 2.73e-05	W = 0.9746 p = 0.2431
D	10:56pm	W = 0.9728 p = 0.05323	W = 0.9644 p = 0.00675	W = 0.8696 p = 1.72e-06	W = 0.9618 p = 0.00087	W = 0.982 p = 0.275	W = 0.9758 p = 0.06419	W = 0.975 p = 0.1182
E	11:06pm	W = 0.9806 p = 0.1581	W = 0.9761 p = 0.1294	W = 0.979 p = 0.164	W = 0.9861 p = 0.2215	W = 0.9682 p = 0.03945	W = 0.9719 p = 0.02725	W = 0.9742 p = 0.1091
F	11:15pm	W = 0.9155 p = 2.13e-05	W = 0.9784 p = 0.3985	W = 0.9442 p = 0.00427	W = 0.985 p = 0.3057	W = 0.9495 p = 0.00193	W = 0.9061 p = 9.42e-06	W = 0.9108 p = 3.60e-05
G	11:23pm	W = 0.9814 p = 0.3963	W = 0.9411 p = 0.03124	W = 0.9605 p = 0.03402	W = 0.9385 p = 0.00052	W = 0.918 p = 0.00057	W = 0.9305 p = 0.00044	W = 0.9805 p = 0.4145
H	11:32pm	W = 0.9701 p = 0.1114	W = 0.9221 p = 0.01855	W = 0.9249 p = 0.00621	W = 0.9826 p = 0.3729	W = 0.9567 p = 0.06907	W = 0.9527 p = 0.01339	W = 0.8948 p = 0.00037
I	11:40pm	W = 0.979 p = 0.4116	W = 0.9473 p = 0.1021	W = 0.9517 p = 0.1488	W = 0.958 p = 0.02088	W = 0.8668 p = 0.00033	W = 0.9708 p = 0.07348	W = 0.9158 p = 0.00238
J	11:49pm	W = 0.9759 p = 0.1628	W = 0.9891 p = 0.8944	W = 0.9442 p = 0.00427	W = 0.9724 p = 0.04225	W = 0.9383 p = 0.01046	W = 0.977 p = 0.07457	W = 0.843 p = 5.07e-06
K	11:59pm	W = 0.976 p = 0.1421	W = 0.9646 p = 0.03597	W = 0.9575 p = 0.01815	W = 0.9918 p = 0.829	W = 0.9329 p = 0.01069	W = 0.972 p = 0.01262	W = 0.9711 p = 0.2358
L	00:12am	W = 0.9778 p = 0.578	W = 0.9871 p = 0.81	W = 0.9623 p = 0.1179	W = 0.9375 p = 0.00291	W = 0.9592 p = 0.2949	W = 0.9901 p = 0.7132	W = 0.9576 p = 0.1698
M	00:21am	W = 0.9528 p = 0.03049	W = 0.9771 p = 0.2344	W = 0.9561 p = 0.0265	W = 0.9645 p = 0.03205	W = 0.9634 p = 0.696	W = 0.9754 p = 0.01767	W = 0.9365 p = 0.03222
N	00:32am	W = 0.9734 p = 0.543	W = 0.985 p = 0.7322	W = 0.9107 p = 0.00306	W = 0.981 p = 0.4163	W = 0.9475 p = 0.6126	W = 0.9583 p = 0.00226	W = 0.9685 p = 0.4786

Figure 4.34 shows the variability in speeds for the 1st B-lane sensor at MP 304. Similarly, Figure 4.35 shows the variability in speeds for the 1st C-lane sensor at MP 304. Figure 4.36 and Figure 4.37 show the variability in speeds for each time segment at the 2nd sensor location at MP 304.5 in the B- and C-lanes, respectively. Figure 4.38 and show the same information for MP 305, Figure 4.39 and Figure 4.40 shows the variability in speeds for the last sensor in the B-lane at MP 305.5.

Even though the data is not normal at all locations, it is assumed that the observations are part of a larger population that has normally-distributed speeds. This assumption allows the investigation of differences in the speeds using t-tests.

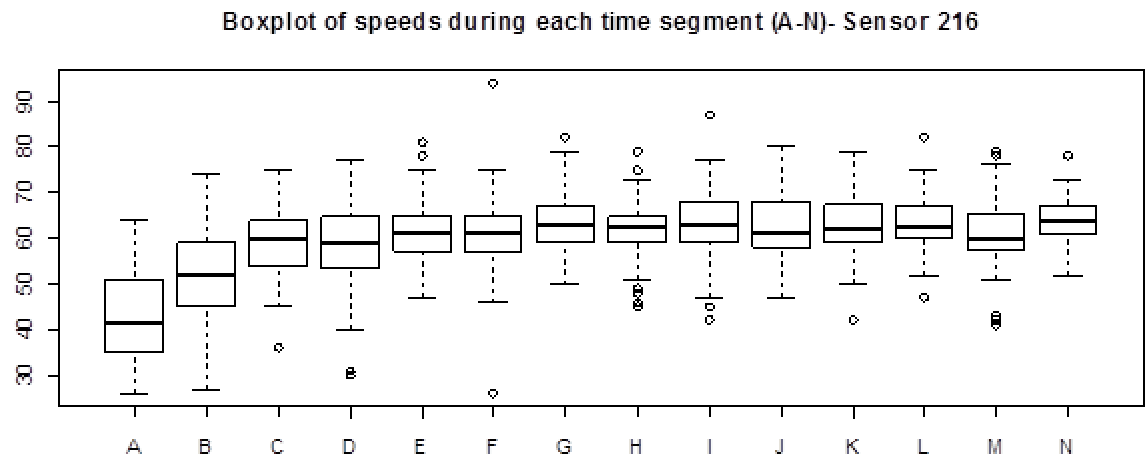

Figure 4.34: Sensor #216 (1st B-lane) Speed Measurements per Time Segment

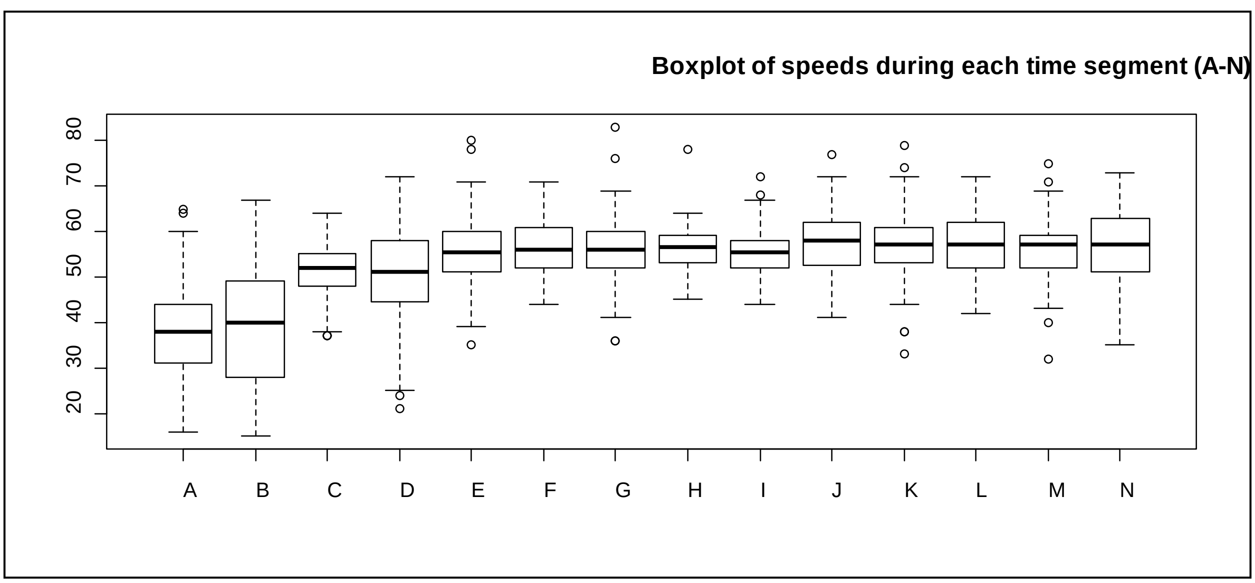

Figure 4.35: Sensor #803 (1st C-lane) Speed Measurements per Time Segment

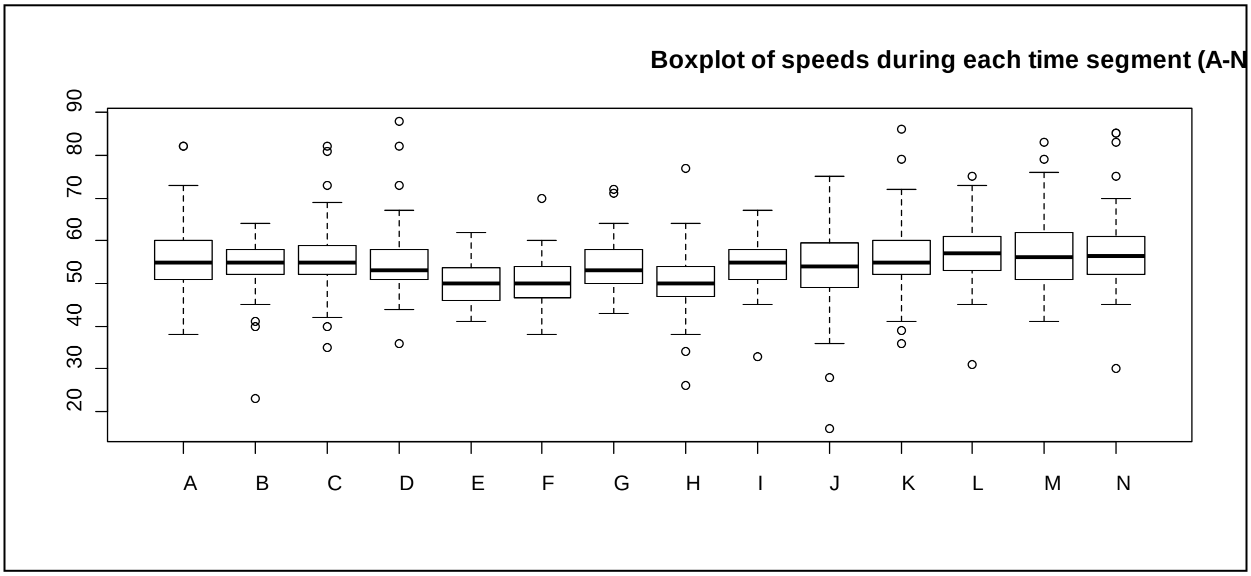

Figure 4.36: Sensor #774 (2nd B-lane) Speed Measurements per Time Segment

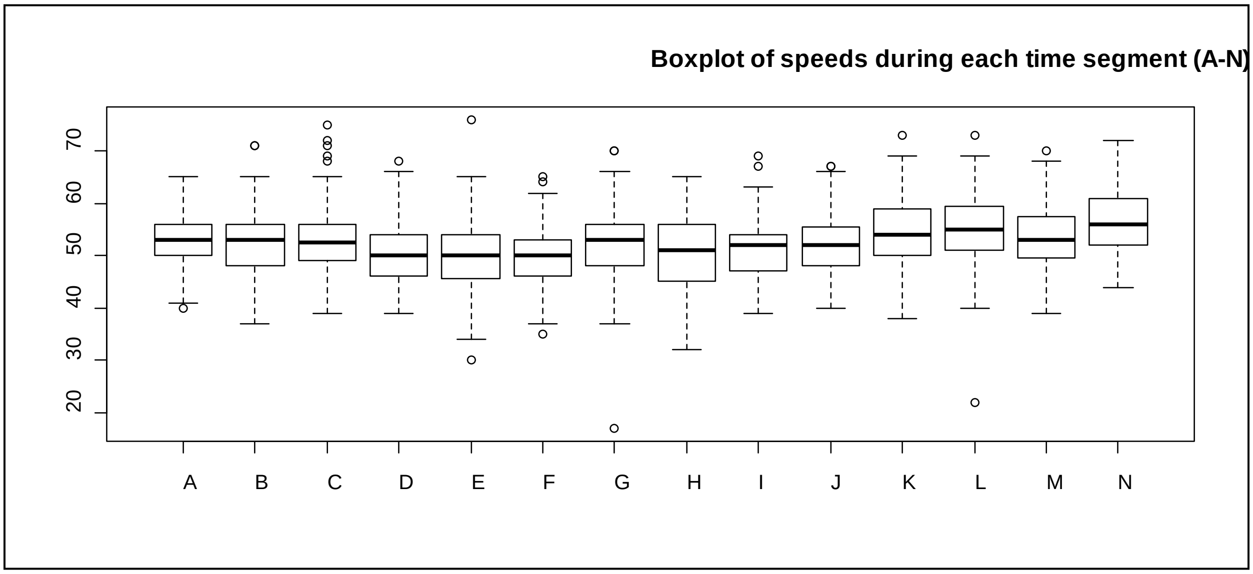

Figure 4.37: Sensor #748 (2nd C-lane) Speed Measurements per Time Segment

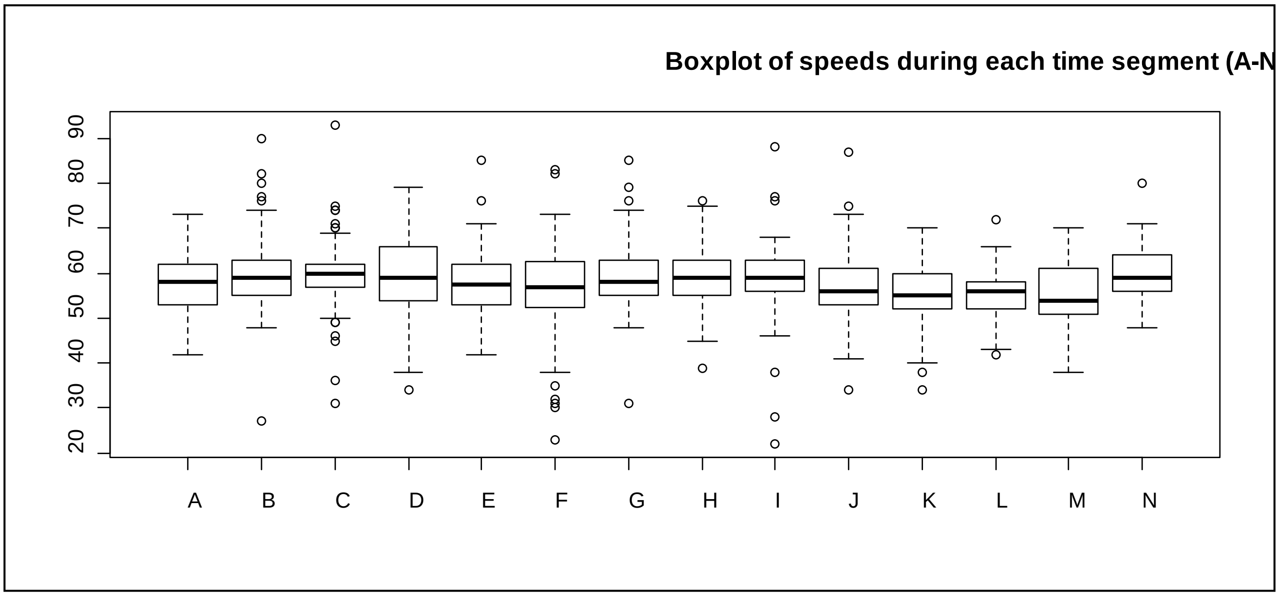

Figure 4.38: Sensor #816 (3rd B-lane) Speed Measurements per Time Segment

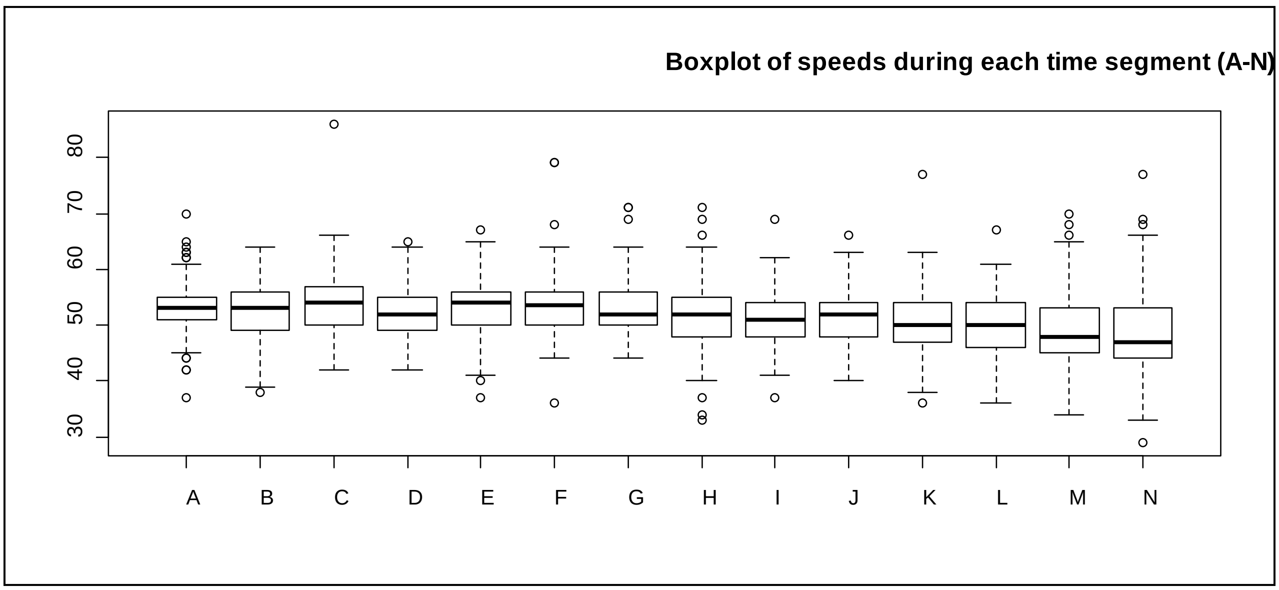

Figure 4.39: Sensor #379 (3rd C-lane) Speed Measurements per Time Segment

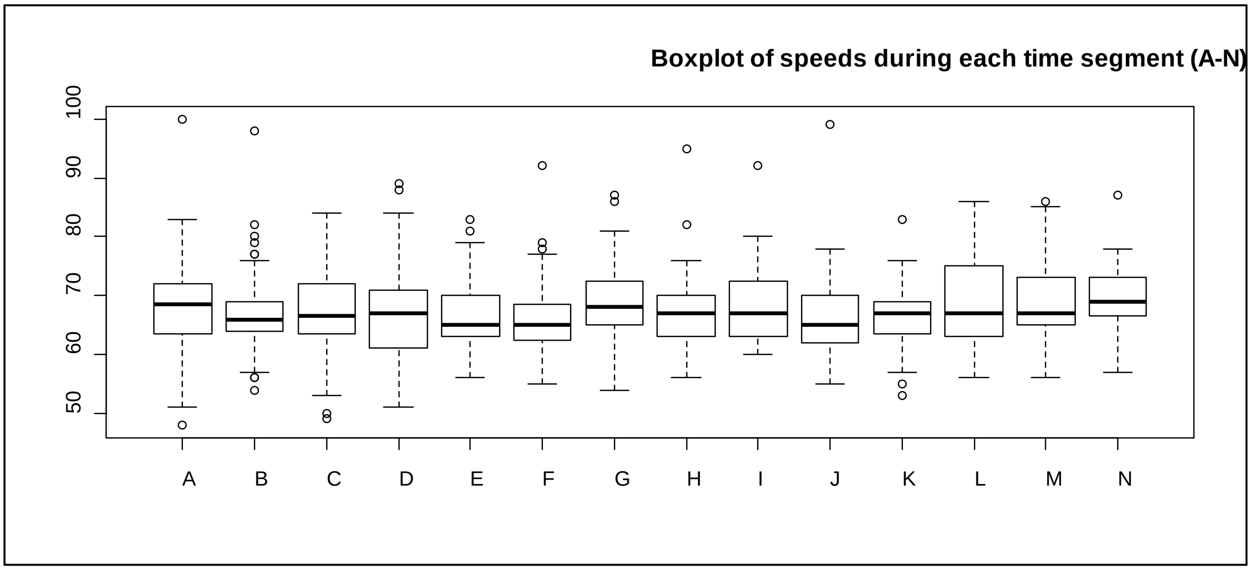

Figure 4.40: Sensor #687 (4th B-lane) Speed Measurements per Time Segment

4.5.3 Speed Comparisons

The Welch two sample t-test was performed on the data to investigate possible differences in driver behavior (Ramsey et al. 2002). Specifically, the mean vehicle speed differences at each time segment between different sensor locations were compared.

During time segments A and B, work was carried out relatively close to the first set of sensors. During time segment A, the work zone was located immediately adjacent to the sensors, while during time segment B the distance from the work zone to the sensors was 0.1 miles. During these time segments there was an increased amount of traffic due to the traffic control setup, and comparisons of these speeds do not generate any useful information regarding the reduction or increase of speeds adjacent to the work zone.

During time segments E and F, work was carried out relatively close to the second set of sensors. During time segment E, the distance from the work zone to the second set of sensors was 0.03 miles prior, while during time segment F, the distance from the work zone to the second set of sensors was 0.07 miles subsequent. The average speeds recorded during time segment E are shown in Table 4.28, and the average speeds recorded during time segment F are shown in Table 4.29. The tables also depict the differences between the mean speeds recorded along with the p-values and the 95% confidence interval of that comparison.

As observed in the tables, during time segment E the mean vehicle speed measured by the 2nd sensor was 11.43 mph slower than the mean speed measured by the 1st sensor with a p-value close to zero and a 95% confidence interval for that difference between 9.69 mph and 13.15 mph. The 1st sensor was placed about 0.5 miles prior to the 2nd sensor.

Table 4.28: Comparison of Mean Speeds during Time Segment E (B-lane – Case 5)

			Avg. Speed 2nd Sensor (mph)	Avg. Speed 3rd Sensor (mph)	Avg. Speed 4th Sensor (mph)
			50.40 mph	**57.78 mph**	**66.30 mph**
Avg. Speed 1st Sensor (mph)	61.83 mph	CI	9.69, 13.15	1.95, 6.15	-6.38, -2.54
		P	2.2e-16	0.0001948	8.61e-06
Avg. Speed 2nd Sensor (mph)	50.40 mph	CI		-9.23, -5.51	-17.54, -14.24
		P		1.062e-12	2.2e-16
Avg. Speed 3rd Sensor (mph)	57.78 mph	CI			-10.56,-6.48
		P			5.973e-14

Table 4.29: Comparison of Mean Speeds during Time Segment F (B-lane – Case 5)

			Avg. Speed 2nd Sensor (mph)	Avg. Speed 3rd Sensor (mph)	Avg. Speed 4th Sensor (mph)
			50.28 mph	**56.96 mph**	**66.12 mph**
Avg. Speed 1st Sensor (mph)	60.81 mph	CI	8.56, 12.49	1.10, 6.58	-7.40, -3.21
		P	2.2e-16	0.006159	1.425e-06
Avg. Speed 2nd Sensor (mph)	50.28 mph	CI		-9.10, -4.25	-17.50, -14.17
		P		2.561e-07	2.2e-16
Avg. Speed 3rd Sensor (mph)	56.96 mph	CI			-11.69,-6.62
		P			4.67e-11

During the same time segment (segment E), the mean vehicle speed measured by the 2nd sensor was 7.38 mph slower than the mean speed measured by the 3rd sensor with a p-value close to zero and a 95% confidence interval for that difference between -9.23 mph and -5.51 mph. The second sensor preceded the third sensors by 0.5 miles.

The mean speed difference is even more pronounced when the 2nd sensor is compared with the 4th sensor. During the time segment E, the mean vehicle speed measured by the 2nd sensor was 15.9 mph slower than the mean speed measured by the 4th sensor with a p-value close to zero and a 95% confidence interval for that difference between -17.54 mph and -14.24 mph. The 2nd sensor preceded the 4thsensors by 1 mile.

During time segment F, the mean vehicle speed measured by the 2nd sensor was 10.53 mph slower than the mean speed measured by the 1st sensor with a p-value close to zero and a 95% confidence interval for that difference between 8.56 mph and 12.49 mph. Similarly, the mean vehicle speed measured by the 2nd sensor was 6.68 mph slower than the mean speed measured by the 3rd sensor with a p-value close to zero and a 95% confidence interval for that difference between -9.10 mph and -4.25 mph.

The mean speed difference is again even more pronounced when the 2nd sensor is compared with the 4th sensor. During the same time segment (segment F), the mean vehicle speed measured by the 2nd sensor was 15.84 mph slower than the mean speed measured by the 4th sensor with a p-value close to zero and a 95% confidence interval for that difference between -17.50 mph and -14.17 mph.

A similar comparison was carried out during the time segments in which work was performed close to the 3rd set of sensors (time segments K and L). During time segment K, the distance of the work zone from the 3rd set of sensors was 0.0 miles, while during time segment L, the distance of the work zone from the 3rd set of sensors was 0.07 miles subsequent. The average speeds recorded during time segment K are shown in Table 4.30. The average speeds recorded during time segment L are shown in Table 4.31. The tables also depict the differences between the mean speeds recorded along with the p-values and the 95% confidence interval of all comparisons.

Table 4.30: Comparison of Mean Speeds during Time Segment K (B-lane – Case 5)

			Avg. Speed 2nd Sensor (mph)	Avg. Speed 3rd Sensor (mph)	Avg. Speed 4th Sensor (mph)
			55.81 mph	**54.86 mph**	**66.32 mph**
Avg. Speed 1st Sensor (mph)	62.75 mph	CI	4.40, 9.48	5.40, 10.37	-5.69, -1.44
		P	2.988e-07	9.31e-09	0.001167
Avg. Speed 2nd Sensor (mph)	55.81 mph	CI		-1.88,3.77	-13.03,-7.99
		P		0.5097	2.579e-13
Avg. Speed 3rd Sensor (mph)	54.86 mph	CI			-13.92,-8.99
		P			1.595e-14

Table 4.31: Comparison of Mean Speeds during Time Segment L (B-lane – Case 5)

			Avg. Speed 2nd Sensor (mph)	Avg. Speed 3rd Sensor (mph)	Avg. Speed 4th Sensor (mph)
			57.18 mph	**55.76 mph**	**68.59 mph**
Avg. Speed 1st Sensor (mph)	63.78 mph	CI	3.56, 9.63	4.95, 11.07	-8.08, -1.53
		P	4.014e-05	1.824e-06	0.004578
Avg. Speed 2nd Sensor (mph)	57.18 mph	CI		-1.67, 4.50	-14.71, -8.10
		P		0.3641	1.387e-09
Avg. Speed 3rd Sensor (mph)	55.76 mph	CI			-16.15, -9.49
		P			1.006e-10

During time segment K, the mean vehicle speed measured by the 3rd sensor was 7.89 mph slower than the mean speed measured by the 1st sensor with a p-value close to zero and a 95% confidence interval for that difference between 5.40 mph and 10.37 mph. During the same time segment, the mean vehicle speeds measured by the 2nd and 3rd sensors did not show any significant difference. The mean difference in speeds was 0.95 mph with a p-value of 0.5097 and a 95% C.I. of -1.88 mph and 3.77 mph.

The mean speed difference becomes significant again when the mean speed measured by the 3rd sensor is compared with the mean speed measured by the 4th sensor. During the same time segment (segment K), the mean vehicle speed measured by the 3rd sensor was 11.46 mph slower than the mean speed measured by the 4th sensor with a p-value close to zero and a 95% confidence interval for that difference between -13.92 mph and -8.99 mph.

Similar results were observed during time segment L. The mean vehicle speed measured by the 3rdsensor was 8.02 mph slower than the mean speed measured by the 1st sensor with a p-value close to zero and a 95% confidence interval for that difference between 4.95 mph and 11.07 mph. Also during the time segment L, the mean vehicle speeds measured by the 2nd and 3rd sensor did not show any significant difference. The mean difference in speeds was 1.42 mph with a p-value of 0.3641 and a 95% C.I. of -1.67 mph and 4.50 mph.

The mean speed difference becomes significant again when the mean speed measured by the 3rd sensor is compared with the mean speed measured by the 4th sensor. During the same time segment (segment L), the mean vehicle speed measured by the 3rd sensor was 12.83 mph slower than the mean speed measured by the 4th sensor with a p-value close to zero and a 95% confidence interval for that difference between -16.15 mph and -9.49 mph.

4.6 CASE STUDY 6 – I-205 MP3

Case study #6 provided a good opportunity to compare the results when the MBT-1® is present to when it is not present. The analysis section for this case study includes the following:

- A discussion on the procedure for the placement of the speed sensors
- A discussion on the data used for the analysis
- Initial descriptive statistics for the data that was collected from each sensor
- Comparisons of speeds between the two nights of the study (with and without the MBT-1® present)
- Comparisons of speeds between different locations along the path of the vehicles

4.6.1 Sensor Setup and Data Collection

As described in Section 3.11.1, six sensors were placed in the northbound lanes of the roadway on both nights of the case study investigation. Figure 4.41 and Figure 4.42 depict the sensor numbers, their locations, and the relative distance between the sensors for both nights of the investigation. The first two sensors, one in each lane, were placed at a distance of 6,500 feet upstream of the work zone. The second set of sensors were placed a distance of 3,800 feet prior to the work zone, again one in each lane. The end of taper sensor was placed a distance of 1,900 feet away from the work zone in the active lane. A final sensor was placed in the active lane adjacent to the work zone.

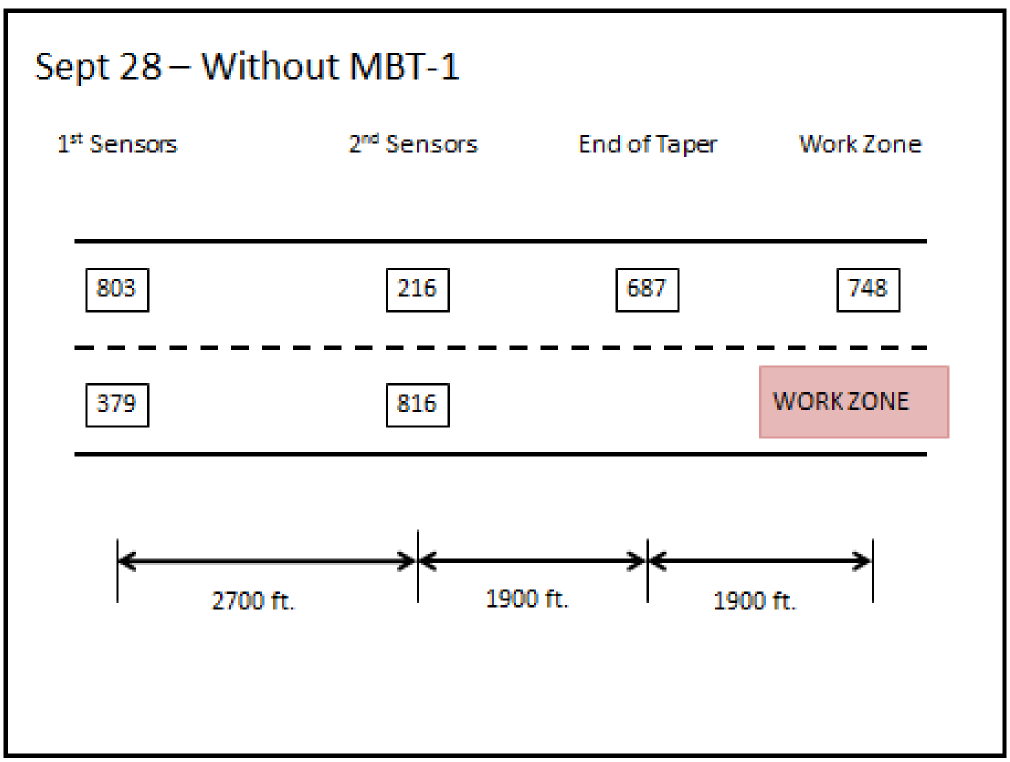

Figure 4.41: Setup of Sensors on September 28 (without MBT-1®)

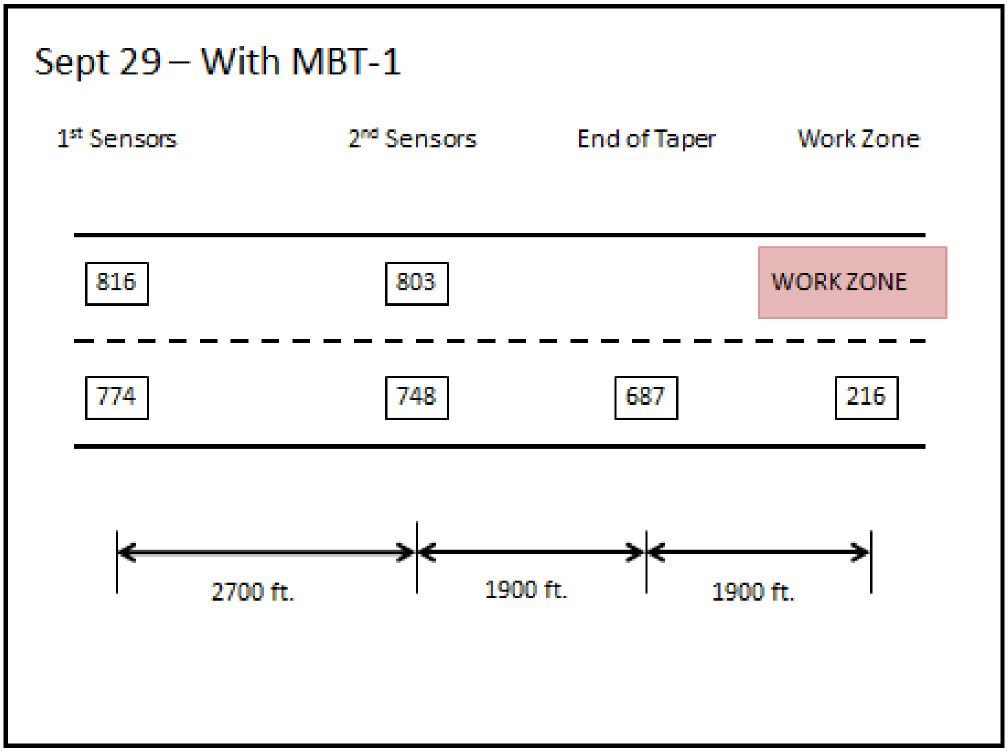

Figure 4.42: Setup of Sensors on September 29 (with MBT-1®)

The speed sensors recorded vehicle speeds and lengths from every vehicle that passed over the sensors. The recorded vehicle data was downloaded from the sensors for the analysis. For each sensor location on each day, the research team created tables and figures showing the variability of the speeds over regular time intervals. The information generated is voluminous and too extensive to include in the body of this report. Therefore, only the tables and figures associated with the sensor adjacent the work zone on September 29 with the MBT-1® present (sensor #216) are shown below. The vehicle data recorded by the other sensors on each day is shown in Appendix M. The information for all of the other sensors is presented in the Appendix in a fashion similar to that for sensor #216 described below.

Table 4.32 shows the time summary of vehicle speeds from sensor #216 that was collected on September 29 with the MBT-1® present. The information was collected and recorded from 10:30 p.m. to 5:00 a.m. The speeds are grouped into 5 mph increments and these increments are shown in the first column of the table. The second column labeled "Total" shows the vehicle speed information for the complete duration of the study (all hours combined) for sensor #216. The following columns show the information collected for each half hour of the study period. The values shown represent the percentage of vehicles in each speed increment. In addition, the table shows the total number of vehicles for that day, average speed of all vehicles for that day, standard deviation of the speeds, the 85th percentile of all vehicle speeds, the minimum and maximum speeds for that day and time period, and the range of all vehicle speeds. The yellow bars and red bars provide a graphical view of the distribution of vehicle speeds. The yellow bars show that the speed for all vehicles is approximately normally distributed, with a center in the 45-49 mph range. The red bars reveal that the speed distribution changes from time period to time period (note: Blank cells in the table indicate time segments in which no or only one vehicle was recorded and a measurable statistic could not be produced).

The total number of vehicles row in the table shows the traffic volume for that day. This information may not be consistent among different traffic sensors placed in sequence, since the vehicles can only be recorded if their drivers pass over each particular sensor. Depending on the location of each sensor in the lane, some vehicles may not travel over the sensor and therefore not be recorded.

Table 4.33, Table 4.34, Table 4.35 and Table 4.36 show similar information to that shown Table 4.32, but the information is separated according to the length (type) of the vehicles being measured. The vehicles are categorized into four length categories. Table 4.33 shows the speed information for vehicles less than 25 feet long, which are normal passenger cars and small pick-ups without a trailer. Table 4.34 shows speeds for vehicles between 25 and 50 feet long, which are mostly long vans, one trailer pick-ups, and small trucks. Table 4.35 shows the speeds for vehicles from 50 to 75 feet in length, which are mid-size, semi-trucks with trailers. Table 4.36 shows the speeds for vehicles longer than 75 feet, which are long trucks. The tables described above and their interpretation are an example of how to understand the additional sensor tables provided in Appendix M (note: Blank cells in the tables indicate time segments in which no or only one vehicle was recorded and a measurable statistic could not be produced).

Table 4.32: Time Summary of Vehicle Speed for September 29 (Sensor #216 WZ)

Vehicle Speed (all vehicles)	Total	2230-2300	2300-2330	2330-0000	0000-0030	0030-0100	0100-0130	0130-0200	0200-0230	0230-0300	0300-0330	0330-0400	0400-0430	0430-0500
MPH														
< 10	0.1%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.7%
10-14	1.8%	6.3%	0.8%	0.0%	0.7%	0.8%	0.0%	2.6%	1.4%	0.0%	3.1%	4.2%	0.0%	0.0%
15-19	4.4%	19.2%	0.8%	1.6%	3.0%	0.8%	1.9%	5.1%	1.4%	1.5%	3.1%	0.0%	0.0%	0.0%
20-24	7.2%	22.5%	8.1%	6.3%	3.0%	3.3%	1.0%	2.6%	4.3%	4.5%	4.7%	2.8%	0.0%	0.0%
25-29	6.8%	12.9%	7.3%	7.9%	3.0%	4.9%	2.9%	10.3%	2.9%	11.9%	3.1%	4.2%	2.5%	0.0%
30-34	10.0%	11.7%	18.7%	10.6%	6.7%	4.9%	10.5%	5.1%	8.6%	4.5%	4.7%	8.5%	7.6%	3.7%
35-39	12.7%	7.1%	22.4%	21.2%	11.9%	13.9%	9.5%	9.0%	10.0%	13.4%	3.1%	12.7%	1.3%	0.0%
40-44	12.7%	5.0%	14.6%	15.3%	14.1%	18.9%	11.4%	20.5%	17.1%	10.4%	10.9%	12.7%	7.6%	7.4%
45-49	14.7%	6.7%	11.8%	15.9%	18.5%	18.0%	19.0%	19.2%	15.7%	16.4%	25.0%	15.5%	16.5%	3.7%
50-54	9.9%	2.1%	7.3%	7.9%	17.8%	11.5%	15.2%	10.3%	12.9%	7.5%	12.5%	16.9%	16.5%	3.7%
55-59	7.6%	4.6%	3.3%	5.3%	10.4%	6.6%	15.2%	7.7%	8.6%	7.5%	7.8%	11.3%	5.1%	44.4%
60-64	4.9%	2.1%	1.6%	3.2%	5.9%	4.1%	5.7%	0.0%	7.1%	9.0%	10.9%	4.2%	19.0%	11.1%
65-69	2.9%	0.0%	1.6%	2.1%	3.0%	4.9%	2.9%	2.6%	5.7%	6.0%	6.3%	1.4%	7.6%	3.7%
70-74	2.9%	0.0%	1.6%	2.1%	2.2%	5.7%	1.9%	3.8%	1.4%	7.5%	4.7%	4.2%	6.3%	14.8%
>=75	1.2%	0.0%	0.0%	0.0%	0.0%	1.6%	2.9%	1.3%	2.9%	0.0%	0.0%	1.4%	10.1%	3.7%
Total # of vehicles	1493	240	246	189	135	122	105	78	70	67	64	71	79	27
Average speed	42.1	29.0	38.9	40.9	45.5	46.4	47.5	42.3	46.3	45.8	47.0	45.0	55.7	56.8
St. Dev.	14.6	12.7	11.2	11.9	12.0	13.1	12.3	14.0	13.6	14.9	14.5	13.8	14.1	14.9
85th percentile	57.0	45.0	50.0	53.0	55.9	60.0	58.4	54.9	61.3	63.1	63.0	57.0	71.0	70.0
Min	7.0	11.0	13.0	9.0	14.0	14.0	16.0	14.0	10.0	16.0	12.0	11.0	25.0	7.0
Max	90.0	64.0	72.0	72.0	74.0	75.0	80.0	80.0	75.0	74.0	74.0	75.0	88.0	90.0
Range	83.0	53.0	59.0	63.0	60.0	61.0	64.0	66.0	65.0	58.0	62.0	64.0	63.0	83.0

Table 4.33: Time Summary of Vehicle (0-25 feet long) Speed for September 29 (Sensor #216 WZ)

Vehicle Speed (0-25 FT Vehicles)	Total	2230-2300	2300-2330	2330-0000	0000-0030	0030-0100	0100-0130	0130-0200	0200-0230	0230-0300	0300-0330	0330-0400	0400-0430	0430-0500
MPH														
< 10	0.2%	0.0%	0.0%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.6%
10-14	2.1%	7.0%	0.9%	0.0%	0.8%	1.0%	0.0%	3.3%	1.6%	0.0%	4.2%	5.5%	0.0%	0.0%
15-19	4.8%	19.2%	0.9%	1.9%	3.4%	1.0%	2.2%	6.6%	1.6%	1.8%	4.2%	0.0%	0.0%	0.0%
20-24	8.1%	23.9%	8.3%	7.5%	3.4%	3.8%	1.1%	1.6%	4.8%	5.5%	6.3%	3.6%	0.0%	0.0%
25-29	7.1%	11.7%	7.8%	8.1%	2.5%	5.8%	3.3%	13.1%	3.2%	12.7%	4.2%	3.6%	3.6%	0.0%
30-34	10.7%	11.7%	18.8%	11.2%	7.6%	5.8%	12.1%	4.9%	7.9%	5.5%	6.3%	9.1%	10.9%	0.0%
35-39	13.2%	6.6%	21.1%	21.1%	13.4%	16.3%	9.9%	9.8%	11.1%	10.9%	4.2%	14.5%	1.8%	0.0%
40-44	12.9%	5.2%	15.1%	16.1%	14.3%	20.2%	11.0%	18.0%	14.3%	9.1%	14.6%	12.7%	7.3%	11.1%
45-49	14.3%	7.0%	11.9%	16.1%	19.3%	14.4%	16.5%	18.0%	17.5%	18.2%	25.0%	10.9%	16.4%	5.6%
50-54	9.8%	2.3%	8.3%	7.5%	19.3%	11.5%	14.3%	9.8%	14.3%	5.5%	8.3%	16.4%	16.4%	5.6%
55-59	7.1%	3.3%	2.8%	3.7%	8.4%	6.7%	16.5%	9.8%	9.5%	9.1%	6.3%	12.7%	5.5%	44.4%
60-64	4.6%	1.9%	1.8%	3.1%	4.2%	4.8%	6.6%	0.0%	7.9%	10.9%	8.3%	5.5%	18.2%	5.6%
65-69	2.5%	0.0%	1.4%	2.5%	3.4%	3.8%	2.2%	0.0%	4.8%	7.3%	6.3%	1.8%	5.5%	0.0%
70-74	1.9%	0.0%	0.9%	0.6%	0.0%	4.8%	2.2%	3.3%	1.6%	3.6%	2.1%	3.6%	5.5%	16.7%
>=75	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	1.6%	0.0%	0.0%	0.0%	0.0%	9.1%	5.6%
Total # of vehicles	1261	213	218	161	119	104	91	61	63	55	48	55	55	18
Average speed	40.8	28.4	38.6	39.8	44.1	44.9	46.9	41.0	45.4	45.0	43.9	44	54	56
St. Dev.	14.2	12.4	11.0	11.4	11.4	12.6	12.4	14.2	13.0	14.9	14.7	14	15	17
85th percentile	55.0	44.0	49.5	50.0	55.0	57.6	58.5	52.0	58.0	61.9	59.9	56	69	71
Min	7.0	11.0	13.0	9.0	14.0	14.0	16.0	14.0	10.0	16.0	12.0	11.0	25.0	7.0
Max	90.0	64.0	70.0	71.0	68.0	74.0	76.0	80.0	74.0	73.0	72.0	72.0	88.0	90.0
Range	83.0	53.0	57.0	62.0	54.0	60.0	60.0	66.0	64.0	57.0	60.0	61.0	63.0	83.0

Table 4.34: Time Summary of Vehicle (25-50 feet long) Speed for September 29 (Sensor #216 WZ)

Vehicle Speed (25-50 FT Vehicles)	Total	2230-2300	2300-2330	2330-0000	0000-0030	0030-0100	0100-0130	0130-0200	0200-0230	0230-0300	0300-0330	0330-0400	0400-0430	0430-0500
MPH														
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	1.1%	11.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	1.1%	5.9%	4.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	5.1%	23.5%	4.2%	4.5%	7.7%	0.0%	0.0%	0.0%	0.0%	10.0%	0.0%	8.3%	0.0%	0.0%
30-34	6.3%	11.8%	16.7%	9.1%	0.0%	0.0%	0.0%	7.1%	16.7%	0.0%	0.0%	0.0%	0.0%	16.7%
35-39	9.7%	11.8%	29.2%	13.6%	0.0%	0.0%	8.3%	7.1%	0.0%	20.0%	0.0%	8.3%	0.0%	0.0%
40-44	12.5%	5.9%	12.5%	9.1%	7.7%	14.3%	8.3%	28.6%	33.3%	20.0%	0.0%	16.7%	13.3%	0.0%
45-49	18.8%	0.0%	12.5%	18.2%	7.7%	50.0%	41.7%	21.4%	0.0%	10.0%	36.4%	33.3%	6.7%	0.0%
50-54	9.7%	0.0%	0.0%	13.6%	7.7%	7.1%	16.7%	14.3%	0.0%	20.0%	9.1%	16.7%	20.0%	0.0%
55-59	12.5%	23.5%	8.3%	13.6%	30.8%	7.1%	8.3%	0.0%	0.0%	0.0%	18.2%	8.3%	6.7%	50.0%
60-64	6.3%	5.9%	0.0%	4.5%	23.1%	0.0%	0.0%	0.0%	0.0%	0.0%	27.3%	0.0%	13.3%	16.7%
65-69	5.7%	0.0%	4.2%	0.0%	0.0%	7.1%	8.3%	14.3%	16.7%	0.0%	0.0%	0.0%	20.0%	16.7%
70-74	7.4%	0.0%	8.3%	13.6%	15.4%	0.0%	0.0%	7.1%	0.0%	20.0%	9.1%	8.3%	6.7%	0.0%
>=75	4.0%	0.0%	0.0%	0.0%	0.0%	14.3%	8.3%	0.0%	33.3%	0.0%	0.0%	0.0%	13.3%	0.0%
Total # of vehicle	176	17	24	22	13	14	12	14	6	10	11	12	15	6
Average speed	49.8	37.6	42.9	49.1	56.2	52.4	51.8	49.3	56.3	48.0	55.5	47.5	60.8	56.2
St. Dev.	13.9	14.7	13.5	13.1	12.2	11.8	11.6	11.8	18.4	14.0	8.3	10.8	13.0	12.0
85th percentile	67.8	56.8	57.1	63.3	65.6	68.4	58.9	65.2	75.0	64.4	61.5	55.8	72.6	65.3
Min	18.0	18.0	20.0	27.0	28.0	40.0	35.0	34.0	34.0	28.0	46.0	28.0	42.0	34.0
Max	86.0	60.0	72.0	72.0	74.0	75.0	80.0	73.0	75.0	71.0	72.0	70.0	86.0	69.0
Range	68.0	42.0	52.0	45.0	46.0	35.0	45.0	39.0	41.0	43.0	26.0	42.0	44.0	35.0

Table 4.35: Time Summary of Vehicle (50-75 feet long) Speed for September 29 (Sensor #216 WZ)

Vehicle Speed (50-75 FT Vehicles)	Total	2230-2300	2300-2330	2330-0000	0000-0030	0030-0100	0100-0130	0130-0200	0200-0230	0230-0300	0300-0330	0330-0400	0400-0430	0430-0500
MPH														
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
15-19	8.8%	37.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
20-24	8.8%	25.0%	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%		0.0%	0.0%	0.0%	0.0%	0.0%
25-29	8.8%	25.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
30-34	8.8%	12.5%	50.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	33.3%	0.0%	0.0%
35-39	11.8%	0.0%	50.0%	40.0%	0.0%	0.0%	0.0%	0.0%		50.0%	0.0%	0.0%	0.0%	0.0%
40-44	5.9%	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	50.0%		0.0%	0.0%	0.0%	0.0%	0.0%
45-49	11.8%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%		0.0%	0.0%	33.3%	50.0%	0.0%
50-54	11.8%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%		0.0%	66.7%	33.3%	0.0%	0.0%
55-59	5.9%	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	50.0%
60-64	5.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	25.0%	50.0%
65-69	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
70-74	11.8%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%		50.0%	33.3%	0.0%	25.0%	0.0%
>=75	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%	0.0%
Total # of vehicle	34	8	2	5	1	1	1	2	0	2	3	3	4	2
Average speed	42.8	22.4	36.5	40.0				31.5		55.5	58.0	44.7	57.0	59.5
St. Dev.	17.2	6.1	3.5	9.9				14.8		26.2	13.9	9.5	12.7	6.4
85th percentile	63.1	28.9	38.3	46.0				38.9		68.5	66.8	50.8	68.0	62.7
Min	16.0	16.0	34.0	27.0				21.0		37.0	50.0	34.0	45.0	55.0
Max	74.0	32.0	39.0	55.0				42.0		74.0	74.0	52.0	72.0	64.0
Range	58.0	16.0	5.0	28.0				21.0		37.0	24.0	18.0	27.0	9.0

Table 4.36: Time Summary of Vehicle (75+ feet long) Speed for September 29 (Sensor #216 WZ)

Vehicle Speed (+75 FT Vehicles)	Total	2230-2300	2300-2330	2330-0000	0000-0030	0030-0100	0100-0130	0130-0200	0200-0230	0230-0300	0300-0330	0330-0400	0400-0430	0430-0500
MPH														
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%
20-24	4.5%	0.0%	50.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%
25-29	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%
30-34	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%
35-39	13.6%	50.0%	50.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%
40-44	13.6%	0.0%	0.0%	0.0%	50.0%	0.0%	100.0%	0.0%	100.0%		0.0%	0.0%	0.0%	0.0%
45-49	13.6%	50.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%		0.0%	0.0%	20.0%	0.0%
50-54	13.6%	0.0%	0.0%	0.0%	0.0%	33.3%	0.0%	0.0%	0.0%		50.0%	0.0%	20.0%	0.0%
55-59	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	0.0%
60-64	9.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	0.0%	40.0%	0.0%
65-69	9.1%	0.0%	0.0%	0.0%	0.0%	33.3%	0.0%	0.0%	0.0%		50.0%	0.0%	0.0%	0.0%
70-74	13.6%	0.0%	0.0%	0.0%	50.0%	33.3%	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%	100.0%
>=75	9.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	100.0%	20.0%	0.0%
Total # of vehicle	22	2	2	1	2	3	1	1	1	0	2	1	5	1
Average speed	54.4	44.0	30.5		57.0	63.7					59.5		61.2	
St. Dev.	14.7	7.1	9.2		19.8	10.4					10.6		11.7	
85th percentile	70.9	47.5	35.1		66.8	70.5					64.8		69.4	
Min	24.0	39.0	24.0		43.0	52.0					52.0		48.0	
Max	79.0	49.0	37.0		71.0	72.0					67.0		79.0	
Range	55.0	10.0	13.0		28.0	20.0					15.0		31.0	

4.6.2 Vehicle Speed Analysis

Figure 4.43 shows the average and 85th percentile speeds of all vehicles for both nights (with and without the MBT-1® present) adjacent to the work zone. Figure 4.44 shows the same information from the sensors that were placed at the end of taper. As observed from these figures, at the beginning of the data collection period (10:30 p.m. – 00:00a.m.), the recorded vehicle speeds were lower than the remainder of the work. This was due to the increased traffic congestion that occurred during the traffic control implementation. Once the effects of the traffic control implementation ended and the traffic congestion cleared, the vehicle speeds increased. For that reason, the speed analysis of this case study only includes the time period between 12:00 a.m. and 4:00 a.m. on both nights, which represents a steady flow of vehicles that were not impacted by the process of setting up the work zone.

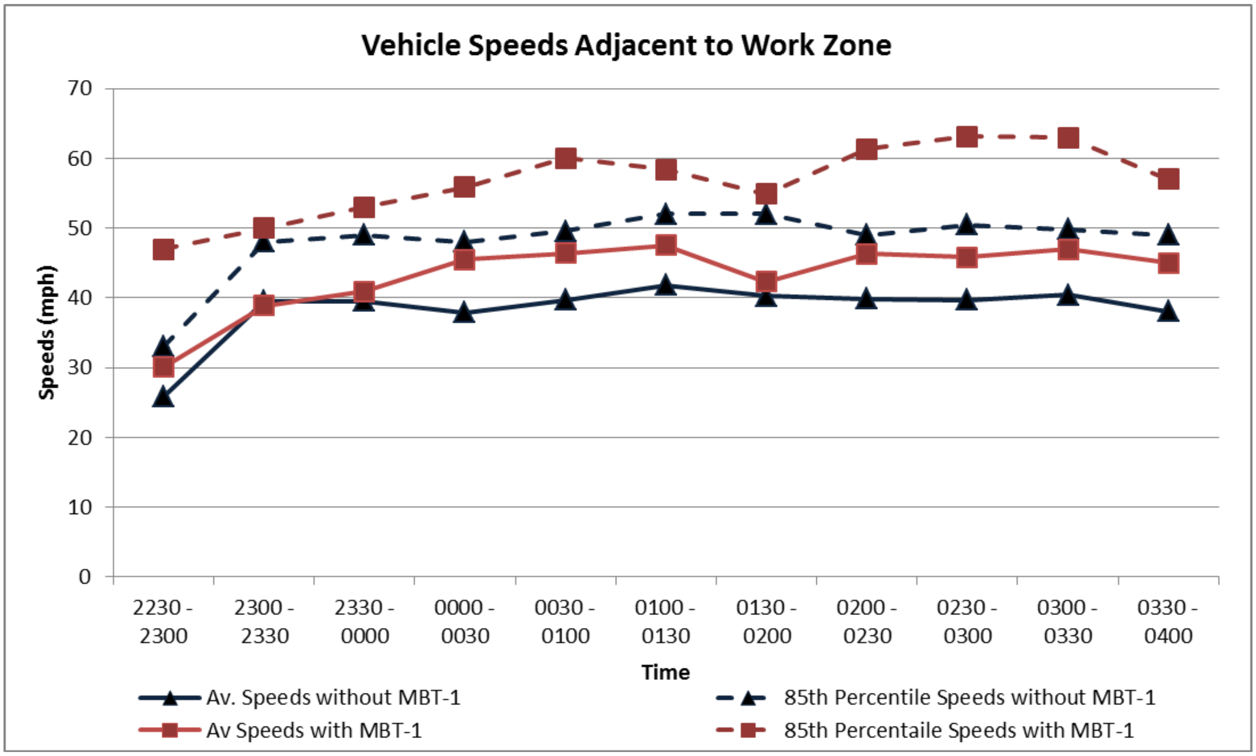

Figure 4.43: Average and 85th Percentile Speeds of Vehicles Adjacent to Work Zone

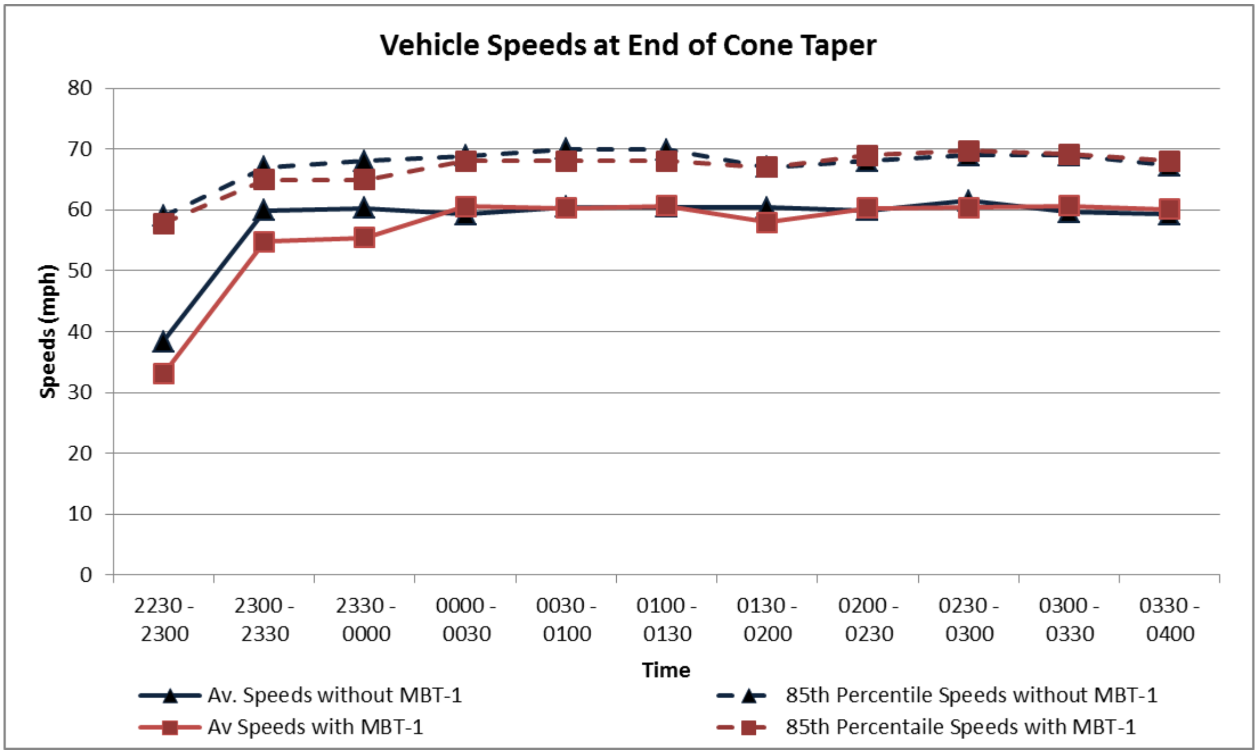

Figure 4.44: Average and 85thPercentile Speeds of Vehicles at End of Taper

An initial review of Figure 4.43 shows that the speeds recorded adjacent to the work zone without the MBT-1® present were lower than the speeds recorded the following night with the MBT-1® present. By comparison, the speeds that were recorded at the end of the cone taper (Figure 4.44) indicate that the vehicles were traveling at similar speeds. This result suggests that the differences recorded by the sensor adjacent to the work zone are due to the change in the work zone characteristics, i.e., with the MBT-1® present compared to without the MBT-1®. The analysis that follows explores this difference in driver behavior.

Table 4.37 shows a summary of all the speeds (average, 85th percentile, and standard deviation) that were recorded during the time period between 12:00 a.m. and 4:00 a.m. at all sensor locations without the MBT-1® present. Similarly Table 4.38 shows all the speeds that were recorded on the following night for the same time period with the MBT-1® in place. The speeds presented in both tables are shown in miles per hour (mph). The speeds of all vehicle groups are shown together and are also broken down further according to the lengths of the vehicles as described in the previous section of this report.

Table 4.37: Summary of Vehicle Speeds Recorded by Sensors without MBT-1® (mph)

	Lane	1st Sensors		2nd Sensors		End of Taper	Work Zone
All Vehicles	A	Sensor #803 Mean: 64.1 85th %: 74.2 St. Dev.:9.7	Sensors #803+#379 Mean: 63.1 85th %: 72.4 St. Dev.:9.1	Sensor #216 Mean: 62.6 85th %: 71.7 St. Dev.:8.7	Sensors #216+#816 Mean: 62.2 85th %: 71.5 St. Dev.:9.0	Sensor #687 Mean: 60.1 85th %: 69.4 St. Dev.:9.0	Sensor #748 Mean: 39.6 85th %: 50.3 St. Dev.:10.3
	B	Sensor #379 Mean: 56.2 85th %: 63.5 St. Dev.:7.1		Sensor #816 Mean: 58.8 85th %: 69.7 St. Dev.:10.5			
0 ft – 25 ft	A	Sensor #803 Mean: 64.8 85th %: 74.4 St. Dev.:9.3	Sensor #803+#379 Mean: 62.8 85th %: 72.9 St. Dev.:8.8	Sensor #216 Mean: 63.3 85th %: 72.2 St. Dev.:8.52	Sensor #216+#816 Mean: 62.7 85th %: 72.0 St. Dev.:8.9	Sensor #687 Mean: 60.7 85th %: 70 St. Dev.:8.9	Sensor #748 Mean: 39.5 85th %: 50.3 St. Dev.:10.5
	B	Sensor #379 Mean: 56.8 85th %: 64.0 St. Dev.:6.9		Sensor #816 Mean: 58.6 85th %: 69.0 St. Dev.:10.1			
25 ft – 50 ft	A	Sensor #803 Mean: 60.1 85th %:73.3 St. Dev.:12.7	Sensor #803+#379 Mean:59.6 85th %: 69.6 St. Dev.:9.57	Sensor #216 Mean: 59.5 85th %: 68.3 St. Dev.:8.5	Sensor #216+#816 Mean: 59.8 85th %: 69.6 St. Dev.:9.5	Sensor #687 Mean: 56.4 85th %: 65.3 St. Dev.: 8.6	Sensor #748 Mean: 42.4 85th %: 51.9 St. Dev.:9.3
	B	Sensor #379 Mean: 52.9 85th %: 59.8 St. Dev.:6.7		Sensor #816 Mean: 62.1 85th %: 78.3 St. Dev.:15.6			
50 ft – 75 ft	A	Sensor #803 Mean: 53.3 85th %:58.9 St. Dev.:5.4	Sensor #803+#379 Mean:55.4 85th %: 62.3 St. Dev.:6.6	Sensor #216 Mean: 56.0 85th %: 63.2 St. Dev.:6.9	Sensor #216+#816 Mean: 56.0 85th %: 62.5 St. Dev.: 6.3	Sensor #687 Mean: 54.8 85th %: 61.0 St. Dev.:6.0	Sensor #748 Mean: 34.7 85th %: 42.8 St. Dev.:7.8
	B	Sensor #379 Mean: 52.2 85th %: 57.8 St. Dev.:5.4		Sensor #816 Mean: 56.0 85th %: 59.3 St. Dev.:3.2			
> 75 ft	A	Sensor #803 Mean: 60.25 85th %:68.5 St. Dev.:7.9	Sensor #803+#379 Mean:60.0 85th %: 69.8 St. Dev.:9.4	Sensor #216 Mean: 59.9 85th %: 70.6 St. Dev.:10.3	Sensor #216+#816 Mean: 59.7 85th %: 69.4 St. Dev.:9.4	Sensor #687 Mean: 55.7 85th %: 63.9 St. Dev.:7.9	Sensor #748 Mean: 41.6 85th %: 50.9 St. Dev.:9.0
	B	Sensor #379 Mean: 52.8 85th %: 64.7 St. Dev.:11.4		Sensor #816 Mean: 58.5 85th %: 59.2 St. Dev.:0.7			

Table 4.38: Summary of Vehicle Speeds Recorded by Sensors with MBT-1® (mph)

	Lane	1st Sensors		2nd Sensors		End of Taper	Work Zone
All Vehicles	A	Sensor #816 Mean: 61.1 85^{th} %:70.0 St. Dev.:8.5	Sensor #816+#774 Mean: 55 85^{th} %: 62.5 St. Dev.:7.1	Sensor #803 Mean: 63.6 85^{th} %: 76.3 St. Dev.:12.2	Sensor #803+#748 Mean: 57.8 85^{th} %: 66.9 St. Dev.:8.8		
	B	Sensor #774 Mean: 54.4 85^{th} %: 61.3 St. Dev.:6.7		Sensor #748 Mean: 57.5 85^{th} %: 66.4 St. Dev.:8.6		Sensor #687 Mean: 60.2 85^{th} %: 69.6 St. Dev.:9.1	Sensor #216 Mean: 45.8 85^{th} %: 59.6 St. Dev.:13.3
0 ft – 25 ft	A	Sensor #816 Mean: 61.1 85^{th} %:70.1 St. Dev.:8.6	Sensor #816+#774 Mean: 55.8 85^{th} %: 62.8 St. Dev.:7.2	Sensor #803 Mean:63.4 85^{th} %: 75.3 St. Dev.:11.5	Sensor #803+#748 Mean: 55.8 85^{th} %: 66.8 St. Dev.:8.7		
	B	Sensor #774 Mean: 54.7 85^{th} %: 61.6 St. Dev.:6.7		Sensor #748 Mean: 57.6 85^{th} %: 66.3 St. Dev.:8.4		Sensor #687 Mean: 60.3 85^{th} %: 69.4 St. Dev.:8.8	Sensor #216 Mean: 44.7 85^{th} %: 58.3 St. Dev.:13.1
25 ft – 50 ft	A	Sensor #816 Mean: 58.0 85^{th} %:61.1 St. Dev.:3	Sensor #816+#774 Mean:51.5 85^{th} %: 57.5 St. Dev.:5.8	Sensor #803 Mean: 88 85^{th} %: NA St. Dev.: NA	Sensor #803+#748 Mean: 57.8 85^{th} %: 69 St. Dev.:10.8		
	B	Sensor #774 Mean: 51.0 85^{th} %: 57.0 St. Dev.:5.7		Sensor #748 Mean: 57.4 85^{th} %: 68.1 St. Dev.:10.3		Sensor #687 Mean: 60.3 85^{th} %: 73.2 St. Dev.:12.4	Sensor #216 Mean: 51.5 85^{th} %: 64.1 St. Dev.:12.1
50 ft – 75 ft	A	Sensor #816 Mean: NA 85^{th} %:NA St. Dev.: NA	Sensor #816+#774 Mean:53.1 85^{th} %: 57.8 St. Dev.:4.5	Sensor #803 Mean: NA 85^{th} %: NA St. Dev.: NA	Sensor #803+#748 Mean: 54.4 85^{th} %: 60.7 St. Dev.:6.1		
	B	Sensor #774 Mean: 53.1 85^{th} %: 57.8 St. Dev.: 4.5		Sensor #748 Mean: 54.4 85^{th} %: 60.7 St. Dev.:6.1		Sensor #687 Mean: 58.1 85^{th} %: 67.1 St. Dev.:8.7	Sensor #216 Mean: 50.4 85^{th} %: 66.8 St. Dev.:15.9
> 75 ft	A	Sensor #816 Mean: 71 85^{th} %:NA St. Dev.: NA	Sensor #816+#774 Mean:53.2 85^{th} %: 63.8 St. Dev.:10.2	Sensor #803 Mean: NA 85^{th} %: NA St. Dev.: NA	Sensor #803+#748 Mean: 54.0 85^{th} %: 55.5 St. Dev.:1.4		
	B	Sensor #774 Mean: 48.7 85^{th} %: 51.6 St. Dev.:2.7		Sensor #748 Mean: 54.0 85^{th} %: 55.5 St. Dev.:1.4		Sensor #687 Mean: 55.6 85^{th} %: 61.4 St. Dev.:5.7	Sensor #216 Mean: 57.5 85^{th} %: 70.8 St. Dev.: 12.8

The Shapiro-Wilk test was performed on the speed measurement to determine whether the recorded speeds are normally distributed (*Shapiro and Wilk 1965*). Table 4.39 shows the results for the normality of the data for the night without the MBT-1®, and Table 4.40 shows the equivalent data for the night with the MBT-1®.

Table 4.39: Shapiro-Wilk Results on Normality of Vehicle Speeds on Sept. 28 without MBT-1®

	Lane	1st Sensors		2nd Sensors		End of Taper	Work Zone
All Vehicles	A	W = 0.9809 p = 8.024e-05	W = 0.9921 p = 3.246e-06	W = 0.9954 p = 0.009688	W = 0.9942 p = 0.000640	W = 0.9965 p = 0.0157	W = 0.9966 p = 0.02313
	B	W = 0.9779 p = 1.227e-07		W = 0.9567 p=0.0005791			
0ft.-25ft.	A	W = 0.9773 p = 5.007e-05	W = 0.993 p = 6.887e-05	W = 0.9961 p = 0.06412	W = 0.9947 p = 0.005248	W = 0.9936 p = 0.000474	W = 0.9975 p = 0.2028
	B	W = 0.9861 p = 0.000137		W = 0.9639 p = 0.006952			
25ft.-50ft.	A	W = 0.8281 p = 0.000144	W = 0.894 p = 1.635e-08	W = 0.93 p = 2.767e-05	W = 0.9298 p = 9.324e-06	W = 0.9668 p = 0.007225	W = 0.9531 p = 0.001514
	B	W = 0.7593 p = 1.231e-08		W = 0.9481 p = 0.5704			
50ft.-75ft.	A	W = 0.888 p = 0.2643	W = 0.888 p = 0.2643	NA	W = 0.8924 p = 0.3309	W = 0.9716 p = 0.6239	W = 0.9781 p = 0.7276
	B	W = 0.984 p = 0.9746		W = 0.8924 p = 0.3309			
>75 ft.	A	W = 0.765 p = 0.0528	W = 0.8874 p = 0.0613	W = 0.8946 p = 0.1585	W = 0.8862 p = 0.0867	W = 0.9524 p = 0.4647	W = 0.9876 p = 0.9907
	B	W = 0.8725 p = 0.1069		NA			

Table 4.40: Shapiro-Wilk Results on Normality of Vehicle Speeds with MBT-1®

	Lane	1st Sensors		2nd Sensors		End of Taper	Work Zone
All Vehicles	A	W = 0.9519 p = 0.003327	W = 0.9787 p = 4.74e-10	W = 0.9807 p = 0.7567	W = 0.9758 p = 6.148e-11		
	B	W=0.9824 p = 3.346e-08		W = 0.977 p= 2.737e-10		W = 0.9897 p= 3.291e-06	W = 0.9927 p = 0.001516
0ft.-25ft.	A	W = 0.9499 p = 0.003415	W = 0.9777 p = 8.713e-10	W = 0.9859 p = 0.9244	W = 0.981 p = 1.384e-08		
	B	W = 0.9809 p = 3.675e-08		W = 0.9808 p = 2.382e-08		W = 0.9929 p = 0.000474	W = 0.9938 p = 0.01463
25ft.-50ft.	A	W = 1 p = NA	W = 0.9195 p = 0.002864	NA	W = 0.8688 p = 1.234e-06		
	B	W = 0.8921 p = 0.000542		W = 0.8766 p = 2.699e-06		W = 0.9455 p = 0.002847	W = 0.9625 p = 0.01512
50ft.-75ft.	A	W = 1 p = NA	W = 0.8889 p = 0.03697	NA	W = 0.9522 p = 0.4608		
	B	W = 0.8889 p = 0.03697		W = 0.9526 p = 0.4993		W = 0.9517 p = 0.4222	W = 0.9118 p = 0.1942
>75 ft.	A	NA	W = 0.7585 p = 0.03559	NA	NA		
	B	W = 0.9393 p = 0.6499		NA		W = 0.8995 p = 0.111	W = 0.8476 p = 0.03974

The speed data appears to be normal for all speed sensor locations when all the vehicles are considered. This result is observed by the very low p-values for each sensor. A p-value below 0.05 suggests that there is less than a 5% probability that the result is due to chance (i.e., the data should be considered as normal and that there is not enough information to reject the hypothesis that the data is not normal). Highlighted with green on both tables are the locations were the data is normal. Locations were the data is not normal, or where there was not enough data to perform a test on normality, are highlighted in red. Because the data is not normal in all situations, a further analysis of the speeds is only performed by considering all the vehicles in one category. Figure 4.45 shows histograms of all the vehicle speeds that were recorded in the four locations on the night without the

MBT-1® (September 28), and Figure 4.46 shows the speeds of the vehicles for the following day with the MBT-1® present. As observed, the speeds appear to be normally distributed.

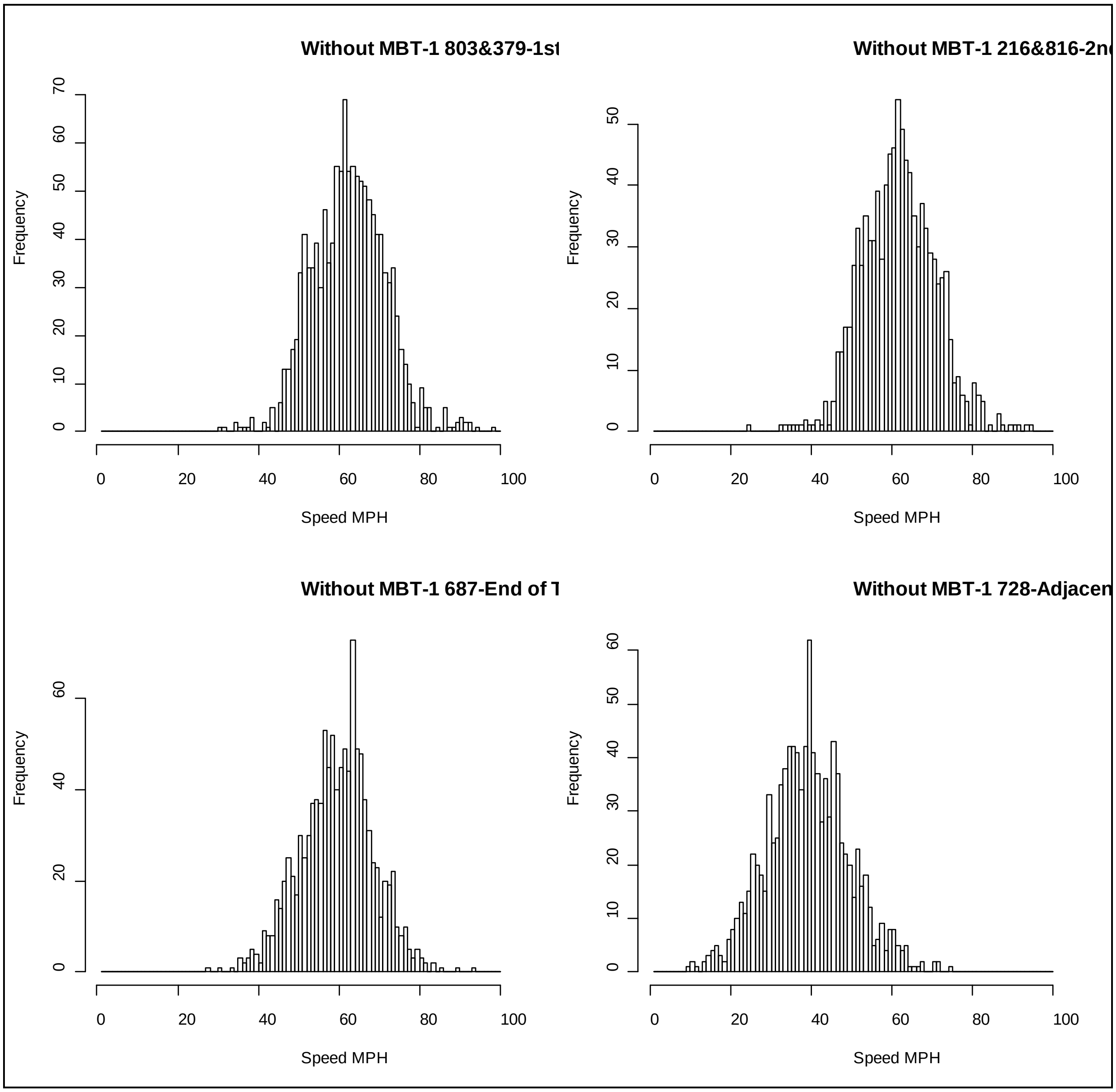

Figure 4.45: Histograms of Speeds Recorded from the Various Sensors without MBT-1®

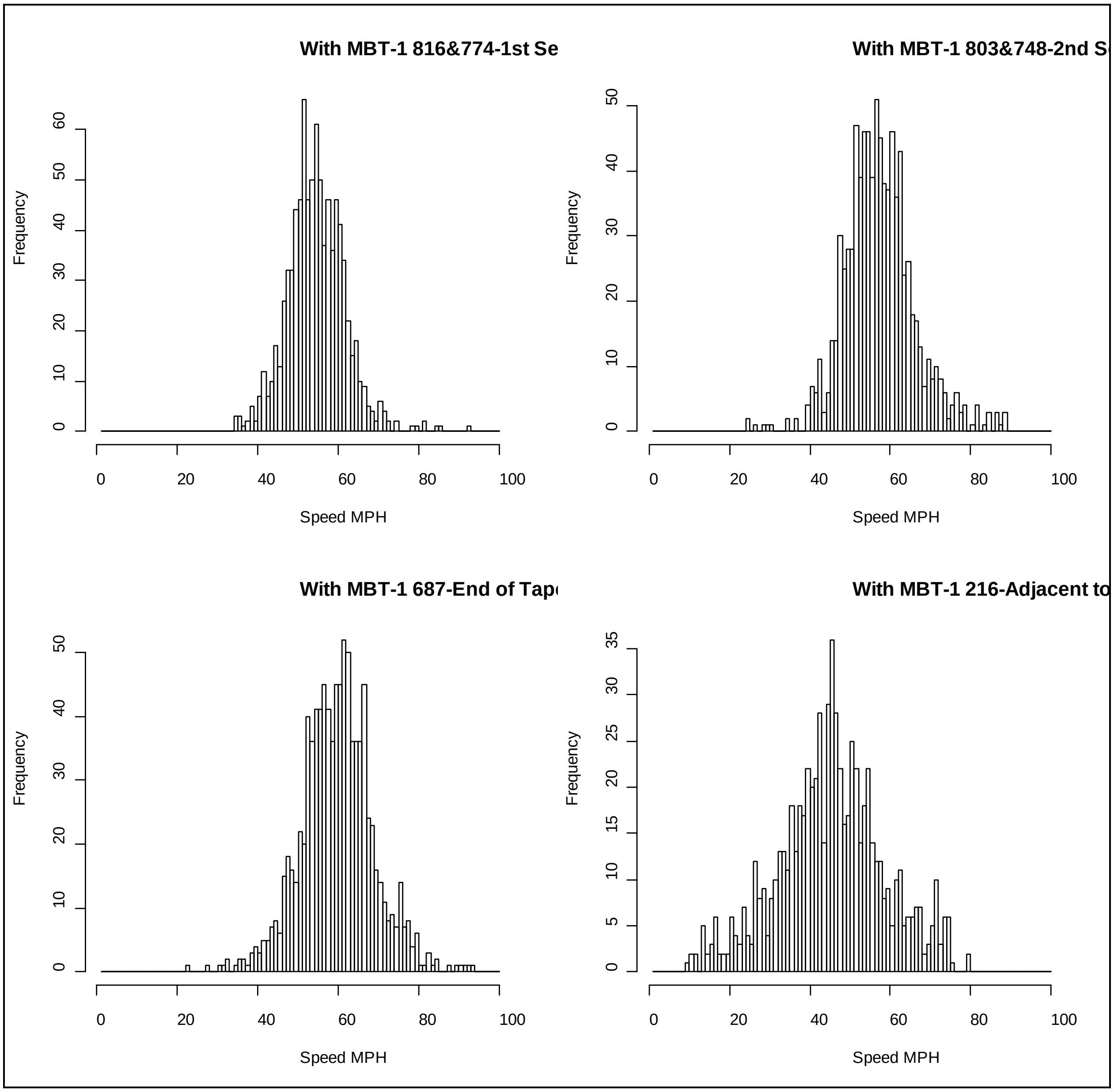

Figure 4.46: Histograms of Speeds Recorded from the Various Sensors with MBT-1®

4.6.3 Vehicle Speed Comparisons

The Welch two-sample t-test was performed on the data to investigate possible differences in driver behavior. This test compares two sets of normally-distributed data that may or may not have the same standard deviation (Ramsey et al. 2002). Specifically the following was investigated based on the mean and 85th percentile speeds:

- Differences in the vehicle speeds at all locations between the two different days
- Differences in the vehicle speeds between the end of the taper and the work zone for both days

4.6.3.1 Differences in speeds between the two different days

Table 4.41 summarizes the t-tests that were performed on the data for all sensor locations. As observed in the table, the speeds in the approach sensors show significant variation. Specifically, the mean speed in the 1st set of sensors with the MBT-1® (September 29) was 55.04 mph, while the mean speed without the MBT-1® (September 28) was 63.07 mph. The p-value for the difference is approximately zero, suggesting that the two groups are different, and the confidence interval (CI) for that difference in speed lies between -8.71 and -7.33 mph. Similarly the p-value for the 85th percentile speed was also approximately zero, suggesting a distinct difference in the 85th percentile speed between the two days. The CI for that difference was from -11.06 to -8.9 mph, and the estimates for the 85th percentile speeds were 62.45 mph with the MBT-1® and 72.45 mph without the MBT-1®. This difference in speeds can be explained by the fact that without the MBT-1® on September 28, traffic was directed to switch to the A-lane (fast lane), while on the following night with the MBT-1® present traffic was directed to switch to the B-lane (slow lane).

Table 4.41: Mean and 85th Percentile Speed Comparisons at All Sensor Locations

	1st Set of Sensors	2nd Set of Sensors	End of Taper	Work Zone
Mean				
T statistic	-22.80	-10.65	0.31	10.39
Degrees of freedom	2097.53	1858.07	1990.02	1268.07
p-value	< 2.2e-16	< 2.2e-16	0.76	< 2.2e-16
Mean Sept. 29 with MBT-1®	55.04 mph	57.76 mph	60.18 mph	45.79 mph
Mean Sept. 28 without MBT-1®	63.07 mph	62.16 mph	60.06 mph	39.63 mph
Lower bound C.I.	-8.71	-5.20	-0.66	5.00
Upper bound C.I.	-7.33	-3.58	0.91	7.33
85th Percentile				
T statistic	-18.55	-7.30	0.44	10.21
Degrees of freedom	2099.58	1860.08	1992.01	1269.79
p-value	2.63e-71	4.14e-13	0.66	1.41e-23
85th % Estimate Sept. 29 with MBT-1®	62.45 mph	66.90 mph	69.63 mph	59.61 mph
85th % Estimate Sept. 28 without MBT-1®	72.45 mph	71.52 mph	69.36 mph	50.33 mph
Lower bound C.I.	-11.06	-5.85	-0.93	7.49
Upper bound C.I.	-8.94	-3.37	1.47	11.05

Similarly, the differences in the speed data recorded by the second set of sensors show again that the speeds with the MBT-1® were slower than without the MBT-1®. Specifically the mean speeds were 57.76 mph and 62.16 mph for the two nights respectively. The CI for the mean speed difference was from -5.2 and -3.58 mph, while the p-value was approximately zero. The estimates for the 85th percentile speeds were 66.91 mph with the MBT-1® and 71.52 mph without the MBT-1®.The CI for the difference in the 85th percentile speeds was from -5.85 and -3.37 mph. The p-value was again approximately zero.

At the end of the taper, the vehicle speeds on both days showed extreme similarity. The differences that were observed in the approach to the work zone were nonexistent at the end of the taper. The mean speed on the day with the MBT-1® present was 60.18 mph while on the day without the MBT-1® the mean was 60.06 mph. The p-value for the difference in the mean speeds was 0.7599 suggesting that the speeds on both days were very similar. The CI for that difference was between -0.66 and 0.90 mph. Since the "0" value is part of that confidence interval, the speeds can be considered to be the same. Similarly for the 85th percentile, the estimate for the speed on the day with the MBT-1® was 69.62 mph, and 69.35mph without the MBT-1®. The CI for the difference was between -0.93 and 1.47 mph, with a p-value of 0.66.

Adjacent to the work zone, the speeds on the day with the MBT-1® present were faster compared to the speeds on the day without the MBT-1®. Specifically, the mean speeds were 45.79 mph and 39.63 mph respectively. The p-value for that difference was approximately zero, while the CI was between 5.00 and 7.32 mph. The 85th percentile speeds showed similar differences. The 85th percentile speed with the MBT-1® was 59.61 mph, while without the MBT-1® the speed was 50.33 mph. The p-value for the difference was also approximately zero, while the CI was between 7.49 and 11.05 mph.

An interesting observation here is that with the MBT-1® the speeds adjacent to the work zone were faster than without the MBT-1®. Additionally, prior to the work zone, the faster approach speeds occurred on the day without the MBT-1® present. As mentioned earlier, the difference in speeds prior to the work zone can be explained by the lane closure difference on each investigated night. Since at the end of taper the speeds were identical, any subsequent difference in speeds can be explained by the difference in the work zone conditions, and likely the presence of the MBT-1®.

4.6.3.2 Differences in speeds between End of Taper and WZ

From the previous section it was observed that the end-of-taper speeds were almost identical with and without the MBT-1®, while the work zone speeds were faster with the MBT-1®. To investigate the amount of reduction in speed between the two nights, t-tests were conducted on the mean and the 85th percentile speeds. Table 4.42 shows the summary of the tests.

Table 4.42: Mean and 85th Percentile Speed Comparisons of End of Taper and WZ Speeds

	Without MBT-1®	**With MBT-1®**
Mean		
T statistic	48.74	24.78
Degrees of freedom	2062.71	1187.78
p-value	2.2e-16	2.2e-16
Mean End of Taper speed	60.06 mph	60.18 mph
Mean WZ speed	39.63 mph	45.79 mph
Lower bound C.I.	19.61	13.25
Upper bound C.I.	21.25	15.52
85th Percentile		
T statistic	29.62	11.26
Degrees of freedom	2064.66	1189.41
p-value	4.56e-161	4.71e-28
85th % Estimate End of Taper speed	69.35 mph	69.62 mph
85th % Estimate WZ speed	50.33 mph	59.61 mph
Lower bound C.I.	17.76	8.27
Upper bound C.I.	20.28	11.76

As observed in the table, without the MBT-1®, the reduction in the mean speed between the end of taper and the work zone was between 19.61 mph and 21.25 mph, with a p-value approximately equal to zero. The 85th percentile speed reduction was between 17.76 mph and 20.28 mph, also with a p-value also approximately zero. Similarly, with the MBT-1® present the reduction in the mean speed between the end of taper and the work zone was between 13.24 mph and 15.52 mph, with a p-value approximately equal to zero. The 85th percentile speed reduction was between 8.27 and 11.76 mph with a p-value also close to zero. This difference in the speed reduction suggests that drivers slow down more if traditional safety measures are used, while with the MBT-1® the speeds were higher. Using vehicle speed as an indicator of mobility, slower speeds through the work zone indicate reduced mobility.

4.7 MAINTENANCE EXPENDITURE ANALYSIS – REGION 1

The research effort to collect Maintenance data provided an opportunity to evaluate the potential extent to which ODOT can use the MBT-1® throughout its maintenance program. The analysis section for the maintenance expenditures in Region 1 contains the following:

- An analysis of the ODOT expenditures according to maintenance work activities
- An analysis of the ODOT expenditures according to section
- An analysis of the ODOT expenditures according to the activities identified as more suitable for MBT-1® use

4.7.1 Analysis According to Work Activities

As described in Section 2.4.2, ODOT maintenance undertakes a number of activities ranging from road maintenance to graffiti removal. The total expenditures for these activities vary from activity-to-activity and from year-to-year. The IDs corresponding to each activity are shown in Table 4.43. Figure 4.47and Figure 4.48 depict the amount of money spent for each activity in Region 1 for years 2010 and 2011, respectively. Highlighted in yellow in the table and in the figures are the activities that were identified to be more suitable for MBT-1® use by ODOT crews.

The overall list of activities was given to ODOT Maintenance supervisors to identify which activities they think are most suitable for MBT-1® use. The highlighted activities were identified by ODOT Maintenance personnel as those for which the MBT-1® would likely be particularly applicable. The perceptions of ODOT Maintenance staff is particularly important regarding how ODOT currently would prioritize the use of the MBT-1®. The MBT-1® may be equally suitable for other activities not regularly performed by ODOT Maintenance, as determined on a case-by-case basis.

Table 4.43: Activity Codes Maintenance

ID	Activity	ID	Activity	ID	Activity
100	Minor Surface Repair	124	Channel Maintenance	144	Traffic Signal Maintenance
101	Major Surface Repair	125	Water Quality Facility	145	Illumination Maintenance
102	Deep Base Repair	128	Horizontal/Vertical Drains	146	Flasher Beacon Maintenance
104	Oil/Mat Chip Sealing	129	Other Drainage Maintenance	147	Pavement Marker Replacement
106	Profiling & Texturing	130	Mowing	148	Delineator Maintenance
107	Inlay Repair	131	Spraying	149	Accident Clean & Repair
109	Concrete Patching	132	Brush Mowing	151	Rail Barrier Maint./Repair
110	Crack Sealing	133	Brush Cutting (Hand)	153	Attenuator Maintenance
111	Shoulder Blading	134	Litter Pickup	154	Cleaning Guardrails
112	Shoulder Rebuilding	135	Youth Litter Patrol	159	Other Traffic Service
116	Sweep/Flush non Pickup	137	Rest Area Maintenance	161	Bridge protective Screening
117	Sweep/Flush Pickup	138	Fence Maintenance	164	Illegal Campsite Cleanup
119	Other Surface & Shoulder Maintenance	139	Other Roadside & Veg.	165	Draw & Toll Bridge Operations
120	Clean & Reshape Ditch	140	Stripping	168	Graffiti Removal
121	Clean Minor Culvert &Inlet	141	Pavement Legend Mark	169	Other Structure Maintenance
122	Repair Erosion	142	Major Sign Inst. Maint.		
123	Minor Clv& Inlet repair	143	Minor Sign Inst. Maint.		

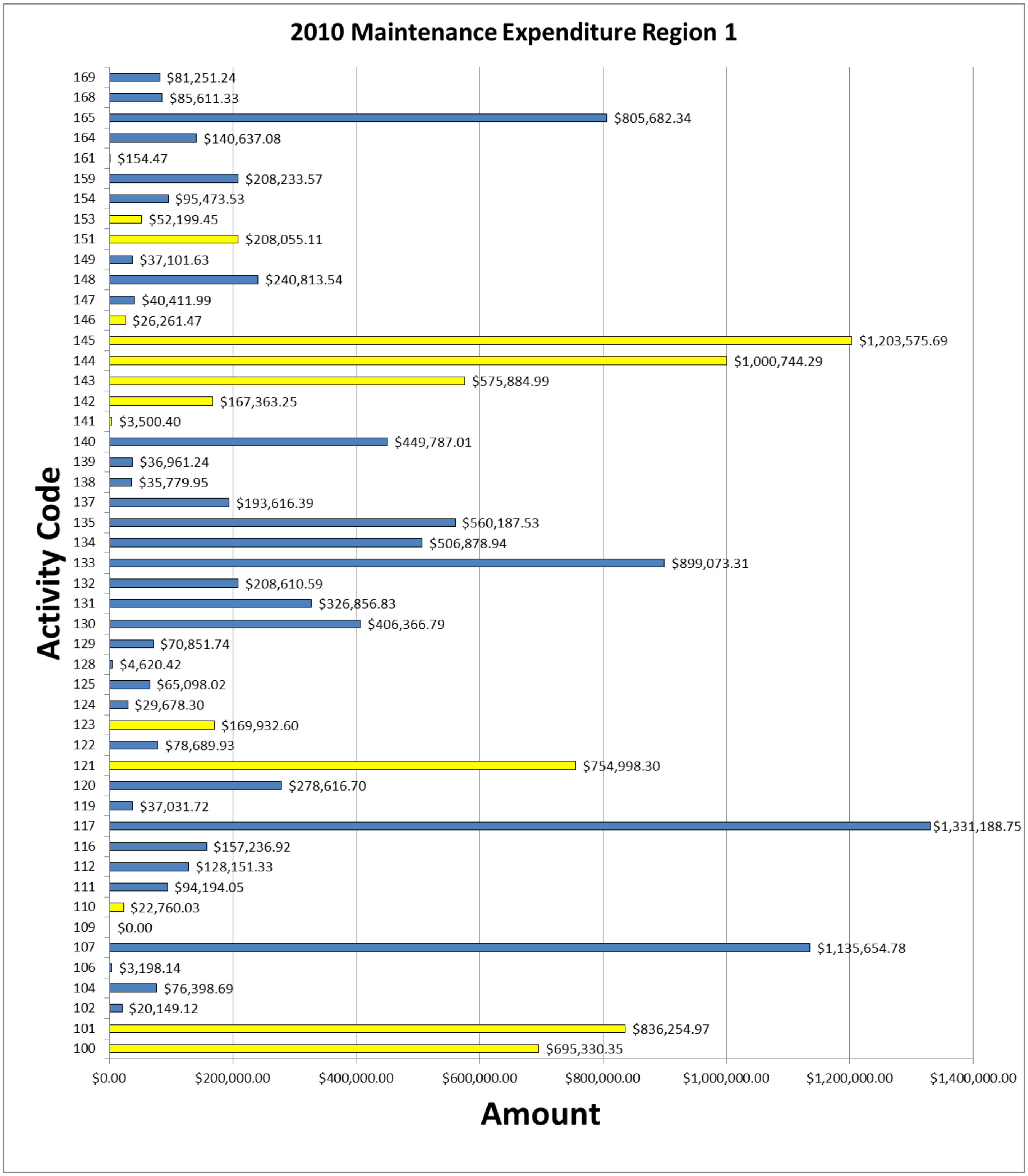

Figure 4.47: ODOT Region 1 Maintenance Expenditures per Activity (2010)

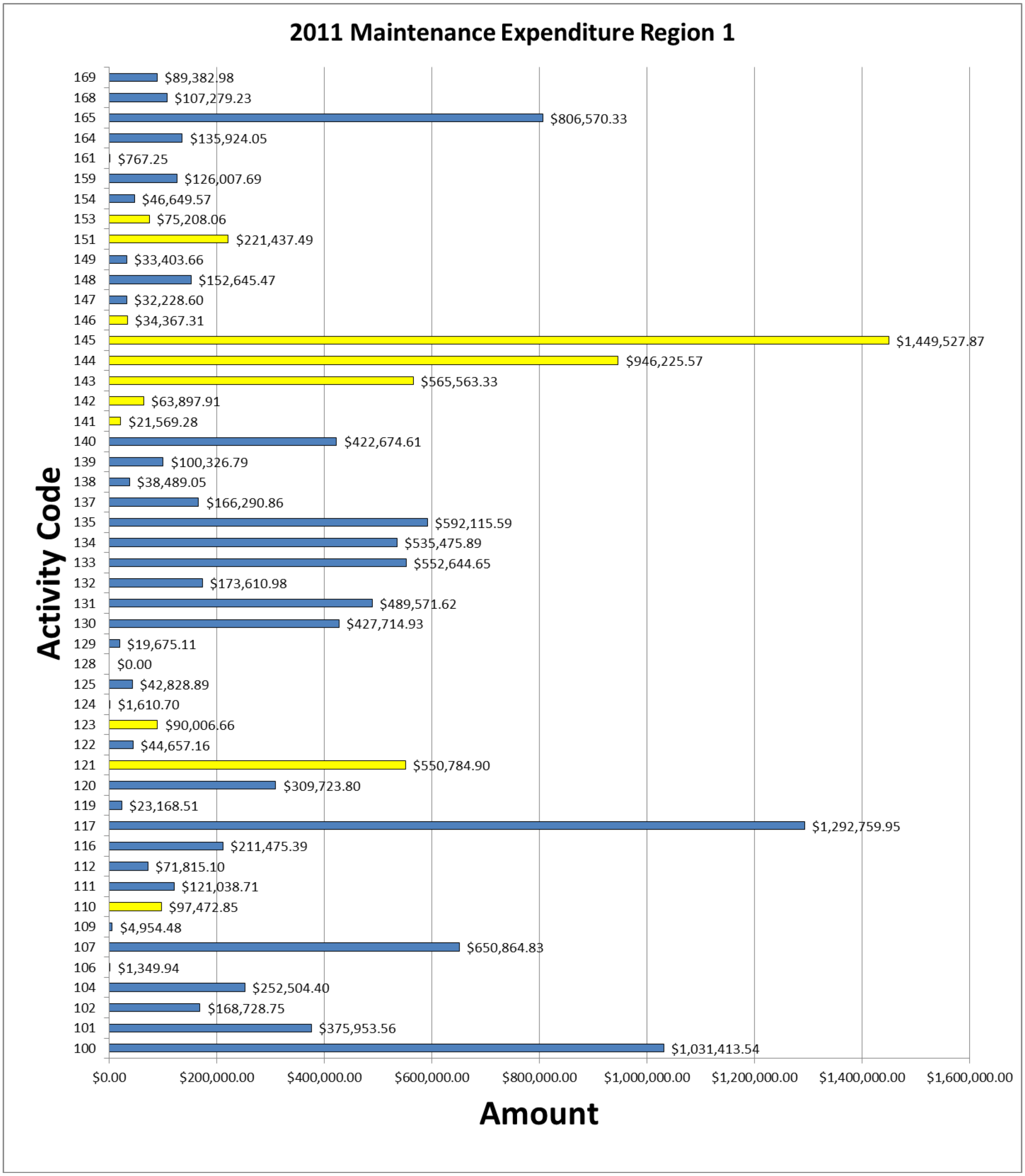

Figure 4.48: ODOT Region 1 Maintenance Expenditure per Activity (2011)

As observed in the figures, the activities that had the highest expenditure value in 2010 were Sweep/Flush Pickup (#117) with a value of $1,331,881, Illumination Maintenance (#145) with a value of $1,203,575, and Inlay Repair (#107) with a value of $1,135,654. In 2011, the three activities with the most expenditure were Illumination Maintenance (#145) with $1,449,527, Sweep/Flush Repair (#117) with$1,292,759, and Minor Surface Repair (#100) with $1,031,413. Of the above-mentioned activities, both Illumination Maintenance and Minor Surface Repair were identified as suitable for MBT-1® use[1].

4.7.2 Analysis according to section

The various section crews that operate in Region 1 perform the maintenance operation in the regions. The expenditure for each section on maintenance operations are shown in Figure 4.49 and Figure 4.50. As observed in 2010, the Electric Crew had the highest expenditures in maintenance operations with $2,272,700, followed by Manning Section with $1,379,825. In 2011, the Electric Crew again had the highest expenditure in maintenance with $2,447,200, followed by N. Portland Section with $1,022,493.

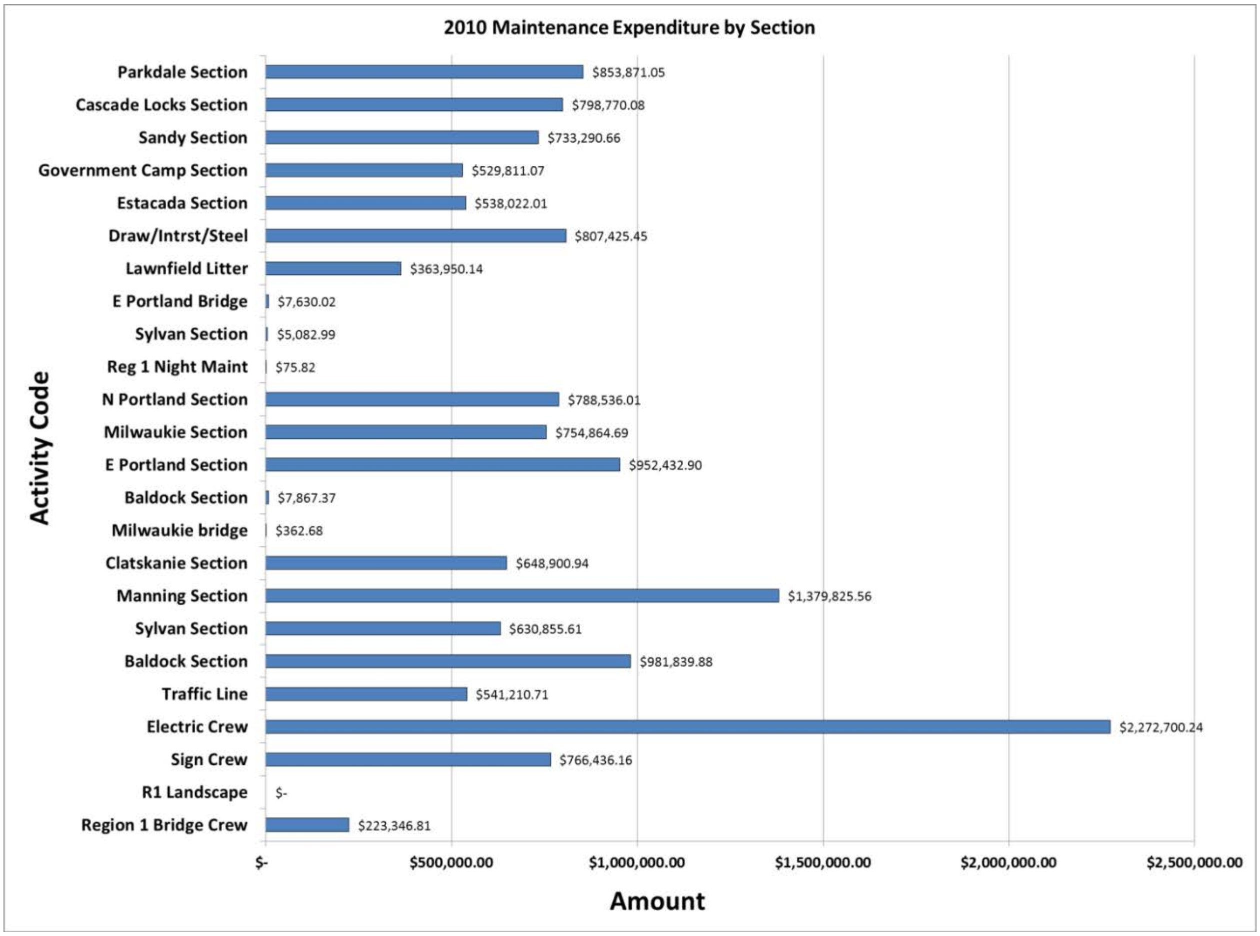

Figure 4.49: Maintenance Expenditure by Section – Region 1 (2010)

[1] The MBT-1® is currently assigned to the ODOT Clackamas Bridge Crew in Region 1.

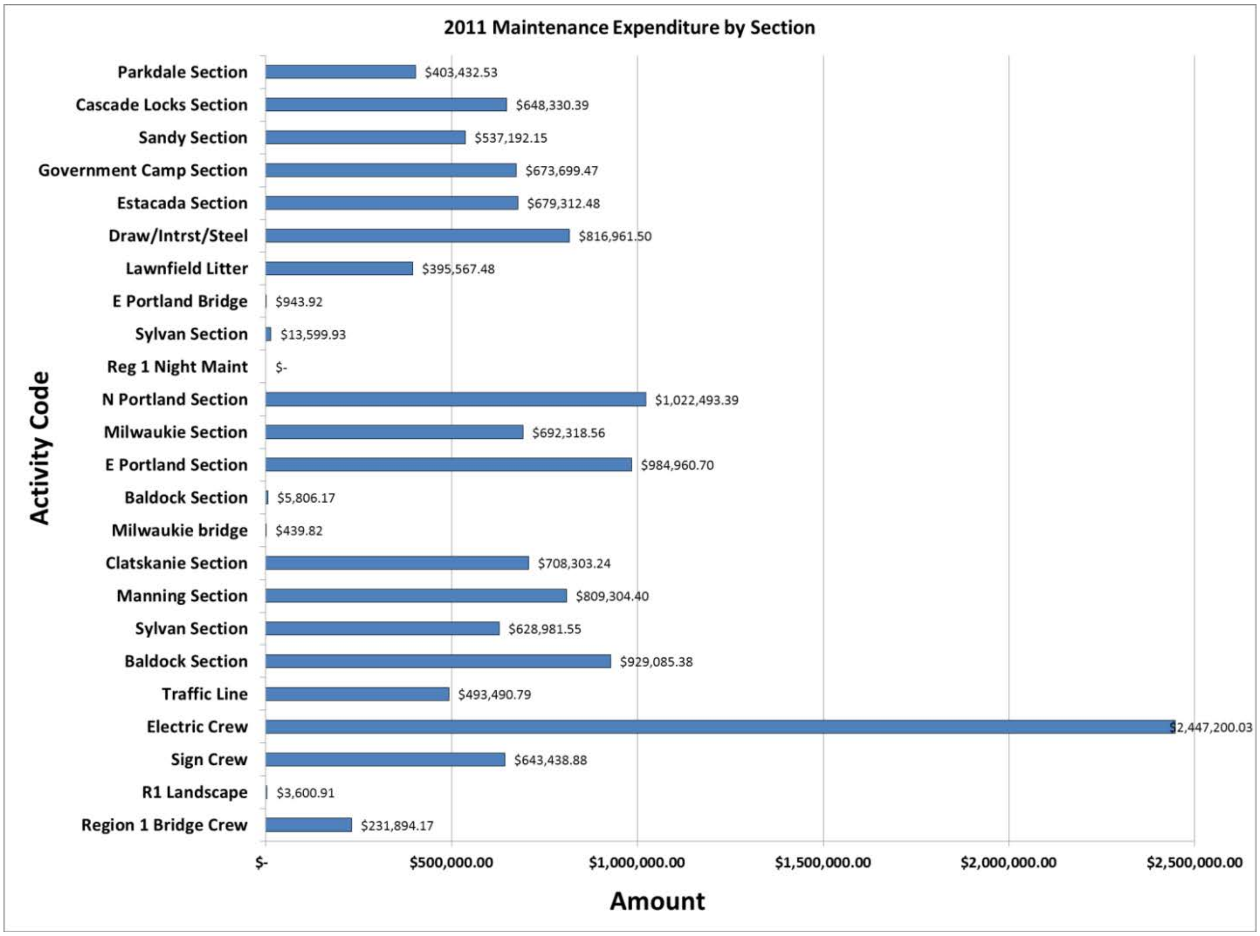

Figure 4.50: Maintenance Expenditure by Section – Region 1 (2011)

The amount of work that is performed in activities that were identified to be suitable for MBT-1® use was also analyzed according to each section in Region 1. Figure 4.51 and Figure 4.52 show that information for 2010 and 2011, respectively. As observed in 2010, the Electric Crew had by far the largest amount of work with $2,229,202, surpassing the Sign Crew which was 2nd with $743,248 in maintenance work. In 2011, the Electric Crew had the greatest amount of work in activities suited for MBT-1® use with $2,419,182, while the Sign Crew was 2nd with $625,856.

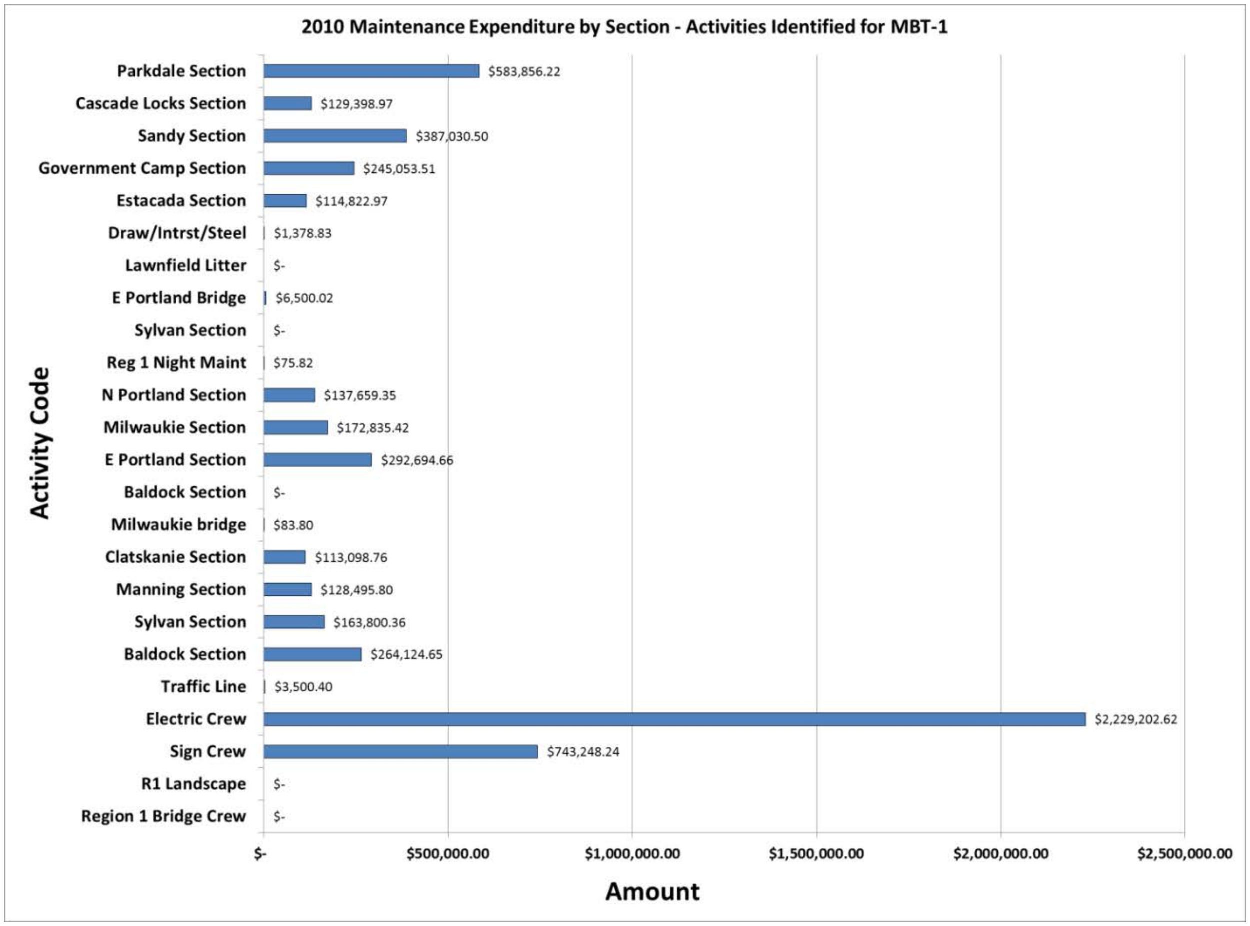

Figure 4.51: Maintenance Expenditure by Section for MBT-1® Identified Activities– Region 1 (2010)

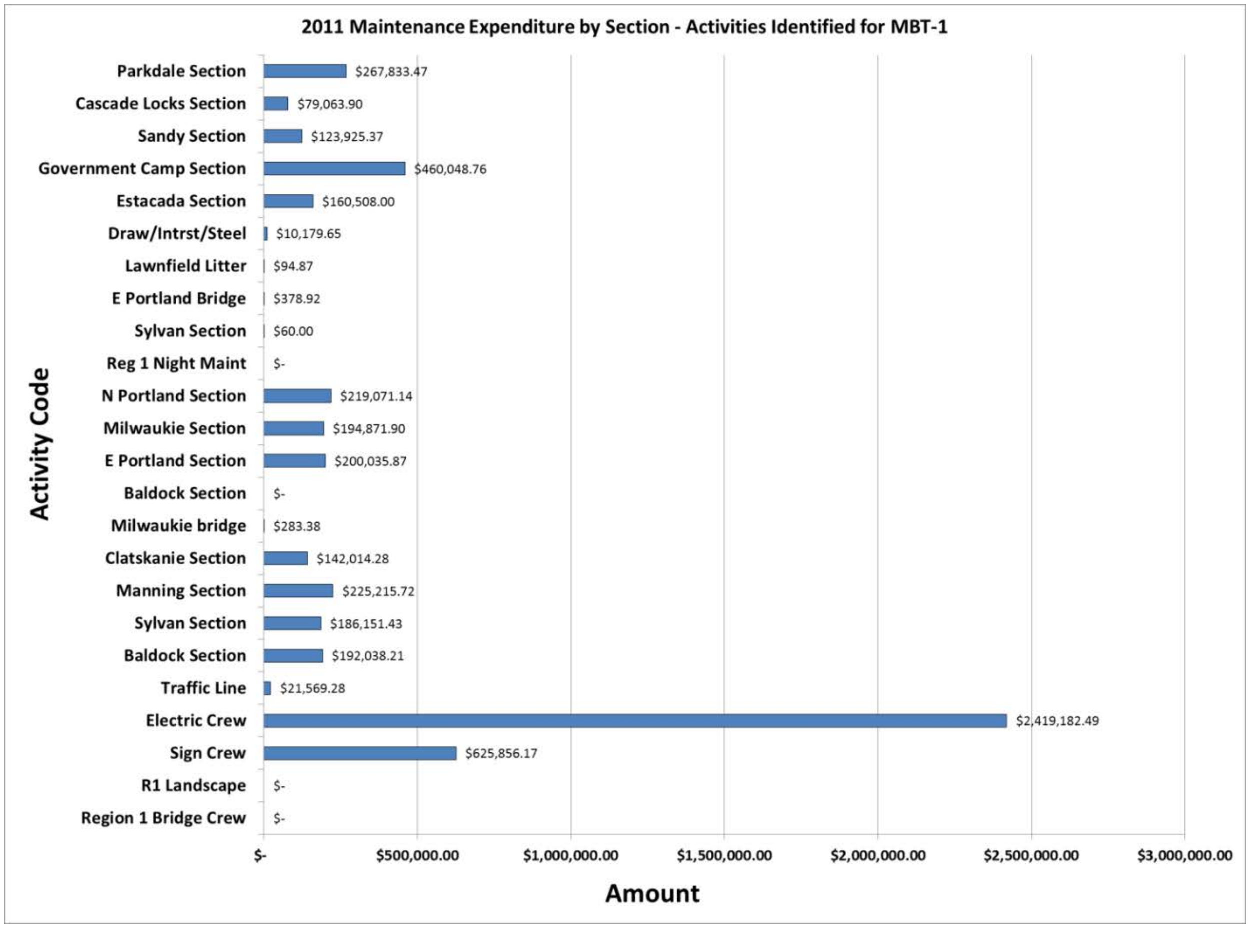

Figure 4.52: Maintenance Expenditure by Section for MBT-1® Identified Activities– Region 1 (2011)

4.7.3 Financial Analysis Conclusions

The above analysis indicates that there is potentially a significant amount of work in which ODOT could use the MBT-1®, and most of the work would be conducted by the Electric Crew. This evaluation assumes that with increased expenditures in operations, there is increased exposure to roadway hazards by the work crews. Since the Electric Crew surpassed all other crews in work that is suitable for MBT-1® use, it would seem fitting that the Electric Crew would use the MBT-1® the most in the future.

4.8 TIME OBSERVATIONS

The MBT-1® may be used in either a right-hand or left-hand configuration. The operations of switching the direction of the MBT-1® were observed and filmed twice during the course of the research study. The first time was on March 7, 2012, and the second on September 27, 2012. Both observations took place at the ODOT laydown yard on I-205 near Exit 10. The time required to switch the MBT-1® was 97 minutes and 109 minutes, respectively. The individual activities and related times to complete the entire operation are listed in more detail in Table 4.44. It is assumed that the times will decrease in the future as ODOT personnel become more familiar with the MBT-1® and have additional opportunities to work on switching the direction. Input from personnel at Mobile Barriers, LLC indicates that crews in other state agencies, following all manufacturer recommended procedures, have reported times of less than 60 minutes to reconfigure the barrier from one side to the other. Mobile Barriers, LLC provides a demonstration video of switching the barrier from one side to another in approximately 17 minutes (Mobile Barriers 2013).

Table 4.44: Timed Observations for Switching MBT-1® Configuration

Time (min)	Work Description (switching MBT-1® direction)
September 27, 2012	
0	Start Work - Start removing attenuator
8	Remove attenuator
11	Lower back supports, get ready to remove caboose, attach hitch to tractor
31	Remove rear axle guard
34	Lower front supports
37	Hitch tractor to caboose
40	Remove truck
42	Remove caboose
44	Move caboose to the other end
45	Place truck on other end- working on connecting it to the MBT-1®
67	Tractor backs up, continue work on caboose
71	Raise front supports
77	Place beacons and supports
87	Attach rear axle guard
109	Finish work - attaching attenuator
March 7, 2012	
0	Start Work - Arrival of truck and move the MBT-1® to suitable location
10	Remove rear axle guard
18	Remove attenuator
32	Remove caboose
34	Remove truck
35	Move caboose to the other end
48	Connect caboose to MBT-1®
62	Attach truck to MBT-1®
90	Attach attenuator
97	Finish Work - Attaching rear axle guard

Use of the MBT-1® may also require adding or removing a wall section to make it longer or shorter. The addition of a wall section was observed only once on March 7, 2012, and the time it took to perform all of the necessary tasks was 118 minutes. The removal of the section was observed again once on March 16, 2012 at the rest area on I-5 close to MP 240. The time it took to remove the section was 215 minutes. Table 4.45 provides a list of the specific activities required to add/remove a wall section and the corresponding observed times for each activity. As with changing the direction of the MBT-1®, it is assumed that the time required to add/remove a wall section will decrease as ODOT employees become more familiar with the process. Mobile Barriers, LLC reports that experienced crews, following recommended operating procedures, typically take less than 60 minutes to add/remove a wall section, and provides a demonstration video of adding a wall section in approximately 20 minutes (*Mobile Barriers 2013*).

Table 4.45: Timed Observations for Switching MBT-1® Configuration

Time (min)	Work Description (adding 20' section)
March 7, 2012	
0	Move MBT-1® to location
8	Bring 20' section with a forklift
10	20' section placed adjacent to MBT-1®
11	Lower support wheels and remove bolts from connection
48	Separate the MBT-1®
115	Finish bolting section
118	Finish work
March 16, 2012	
0	MBT-1® arrived at the shoulder close to the exit to the MP 240 rest area on I-5
15	Set up of work zone
45	Start removing bolts from middle section
83	Finished unbolting section to be removed
145	Removal of ballast tank to straighten the MBT-1® section (even distribution of weight)
150	Truck attached to the MBT-1® and started bolting
167	Finished bolting MBT-1® sections together
175	Place ballast tank on trailer
205	Place section on MBT-1® and strap it down
215	Finish work - Strapping 20' section on MBT-1®

During the removal of the section on March 28, it was observed that the sloping ground caused the truck and a section of the trailer to become twisted as observed in Figure 4.53. To counteract this issue, the ballast tank on the MBT-1® was removed in order to allow the MBT-1® to be connected properly. This issue caused a significant amount of the delay experienced by the crew[2].

Figure 4.53: MBT-1® Twisting during Assembly

[2] The manufacturer recommends assembly at a level location (*Mobile Barriers, 2010*)

5.0 CONCLUSIONS

Based on the research results and analysis, the MBT-1® was found to be an effective and beneficial tool for ODOT maintenance crews. This is especially true in regards to worker safety. The MBT-1® showed that it is able to provide enhanced protection of workers, by both reducing and eliminating safety concerns. In addition, the workers' general response was that they felt safer with the MBT-1® present. With regards to vehicle speed through the work zone, the results reveal that as vehicles pass through the work zone, the speed reductions next to the maintenance work zones were less with the MBT-1® present than with solely traditional safety measures.

In nearly all the case studies, the workers expressed that they feel safer behind the MBT-1®. In comparison to traditional measures in the first case study (Fremont Bridge), all of the seven workers from the bridge crew who completed the survey stated that they feel safer with the MBT-1® present. In case study three (Interstate Bridge), all nine workers who responded to the survey said that they feel safer with the MBT-1®. Similarly, all six workers felt safer with the MBT-1® in case study six (I-205). Some factors that attribute to this positive view of the MBT-1® towards safety are the following:

- The MBT-1® is a hard barrier between the work area and passing traffic which provides a higher level of comfort for the workers.
- The presence of the MBT-1® allows the workers to perform their tasks without paying as much attention to the adjacent traffic that is passing a few feet away from them. This comfort and protection eliminates the need for a worker to act as a spotter for possible hazards that they might be exposed to from the passing vehicles.
- Noise from the adjacent traffic to which the workers are exposed is significantly reduced when using the MBT-1®. Most of the workers commented that they could carry on a conversation with a co-worker in a normal voice when standing behind the MBT-1®. Without the barrier, the workers have to speak louder in order to give instructions and coordinate their work.
- The MBT-1® facilitates the installation of additional lighting and the work zone can be illuminated to a very comfortable level, reducing the need for additional lighting equipment. Eliminating the need for additional light equipment allows the work site to be less crowded. Placing the lights on the MBT-1® also facilitates providing light right at the work area that does not create disabling glare for the passing motorists.

The MBT-1® has a variety of options that help to increase worker efficiency while performing their tasks. The storage compartments allow workers to carry their materials and tools inside the MBT-1® right to the work area, eliminating the need for additional vehicles for that purpose. As observed in case study #5 (I-5 HOV markers), the workers carried all of their equipment in the MBT-1® and had the equipment readily accessible every time the workers stopped to place an HOV marker. This storage ability eliminated the need to load and unload equipment from other vehicles each time the workers stopped at a new location.

Motorists are also positively affected by the MBT-1®. Vehicle speeds passed the work area are faster with the MBT-1® present than without the MBT-1®. This result was observed in case studies 1 and 6 for which there was a comparison of the MBT-1® with traditional safety measures in terms of vehicle speeds. In case study #1 (Fremont Bridge), the mean vehicle speed adjacent to the work area with the MBT-1® present was 49.21 mph, while without the MBT-1® the mean speed was 45.24 mph. This difference is much more evident in case study #6 (I-205) where the mean speed adjacent the work area during the night when the MBT-1® was used was 45.79 mph. The mean speed when traditional safety measures were used was 39.63 mph. It should be noted that, with respect to the variability in speed amongst the vehicles passing through the work zone, the data was mixed. In some instances the variance (as indicated by the standard deviation in speeds) was less with the MBT-1® present, and in other cases it was less without the MBT-1®.

When passing by the work area, the height of the MBT-1® blocks the driver's view into the work area for most passenger cars and pick-ups. This is the case even without the additional screen present along the top edge of the MBT-1®. When observing drivers as they passed by in the active lane on Case Study #1, the drivers less frequently turned their head to look at the work area when the MBT-1® was present. As a result, it appears that the drivers are not as distracted by the on-going work with the MBT-1® present.

The researchers found that there is a need for ODOT employees who operate the MBT-1® to practice positioning the MBT-1® on construction sites. In some cases, the operators struggled to get the MBT-1® in position. Additional practice maneuvering the MBT-1® will help to avoid the repetitive back and forth movements of the barrier close to the work zone to position it properly. It is believed that with additional uses of the barrier and with the assignment of dedicated drivers, the ability and time needed to maneuver and position the MBT-1® will improve.

It is also believed that the time required to switch the direction of the MBT-1® (from left-hand to right-hand, and vice versa), and to add and remove wall sections, will greatly improve with time as the crews get more experience in performing these operations. In addition, the manufacturer's guidelines should be followed during these activities. As observed during the removal of a 20-foot section of the barrier, the sloping ground at the site caused a significant amount of the delay in performing that task. Adequate planning should be undertaken to perform these operations on level ground and in areas where there is sufficient room for operating the needed support equipment.

The case studies also revealed some limitations in using the MBT-1® for some activities performed by ODOT maintenance. For example, as observed in case study #4, the barrier was not used during the excavation of the drill shaft because the shoulder could not facilitate the presence of the barrier, the drill rig, and the other vehicles needed during the operations. Sufficient space is needed on the roadway to place the MBT-1® without obstructing traffic, creating an obstacle for passing traffic to maneuver around or avoid, or interfering with the work operations. The barrier should not encroach excessively into the travel lane and force the passing vehicles out of the travel lane, especially when there are additional obstacles upstream and downstream of the work area.

Finally, to maximize the overall benefit of the barrier to ODOT operations, it is best if the primary users of the MBT-1® be ODOT sections that perform a large amount of work within ODOT. The research identified several work operations which are particularly suitable for MBT-1® use, and also identified those operations which are conducted most often by ODOT. The analysis shows that ODOT will gain significant benefit from the MBT-1® based on the extent to which it can potentially be used. As described in Section 4.7of this report, the MBT-1® is expected to be mostly applicable to the work performed by the Electric Crew and the Sign Crew, both of which have high annual expenditures.

6.0 GUIDELINES AND RECOMMENDATIONS

The case studies and research results provide an opportunity to develop recommendations to ODOT for implementing the MBT-1® and for further investigation. It is anticipated that ODOT will use the MBT-1® for a variety of work operations, most often related to maintenance. The MBT-1® is applicable to short-term construction operations as well; however its level of feasibility when compared to other positive barriers may diminish for construction operations with longer duration. The research team, after reviewing the case study findings and analysis of the data, provide the following recommendations regarding the use of the MBT-1® for ODOT maintenance activities:

1. The MBT-1® is most applicable to and recommended for use on operations that are short-term, especially those that have a duration of one work shift or less where the work zone closure and worker protection is placed and then removed with each work shift. If continuous, positive protection measures are needed for a longer period of time (e.g., continuous for several days, weeks, or months), then other methods, such as a concrete barrier or movable barrier, are likely more feasible. As observed in case study #2 (I-5 near Brownsville), placement of the barrier on the road resulted in the barrier being damaged by passing semi-trucks. The MBT-1® required expensive repairs and could not be used for a long period of time afterwards while the repairs took place.

2. When the barrier is moved to a work location, additional coordination is needed with the traffic control crews to plan the travel route, identify a temporary storage location if needed, and discuss the logistics of placing it at the work zone as traffic control is taking place. The coordination should take into consideration the length and maneuverability of the barrier, especially if two wall sections are added.

3. To mobilize the MBT-1® more quickly, it is suggested that ODOT develop a method for efficiently obtaining a permit for its use. A special permit may be needed to accommodate the extended length of the barrier when additional wall sections are added.

4. A semi-truck should be permanently assigned to the MBT-1® in order to maximize its use by all ODOT sections. Having a dedicated semi-truck reduces the amount of logistics that need to be planned every time the semi-truck is used for another operation.

5. The MBT-1® should be stored at a location that is easy to access based on the typical barrier configuration, and where the operations for switching direction, adding a section, and removing a section can be performed without the need to re-locate the MBT-1®. Also, the storage location should be flat (not sloped) in order to allow for efficient performance of these operations.

6. ODOT should develop comprehensive guidelines for all positive protection measures used within the Department. Such guidelines could include a decision tree or matrix to assist section managers in choosing which positive protection measure(s) to use. The decision matrix would include consideration of multiple factors including the duration of the work, type of work operation, location, ease of access, and the availability of traffic control resources and equipment.

7. There is a need for a means by which state agencies that own a barrier and other similar positive protection measures, as well as other private users of the barrier, can share experiences and information regarding their use of, lessons learned from, and methods to improve the use of mobile barriers. This system of information sharing should be independent of the manufacturer of the barrier. Cooperation between users will reduce the amount of guess work and significantly reduce the learning curve for subsequent mobile barrier users.

8. Finally, the researchers recommend some modifications be made to ODOT's MBT-1® in order to improve its use by maintenance crews. These are:

    a. The installation of a removable skirt along the length of the bottom edge of the barrier to eliminate possible debris from entering the active lanes from the work area during jackhammering of the pavement. The skirt will also prevent debris in the travel lane from coming into the work area as vehicles pass by. Such a skirt is available from Mobile Barriers and/or can be separately crafted from common netted trailer tarp and hung from the lower edge of the MBT-1®.

    b. A camera should be installed on the mobile barrier that would allow the driver to observe the work zone from the vehicle. This ability to easily view the work area is necessary for rolling work zones, where the driver needs to place the MBT-1® at precise locations on the highway. Such cameras, with both audio and visual connections to monitors inside the cab, are available from Mobile Barriers and/or may likewise be separately obtained. The camera systems may be powered directly from the integral power system already plumbed throughout the barrier.

7.0 REFERENCES

AASHTO. *Manual for Assessing Safety Hardware*, 1st Edition. AASHTO, 2009. https://bookstore.transportation.org/collection_detail.aspx?ID=34. Accessed July 20, 2011.

AASHTO. *Summary of Differences between MASH and NCHRP 350*. AASHTO, 2013. https://bookstore.transportation.org/imageview.aspx?id=708&DB=3. Accessed June 5, 2013.

Antonucci, N.D., J.E. Bryden, T.R. Neumen, R. Pfefer, and K. Slack. Guidance for Implementation of the AASHTO Strategic Highway Safety Plan Volume 17: A Guide for Reducing Work Zone Collisions, Report 500. *National Cooperative Highway Research Program (NCHRP)*, Transportation Research Board. 2005.

Artimovich, N. *NCHRP Report 350 Devices in Work Zones*. FHWA Office of Safety Design, Washington, D.C., 2004. http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/nchrp_350/docs/wz350april04.pdf. Accessed July 20, 2011.

ATSSA. *A Vision for Safer Roads in America.* The American Traffic Safety Services Association, 2008. http://www.atssa.com/galleries/default-file/Toward%20Zero%20Deaths%20FINAL.pdf. Accessed September 12, 2013.

Barrier Systems. *Quickchange Moveable Barrier Systems for Construction*. Barrier Systems, Rio Vista, CA, 2008.

Beason, W.L. Truck-Mounted Portable Maintenance Barrier.*Transportation Research Record*, No. 1024, 1985.

Caldwell, C. *Crashworthiness Testing of a Portable Maintenance Work-Zone Barrier*. CalTrans, Division of Research and Innovation, Office of Safety Innovation and Cooperative Research, Report No. FHWA/CA08-0277, 2008.

Caltrans DRI. *Caltrans Mobile Work Zone Protection System: The Balsi Beam*.2007. http://www.dot.ca.gov/newtech/researchreports/two-page_summaries/balsi_beam_2-pager.pdf. Accessed July 20, 2011.

CDOT.*Guidelines for the Use of Positive Protection in Work Zones.* Colorado Department of Transportation, 2010.

EAS. *Energy Absorbtion Systems Triton TL-2 Barrier*. E.A.S., Inc., Chicago, IL, 2012a.

EAS.*Energy Absorbtion Systems Triton TL-3 Barrier*. E.A.S., Inc., Chicago, IL, 2012b.

EAS. *Energy Absorbtion Systems Vulcan Barrier*. E.A.S., Inc., Chicago, IL, 2012c.

FHWA. *Manual on Uniform Traffic Control Devices*. Federal Highway Administration, U.S. Department of Transportation, 2009a.

FHWA. *Most Common Types of Crashes by Work Zone Area*. Federal Highway Administration, FHWA-SA-O3-012, U.S. Department of Transporation, 2003a.

FHWA. *Positive Protection - Reducing Risk, Protecting Workers and Motorists*. Federal Highway Administration, U.S. Department of Transportation, 2003b.

FHWA. *Standard Highway Signs*. Federal Highway Administration, U.S. Department of Transportation, 2004.

FHWA. *Toward Zero Deaths*. Federal Highway Administration, U.S. Department of Transportation, 2009b. http://safety.fhwa.dot.gov/tzd/. Accessed September 9, 2013.

Gomez-Leon, S. *NCHRP Report 350 Update, Test 3-11 Full-Scale Crash Evaluation of a Mobile Barrier Trailer, Report Revision 1*. Southwest Research Institute, No. 18.13922, Rev. 1, 2008.

Hallowell, M.R., J.B. Protzman, and K.R. Molenaar. Mobile Barrier Trailer: Analysis of an Emerging Work Zone Protection System. *Professional Safety*. Journal of the American Society of Safety Engineers, Vol. 55, No. 10, 2010, pp. 31-38.

Jewell, J. and C. Caldwell. *Crashworthiness Testing for a Portable Maintenance Work Zone Barrier*. Roadside Safety Research Group, CALTRANS, 2008.

Kamga, C., and S. Washington. *Portable Work Zone Barrier - Mobile Barriers Mobile Barrier Trailer (MBT-1®)*. New Jersey Institute of Technology, 2009.

Khattak, A.J., A. Khattak, and F.M. Council. Effects of Work Zone Presence on Injury and Non-Injury Crashes. *Accident Analysis and Prevention*,Vol. 34, 2002, pp. 19-29.

MASH. *Manual for Assessing Safety Hardware (MASH).* FHWA, 2013. http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/ctrmeasures/mash/mash.pdf. Accessed June 2013.

Mobile Barriers. *MUTCD Guidance*. Mobile Barriers, 2009.

Mobile Barriers. *MBT-1® Specifications - Long Form.* Mobile Barriers, 2010.

Mobile Barriers. *Mobile Barriers MBT-1® - Barrier Sysytem - Positive Protection for Workzones*. 2012. http://www.mobilebarriers.com/specs.htm. Accessed December 2012

Mobile Barriers. *Mobile Barriers MBT-1® - Reconfiguration Videos*. 2013. http://www.mobilebarriers.com/reconfiguration-mobile-barrier.html. Accessed May 2013.

Muttart, J.W., D.L. Fisher, M. Knodler, and A. Pollatsek. Driving Simulator Evaluation of Driver Performance During Hands-Free Cell Phone Operation in a Work Zone: Driving Without a Clue. Transportation Research Board (TRB) Annual Meeting, 2007.

NCHRP. Recomended Procedures for the Safety Performance Evaluation of Highway Features. *National Cooperative Highway Research Program Report 350*. Transportation Research Board, 1993. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_350-a.pdf. Accessed September 21, 2011.

Nicole, D. Letter to Kevin Groenweg and Mobile Barriers LLC RE: FHWA Acceptance of a Roadside Device, FHWA, 2008. http://www.mobilebarriers.com/images/Mobile-Barriers-MBT-1-FHWA-Acceptance-Letter-080605.pdf. Accessed December 2012

NHTSA. *Fatality Analysis Reporting System (FARS) Encyclopedia*. 2011. http://www-fars.nhtsa.dot.gov/Main/index.aspx. Accessed September 21, 2011.

ODOT. *Maintenance Guide*. Oregon Department of Transportation, 2004.

ODOT. *Oregon National Data Chart*. 2011a. http://www.oregon.gov/ODOT/TS/docs/Workzone/WZ_Oregon_Natl_Data_Chart_20110324.pdf?ga=t. Accessed September 21, 2011.

ODOT. *Oregon Temporary Traffic Control Handbook*. Oregon Department of Transportation, 2011b.

ODOT. *Traffic Control Plans Design Manual*. Oregon Department of Transportation, 2011c.

ODOT. *ODOT Sign Policy and Guidelines*. Oregon Department of Transportation, 2011d.

ODOT. *Work Zone Safety Fact Sheet & Safety Tips*. Oregon Department of Transportation, 2012.

ODOT. *Oregon DMV Vehicle Permits*. 2013. http://www.oregon.gov/ODOT/DMV/Pages/vehicle/trippermit.aspx. Accessed April 10, 2013.

Ogelsby, H.C, H.W. Parker, and G.A. Howell. *Productivity Improvement in Construction*, McGraw-Hill, New York, NY, 1989.

OR-OSHA. *Oregon Occupational Safety and Health Standards - Division 3 - Construction*, Oregon Occupational Safety and Health Division, 2011.

Pratt, S.G., D.E. Fosbroke, and S.M. Marsh. *Building Safer Highway Work Zones: Measures to Prevent Worker Injuries from Vehicles and Equipment*. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, 2001.

Ramsey, F.L., and Schafer, D.W. *The Statistical Sleuth*, Duxbury, Pacific Grove, CA, 2002.

Ross, H.E., D.L. Sicking, R.A. Zimmer, and J.D. Michie. Recommended Procedures for the Safety Performance Evaluation of Highway Features. *National Cooperative Highway Research Program (NCHRP) Report 350*, Transportation Research Board, Washington, D.C., 1993.

Schrank, D., and T. Lomax. *The 2007 Urban Mobility Report*. Texas Transportation Institute (TTI), College Station, TX, 2007.

Shapiro, S.S., and M.B. Wilk. An Analysis of Variance Test for Normality (complete samples). *Biometrika,* Vol. 52, No. 3-4, 1965, pp.591–611.

Sicking, D.L., H.E. Ross, D.L. Ivey, and T.J. Hirsch. *A Portable Traffic Barrier for Work Zones,* Texas Transportation Institute (TTI), 1982.

Stockton, J. Personal Interview Regarding Mobile Barriers, LLC. December 14, 2011.

South, L.J. Work Zone Safety - Keep the Message Alive. *The American Transportation Builder,* Vol. 65, No.4, 1998, pp. 10-11.

Stidger, R. The 11 Best Ways to Improve Work Zone Safety. *Better Roads*, Vol. 60, No. 7, 1990, pp. 20-23.

Sun, D., R.F. Benekohal, and W. Arya. An In-Depth Analysis on Vehicle Following Gaps in Highway Work Zones: The Direct and Interdependent Impact of Leading Vehicle. 2006 Transportation Research Board (TRB) Annual Meeting. 2007.

Tsyganov, A., R. Machemehl, and R. Harrison. *Complex Work Zone Safety.* CTR Research Report 4021-3, The University of Texas, Austin, TX, 2003.

Ullman, G.L., V. Iragavarapu, and D. Sun. *Work Zone Positive Protection Guidelines*. Texas Transportation Institute, The Texas A&M University, 2010.

Upchurch, J. Work Zone Accidents in Arizona: An Analysis of Accidents and Selection of Countermeasures. Institute of Transportation Engineers 2000 District 6 Annual Meeting, 2000.

Vaisala. *Vaisala Nu-Metrics Portable Traffic Analyzer*. Vaisala, 2010.

Zhu, W., K. Boriboonsomsin, and M. Barth. Defining a Freeway Mobility Index for Roadway Navigation. *Journal of Intelligent Transportation Systems: Technology Planning, and Operations*, Taylor and Francis, Vol. 14, No. 1, 2010, pp. 37-50.