

# Improved Work Zone Design Guidelines and Enhanced Model of Travel Delays in Work Zones

## Phase I: Portability and Scalability of Interarrival and Service Time Probability Distribution Functions for Different Locations in Ohio and the Establishment of Improved Work Zone Design Guidelines

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for the  
Ohio Department of Transportation  
Office of Research and Development

and the  
United States Department of Transportation  
Federal Highway Administration

SJN 14808(0)

January 2006



**OHIO**  
UNIVERSITY

Ohio Research Institute for  
Transportation and the Environment





<b>1. Report No.</b> FHWA/OH-2006/1	<b>2. Government Accession No.</b>	<b>3. Recipient's Catalog No.</b>	
<b>4. Title and Subtitle</b> Improved Work Zone Design Guidelines and Enhanced Model of Travel Delays in Work Zones. Phase I: Portability and Scalability of Interarrival and Service Time Probability Distribution Functions for Different Locations in Ohio and the Establishment of Improved Work Zone Design Guidelines		<b>5. Report Date</b> January 2006	
		<b>6. Performing Organization Code</b>	
<b>7. Author(s)</b> Helmut T. Zwahlen and Erdinc Oner		<b>8. Performing Organization Report No.</b>	
<b>9. Performing Organization Name and Address</b> Ohio University Human Factors and Ergonomics Laboratory Ohio Research Institute for Transportation and the Environment Russ College of Engineering & Technology Athens, Ohio 45701-2979		<b>10. Work Unit No. (TRAIS)</b>	
		<b>11. Contact or Grant No.</b> State Job No.14808(0)	
<b>12. Sponsoring Agency Name and Address</b> Ohio Department of Transportation 1980 West Broad Street Columbus, OH 43223		<b>13. Type of Report and Period Covered</b> Final Report	
		<b>14. Sponsoring Agency Code</b>	
<b>15. Supplementary Notes</b> Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.			
<b>16. Abstract</b> The project focuses on two major issues - the improvement of current work zone design practices and an analysis of vehicle interarrival time (IAT) and speed distributions for the development of a digital computer simulation model for queues and travel delays in work zones. Important considerations in the development of work zone design guidelines include guidance, delineation, and the safety of workers and drivers. A nationwide survey of current work zone best practices was conducted. Based on the review of the existing ODOT guidelines, superior practices available in other states, relevant research, and professional judgment of personnel involved in work zone activities, a set of guidelines for work zone design are proposed. It is anticipated that these research findings will result in the better design of work zones which will minimize traffic delays and improve safety. In the second part of the project trailers, each using two Wavetronix microwave radar units in side-fire mode, were developed to nonintrusively measure traffic. The traffic was measured at six work zones sites with different types of lane configurations at different freeways in Ohio. Traffic on the road was also independently measured using video and radar, and the results compared to records from the trailers to verify that the trailers were measuring the traffic with reasonable accuracy. IAT data of successive vehicles in free-flowing traffic ahead of work zones were analyzed and IAT distributions were generated as a function of the traffic volume for each lane and relationships between traffic volumes and cumulative IAT distributions were established allowing a direct conversion from hourly traffic counts to corresponding cumulative IAT distributions. This conversion method produces fairly accurate cumulative IAT distributions for selected hourly traffic volumes. It was also found that the same cumulative IAT distribution can be used to model the free-flowing traffic at other freeway locations in Ohio, which means that the IAT distributions are portable and scalable and a microscopic digital computer simulation model based on queueing theory may be developed to investigate traffic delays in work zones.			
<b>17. Key Words</b> Work zone design guidelines, entrance ramps, exit ramps, ramp closures, ramp metering, acceleration lanes, deceleration lanes, signing materials, portable changeable message signs, arrow panels, drums, rumble strips, regulatory signs, warning signs, guide signs, speed control, pedestrian safety, worker safety, equipment marking, flaggers, glare screens, lighting, guard rails, barrier markers, delineation devices, pavement markings, raised pavement markers, curve radii, work zone traffic data, headways, freeway interarrival time distributions, speed distributions, traffic volumes		<b>18. Distribution Statement</b> No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
<b>19. Security Classif. (of this report)</b> Unclassified	<b>20. Security Classif. (of this page)</b> Unclassified	<b>21. No. of Pages</b> 224	<b>22. Price</b>

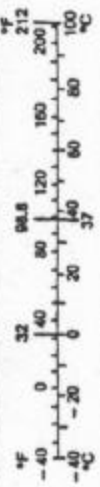
# SI\* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
in	inches	25.4	millimètres	mm
ft	feet	0.305	mètres	m
yd	yards	0.914	mètres	m
mi	miles	1.61	kilomètres	km
<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	millimètres squared	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	mètres squared	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	mètres squared	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	kilomètres squared	km <sup>2</sup>
<b>VOLUME</b>				
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft <sup>3</sup>	cubic feet	0.028	mètres cubed	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	mètres cubed	m <sup>3</sup>
NOTE: Volumes greater than 1000 L shall be shown in m <sup>3</sup> .				
<b>MASS</b>				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
<b>TEMPERATURE (exact)</b>				
*F	Fahrenheit temperature	$5(F-32)/9$	Celsius temperature	*C

## APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
mm	millimètres	0.039	inches	in
m	mètres	3.28	feet	ft
m	mètres	1.09	yards	yd
km	kilomètres	0.621	miles	mi
<b>AREA</b>				
mm <sup>2</sup>	millimètres squared	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	mètres squared	10.764	square feet	ft <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	kilomètres squared	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>				
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m <sup>3</sup>	mètres cubed	35.315	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	mètres cubed	1.358	cubic yards	yd <sup>3</sup>
<b>MASS</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
<b>TEMPERATURE (exact)</b>				
*C	Celsius temperature	$1.8C + 32$	Fahrenheit temperature	*F



\* SI is the symbol for the International System of Measurement

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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

Final Report  
January 2006

## ACKNOWLEDGEMENTS

A number of people have assisted in performing the research presented in this report and we thank all of them for their help. Among these are Andrew Russ, Research Engineer/Scientist, Gianantonio Scaramuzza, Research Engineer, and graduate students Fazleena F. Badurdeen, Sahika Vatan, Meghna Parthasarathy, Royston Lobo, Maimuna Rangwala, and Chandrasekhar Ganduri who worked on the literature review, evaluation of work zone design guidelines, product review, work zone data collection, work zone data analysis, and the preparation of the draft final report.

The researchers have interviewed several experts in simulation modeling including Dusan Sormaz, Associate Professor, Industrial and Manufacturing Systems Engineering Department, Ohio University, Michael Drevna, Director, Advanced Manufacturing Consulting Solutions, Rockwell Automation, and Deborah Curtis, Highway Research Engineer, Federal Highway Administration, Office of Operations Research & Development. Their input is appreciated.

We acknowledge the contributions and inputs made by Joe Bowman and Tom Morrison, Treehaven Technologies, Logan Harris, Wavetronix LLC, Dave Gardner and Tony Manch, ODOT Office of Technical Services, Larry Burnette, Athens County Garage Manager, Tom Lau, I-270 Work Zone Project Engineer, George Rak, I-76 Work Zone Project Engineer, John Grasso, I-75 Work Zone Project Engineer, Frank Hinkle, ODOT Cleveland Garage Transportation Manager, and David Reich, ODOT Portage County Manager. We also acknowledge the contributions and inputs made by Douglas J. Mace, President, The Last Resource, Inc., Beelefonte, PA, and Richard Schwab, Consultant, formerly with the Federal Highway Administration, Alexandria, VA.

We also thank David Holstein, Administrator of the Office of Traffic Engineering, and Mack Braxton and Ken Linger of the ODOT Office of Traffic Engineering for their technical and logistical support. We also thank Monique Evans, Administrator of the Office of Research and Development, for her administrative support.

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## 1. INTRODUCTION

Work zones on heavily traveled divided highways present problems to motorists in the form of traffic delays and increased accident risks due to sometimes reduced motorist guidance, dense traffic, and other driving difficulties. The delays are associated with slowing and merging traffic, either in lane reductions at the beginning of the work zone, or at entrance ramps that are open in the work zone. There is demand by motorists both for better roads and for unimpeded roads. Room for improvement is seen in reducing the levels of frustration motorists experience with work zone delays and in increasing the safety of work zones. This project developed two interrelated ideas for the problem of traffic delays in work zones:

1. A complete analysis of the interarrival time and service time distributions of traffic in work zones with respect to portability and scalability was performed to lay the ground work for the development of a better and more extensive digital computer simulation program for modeling the expected delays in complex work zones in the future.
2. Improved work zone design guidelines that would provide better motorist guidance and smooth the merger processes and traffic flows that are primarily responsible for queues in work zones.

A major goal of this project was to establish the portability, scalability, and limitations of the interarrival time (IAT) and service time (ST) distributions or speed distributions in the work zone restriction used to model the traffic flow in a simulation program. Scalability means that the IAT distributions can be generated with reasonable accuracy from hourly traffic volumes. Portability implies IAT distributions have similar form for different locations in Ohio. Towards this end, a concerted data collection effort was undertaken to record complete traffic data from a variety of complex work zone configurations at six work zones in Ohio. Special purpose trailers were employed for this purpose. Recommendations based on the analysis of these distributions for the development of a simulation model are also proposed in this report.

As part of the project, different surveys were conducted to obtain assessments of the current understanding of work zone design practices and traffic issues. For assessing the current best practices in designing work zones, a survey to investigate the design guidelines, present research/evaluations on the subject, reports and other publications was sent out to all the state and provincial departments of transportation in the United States and Canada. A survey of ODOT Districts was conducted to determine current and future estimates of traffic, vehicle queues and delay times in work zones.

The research proposed design guidelines for work zones in general, for merges and for entrance and exit ramps including minimum lengths for acceleration and deceleration lanes. Important considerations in the development of design guidelines included the safety of workers and the safety and comfort of drivers. Improved driver guidance and delineation cues for drivers in work zones for acceleration and deceleration lanes and exit and entrance ramp areas were also established in this study. The recommendations are supplemented with literature and product reviews or anecdotal evidence where available. Finally, additional guidelines that can be implemented by ODOT in order to improve the work zone operations are proposed based on the review of the existing ODOT guidelines, superior practices available in other states, relevant research, and professional judgment of personnel involved in work zone activities.

## **1. SURVEYS**

### **1.1.ODOT Districts Survey**

A survey was conducted to investigate input parameters for the development of a Monte Carlo computer simulation program to simulate the traffic, vehicle queues and delay times in work zones. An email questionnaire was developed for this purpose and was sent out to personnel at district ODOT departments. The respondents were asked to provide estimates of the work zone construction and operating conditions in the next five to ten year horizon, based on their judgment. A copy of the cover letter, questionnaire, and the list of personnel who were contacted are shown in Appendix A.

#### ***1.1.1.Survey Results***

The survey had nine respondents from the twelve persons contacted. The responses for survey questions 1, 4, 5, 6 and 7 are shown in Table 1. The entries in this table indicate the number of respondents (frequency) who chose the response shown in column heading.

The responses for the survey questions 2 and 3 are tabulated in Table 2 and Table 3 respectively. The entries in this table indicate the number of respondents who chose the frequency of occurrence of the provided work zone scenarios.

The responses for survey questions 8, 9, 10 and 11 are shown in Table 4. The different responses for each question are indicated in the rightmost column of this table.

**Table 1: Summary of Responses for the ODOT District Survey – Questions 1, 4, 5, 6 & 7**

SUMMARY OF ODOT DISTRICT SURVEY (Questions - 1, 4, 5, 6 and 7)																		
No.	QUESTIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Min	Max
1	Looking at the next 5 to 10 years what is the maximum and most typical number of traffic lanes where you would expect a reduction in the number of lanes or a reduction in the width of the lanes in the work zone?																	
	Maximum number of lanes		2	3	3		1										2	6
	Most typical number of lanes	2	3	2	2												1	4
4	Looking at the next 5 to 10 years what is the maximum and typical number of exit ramps that you would expect in a work zone in your district?																	
	Maximum number of exit ramps			1	1		3				3						3	10
	Most typical number of exit ramps		0-2,2		3		2										0	6
5	Looking at the next 5 to 10 years what is the maximum and typical number of entrance ramps that you would expect in a work zone in your district?																	
	Maximum number of entrance ramps			1	1		3				3						3	10
	Most typical number of entrance ramps		0-2,2		3		2										0	6
6	Looking at the next 5 to 10 years what do you expect would be the maximum and typical length of a work zone where a reduction in the number of lanes or a crossover exists?																	
	Maximum length (miles)		1	1		3		1	1		1					1	2	15
	Typical length (miles)	2	1	4				2									1	7
7	Looking at the next 5 to 10 years what do you expect would be the minimum and most typical width of a reduced lane in a work zone?																	
	Minimum width of the reduced lane (feet)									1	7	1					9	11
	Typical width of the reduced lane (feet)										1	7	1				10	12

**Table 2: Summary of Responses for the ODOT District Survey – Question 2**

	Key	Frequently	Often	Sometimes	Rarely	Never	Not app.
No.	QUESTIONS	1	2	3	4	5	N/A
2	Looking at the next 5 to 10 years please indicate the frequency of the following reduction in number of lanes in a work zone for extended periods of time (weeks, months) based on the key provided below. Select only the <u>most appropriate</u> for each line.						
	2 lanes reduced down to 1 lane	1	4	1		3	
	3 lanes reduced down to 2 lanes		1	4	2	2	
	3 lanes reduced down to 1 lane				5	4	
	4 lanes reduced down to 3 lanes	1		1	4	3	
	4 lanes reduced down to 2 lanes		1	2		6	
	4 lanes reduced down to 1 lane				1	8	
	5 lanes reduced down to 4 lanes			1	2	5	1
	5 lanes reduced down to 3 lanes			1		6	2
	5 lanes reduced down to 2 lanes				1	6	2
	6 lanes reduced down to 5 lanes			2		5	2
	6 lanes reduced down to 4 lanes		1	1		5	2
	6 lanes reduced down to 3 lanes				1	6	2

**Table 3: Summary of Responses for the ODOT District Survey – Question 3**

	Key	Frequently	Often	Sometimes	Rarely	Never	Not app.
No.	QUESTIONS	1	2	3	4	5	N/A
3	Looking at the next 5 to 10 years please indicate the frequency of the following for extended periods of time (weeks, months) based on the key provided below. Select only the most appropriate for each line.						
	2 lanes with crossover (No number of lane reduction)	1	1	4	3		
	2 lanes (No number of lane reduction) with reduction in width of lanes	3	2	2	1	1	
	3 lanes with crossover (No number of lane reduction)		1	2	3	3	
	3 lanes (No number of lane reduction) with reduction in width of lanes	1	2	2	1	3	
	4 lanes with crossover (No number of lane reduction)		1	1	1	5	1
	4 lanes (No number of lane reduction) with reduction in width of lanes		2		1	5	1
	5 lanes with crossover (No number of lane reduction)			1		6	2
	5 lanes (No number of lane reduction) with reduction in width of lanes		1	1		5	2
	6 lanes with crossover (No number of lane reduction)			1		6	2
	6 lanes (No number of lane reduction) with reduction in width of lanes			1		6	2

**Table 4: Summary of Responses for the ODOT District Survey – Questions 8, 9, 10 and 11**

SUMMARY OF ODOT DISTRICT SURVEY (Questions – 8, 9, 10 and 11)		
No.	QUESTIONS	RESPONSES
8	Looking at the next 5 to 10 years do you have any criteria in your district for closing entrance ramps? If yes please explain.	Never done 24-7, If unavoidable then close at night
		Done for ramps that are not used much. Peak hour less than 300 vehicles/hr and if there is an entrance ramp close by say within 3/4th of a mile
		In urban areas close entrances where mainline traffic is reduced to one lane in each direction to facilitate flow and remove conflicts from merging traffic
		If construction requires closure or all of the following 3 reasons occur: (1) If the ramp merge criteria cannot meet ODOT's criteria. (2) If there is another ramp within a reasonable distance. (3) If it is politically feasible
9	Looking at the next 5 to 10 years do you have any criteria in your district for closing exit ramps? If yes please explain.	Never done 24-7, If unavoidable then close at night
		Done for ramps that are not used much. Peak hour less than 300 vehicles/hr and if there is an entrance ramp close by say within 3/4th of a mile
		In urban areas close entrances where mainline traffic is reduced to one lane in each direction to facilitate flow and remove conflicts from merging traffic
		If construction requires closure or all of the following 3 reasons occur: (1) If the ramp is not required for emergency vehicles (e.g. Hospital near the ramp). (2) If there is another ramp within a reasonable distance. (3) If it is politically feasible
10	Looking at the next 5 to 10 years would you recommend opening the entrance ramp access during periods of low mainline traffic in work zone areas?	Yes-6 (2- Have done it and works well), No-2
11	What can be done to improve entrance and exit ramp operations in work zones? Please explain.	(1) Maximize acceleration and deceleration lane length and width (2) Minimize closure time through interim completion times and liquidated damage charges
		Provide adequate decision sight distance
		Signing well and provide proper tapers for acceleration and deceleration
		Temporary pavement. Move traffic over
		One suggestion is to provide a water filled barrier or some other device in advance of the exit ramp which will "train" the motorist as to where the location of the ramp is within the work zone



## **1.2.Statewide Department of Transportation Survey**

An email questionnaire of work zone best practices to investigate the design guidelines, present research/evaluations on the subject, reports and other publications was sent out to all the departments of transportation of states and provinces in the United States and Canada. The respondents were asked to comment on whether or not they conducted any research on the topics listed and to list the references for those on which they had conducted research. Copies of the cover letter, questionnaire, and the list of personnel who were contacted in the states and Canadian provinces and territories are shown in Appendix A.

Only two of the states and one of the Canadian provinces responded to the email survey that was conducted. This may be due to the open-ended nature of the questions, which requested written responses rather than selecting from multiple responses. Since the aim of the questionnaire was to generate leads for further investigation, the open-ended format was considered appropriate. It should also be noted that we did get some information from other states that did not return a questionnaire. For instance Pennsylvania shared with us presentations and reports regarding several innovations in accident mitigation that they had tested.

Since the number of replies was so tiny, no statistics have been generated, but rather the information obtained from each state is discussed in detail.

### ***1.2.1.Survey Results***

#### ***Iowa***

*Highway Lighting:* The Iowa Department of Transportation (DOT) has a regulation that states when the traffic is diverted from its normal travel path within the construction work zone the use of temporary pole mounted luminaires is required in addition to the preexisting roadside lighting. The specifications for the use of temporary lighting are given in Standard Road Plan RM-49 [1].

*Roadway Delineation:* The Iowa DOT uses temporary post-mounted delineators for delineation purposes in the construction work zone depending on the need. Temporary post-mounted delineators provide adequate guidance at day and night, especially when they are used in conjunction with temporary pavement markings.

*Construction Barrels:* Iowa DOT uses drums only in merge area tapers. The use of other Traffic Control Devices (TCDs), such as cones [daytime only], Type I barricades, Type II barricades, vertical panels, and new 42-inch (107-centimeter (cm)) channelizers [typically used is the Grabber Cone], along the lane lines are allowed. Spacings of the devices used depend on the existing speed limits. In addition Iowa DOT does not use additional arrows with drums.

*Retroreflective Sheeting Material:* All of the Iowa vertical work zone devices are sheeted with ASTM D-4956 Type II or Type IV sheetings except than the 42-inch (107 cm) channelizers. 3M's fluorescent orange diamond grade sheeting or equivalent and ASTM Type III or Type IV sheeting for the white stripes are used in the 42-inch (107 cm) channelizers. In all signs (either post mounted or skid mounted) 3M's orange fluorescent orange diamond grade sheeting is used.

*Speed Control:* The Iowa DOT funds the use of extra enforcement at high volume, complex work zones. Iowa enforces double fines in the work zones.

*Glare Screens and Jersey Barriers:* Glare screens are used for high volume, complex work zones in Iowa. They are used for shielding the work area from view and they are used to separate opposing traffic on highways with two lanes in each direction. A 32-inch (81 cm) F-shape temporary concrete barrier is used in work zones. The glare screen height is typically between 24 and 30 inches (61 and 76 cm).

*Acceleration Lane Length:* An acceleration lane length of 250-300 feet (76-91 m) is used in work zones regardless of the speed limit.

*Pavement Marking:* In high volume, complex work zones temporary pavement markings are supplemented with raised temporary pavement markers spaced at every 10 feet (3 m), which improves nighttime wet weather delineation. Most pavement markings are 4 inches (10 cm) wide, but in high volume, complex work zones 8-inch (20 cm) wide pavement markings are used in lane shifts for all markings.

*Placement of TCDs:* Iowa DOT uses standard work zone drawings to describe the setup of TCDs in a work zone [2]. In addition to the standards, the Iowa DOT performs work zone training classes for staff members in the DOT's construction and maintenance departments, counties, cities, utilities, and contractors since 1983. The classes for Iowa DOT construction inspection staff and contractors emphasize the correct TCD placement and maintenance for the efficient flow of the traffic through the construction zone.

## ***Indiana***

*Highway Lighting:* Indiana DOT uses steady-burning warning lights atop drums and flashing warning lights attached to the construction signs at night in addition to the preexisting roadside lighting.

*Roadway Delineation:* 4 feet (1.2 m) long broken temporary pavement markings are used to delineate the lanes and temporary solid edgelines, either tape or paint, are used to delineate crossover lanes, tapers, and separated two-lane two-way traffic which are not separated by temporary concrete barriers.

*Construction Barrels:* Indiana DOT places white reflective sheeting material strips on barrels such that they would cover half of the barrel to increase its visibility and effectiveness. They do not use directional arrows on barrels to guide drivers.

*Retroreflective Sheeting Material:* Indiana DOT uses high-intensity reflective sheeting material in the work zones in accordance with AASHTO M268, Type I, Type II, Type III, or Type IV.

*Speed Control:* Speed limit signs are posted at the beginning of work zones with the message "Fines Higher in the Work Zones". In addition to these message signs Indiana DOT also places message signs at the beginning of work zones showing the actual work zone fines for speeding,

tailgating, and reckless driving. Do Not Pass signs and warning lights are placed in advance of lane drops to deter motorists from remaining in the lane until the taper begins.

*Glare Screens and Jersey Barriers:* the Indiana DOT does not usually use glare screens for opposing traffic or obstruct the view of construction activities. The height of the glare screens is 18 inches (46 cm) when they are used. Indiana DOT uses F-type temporary concrete barriers with a height of 32 inches (81 cm).

*Acceleration Lane Length:* the acceleration lane lengths used by the Indiana DOT are dependent on the work zone speed limit. At rural locations the work zone speed limit is 55 mph (88 km/h) for Indiana, Assuming an average ramp running speed of 30 mph (48 km/h), they use an acceleration lane length of 375 feet (114 m). At urban locations the work zone speed limit is 45 mph (72 km/h). Assuming an average ramp running speed of 25 mph (40 km/h), they use an acceleration lane length of 300 feet (91 m).

*Pavement Marking:* Indiana DOT uses glass beads to increase the reflectivity of the pavement markings at night. The pavement marking width of 4 inches (10 cm) is used in Indiana. Placement of TCDs: MUTCD and the ASSHTO Policy on Geometric Design of Highways and Streets are used for the setup of TCDs in the work zones.

### ***Saskatchewan***

*Highway Lighting:* In addition to the pre-existing roadside lighting Saskatchewan Highways and Transportation uses portable flashing light/arrow boards and low intensity flashing warning lights (typically at barricades) at night.

*Roadway Delineation:* Chevron signs, traffic cones, delineator boards, glo-posts, and flexible drum barrels are used for roadway delineation.

*Construction Barrels:* Barrels are not usually used on Saskatchewan roadways.

*Retroreflective Sheeting Material:* Various sheeting materials are used for different devices by Saskatchewan Highways and Transportation. Construction Ahead, Road Work and Flagger signs require the background to be made of prismatic lens fluorescent reflective sheeting (Fluorescent Diamond Grade). Most regulatory signs & flagger's paddles require wide angle prismatic lens reflectivity (Diamond Grade). Most construction signs (Barricade Ahead, Fresh Oil etc.) require encapsulated lens reflectivity (High Intensity Grade). A few construction signs (e.g. barricade boards, Pilot Vehicle Follow Me) may use retroreflective enclosed lens reflectivity (Engineering Grade).

*Speed Control:* Additional traffic enforcement is requested by the contractors and field engineers if problems are observed in the work zones.

*Glare Screens and Jersey Barriers:* Glare screens are not used by Saskatchewan Highways and Transportation. The nominal height of the Jersey barrier they use is 32 inches (81 cm).

*Pavement Marking:* Saskatchewan Highways and Transportation uses pavement markers along with the pavement marking to ensure wet/dark visibility.

*Placement of TCDs:* Saskatchewan Highways and Transportation uses the department's Traffic Control Devices Manual for Work Zones to determine the optimal and standard placement of TCDs in the work zones.

### **1.3. Interviews with Traffic Simulation Experts**

One of the objectives of this project is to assess portability and scalability of IAT distributions which may be used in digital computer simulation models. After the successful assessment of portability and scalability, the second phase of this project is to develop a more extensive digital computer simulation program to better model the traffic in work zones.

The researchers have interviewed several experts in simulation modeling including Dusan Sormaz, Associate Professor, Industrial and Manufacturing Systems Engineering Department, Ohio University, Michael Drevna, Director, Advanced Manufacturing Consulting Solutions, Rockwell Automation, and Deborah Curtis, Highway Research Engineer, Federal Highway Administration, Office of Operations Research & Development.

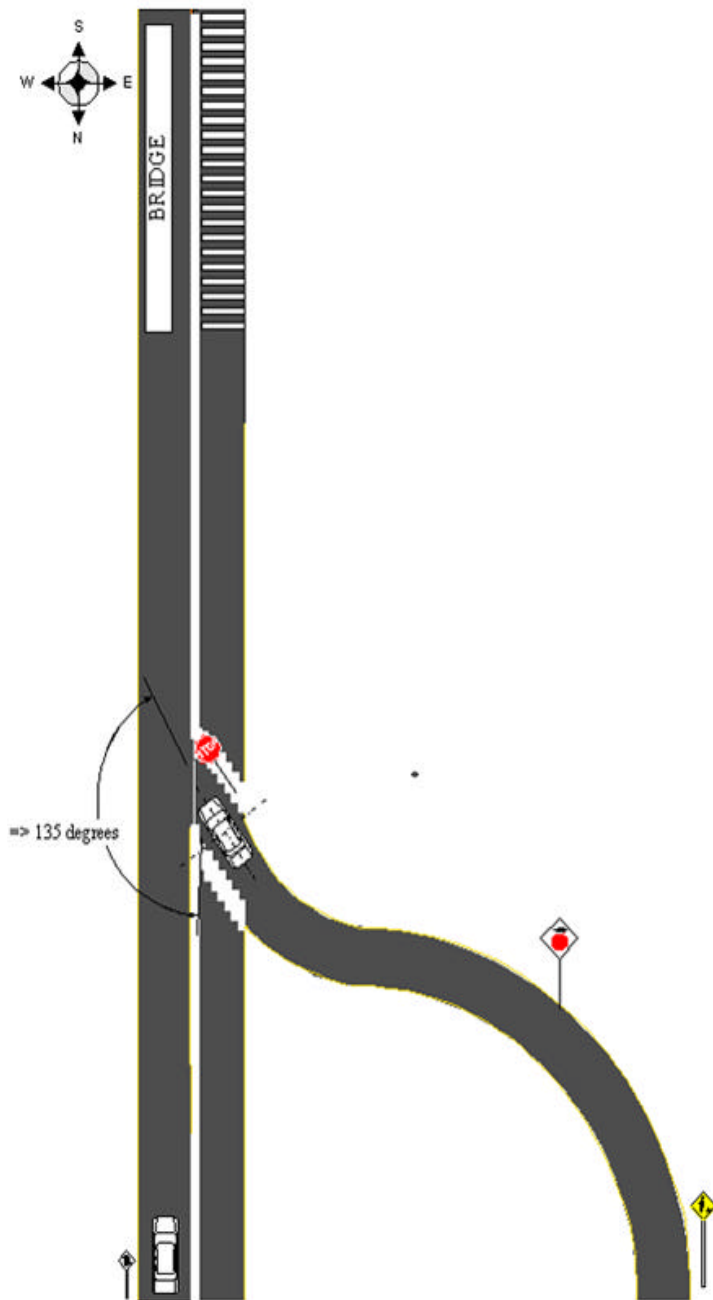
One of the digital computer simulation models available in the market is the Quickzone Delay Estimation Program. The Quickzone work zone delay estimation program was developed by The Federal Highway Administration (FHWA) in cooperation with Mitretek Systems. It uses a deterministic queueing model to simulate traffic going through work zones to determine when there would be traffic backups. It is a tool intended for highway engineers to determine how to set up a work zone to minimize traffic disruption. In an effort to evaluate the Quickzone Delay Estimation Program in detail and discuss the aim and the scope of this project the researchers interviewed Deborah Curtis, Highway Research Engineer, Federal Highway Administration, Office of Operations Research & Development, who is the coordinator of the Quickzone Delay Estimation Program project.

ARENA is another software program that can be used for modeling traffic in work zones to estimate queue lengths and delays. The researchers interviewed Dusan Sormaz, Associate Professor, Industrial and Manufacturing Systems Engineering Department, Ohio University and Michael Drevna, Director, Advanced Manufacturing Consulting Solutions, Rockwell Automation, to investigate the applicability of ARENA simulation program for the use in the Phase II of this project.

## 2. WORK ZONE DESIGN GUIDELINES

### 2.1. Entrance and Exit Ramp Configurations

Figure 1 shows an example of a poorly configured entrance onto a work zone. The driver must turn body, head, and eyes more than 140 degrees to check for approaching southbound traffic. He or she cannot use the rearview mirror because the angle is not great enough. This is a very dangerous situation especially for older drivers who have limited body movements [3].



**Figure 1: A poorly configured entrance onto a work zone with a very large head turning angle**

One way to improve the situation is to use a short merge lane. A Yield Ahead sign and two Yield signs are implemented also. This is illustrated in Figure 2. The merge lane should be able to accommodate two semi trucks. This configuration allows the driver to use the rearview mirror to check for approaching mainline traffic. The mainline speed limit is 35 mph (56 km/h).

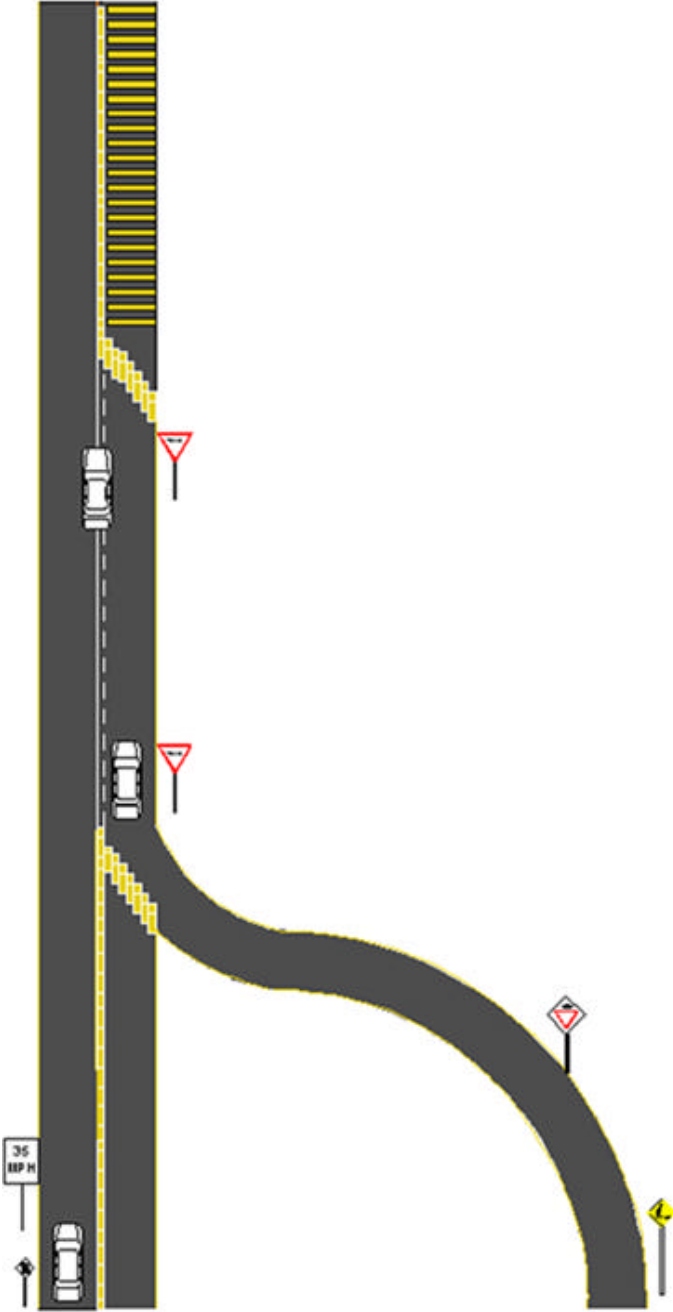
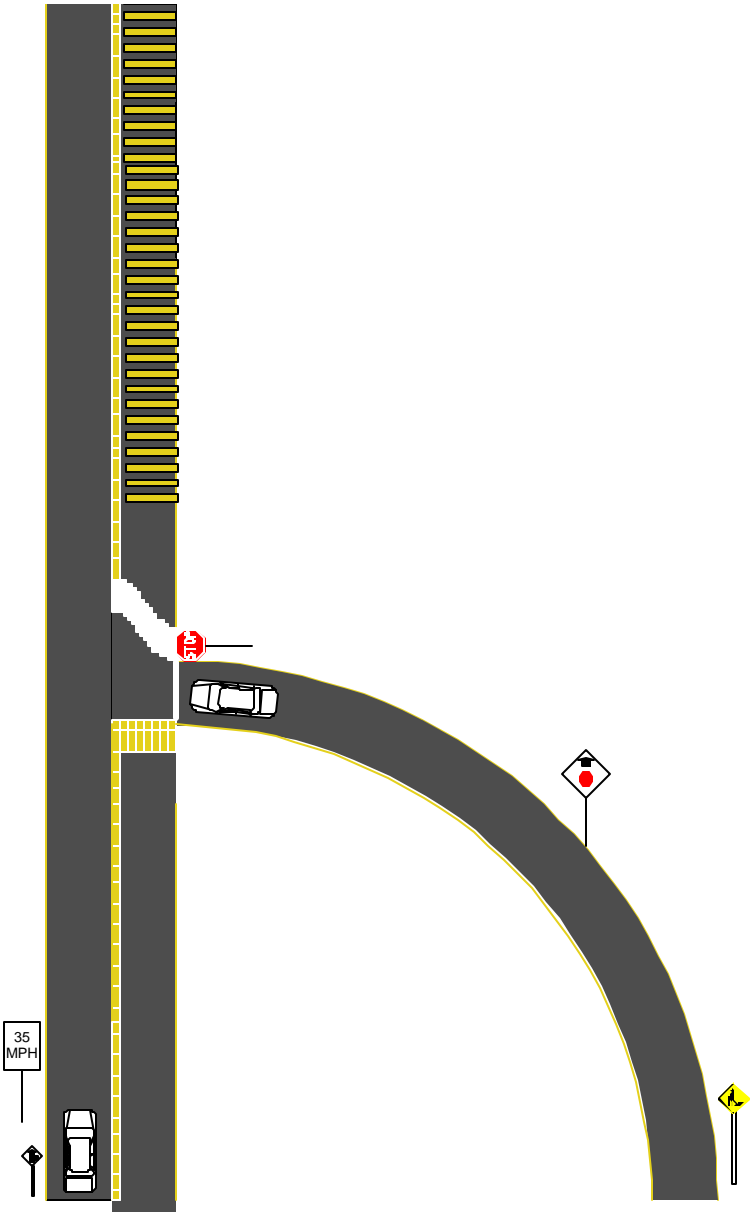


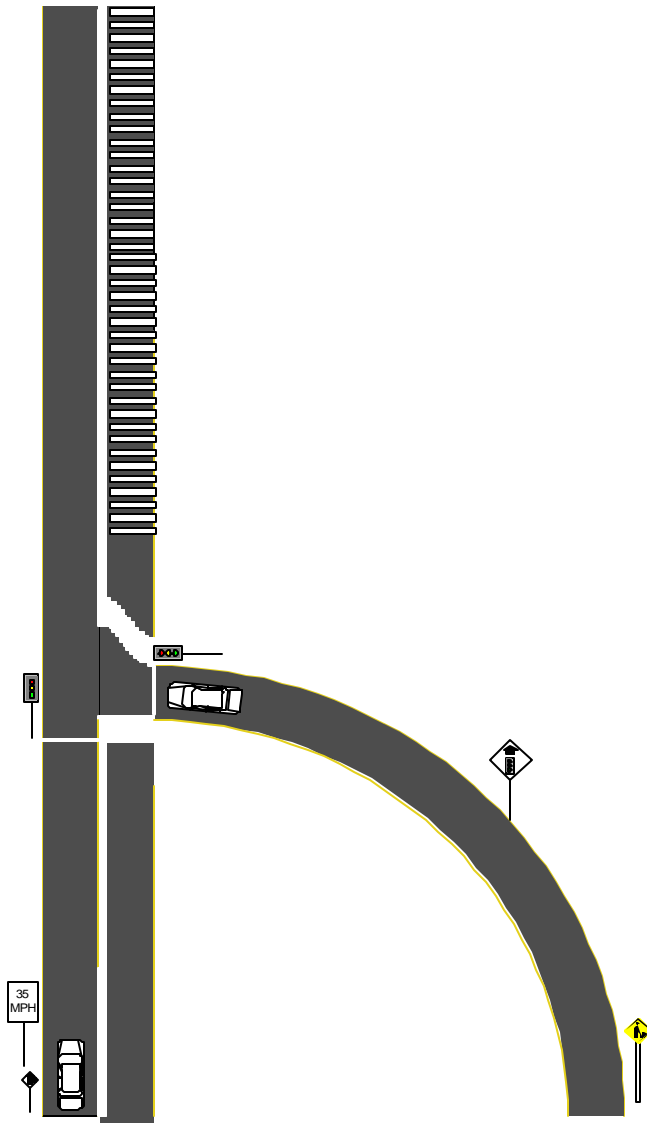
Figure 2: Improved entrance to work zone using merge lane and yield signs

Figure 3 shows another improved configuration, where the road approaches perpendicularly. There is a stop sign and stop bar some distance from the main line that will allow tractor-trailer right turns. The drivers need to turn body, head, and eyes only 90 degrees, making it much easier to check for approaching mainline traffic than in the original configuration. The mainline speed limit is 35 mph (56 km/h). This essentially eliminates the ramp, and will only work if there is sufficient visibility and also a sufficient number of gaps to allow vehicles to enter the roadway.



**Figure 3: Improved entrance onto work zone with perpendicular approach and stop sign**

A third improved entrance configuration using traffic Signal Ahead sign and traffic signal is shown in Figure 4. Again the side road approaches at a 90 degree angle, which makes it much easier to check for mainline traffic. The stop bar is set back to accommodate turns by large trucks. The traffic signal greatly reduces perceptual requirements for entering drivers. The mainline speed limit is 35 mph (56 km/h). Traffic control is accomplished with a signal, which will reduce the maximum volume possible on the main line.

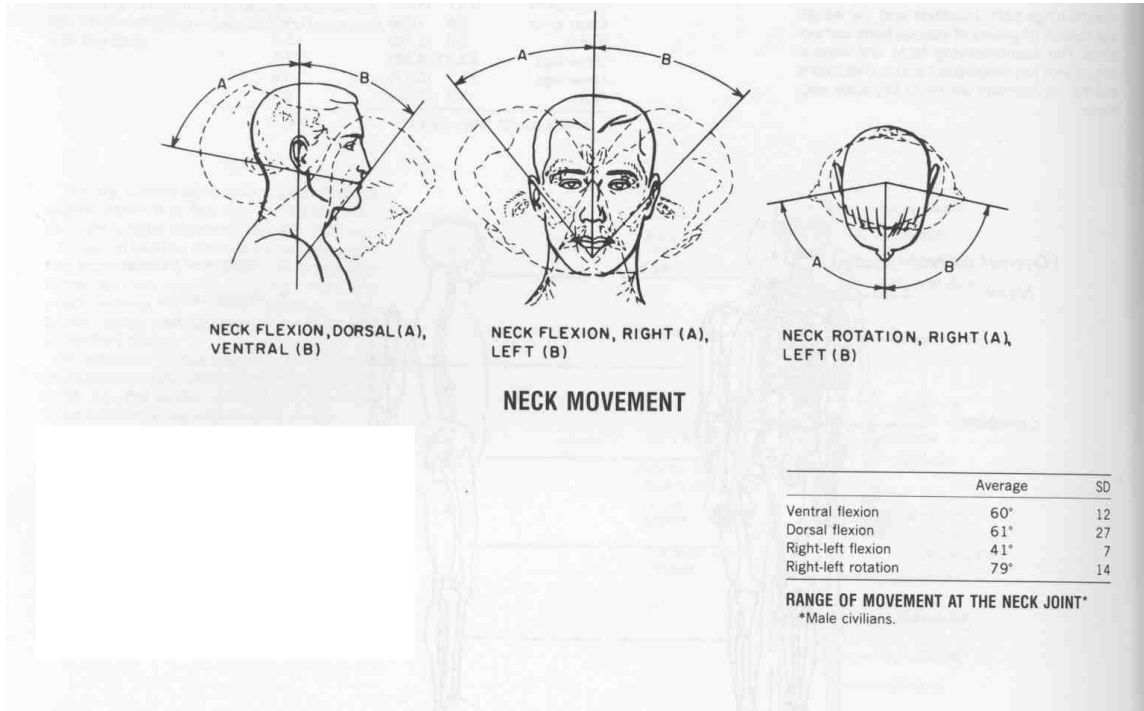


**Figure 4: Improved entrance onto work zone using perpendicular approach and traffic signal**

Figure 5 and Table 5 are from the *Human Factors Design Handbook* [1] illustrate the limits of human neck motion and visual field and show why the original entrance configuration made it so difficult for drivers to view oncoming traffic.



It is important to design entrances onto work zones so that drivers can easily see mainline traffic, either with a 90 degree approach angle or a parallel merge lane sufficient to accommodate two tractor-trailers.



**Figure 5: Range of neck movement, from the *Human Factors Design Handbook* [3 , p. 550]**

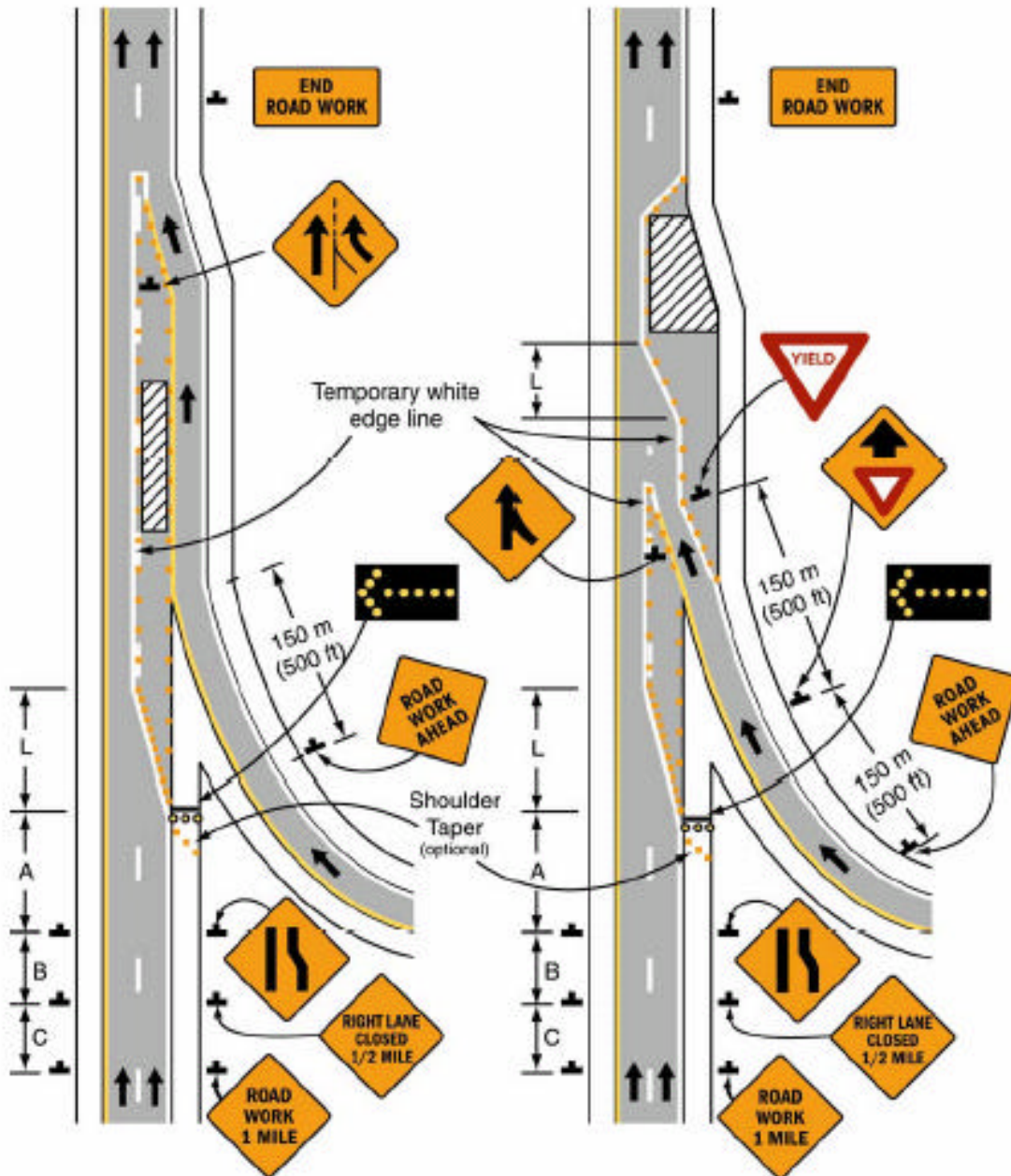
**Table 5: Limits of the visual field under various kinds of restraint, from the *Human Factors Design Handbook* [3]**

Movement Permitted	Type of Field and Factors Limiting Field	Horizontal Limits		Vertical Limits	
		Temporal Ambinocular Field (Each Side)	Nasal Binocular Field (Each Side)	Field Angle Up	Field Angle Down
Moderate movements of head and eyes assumed as:	Range of fixation	60°		45°	
Eyes: 15° right or left	Eye deviation (assumed)	15°	15°	15°	15°
15° up or down	Peripheral field from point of fixation	95°	(45°)	46°	67°
Head: 45° right or left	Net peripheral field from central fixation	110°	60°	61°	82°
30° up or down	Head rotation (assumed)	45°	45°	30°	30°
	Total peripheral field (from central body line)	155°	105°	91°	112°
Head fixed					
Eyes fixed (central position with respect to head)	Field of peripheral vision (central fixation)	95°	60°	46°	67°
Head fixed	Limits of eye deviation				
Eye maximum deviation	(= range of fixation)	74°	55°	48°	66°
	Peripheral field (from point of fixation)	91°	Approx(5°)	18°	16°
	Total peripheral field (from central head line)	165°	60°	66°	82°
Head maximum movement	Limits of head motion	60°		45°	
Eyes fixed (central with respect to head)	(= range of fixation)	72°	72°	80°	90°
	Peripheral field (from point of fixation)	95°	60°	46°	67°
	Total peripheral field (from central body line)	167°	132°	126°	157°
Maximum movement of head and eyes	Limits of head motion	72°	72°	80°	90°
	Maximum eye deviation	74°	55°	48°	66°
	Range of fixation (from central body line)	146°	127°	128°	156°
	Peripheral field (from point of fixation)	91°	Approx (5°)	18°	16°
	Total peripheral field (from central body line)	237°	132°	146°	172°

J. W. Wulfeck, et al., *Vision in Military Aviation*, WADC Technical Report 58-399, 1958.

**THE LIMITS OF THE VISUAL FIELD UNDER VARIOUS KINDS OF RESTRAINT**

The following figure shows a work zone design when there is work in the vicinity of an entrance ramp.



**Figure 6: Work in vicinity of entrance ramp (Adapted from [4] p.6-223)**

Notes for Figure 6: [4]

Guidance: An acceleration lane of sufficient length should be provided whenever possible as shown on the left diagram.

Standard: For the information shown on the right diagram of the typical application, where inadequate acceleration distance exists for the temporary entrance, the YIELD sign shall be replaced with STOP signs (one on each side of the approach).

Guidance: When used, the YIELD or STOP sign should be located so that ramp motor vehicle traffic has adequate sight distance of oncoming mainline motor vehicle traffic to select a safe gap in the mainline motor vehicle traffic flow. Also, a longer acceleration lane should be provided beyond the sign to reduce the gap size needed. If insufficient gaps are available, consideration should be given to closing the ramp. [Note by report authors: criteria for closing ramps will be investigated in Phase II of this research project when the traffic simulation program is developed.]

Where STOP signs are used, a temporary stop line should be placed across the ramp at the desired stop location. The right lane should be closed sufficiently in advance to stabilize motor vehicle traffic flow before encountering the merge. The mainline merging taper with the arrow panel at its starting point should be located sufficiently in advance so that the arrow panel is not confusing to drivers on the entrance ramp, and so that the mainline merging motor vehicle traffic from the lane closure has the opportunity to stabilize before encountering the motor vehicle traffic emerging from the ramp. If the ramp curves sharply to the right, warning signs with Advisory Speed Limits located in advance of the entrance terminal should be placed in pairs (one on each side of the ramp).

Option: A type B high-intensity warning flasher with a red lens may be placed above the STOP sign. Where the acceleration distance is significantly reduced, a supplemental plaque may be placed below the YIELD AHEAD sign reading NO MERGE AREA.

Figure 7 shows a partial exit ramp closure. Notes for Figure 29 [4]: “Guidance: Truck off-tracking should be considered when determining whether the minimum lane width of 3 m (10 ft) is adequate.”

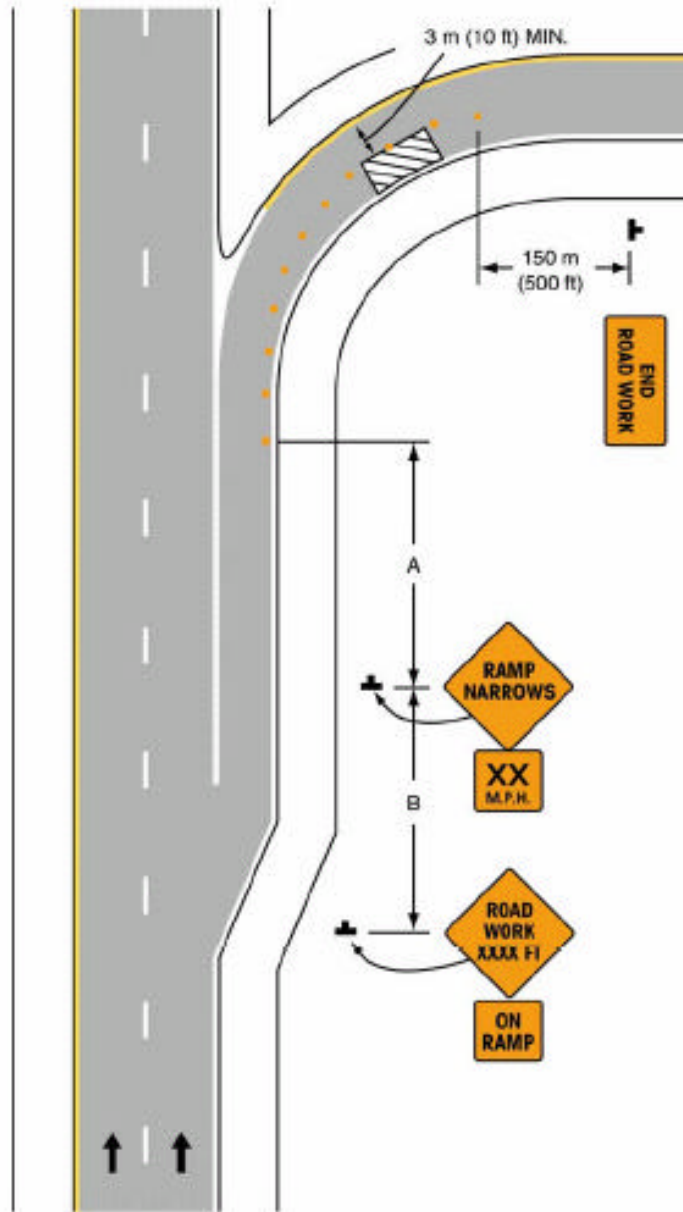


Figure 7: Partial Exit ramp closure (Adapted from [43] p.6-221)

### 2.1.1. Basis for recommendation

Due to limitations in neck movement that restrict the visual field of the driver it is important to design entrances onto work zones so that drivers can easily see mainline traffic, either with a 90-degree approach angle or a parallel merge lane sufficient to accommodate two tractor-trailers.

### 2.1.2. Implementation

Implement the 90-degree approach angle to design entrances onto work zones wherever it is not possible to create a sufficiently long entrance ramp.

### ***2.1.3. Estimated costs***

The estimated cost is not known.

### ***2.1.4. Benefits and risks***

Provides better visibility of mainline traffic especially for older drivers due to restricted neck movement.

## **2.2. Ramp Closures and Metering**

According to Section 640-4 of the TEM ramp closures in urban work zones are to be based on two factors, volume considerations and geometric considerations. While such closures could significantly improve traffic flow, there must always be detours provided. The geometric considerations are also to be taken into account before a ramp can be closed.

Different responses were received to the question concerning what criteria are used to determine entrance ramp closures in work zones that was included in the Work Zone Best Practices survey [5]. Four of the seven states that responded specifically stated that they do not allow ramp closures unless there are no other alternatives. Three of these states also indicate that if the ramps must be closed, they are only closed during off-peak periods. Thus while the closure of entrance ramps can reduce the volume of traffic through the work zone it inconveniences the traveler. And during peak hours ramp closures may lead to unacceptable traffic congestion in other routes and designated detours. Therefore it is necessary to develop a methodology that can be used to determine when and if a ramp could be closed in order to expedite work zone operations. No such methodology has been found in the literature. A methodology for ramp closures will be developed with the simulation program and evaluation in Phase II of this research project.

Algorithms or programs to specific to work zones to determine when to close ramps did not turn up in the literature search. It is expected that the software to be developed in Phase II of this study will help fill that need.

### ***2.2.1. Basis for Recommendation***

Ramp closures are based on two factors, volume considerations and geometric considerations. Closure of the entrance ramps can reduce the volume of traffic through work zone. The reduced volume in the work zone provides better traffic flow.

### ***2.2.2. Implementation***

The most important consideration in ramp closing is providing detours for the closed ramp. Ramp metering may be considered as an alternative to ramp closure, depending on the capacity situation in the work zone; metering may save the costs of marking and implementing detours. Metering is discussed in the next section.

### **2.2.3. Estimated Cost**

The cost is not known at the moment.

### **2.2.4. Benefits and Risks**

Ramp closures reduce the volume of traffic through the work zone, and they provide improved traffic flow in the work zone. Ramp closures during peak hours may lead to unacceptable traffic congestion in other routes and designated detours, however.

### **2.2.5. Other Considerations**

In the Work Zone Best Practices Survey and other inquiries conducted for this project four of the seven responding states stated that they do not allow ramp closures unless there are no other alternatives. Three of these states indicated that if the ramp has to be closed, they are closed only during off-peak periods. The benefits and drawbacks of ramp closures will be determined in the next phase of this study. A study should be performed to evaluate ramp metering equipment.

## **2.3. Ramp Metering**

One approach is to use ramp meters for traffic control purposes. Wireless communication and video image processing technology can be used to pass on traffic data to a control center from where ramp closing/opening decisions are transmitted to the ramp meters depending on traffic volume. The literature search did not turn up any references to ramp metering specific to their application to work zones; however some information on the topic of static ramp metering can give some idea of the benefits and limitations of the devices.

Algorithms or programs to specific to work zones to determine when to meter ramps did not turn up in the literature search. It is expected that the software to be developed in Phase II of this study will help fill this need.

Studies have been conducted on permanent ramp meters and their impact on traffic flow by the DOTs of Minnesota, Utah, and Michigan, with the evaluation done by Minnesota being the most extensive one. These studies have analyzed different factors that influence traffic flow on freeways and commuter roads in relation to ramps. These analyses include travel time comparisons on the freeway and the ramps, travel reliability on the freeway and the ramps, traffic variability and volume on the freeway and ramps. The studies also include safety statistics, benefit/cost comparisons, emission comparisons and traveler surveys.

The Minnesota DOT's Twin Cities Ramp Meter Evaluation study of 2001 emphasizes the effectiveness of ramp meter usage by comparing "Metered" and "Not Metered" traffic situations along some chosen corridors [7]. These two situations are compared in their totality with respect to all the aspects mentioned above. Their results prove that ramp meter usage is beneficial to traffic stabilization. Specific travel time statistics showed that freeway travel time was 22% less than before and freeway speeds were 14% greater with the use of ramp meters [7]. The study also included safety statistics with respect to ramp meter usage and it was found that for the

period of evaluation the number of crashes that occurred in the absence of ramp meters was 82% higher than when the ramp meters were present. This value was 26% higher than the number that was obtained from a seasonally adjusted rate (arrived at from a study of historical crash data for equivalent periods) [7]. The benefit/cost ratio in this study was found to be 5.1:1, thus proving that the implementation of ramp meters was economically viable for Minnesota [7]. All these results favorable to ramp meters were also substantiated with the help of qualitative data obtained from focus groups and traveler surveys, though about 65% of travelers felt that the ramp metering technique had to be modified [7].

Metering has a limited effect, however. Minnesota has installed ramp meters on Highway 10 in suburban Minneapolis and measured their effect on ordinary (non work zone) traffic [8]. The Minnesota DOT reports that with the meters there was an improvement of about 5% in highway capacity over pre-metered conditions, which was sufficient to increase the average speeds during the two hours of peak congestion from 20-30 mph (32-48 km/h) to 50 mph (80 km/h). The average wait on the on-ramps is about 2 minutes. So it is clear that metering can increase the capacity of a road and this would be expected to carry over to work zone areas with entrance ramps as well. However this increase is limited to about 5% of capacity; if the work zone would be flooded to more than 5-10% more than the maximum capacity of the work zone, ramp metering may not be enough to eliminate congestion. Minnesota has further tinkered with its ramp metering algorithm, called “stratified zone metering” [9], to reduce the waits at entrance ramps, which reduces the overall volume somewhat but is clearly preferred by road users who had previously experienced overly long delays. In Minnesota’s stratified zone metering algorithm, the maximum wait is set at 4 minutes, beyond which the meters are turned off.

The study conducted by the Utah DOT involves a simulation of the metered area to compare the effectiveness of three coordinated ramp metering algorithms against a local responsive ramp metering technique and a no metering situation [10] Though the comparison results were not definitive with regard to the best ramp-metering algorithm to be used, the simulation proved that ramp meter usage reduced travel time and improved level of service. The study also showed that ramp metering could be used to reduce the extent of post-accident congestion in the freeway.

The study conducted by the Michigan DOT analyzed the impacts of an Intelligent Transportation System (ITS) on congestion in a specific corridor in Detroit.[11] Hence, this study encompassed all the aspects of Detroit’s ITS systems such as Internet based pre-trip information, highway advisory radio (HAR), ramp metering, and changeable message signs (CMS). Modeling and comparison of four alternatives was done – No ITS, Ramp metering (only), CMS (only) and existing ITS. Results of this analysis with regard to ramp metering in specific are that ramp metering is valuable in reducing travel time and improving the performance of the region when a major incident has occurred. But the study also states that the usefulness of ramp metering could be questioned in the absence of incidents or during the occurrence of minor incidents.

In an ongoing effort to smooth traffic flow; the Washington State Department of transportation (WSDOT) has sponsored research since 1994 to improve its ramp metering algorithm. After lengthy development and testing, a new algorithm has proved so successful that



WSDOT is using it in the greater Seattle area to meter more than 100 ramps on Interstates 5, 405, and 90, and on State Route 520 [12].

Currently, only Columbus, among Ohio's cities, has demonstrated a general political acceptance of ramp metering, while other major Ohio cities have rejected this function [14].

The ODOT Policy on traffic management in work zones interstate and other freeways [15] states that ramp metering may be warranted when additional traffic capacity is needed for short term.

The measures of effectiveness for ramp metering are spare freeway capacity, total delay at the ramps, queue length, and average speed on the freeway at the merge areas. Spare freeway capacity is the number of vehicles demanding access through on-ramps that can be served by the freeway. The spare freeway capacity is the difference between the capacity of the freeway at that section and the demand volume that is entering the freeway and indicates the additional number of vehicles that can be served by the freeway. The demand on the ramp is obtained from the ramp detector, which gives the volume for a particular interval of time [6].

The efficiency of the freeway also is determined by the amount of delay experienced by the vehicle waiting for an access to the freeway. This delay would be the same as the control delay experienced at intersections of surface streets. When ramp metering is in operation, then it only allows one vehicle per every green given by the signal. Ramp metering regulates the demand that is seeking an entry and there by stabilizes flow of traffic on the freeway. The ramp metering policy is activated when the demand exceeds the spare capacity on the freeway endangering smooth flow and creating bottleneck conditions [6].

Ramp queue length gives a measure of the effectiveness of a signal and the congested conditions on the road. It also provides a measure of storage demand, which can be compared, to available storage and then spillage onto arterials can be monitored [6].

### ***2.3.1. Basis for recommendation***

Ramp meters aid in regulating traffic flow from the entrance ramp into the mainline and can increase the capacity of the mainline by as much as 5%.

### ***2.3.2. Implementation***

Install the ramp meters and the associated loop detector or traffic sensor based on the measures of effectiveness at the work zone vicinity, such as traffic volume and average speed on the mainline and queue lengths and times on ramps. The metering rate should be based on the prevailing traffic conditions (for example: traffic volume) at the ramp. When implemented ramp metering should be accompanied with appropriate signs to guide the traffic. A more detailed study of ramp metering is proposed for the next phase of this research project.

### **2.3.3. Estimated costs**

The cost of installing ramp meters in the work zones can be approximated with the aid of the costs specified in the ramp meter evaluations performed by the other State DOTs. The Minnesota DOT estimated a total ramp meter installation cost of \$7,877,275 for the entire state. This cost includes operational costs, maintenance costs, personnel costs, management costs and R & D costs. Installing a single permanent ramp meter costs approximately \$50,000 [7]. A portable ramp meter system sold by ITS, Inc. costs in the \$3000-\$4000 range.

### **2.3.4. Benefits and risks**

Use of ramp meters for traffic flow stabilization within a work zone is beneficial in a number of ways. The traffic within the work zone is regulated by lower traffic speed variability and lower travel time thus increasing travel time reliability while the traffic on the ramp experiences greater speed variability and higher travel time with decreasing travel time reliability when ramp meters are used. However, the benefits of the former outweigh the problems of the latter. Minnesota estimated the benefit to cost ratio at about 5.1:1. The only criteria category found to be worsened by ramp metering was fuel consumption, with an annual increase of 5.5 million gallons of fuel consumed [12].

## **2.4. Late Merge and Indiana Lane Merge System**

An innovation used in Pennsylvania is “late merge” [16]. This is a strategy to reduce queue lengths by placing signs in advance of the taper that read “Use both lanes to merge” and then signs at the taper that read “Merge here Take your turn”. The idea is to have traffic merge at the taper rather than well in advance. Response by motorists has been positive. Queue lengths have been reduced, but not as much as possible since truckers still tend to block both lanes to preserve their position in line. It will also take time for drivers to fully understand and accept the concept. Also, nothing is said about the impact on travel time delay, which is most likely unchanged or only very slightly reduced.

There is a safety concern with late merge, namely that during low volume off-peak times it may be more difficult for drivers to decide who has the right of way, i.e. whose turn it is to merge [17]. This problem can be mitigated somewhat by advance signs that indicate which lane is closed that allow motorists to merge into the open lane in advance when traffic is low, though such signs can also counter the late merge concept during congested times because some drivers will be tempted to merge early.

A different idea has been tried in Indiana, called the Indiana Lane Merge System (ILMS). This is a dynamic early merge system, with a dynamic no passing zone [17]. It has also been described as a dynamic late merge [18]. In addition to the usual signs in advance of a work zone there are signs that read “Do Not Pass When Flashing” signs with strobe lights that are activated by queue detectors that detect when traffic has become congested downstream. The goal is to get drivers to merge into the open lane as soon as possible, and possibly ticket those that try to zip ahead in the closed lane. The system reduces the number of forced merges and smoothes traffic flow, but at a cost of 5-6% decreased capacity [19]. Though another report says that capacity increases by about 5% (from 1460 passenger car per hour (pcph) to 1540 pcph) with forced merges reduced by 98% (from 20/hour to 0.4/hour) [18]. Guidelines for setting up a

system are published, and include determination of a congested distance based on queue sizes and traffic densities. It is recommended that the system be applied where there are no interchanges in the immediate vicinity upstream of the taper and where the congested distance or queue length is expected to be longer than 3 km. Parameters to set include number and placement of signs, threshold detector occupancy, an aggregation period to prevent too great a sensitivity to very short fluctuations or platoons in traffic, and a minimum activation time for the signs [20].

McCoy and Pesti [17] advocate a dynamic late merge concept to try to use the best of both approaches. In essence there are signs that direct users to “use both lanes to merge” and to “merge here take your turn” that are activated when congestion occurs and which turn off when congestion ends. This addresses the safety concern the authors brought up with the late merge signage, namely that during low volume off-peak times it may be more difficult for drivers to decide who has the right of way, i.e. whose turn it is to merge. ODOT should consider implementing some form of late merge to reduce queue lengths and overall time delays. Past ODOT investigations of the late merge system indicated results were not good in Ohio, however.

For these new merge ideas to work best, the section of road ahead of the work zone should not have any entrance or exit ramps.

## **2.5. Signing Materials**

The specifications for different types of sign sheeting materials to be used for temporary traffic control devices are outlined in the OMUTCD, the TEM and the CMS.

OMUTCD Section 6F.02 specifies that “warning signs used in temporary traffic control zones shall have a black legend on orange background” [4, p. 6-38]. Due to the additional margin of safety provided owing to its higher conspicuity, fluorescent red-orange or fluorescent yellow-orange is deemed acceptable for use instead of the color orange (Section 7A-3). The literature shows that fluorescent orange sheeting material is more conspicuous than the standard non-fluorescent orange (Burns et al. [21], Collins [22]). Hawkins et al. [23] found that the fluorescent orange products had greater recognition distances and color perception accuracy than those of non-fluorescent orange products. Through a national survey conducted to evaluate the experiences, practices, and uses that other state transportation agencies have had with fluorescent signs, Hawkins et al. found that 83% of the respondents believed fluorescent orange signs were worth the additional cost. In another study Fontaine and Hawkins [24] found that fluorescent material, which is made of prismatic reflective sheeting, appeared brighter than other beaded reflective materials.

Research also shows that the nighttime conspicuity of fluorescent orange signs is superior to signs made of other fluorescent sheeting materials (Zwahlen and Schnell [25]). Hummer and Scheffler [26] conducted a study to investigate if this increased conspicuity led to improved operational performance in work zone activities. They found that TCDs with fluorescent orange sheeting materials caused some positive changes in driver behavior in terms of lowered traffic conflicts and decreased speed variances in the work zones. These results advocate the use of fluorescent orange sheeting material for work zone TCDs to ensure maximum conspicuity. This is not sufficiently emphasized in the existing ODOT work zone guidelines and should be

modified appropriately. Larger and simpler signs with retroreflective materials can also help reduce road accidents [27]. Thus the existing guidelines have to be modified to indicate that fluorescent orange sheeting materials are ‘preferable’ for all TCDs used in work zones.

The CMS Item 614.03 specifies that Type G (ASTM D 4956 Type III or IV) or Type H (ASTM D 4956 Type VII or VIII) reflective sheeting (complying with Items 730.19 and 730.192 respectively) be used for faces of construction signs, barricades, vertical panels, object markers, and stripes on glare screen panels.

Zwahlen et al. [28] found that Type VII reflective sheeting is best for use when increased nighttime legibility is required from a longer distance whereas Type IX reflective sheeting is best when higher legibility is required from a shorter distance. We recommend the use of Type IX fluorescent sheeting materials in the ODOT specifications because it is the most conspicuous material at near distances where drivers will be navigating through the work zone.

The daytime legibility of a fluorescent sheeting material depends on the chromaticity coordinates of the material. However retroreflectivity at nighttime is dependent on the angularity. The current ODOT CMS stipulates only the observation and entrance angles for fluorescent sheeting used for TCDs. The photometric requirements for fluorescent orange sheeting specified in CMS Item 730.192 are given in the table below.

**Table 6: Photometric requirements for Type IX fluorescent orange sheeting**

Observation Angle (degree)	Entrance Angle (degree)	Minimum Coefficient of Retroreflection cd/ft <sup>2</sup> or cd/lx·m <sup>2</sup>
0.2	-4	200
0.2	+30	120
0.5	-4	80
0.5	+30	50

Brich [29] conducted a study to evaluate the appropriateness of the retroreflective sign sheeting specification for fluorescent orange construction and maintenance signs used by the Virginia DOT. Virginia DOT's specifications are a 50-degree entrance angle with observation angles of 0.2 and 0.5 degrees (observation angles are similar to those of ODOT). By evaluating 1865 fluorescent traffic signs in 232 work zones Brich made several recommendations that can help improve sign effectiveness. It was found that reduced entrance angles will allow a factor of safety for misaligned signs or signs with placements that are less than ideal. Brich recommends changing Virginia DOT's entrance angle specification to 40 degrees to allow for this. ODOT's specification for the entrance angle appears satisfactory in this regard. He also recommends that the observation angle should be increased to 1.0 degree to better ensure that the signs will remain visible to a greater range of vehicle types (passenger cars, SUVs, minivans, and tractor-trailers). Brich highlights that four angles are required to describe a prismatic lens retroreflective material: entrance, observation, orientation, and rotation angles. Due to the asymmetrical nature of prismatic retroreflective materials, orientation and rotation angles too affect performance. Thus including specifications for orientation and rotation angles will help increase the effectiveness of the retroreflective traffic signs used in work zones. Therefore ODOT should consider modifying the specification for fluorescent orange sheeting used in work zone to include appropriate orientation and rotation angles.

### ***2.5.1. Basis for Recommendation***

Type IX fluorescent sheeting materials are the most conspicuous materials at near distances. Type IX sheeting material is also the best recognized sheeting material by the older drivers during nighttime traffic conditions. The use of fluorescent orange sheeting materials for traffic signs is beneficial from a human factors perspective because it would enable better legibility and conspicuity of traffic sign materials. Modifying the sheeting material specifications to include the orientation and rotation angles will ensure well aligned and erected signs that could be easily noticed by drivers.

### ***2.5.2. Implementation***

The existing guidelines have to be modified to indicate that fluorescent orange signs are preferable for all TCDs used in work zones.

### ***2.5.3. Estimated Cost***

The cost involved in modifying the standards can be considered not very significant compared to the cost of introducing Type IX materials for traffic signs where applicable. The cost of Type IX sheeting material is about 3.7 times that of Type III High Intensity Grade sheeting material. The additional cost is offset by the improved performance and greater durability of these Type IX materials. Type VIII materials may provide some of the same benefits at a slightly lower cost than Type IX.

### ***2.5.4. Benefits and Risks***

The use of Type IX sheeting material will provide higher legibility from shorter distances in work zone during nighttime driving conditions.

### ***2.5.5. Evaluation and Research***

Further research may be necessary to determine the appropriate specifications for the orientation and rotation angles for Ohio traffic signs.

## **2.6. Portable Changeable Message Signs (PCMSs)**

Section 605-9 of the TEM and section 6F.52 of the OMUTCD outline the standards with respect to the design and application of Portable Changeable Message Signs (PCMSs). The main components of a PCMS, also known as a variable message sign, include the message sign panel, control systems, power source, and mounting and transporting equipment.

The message sign panel is to be designed with reverse colors for the letters and background (orange letters on black background) while otherwise complying with the general guidelines for designing work zone signs. Each message is to contain at most two displays with up to three lines of eight characters per line. The factors to be considered in designing PCMSs to ensure that a clear and distinct message is always communicated to the drivers are also outlined in the specific sections of the documents listed.

The primary purpose of these devices is to advise drivers of unexpected traffic and routing conditions that occur due to work zone operations. Typical applications of these devices include:

1. Where the speed of motor vehicle traffic is expected to drop substantially
2. Where significant queuing and delays are expected
3. Where adverse environmental conditions are present
4. Where there are changes in alignment or surface conditions
5. Where advance notice of ramp, lane or roadway closures is needed
6. Where crash or incident management is needed
7. Where changes in the road user pattern occur

Spacing between PCMSs when multiple signs are used is specified in table 697-11 of the TEM [96, p. 6-201] and is shown in Table 7 below. The guidelines also outline the procedure to be followed in the placement and erection of PCMSs to ensure maximum legibility to drivers.

**Table 7: Suggested PCMS spacing [96, p. 6-201]**

Road Type	Distance Between Signs – feet (meters)		
	A*	B**	C***
Urban (low speed, e.g., < 40 mph (64 km/h))	100 (61)	100 (61)	100 (61)
Urban (high speed, e.g., > 45 mph (72 km/h))	350 (107)	350 (107)	350 (107)
Rural	500 (152)	500 (152)	500 (152)
Expressway/Freeway	1000 (305)	1500 (488)	2640 (792)

\* The “A” dimension is for the sign nearest the transition or point of restriction.

\*\* The “B” dimension is for the next sign upstream of the transition or restriction.

\*\*\* The “C” dimension is for the first sign (in a three-sign series) that the driver encounters in a temporary traffic control zone.

PCMSs can also be used very effectively to improve traffic flow and reduce congestion in work zone areas in several other situations. Using PCMSs to provide real time driver delay and alternate route information (in addition to using for route diversion) ahead of a work zone will ensure efficient flow of work zone traffic and minimize delay for motorists as some of them may choose the alternate route(s) suggested. This also ensures “customer” or motorist happiness.

Walton et al. [30] conducted a study to evaluate the usage of changeable message signs in Kentucky and develop recommendations for the management and use of these devices to improve traffic flow. As part of the study they also reviewed policies, articles, and reports about the use and applications of PCMSs pertaining to 12 states. In addition the MUTCD guidelines and the American Traffic Safety Services Association (ATSSA) policies were also reviewed. Based on this extensive review and the statewide study they recommend that PCMSs can be effectively used to provide real-time information and also to inform drivers of detours or alternate routes. Steinke et al. [31] also report on the extensive use of PCMSs to re-route traffic and provide alternate route information in European highways. These applications of PCMS can contribute to improving traffic flow in work zone areas are not included in the recommended list of applications in ODOT work zone guidelines. Therefore ODOT should consider including these as possible applications for PCMSs in order to increase the efficiency of traffic flow.

It is worth noting that not all countries embrace the idea of rerouting traffic. In Switzerland, some traffic safety experts do not like to see traffic diverted from freeways onto urban or rural two-lane roads. This is because the geometry and characteristics of such roads leads to substantially more accidents per vehicle mile compared to freeways. These Swiss traffic safety experts would rather have traffic sit and wait but be safer.

In addition to providing alternate route information and notification, PCMSs can be used in conjunction with microwave radar to provide drivers with the time to travel through the work zone. Such a real-time travel time prediction system has been created by Prahlad Pant of the University of Cincinnati and was evaluated on a work site in I275 in Dayton by Zwahlen and Russ [32, 33]. It was found that the system was generally accurate in presenting the time to travel to the end of the work zone. The system was also well received by motorists, particularly

those who used that freeway regularly. Such a system is recommended for use in urban work zones subject to bad congestion.

In addition to the above, PCMSs can also be used to provide information about the road conditions as they change due to weather. Using PCMSs to provide drivers information on dry/wet, slippery and, inclement weather can be useful in assuring the highest possible safety of drivers and construction workers. This is another application for PCMSs that should be considered for inclusion in the ODOT guidelines.

The effectiveness of PCMSs can further be improved by combining them with radar units for speed control. Garber and Patel [34] conducted a study to evaluate the effectiveness of using PCMSs in controlling vehicle speeds in work zones. The changeable message signs used were the standard message display board (American Signal Company, CMS-T300), but with a radar unit attached at the side. Four different radar-activated displays were used to warn drivers that their speed exceeded the maximum safe speed. If the radar is activated and detects a speed higher than a preset threshold speed, then the message display was programmed to flash a particular message.

They experimented with four different types of messages in seven interstate work zones in Virginia. At  $\alpha = 0.05$  significance level they found all the message signs to be effective in significantly reducing the average speeds of those vehicles traveling at 59 mph (95 km/h) or faster in a 55 mph (88 km/h) work zone when compared to the results when using other MUTCD signing only. The messages were rated according to their level of effectiveness in the order (1) You are Speeding Slow Down, (2) High Speed Slow Down, (3) Reduce Speed in Work Zone and, (4) Excessive Speed Slow Down. The findings of this study indicate that PCMS can be very effectively used for speed control in work zones when combined with radar units. The usefulness of these units can be further improved by using photo-radar techniques [34]. This will allow a more personalized message to be displayed, for instance one including the driver's license plate number. However the message may also be considered more threatening by drivers due to visual information possibly being retained by the processing unit. Displaying personalized speeding messages is another application of PCMSs that can be considered for use in high-speed work zones and for possible inclusion in the ODOT guidelines.

### ***2.6.1. Basis for Recommendations***

Using the PCMS for the applications indicated above is advantageous from a traffic flow perspective as they will help ensure efficient flow of work zone traffic and minimize delay for motorists as some of them may choose the alternate route(s) suggested. This also ensures "customer" or motorist happiness. Providing inclement weather information using PCMS is beneficial from a human factors perspective as driver safety is improved. Using PCMSs to display personalized speeding messages may be a more effective means of controlling speed in work zones.



### 2.6.2. Implementation

The applications recommended in the Draft Report are not included in the current list of potential uses for PCMS that is included in the Ohio work zone guidelines. Therefore the existing guidelines would have to be modified to cover these areas as well.

### 2.6.3. Estimated Cost

No incremental costs will be involved if the existing PCMS used. However, if implementation requires the purchase of additional PCMS, that cost will have to be considered. The unit price of portable changeable message sign is estimated as \$6,000.

### 2.6.4. Benefits and Risks

The major benefit that can be expected from extending the use of PCMS to cover the suggested applications is better traffic flow through work zones. Using the PCMSs to display inclement weather information would also lead to improved safety in work zone areas.

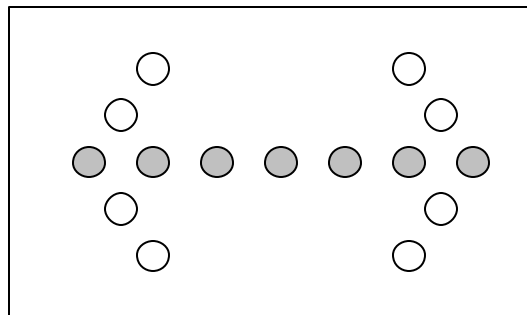
### 2.6.5. Other Considerations

One important consideration that has to be decided is how these messages will be conveyed on a PCMS without causing confusion, the length of message to avoid information overload, and the spacing between such PCMSs.

## 2.7. Arrow Panels

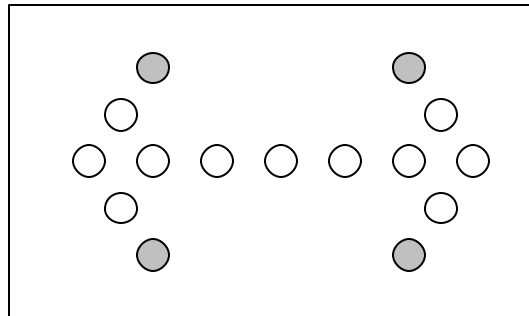
The specifications for arrow panels used in work zones are outlined in OMUTCD section 6F.53, TEM section 605-10 and the Standard Construction Drawing SCD MT-35.10. The design and application requirements of flashing arrow panels used in work zones are outlined in these documents.

The different modes in which the arrow panels are to be used are illustrated in Section Figure 6F-3 of the OMUTCD. According to this the arrow panel may be used in a horizontal flashing bar in the caution mode (Figure 8).



**Figure 8: Arrow panel display for the ‘Caution’ mode as given in present ODOT guidelines. (Adapted from OMUTCD Figure 6F-3)**

However using the arrow panel as a flashing bar in the caution mode may lead to driver confusion [37]. Motorists may misunderstand it as a faulty arrow panel whose arrowhead lights are not operating. Therefore to avoid this situation, the use of the four outer flashing lights of the arrow panel for the caution mode is displayed in the revision to the MUTCD [35]. This is also demonstrated in a video on the use of advanced warning (flashing) arrow panels produced by the FHWA [37]. The modified arrow panel display for the caution mode is shown in Figure 9. However this configuration has the disadvantage that if one of the bulbs burns out the display is seriously compromised. The flashing yellow line is better, if a flashing caution mode is really desired. Both modes are now also displayed in the 2003 OMUTCD.



**Figure 9: Arrow panel display for the ‘Caution’ mode as given in MUTCD and FHWA video (layout for Type C panel shown)**

However, the best option may be to simply turn the signs off if there is no lane closure. This saves energy and avoids possible driver distraction or confusion with a flashing arrow indicating a lane closure. ODOT should consider minimizing the use of flashing caution modes for arrow signs, simply leaving signs off when no lanes are closed.

ODOT specifications also recommend approximately 3L (L = taper length) distance between arrow panel signs when more than one are used. However the FHWA video [37] recommends that this distance should be at least three times the taper length (L) given in the MUTCD and never less than 1000 ft (305 m). The 3L distance specified in Section 6C.19 of the OMUTCD can be much lower than 1000 ft (305 m) depending on the prevailing speed (S) and road width (W): taper length  $L = WS$  when posted speed  $\geq 45$  mph (72 km/h) or

$L = \frac{WS^2}{60}$  when posted speed  $\leq 40$  mph (64 km/h)]. A lower spacing can result in driver confusion and the arrow panels may not be effective in conveying the message intended. Thus a minimum spacing of 1000 ft (305 m) between arrow signs should be considered for use in Ohio.

The above paragraph was written in 2002 while the OMUTCD was being revised. In the current edition, there is guidance added that when speeds are greater than or equal to 50 mph, the minimum taper length should be 300 ft (90 m) minimum, which would make 3L at least 900 ft (270 m), which is probably adequate.

### ***2.7.1. Basis for Recommendation***

Low spacing between arrow panels may not be effective in conveying the intended message as it can lead to confusion. A higher spacing that conveys the message clearly at appropriate intervals is necessary if one considers the human factors perspective.

### ***2.7.2. Implementation***

We originally recommended that the then existing 1999 guidelines would have to be modified to indicate that a minimum spacing of 1000ft (305 m) is required on freeways. A note on guidance in the OMUTCD section on tapers (6C.19) has already been added indicating a minimum taper length L of 300 ft where speeds are greater than or equal to 50 mph, which is probably adequate as it makes the 3L separation distance between arrow panels at least 900 ft (270 m). Including a similar note with Figure 6H-37 would be helpful.

### ***2.7.3. Estimated Cost***

This recommendation would not involve any extra cost as no additional arrow panels will be required.

### ***2.7.4. Benefits and Risks***

Using the arrow panels in the recommended mode will reduce the confusion resulted from the lower spacing between the panels. Also fewer arrow panels will be required for work zone operations.

## **2.8. Drums**

The specifications pertaining to the use of drums in work zone operations are outlined in sections 6F.59 in the OMUTD, section 605-11.4 in the TEM, and several SCDs. Drums can be used to delineate an unusual vehicle path that has resulted due to construction activity. The effectiveness of drums as a delineation device depends on their ability to simulate a clear path and conspicuity during both day and nighttime. Effective delineation of the vehicle path using drums is often reduced due to drums not being positioned closely, over-turned drums, or in some cases drums not being clearly visible due to dust. Drum spacing for various road types, freeway speed limits and taper area are specified in the existing SCDs. It is specified that the drums should be spaced 40' (12m) center-to-center within the work area and 10' (3m) center-to-center in the taper area when they are used for signalized closing of 1 lane of a 2 lane highway [38]. If the drums are used for freeway/expressway closure the drums spacing is to be 25' (8m) center-to-center [39]. The drum spacing to be followed, as per ODOT guidelines, when the devices are used in multi-lane divided and undivided highways with various speed limits are summarized in the table below.

**Table 8: Center-to-center distances of drums in different applications**

Closing right or left lane of a multi-lane divided highway*		Closing right lane of a undivided highway**		Closing left lane of a multi-lane undivided highway***	
Normal speed limit (mph (km/h))	Maximum spacing of drums ft (m)	Normal speed limit (mph (km/h))	Maximum spacing of drums ft (m)	Normal speed limit (mph (km/h))	Maximum spacing of drums ft (m)
30-40 (48-64)	30 (9)	20-25 (32-40)	20 (6)	20-25 (32-40)	20 (6)
45-55 (72-88)	40 (12)	30-40 (48-64)	30 (9)	30-40 (48-64)	30 (9)
60-65 (96-104)	60 (18)	45-55 (72-88)	40 (12)	45-55 (72-88)	40 (12)

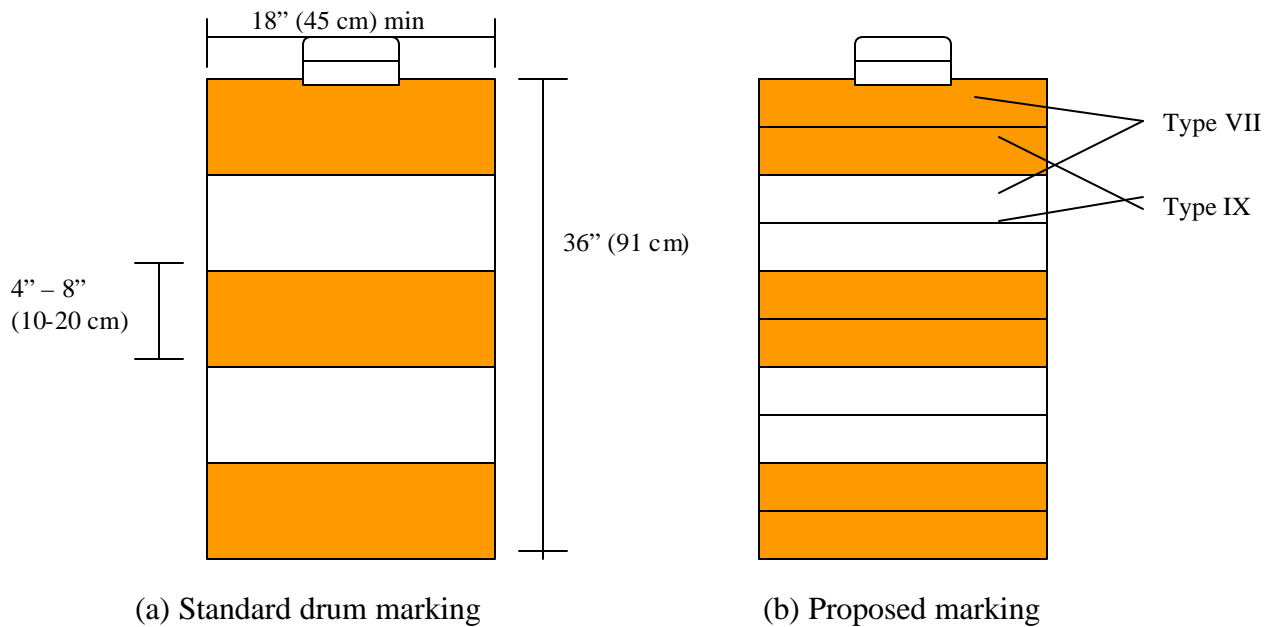
\* SCD MT-95.30

\*\* SCD MT- 95.31

\*\*\* SCD MT-95.32

As specified in the OMUTCD (Section 6F.55) the spacing of channelizing devices should not exceed a distance in meters (feet) equal to 0.2 times the speed limit in km/h (1.0 times the speed limit in mph) when used for taper channelization, and a distance in meters (feet) equal to 0.4 times the speed limit in km/h (2.0 times the speed limit in mph) when used for tangent channelization [40]. While most of the state manuals on uniform traffic control devices recommend the same spacing as in the MUTCD at least one state was found where higher distances were specified [42]. The drum spacing distances outlined in the ODOT guidelines, as discussed above, agree with the specifications in the MUTCD. However, effective traffic channelization depends on whether these distances are maintained at all times in the work zone. If not it is likely that drivers will be confused about the correct path that should be followed in maneuvering through the work zone. Therefore it must be ensured that these specifications are always strictly adhered to. The TEM also specifies that drums shall be kept clean free from dust or any other residue. This requirement must be strictly imposed in order to ensure maximum visibility of drums.

The markings on the drums are to be orange and white reflectorized stripes (section 6F.56 OMUTCD). As discussed previously in the section on signage materials, Type G or H material is recommended for drums as well. Using retroreflective sheeting material for the orange and white stripes helps increase the conspicuity of drums. Some reflective sheeting materials are found to be more legible from longer distances while others are found to be better when viewed from a shorter distance. Zwahlen et al. [28] found Type VII reflective sheeting materials to have a higher legibility when viewed from afar whereas Type IX material was best when viewed from a shorter distance. This property of the different types of materials can be used to make the drums more visible to the driver from far out as well as close in. Thus instead of using a single strip of material of a particular color (orange or white) two strips (each half the original width) of Type VII and Type IX of the same color can be used as shown in Figure 10. This will make the drums more visible at both near and far distances.



**Figure 10: Using Type VII and Type IX reflective sheeting material on drums. (a) Standard drum marking with orange and white strips and (b) Proposed drum marking with alternate strips of Type VII and Type IX material to replace single strip.**

Delineation of the travel path can also be improved by placing directional arrows on the barrels to indicate in which direction the motorists should drive. This will help give the driver clear directions on how to maneuver through the work zone. Placing directional arrows on barrels would be especially useful in situations where there are several lanes and the driver has to know which path should be followed.

To meet this need, a direction indicator barricade has been developed under the SHRP and used in several states, and evaluated in Georgia [44]. One is depicted in Figure 11. It has a 60 cm by 30 cm (24 in by 12 in) horizontal arrow panel and a 60 cm by 20 cm (24 in by 8 in) bias-striped panel mounted on a plastic barricade. Georgia DOT employees indicate the new barricade is far superior to barrels, and crews continued to use them after the initial testing. They are also more compact than regular barrels, making them easier and faster to set up and remove. Being more compact than barrels, more can be loaded onto a single truck. Georgia DOT crews also reported that drivers were more aware of the barricades than they were of barrels, but that could be a novelty effect. The devices have also been evaluated in Alabama, Arkansas, Illinois, and South Dakota.



**Figure 11: Direction Indicator Barricade [44]**

Initial highway testing of the direction indicator barricade in the early 1990s [45] suggested that these devices were slightly less effective than barrels in preventing closed-lane violations, an effect ascribed to the larger size and conspicuity of the barrels. It was recommended that a combination of the two devices, that is a barrel with a directional arrow, would combine the best of both devices.

These additional recommendations would serve to increase the usefulness of drums as effective delineation devices. Therefore ODOT should consider revising the work zone guidelines to provide for these requirements. Some of these recommendations have been incorporated into the 2003 OMUTCD.

The center-to-center drum spacing for non-linear road sections is specified as 20' (6 m) in ODOT Standard Construction MT Series Drawings. This is satisfactory given that better delineation is required in such areas. The drawings also specify different center-to-center spacing of drums for linear road sections based on specified driving speed. For example, when the speed is 30-40 mph (48-64 km/h), the center-to-center distance is specified as 30' (10 m) and increases for higher speeds. However, it is questionable if varying drum spacing distances need to be used depending on speed specified. Instead, it may be more appropriate to use 30' (10 m) in all situations with linear road sections. The tables for maximum spacing of drums on MT 95-30, MT 95-31, MT 95-32, MT 95-40, MT 95-41, MT 95-60, MT 96-61, MT 102-10, and MT 102-20 might be changed according to this suggestion.

### ***2.8.1. Basis for Recommendation***

Maintaining a closer spacing between the drums will ensure effective traffic channelization and is beneficial from a human factors perspective and also for better traffic flow. Using two different types of fluorescent sheeting materials for the drums stripes will ensure increased visibility which will provide better guidance for the motorists, especially for older drivers and is therefore advantageous from a human factors perspective. Using directional arrows on barrels would be especially useful in situations where there are several lanes and the driver has to know which path should be followed.

### ***2.8.2. Implementation***

The recommended modifications will have to be incorporated in the relevant work zone standards. In addition the drum drawing contained in the OMUTCD would also have to be changed to reflect the use of two different materials for the stripes.

### ***2.8.3. Estimated Cost***

Direction indicator barricades cost more than traditional barrels, \$136.73 each from one vendor (Off the Wall Products in Salt Lake City UT), but require less time to set up and maintain, resulting in an expected long-term cost savings. It is not known how much direction indicator barrels would cost. There would be an increased cost where more drums are used.

### ***2.8.4. Benefits and Risks***

The recommendations will provide better channelization and traffic flow in the work zone, provided that drums are properly aligned and maintained. Any alignment problems can be fixed during or following periodic visual inspections that should be carried out as a matter of course in operating any work zone.

### ***2.8.5. Evaluations and Research***

In order to evaluate the spacing distance between drums and the effectiveness of using two stripes Type VII and Type IX, a study should be conducted.

## **2.9. Rumble Strips**

Section 605-17 of the TEM outlines the use of rumble strips for construction activities. The main application specified is to alert drivers to unusual motor vehicle traffic conditions by placing them transverse to traffic movement.

Several studies have found the use of continuous shoulder rumble strips to be very effective in combating driver inattention. Perrillo [46] reports that continuous shoulder rumble strips have been used as an effective counter measure to achieve a 65% reduction in crashes in the state of New York. Another study tested the effectiveness of the use of shoulder rumble strips on the Pennsylvania Turnpike [47]. It was found that drift-off-road accidents were reduced by 60% after the installation of an innovative type of rumble strip. Cheng et al. [48] found that freeways without shoulder rumble strips experienced a higher rate of accidents over those highways with shoulder rumble strips. All these studies report circumstances where continuous shoulder rumble strips have been used very effectively to reduce the occurrence of accidents on highways.

Extending the application of rumble strips to roadway edge lines and centerlines between opposing directions of traffic in construction zones could offer similar benefits. These devices provide a distinct warning sound and vibration when the drivers drift out of the lane. Thus they can be used to ensure that drivers stay in the appropriate lane when driving through a construction zone, increasing the safety of drivers as well as that of construction workers and the equipment used. Therefore ODOT should consider revising the guidelines to recommend

installing continuous rumble strips on shoulders in construction zones. Rumble strips should also be installed on centerlines where there is traffic flowing in opposite directions and not separated by jersey barriers or other traffic control devices.

### ***2.9.1. Basis for Recommendation***

The installation of rumble strips along the shoulders and centerlines separating opposing traffic would serve as a warning sign for drivers who drift away from the driving path. This would ensure driver and worker safety from a human factors perspective.

### ***2.9.2. Implementation***

This recommendation involves the extension of the use of rumble strips to shoulders and centerlines separating opposing traffic, which are not included in the guidelines. Therefore the relevant standards would have to be changed accordingly.

### ***2.9.3. Estimated Cost***

This cost is not known at the moment.

### ***2.9.4. Benefits and Risks***

Rumble Strips will increase driver and worker safety in the work zone and reduce accidents due to traveling off the road. Fewer accidents mean better traffic flow.

### ***2.9.5. Evaluations and Research***

The exact location of rumble strips along the shoulders would have to be decided cautiously. Installing rumble strips would mean that other delineation devices used at present (drums, cones etc.) be placed outside the rumble strips intruding into the work area. The rumble strips may also decrease the width of the road section. These are important issues that have to be considered in the installation of rumble strips.

## **2.10. Regulatory, Warning, and Guide Signs**

A detailed description of the various regulatory and warning signs to be used to inform motorists of legal requirements and specific hazards that may be encountered in the work zone respectively are described in the OMUTCD (Sections 6F.02-6F.50). TEM Section 605-4 outlines the standards to be followed in the erection of regulatory signs not included in the OMUTCD – Work Zone Speed Limit sign and Fines Doubled sign. Several guide signs that are not included in the OMUTCD are included in the TEM section 605-8.

Several other innovative signs could be included in work zone areas to collect information from the public, to assure motorist happiness and respect for TCDs. A sign with a message akin to ‘Thank You for Your Patience’ may help decrease the disregard drivers may have towards work zone operations. Including a sign with an 800 number for comments will also be very useful in improving activities of the particular work zone in which the sign is installed if not those at other sites. These are two important signs that ODOT ought to consider including in the work zone guidelines to ensure improved cooperation from drivers.



Signs can also be used to give out project information that may help drivers accept the temporary delays. Messages can focus on project content information, such as “Working to improve your safety”, “Working to reduce your commuting time”, or “We are adding a lane”. Project data can also be given such as the construction end date, amount of work done, or length of work zone. This has been done in some work zones, but is probably a good idea in any work zone where the end of the zone cannot be seen from the beginning of the zone. Another possibility is positively formulated driver performance information, such as “Last month over 80% of drivers did not speed”, or The number of accidents in this work zone in the past month.

Some states also use several other signs to improve work zone safety. For example the Pennsylvania DOT uses signs that read as ‘Slow Down My Mom/Daddy Works Here’ [50]. Such signs tug at the heart strings of drivers and make them slow down. A possible improvement may be to use self-interest, as in “Slow Down. It’s for Your Own Safety”. Another group of signs that is used in long-term construction project sites are the web site information signs (Figure 12). Steinke et al. [31] found that improving communication with motorists (both before and during work) is one of the methods used in European countries to improve traffic flow in work zones. Displaying signs that clearly indicate the website where first hand information is available is very useful in educating drivers. This is also an effective means of communicating project information to drivers who use the particular road regularly. Therefore ODOT could consider including innovative signs such these to increase the safety of workers, obtain the cooperation of motorists by creating methods to improve communication, and to promote the Buckeye Traffic website (OTIS) which has construction information.



**Figure 12: Innovative signs used by the Pennsylvania DOT to improve safety in work zones**

A sign that can be observed in Ohio work zone operations is the “Resume Legal Speed” sign that is erected just after the end of the construction zone. The message conveyed by this sign is likely to cause confusion among drivers for two reasons. First it implies that the speed maintained by the driver so far within the work zone may not be the legal speed. Secondly, motorists are not given any information regarding the legal speed in that particular part of the road. Motorists may have to travel several miles before finding a speed limit sign. For these reasons the effectiveness of the “Resume Legal Speed” sign has to be re-evaluated. It would be more useful to drivers if a speed limit sign were erected instead of a “Resume legal speed” sign at the end of a work zone.

Another work zone sign that is not very effective in use is the “Fines Doubled In Work Area” sign. They are often found to work initially but only for a short time [51]. This may be attributed to law enforcement officers staying out of the work zone and consequently the message is not enforced. However using variable message signs with photo-radar units may be a

more effective means of regulating the speed in work zones. One can also try tripling fines in work zones.

Increasing the size of work zone traffic signs is another step that could be taken to ensure that all signs are clearly visible under day and nighttime conditions as well as all weather conditions. Having larger, simpler, and clear signs has been included as one of the top-ten improvements that can help create safer roads by AAA [52]. To improve traffic flow and safety in work zone areas, we recommend that all work zone traffic signs with worded legends be increased by 6" so that they are easily readable. Therefore signs that are 30"x30", 36"x36", and 48"x48" should be increased to 36"x36", 42"x42", and 54"x54" respectively. It is also recommended that word messages be made simpler where possible.

### ***2.10.1. Basis for Recommendation***

The suggested new signs contribute to assuring motorist happiness and also improves the cooperation from drivers. Since first hand information can be gathered from drivers through a sign with a toll-free telephone number, it would also contribute to improve work zone operations. Therefore the signs will be beneficial from a human factors perspective as they contribute to worker and motorist safety, and would also improve traffic flow.

### ***2.10.2. Implementation***

New signs to assure motorist happiness and improve the cooperation from the drivers should be included in the guidelines. In addition toll-free phone number sign for soliciting feedback from drivers should be included in the guidelines.

### ***2.10.3. Estimated Cost***

This cost is not known at the moment.

### ***2.10.4. Benefits and Risks***

These recommendations will ensure improved cooperation from drivers and improve work zone safety.

### ***2.10.5. Other Considerations***

Some states use several signs to improve work zone safety. The applicability of these signs in Ohio should be evaluated and the effectiveness of these signs should be determined.

## **2.11. Speed Control**

At present, speed control in work zones consists of installing reduced speed limit signs and the "Fines doubled in work zones" sign. Failure of drivers to observe these speed limits is a major safety problem leading to many worker and motorist injuries and deaths. This is a major problem in work zones.

To control speed in work zones, one can envision three levels of increased attention and enforcement, each requiring more effort. Some of these measures are also discussed elsewhere in this report.

Level one consists of a statistics board, perhaps on a Portable Changeable Message Sign (PCMS), which includes a statement such as “Over 80% of motorists obey the speed limit in work zones”. The statement is phrased positively to encourage motorists to also obey the speed limit. The “Fines doubled in work zones” sign can be replaced with a “Fines tripled in work zones” sign. For the effect of this sign change to be realized, additional enforcement is needed. The additional enforcement may require extra pay for the law enforcement officers performing the duties, and this can be paid for by the contractor with project funds budgeted for this purpose. These funds should ultimately be recovered from the increase in collected fines.

Additionally a second pair of speed limit signs, one on each side of the road, could be placed one-half mile downstream from the first set of speed limit signs. Speed limit signs on both sides of road should be longitudinally spaced more closely throughout the work zone and combined with transverse rumble strips in order to provide to the driver a more frequent visual, auditory, and vibrational signal. These extra signs should reinforce and emphasize the reduced speed limit message.

Level two also involves additional enforcement. In addition, drivers are provided with active feedback on a speed display that displays the speed limit and next to it, in large lights “Your speed” as measured by radar. Placed near the beginning of a work zone, the sign serves the purpose of providing drivers with fair warning of possible enforcement efforts further down the work zone.

Level three includes around the clock patrol or enforcement by automatic camera with tickets mailed to car registrants. There may be some questions regarding the legality of the automatic camera enforcement approach to be sorted out, but it can be installed and used in limited space areas where conventional enforcement is difficult or impossible. It has been observed, however, that the physical presence of police reduces work zone traffic capacity by about 14% in rural freeway work zones [19]. The effectiveness of additional law enforcement presence in work zones has been thoroughly reviewed [53]. For such an approach to be effective, the following needs to be done:

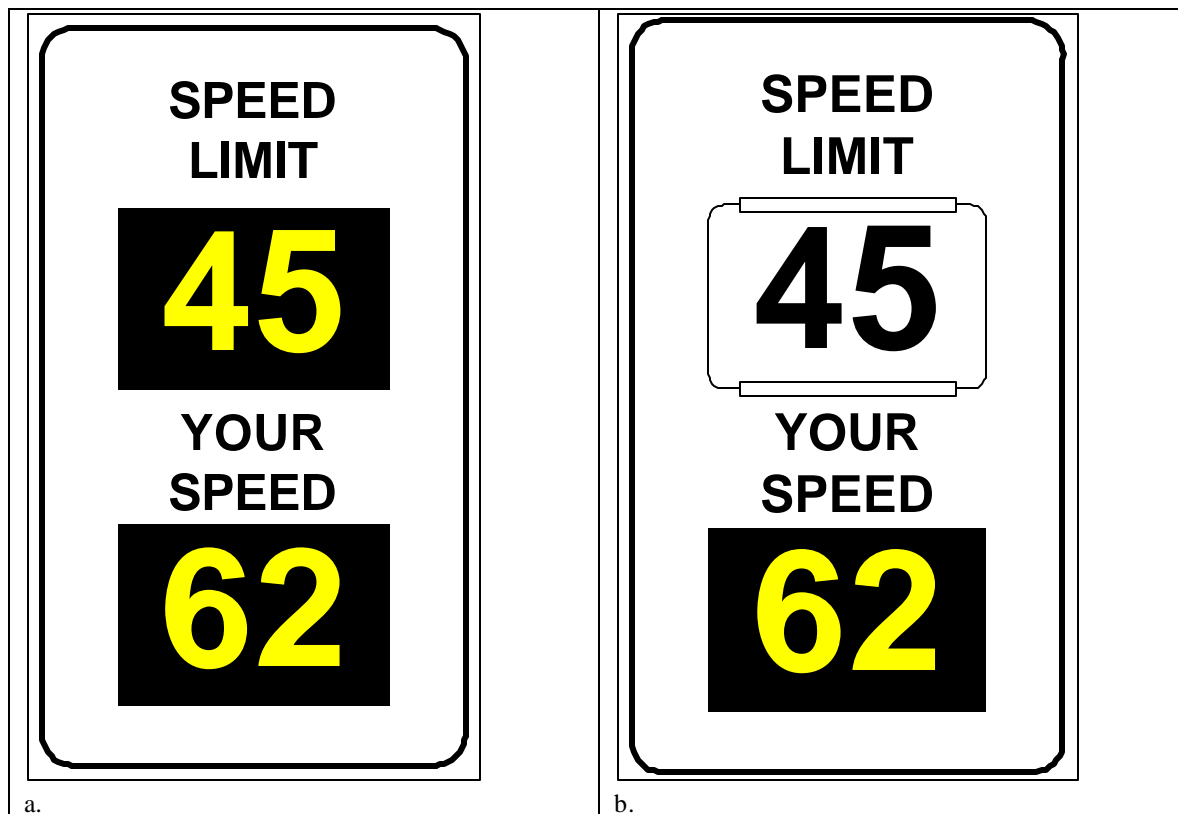
- Establish predictable funding levels and sources
- Establish agreement between law enforcement agencies and ODOT.
- Additional focused training for enforcement personnel.
- Establish individual points of contact in each agency.
- Keep and maintain detailed records of enhanced enforcement.

The visible presence of law enforcement with radar has been shown to reduce average speed or traffic by 5-10 mph (8-16 km/h), but the reduction is lost within an hour or two of law enforcement leaving the area.

Automated speed enforcement using a camera has been used extensively worldwide [53]. They are less common in the United States, but have been shown to decrease crashes, for

instance at Paradise Valley Arizona where crashes went from 460 in 1986 to 224 in 1992. West Valley, Utah had a decline from 2130 to 1710 crashes over two years. Automated speed enforcement also gets around the problem that when an additional officer is chasing and apprehending a speeder, the vehicle is no longer as visible in its station in the work zone. There are two options for automated speed enforcement – one is to send the pictures electronically downstream to law enforcement personnel who stop the vehicles and write tickets at the site, and the other is to mail the tickets to the registered car owner. The former option provides the benefit of immediate feedback and also targets the actual driver of the vehicle, who may not necessarily be the registered owner (for instance a spouse or child of the owner). A Texas Transportation Institute study reviewed in [53] found that officers could correctly identify vehicles downstream 84-88% of the time. The speed threshold of the system sending pictures downstream needs to be set at a level that doesn't overload the system.

It may be helpful in speed control efforts to use variable speed limit signs that also display the driver's speed. The speed limit may be controlled remotely and displayed with a light display, or as a cheaper alternative the speed limit may be displayed with a removable panel. The two signs are shown in Figure 13.



**Figure 13: Speed limit signs with driver feedback for use in work zones. a) With speed limit and driver's speed displayed with luminous display. b) With driver's speed on luminous display and speed limit on a removable panel**

Another important consideration in speed control in work zones is determining the speed limit when there is no work going on. Drivers tend to maintain a higher speed if they do not see a crew or machine working in the work zone. A speed limit sign equipped with amber flashers at the top and bottom may be used for the speed control in work zone. Flashers will be operated when there is actually construction work going on and the reduced speed limit is effective. A sample drawing for the flashing speed limit sign is given in Figure 14.



**Figure 14: Flashing Speed Limit Sign**

### ***2.11.1. Basis for Recommendation***

Speed control recommendations will provide better traffic flow in the work zone, and by forcing the drivers to obey the speed limitations the work zone area will turn out to be a safer environment both for the workers and the drivers. Speed limit signs on both sides of the road combined with transverse rumble strips will provide to the driver a more frequent visual, auditory, and vibrational signal. A flashing speed limit sign will better catch drivers' attention

when operating, and will respect the drivers' perception that there is less need to slow down when there is no work occurring at the time, which will tend to improve respect for the speed limit when the sign is flashing.

### ***2.11.2. Implementation***

Improving speed control in work zones can be achieved through three steps. The first step is providing additional signs, which will positively encourage motorists to obey the speed limit, such as "Over 80% of the motorists obey the speed limit in work zones". These additional signs should be included in the design guidelines. Flashing speed limit signs and additional reduced speed limit signs can also be added. Flashing signs will require some extra attention so that they are turned on when work is started and turned off when work is over for the day.

In level two the speed of the vehicles in the work zones will be measured and displayed next to the speed limit in the work zone. Speed limit and the measured speed limit of the vehicles can be displayed with a PCMS. The use of PCMSs for speed control should be included in the work zone design guidelines. In order to display the speed of the vehicles in the traffic, the PCMS units should be equipped with radar equipment.

The third level of controlling speed in work zones is the use of radar units with automatic camera. Speeding vehicles will be photographed in the work zones and the tickets will be sent to the address of the drivers. The use of camera and radar unit should be included in the work zone design guidelines.

The one method which has been shown to clearly work is the presence of uniformed law enforcement personnel, however this is costly and may not be practical in confined work zone areas. It may be possible to design the work zone to include provisions for speed enforcement, such as a bay where a police car can be parked.

The law for the fines doubled in the work zone should be changed to the fines tripled in the work zone.

### ***2.11.3. Estimated Cost***

The monthly rental cost for speed monitors is \$345. They can be used to display the speed of the oncoming vehicle and near the measured speed the speed limit in the work zone area can be displayed. The state of Washington estimates \$50,000 for implementation of a simple photo enforcement installation with two cameras, a VMS and control equipment. Flashing speed limit signs will cost about the same as similar signs for school zones, and additional static speed limit signs placed a half mile after the initial lower speed limit signs will cost even less. Level three enforcement will require additional pay for law enforcement personnel.

### ***2.11.4. Benefits and Risks***

These speed control recommendations may provide better traffic flow in the work zone, and by forcing the drivers to obey the speed limitations the work zone area will become a safer environment both for the workers and the drivers. Better signing will help improve conformity

with speed limits, and flashing signs that are accurately operated (i.e. not left on when there is no work) will improve public acceptance of reduced speed limits in work zones when there is work going on.

### ***2.11.5. Evaluations and Research***

The recommendations should be analyzed separately, and the effectiveness of each recommendation should be evaluated. The effectiveness of messages for speed control, displaying the speed of the vehicles in the traffic with the legal speed, the use of the automatic camera for identifying speeding vehicles, and sending the fines to the address of the car registrants, and tripling the fines in work zones should be evaluated.

## **2.12. Pedestrian and Worker Safety**

Pedestrian and Worker Safety is analyzed in the TEM Section 603. It is stated that, in addition to creating vehicular restrictions, work zones and incident areas may also cause conflicts for pedestrian traffic and workers. Pedestrians and workers are exposed to hazardous conditions from both the work activity and the traffic.

### ***2.12.1. Pedestrian Considerations***

TEM Section 603-2 covers pedestrian considerations. This section states that where pedestrian traffic is present, pedestrian safety and needs must be addressed. There are three threshold considerations in planning for pedestrian safety in temporary traffic control zones on highways and streets:

1. Pedestrians should not be led into conflicts with work vehicles, equipment, or operations.
2. Pedestrians should not be led into conflicts with vehicles moving through or around the work zone or incident area.
3. Pedestrians should be provided with a safe, convenient travel path that replicates as nearly as possible the most desirable characteristics of sidewalks or footpaths.

In accommodating the needs of pedestrians, it should always be remembered that the range of pedestrians that can be expected is very wide, including the blind, the hearing impaired, and those with walking handicaps. All pedestrians need protection from potential injury and a smooth, clearly delineated travel path. TEM Section 603-2 refers to TEM Figure 698-31 and TEM Figure 698-32.

TEM Figure 698-31 discusses sideways closures and bypass walkway and this figure is explained in TEM 607-28. The following additional guidelines should be used with this figure:

1. Where sidewalks exist, provisions shall be made for disabled pedestrians.
2. Only the temporary traffic control devices related to pedestrians are shown. Other devices, such as lane closure signing or ROAD NARROWS signs (OW-51), may be used to control motor vehicle traffic.
3. Street lighting should be considered.
4. For nighttime closures, Type A flashing warning lights should be used on barricades that support signs and close sidewalks. Type C steady-burn lights should be used on channelizing devices separating the temporary sidewalks from motor vehicle traffic flow.

5. Where high speeds are anticipated, a temporary traffic barrier and, if necessary, a crash cushion should be used to separate the temporary sidewalks from motor vehicle traffic.
6. Signs, such as KEEP RIGHT (LEFT) (R-37), may be placed along a temporary sidewalk to guide or direct pedestrians.

TEM Figure 698-32 considers crosswalk closures and pedestrian detours and TEM 607-29 provides an explanation of the figure. The following additional guidelines should be used with this figure:

1. Where sidewalks exist, provisions shall be made for disabled persons.
2. Curb parking shall be prohibited for at least 50 feet (15 meters) in advance of the mid-block crosswalk.
3. Only the temporary traffic control devices related to pedestrians are shown. Other devices, such as lane closure signing or ROAD NARROWS signs (OW-51), may be used to control motor vehicle traffic.
4. Street lighting may be considered.
5. For nighttime closures, Type A flashing warning lights should be used on barricades supporting signs and closing sidewalks. Type C steady-burn lights should be used on channelizing devices separating the work space from motor vehicle traffic.
6. Pedestrian traffic signal displays controlling closed crosswalks should be covered or deactivated.
7. In order to maintain the systematic use of the fluorescent yellow-green background for Pedestrian, Bicycle, and School Warning Signs in a jurisdiction, the fluorescent yellow-green background for Pedestrian, Bicycle and School Warning Signs may be used in temporary traffic control zones.

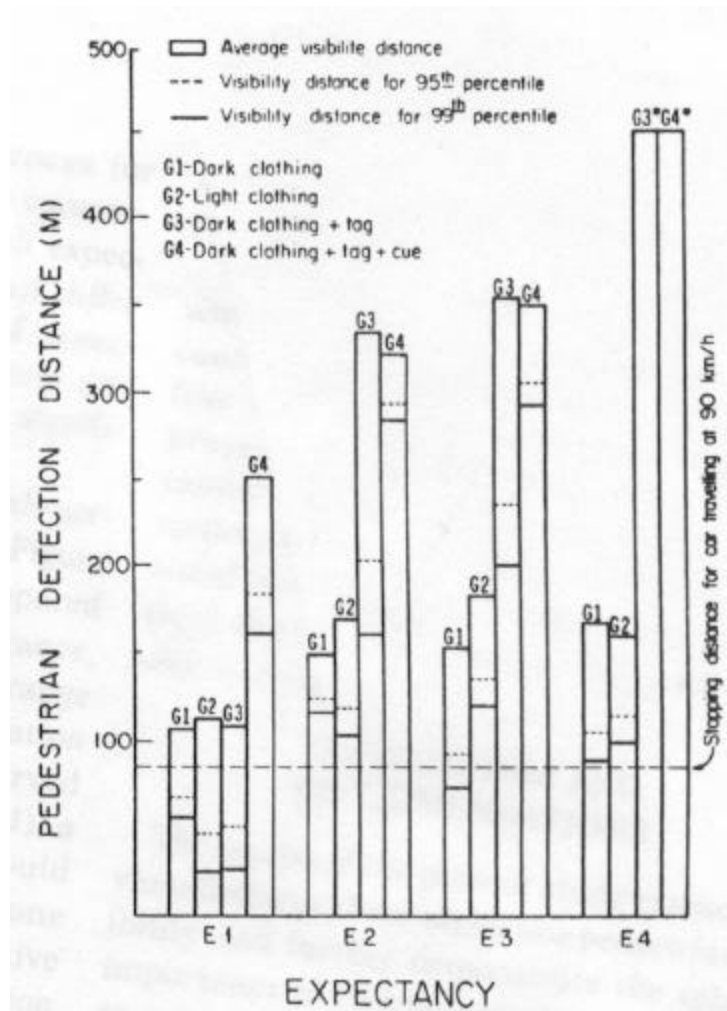
In addition, TEM Section 603-2 refers to SCDs MT-110.10, 110.20 and 110.30, since they include information on traffic control for a pedestrian detour.

Nighttime pedestrian visibility has been studied under various combinations of driver's expectancy, clothing reflectance, and detection criterion. In the nighttime pedestrian accident reports on record at the Indiana Department of Motor Vehicles for 1966, 87 percent of the drivers whose automobile struck a pedestrian at night claimed difficulty in seeing the pedestrian, while only 11.8 percent made the same claim during daytime [54].

Shinar [55] studied nighttime pedestrian visibility under various combinations of driver expectancy, and pedestrian clothing characteristics (dark clothing, light clothing, and dark clothing with retroreflective tags), and the detection criterion (pedestrian versus retroreflective tag). It is stated in the abstract that visibility distance increases with expectancy, but the magnitude of the effect varies as a function of whether or not the pedestrian is unexpected, the usefulness of the tag is significant only if the driver can rely on it as a criterion for detection (by prior knowledge of the association between the tag and the pedestrian). The difference in visibility when the tag is not associated with the pedestrian may explain the less-than-expected effectiveness of retroreflective materials on accident reduction. The average visibility distance for the pedestrian with dark clothing is found 144m, for the pedestrian with light clothing it is found 155 m., and for the pedestrian with dark clothing with a retroreflective tag attached is found 312m. According to the Shinar's study [55], it can be concluded that the use of



retroreflective material in pedestrian clothing doubles the visibility distance of the pedestrian during nighttime.



Expectancy situations  
 E1-The level of least expectancy obtained from the detection distance of the first trial after the termination of the practice phase.  
 E2-After obtaining the visibility distance for E1, the experimenter in the car informed the subjects that on the following trials the pedestrian could appear anywhere within the next 2-km segment of the road in either the center, right, or left side of the driving lane.  
 E3-On these trials the subjects were informed how far down the road the pedestrian was standing but were not informed as to his position in the lane.  
 E4-In this condition the car was stationary and the pedestrian first walked away from it until he disappeared from the subject's view and then approached it.

**Figure 15: Mean pedestrian detection distance as a function of expectancy, instructions and clothing reflectance adapted from Shinar [55] (1 m = 3.28 ft).**

SCD MT-110.10 discusses the detouring of pedestrians onto temporary walkways on roadways, SCD MT-110.20 is about the detouring of pedestrians to the other side of the street, and SCD MT-110.30 mentions the detouring of pedestrians to another facility. In all the aforementioned drawings, separator types and separator requirements are presented.

Further it is stated that if a temporary barrier is erected to shield pedestrians, it should be designed to suit site conditions. Depending on the possible motor vehicle speed and angle of impact, temporary traffic barriers might deflect upon impact by an errant vehicle. Guidance for locating and designing temporary traffic barriers can be found in Chapter 9 of AASHTO's Roadside Design Guide (Section 193-12).

### ***2.12.2. Worker Clothing for Visibility***

TEM Section 603-3 is related to worker safety considerations at work zones. It is stated that temporary traffic control zones present temporary and constantly changing conditions that are unexpected by the road user. This creates an even higher degree of vulnerability for personnel working on or near the roadway. Maintaining temporary traffic control zones with road user flow inhibited as little as possible and using temporary traffic control devices that get the road user's attention and provide positive direction are of particular importance.

TEM Section 603-3 states that the following are key elements of traffic control management that should be considered in any procedure for assuring worker safety:  
Training - All workers should be trained in how to work next to motor vehicle traffic in a way that minimizes their vulnerability. Workers having specific temporary traffic control responsibilities should be trained in temporary traffic control techniques, device usage, and placement.

Worker Clothing - Workers close to the motor vehicle pathway should wear bright, highly visible clothing. OMUTCD Section 7H-3 is related to flagger clothing. OMUTCD Section 7H-3 states that the use of orange clothing such as vest, shirt or jacket shall be required for flagger. For nighttime conditions similar outside garments shall be reflectorized. Further, it is stated that flaggers must, at all times, be clearly visible to approaching traffic from a distance that is sufficient to permit proper response by the motorist to the flagging instructions. In positioning flaggers, consideration must be given to maintaining color contrast between the flagger's protective garment and his background. It should be noted that all these instructions are specifically for flaggers and there are no rules stated for other workers.

Temporary Traffic Barriers - Temporary traffic barriers should be placed along the work space depending on such factors as lateral clearance of workers from adjacent traffic, speed of traffic, duration of operations, time of day, and volume of traffic.

Speed Reduction - Reducing the speed of motor vehicle traffic, mainly through regulatory speed zoning, funneling, use of law enforcement officials, lane reduction or flaggers may be considered.

Shadow Vehicle - In the case of mobile and constantly moving operations, such as pothole patching and striping operations, a shadow vehicle, equipped with appropriate lights,

Warning Signs and/or a rear-mounted impact attenuator may be used to protect the workers from impacts by errant vehicles.

Road Closure - If alternate routes are available to handle road users, the road may be closed temporarily. Getting traffic off the road enhances worker safety. Road closure may also facilitate quicker project completion and thus further reduce worker vulnerability.

Police Use - In highly vulnerable work situations, particularly those of relatively short duration, police units may be stationed to heighten the awareness of passing motor vehicle traffic and to improve safety through the temporary traffic control zone.

Lighting - For nighttime work, the work zone and approaches may be lighted.

Special Devices - Judicious use of special warning and control devices may be helpful for certain difficult work area situations. These include rumble strips, changeable message signs, hazard identification beacons, flags and warning lights. Intrusion warning devices may be used to alert workers to the approach of errant vehicles. However, misuse or overuse of special devices or techniques may lessen their effectiveness.

Public Information - Improved driver performance may be realized through a well-prepared and complete public relations effort that covers the nature of the work, etc. This is explained in Section 600-4 of the TEM.

An infrared intrusion alarm is proposed in the project entitled "New Work Zone Safety" [56]. This is a video cassette produced by the SHRP and FHWA in year 1992. An infrared intrusion alarm is a device that can be used to warn workers of errant drivers. The device is made up of two parts: a lightweight easy to setup detector and a receiver/siren unit. The detector is setup at the beginning of the work zone and the receiver is positioned inside the area where workers are engaged in maintenance activities. If an errant driver enters the work zone and clashes with the barrier devices that are set up, the siren will go off and the workers have sufficient time to take precautions.

These alarms were tested in New York and Vermont and met with general acceptance, the main difficulty being with set up on work zones with narrow shoulders. The cost of a system is \$3000 [57].

Pratt et al. [58] published a report on building safer highway work zones: measures to prevent worker injuries from vehicles and equipment. It is stated in this report, citing unpublished data from the Bureau of Labor Statistics, that between 1992 and 1998, the Census of Fatal Occupational Injuries (CFOI) reported 841 worker fatalities in SIC 1611 (Highway and Street Construction). As Table 9 shows, the majority of fatalities occurred inside work zones, with vehicle and equipment related incidents similar to those described above the predominant type of fatal event.

**Table 9: Fatalities in the highway and street construction industry (SIC 1611), CFOI, 1992-1998**

	<b>Number</b>	<b>Percent</b>
<b>Occurred in a highway or street construction work zone:</b>	<b>492</b>	<b>58.5%</b>
Vehicle or equipment related	465	55.3%
Other event	27	3.2%
<b>Occurred outside a work zone:</b>	<b>349</b>	<b>41.5%</b>
Vehicle or equipment related	198	23.5%
Other event	151	18%
<b>Total</b>	<b>841</b>	<b>100%</b>

This report mentions injury prevention measures in detail such as work zone layout, use of temporary traffic control devices, motorist education and speed, enforcement, flaggers, high-visibility apparel, illumination of the work zone, developing internal traffic control plans, implementing internal traffic control plans, accountability and coordination at the work site, equipment operation and maintenance, safe equipment operation around workers on foot, training and certification, changes in the contracting process, laboratory and field research needs, and data and record keeping.

Good visibility and high detectability of targets like vehicles and humans on roadways during daytime and nighttime is a very important factor in traffic safety. Higher visibility of vehicles in traffic and on the roadways has the potential to decrease the number of accidents caused by the non-detection or late detection of vehicles. There are very few studies reported in the literature, which determine the visibility treatment for personnel such as highway patrol personnel and construction zone workers working on the roads during daytime and nighttime. The available literature is mostly related with the detection and recognition of pedestrians and the conspicuity and visibility of pedestrian targets during daytime and nighttime.

Studies related to the visibility of pedestrian targets have been conducted for reflectorized and non-reflectorized color targets. The studies show that the visibility and detectability of the targets during daytime does not show much difference between reflectorized and non-reflectorized color targets. However, reflectorized targets are much superior than non-reflectorized targets from a detectability point of view at nighttime.

Fontaine and Hawkins [24] conducted a study on effective treatments to improve driver and worker safety at short-term work zones. This publication catalogs several devices that were found to be effective at improving driver and worker safety at short-term work zones. The devices included are: fluorescent yellow-green worker vests and hard hat covers, portable variable message signs, speed display trailers, fluorescent orange roll-up signs, radar drones, and retroreflective magnetic strips for work vehicles. The catalog provides a brief description of each treatment, along with a summary of the treatment’s effectiveness, and recommendations for its use at short-term work zones.

On the other hand, Stidger [51] stated that reflective garments that are clearly visible from all angles can help, rather than using vests with no side coverage. Further, he mentions that

training workers is vital since many work zone injuries are caused by simple worker carelessness.

Cotrell [59] prepared a report on improving night work zone traffic control. The objective of this study was to examine traffic control for night work zones from the perspective of both agencies and motorists. The author has investigated practices of state departments of transportation, identifying the problems associated with traffic control for night work zones and identifying potential strategies to resolve them. In this report there is a section on improving the visibility of workers. In the Virginia Work Area Protection Manual, work clothing is described as follows: “The retroreflective material shall be visible at a minimum distance of 1,000 feet (305 m). The retroreflective clothing shall be designed to identify clearly the wearer as a person and be visible through the full range of body motions” [52]. It is mentioned that in practice, a safety vest with retroreflective material is worn in Virginia. To make the full range of body visible, the motion of worker’s arms and legs should be visible. In a study on safety service patrol uniforms, Brich [61] concluded that the addition of circumferential retroreflective bands on the limbs and major hinge points (knees and elbows) provides for enhanced recognition of a person during nighttime. This study recommended a safety service patrol uniform design that makes the full range of body motion visible at night. One way to accomplish this is to sew white retroreflective bands on high-visibility clothing as proposed for the safety service patrol uniforms [61]. The Minnesota DOT uses highly visible vests, pants and caps [62]. It is mentioned in the report that, other options include placing removable bands over clothing at a level slightly above the wrists, elbows, ankles, and knees or sewing the bands onto work clothing. The American Society of Testing Materials is considering developing specifications for nighttime visibility of workers. This study further mentions that retroreflective hard hats should be required. The New York DOT requires a retroreflective strip 7.6 cm (3 in) long and 2.5 cm (1 in) high placed on each side of the hard hats [63]. Hard hats should be visible from all sides. Another item that can enhance recognition of a person at night is a flashing light either attached to a person or made into a vest. It is also stated that although light adds visibility to the worker, it does not make full body motion visible.

Fontaine et al. [64] evaluated traffic control devices for rural high-speed maintenance work zones. This is the report for second year activities and also includes final recommendations. They have concluded that the fluorescent orange signs, vehicle visibility improvements, and yellow-green worker vests acted to improve the conspicuity of workers.

Blomberg et al. [65] conducted a nighttime field study in order to determine the detection and recognition of pedestrians at night using reflectorized and non-reflectorized color targets with different target sizes. The data presented in his study clearly indicates that retroreflective treatments on pedestrians can increase the distance at which they are detected and recognized. Thus, it is a reasonable extension of these results to postulate a safety benefit from the widespread use of appropriately designed retroreflective garments at night. However, it must be remembered that all subjects in the reported experiments were alert, had normal vision and were neither fatigued nor intoxicated when the data were collected.

Zwahlen and Vel [66] conducted a daytime field study to determine the conspicuity in terms of visual detection and recognition of different fluorescent and non-fluorescent color

targets against different backgrounds. Their study is summarized in the following abstract. A daytime field study was conducted to determine the conspicuity in terms of peripheral visual detection and recognition of different fluorescent and non-fluorescent color targets against different backgrounds. The color targets (6 x 12 in.), of which six were non-fluorescent and four were fluorescent, were tested against different non-uniform multicolored backgrounds. Three different painted plywood boards of 4 x 4 ft (1.2 x 1.2 m) depicting typical city, fall foliage, and spring foliage background colors were used as the backgrounds. The stimuli (color targets) were presented at three different peripheral angles (20, 30, and 40 degrees to the right of the line of the sight) against the different backgrounds. Twelve subjects with normal color vision between the ages of 20 and 22 years participated in the experiment, which was conducted on an unused airport runway. A randomized block experimental design was used in such a way that for each subject the order of presentation of the three peripheral angles was random so that each angle occurred exactly once. Furthermore, for a given angle the order of presentation for the backgrounds was randomized so that each background occurred exactly once. For each background and for each of the two blocks of 10 colors each color was randomized in such a way that each color target appeared exactly once in the first block as Replication 1 and exactly once in the second block as Replication 2. Daytime chromaticity measurements were recorded for all of the color targets and background colors along with daytime luminance measurements of all of the color targets and backgrounds.

The data were analyzed for two conditions: (a) detection percentage of total responses on the basis of the total number of presentations in which the subject detected the presence of a color target but in which the subject's color recognition response could be either the correct color or an incorrect color and (b) recognition percentage of the correct color target recognitions on the basis of the total number of presentations in which a subject's response with regard to the recognition of the color of the target was correct. In general, fluorescent yellow was found to be best detected and fluorescent orange was found to be best recognized against any of the three backgrounds investigated.

Looking at the results of the study and the increased detection and recognition performances achieved with fluorescent colors for the conditions investigated in the study are considerably more conspicuous during daytime in terms of the peripheral detection and recognition percentages. It is recommended that designers of traffic signs, personal conspicuity enhancement items and devices, and roadside traffic control devices consider the superior visual conspicuity properties of fluorescent colors (especially fluorescent yellow-green and fluorescent orange) and incorporate them in designs when the highest possible daytime target conspicuity is absolutely necessary (Figure 16 and Figure 17).

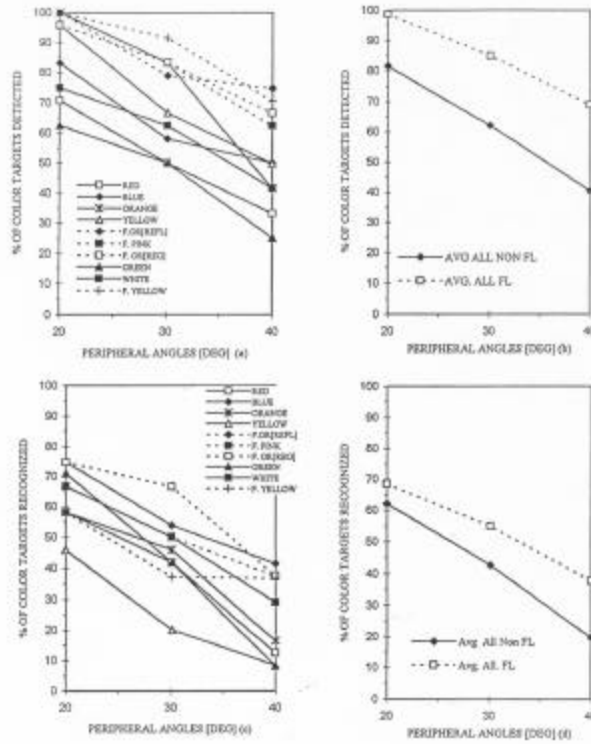
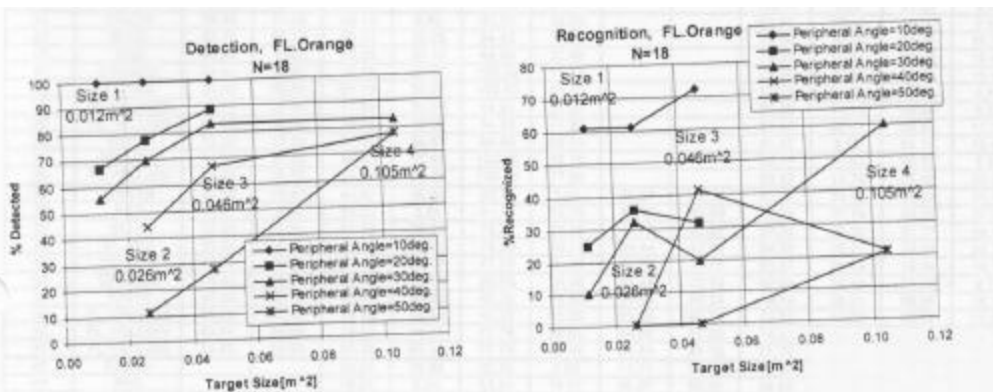


Figure 3) Percentage of Color Targets Detected and Recognized as a Function of Peripheral Angles [degrees] against Multi-Colored CITY BACKGROUND. (Gray with Red Designs)  
 a) Percentage of color targets detected for all ten colors.  
 b) Percentage of color targets detected for average of all fluorescent colors (N=6) and for average of all non fluorescent colors (N=6).  
 c) Percentage of color targets recognized for all ten colors.  
 d) Percentage of color targets recognized for average of all fluorescent colors (N=6) and for average of all non fluorescent colors (N=6).  
 12 subjects, 2 replications (N=24)

Figure 16: Detection of targets recognized as a function of color and state of fluorescence, from Zwahlen et al. [66]



a) Percentage of Fluorescent Orange Color Targets Detected and Recognized, as a Function of Target Size (Size 1: 0.076m x 0.152m, Size 2: 0.114m x 0.229m, Size 3: 0.152m x 0.305m, Size 4: 0.229m x 0.457m)

Figure 17: Percentage of fluorescent orange color targets detected and recognized as a function of target size, from Zwahlen et al. (1 in<sup>2</sup>=6.45cm<sup>2</sup>=6.45x10<sup>-4</sup>m<sup>2</sup>, 1 in = .0254 m) [66]

Zwahlen and Schnell [67] investigated the daytime conspicuity of fluorescent and non-fluorescent color targets in the field against green background in terms of visual detection and recognition. Their study is summarized in the following abstract. Daytime conspicuity of fluorescent and non-fluorescent color targets was investigated in the field against green background in terms of visual detection and recognition, as a function of the peripheral angle and the target size. Two groups of 9 young, healthy subjects each were used. The colors white, blue, green, red, fluorescent red, fluorescent yellow-green, yellow, fluorescent yellow, orange, fluorescent orange were presented for 2 seconds at a radial distance of 30m under the peripheral viewing angles of 10°, 20°, 30° for group 1, and 30°, 40°, 50° for group 2. The target sizes 0.076m (3 in) x 0.152m (6 in), 0.114m (4.5 in) x 0.229m (9 in), and 0.152m (6 in) x 0.305m (12 in) were used in group 1, and 0.114m (4.5 in) x 0.229m (9 in), 0.152m (6 in) x 0.305m (12 in), and 0.229 (9 in) x 0.457m (18 in) were used in group 2. Fluorescent color targets (especially fluorescent yellow-green) were better peripherally detected than the non-fluorescent color targets. White, blue, and green were better recognized but exhibited relatively poor peripheral conspicuity. Therefore it appears that if one wants to maximize the peripheral daytime conspicuity, both highly conspicuous fluorescent colors along with a fairly large target size should be selected. Such a target configuration may for example be needed to attract a driver's attention in situations where a target is located in an observer's visual periphery (peripheral angle > 20°), for example a target approaching a driver at an intersection from a left or right side street.

There are two philosophies on fluorescent colors for worker vests. The first is to use fluorescent orange to match the fluorescent orange color scheme used on signs, other traffic control devices, and equipment in the construction zone. The second is to use fluorescent yellow-green because that color is associated with situations where risks to human life are greatest, such as pedestrian crossings in school zones and bicycle crossings. Either color is highly conspicuous and during daytime would be acceptable for workers' vests and clothing. However, one can argue that there is some risk of fluorescent orange worker clothing blending in with fluorescent orange barrels and other fluorescent orange traffic control devices.

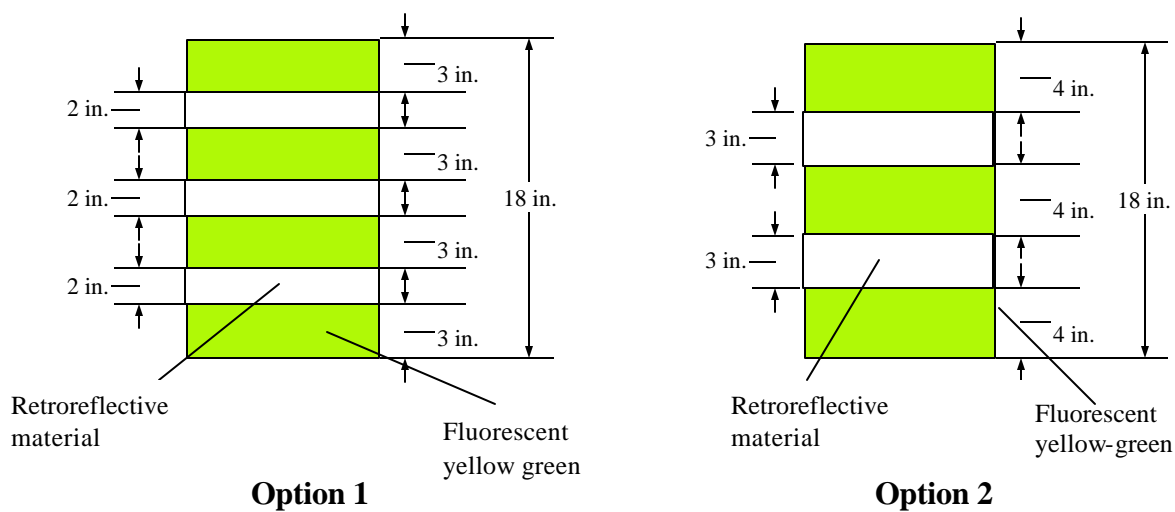
According to the aforementioned literature, specifically the Shinar study [55], the following design recommendations for construction zone workers and highway patrolmen are made.

- Shinar [55] states that retroreflective material used on clothing doubles the recognition distance of pedestrians.
- The use of fluorescent colors in clothing of construction zone workers and highway patrolmen increases the visibility of them.
- The research conducted by Zwahlen et al. [66] indicates the highest recognition distance of targets is observed for fluorescent yellow-green targets during daytime. Thus in order to increase the visibility of construction zone workers and highway patrolmen in the field, fluorescent yellow-green materials should be attached to their clothes.
- For nighttime visibility, retroreflective materials should be attached to personnel to provide greater visibility
- Any vests or other outer garments used, particularly in summer, need to be comfortable. They must breathe and not be heavy or interfere with movement. Workers must wear the clothing to be protected.

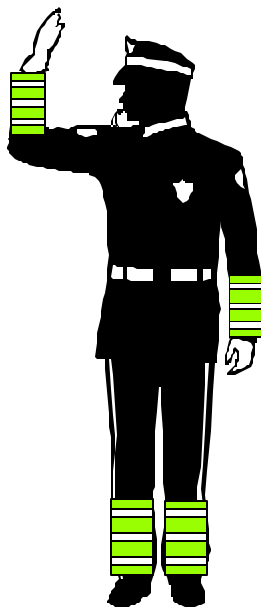


- Different protective clothing options in summer and winter may be required to make clothing comfortable.
- Protective clothing must provide optimum visibility in both wet and dry weather.
- Protective clothing will need to be replaced regularly, before the fluorescence and retroreflectivity decrease significantly.
- Vests and outer garments worn by construction workers need to be designed to break away or tear off or apart if they get caught on construction equipment.
- Protective clothing needs to follow OSHA standards.

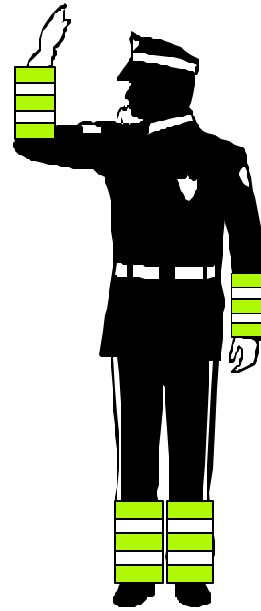
Elastic sleeves, shown in Figure 18, can be used for providing fluorescent and retroreflective markings to the arms and the legs of workers and patrolmen in the field. These are a low cost stopgap measure. During field work, the workers and highway patrolmen would wear these elastic sleeves to their arms and legs during daytime and nighttime. The elastic sleeve has a fluorescent yellow-green color to provide greater visibility during daytime. White retroreflective material is also used to provide greater visibility of the sleeve wearers in the field during nighttime. The elastic sleeves are attached to the arms and legs of the highway patrolmen in the field to increase the visibility of the highway patrolmen (Figure 19). Figure 20 shows the real life application of fluorescent and retroreflective materials on worker clothing.



**Figure 18: Elastic sleeves for increasing the daytime and nighttime visibility of highway patrolmen in the field (2 in = 5 cm, 3 in = 7.5 cm, 4 in = 10 cm, 18 in = 45 cm)**



Option 1



Option 2

**Figure 19: Elastic sleeves worn by construction zone workers or highway patrolmen**



**Figure 20: Example of Conspicuous Daytime and Nighttime Clothing Used in England  
(Picture from *The Columbus Dispatch*, January 22, 2003, p. A11)**

### **2.12.3. Basis for Recommendation**

The highest recognition distance of targets is observed for fluorescent yellow-green targets during daytime and highest recognition distance of targets is observed for retroreflective targets during nighttime. Better visibility of the workers increases their safety by giving drivers more warning to avoid accidents.

#### **2.12.4. Implementation**

In order to increase the visibility and recognition of the workers in work zones, fluorescent yellow-green vests equipped with retroreflective markings should be used. The specifications for the vests will be used by the workers in the work zone should be included in the work zone design guidelines.

#### **2.12.5. Estimated Cost**

The price of retroreflective material equipped safety vests is between \$10 and \$25.

#### **2.12.6. Benefits and Risks**

These vests will provide better recognition distances for workers and increase workers' safety in the work zone.

### **2.13. Equipment Marking**

It would appear to be beneficial to also mark construction machinery used near traffic with conspicuous retroreflective markings. However only the vaguest recommendations have been found in the various Ohio standards, other state or federal documents, or the literature. For instance, CMS Section 614.12 discusses pavement marking operations and states that operations shall be carried out in a truck equipped with necessary flashers and signs, but does not specify further.

More detailed information on the vehicle lighting specifications is given in the New York State Department of Transportation (NYSDOT) guidelines [68]. The vehicle warning light configurations for different types of vehicles is specified in NYSDOT Vehicle Warning Lighting Standards.

- Pickup Trucks/SUVs/Vans: Dual two-bulb rotating beacon plus two supplemental flashers and tailgate striping. As orange flags to enhance visibility.
- Large Dump Trucks: Dual, two-bulb rotating beacons, swing lights, plus dual 4-way flashers (one set at taillight level and one set in the upright of the dump body)
- Small Dump/Stake Body Trucks: Dual, two-bulb rotating beacons plus 4-way flashers and swing lights.
- Mowers/Loaders: Single, two-bulb rotating beacon and 4-way flashers.
- Excavators/Truck-Mounted Cranes: Single, two-bulb rotating beacon and 4-way flashers. If the turntable extends beyond the sides of the vehicle, add an additional two-bulb rotating beacon mounted on the turntable as close to the edge as practical.
- Paint Striper: Dual (one front and one rear), two-bulb rotating beacons with 4-way flashers and arrow board.
- Light Bars: are prohibited.
- Other Visibility Enhancements:
- Painted Markings: They might be applied to rear of all vehicles where configuration permits. Dark blue on yellow stripe sloping downward to the left at a 45 angle. Use 8

inch (20 cm) stripe, at two foot spacing on large vehicles. Use 6 inch (15 cm) stripe with 18 inch (46 cm) spacing on smaller vehicles.

- Orange Flags: Mount on rear corners of vehicles or equipment to enhance visibility.

There may be some OSHA standards for equipment marking, though these are more likely for the safety of workers rather than for the safety of drives. It is expected that enhanced visibility of equipment to workers would also help drivers. It would be a matter of common sense to include some retroreflective markings on all sides of a piece of construction equipment so that it is more clearly visible and recognizable at night.

### ***2.13.1. Basis for Recommendation***

The highest recognition distance of targets is observed for fluorescent yellow-green targets during daytime and highest recognition distance of targets is observed for retroreflective targets during nighttime. Better visibility of the construction equipment increases the safety by giving drivers more warning to avoid accidents.

### ***2.13.2. Implementation***

In order to increase the visibility and recognition of the construction equipment in work zones, rotating beacons, flashers, and retroreflective striping should be used. The specifications for the equipment marking and lighting should be included in detail in the work zone design guidelines.

### ***2.13.3. Estimated Cost***

The price of equipment marking is not known at the moment.

### ***2.13.4. Benefits and Risks***

Improved equipment marking and lighting will provide better recognition distances for construction equipment and increase the drivers' and workers' safety in the work zone.

## **2.14. Flaggers**

TEM Section 604 is related to Flagger Control and provides information supplementing that presented in OMUTCD Chapter 6E. It is stated in TEM Section 604-2 that since flaggers are responsible for public safety and make the greatest number of public contacts of all highway workers, they should have the minimum qualifications described in the OMUTCD.

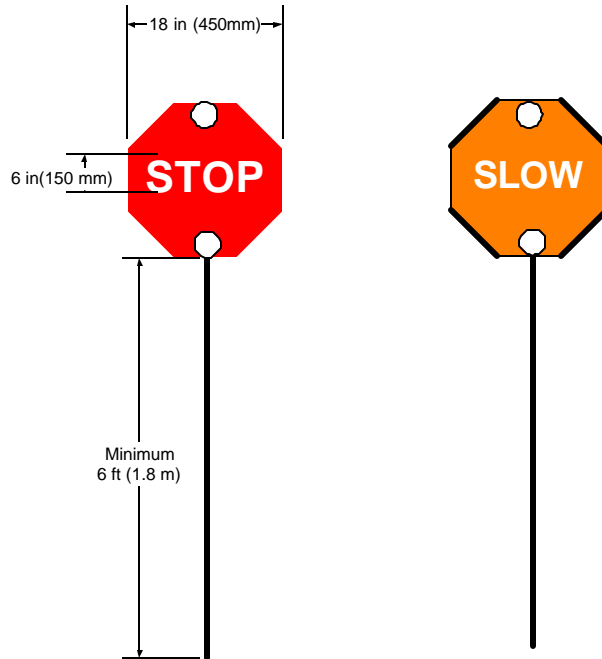
OMUTCD Section 6E.01 states that a flagger should possess the following minimum qualifications:

- Sense of responsibility for safety of public and the workers,
- Adequate training in safe traffic control practices.
- Average intelligence,
- Good physical condition, including sight, mobility, and hearing
- Mental alertness and the ability to react in an emergency,

- Courteous but firm manner,
- Neat appearance,

As stated in a previous section of this report, OMUTCD Section 6E.02 provides info on flagger clothing. It states that the use of orange clothing such as vest, shirt or jacket shall be required for flagger. For nighttime conditions similar outside garments shall be reflectorized. Further, it is stated that flaggers must, at all times, be clearly visible to approaching traffic at a distance that is sufficient to permit proper response by the motorist to the flagging instructions. In positioning flaggers, consideration must be given to maintaining color contrast between flagger's protective garment and his background. TEM Section 604-3 also discusses high-visibility clothing for flaggers. The same high-visibility clothing is recommended for law enforcement officers (LEOs) when they provide traffic control. Occupational Safety and Health Administration (OSHA) also presents the specifications for the flagger clothing. OSHA refers to the MUTCD Millennium edition for flagger clothing in work zones [69].

TEM Section 604-4 is related to hand-signaling devices. OMUTCD Section 6E.03 addresses the basic requirements for hand-signaling devices used to control road users through temporary traffic control zones. As noted in that section, the STOP/SLOW sign paddle is the primary hand-signaling device. OMUTCD 6E.03 says the following regarding sign paddles: Sign paddles should be at least 18 inches (45 cm) wide with letters at least 6 inches (15 cm) high. A rigid handle should be provided. This combination sign may be fabricated from sheet metal or other light semirigid material. The background of the STOP face shall be red with white letters and border. The background of the SLOW shall be orange with black letters and border. When used at night the STOP face shall be reflectorized red with white reflectorized letters and border, and the SLOW face shall be reflectorized orange with black letters and border. In addition to the provisions in OMUTCD Section 6E.03, the STOP/SLOW sign paddle shall have an octagonal shape on a rigid handle. The length of the handle should be a minimum of 6 foot (1.8 meter) from the bottom of the octagonal shape (Figure 21). The STOP/SLOW paddle may be modified to improve conspicuity by incorporating white flashing lights. Two lights may be installed and centered vertically above and below the STOP legend, or centered horizontally on either side of the STOP legend. Instead of this two-light arrangement, one light may be centered below the STOP legend.



**Figure 21: Drawing of the Recommended Flashing Stop/Slow Paddles (meets the MUTCD specifications)**

A different type of stop/slow sign was tested in the project entitled “New Work Zone Safety Devices” [56]. This is described in a video cassette produced by the SHRP and FHWA in 1992. This sign was tested to overcome the difficulty flaggers have in attracting the attention of the drivers. These signs have flashing lights at the top and bottom. This makes them more visible and ensures immediate recognition by drivers. The signs are equipped with ten rechargeable gel batteries, which can be switched on when necessary.

As noted in the OMUTCD, flag use should be limited to emergency situations; however, they may also be appropriate at some intersections and at low-speed and/or low-volume locations which can best be controlled by a single flagger. OMUTCD Section 6E.03 states that flags used for signaling purposes shall be a minimum of 24 by 24 inches (61x61 cm) in size, made of a good grade of red material securely fastened to a staff approximately 3 feet (0.9 m) in length. The free edge should be weighted to insure that the flag will hang vertically, even in heavy winds.

TEM Section 604-5 is related to hand-signaling procedures. STOP/SLOW sign paddle and flag usage is illustrated in OMUTCD 6E-1. The signaling procedures used with the paddle or the flag shall be as described in OMUTCD Section 6E.04:

- When signaling traffic to stop, with either the paddle or the flag, the free arm shall be raised with the palm toward approaching traffic.
- To “alert and slow traffic,” the flagger holding the SLOW paddle face toward road users may motion up and down with the free hand, palm down. However, when signaling with a flag, to alert or slow traffic the flagger shall keep the free hand down.

- The ATSSA publishes a pocket-sized Flagger Handbook which may be used for easy reference on flagging procedures.

TEM Section 604-6 is related to flagger stations. Except as noted below for a single flagger at a “spot” location, flagger stations shall be located far enough ahead of the work space, so that approaching traffic has sufficient distance to stop before entering the work space. This section refers to OMUTCD Section 6E.05. Further, OMUTCD Table 6E-1 provides guidelines for determining the distance of the flagger station in advance of the work space.

**Table 10: Distance of flagger station in advance of the work space (adapted from [4, p. 6-36])**

Speed (mph)	Length (feet)	Speed (kph)	Length (meters)
20	35	30	10
25	55	40	15
30	85	50	30
35	120	60	45
40	170	70	65
45	220	80	85
50	280	90	110
55	335	100	135
60	415	110	170
65	485	120	205

\* Posted speed, off-peak 85<sup>th</sup> percentile speed prior to work starting, or the anticipated operating speed in miles per hour.

These distances may be increased for downgrades and other conditions that affect stopping distance. The flagger should stand either on the shoulder adjacent to the traffic being controlled or in the barricaded lane. A flagger should only stand in the lane being used by moving road users after the road users have stopped. The flagger should be clearly visible to the first approaching driver at all times. The flagger should also be visible to following drivers. The flagger should be stationed sufficiently in advance of the workers to warn them (for example, with audible warning devices such as horns, whistles, etc.) of approaching danger by out-of-control vehicles. The flagger should stand alone, never permitting a group of workers to congregate around the flagger station. At “spot” lane closures where adequate sight distance is available for the safe handling of traffic, the use of one flagger may be sufficient (Figure 698-21 and Section 607-18). At such a “spot” obstruction, a position may have to be taken on the shoulder opposite the barricaded section to operate effectively. Flagger stations should be preceded by proper advance Warning Signs. At night, flagger stations should be illuminated.

It is important that the signs warning that a flagger is ahead not be too far ahead of the actual work location and the flagger. The flagger must be visible from the location of the last flagger symbol sign. In night situations, where traffic control devices must be visible at 600 feet (183 m), the flagger must be no more than 600 feet (183 m) from the last sign and clearly visible.

A stopped traffic sign could be alternated with the flagger sign, particularly in areas where there are curves or obstructions as the work zone is approached. One could use a standard “Watch for stopped traffic” sign or a “Slowed or stopped traffic” sign, though even better would be an adaptation of the Swiss sign shown in Figure 22, from [70], which uses symbols instead of words to convey the same message. We recommend the use of a version of this stopped traffic sign modified for use in Ohio, e.g. with the black cars on a fluorescent orange background.



**Figure 22: Swiss sign used to indicate stopped traffic ahead [70]**

Fontaine et al. [64] evaluated traffic control devices for rural high speed maintenance work zones. This is the report for second year activities and also includes final recommendations. Beyond other six devices evaluated, they have also evaluated a radar activated flagger paddle, but on a more visible basis. They have stated that the effectiveness of the devices evaluated was assessed based on the vehicle speeds in the work zone, the ease of the installation and removal, the impact of the device on vehicle conflicts, and worker comments.

Sutton and Bahar [71] evaluated the flashing STOP/SLOW paddle and based on the impressions of the flaggers concluded that the flashing STOP/SLOW paddles are effective in attracting the attention of motorists. However, because of the increased weight, and difficulty in controlling the devices in adverse conditions, the devices were not endorsed. The devices have a distinct effect on motorists by drawing attention to the flagger, but other more suitable devices are available to supplement the standard STOP/SLOW paddle with highly visible flagger attire, and hand held devices that use illumination to attract the motorists’ attention. Further, they have stated based on this evaluation that the use of flashing STOP/SLOW paddles could be considered as an option for use under the following conditions:

- The stature of the flagger is adequate to control the device in adverse weather, and can endure the additional weight for the duration of the traffic control session.
- The staff for supporting the paddle is of adequate height that the flagger can clearly see beneath the sign, so as not to obstruct the flaggers’ visibility.
- The length of staff for supporting the paddle should accommodate other flagging devices, such as hand held radio for 2-way communications between flaggers when necessary. This is to allow a free hand for directional signals, while accommodating the flaggers’ needs for other associated equipment.



One alternative for the STOP/SLOW paddle flashers might be high beam flashlights. The Z2 flashlight manufactured by Surefire produces 65 lumens for 60 minutes with two 3-volt batteries [72]. The price of the Z2 flashlight is \$86. The specifications for different high beam flashlights are given in [72].

In a study conducted by Woodson and Conover, the researchers recommended flash rates of about 3 to 10 per second with duration of at least 0.05 second. In his study Markowitz made the point that the range of 60 to 120 flashes per minute (1 to 2 per second) appeared to be compatible with human discrimination capabilities [73].

The Iowa DOT and the FHWA [74] also analyzed the flashing stop/slow sign and concluded that the flashing stop/slow paddle is popular with road crews in Iowa because it succeeds where other means have failed. Further they have mentioned that the paddle's benefits include:

- Improved motorist response to warning signals.
- Improved safety for workers and motorists.
- The Maine DOT and the FHWA [75] also analyzed the flashing stop/slow paddle in terms of worker safety on back roads. The authors reported several advantages:
- Flaggers feel better protected from traffic.
- Drivers pay more attention to flaggers and their instructions.
- Working conditions are safer.

It is also important that the flaggers use standardized paddles and signs. This will aid in driver recognition of flagger instructions. In addition to ODOT guidelines, STOP/SLOW sign paddles shall have flashing lights at the top and bottom. This makes them more visible and ensures immediate recognition by drivers. The signs might be equipped with rechargeable gel batteries, which can be switched on when necessary. The batteries might be located at the rigid handle.

Flashing STOP/SLOW sign paddles and the distance between the flagger and the last flagger sign makes flaggers more visible and ensures immediate recognition by drivers. The flashing STOP/SLOW sign paddles might be equipped with rechargeable gel batteries, which can be switched on when necessary. The batteries might be located at the rigid handle.

The position of the flagger and the starting point of the work zone area should not be far from the last flagger sign. If traffic is likely to backup frequently multiple flagger signs should be placed in the work zone. The flagger should not be farther than 600 ft (183 m) from the flagger sign during night conditions.

Also a stopped traffic sign could be alternated with the flagger sign, particularly in areas where there are curves or obstructions as the work zone is approached. New stopped traffic sign should be made and distributed.

STOP/SLOW sign paddles shall have flashing lights at the top and the bottom. The signs can be equipped with rechargeable gel batteries, which can be switched on when necessary.

Flashing lights will increase the visibility and recognition of the flaggers. These recommendations should be included in the work zone design guidelines.

The estimated cost of flashing STOP/SLOW sign paddles differ within the price range of \$95 to \$739. The Z2 flashlight costs \$86. The cost of diamond grade signs similar to the recommended stopped traffic sign differs within the price range of \$45 to \$145.

**Table 11: List of Flashing STOP/SLOW Paddle Manufacturers (18 in =45 cm; 24 in =61 cm) [76]**

MANUFACTURER	TYPE LIGHT	LIGHT POSITION	COST
Med fax. Inc. La Center. WA 98629 206/263-3076, Jack Neighbors	One Strobe Light	Located in the handle below the STOP sign permitting use of 18 inch or 24 inch signs	\$99 Paddle \$16 Stand
Graham-Migletz Enterprises, Inc., P.O. Box 348, Independence, MO 64050 816/254-1788, Jerry Graham	Two Halogen Lights	Located above and below the STOP message	\$400
Columbia Safety Sign Corp. 314 Buckeye St.. Woodland, WA 98674 206/225-7688, John Valdez	One Strobe Light	Located in handle at lower edge of sign. Flashes STOP side only	\$95
A/C Enterprise 6621 Idaho Str., Vancouver, WA 98661 206/695-4050, Monte Arehart	Two Strobe Lights	Located on each side of STOP and SLOW messages	\$175
Action-West 305 West Main St., Kelso, WA 98626 206/577-9150, Michael Williams	Two Strobe Lights	Located right and left of total sign for STOP and SLOW messages	18" \$149 24" \$165
Brittney Safety Signs, Inc. 6947 E. 22 <sup>nd</sup> St., Suite B. Tucson, AZ 85713, 602/884-9283, John Hagemann	Two 12-Volt Auto Lights	Located above and below STOP and SLOW messages	24" \$250

One of the suppliers of flashing STOP/SLOW paddles is Interport Trading Corporation [77]. The flashing STOP/SLOW paddles produced by the company are 18 in (45 cm) signs with diamond grade sheeting on a 55 in (140 cm) mast. The flashing stop/slow paddles are visible at 2100 ft (650 m) in standard daytime conditions. The paddles are equipped with rechargeable NiCad battery packs located in the staff. The unit price for these flashing STOP/SLOW paddles is \$739.

A & A Safety Incorporation [78] is one of the suppliers of the flashing STOP/SLOW paddles in Ohio. The company produces STOP/SLOW paddles with LED. The unit price for the flashing STOP/SLOW paddles produced by A&A Safety Incorporation is \$164.

RoDon Corporation [79] in Illinois is another supplier of flashing STOP/SLOW Paddles. The paddles can be switched between off, single flash, and triple flash modes. The flashers are deactivated when the paddle is positioned horizontally or upside down. The units are powered with rechargeable batteries, and it provides 12-24 hour continuous use between charges. The flashing STOP/SLOW paddles are visible in sunny daytime conditions. The picture of the RoDon Flashing STOP/SLOW Paddles is given in Figure 23.



**Figure 23: RoDon Corporation Flashing STOP/SLOW Paddles**

### ***2.14.1. Benefits and Risks***

Flashing STOP/SLOW sign paddles and the distance between the flagger and the last flagger sign makes flaggers more visible and ensures immediate recognition by drivers.

Flashing STOP/SLOW sign paddles are evaluated by Federal Highway Administration (FHWA) under the Strategic Highway Research Program (SHRP) [80]. According to the project, participating state DOTs reported the advantages of flashing STOP/SLOW paddles as follows:

- Flashing STOP/SLOW sign paddles get drivers' attention more effectively than do conventional devices.
- Flaggers using flashing stop/slow paddles are more successful at getting drivers to slow down.
- Drivers are more aware of work zones.
- Flaggers are better able to protect other workers at temporary work zones.

### ***2.14.2. Evaluation and Research***

Flashing STOP/SLOW paddles are evaluated in a research project sponsored by Strategic Highway Research Program, National Research Council [81]. In this project the researchers evaluated a flashing stop/slow paddle with two lights mounted above and below stop message. The flagger alerts the oncoming traffic by pressing a button on the side of the flashing stop/slow paddle, which activates the lights on the stop face aimed at the traffic. The lights, powerful enough to be seen at distances up to 2,100 ft (640.1 m), flash alternately through 10 cycles. The device is tested on open highway in New York, Texas, and Virginia. The speed data summary of driver responses in all three states are given in Table 12

**Table 12: Speed Data Summary for the Flashing Stop/Slow Paddle**

New York	Standard Flagger Paddle				Flashing Stop/Slow Paddle			
	Advance speed		Approach Speed		Advance speed		Approach Speed	
	(mph)	(kph)	(mph)	(kph)	(mph)	(kph)	(mph)	(kph)
15 <sup>th</sup> Percentile	44.7	71.52	30.7	49.12	45.9	73.44	33.2	53.12
Mean	52.8	84.48	37.5	60	51.7	82.72	45.2	72.32
85 <sup>th</sup> Percentile	53.9	86.24	44.3	70.88	59.8	95.68	57.3	91.68
Standard Deviation	7.32	11.712	6.6	10.56	6.49	10.384	10.54	16.864
<b>Texas</b>			No Work/No Flagger	Work/Flag	Work/Flashing Stop/Slow Paddle			
Location 1								
Sample Size			25	21	23			
Mean			56	57	58			
Standard Deviation			6	5	7			
Location 2								
Sample Size			29	23	23			
Mean			52	48	49			
Standard Deviation			5	6	6			
Average Braking Distance from Flagger			n/a	753 ft (229 m)	709 ft (216 m)			
Standard Deviation			n/a	124 ft (38 m)	125 ft (38 m)			
Location 3								
Sample Size			25	11	1			
Mean			54	36	46			
Standard Deviation			4	8	n/a			
Vehicles Stopped (percent)			n/a	50%	96%			
Virginia	Standard Flagger Paddle				Flashing Stop/Slow Paddle			
	Advance Speed		Approach Speed		Advance Speed		Approach Speed	
	(mph)	(kph)	(mph)	(kph)	(mph)	(kph)	(mph)	(kph)
15 <sup>th</sup> Percentile	34.1	54.56	34.1	54.56	37.2	59.52	32.8	52.48
Mean	38.3	61.28	41	65.6	41.1	65.76	38.4	61.44
85 <sup>th</sup> Percentile	43.6	69.76	50.1	80.16	45.3	72.48	45.5	72.8
Standard Deviation	4.6	7.36	7.33	11.728	4.66	7.456	5.35	8.56

The findings of the field experiment showed that the attention-gaining capability of the Flashing Stop/Slow Paddle provides the flagger with the ability to choose the point at which to slow oncoming traffic. The effectiveness of the Flashing Stop/Slow Paddle to induce slowing of approaching vehicles at an advance location designated by the flagger has been demonstrated in field studies undertaken in New York, Virginia, and Texas. This feature is particularly advantageous under conditions of limited sight distance, where maintenance activity is more likely to surprise approaching motorists. The demonstrated safety benefit of this feature is to reduce the likelihood of rear-end accidents due to sudden slowing and to reduce the likelihood of high-speed vehicles entering the work zone [82]

### ***2.14.3. Other Considerations***

The effectiveness of the distance between the flagger and the last flagger sign distance should be evaluated. In addition, the recognition distance for the flagger should be determined in order to increase the safety of the flaggers. Flashing Stop/Slow paddles from different suppliers might be evaluated. Recognition distances for different devices and their batteries can be evaluated.

## **2.15. Glare Screens**

### ***2.15.1. Present standards and guidelines***

Glare screens are designed and used to shield motorists' eyes from the glare of headlights of oncoming vehicles. They can also serve other purposes, namely to obscure the view of construction work and reduce rubbernecking and perhaps to reduce work zone dust settling onto the roadway. Reducing rubbernecking is key to minimizing the formation of queues due to slowing traffic.

In Section 604 of State of Ohio Department of Transportation Location and Design Manual Volume I, glare screens are defined. Glare screens are used primarily for the shielding of motorists from headlight glare of opposing traffic. They are normally used in the median of divided highways but may be used in other areas where a specific problem exists or anticipated. Glare screen use is justified based on traffic volumes and median widths in unlighted sections, and on traffic volumes and the number of lanes in lighted sections. Figure 604-1 in L&D Manual I shows this relationship. In Section 604-2 expected performance characteristics of glare screens are given. Glare screening may be accomplished in a number of ways. Section 604-3 gives the glare screen options.

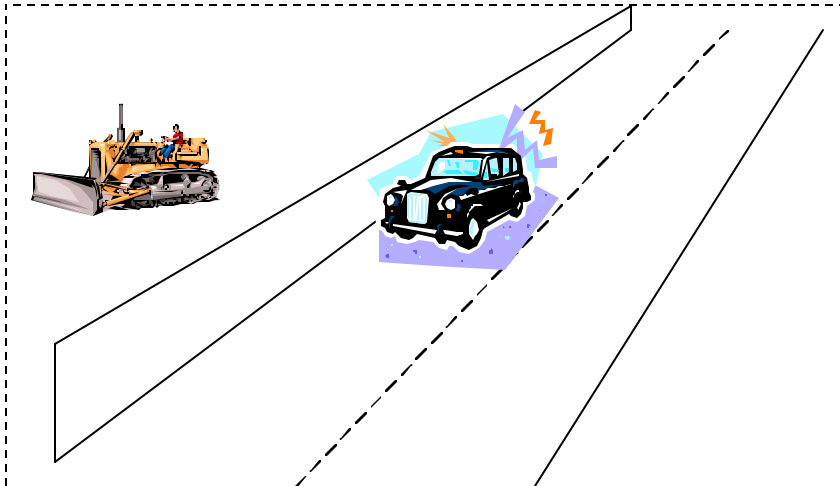
In Section 605-18 of the TEM screens are explained. Screens are used to block the road users' view of activities that can be distracting. Screens might improve safety and motor vehicle traffic flow where volumes approach the roadway capacity because they discourage gawking and reduce headlight glare from oncoming motor vehicle traffic. They can also help contain the work area and reduce the accumulation of dust and debris on the pavement. On ODOT-maintained highways a glare screen shall be used at all crossover locations. The upper portion of the 50-inch (127 cm) portable concrete barrier (PCB) serves as a glare screen. (Figure SCD-RM 4-1).

In Section 642-21 of the TEM, 50-inch portable concrete barrier and 32-inch (81 cm) portable concrete barriers are described. In Standard Construction Drawing RM-4.1, the specifications of 50-inch (127 cm) portable concrete barrier are given. Portable concrete barriers that are 32 inches (81 cm) high with an 18 inch (46 cm) minimum height glare screen may be substituted at the option of the contractor. Paddle or intermittent type glare screens shall be designed using a 20-degree cut-off angle based on tangent alignment. That spacing shall be used throughout the barrier length without regard to barrier curvature.

The glare screen system shall be securely fastened to the 32-inch (81 cm) portable concrete barrier using the hardware and procedures specified by the manufacturer.

In Table 697-1c of the TEM, the objectives of glare screen use are given; they are used to maximize motorist/worker safety and maximize corridor capacity. Glare screens are an effective way to separate work and keep traffic moving, make work safer, and reduce rubbernecking. The cons of glare screens are that they take longer to set up than drums, cost more than 32 inch (81 cm) barriers without screens, may reduce driving speed, and can interfere with wide loads. There are restrictions on glare screen widths in certain areas, and there are also sight restrictions at intersections and ramps.

Existing standards for glare screens are designed to reduce glare from headlights of oncoming traffic. To reduce rubbernecking behavior due to interest for work zone activities, glare screen height would need to be raised considerably.



**Figure 24: Depiction of glare screen used to obscure view of work zone from traffic**

### ***2.15.2. Height of screens to obscure work zone activities***

In the study, “Driver-Headlamp Dimensions, Driver Characteristics, and Vehicle and Environmental Factors in Retroreflective Target Visibility Calculations” conducted by Zwahlen and Schnell [83] the average driver eye heights for various vehicle types are calculated. 1988 U.S. Army Personnel Data is used in the calculation of the driver eye height positions. The maximum eye height position resulted from the use of the data for average large vans or bus,

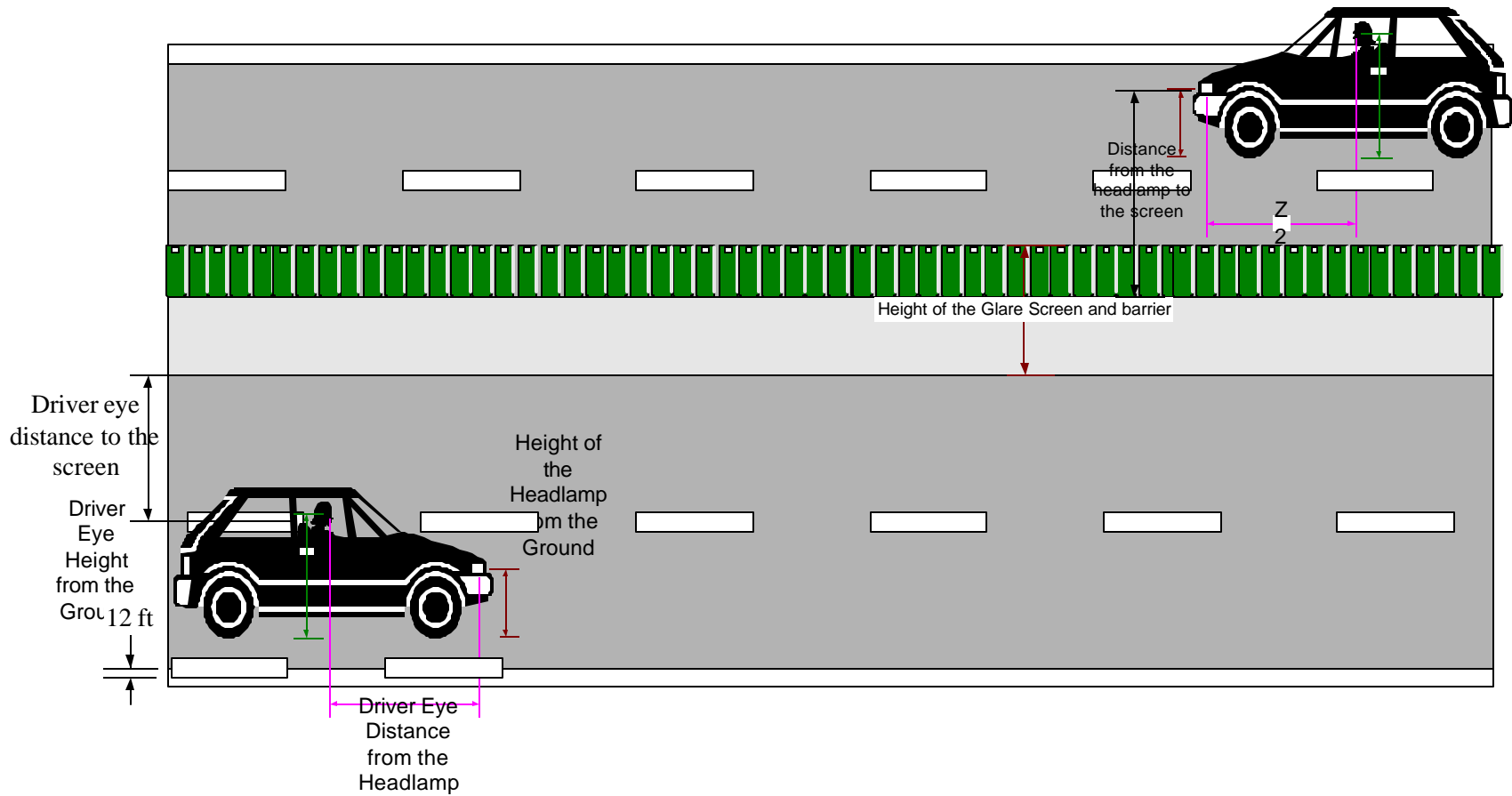
which have dimensions similar to those of trucks. The 95<sup>th</sup>-percentile adult driver eye height of a large van or bus is found to be 1920 mm (76.1 in), as indicated in Table 13 [83].

### ***2.15.3. Computing height of screens to shield drivers from glare of oncoming cars***

The second purpose glare screen are used for is to reduce headlight glare from oncoming motor vehicle traffic. The height of glare screens should accommodate most motorists, including truck and bus drivers. This height depends basically on 4 variables:

- The height of the driver's eye
- The height of the headlamps of the oncoming vehicle
- The eye distance from the driver in the vehicle to the glare screen in the direction perpendicular to travel
- The headlamp distance from the oncoming vehicle to the glare screen in the direction perpendicular to travel

The last two variables will be different depending on which lane the vehicle is in. Figure 25 illustrates these variables.



**Figure 25: Variables used in the calculation of the recommended glare screen heights. Lane width is 12 ft (3.66 m).**



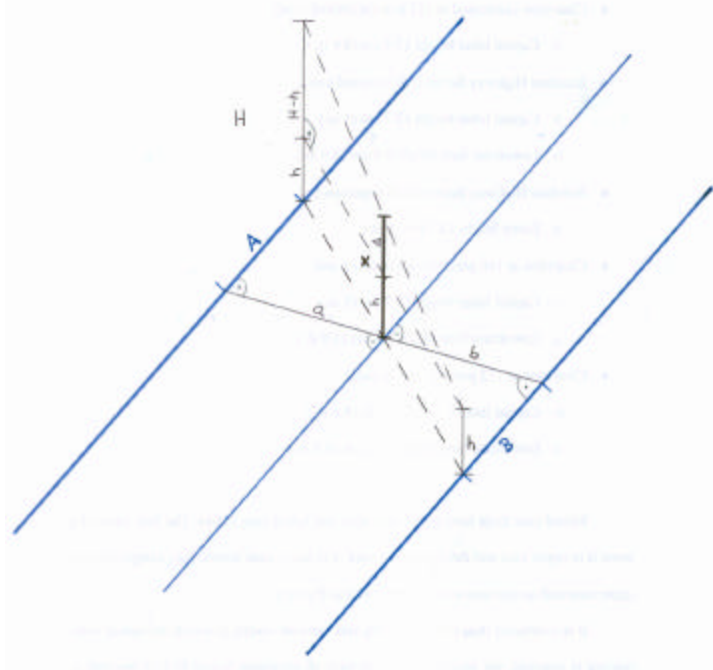
The values of the aforementioned variables can be obtained from the paper of Zwahlen and Schnell [83]. The values apply for 95% of all adults. For the eye distance to the glare screen it is assumed, that the vehicle is driving in the center of a 12 ft (3.66 m) wide lane.

**Table 13: 95th percentile longitudinal and vertical eye positions resulting from applying 1988 US Army personnel anthropometric data to average dimensions of surveyed vehicles. Adapted from Zwahlen and Schnell [83]**

Vehicle type	95 <sup>th</sup> percentile Vertical distance from ground to eyes (mm)			95 <sup>th</sup> percentile Vertical distance from ground to headlamps (mm)	Driver eye distance from the center of the vehicle	Headlamp distance from the center of the vehicle
	Female (N=2208)	Male (N=1774)	Adults (N=3982)			
Compact car (N=12 cars)	1202 (47.3 in)	1256 (49.4 in)	1242 (48.9 in)	620 (24.41 in)	332 (13.37 in)	527 (20.75 in)
Minivans (N=5 vans)	1530 (60.2 in)	1584 (62.4 in)	1570 (61.8 in)	756 (29.76 in)	425 (16.73 in)	677 (26.65 in)
Large vans or buses (N=7 vehicles)	1880 (74 in)	1934 (76.1 in)	1920 (75.6 in)	832 (32.76 in)	493 (19.41 in)	729 (28.7 in)

Calculations for all possible combinations of car type and lane were done. The geometrical model and the resulting formulas are in Figure 26. **Table 14** [mm] and **Table 15** [in] show the results for the different combinations of vehicles and lane positions.

**Figure 26: Derivation of Barrier Height for Different Vehicle Types and Positions**



Given:

- H = height of drivers eyes
- h = height headlamps of oncoming car
- a = perpendicular distance of drivers eyes from glare screen
- b = perpendicular distance of headlamps of oncoming car from glare screen
- A + B = longitudinal distance between cars

Unknown:

x = total barrier height

Derivation:

$$x = h + \Delta$$

$$\frac{H - h}{\sqrt{A^2 + a^2} + \sqrt{B^2 + b^2}} = \frac{\Delta}{\sqrt{B^2 + b^2}}$$

$$\Delta = \frac{(H - h) \cdot \sqrt{B^2 + b^2}}{\sqrt{A^2 + a^2} + \sqrt{B^2 + b^2}}$$

substitute  $A$  and  $B$

$$\boxed{\begin{array}{l} A + B = D \\ \frac{A}{B} = \frac{a}{b} \\ A = B - D \end{array}}$$

$$\rightarrow \frac{D - B}{B} = \frac{a}{b}$$

$$\rightarrow D - B = \frac{a}{b} \cdot B \Rightarrow A = D - \frac{b \cdot D}{a + b}$$

$$\rightarrow D = \left(\frac{a}{b} + 1\right) \cdot B \rightarrow A = D \cdot \left(1 - \frac{b}{a + b}\right)$$

$$\rightarrow \underline{B = \frac{b \cdot D}{a + b}} \quad \rightarrow \underline{A = D \cdot \left(\frac{a}{a + b}\right)}$$

$$\Rightarrow \Delta = \frac{(H - h) \cdot \sqrt{\frac{b^2 D^2}{(a + b)^2} + b^2}}{\sqrt{\frac{a^2 D^2}{(a + b)^2} + a^2} + \sqrt{\frac{b^2 D^2}{(a + b)^2} + b^2}}$$

$$\Rightarrow x = h + \frac{(H - h) \cdot \sqrt{\frac{b^2 D^2}{(a + b)^2} + b^2}}{\sqrt{\frac{a^2 D^2}{(a + b)^2} + a^2} + \sqrt{\frac{b^2 D^2}{(a + b)^2} + b^2}} = h + \frac{(H - h) \cdot b}{a + b}$$

**Table 14: Calculated total height of glare screen for 95% of drivers [mm]**

Driver on the right lane, oncoming vehicle on the opposite right lane

		Drivers eye position		
		compact car	minivan	large van or bus
Headlamp position	compact car	955	1136	1330
	minivan	1021	1203	1399
	large van or bus	1056	1239	1435

Driver on the right lane, oncoming vehicle on the opposite left lane

		Drivers eye position		
		compact car	minivan	large van or bus
Headlamp position	compact car	815	922	1037
	minivan	915	1026	1145
	large van or bus	968	1080	1201

Driver on the left lane, oncoming vehicle on the opposite right lane

		Drivers eye position		
		compact car	minivan	large van or bus
Headlamp position	compact car	1118	1390	1684
	minivan	1147	1419	1713
	large van or bus	1162	1434	1728

Driver on the left lane, oncoming vehicle on the opposite left lane

		Drivers eye position		
		compact car	minivan	large van or bus
Headlamp position	compact car	1000	1215	1450
	minivan	1060	1278	1515
	large van or bus	1091	1308	1547

**Table 15: Calculated total height of glare screen for 95% of drivers [in]**

Driver on the right lane, oncoming vehicle on the opposite right lane

		Drivers eye position		
		compact car	minivan	large van or bus
Headlamp position	compact car	38	45	52
	minivan	40	47	55
	large van or bus	42	49	56

Driver on the right lane, oncoming vehicle on the opposite left lane

		Drivers eye position		
		compact car	minivan	large van or bus
Headlamp position	compact car	32	36	41
	minivan	36	40	45
	large van or bus	38	43	47

Driver on the left lane, oncoming vehicle on the opposite right lane

		Drivers eye position		
		compact car	minivan	large van or bus
Headlamp position	compact car	44	55	66
	minivan	45	56	67
	large van or bus	46	56	68

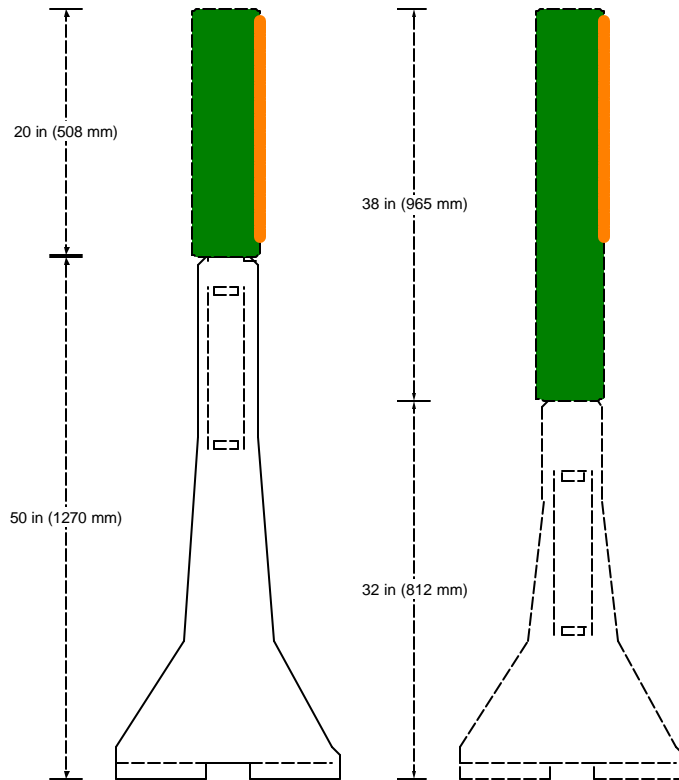
Driver on the left lane, oncoming vehicle on the opposite left lane

		Drivers eye position		
		compact car	minivan	large van or bus
Headlamp position	compact car	39	48	57
	minivan	42	50	60
	large van or bus	43	51	61

It follows that to prevent 95% of large van and bus drivers from the glare of oncoming large vans and busses, the total height of the separator should be 70 inches (178 cm). This height will also protect drivers of other types of vehicles from all normal headlight configurations, e.g. compact car from large van or bus. This height may be obtained by adding a 20-inch (50 cm) glare screen onto a 50-inch (127 cm) portable concrete barrier or a 38-inch (97 cm) glare screen onto a 32-inch (81 cm) portable concrete barrier. However 32-inch (81 cm) portable concrete barrier along with 38-inch (97 cm) glare screens are less effective in preventing large SUV's, pick-ups, trucks, buses, and other large vehicles from running over the barriers. Temporary concrete barriers are recommended to be 50-inch (127 cm) high in order to be effective for large vehicles.

In addition to reducing headlight glare from oncoming motor vehicle traffic, glare screens can improve the delineation. To achieve this purpose glare screens should be equipped with reflective stripes as shown below. [85]. The distance between single boards should be 10 in to 20 in (25-50 cm). Furthermore, the screens used in the work zone can also help contain the work area and reduce the accumulation of dust and debris on the pavement. Taking into consideration

all discussed requirements it is recommended to design glare screens as shown in Figure 27 below.



**Figure 27: Drawing of proposed glare screens of 70 inch (178 cm) height to shield 95% of all drivers, including those of trucks and busses. On the left is a 20 inch (50 cm) glare screen mounted on a 50 inch (127 cm) jersey barrier and on the right is a 38 inch (97 cm) glare screen mounted on a 32 inch (81 cm) jersey barrier. Each glare screen is equipped with a reflective fluorescent orange strip made of Type IX retroreflective sheeting.**

#### **2.15.4. Basis for Recommendation**

Glare screens will reduce the headlight glare from oncoming motor vehicle traffic. By equipping them with reflective stripes, they will also be effective for the delineation of the traffic through the work zone. Glare screens also can help reduce the accumulation of dust and debris on the pavement.

Reducing glare from the oncoming vehicles will improve the comfort level of drivers during nighttime conditions, and especially for older drivers. Older drivers are more affected by glare in nighttime driving conditions. Using retroreflective stripes with glare screens will also improve the traffic flow. Better guidance in the work zone area will be achieved with the reflective stripes.

### ***2.15.5. Implementation***

When using 50-inch (127 cm) high portable concrete barriers, 20-inch (50 cm) high glare screens will be sufficient to prevent the glare, and for the 32-inch (81 cm) high portable concrete barriers 38-inch (97 cm) high glare screens will be sufficient. The height requirements for the glare screens should be included in the work zone design guidelines. Glare screens should be mounted to jersey barriers through the work zones.

### ***2.15.6. Estimated Cost***

The cost of 97.5 inch (248 cm) long base rail with four 20 inch (50 cm) high glare screens equipped with high intensity reflective film is \$81.32.

### ***2.15.7. Benefits and Risks***

Glare screen will improve the traffic flow in the work zone area by providing better guidance and by preventing the rubbernecking behavior of drivers gawking at work zone activities. In addition, preventing glare will increase the comfort level of the drivers.

### ***2.15.8. Other Considerations***

The maintenance of glare screens is an important consideration for implementation. After the implementation of the glare screens in the work zone area, they have to be checked on a regular basis. Missing screens should be replaced. The screens should be kept clean to maintain reflectivity and delineation from the reflective stripes. This implies additional maintenance costs.

## **2.16. Lighting**

TEM Section 605-12 covers lighting devices. TEM Section 605-12.1 states that lighting devices should be provided in temporary traffic control zones based on engineering judgment. TEM Section 605-12 refers to the OMUTCD Section 6F.69. OMUTCD Section 6F.69 mentions that lighting devices may be used to supplement retroreflectorized signs, barriers, and channelizing devices.

Previous research has indicated that lighting is one of the most important elements of nighttime construction [86]. Safety in work zone, traffic control, quality of work, and workers' morale are all directly related to work zone lighting. Limited or restricted visibility is an obvious drawback of nighttime construction. However, with proper lighting conditions construction operations can be performed at night as well as during the day. On the other hand, improper lighting directly contributes to increases in worker injury rates [87]. Lack of lighting can also adversely affect work quality because many defect causes, such as shadows, tack spread, asphalt droppings, and so forth, cannot be properly controlled [88]. Ellis et al. [86] further state that despite the importance of the lighting conditions the lighting specifications of the many states are minimally defined and most of the specified requirements are not adequate.

Four types of lighting devices are commonly used in temporary traffic control zones:

- floodlights
- flashing warning beacons
- warning lights
- steady-burn electric lamps.

TEM Section 605-12.2 is about floodlights. When nighttime work is being performed, floodlights should be used to illuminate the work area, flagger stations, equipment crossings and other areas. TEM Section 605-12.2 states that floodlighting shall not produce a disabling glare condition for approaching road users. Further, the adequacy of the floodlight placement and elimination of potential glare should be determined by driving through and observing the floodlighted area from each direction on all approaching roadways after the initial floodlight setup, at night, and periodically. Ellis et al. [86] state that decisions pertaining to work zone lighting are left to the discretion of site engineers and contractors, however; instead, specifications shall be stated throughout the state.

Lighting is often provided to illuminate the roadway at locations of significant geometric change. For example: All temporary crossover areas shall be illuminated as shown in SCD MT-100.00. When a lane shift will be used for over fourteen consecutive days and existing lighting is not available, consideration may be given to providing a temporary lighting system along the tapers. Illumination of shift areas is illustrated in SCD MT-102.10 (Transition Plan for Use of Shoulder with PCB).

Lighting shall be provided along tapers on high-speed highways, which are not permanently lighted if the taper rate does not meet the minimum requirements called for in Table II of SCD 102.10. Continuous lighting of the work areas between tapers is only required when the tapers are provided with temporary lighting and the distance between the tapers is less than 2000 feet (610 meters).

OMUTCD Section 6F.70 is related to Floodlights. TEM Section 605-12.3 concerns flashing warning beacons (flashing electric lights/hazard identification beacons). They are often used to supplement a temporary traffic control device. TEM Section 605-12.3 refers to OMUTCD Sections 6F.71 for operation and placement information of flashing warning beacons. As noted in the example in OMUTCD Section 6F.71, the temporary terminus of a freeway is an example of a location where flashing warning beacons alert drivers to the changing roadway conditions and the need to reduce speed in transitioning from the freeway to another roadway type.

TEM Section 605-12.4 is about steady-burning electric lamps. Steady-burn electric lamps are a series of low-wattage, yellow, electric lamps, generally hardwired to a 110-volt external power source. They may be used in place of Type C steady-burning warning lights that are explained in TEM Section 605-12.5.

TEM Section 605-12.5 covers warning lights. As noted in OMUTCD Section 6F.72, warning lights are portable, lens-directed, enclosed, low wattage, normally battery-powered, yellow lights which may be mounted on barricades, drums, vertical panels or other suitable

supports. They may be used in either flashing (Type A or B) or steady (Type C) modes. The lightweight and portability of warning lights are advantages that make these devices useful as supplements to the retroreflectorization on signs and channelizing devices. The flashing lights are effective in attracting road users' attention. Warning lights shall be in accordance with the current ITE purchase specification for flashing and steady-burn warning lights (OMUTCD Section 1A.11). When warning lights are used, they shall be mounted on signs or channelizing devices in a manner that if hit by an errant vehicle they will not be likely to penetrate the windshield. The maximum spacing for warning lights should be identical to the channelizing device spacing requirements. When used to delineate a curve, Type C warning lights should only be used on devices on the outside of the curve, and not on the inside of the curve.

TEM Section 605-12.5 refers to OMUTCD Section 6F.72 and TEM Section 605-11.4.2 for additional information about the use of steady-burning warning lights with drums.

TEM Section 605-12 does not include information about temporary roadway lighting. The only place that refers to temporary roadway lighting is TEM Section 606-5.

TEM Section 605-13 is about temporary traffic control signals. It is stated that it is often necessary to install temporary traffic signals in order to maintain traffic through temporary traffic control zones. TEM Section 605-13 refers to OMUTCD Section 6F.74 and to OMUTCD Part 4, which governs permanent traffic signals. TEM Section 605-13 provides additional information on the use of traffic signals in temporary traffic control zones and refers to TEM Part 4 for applicable information. Temporary traffic control signals are typically used in work zones such as temporary haul road crossings; temporary one-way operations along a one-lane, two-way highway; temporary one-way operations on bridges, reversible lanes, and intersections. TEM Figure 698-16 and the SCDs MT-96.10, 96.11 and 96.21 address the use of temporary traffic signals to maintain two-way traffic in a single lane.

Further, TEM Section 605-13 refers to OMUTCD Part 4 and TEM Part 4 for design of traffic signals and to TEM Section 642 (the maintenance of traffic signals and flasher notes) for common procedures for maintaining traffic signals during construction. One suggestion that could be used to cut down on glare for drivers from work site illumination is to have the contractor or a state official drive through the work zone in both directions at night, and then report their findings back by email immediately to the ODOT Office of Traffic Engineering.

The Ellis et al [86] study is unique in the illumination area. Their research conclusions are summarized in Table 16 and Table 17.



**Table 16: Suggested illumination categories and levels for typical highway construction and maintenance tasks adapted from [55]**

Task No.	Task Description (Construction)	Factors					Compared Averages	Suggested Illumination	
		Imp.	Refl.	Spd.	Size	Dist.		Category	Level lx (fc)
1	Excavation - regular, lateral ditch, channel	L	L	N	L	L	1.3	I	54 (5)
2	Embankment, filling and compaction	L	L	M	L	L	0.8	I	54 (5)
3	Barrier walls, traffic separators	M	M	N	M	L	10	II	108 (10)
4	Milling and removal	M	M	M	M	L	10	II	108 (10)
5	Resurfacing	M	H	M	L	L	10	II	108 (10)
6	Concrete pavement construction	M	H	L	M	L	10	II	108 (10)
7	Subgrade stabilization & construction	L	L	L	L	M	1.86	I	54 (5)
8	Base courses - clay, cement, asphalt	M	L	M	M	L	10	II	108 (10)
9	Surface treatment	M	H	M	L	L	10	II	108 (10)
10	Waterproofing/sealing	M	H	M	M	M	10	II	108 (10)
11	Sidewalks	M	M	L	L	M	20	II	108 (10)
12	Riprap	M	M	L	M	M	17.5	II	108 (10)
13	Guardrail, fencing	M	M	N	M	M	15.7	II	108 (10)
14	Painting stripes/markers/metal buttons	M	H	M	S	L	10	II	108 (10)
15	Landscaping, grassing, sodding	L	L	N	L	L	1.3	I	54 (5)
16	Highway signing	M	M	N	M	M	15.7	II	108 (10)
17	Traffic signals	H	M	N	S	S	43.3	III	216 (20)
18	Highway lighting system	H	M	N	S	M	70	III	216 (20)
19	Bridge decks	M	L	N	M	M	10	II	108 (10)
20	Drainage structures, culverts, storm sewer	M	M	N	L	M	13.3	II	108 (10)
21	Other concrete structures	M	H	L	M	L	10	II	108 (10)
(Maintenance)									
22	Maintenance of earthwork/embankment	L	L	M	L	L	0.6	I	54 (5)
23	Reworking shoulders	L	H	M	L	L	0.4	I	54 (5)
24	Repair of concrete pavement	M	M	M	S	M	10	II	108 (10)
25	Crack filling	H	M	L	F	M	30	III	216 (20)
26	Pot filling	M	M	N	F	M	13.3	II	108 (10)
27	Resetting guardrail/fencing	M	M	N	M	M	15.7	II	108 (10)

**Table 17: Summary of illumination measurements by work task adapted from [55]**

Category Target Illumination Level	Task	Measured Illumination (Average)
I 54 lx (5 fc)	Water movement Sweeping Clean up Pavement rolling	54 - 60.4 lx (5.0 - 5.6 fc)
II 108 lx (10 fc)	Asphalt paving Worker activity around paver Racking, shoveling asphalt	154.4 lx (14.3 fc)
III 216 lx (20 fc)	Maintenance of equipment Setup of asphalt distributor	382.3 lx (35.4 fc)

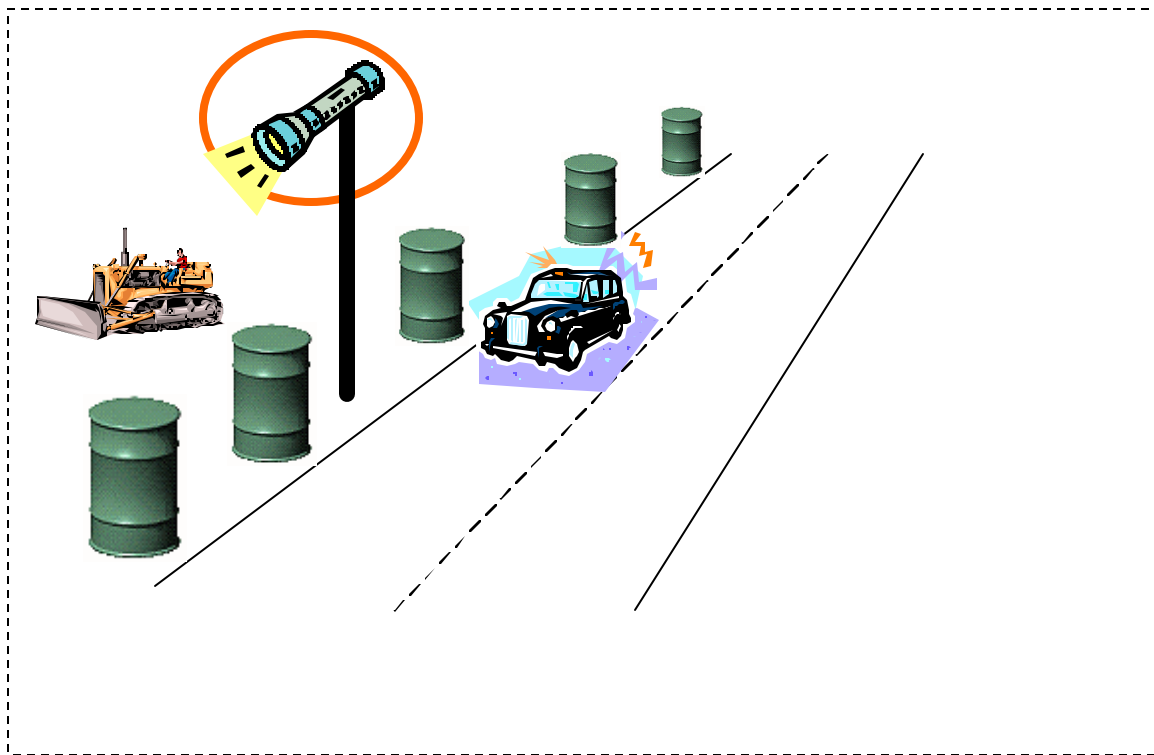
The resulting illumination guidelines present three categories of illumination requirements with suggested target illumination values. Ellis et al. [86] presents those three categories as follows:

Category I, 54 lux (5 fc): recommended for general illumination in a work zone primarily for safety in the area where crew movement is expected to take place or is taking place and for tasks for which low accuracy is sufficient, such as those involving slow moving equipment and requiring visual tasks with large objects;

Category II, 108 lux (10 fc): recommended for illumination on and around construction equipment and for the visual tasks associated with the equipment, such as resurfacing, and

Category III, 216 lux (20 fc): recommended for tasks that present higher levels of visual difficulty and require significant attention from the observer, such as crack filling, critical connections, and maintenance of electrical devices or moving machinery.

More detailed information is presented in the *Guidelines for Work Zone Illumination Design* [90]. Figure 28 depicts a work zone illumination setup where the illumination is aimed away from drivers to minimize glare.



**Figure 28: Depiction of work zone illumination facing away from traffic to avoid glare on drivers**

### **2.16.1. Basis for Recommendation**

The standardization of lighting in the work zone area will provide better visibility for the drivers in the work zone. Better illumination in the work zone will reduce glare for drivers.

### **2.16.2. Implementation**

The required levels of illumination for each category should be included in the work zone design guidelines.

### **2.16.3. Estimated Cost**

The state official or a contractor staff will drive through the work zone area after the implementation of illumination devices. Time and salary of state official or contractor evaluating the lighting implementation should be included.

### **2.16.4. Benefits and Risks**

Reducing glare caused by the illumination of the work zone area will improve the drivers' safety and visibility and it will reduce the accidents in the work zone.

## **2.17. Materials and Hardware**

The approach to be followed in ensuring the safety performance evaluation of highway features such as those used for separating traffic from all roadside appurtenances such as traffic barriers, barrier terminals and crash cushions, bridge railings, sign and light pole supports, and work zone hardware is explained in Section 620 of the TEM.

As outlined, all ODOT maintenance of highway operations, regardless of whether the highway is on the National Highway System or not, are to follow the safety criteria outlined in the NCHRP Report 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* [91]. These are in addition to the requirements outlined in the OMUTCD and the TEM.

Section 620 of the TEM also outlines the requirements for sheeting materials used in temporary traffic control devices. The adequacy of ODOT sheeting material specifications and modifications necessary were discussed in a previous section. Those recommendations should also be applied here to temporary TCD sheeting materials.

Standards provided in the AASHTO's *Quality Standards for Work Zone Traffic Control Devices* [9292] are also to be utilized in determining the appropriateness of TCD sheeting material. This standard is a source for contractors and agency personnel to judge when a traffic control device has outlived its usefulness. Descriptions of work zone devices are illustrated with three levels of device conditions: acceptable, marginal, and unacceptable. Devices described include signs, barricades, drums, cones, tubes, warning lights, arrow displays, portable changeable message signs, pavement markings, and markers. However, when traveling through the various construction zones in the state of Ohio, one can often observe many TCDs that can be categorized as 'unacceptable' according to the ASSTA standard, such as drums with missing reflective material or substantial disfigurement, cones with large areas of staining due to asphalt splatter or other impurities, etc. Therefore, it is always necessary to ensure that the ASSTA standards are strictly adhered to in work zones.

## **2.18. Planning and Programming**

Section 630 of the TEM provides guidelines on planning and programming temporary traffic control operations. The compendium of traffic control operations provides a very comprehensive summary of the advantages, disadvantages, restrictions and also when to use each type of device or operation.

ODOT Policy 516-003(P) also provides additional guidelines for traffic management in work zones interstates and other freeways. The procedure to be followed and personnel responsible in preparing Permitted Lane Closure Maps (PLCM) for each of the districts is outlined in this policy. The PLCM defines the allowable times a lane(s) may be closed on the Interstate/freeway system in that district. Thus compliance to the PLCM in managing construction zones within the district will ensure efficient traffic flow through these regions.

## **2.19. Design Information**

Section 640 of the TEM provides guidelines and references used in designing the maintenance of traffic portion of a highway construction plan. Maintenance of Traffic Plans are to be prepared considering the capacity constraints on the roads. The capacity constraints to be considered in the various types of facilities are discussed in detail in this section. In addition information is also provided in the Location and Design Manuals [93].

A discussion of the geometrics that should be used in determining the minimum road width in construction zones is provided. Thus according to this guideline road width should not be less than 10 feet (3 m) on any highway unless the lane widths on the existing facility are less than 10 feet (3 m).

The sequence of construction activities necessary to coordinate the maintenance of traffic details is also to be included in the construction plans. The sequence is to include the different stages, phases and steps involved especially in large-scale projects.

Section 640-4 of the TEM specifies the procedure to be followed in implementing lane closures in construction work zones. Lane closures should be implemented only after evaluating the impact on traffic flow. A methodology that can aid in determining the most appropriate partial lane closure strategy for interstate work zones depending on the features of a project (work zone length, traffic volume, duration, accident information etc.) was experimented by Pal and Sinha [94]. They also developed software that can be used easily to determine the most suitable strategy. The issue of lane closures is closely related to the issue of creating temporary traffic lanes to maintain traffic flow. Nothing in the literature was found pertaining to the creation of and criteria for using temporary lanes; this question will ultimately be addressed in Phase 2 of this research project.

The literature search did not turn up any software for automatic traffic control device placement. None of the surveyed states indicated that they used such a system to plan their work zones.

## **2.20. Plan Preparation/Production**

Section 641 of the TEM describes the various sources which contain information on plan preparation and plan production as they relate to work zone operations. The Temporary Traffic Control Plan and the different components that have to be included in such a plan are also detailed. Information about plan sheets, plan notes, sequence of operation notes, designer notes, quantities, plan reviews, waiver approval and, traffic plan insert sheets are provided. In addition detailed information about each of the different Standard Construction Drawings (SCDs) and their applications is also presented.

## **2.21. Guard Rails, Barrier Markers, and Delineation Devices**

Guard rails, barrier markers, and delineation devices appear to have been standardized in every state in that every state, including Ohio, appears to follow the federal MUTCD. No innovations in this area were uncovered by the survey of state departments of transportation and nothing new was found in the literature.

## **2.22. Public Education**

The Ohio Department of Public Safety publishes the *Digest of Ohio Motor Vehicle Laws* that is studied by people wanting to get a driver's license [95]. The current (11/02) edition has half a page on construction zones (page 54), focusing on signs used. It is recommended that the treatment of work zones in the *Digest of Ohio Motor Vehicle Laws* be substantially increased, including information on the nature of hazards to workers and drivers in a construction zone and the law that fines are doubled (or tripled if another recommendation of this report is implemented). Drivers should be informed of the necessity to choose safety over speed in work zones.

In the section on night driving (page 59), there is no caution against driving at a speed faster than that with a stopping distance less than your headlight beam distance. While this isn't strictly a work zone issue, it does become important in work zones, for instance if a traffic control device gets out of place.

## **2.23. Pavement Markings and Raised Pavement Markers**

Part 600 of Traffic Engineering Manual [96] concerns temporary traffic control. Section 606 deals with the types of temporary traffic control zone activities, Section 607 describes typical applications, Section 640 provides design information, and Section 641 presents plan preparation/production information. There are four TEM Sections specifically related to crossovers within the aforementioned TEM Sections: Section 606-16, Section 607-38 through 607-40, Section 640-12, and Section 641-9. Table 697-14 presents crossover design details. Drawings of crossovers are presented in Figure 698-41 (median crossover on freeway), Figure 698-42 (median crossover for entrance ramp), Figure 698-43 (median crossover for exit ramp), Figure 698-48 (crossover design details), and Figure 698-49 (crossover design plan view).

The Standard Construction Drawings [98] also include specific drawings for crossovers at work zones. SCD MT-95.70 is the main drawing for crossovers and provides design guidelines for two-lane, two way operation for use on four lane divided roadways (portable concrete

barrier). SCD MT-95.30 (closing right or left lane of a multi-lane divided highway with drums), SCD MT-101.60 (gates and barricades), SCD MT-101.70 (portable concrete barrier delineation), and SCD MT-95.82 (adjustment for two-lane, two way operation on four lane divided roadways) are further referenced in SCD MT-95.30 and TEM Section 640.12 since they are also relevant to crossover design. It is also specified that all crossover areas shall be illuminated according to SCD MT-100.00 (work zone crossover lighting system).

TEM Section 606-16 provides very limited information about delineation. It is stated here that “A good array of channelizing devices, delineators, and full-length, properly placed markings should be used to provide drivers with a clearly defined travel path.” Further, it is mentioned that “Temporary traffic barriers and the excessive use of temporary traffic control devices cannot compensate for poor geometric and roadway cross-section design of crossovers.”

TEM Section 607-12 together with OMUTCD Figure 6H-39 provides information related to median crossovers on freeways. The information regarding driver guidance contained in the standard is “Channelizing devices or temporary traffic barriers shall be used to separate opposing motor vehicle traffic”. Additional guidance is given, including “For long term work on high speed, high volume highways, consideration should be given to using a temporary traffic barrier to separate opposing motor vehicle traffic.” Most of the other information not only in this TEM Section but also in the figure is related to signing. TEM Section 607-13 and Figure 698-4 and OMUTCD Figure 6H-40 are about median crossovers for entrance ramps; however neither provides any information about delineation practices.

It is mentioned in TEM Section 620-6 that the pavement markings shall conform to CMS Item 614.10. However, additional information on pavement markings is provided in CMS Item 614.11 and not in 614.10. This typographical error needs to be corrected.

TEM Section 640-12 deals with crossover construction. It is stated that “Adjacent lanes, carrying traffic flowing in opposite directions on what are normally divided highways, shall be separated by a concrete barrier.” No other information about driver guidance is provided.

TEM Section 641-9 together with SCD MT-65-70, SCD MT-95-82 and SCD MT-100.00 provides the most detailed information about two-lane, two way operations on four-lane divided highways. TEM Section 641-9.4 is about pavement markings and refers other TEM Sections such as TEM Section 605-11.10, TEM Section 605-11.11, and CMS Item 614-10 for additional information on work zone pavement markings. TEM Section 605-12 and SCD MT-101.20 is also referenced for information about work zone raised pavement markers.

TEM Subsection 641-9.6 is about the provisions for reverse flow and use of shoulder; it states that: “If any bridge parapets, safety curbs, etc. restrict the width available for the lane throughout the remainder. If this construction would bring the available lane width to less than 10 feet (3 m), the shoulder should not normally be used. Even if 10-foot (3-meter) or wider lanes are still provided, the obstruction should be well delineated. Bridge end markers (X-6) and barrier reflectors on guardrail or parapets will usually be desirable and may be reduced to 25 foot (7.6 meter) spacing when very close to the traffic lane. When old style safety curbs are encountered, they should be painted (reflectorized curb markings) on the approach ends and

trailing ends, and barrier reflectors should be applied to the top of the curb to delineate it.” Moreover, “When two lanes will be provided in one direction by using the shoulder, the line separating them will be coincidental with the permanent edge line. Rather than require a contractor to remove parts of an existing white edge line to convert it to a standard dashed lane line, it is permissible to allow it to remain as a solid white lane line (OMUTCD Section 3B-2).

Construction and Material Specifications (CMS) Section 614.11 concerns work zone pavement markings. The contractor shall “furnish, install, maintain, and, when necessary, remove work zone retroreflective pavement markings on existing, reconstructed, resurfaced or temporary roads within the work limits”. There are requirements given for the type and durability of the pavement markings.

The CMS also specifies that the contractor ensure that work zone markings are complete and in place on all pavement, including ramps, before exposing the pavement to traffic. When work zone markings conflict with the traffic pattern, they shall be removed according to CMS Section 641.10. Also specified is the removal and covering up of markings and raised pavement markers.

CMS Section 614.12 is about pavement marking operations. It specifies that pavement marking vehicles should be properly and conspicuously marked and additional vehicles will be positioned to provide drivers with advance warning of the operations. The section also prescribes that pavement marking operations must be conducted so that traffic passes on one side only. Stationary operations such as loading material should be conducted with the equipment completely off the traveling lanes.

TEM Section 605-11.10 (pavement markings), TEM Section 605-11.11 (temporary pavement markings), and CMS Item 614-10 contain additional information on work zone pavement markings. TEM Section 605-12 (lighting devices) and SCD MT-101.20 are also referenced for information about work zone raised pavement markers.

TEM Section 605-11.10 is about pavement markings and provides additional information and support for information in OMUTCD Section 7F-12. OMUTCD Section 7F-12 is about pavement marking applications during construction and maintenance operations. OMUTCD Section 7F-12 states that “The intended vehicle path should be clearly defined during day, night, and twilight periods, under both wet and dry pavement conditions.” Further, “Where temporary pavement markings are used, they may be installed to a lesser dimensional standard than that specified for permanent markings. Not less than one 4 inch (10 cm) wide by one foot long temporary pavement marking or one reflective raised pavement marker shall be used for each 50 feet (15 m) of pavement on which a permanent dashed line would be applied.” Moreover, “When it will be necessary to change traffic patterns during the period of construction activity, a removable traffic marking tape (which can be quickly and cleanly removed with little or no difficulty) may be advantageous. Reflective raised pavement markers may be used to supplement temporary pavement marking.”

While there is a lot of information on pavement markings and RPMs, nothing is quantitatively specified for crossover sections and for nighttime wet weather conditions with the

exception of the previously quoted statement from OMUTCD Section 7F-12, reinforced in TEM Section 605-11.11. No information is given as to what pavement marking materials are to be used to assure clearly defined delineation during nighttime wet weather conditions other than 642 paint or 740 materials which are for all practical purposes not wet weather retroreflective materials. Because of the need to maintain definition in wet weather, the use of special wet-weather suitable pavement marking tape, such as 3M 750 tape, is recommended.

Further, nothing is related specifically to crossover sections. Crossover sections are sections of the roadway in a work zone where driver guidance is at night under wet weather conditions is especially important.

TEM Section 605-10-1 states that “Road users should be provided pavement markings within a temporary traffic control zone comparable to the pavement markings normally maintained along such roadways, particularly at either end of the temporary traffic control zone.”

SCD MT 95-80 provides information on two-lane two way operations for use on four-lane divided roadways (asphalt curb divider). In this drawing it is stated that “Drums shall be spaced at 40’ (12 m) C-C unless otherwise stated.” Further, “The edge lines adjacent to the barrier may be painted only if they will be destroyed or surfaced over in the next stage of work. They shall be installed with removable tape if on the final surface. In order to change the color of the edge line next to the median, it may be heavily painted over (with subsequent over painting if necessary during the life of the work stage to maintain day and night color) except that this procedure will not be permitted for a line on the final surface. The existing conflicting pavement markings and reflectors from the raised pavement markers shall be removed and the appropriate color temporary edge lines shall be applied. The right lane edge line in the two way traffic section shall be white. All pavement markings will cross normal traffic lanes shall be installed using removable (740.06, Type I) tape, unless the area will be resurfaced prior to implementing the next traffic stage. After completion of the work, temporary pavement markings shall be removed in accordance with 641.10 and the original markings and raised pavement marker reflectors shall be restored at no additional cost.” There are two other statements in this section. They are “No reflectors or other channelizing devices shall be permitted on the face of the PCB facing the existing crossover, from PC to the end of the barrier” and “No temporary yellow edge line shall be placed adjacent to PCB or curb divider between P.T. and P.C. unless specified in the plans.”

SCD MT-101.20 presents the guidelines for work zone raised pavement markings. It is stated that “the markers shall be yellow or white”. Further, “All markers and retroreflectors shall be sufficient strength and properly shaped so as not to be dislodged or broken by impacts from vehicles tires, including those of high pressure truck tires loaded to 4500 pounds (2040 kilograms). Retroreflectors shall be provided in one or two directions on each marker as required by usage and shall return white or yellow light as is appropriate for application. The reflector shall have an effective area of 0.35 sq. inches (225 sq. mm for Type A or 3.0 sq. inches (1935 sq. mm) for Type B. Its brightness or specific intensity (when tested at 0.2 degree angle of observation and the following angles of incidence shall meet or exceed the following:



**Table 18: Table from SCD MT-101.20**

Specific Intensity		
Type A		
Incidence Angle (degrees)	White fc (lx)	Yellow fc (lx)
0	1 (10.7)	0.6 (6.4)
20	0.4 (4.2)	0.24 (2.5)
45	-	-
Type B		
	White fc (lx)	Yellow fc (lx)
0	3 (32.1)	1.8 (19.2)
20	1.2 (12.8)	0.72 (7.7)
45	0.3 (3.2)	0.2 (2.1)

Angle of incidence formed by a ray from light source to the marker and the normal to the leading edge of the marker face (also horizontal angle).

Angle of observation formed by a ray from light source to the marker and the returned ray from the marker to the measuring receptor.

Specific intensity is the mean candlepower of the reflected light (at given incidence and divergence angles) for each foot candle (10.7 lux) at the reflector plane (on a plane perpendicular to the incident light).

Type A markers are intended to provide high visibility both day and night. Their daytime visibility shall be assured by size, shape and color as follows:

- The markers shall be a high visibility yellow or white colors which will not degrade substantially due to traffic wear and which will match the color of reflector.
- When viewed from above, the markers shall have a visible area of not less than 14 sq. inches (9030 sq. mm).
- When viewed from the front, parallel to the pavement, as from approaching traffic, the marker shall have a width of approximately 4 inches (10 cm) and a visible area of not less than 1.5 sq. inches (970 sq. mm).

Type B markers are intended to provide high visibility at night by retroreflecting light from automotive headlights back to the driver.

This section also provides installation guidelines for the contractor and the project engineer. These include the statements: “The markers shall be placed accurately to depict straight or uniformly curving lines. When used to supplement work zone pavement markings, they shall be placed on or immediately adjacent to the pavement marking. Locations shall be adjusted up to 12 inches (30 cm) longitudinally or 6 inches (15 cm) laterally to avoid placement on joints, or on cracked or deteriorated pavement. Markers shall not be placed directly on pavement markings if this detracts from their ability to remain attached to the pavement.

Further, SCD MT 101-20 provides details for application of raised pavement markers, including spacing.

When required to supplement pavement marking, work zone raised pavement markers shall be placed as follows:

**Table 19: Table from SCD MT 101-20 on using RPMs to supplement pavement markings**

LINE	TYPE	SPACING
EDGE LINE	A or B	20' (6 m) C/C
LANE LINE	A or B	40' (12 m) C/C*
CENTER LINE (SINGLE BROKEN)	A or B	40' (12 m) C/C*
CENTER LINE (DOUBLE/SOLID)	A or B	2 UNITS SIDE BY SIDE 4" (100 mm) APART 20' (6 m) C/C
CHANNELIZING LINE (INCLUDES EXIT GORE NOSE)	A or B	10' (3 m) C/C

**\*CENTERED IN GAP**

When used to substitute for (replace) pavement marking, work zone raised pavement markers shall be placed as follows:

**Table 20: Table from SCD MT 101-20 on using RPMs to substitute for pavement markings**

LINE	TYPE	SPACING
EDGE LINE	A	5' (1.5 M) C/C
LANE LINE	A	5· 2.5' (0.75 M) C/C 30' (9 M) GAP [40' (12 m) CYCLE]
CHANNELIZING LINE (INCLUDES EXIT GORE NOSE)	A	5' (1.5 m) C/C
EDGE LINE (TWO COLOR) (WHITE / YELLOW)	A	BACK TO BACK 5' (1.5 M) C/C

Yellow markers used to separate opposite flows of traffic (center lines) shall include retroreflectors for both directions. All other yellow and white markers shall provide retroreflectivity for one direction only.

SCD MT-96-10 provides information about signalized closing of 1 lane of a 2 lane highway with drums. It is stated in this section that "Work zone center line, solid, double, shall

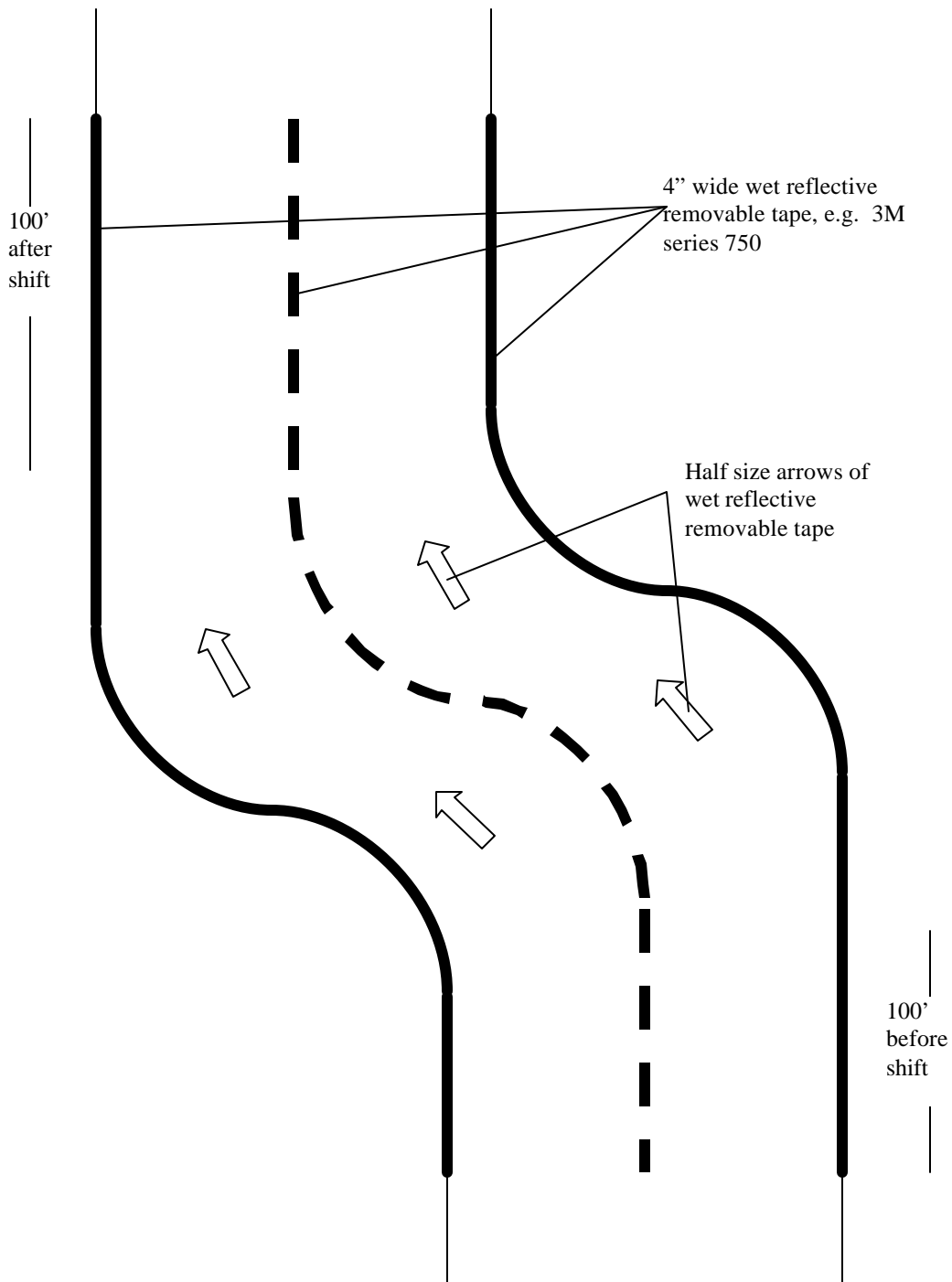
be installed and maintained when existing center line, solid double is not in place. 12” (300 mm) stop lines shall be installed. Existing conflicting pavement markings and raised markings shall be removed. Work zone edge lines which would conflict with final traffic lanes shall be removable (740.06 type I) tape unless they will be resurfaced in the next phase.” Further, “Work zone raised pavement markers shall be provided as per MT-101.20.” SCD MT 96.11 is about the signalized closing of one lane of a two lane highway with portable concrete barriers. In addition to SCD MT-96.10, this drawing states that “Work Zone Raised Pavement Markers (WZRPMs) to simulate a two color edge line shall be provided.”

As mentioned in many places in this document, OMUTCD Part 3 is about markings and OMUTCD Section 3A is about general principles while Section 3B provides information on applications of pavement markings. However, the markings that would be applied during the construction are mentioned in OMUTCD Section 6F.65 and 6F.66 which was discussed in earlier paragraphs.

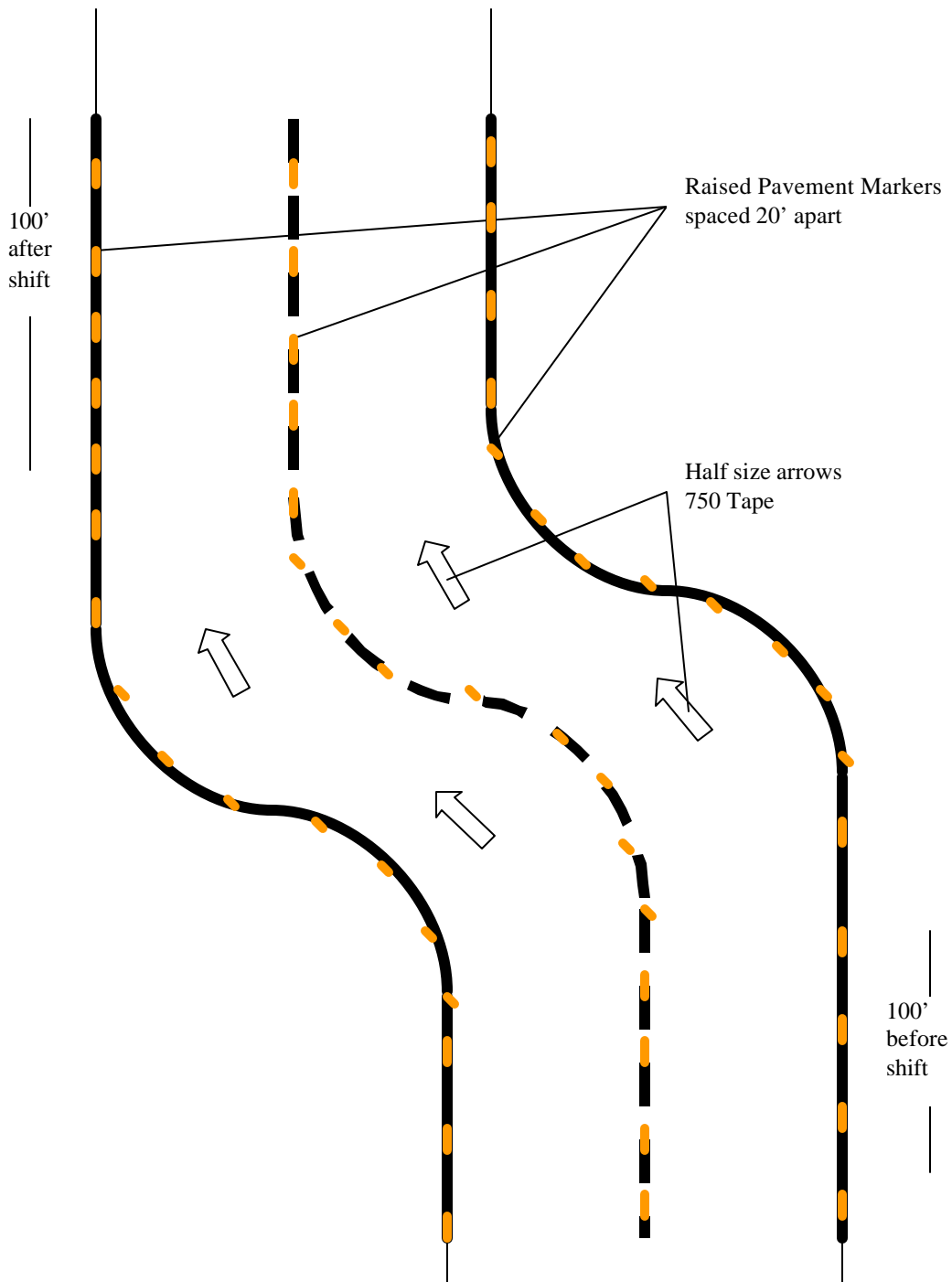
### ***2.23.1. Directional Arrows on Pavement***

The use of directional pavement arrows in the center of the lane is addressed neither in the Ohio standards nor in the literature. It is expected that adding such arrows can only help drivers navigate through a work zone, so their use, particularly at lane shifts and crossovers, is recommended. One may want to consider the low-wear, material saving half-size arrows previously tested and recommended for general use by Zwahlen, Schnell, and O’Connell [99].

The recommended implementation of 3M 750 wet retroreflective removable pavement marking tape and half-size arrows is shown in Figure 29. An alternate implementation using raised pavement markers and half-size arrows of 750 tape is shown in Figure 30.



**Figure 29: Recommended implementation of pavement marking materials in a lane shift. A high visibility retroreflective marking such as 3M 750 tape is suggested. Half-size arrows provide additional guidance to drivers. (4"=10 cm; 100'=30 m)**



**Figure 30: Recommended implementation of raised pavement markers in a lane shift. Half-size arrows made with a high visibility retroreflective marking such as 3M 750 tape provide additional guidance to drivers (20'=6m; 100'= 30 m)**

**2.23.2. Raised Pavement Markers**

In rural highways, in flat or rolling terrain, the desirable median width is 60 to 84 ft (18 to 25 m). The minimum median width is normally 40 ft (12m). In lane shift sections of work zones a median width of 40 ft (12 m) is considered. The minimum radius of curvature at the lane shift is dependent on the design speed.

The minimum curve radius R is calculated according to the following formula from our recommendations based on Swiss Standards. The computed curve radius values are given in Table 21 and the graph for the relationship between the design speed and the curve radius are given in Figure 31 and Figure 32. These assume a lateral acceleration at the design speed of  $a_y=0.106g=1.04 \text{ m/s}^2=3.39 \text{ ft/s}^2$ . The computed R values are larger than ODOT minimums for curves with superelevation, but represent reasonable typical values.

$$R = V_p^2 / 13.5$$

R=Radius in m

$V_p$ =Design speed in km/h

$$R = V_p^2 / 1.601$$

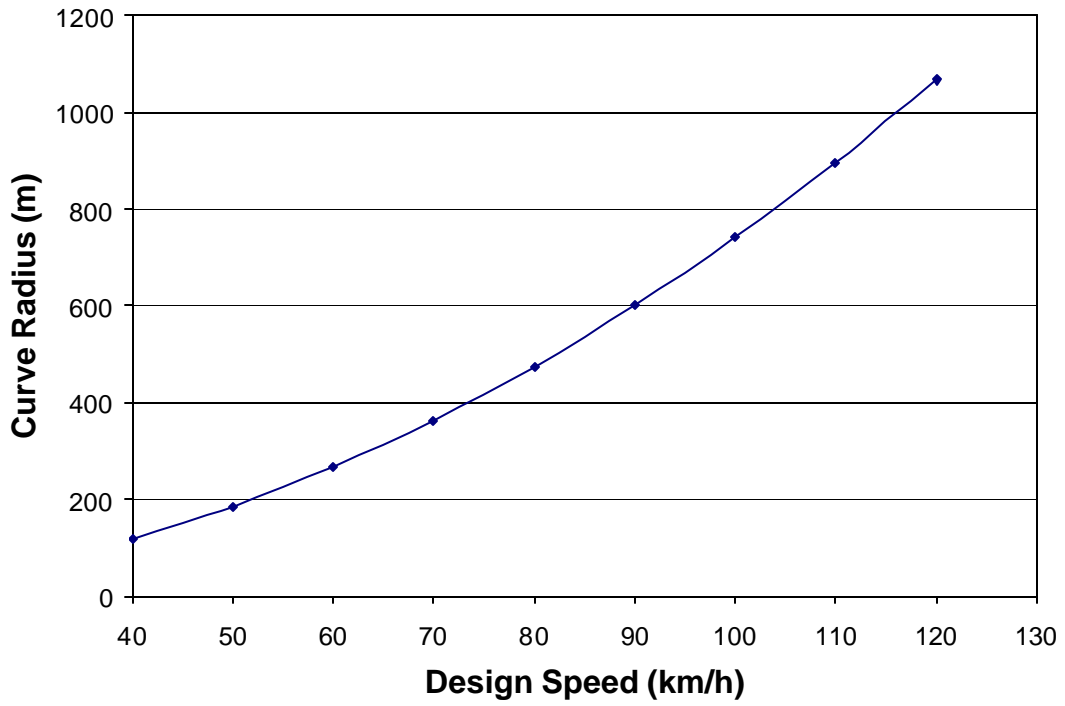
R=Radius in ft

$V_p$ =Design speed in mph

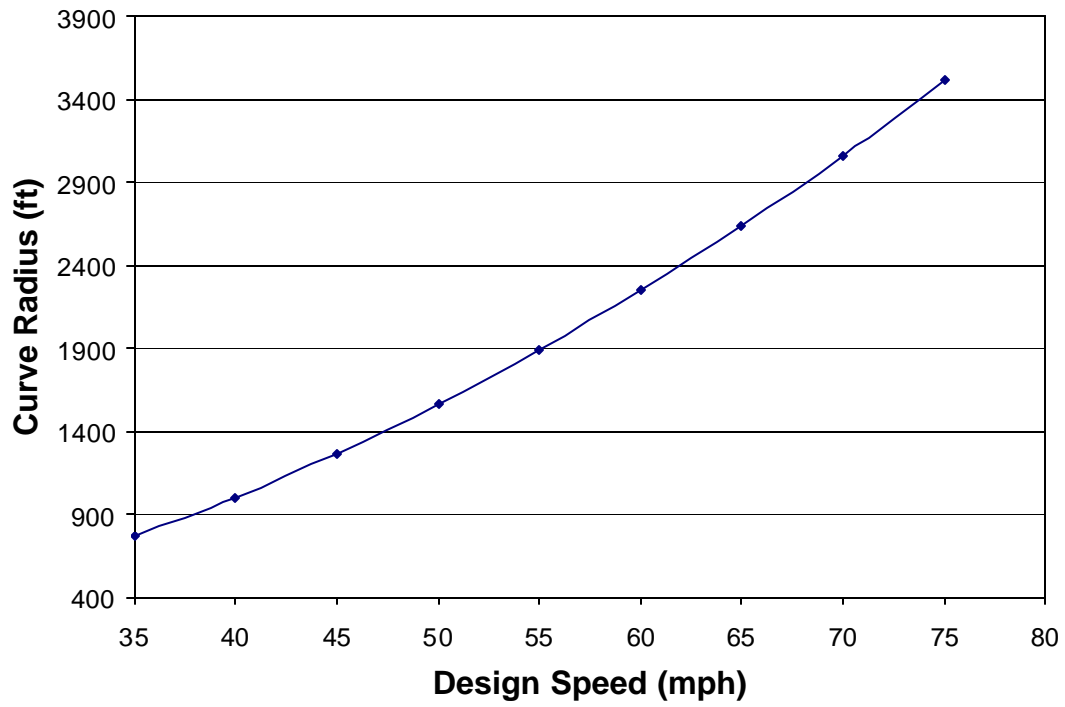
**Table 21: Calculated Typical Curve Radius Values for Different Design Speeds**

Design Speed $V_p$ (km/h)	Curve Radius R (meters)
40	119
50	185
60	267
70	363
80	474
90	600
100	741
110	896
120	1067

Design Speed $V_p$ (mph)	Curve Radius R (feet)
35	765
40	999
45	1265
50	1562
55	1889
60	2249
65	2639
70	3061
75	3513



**Figure 31: Comparison of Design Speed (km/h) versus Curve Radius (m)**



**Figure 32: Comparison of Design Speed (mph) versus Curve Radius (ft)**

Then using the following formula, longitudinal length of the lane shift is calculated.

$$L_v = V_p * \sqrt{W} / 3$$

$L_v$  = Longitudinal Distance of the lane shift section in m

$V_p$  = Design Speed in km/h

$W$  = Width of lane shift in m

$$L_v = 1.673 V_p * \sqrt{W}$$

$L_v$  = Longitudinal Distance of the lane shift section in ft

$V_p$  = Design Speed in mph

$W$  = Width of lane shift in ft

From the longitudinal length, the actual length of the road section may be computed.

$$L_h = \sqrt{L_v^2 + W^2}$$

$L_h$  = Curve Length of the lane shift section

$L_v$  = Longitudinal Distance of the lane shift section

$W$  = Width of lane shift

This formula works with both metric and English units provided all variables are in matching units.

The width of the lane shift for a crossover would be the width of the median plus the width of one lane. Assuming a 40 foot (12.19 m) median and a standard 12 ft (3.66 m) lane width, the shift  $W$  is 52 ft (15.85 m).

**Table 22: Calculated Curve Lengths for the Lane Shift Section for Different Design Speeds**

Design Speed (km/h)	$L_v$ (meters)	$L_h$ (meters)
40	146	151
50	183	187
60	219	223
70	256	259
80	292	295
90	329	331
100	365	367
110	402	404
120	438	440

Design Speed (mph)	$L_v$ (feet)	$L_h$ (feet)
25	479	497
31	599	613
37	719	731
43	839	849
50	958	967
56	1078	1086
62	1198	1205
68	1318	1324
75	1438	1444

**Note: These curve length values are not rounded. A lane shift width of 52 ft (15.85 m) is assumed, composed of a 40 ft (12.19 m) median and 12 ft (3.66 m) lane width, for a full crossover.**

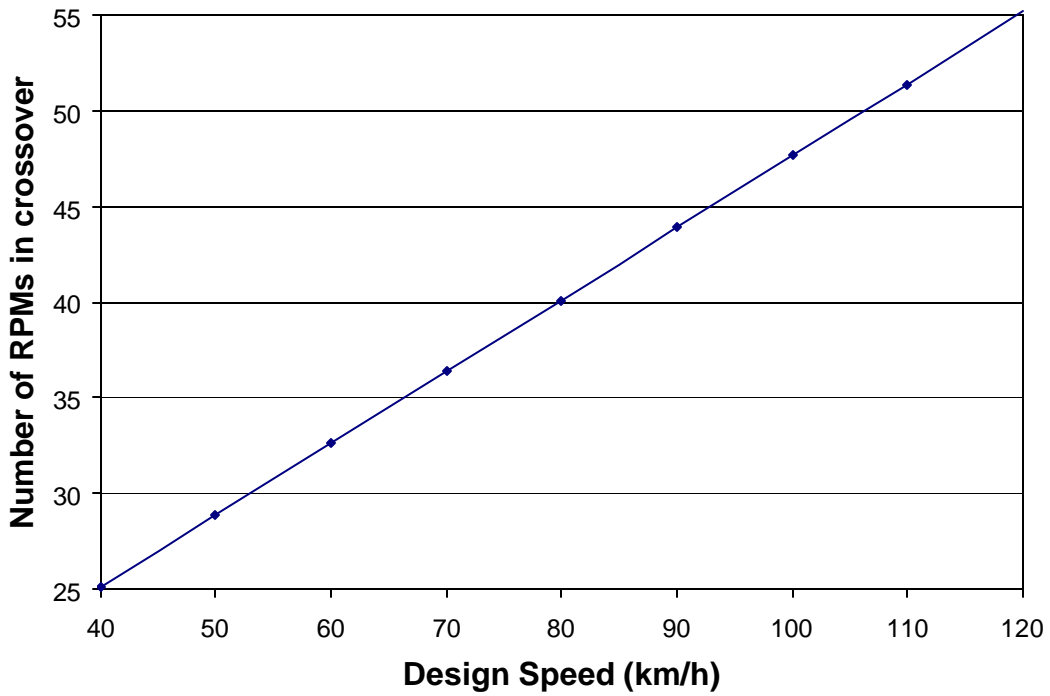


**Table 23: Required Number of RPMs in Crossover Lane Shift Sections (metric units on top, English units on bottom)**

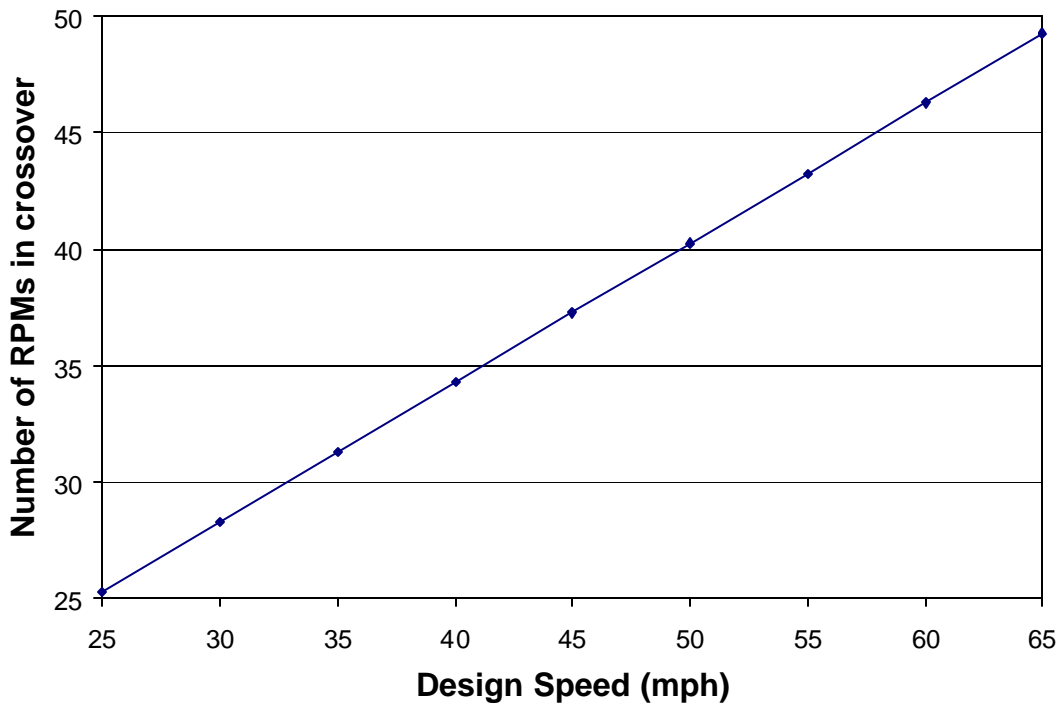
Design Speed (km/h)	$Lh$ (m)	Approximate Required Number of RPMs per Line in Curved Sections Using 6 m Spacing	Approximate Required Number of RPMs per Line in Curved Sections Including both Tangent 30 m Sections Using 6m Spacing
40	93	15	25
50	116	19	29
60	139	23	33
70	162	27	36
80	185	30	40
90	207	34	44
100	230	38	48
110	253	42	51
120	276	45	55

Design Speed (mph)	$Lh$ (feet)	Approximate Required Number of RPMs per Line in Curved Sections Using 20 ft Spacing	Approximate Required Number of RPMs per Line in Curved Sections Including both Tangent 100 ft Sections Using 20 ft Spacing
25	306	15	25
30	366	18	28
35	425	21	31
40	485	24	34
45	545	27	37
50	605	30	40
55	666	33	43
60	726	36	46
65	786	39	49

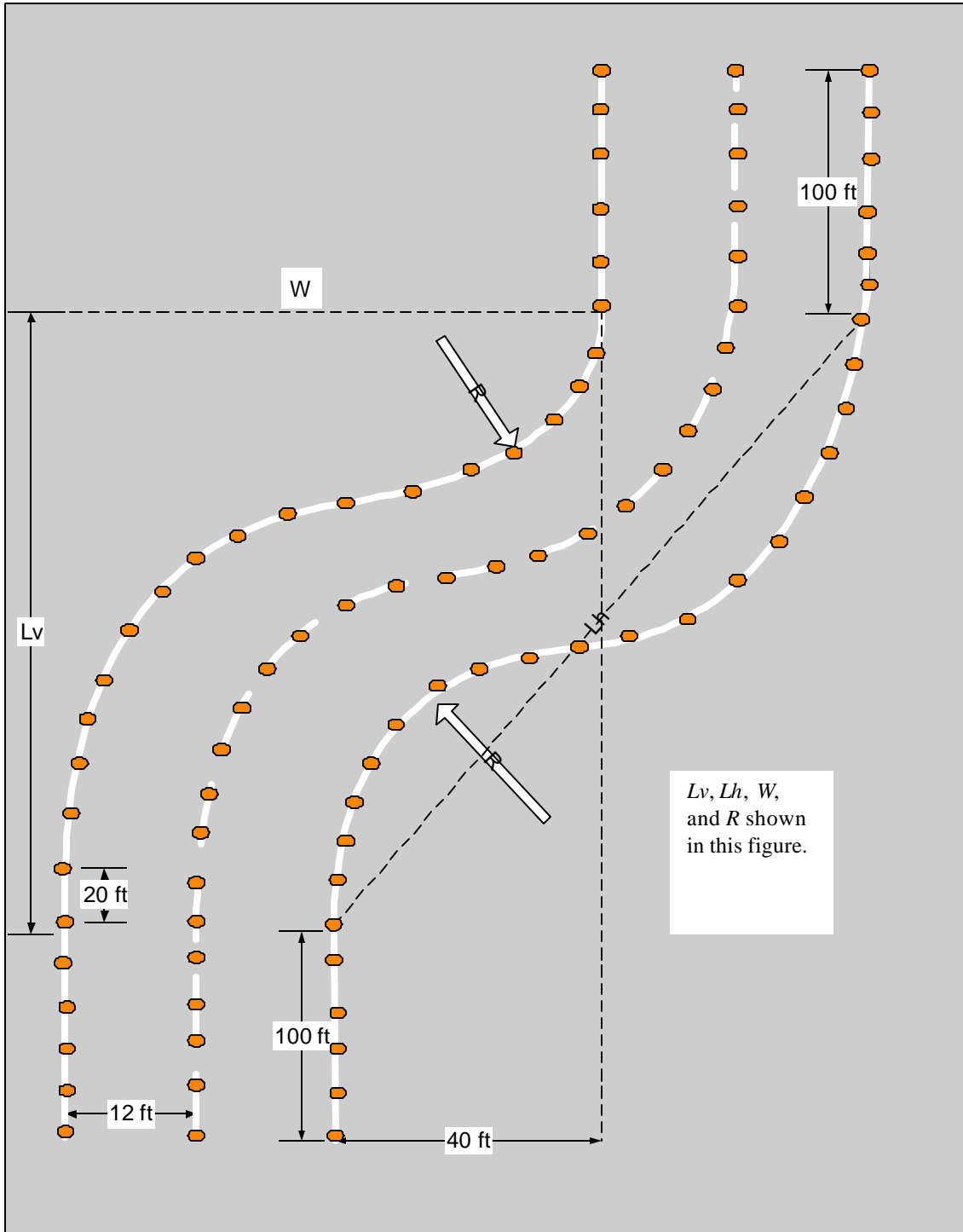
**Note: A lane shift width of 52 ft (15.85 m) is assumed, composed of a 40 ft (12.19 m) median and 12 ft (3.66 m) lane width, for a full crossover.**



**Figure 33: Comparison of Design Speed (km/h) versus Approximate Required Number of RPMs for a crossover of width 15.85 m (12.19 m median plus 3.66 m lane)**



**Figure 34: Comparison of Design Speed (mph) versus Approximate Required Number of RPMs for a crossover of width 52 ft (40 ft median plus 12 ft lane)**



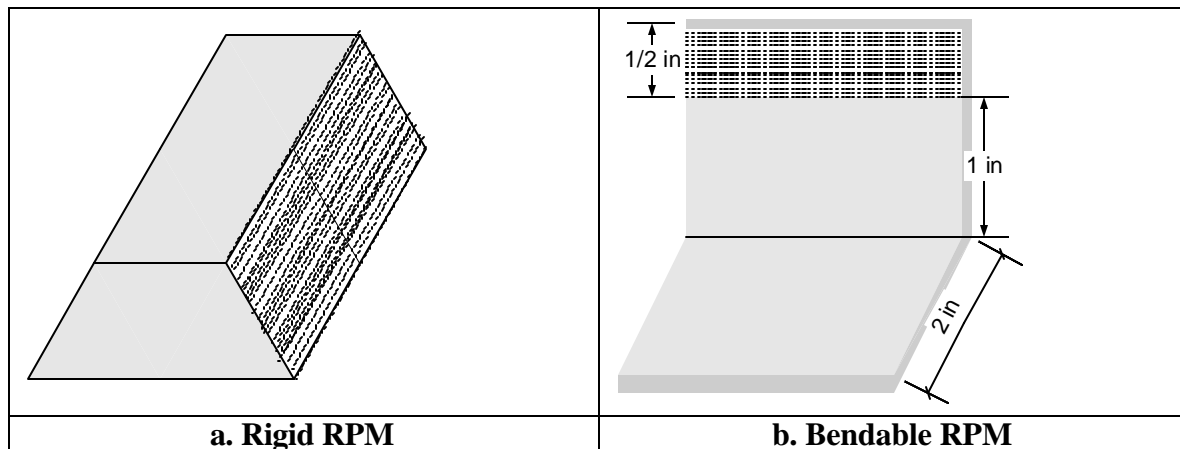
**Figure 35: Implementation of RPMs at a Lane Shift Section (12'=3.66m; 20'=6m; 100'=30m).**

In the lane shift sections of construction work zones, regular paint and beaded pavement marking (for daytime visibility) plus raised pavement markers should be used in order to provide better guidance to drivers through the work zone. Present raised pavement markers have

retroreflectivity which is based on relatively narrow observation angle and entrance angle performance.

Photometric properties may need to be reevaluated and possibly a new product with better retroreflectivity performance at larger observation and entrance angles may be beneficial. Raised pavement markers with narrow versus larger observation and entrance angles show similar retroreflectivity characteristics like Type VII and Type IX sheeting materials.

In the lane shift sections of construction work zones, regular paint and beaded pavement marking (for daytime visibility) plus raised pavement markers should be used in order to provide better guidance to drivers through the work zone. Raised pavement markers with larger entrance and observation angles would be better for entrance and exit ramps or curves with small radii since the markers are not required to be seen at distance up to 1000 ft (305 m) or more. ODOT should prepare an evaluation plan and the evaluation modification has to have the objective to determine which among a number of selected pavement marking and/or RPM treatments (up to five) would most effectively provide night time wet weather delineation. Maybe if wearability can be improved bendable vertical plastic yellow or white surface markers with a retroreflective horizontal stripe spaced a 10 feet (3.05 m) intervals may be also usable in lieu of paint and beads and rigid plastic RPMs; examples are shown in Figure 36. When raised pavement markings are used, it is imperative that the contractor inspect RPMs and replace broken markings on a daily basis.



**Figure 36: Recommended Raised Pavement Markers (1 in=2.54 cm).**

### 2.23.3. Basis for Recommendation

The use of special wet weather suitable pavement marking tape will improve visibility and will provide better guidance for drivers. In addition the use of directional pavement arrows will also improve guidance through the work zone area, especially for crossovers and lane shifts.

#### **2.23.4. Implementation**

The use of wet weather suitable pavement marking tape should be included in the work zone design guidelines. The number of raised pavement markers and the spacing between these markers should also be included in the guidelines. In the crossover sections, directional arrows on pavement drawings should be included and the specifications for the directional arrows should be included in the guidelines.

#### **2.23.5. Estimated Cost**

This cost is not known at the moment.

#### **2.23.6. Benefits and Risks**

The recommendations will provide better guidance for the drivers during wet weather conditions and nighttime driving conditions. They will improve the traffic flow and the visibility for the drivers according to the human factors perspective.

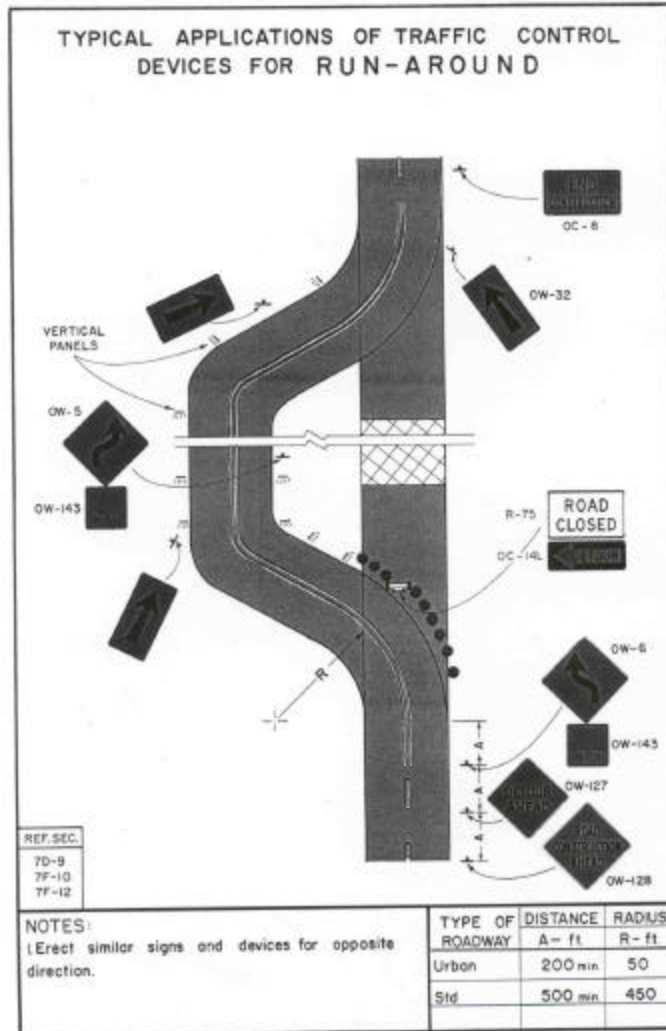
#### **2.23.7. Evaluation and Research**

The delineation in the work zone crossover and lane shifting sections during wet weather conditions can be improved by using raised pavement markers or wet weather pavement markings. Both of the alternatives should be evaluated. Their effectiveness should be determined. Sufficient raised pavement marker spacing for better guidance in work zone crossover areas during nighttime and wet weather driving conditions should be determined.

### **2.24. Curve Radii in Lane Shift Sections**

The correct choice of minimum curve radii in lane shift sections helps provide an efficient traffic flow and a good safety level for drivers and workers. It can furthermore improve the guidance and therefore the safety at lane shifts.

The literature review turned up no data on curve radii in work zone lane shifts. The only statement concerning roughly this topic was found in the 1999 OMUTCD [101]. Table 7-58 treating “Typical Applications of Traffic Control Devices for Run-Around” gives a figure for the radius of the run-around (50 ft (15 m) in urban area / 450 ft (137 m) std.). The OMUTCD figure is reproduced as Figure 37 below. The given numbers are speed-independent, but one would expect that these radii would be speed dependent. No equivalent table was located in the current (2003) OMUTCD [4], though Figure 6H-7 appears to be very similar to Figure 37. Figure 6H-7 does not include curve radius information.



**Figure 37: Drawing of typical applications of traffic control devices for run-around, from the 1999 OMUTCD [101] (1 ft = 0.305 m).**

In ODOT design guidelines Figure 698-46B distances required for the lane shift sections are given. Decision sight distance values are used for different design speed values for determining the required length of lane shift sections. When the lane shift sections are assumed as curves in highways, it is observed that the curve radius values used in Figure 698-46B are higher than the minimum acceptable curve radii calculated.

Minimum curve radii without superelevation for rural highways and urban streets and highways are given in ODOT Location and Design Manual, Volume I, Section 202.

Table 24 shows the ODOT curve radius specifications without superelevation, and minimum curve radius specifications for different roadway configurations. Minimum curve radius specifications are adapted from the ODOT Location and Design Manual, Volume I, Section 202.

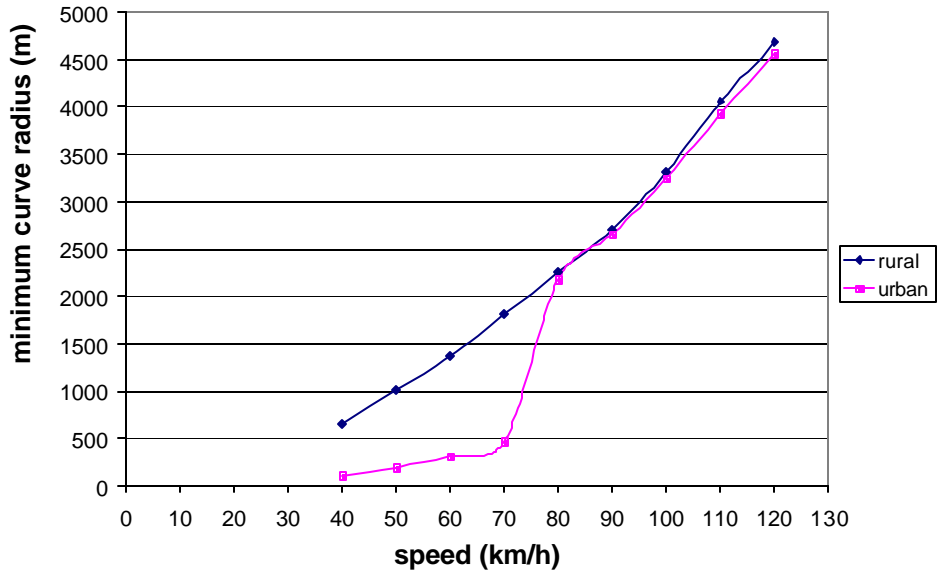
**Table 24: ODOT Minimum Curve Radius Specifications**

Design Speed (km/h)	Curve Radius (meters)				
	ODOT Minimum Curve Radius without Superelevation (rural)	ODOT Minimum Curve Radius without Superelevation (urban streets & highways)	ODOT Specifications Rural Highways (superelevation rate 0.080, 2-lane)	ODOT Specifications Urban Highways (superelevation rate 0.080, 2-lane)	ODOT Specifications Urban Streets and Temporary Roads (superelevation rate 0.040, 2-lane)
40	660	110	50	-	45
50	1010	200	80	-	75
60	1370	310	120	-	125
70	1810	470	170	-	185
80	2260	2180	230	250	-
90	2710	2660	305	340	-
100	3320	3250	400	450	-
110	4060	3930	520	585	-
120	4680	4570	665	755	-

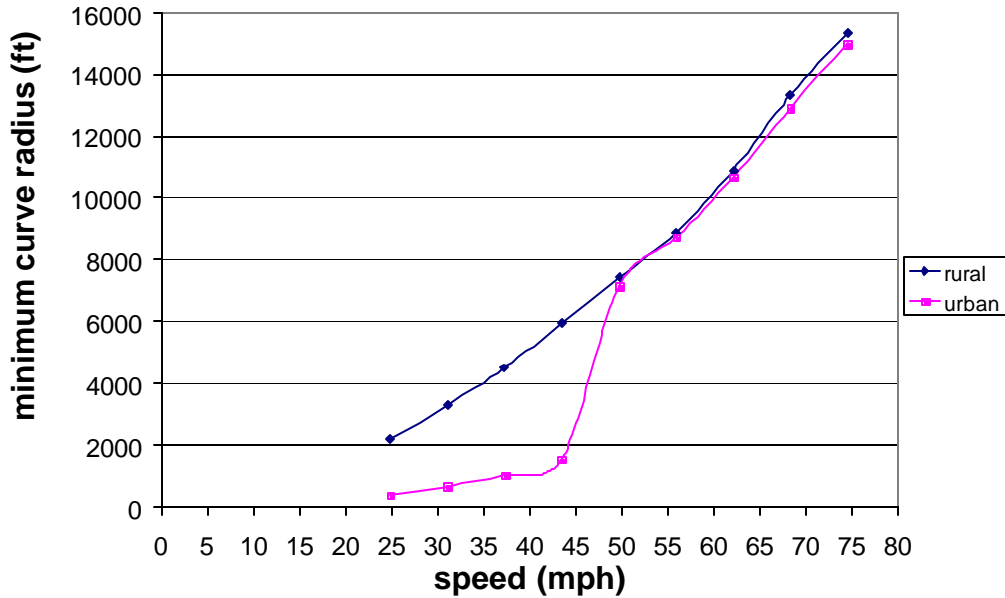
Design Speed (mph)	Curve Radius (feet)				
	ODOT Minimum Curve Radius without Superelevation (rural)	ODOT Minimum Curve Radius without Superelevation (urban streets & highways)	ODOT Specifications Rural Highways (superelevation rate 0.080, 2-lane)	ODOT Specifications Urban Highways (superelevation rate 0.080, 2-lane)	ODOT Specifications Urban Streets and Temporary Roads (superelevation rate 0.040, 2-lane)
24.9	2165	361	164	-	148
31.1	3314	656	262	-	246
37.3	4495	1017	394	-	410
43.5	5938	1542	558	-	607
49.7	7415	7152	755	820	-
55.9	8891	8727	1001	1115	-
62.1	10892	10663	1312	1476	-
68.4	13320	12894	1706	1919	-
74.6	15354	14993	2182	2477	-

The minimum curve radii in rural and urban highways are also plotted in Figure 38.

**ODOT Minimum Curve Radius without Superelevation**



**ODOT Minimum Curve Radius without Superelevation**



**Figure 38. ODOT minimum curve radius as a function of speed without superelevation. Top in metric units, bottom in English units.**

In Table 25 lateral acceleration values which are used in the calculation of the minimum curve radius lengths in terms of g are given.



**Table 25: Lateral Acceleration Values used in the Calculation of Curve Radius without Superelevation**

Design Speed	Lateral Acceleration for the Minimum Curve Radius without Superelevation (rural)	Lateral Acceleration for the Minimum Curve Radius without Superelevation (urban streets and highways)
km/h (mph)	(g units)	(g units)
40 (24.8)	0.019	0.114
50 (31.0)	0.019	0.098
60 (37.2)	0.021	0.091
70 (43.4)	0.021	0.082
80 (49.7)	0.022	0.023
90 (55.9)	0.024	0.024
100 (62.1)	0.024	0.024
110 (68.3)	0.023	0.024
120 (74.5)	0.024	0.025

In Table 26 minimum curve radius values specified by American Association of State Highway and Transportation Officials (AASHTO) and ODOT are compared. It is observed that the minimum curve radius without superelevation values specified by ODOT in Table 25 are smaller than the AASHTO specifications in Table 26. The minimum curve radius without superelevation values should be equal to the AASHTO standards.

**Table 26: Minimum Curve Radii for Design of Rural Highways, Urban Freeways, and High-Speed Urban Streets without Superelevation**

Design Speed (km/h)	AASHTO Minimum Curve Radius without Superelevation (m)	ODOT Minimum Curve Radius without Superelevation (urban streets & highways) (m)	Design Speed (mph)	AASHTO Minimum Curve Radius without Superelevation (ft)	ODOT Minimum Curve Radius without Superelevation (urban streets & highways) (ft)
40	800	660	25	2625	2165
50	1110	1010	31.25	3642	3314
60	1530	1370	37.5	5020	4495
70	2020	1810	43.75	6627	5938
80	2500	2260	50	8202	7415
90	3030	2710	56.25	9941	8891
100	3700	3320	62.5	12139	10892
110	4270	4060	68.75	14009	13320
120	4990	4680	75	16371	15354

Source: *A Policy on Geometric Design of Highways and Streets* (The Green Book). Washington, DC. American Association of State Highway and Transportation Officials, 2001 4<sup>th</sup> Ed. [102]

### 2.24.1. Radius of Lane Shifts at Highway Shifts

A lateral acceleration formula is used for calculating the curve radii in lane shift sections of highways [103]:

$$a_y = \frac{V^2}{gR}$$

Where;

$a_y$  = Lateral acceleration (in g units)

V= Vehicle speed (m/s or ft/s)

g= Gravitational acceleration ( $1g=9.81 \text{ m/s}^2 = 32 \text{ ft/s}^2$ )

R= Curve radius (m or ft)

Curve radius (R) is calculated with the formula.

$$R = \frac{V^2}{a_y g}$$

In the study conducted by Zwahlen [104], the lateral accelerations for a moderate curve and a sharp curve were calculated. The minimum speeds observed for the moderate curve were 43.7 mph (70km/h), 42 mph (67 km/h), 43.6 mph (70 km/h), and 41.2 mph (66 km/h). And the minimum speeds observed for the sharp curve were 32.7 mph (52km/h), 29.5 mph (47 km/h), 33.2 mph (53 km/h), and 32.3 mph (51 km/h). The radius of the moderate curve in the study was 465 ft (141.8 m) and the radius of the sharp curve was 220 ft (67.1 m). These lateral acceleration rates can be considered as the average lateral acceleration rates which are acceptable by the drivers. The lateral acceleration values for moderate curves differ within the range of 0.161g to 0.190g and for sharp curves it differs within the range of 0.182g to 0.274g. Using the observed lateral acceleration values in the study, curve radii are calculated for the values of 0.15g, 0.20g, and 0.25g for different design speeds. The calculated curve radius values are given in Table 27.

**Table 27: Curve Radius Values Calculated for Different Design Speeds Based on Observed Lateral Acceleration Values Experienced by Drivers**

	Assumed Lateral Acceleration 0.15 g	Assumed Lateral Acceleration 0.20 g	Assumed Lateral Acceleration 0.25 g
Design Speed km/h (mph)	Curve Radius m (ft)	Curve Radius m (ft)	Curve Radius m (ft)
40 (25)	84 (275)	63 (207)	50 (164)
50 (31)	131 (430)	98 (322)	79 (259)
60 (37)	189 (619)	142 (466)	113 (371)
70 (43)	257 (843)	193 (633)	154 (505)
80 (50)	336 (1101)	252 (827)	201 (659)
90 (56)	425 (1394)	319 (1047)	255 (837)
100 (62)	524 (1721)	393 (1289)	315 (1034)
110 (68)	635 (2082)	476 (1562)	381 (1250)
120 (75)	755 (2478)	566 (1857)	453 (1486)

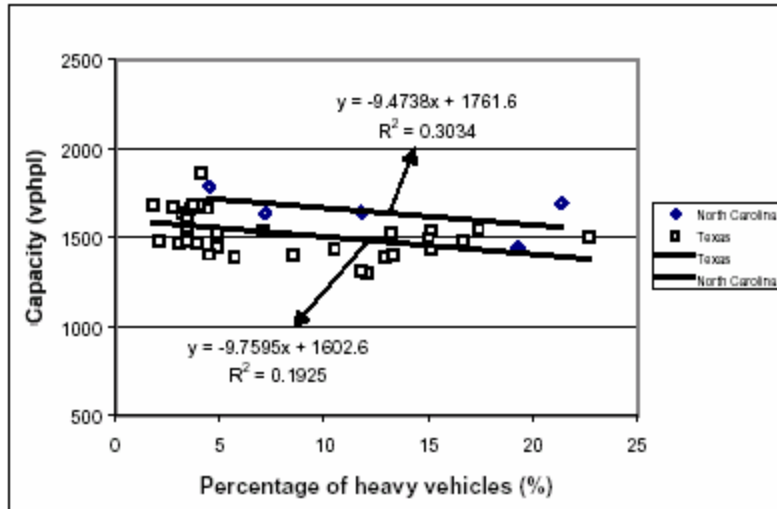
It is observed that the lateral acceleration values used by ODOT in the calculation of curve radii are lower than the acceptable lateral acceleration values by drivers. ODOT curve radii lengths are higher than the minimum acceptable curve radii lengths based on these accelerations. Current ODOT curve radius values therefore probably provide adequate efficient traffic flow and safety for drivers and workers even though they are somewhat lower than the values recommended by AASHTO.

## **2.25. System or Procedure for Adding Temporary Traffic Lanes**

In order to maintain traffic through a work zone on a busy road, an additional temporary lane may be required. However building a temporary lane is a great expense; the decision to build a lane is based on being able to estimate the size of the queue that will build up in a work zone. At present the answer to this problem is limited. A previous study indicated that for simple work zones without entrance or exit ramps a combination of QueWZ92 program and an ODOT spreadsheet gave results with errors ranging from 1% to 18.5% [105]. For more complicated work zones, a more sophisticated model is needed, and development of such a model is planned for Phase II of this research.

## **2.26. Effects of Large Vehicles on Work Zone Capacity**

Kim, Lovell, and Paracha studied various factors to develop a methodology to estimate capacity in work zones [106]. One of these was the effect of a large percentage of trucks on traffic capacity. Using data collected in Texas and North Carolina, the researchers performed a regression of capacity in vehicles per hour per lane (vphpl) versus percentage of heavy vehicles. In North Carolina, the intercept of the fit was 1761 vphpl, which represents the capacity if there were no trucks. The fit was  $1761.6 - 9.4738HV$ , where HV is the percentage of heavy vehicles. Thus if there are 10% trucks, the capacity is reduced by about 95 vphpl, or 5.4%. In Texas, the fit was  $1602.6 - 9.7595VH$ , so a 10% truck percentage would reduce capacity by about 98 vehicles, or 6.1%. The  $R^2$  correlation coefficients were 0.3034 for North Carolina and 0.1925 for Texas, indicating that the variation in capacity was influenced by other factors as well. The authors' plot of capacity versus truck percentage is shown in Figure 39. Other factors considered by the authors included number of open and closed lanes, location of closed lanes (e.g. left or right), driver population (most peak hour drivers are assumed to be commuters familiar with the route), entrance ramp volume, lateral distance to open travel lanes (essentially considers if TCDs are placed too close to the open lane edge), length and grade of work zone, intensity of work activity, work duration (long-term work zone versus short-term), weather, and work time (day or night). Of these, it is worth remarking that the authors cite a paper by Ahmed et al. [107] that suggests that commuters are more familiar with the route and work zone configuration, but Kim, Lovell, and Paracha state that the suggested adjustment factors in the Highway Capacity Manual [108] are not supported by their data. The authors also cite a paper by Krammes and Lopez [109] that suggests that work zone capacity can be reduced by the average volume of entrance ramps located within the channelizing taper or within 152 m (500 ft) downstream of the end of the taper, but by no more than half the capacity of one open lane through the work zone.



**Figure 39: Relationship between work zone capacity and percentage of heavy vehicles observed in Texas and North Carolina [106]**

The literature did not contain many work zone improvement measures that were specific to trucks and large vehicles. One item that may be of use is the Wizard CB Alert System [109]. This device is an unmanned CB radio transmitter that broadcasts a recorded warning about an upcoming work zone (or other message) up to 18 seconds long on a regular cycle every 30, 60, or 90 seconds. It has a maximum range of about 4 miles, though that may be compromised by geography and other factors affecting radio transmission. Messages are typically broadcast on channel 19 as it is monitored by most truckers, though any channel may be used. It functions much like HAR, but is aimed more at truckers, most of whom use CB radios. It may provide further advance warning of approaching work zones than signing, particularly in temporary work zone areas.

The device was tested in Texas by the Texas Transportation Institute [110]. The device was found to statistically significantly reduce truck speeds in the early portion of two work zones studied, though the magnitude of the effect was small, under 2 mph (3.2 km/h). The effectiveness of the device in Texas was limited by the large number of Spanish speaking truckers who did not use CB radios or who monitored channels other than 19.

In an earlier evaluation in Iowa [111], truckers were surveyed about the system after passing through a stretch of highway that was being painted. 75% of the 59 truckers surveyed (those who had CB radios tuned to channel 19 and had seen the paint crew) had heard the system announcement; for 40% of the total the Wizard CB provided the first notification of the upcoming work zone. Of the 44 that received the message, 89% (39) thought the message was effective. All but one (98%) thought the message was not annoying, and all the drivers thought the system's continued use would be beneficial. The survey also ascertained that 80% of the truckers surveyed had CB radios tuned to channel 19, so this device will not reach about a fifth of the truck driving population, and perhaps more if much of the traffic is local commercial traffic rather than long distance trucking.

## 2.27. Modifications to ODOT's Standard Construction Drawings

The proposed modifications to ODOT construction drawings are tabulated in Table 28. Further information on the changes made to the standard construction drawings can be found in Appendix B, which is available as an electronic supplement from the Human Factors Laboratory.

**Table 28: Recommended modifications to Standard Construction Drawings (MT Series).  
See Appendix B for modified drawings.**

Drawing No.	Maintenance of Traffic	Modifications to the Standard Construction Drawings
MT-35.10	Flashing Arrow Panel	No Changes
MT-95.30	Closing Right Or Left Lane Of A Multi-Lane Divided Highway With Drums	8* When multiple arrow panels are used the spacing should be approximately 3L, but not less than 1000 ft (305 m).
MT-95.31	Closing Right Lane Of A Multi-Lane Undivided Highway With Drums	8* When multiple arrow panels are used the spacing should be approximately 3L, but not less than 1000 ft (305 m).
MT-95.32	Closing Left Lane Of A Multi-Lane Undivided Highway With Drums	8* When multiple arrow panels are used the spacing should be approximately 3L, but not less than 1000 ft (305 m).
MT-95.40	Closing Right Or Left Lane Of A Multi-Lane Divided Highway With Portable Concrete Barrier	6* When multiple arrow panels are used the spacing should be approximately 3L, but not less than 1000 ft (305m).
MT-95.41	Closing Right Lane Of A Multi-Lane Undivided Highway With Portable Concrete Barrier	7* When multiple arrow panels are used the spacing should be approximately 3L, but not less than 1000 ft (305 m).
MT-95.60	Closure of Two-Way left Turn Lane	No Changes
MT-95.61	Closure Of Right Lane Of Three Lane Section With Two-Way Left Turn Lane	No Changes
MT-95.70	Two-Lane, Two-Way Operation For Use On Four Lane Divided Roadways (Portable Concrete Barrier-PCB)	15* For R values refer to table attached. (Same as Table 24 in this report)
MT-95.80	Two-Lane, Two-Way Operation For Use On Four Lane Divided Roadways (Asphalt Curb Divider)	17* For R values refer to table attached (Same as Table 24 in this report)

**Table 28: Recommended modifications to Standard Construction Drawings (MT Series).  
See Appendix B for modified drawings. (continued)**

Drawing No.	Maintenance of Traffic	Modifications to the Standard Construction Drawings
MT-95.81	Two-Lane, Two-Way Operations For Use On Four Lane Divided Roadways (Asphalt Curb Divider With Delineation)	No Changes
MT-95.82	Adjustment For Two Lane, Two-Way Operation On Four Lane Divided Roadways	No Changes
MT-96.10	Signalized Closing 1 Lane Of A 2 Lane Highway With Drums	No Changes
MT-96.11	Signalized Closing 1 Lane Of A 2 Lane Highway With PCB	No Changes
MT-96.20	Details For Signalized Closing 1 Lane Of A 2 Lane Highway - Side Mounted	No Changes
MT-96.21	Details For Signalized Closing 1 Lane Of A 2 Lane Highway - Overhead Mounted	No Changes
MT-96.25	Pre-Timed-Wiring Diagram For Signalized Closing 1 Lane Of A 2 Lane Highway	No Changes
MT-96.26	Actuated-Wiring Diagram For Signalized Closing 1 Lane Of A 2 Lane Highway	No Changes
MT-97.10	Flaggers Closing 1 Lane Of A 2 Lane Highway For Stationary Operations	No Changes
MT-97.11	Flaggers Closing 1 Lane Of A 2 Lane Highway For Paving Operations	No Changes
MT-97.12	Flaggers Closing 1 Lane Of A 2 Lane Highway For Paving Operations (FED)	No Changes
MT-98.12	Lane Closure In Deceleration Lane	No Changes
MT-98.13	Lane Closure Before Exit Gore	No Changes
MT-98.14	Lane Closure At Exit Gore	No Changes
MT-98.16 04/28/03	Short Term Lane Closure At Entrance Ramp	No Changes
MT-98.17	Typical Lane Closure In Deceleration Lane And Ramp For Closing Inside Portion Of Curve	No Changes

**Table 28: Recommended modifications to Standard Construction Drawings (MT Series).  
See Appendix B for modified drawings. (continued)**

Drawing No.	Maintenance of Traffic	Modifications to the Standard Construction Drawings
MT-98.20 04/28/03	Long Term Lane Closure at Entrance Ramp: Plan B	No Changes
MT-99.20m	Traffic Control For Long Line Pavement Marking Operations	No Changes
MT-99.50	Freeway/Expressway Closure Using Drums	No Changes
MT-99.51	Freeway/Expressway Closure Using Temporary Concrete Median Barrier	No Changes
MT-99.60	Short Duration Closing of Rural Divided Highway	No Changes
MT-100.00	Temporary Crossover Lighting System	No Changes
MT-101.20	Temporary Raised Pavement Markers	Recommended implementation of pavement marking materials in a lane shift. A high visibility retroreflective marking such as 3M 750 tape is suggested. Half size arrows provide additional guidance to drivers.
MT-101.60	Gates And Barricades In Position	No Changes
MT-101.70	Portable Concrete Barrier	32 in (812 mm) High PCB (Glare Screen Height 38 in (965 mm)) 50 in (1270 mm) High PCB (Glare Screen Height 20 in (508 mm)) Strip of retroreflective sheeting material on glare screen. (See figures)
MT-102.10	Transition Plan For Use Of Shoulder With PCB	17* For R values, refer to tables attached. (Same as Table 24 in this report)
MT-102.20	Transition Plan For Use Of Shoulder With Drum	15* For R values, refer to tables attached. (Same as Table 24 in this report)
MT-105.10	Temporary Sign Support	No Changes
MT-105.11	Temporary Sign Support	No Changes
MT-110.10	Detour Of Pedestrians To Temporary Walkway On Roadway	No Changes
MT-110.20	Detour Of Pedestrians To Other Side Of Street	No Changes
MT-110.30	Detour Of Pedestrians To Another Facility	No Changes
MT-120.00	New Signal Activation	No Changes
MT-98.18	Typical Lane Closure In Ramp For Closing In Ramp For Closing Outside Portion Of Curve	No Changes
MT-98.19	Exit Ramp Closure	No Changes

### **3. WORK ZONE DATA COLLECTION**

A concerted effort was made to gather complete traffic data from a variety of complex work zone configurations in order to understand the interarrival time distribution, which is the distribution of cars entering the zone through the main line or entrance ramps, and the service time distribution, which measures the effect of the taper at the entrance of a work zone on vehicle travel.

#### **3.1. Data Collection Equipment**

Microwave radar detectors such as those made by IRD [112] and Wavetronix [113] have been developed to collect traffic data nonintrusively from above or beside the road. These detectors use a microwave radar beam that is reflected by passing traffic as the means of detection. The units work in two modes, forward-fire and side-fire. In forward fire, the radar unit is aimed up along a lane of oncoming traffic and the radar unit monitors traffic in that one lane. This allows for more accurate speed determinations but requires a separate unit for each lane and may require traffic control to position the radar on a cantilever post or bridge. In side-fire mode the radar unit is aimed from the side of the road across passing traffic, and the radar unit detects when the beam pattern is broken and reflected back. In side-fire mode speed and hence length determinations are not as accurate, but one can cover several lanes with one radar unit; Wavetronix advertises a capability of monitoring up to 8 lanes of traffic with one of their units in side-fire mode [113, p. 17].

The traffic measurement trailer system used in this project was designed and developed by Treehaven Technologies of Powell, Ohio [114]. The trailer in operation is depicted in Figure 40. The trailer consists of a custom-made steel frame with a solar panel plus battery box, as shown in Figure 41, containing four deep-cycle gel batteries and a power controller, manufactured and assembled by Solar Traffic Controls. The solar power unit is rated at 225 W and outputs 12V DC; it comes with a Pro-Star 15 charge controller capable of regulating up to 15 A of current. Each battery is rated at 115 Ah, which is designed so that the system can run for 8 days on fully charged batteries without sunlight. There is a Xantrex Link 10 system meter that can be used to monitor voltage, current, charge (in Amp-hours) and estimated time that the batteries can sustain the current load (in hours). The trailer has two telescoping poles capable of reaching a height of 20 feet (6.1 m) and four sockets so that the poles can be erected on either side of the trailer. For transport the poles are placed in the front sockets and tilted back against the fenders, where clamps hold the poles in place. At each corner are Bulldog crank legs that allow the trailer to be leveled on slopes up to 30°, and there is a leveling bubble mounted on the trailer for verifying the trailer's level status. The towing tongue is detachable as an anti-theft precaution; special lock nuts are also used on the wheels as another anti-theft measure.





**Figure 40: Microwave radar trailer set up to collect data a) rear view with solar panel in use, b) side view with solar panel in storage position**



**Figure 41: Inside view - battery box showing microcontroller at left, batteries at center, and power monitor at right**

One Wavetronix model SS105 SmartSensor radar unit, operating in side-fire mode, is attached to each pole. There is a cable from each sensor running down to the battery box, where

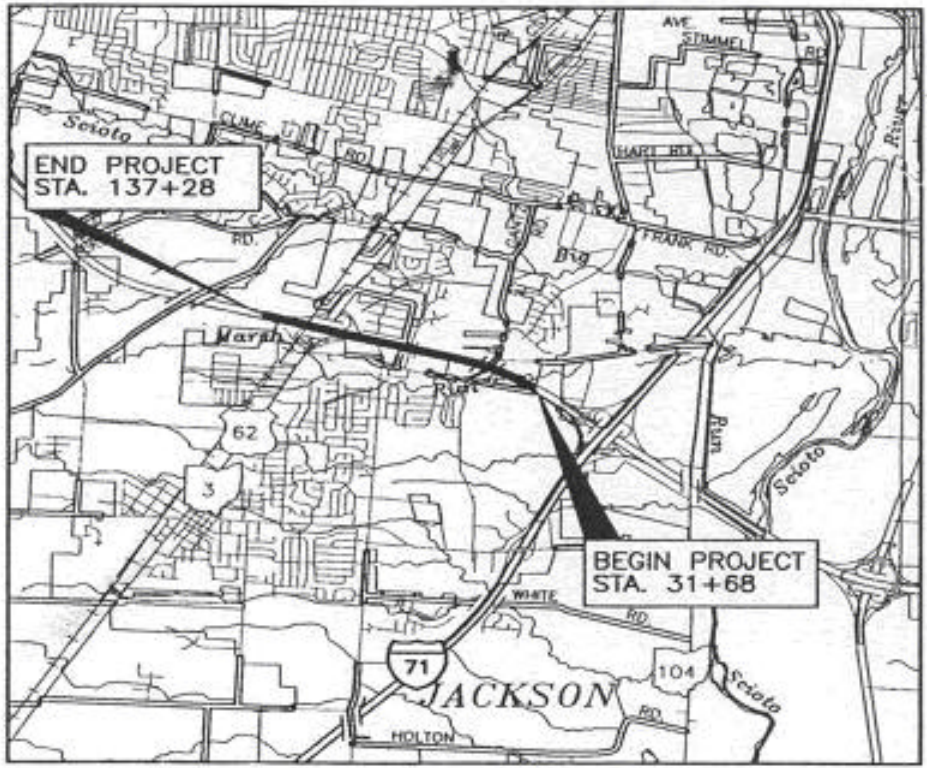
there is a connection to the controller unit that is contained in the battery box. The controller is a small computer that collects the data from each radar sensor and combines the data into a single text file. The text file is stored on the computer's hard drive and also simultaneously written to a 256 MB flash memory card. Data files can either be downloaded via ftp through a crossover network cable or read by removing the flashcard and inserting it into a flashcard reader. While downloading data, the controller is designed to continue collecting data to a temporary buffer that is appended to the data file when the trailer is returned to run mode. The controller has a pass-through setting that allows the user to access and configure the individual radar sensors.

### **3.2. Description of Work Zone Data Collection Sites**

A total of six sites were chosen for this study. A brief description of each work zone location follows:

#### ***3.2.1. I-270 Eastbound/Westbound Work Zone in Columbus***

This construction work zone is identified as FRA-270-0.60 on construction drawings. The construction work involved replacing the pavement, widening the median shoulder, preventive maintenance on structures, and replacement of traffic control signs and guardrails on I-270 in Jackson Township in Franklin County. The work zone was a two mile stretch on I-270 extending from 0.6 miles west of I-71 (south side) to 0.47 mile west of US-62. The map of the construction work zone site is given in Figure 42. The speed limit on I-270 was 65 mph (105 km/h) before the construction zone, and it was 55 mph (88 km/h) through the construction zone.



LOCATION MAP

LATITUDE: N39°54'10"

LONGITUDE: W83°04'00"

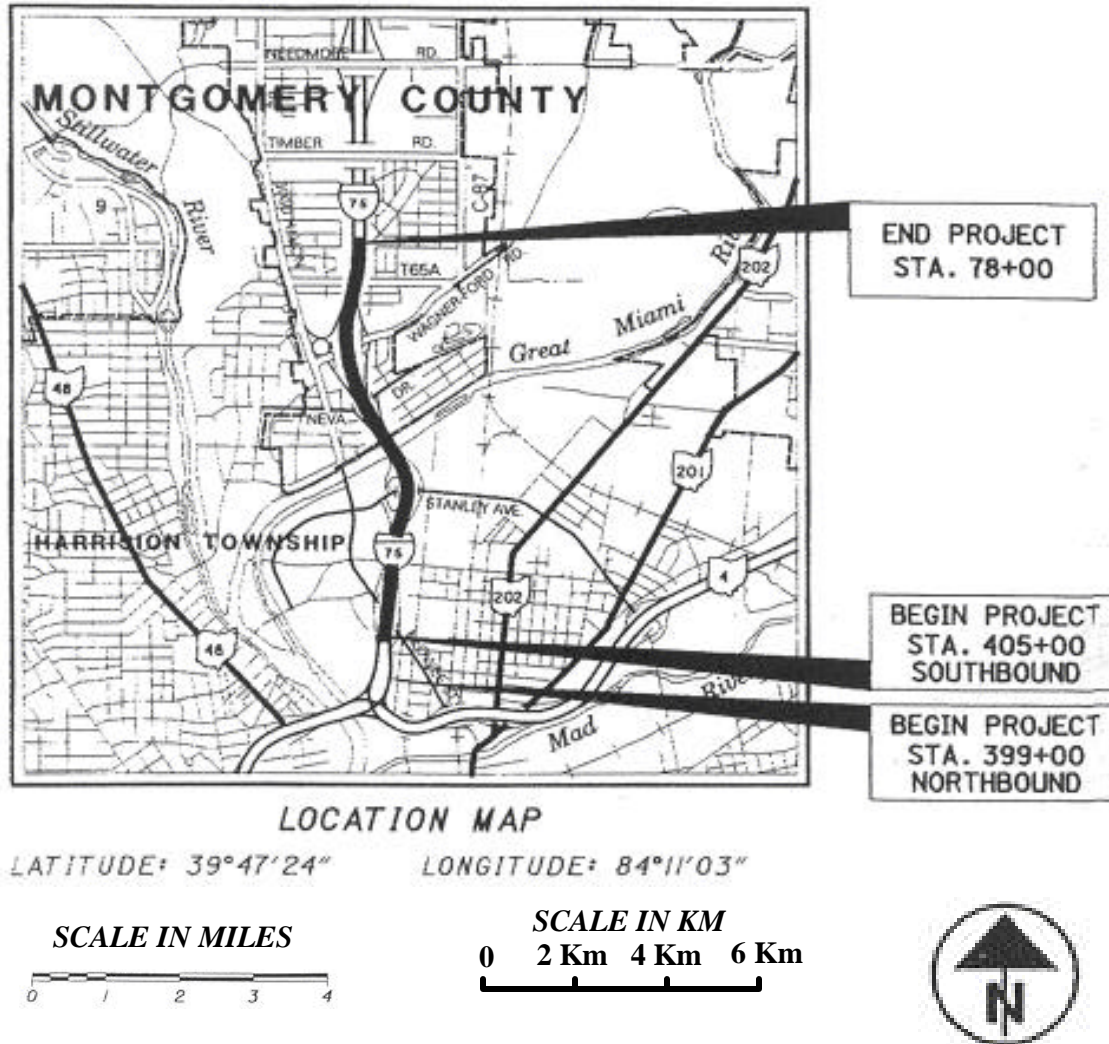
SCALE



**Figure 42: Map of work zone on I-270 Columbus**

**3.2.2. I-75 Southbound Work near Zone Dayton**

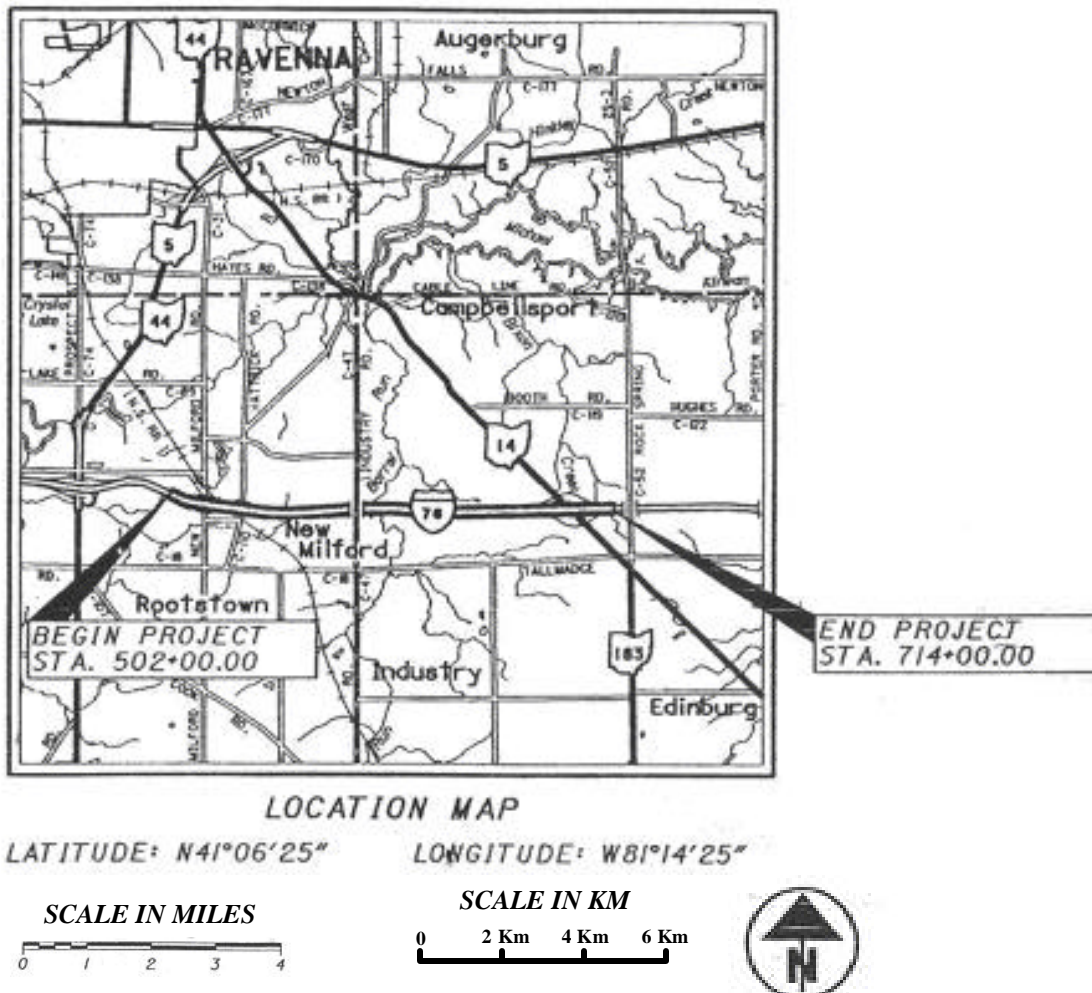
This work zone involved rehabilitation of bridges and resurfacing of pavement on I-75 in Harrison township of Montgomery county. It is identified as MOT-75-14.36 in ODOT construction drawings. The legal speed of I-75 southbound was 55 mph (88 km/h) before the construction zone and 45 mph (72 km/h) through the construction zone. A map of the construction work site is provided in Figure 43.



**Figure 43: Map of work zone on I-75 Dayton**

**3.2.3. I-76 Westbound Work Zone near Rootstown**

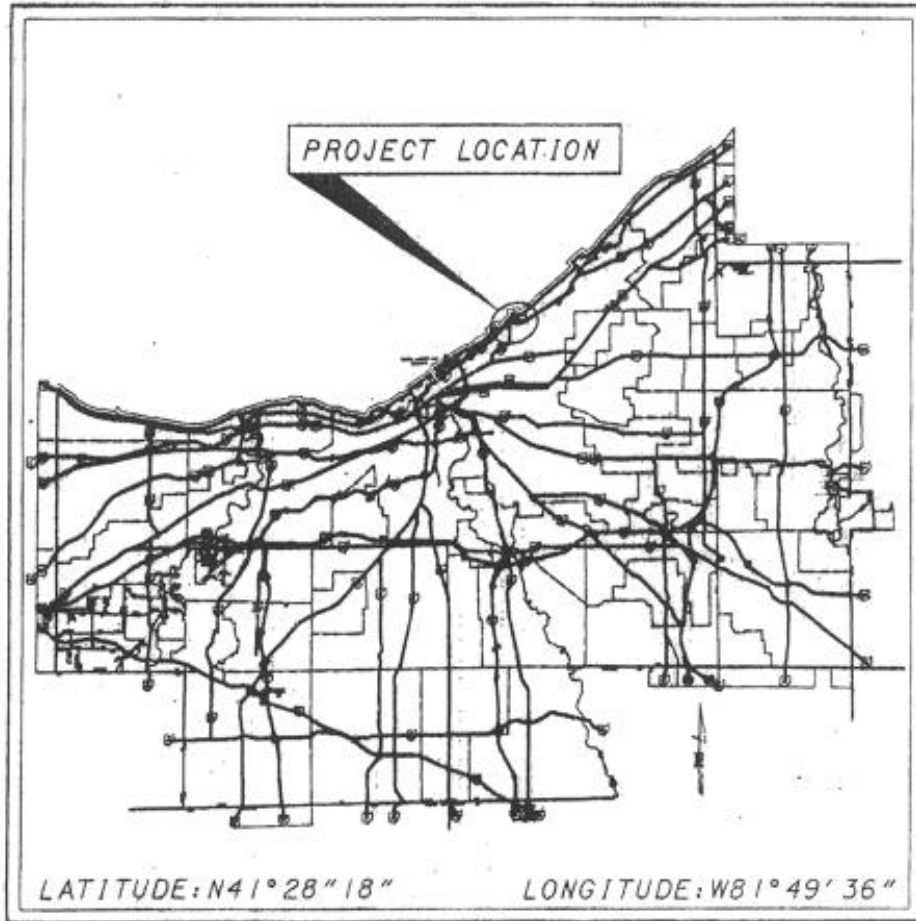
This construction work zone was Ohio State Job Number 534.03, also identified as POR-76-9.50 on construction drawings. It was a bridge repair and pavement resurfacing job on I-76 in Rootstown and Edinburg Townships in Portage County. It extends from State Route 14 on the east to State Route 44 on the west. The map of the construction work zone site is given in Figure 44. In the summer of 2004, both lanes of eastbound traffic are crossed over to the westbound direction and the westbound traffic was reduced to a single lane for about 1.1 miles. The speed limit on I-76 was 65 mph (105 km/h) before the construction zone, and it was 55 mph (88 km/h) through the construction zone.



**Figure 44: Map of work zone on I-76 near Rootstown**

**3.2.4. I- 90 Eastbound/Westbound Work Zone in Cleveland**

This construction work zone is identified as CUY-90-20.35 in the construction drawings. It involved rehabilitation of seven bridges and other minor repairs along I-70 in the city of Cleveland, Cuyahoga County. The speed limit before and through the construction zone was 55 miles per hour. A map of the work zone is shown in Figure 45.



LOCATION MAP

SCALE IN MILES



SCALE IN KM



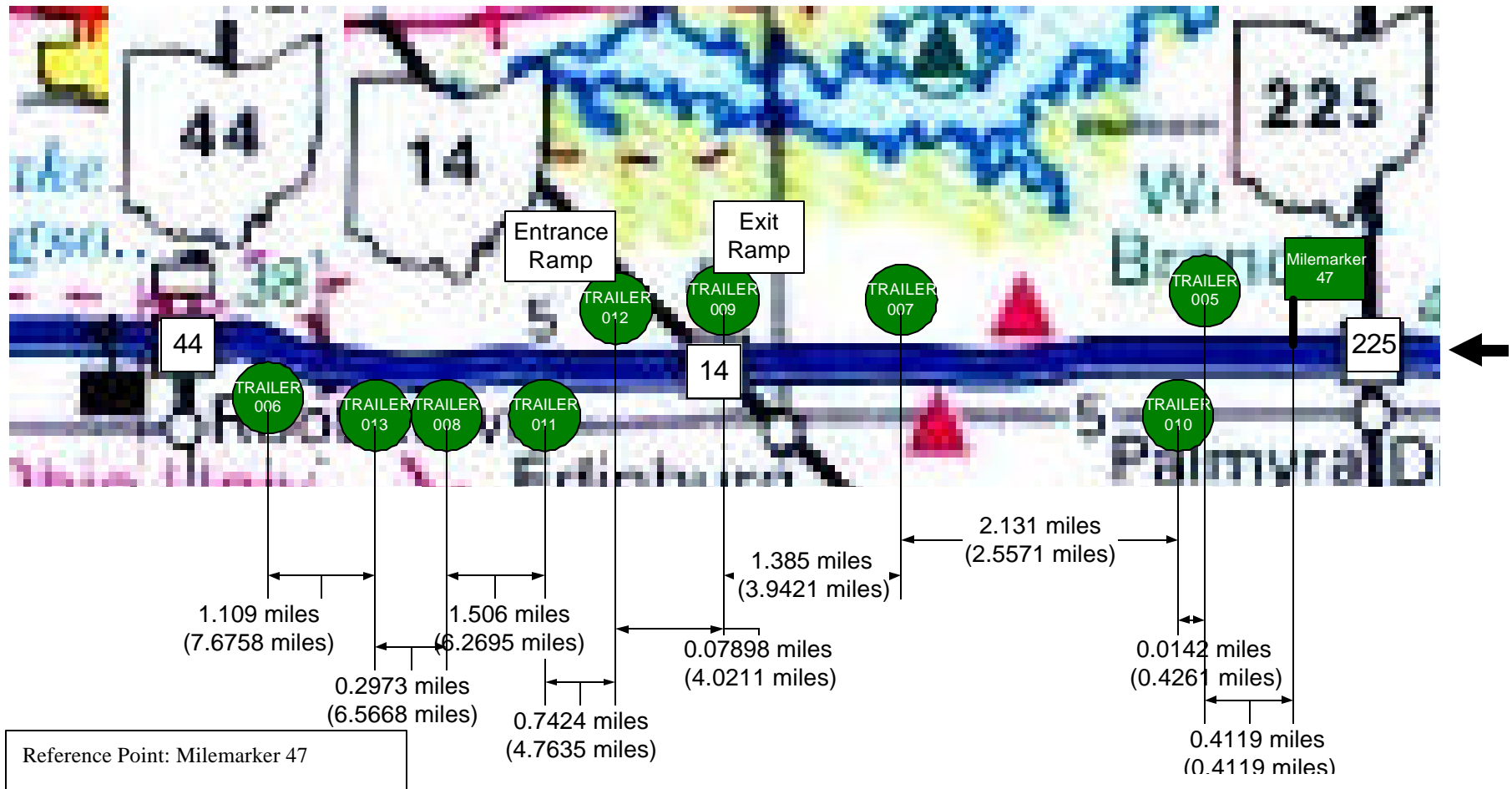
Figure 45: Map of work zone on I-90 Cleveland

### 3.3.Data Collection

Microwave radar trailers as described above were set up at the work zone locations described. The time periods of data collection and the number of microwave radar trailers used are given in Table 29. The traffic before and through the work zone was monitored for at least 3 days at each work zone site and location. The vehicles entering and exiting the mainline traffic through the ramps were also recorded. In Figure 46 through Figure 56, locations for each trailer along with the distances between them are given for each work zone site. The trailers were given identification numbers by the researchers, and those numbers are referred to in these figures.

**Table 29: Number of Microwave Radar Trailers used at the Work Zone Locations**

Site Number	Site	Number of Trailers	Period of Data Collection
1	I - 76 Westbound near Akron	8	08-17-04 to 08-24-04
2	I-270 Westbound near Columbus	9	08-27-04 to 09-01-04
3	I-270 Eastbound near Columbus	9	08-31-04 to 09-04-04
4	I-90 Eastbound near Cleveland	10	09-13-04 to 09-18-04
5	I-90 Westbound near Cleveland	6	09-16-04 to 09-20-04
6	I-75 Southbound near Dayton	1	09-15-04 to 09-21-04

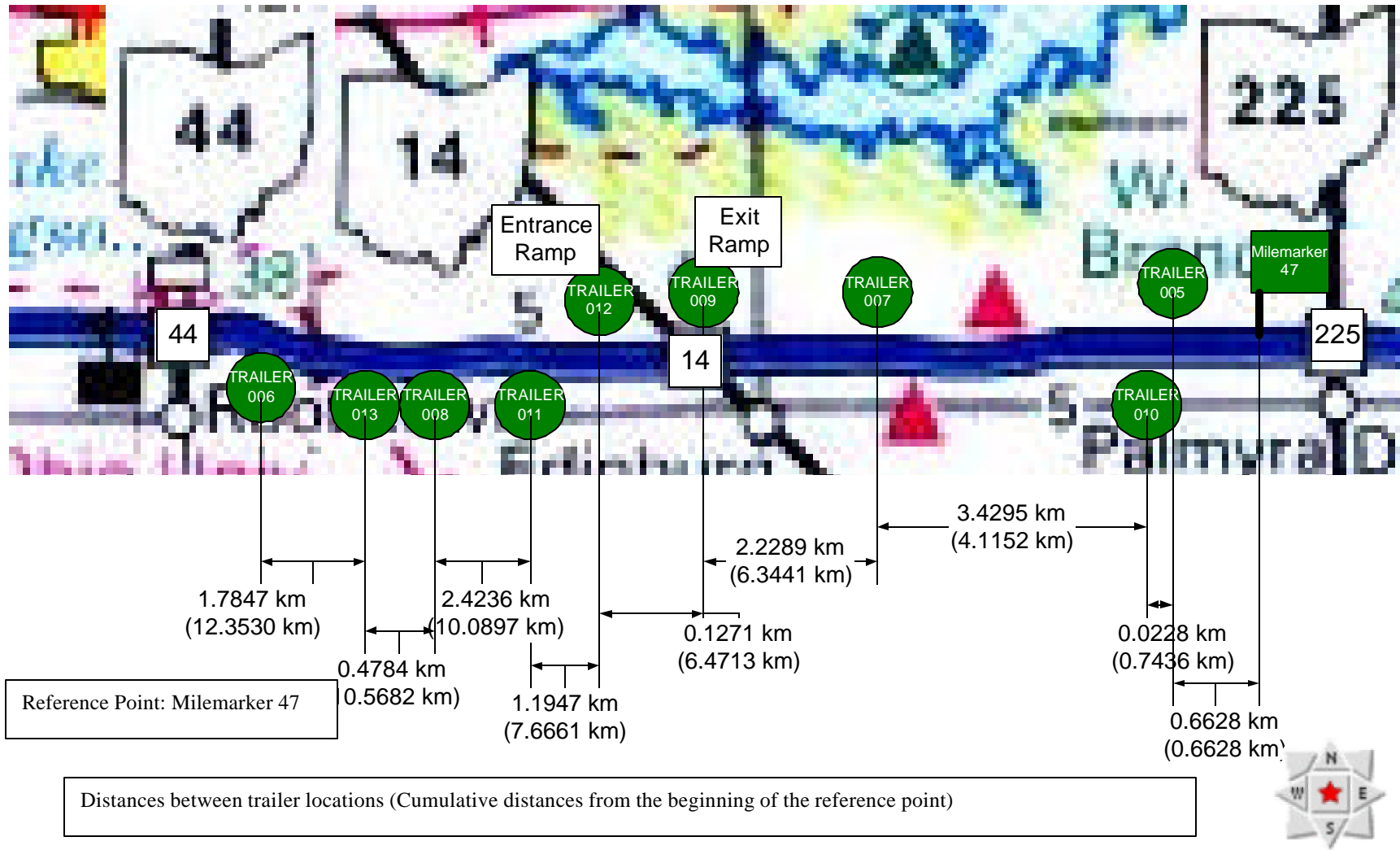


Distances between trailer locations (Cumulative distances from the beginning of the reference point)

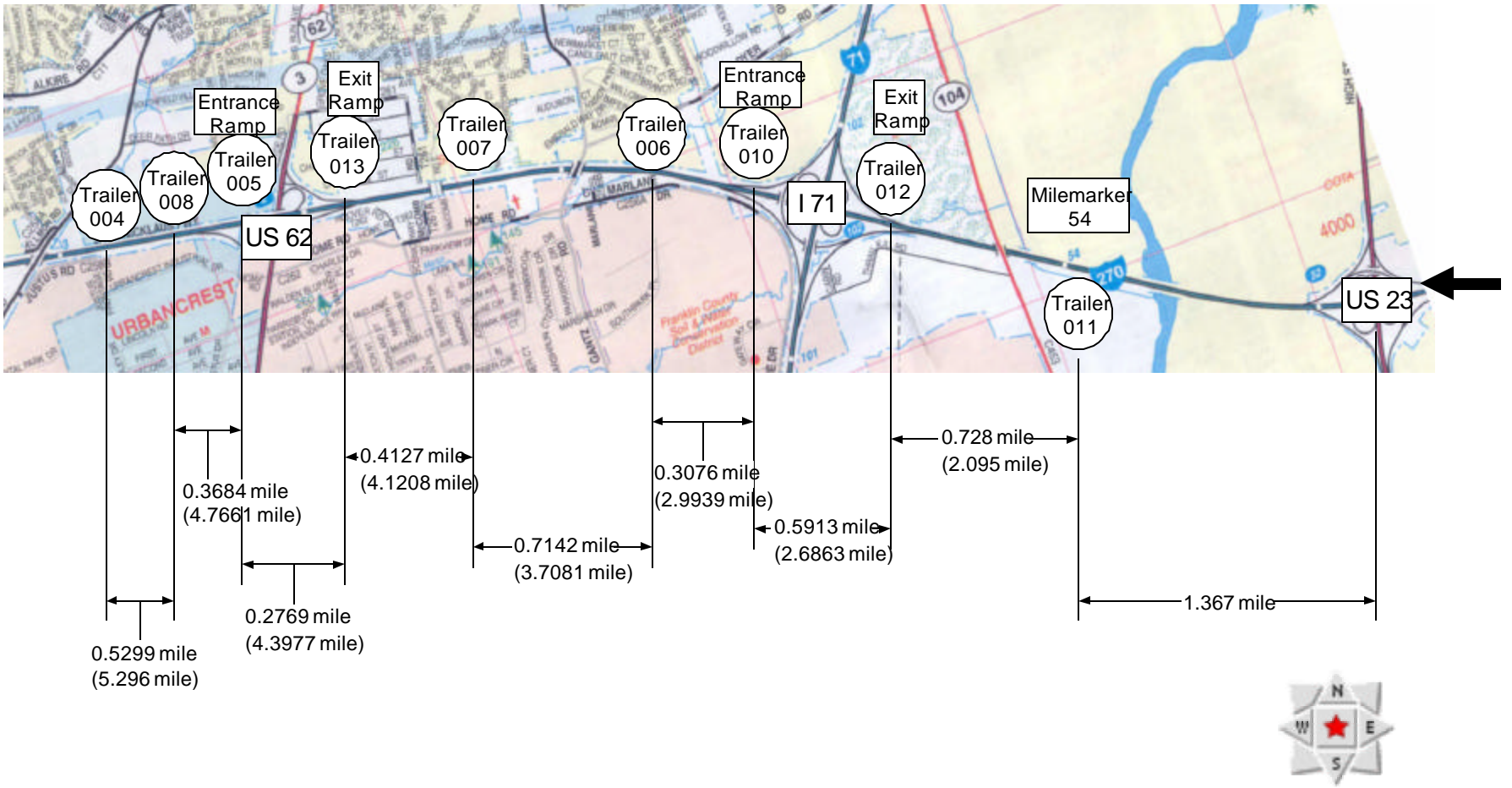


Figure 46: Trailer Locations at I-76 Westbound near Rootstown Work Zone with distances in miles.





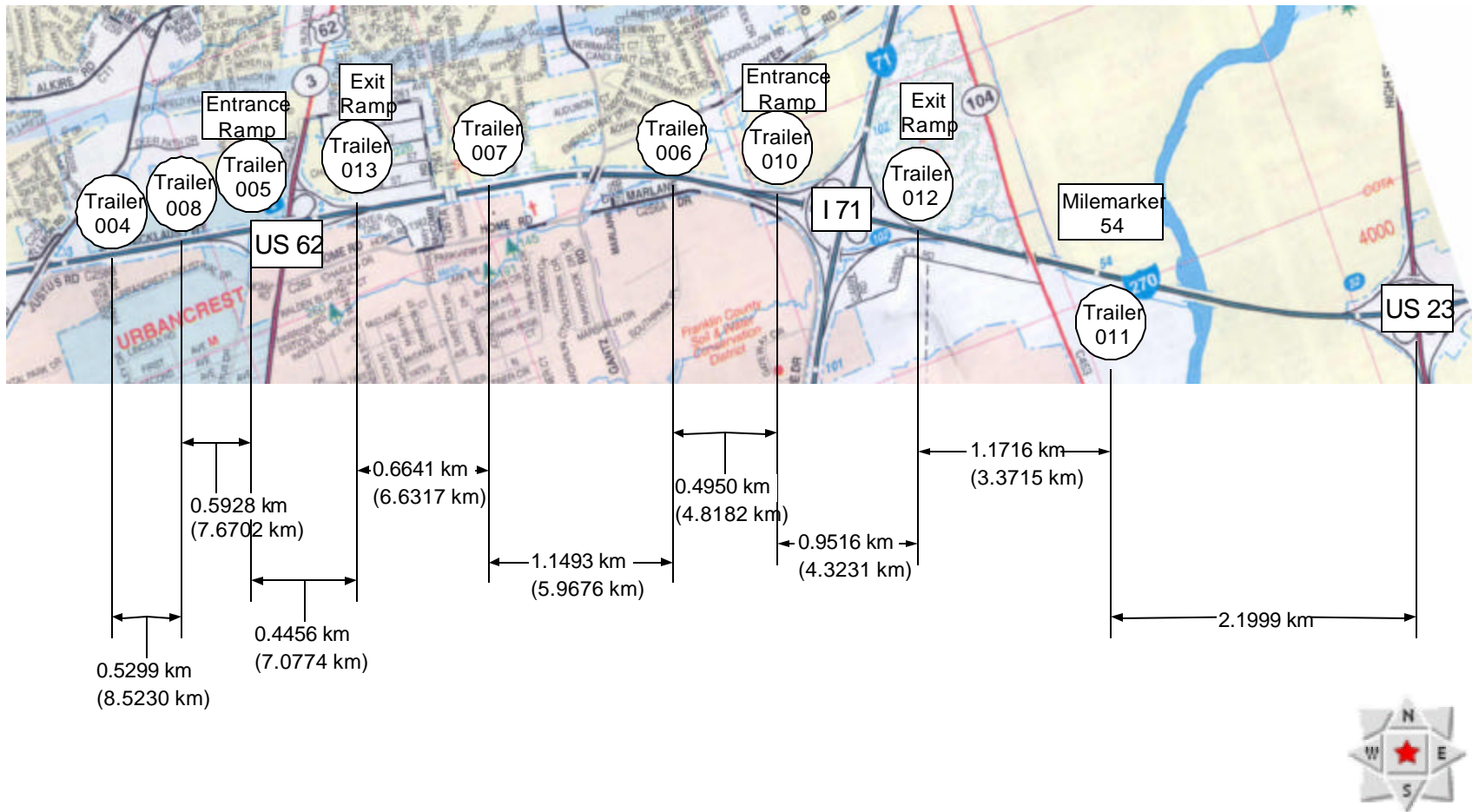
**Figure 47: Trailer Locations at I-76 Westbound near Rootstown Work Zone with distances in km.**



Reference Point: Beginning of the Entrance Ramp from US 23

Distances between trailer locations (Cumulative distances from the beginning of the reference point)

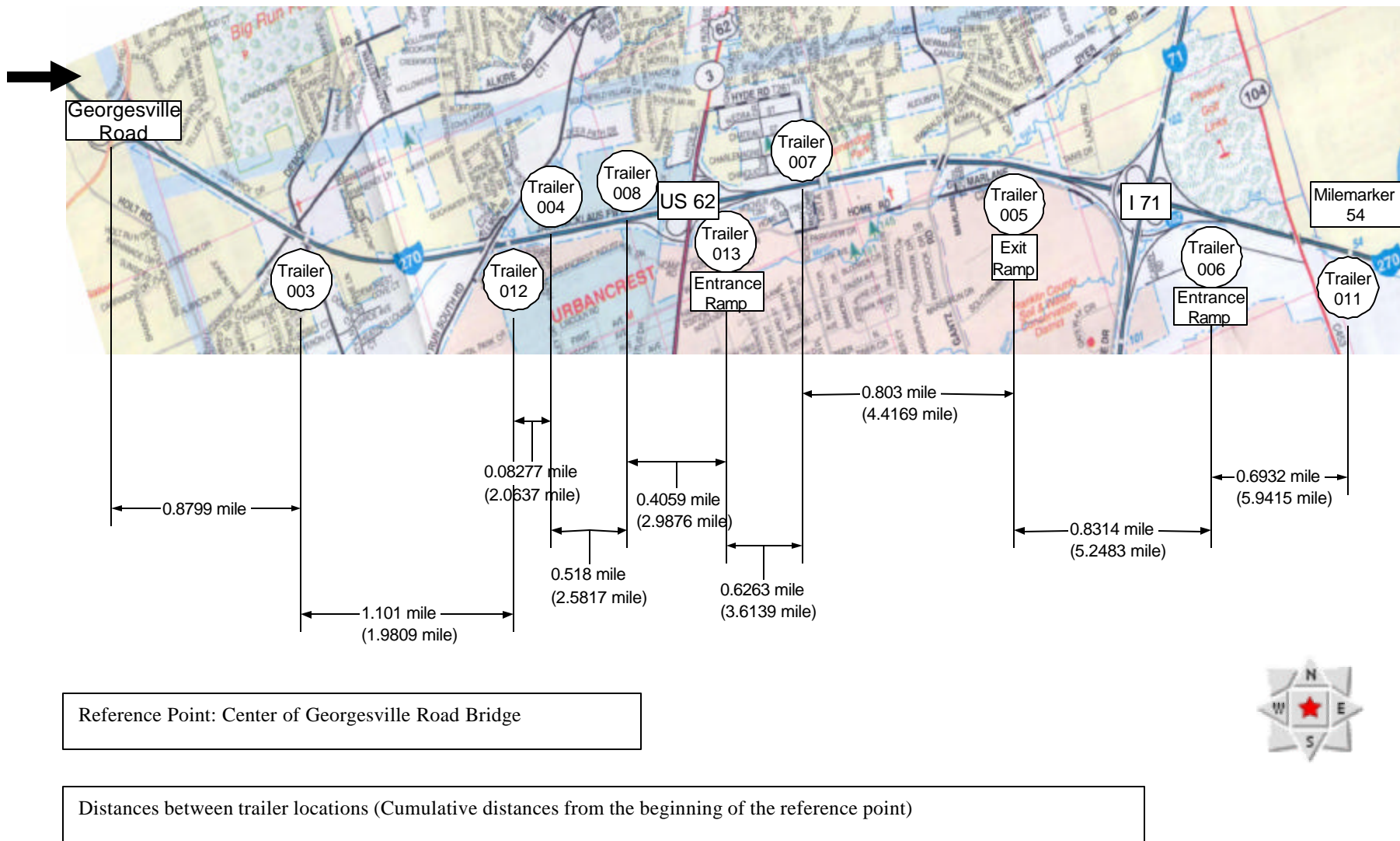
**Figure 48: Trailer Locations at I-270 Westbound Columbus Work Zone with distances in miles.**



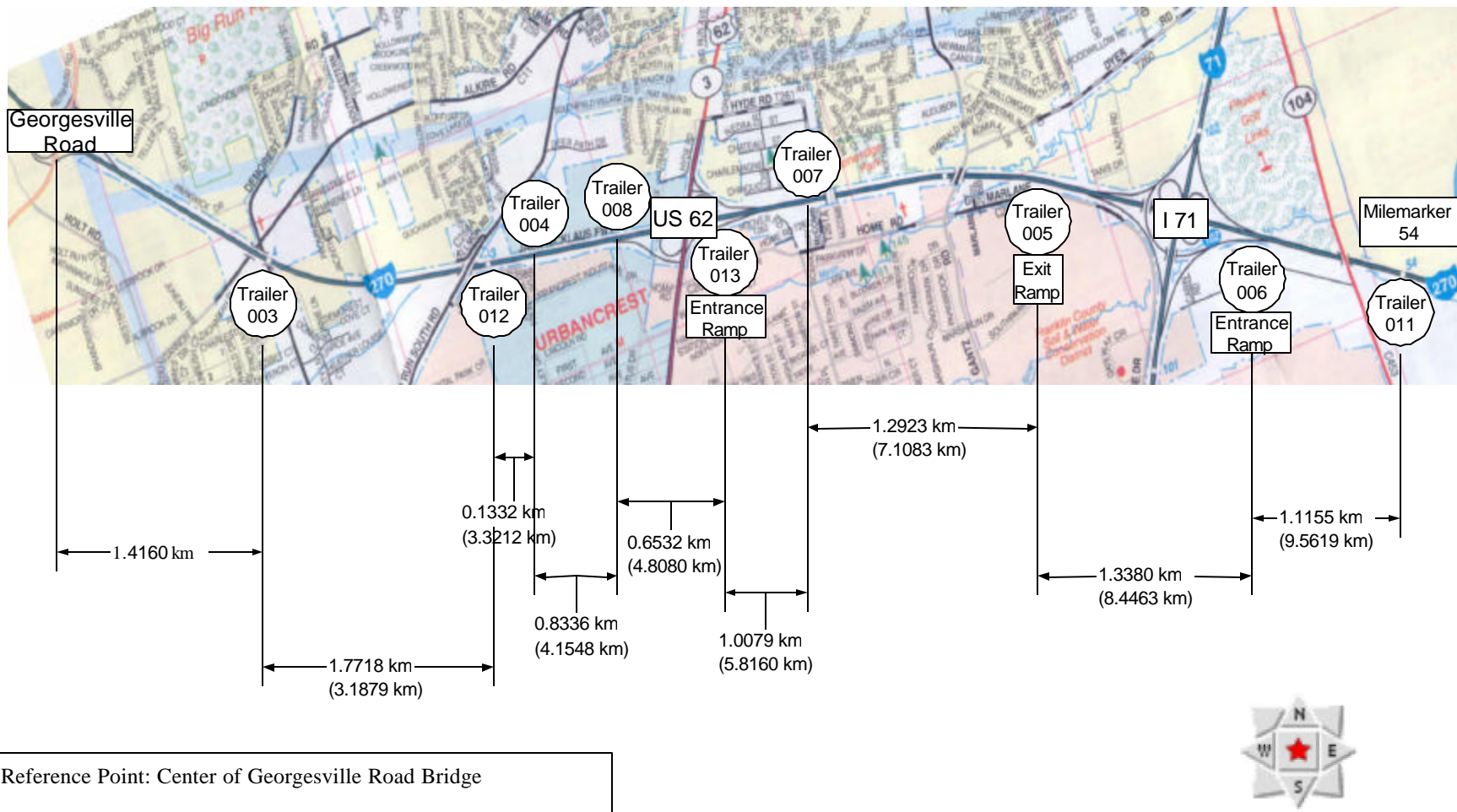
Reference Point: Beginning of the Entrance Ramp from US 23

Distances between trailer locations (Cumulative distances from the beginning of the reference point)

**Figure 49: Trailer Locations at I-270 Westbound Columbus Work Zone with distances in km**



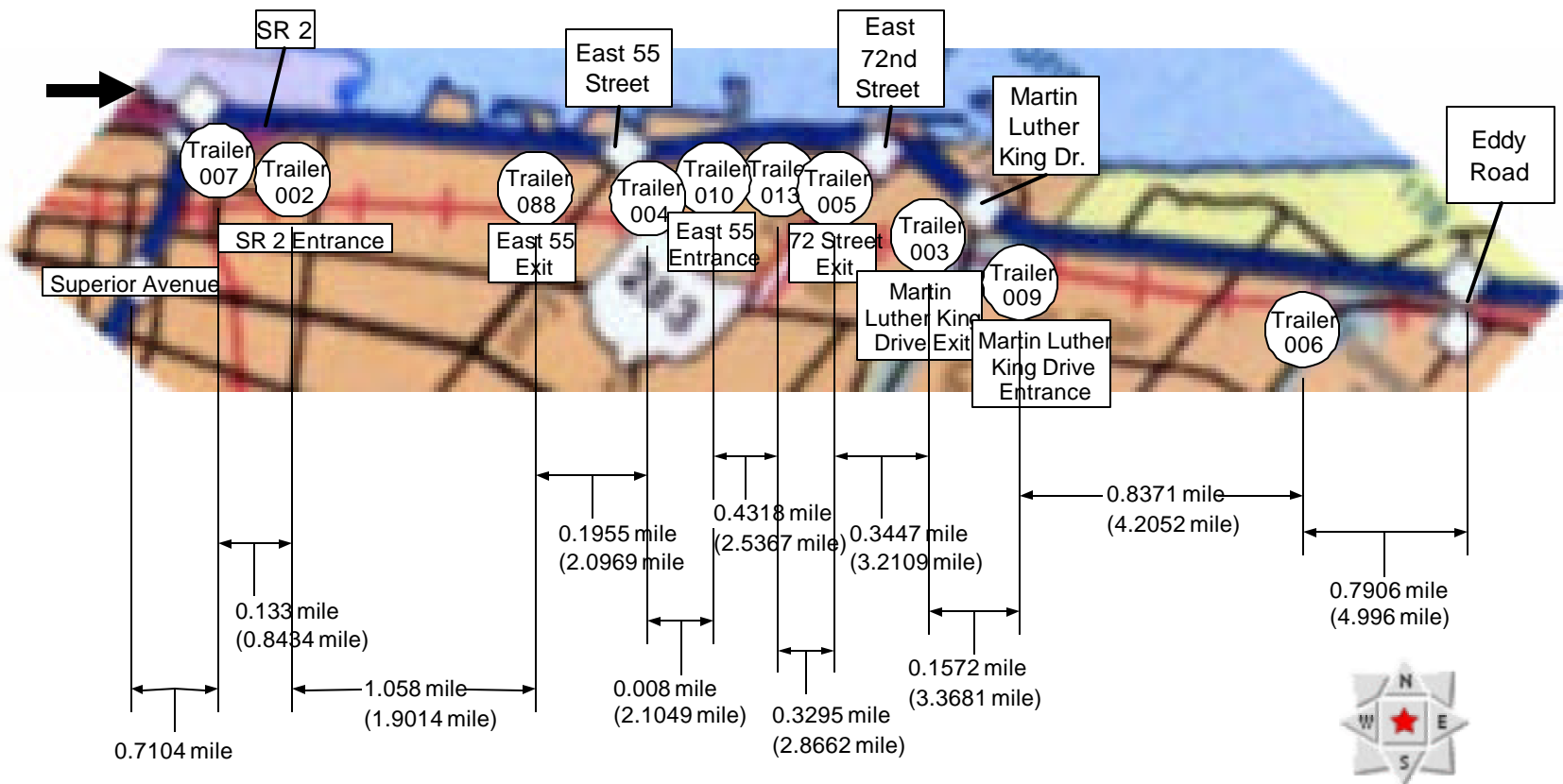
**Figure 50: Trailer Locations at I-270 Eastbound Columbus Work Zone with distances in miles.**



Reference Point: Center of Georgesville Road Bridge

Distances between trailer locations (Cumulative distances from the beginning of the reference point)

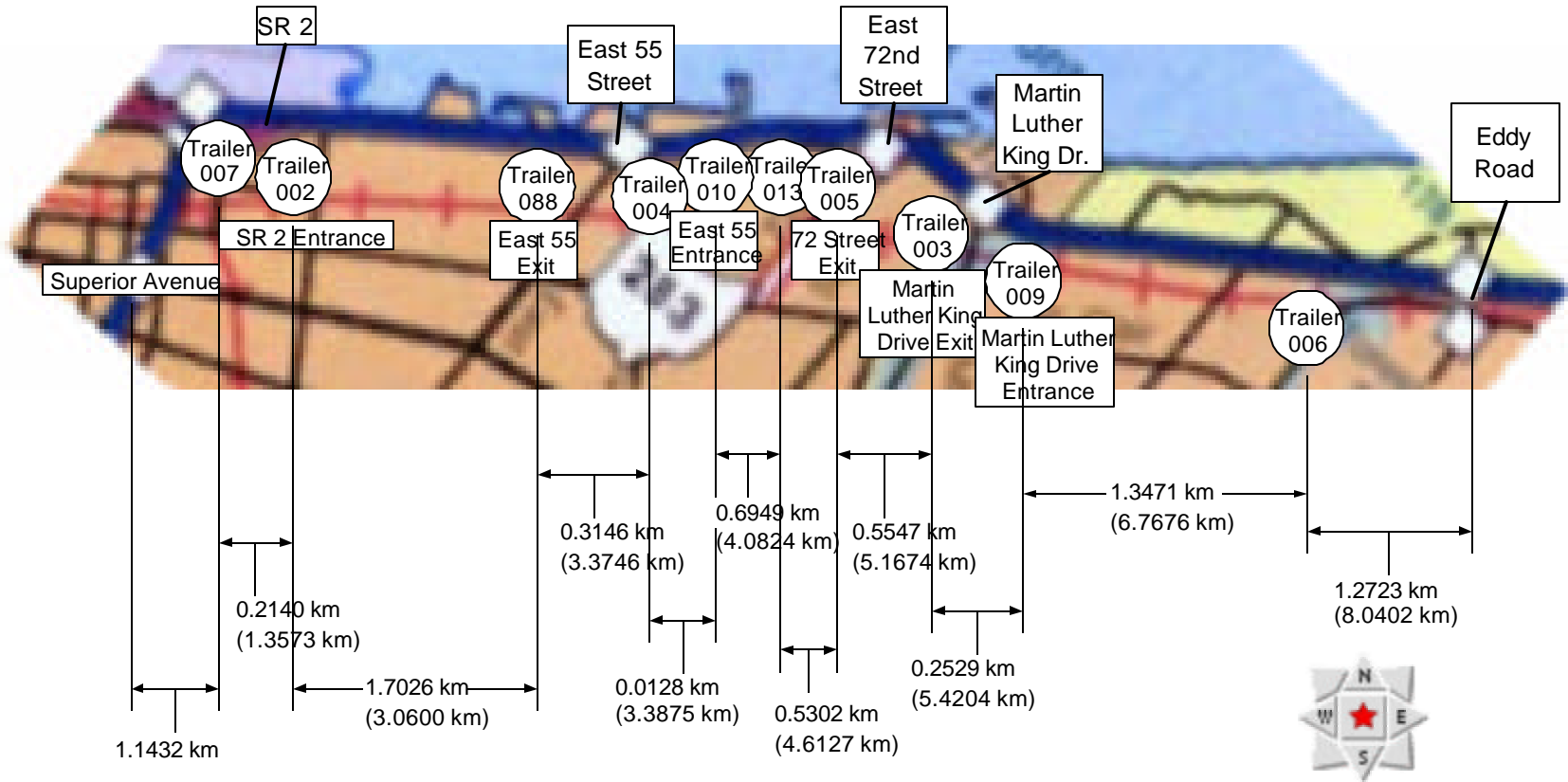
**Figure 51: Trailer Locations at I-270 Eastbound Columbus Work Zone with distances in km.**



Reference Point: Beginning of the Entrance Ramp from Superior Avenue

Distances between trailer locations (Cumulative distances from the beginning of the reference point)

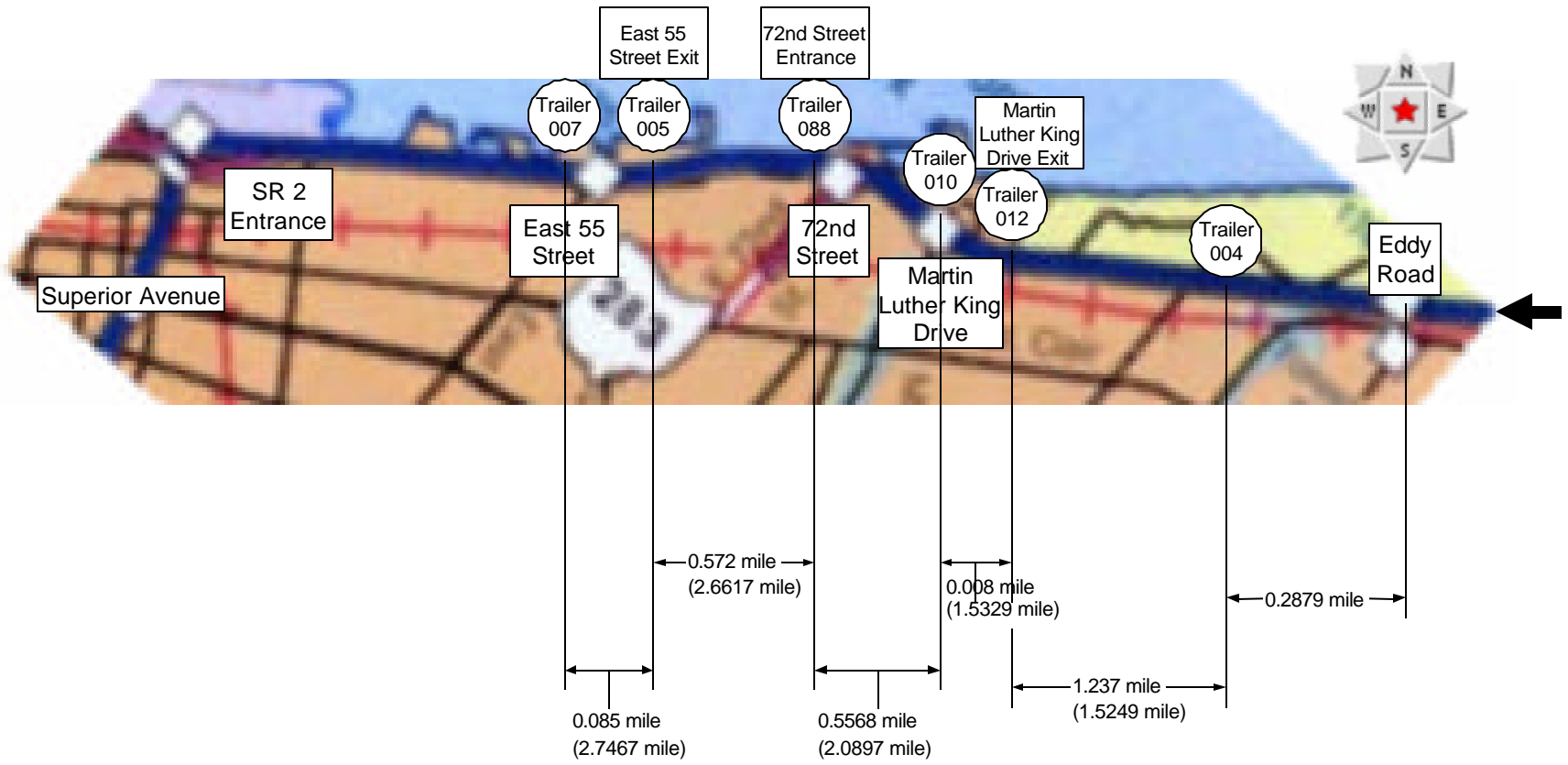
**Figure 52: Trailer Locations at I-90 Eastbound Cleveland Work Zone with distances in miles.**



Reference Point: Beginning of the Entrance Ramp from Superior Avenue

Distances between trailer locations (Cumulative distances from the beginning of the reference point)

**Figure 53: Trailer Locations at I-90 Eastbound Cleveland Work Zone with distances in km.**

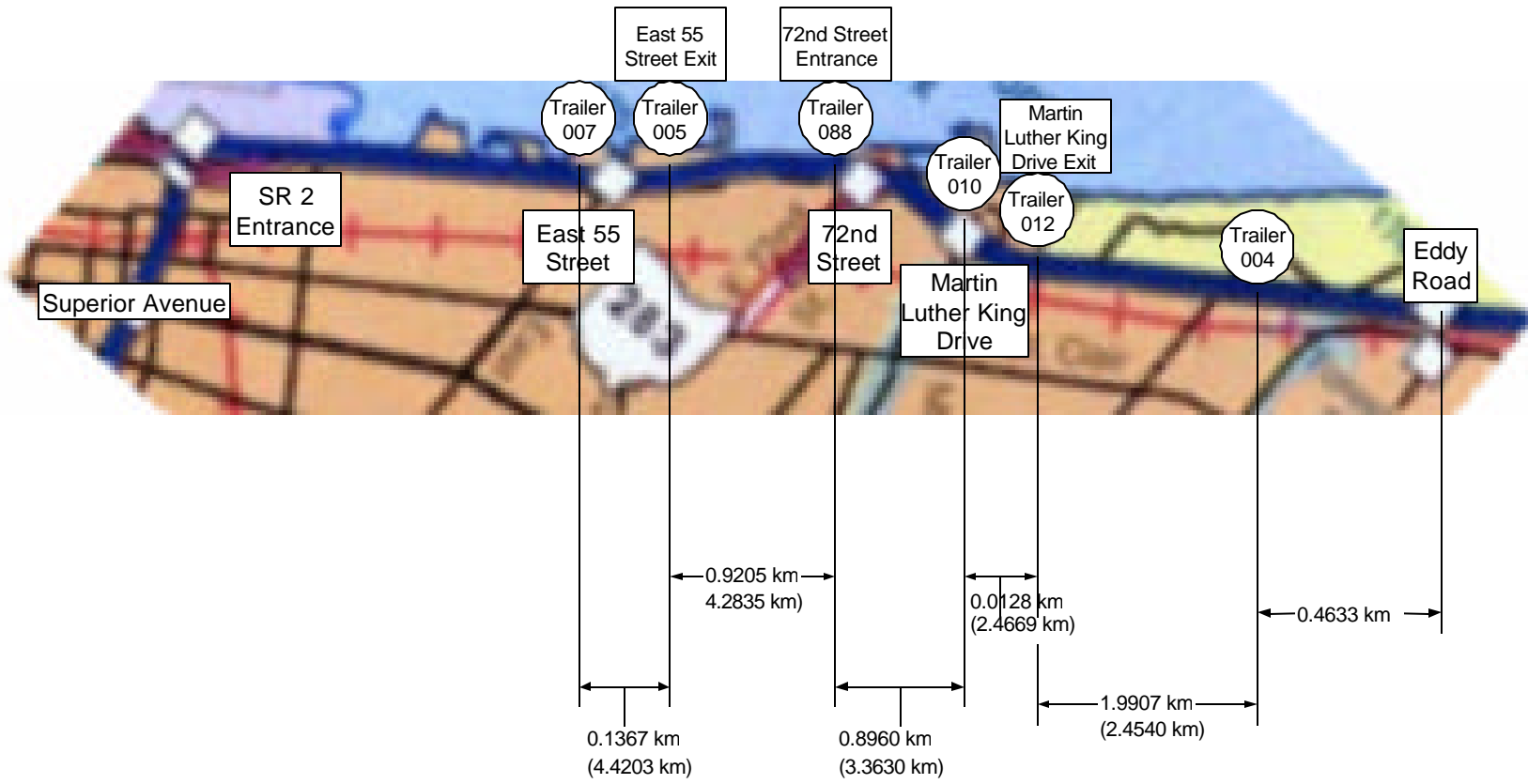


Reference Point: Beginning of the Entrance Ramp from Eddy Road

Distances between trailer locations (Cumulative distances from the beginning of the reference point)

**Figure 54: Trailer Locations at I-90 Westbound Cleveland Work Zone with distances in miles.**

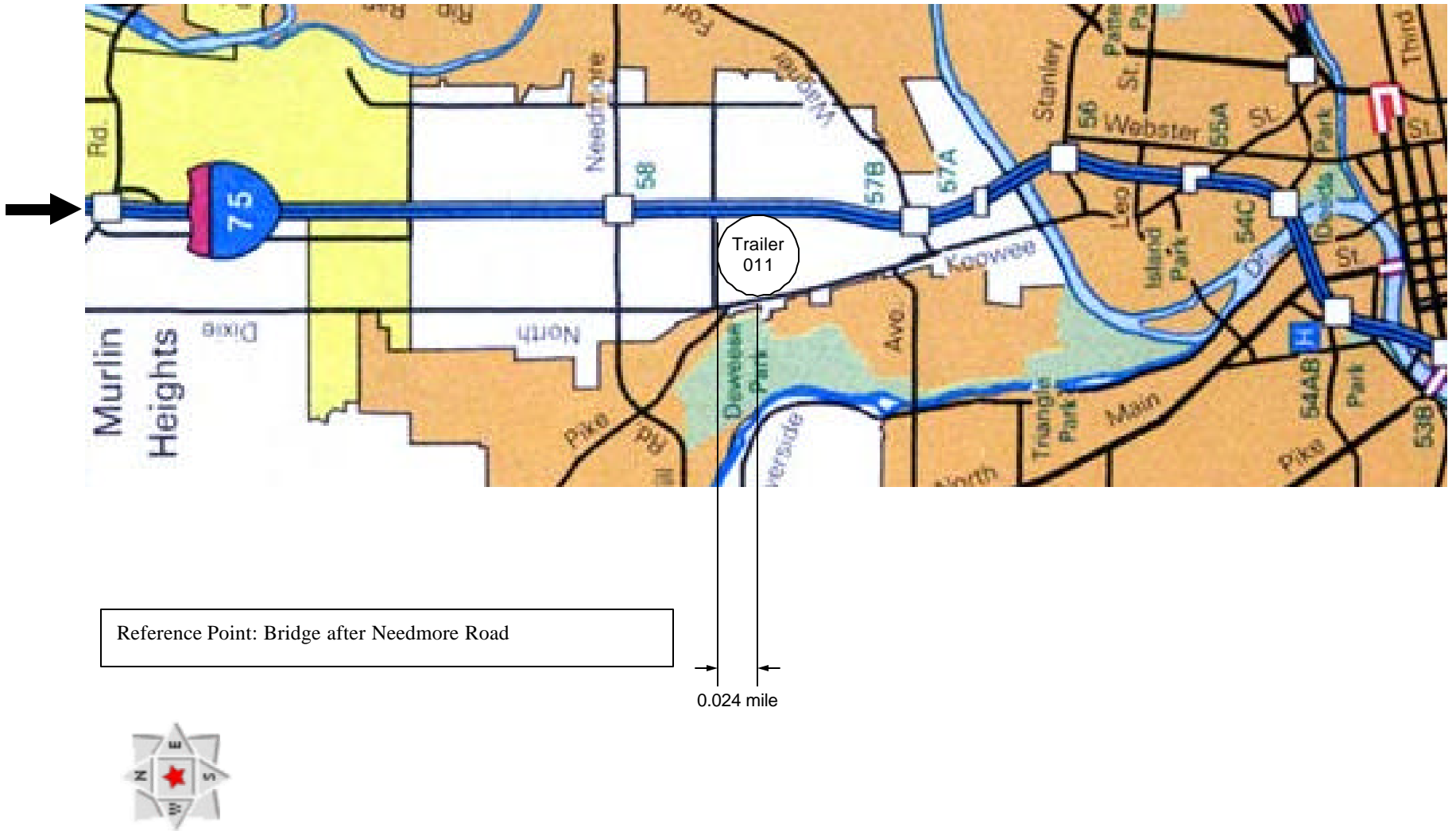




Reference Point: Beginning of the Entrance Ramp from Eddy Road

Distances between trailer locations (Cumulative distances from the beginning of the reference point)

**Figure 55: Trailer Locations at I-90 Westbound Cleveland Work Zone with distances in km.**



**Figure 56: Trailer Location at I-75 Southbound near Dayton Work Zone (0.024 mi = 0.0384 km).**

The trailer setup procedure began with parking and unhitching the trailer, then raising the trailer wheels off the ground and leveling the trailer using the stabilizing legs. Then the solar panel was positioned to catch the maximum amount of solar radiation. The next step was placing the collapsed poles in the mounting tubes. Then the offset of the pole base from the road edge was measured to determine the proper mounting height for the sensors, which was typically about 20 feet (6.1 m). Next came placing the sensors at the proper pole height, measured by tilting the poles to a horizontal position, extending and measuring with a tape measure. The poles with the sensors firmly attached were then collapsed and positioned vertically. The proper tilt of each sensor was adjusted using a tiltmeter and the data communication cable attached. The poles were then extended to their full height. A laptop computer was then connected with a null-modem serial cable and the controller turned on and set to calibrate the first radar unit. After the first sensor was set up using the manufacturer's procedure, which involved using the SmartSensor's autoconfiguration feature and then possibly fine tuning the lane boundaries manually, the second sensor was similarly configured. Part of the configuration procedure was to synchronize each the sensor with the clock of the computer used to access the system; the sensors then resynchronized with each other every eleven minutes (this time could be adjusted by the user). Setup took about half an hour plus time for sensor configuration, which took another 15 minutes or so with continuous traffic in all lanes or longer if traffic was sparse. An external laptop computer could be connected using the null-modem cable and Hyperterminal used to monitor output from the controller in real time or to program it. Alternatively, a mouse, keyboard, and monitor could be directly connected to the controller.

A sample of the data as collected by the trailer's controller is shown in Table 30. The data collected by the system include time to the nearest millisecond (though the system is configured to use 2.477-ms time increments), lane of traffic, then a set of data from the first sensor: a timestamp in 2.5-ms time increments, duration of the radar image in 2.477-ms time increments, a moving average speed based on the last 16 vehicles in mph, and a vehicle class. Next comes the same set of data for the second sensor, then an average of the two running average speeds in mph, vehicle length in feet, and per vehicle speeds for each sensor in mph. All speeds are rounded to whole mph values, and all lengths to even feet values. In this research the sensors have been configured to bin vehicles into three classes: class 0 is 0-20 ft (0-6.1 m), class 1 is 21-40 ft (6.1-12.2 m), and class 2 is anything at least 41 ft (12.2 m) long. The two radar sensors are needed to properly determine vehicle length, though each sensor classifies vehicles into length bins. There are thus three length classification data items in the record: a length in feet, a classification by sensor 1, and a classification by sensor 2.

The "per vehicle speeds" are reported for each sensor, but the terminology used is somewhat misleading. "Per vehicle speed Sensor 1" is actually the speed computed by taking the difference between the timestamps for each sensor, representing the leading edge of the vehicle triggering the radar beams, converting to seconds by multiplying by 2.477/1000, then dividing that into the 7 foot (2.1 m) longitudinal distance between the two radar units and converting from ft/s to mph. "Per vehicle speed Sensor 2" is computed using the trailing edge of the vehicle trace, and is computed in the same manner except that instead of using the timestamp value for each sensor, the timestamp + duration from each sensor is substituted. The per vehicle speeds reported for each sensor can vary widely (values as high as 937 mph (1507 km/h) have been recorded) and thus are disregarded in the analysis. The radar trailer measures

vehicle length by taking the average of the two moving average speeds, converting to ft/s, multiplying by the average of the two durations, multiplying by 2.477/1000 to convert to seconds, then subtracting 6 feet (1.8 m) for the width of the radar beam field.

**Table 30: Sample of data file as recorded by trailer (1 mph = 1.6 km/h).**

Year	Day	Month	Hour	Minute	Second	ms	Lane	Sensor	TimeStamp (2.5ms)	Duration (2.477ms)	Sensor Average Speed (mph)	Class	Sensor	TimeStamp (2.5ms)	Duration (2.477ms)	Sensor Average Speed (mph)	Class	Average of Two Speeds (mph)	Vehicle Length (ft)	Per Vehicle Speed Sensor 1 (mph)	Per Vehicle Speed Sensor 2 (mph)
2004	13	7	12	29	18	7	1	1	13663203	113	61	1	2	13663219	125	67	1	64	21	120	68
2004	13	7	12	29	20	297	1	1	13664119	106	61	0	2	13664124	87	68	0	64	16	385	137
2004	13	7	12	29	33	492	1	1	13669397	106	61	0	2	13669414	108	70	1	65	19	113	101
2004	13	7	12	30	39	457	2	1	13695783	117	48	0	2	13695808	93	66	0	57	15	77	999
2004	13	7	12	30	41	425	2	1	13696570	112	48	0	2	13696586	138	66	1	57	19	120	45
2004	13	7	12	33	3	340	1	1	13753336	347	58	2	2	13753351	391	67	2	62	77	128	32
2004	13	7	12	33	23	952	1	1	13761581	97	58	0	2	13761606	100	66	0	62	16	77	68
2004	13	7	12	34	6	530	2	1	13778612	108	55	0	2	13778637	99	58	0	56	14	77	120

Notes:

- Lane 1 is the lane nearest to the trailer, Lane 2 is second nearest, and so on.
- Sensor 1 is the first sensor triggered by passing traffic (upstream), Sensor 2 is the second (downstream).
- Timestamp is in 2.5 ms units, Duration is in 2.477 ms units.
- Sensor Average Speed is the average of the last 16 vehicles recorded by the sensor.
- Class 0 = length 0-20 feet (0-6.1 m); Class 1 = length 21-40 feet (6.1-12.2 m); class 2 = length > 40 feet (12.2 m).
- Vehicle Length is computed by taking the average speed, converting to feet per second, multiplying by the duration converted (approximately) to seconds, and subtracting 6 feet (1.8 m) for the beam width.
- Per Vehicle Speed Sensor 1 is computed by taking the time the leading edge of the vehicle breaks the radar beam in each sensor, subtracting, converting to seconds, and dividing that into the 7 ft (2.1 m) distance between the sensors.
- Per Vehicle Speed Sensor 2 is computed by taking the time the trailing edge of the vehicle leaves the radar beam plus the duration for each sensor, subtracting, converting to seconds, and dividing that into the 7 ft (2.1 m) distance between the sensors.

Ohio Research Institute for Transportation and the Environment (ORITE) researchers validated the trailer measurements by separately measuring traffic for approximately half an hour to an hour and a half at each trailer location. The traffic was videotaped with a time-stamped video synchronized to the same laptop the radar units were synchronized with. Later the videotape was analyzed and vehicles in each lane correlated with data records downloaded from the trailer. Vehicle speeds were measured with a Kustom Signals TR-6 radar unit and recorded by hand, along with a notation of the type of vehicle (passenger vehicle, large truck) to correlate with the video record. This procedure was repeated three times on different days at the first trailer locations at every site and one time at the other trailer locations when the system was collecting data in all lanes. The speeds of the vehicles at I-76 Westbound work zone were not recorded by the ORITE research team. I-76 Westbound work zone was the first work zone site where traffic data were collected and because of the amount of time required to fully familiarize the researchers with trailer operation in a field situation the ORITE research team did not have the time to manually record vehicle speeds.

### **3.4. Data Analysis**

The trailer data were downloaded in text file format and imported into Microsoft Excel and the ORITE recorded data were documented in a Microsoft Excel spreadsheet.

#### ***3.4.1. Phantoms and Misses Analysis***

A total of 3 days of data (about 72 hours) were collected in the field with the microwave radar trailers at each site. The downloaded text file from the trailer was imported into Microsoft Excel, and the ORITE data were entered into a separate worksheet in the same Excel file. ORITE vehicle arrival data records were matched against the radar trailer data, and misses (a vehicle observed on the video but not detected by the trailer) and phantoms (vehicles reported by the trailer but not seen in the video) were identified. The net error was tabulated. This is the number of phantoms minus the number of misses; thus a negative value represents an undercount by the trailer system (more misses than phantoms). The net error observed was in most cases within the range of  $\pm 5\%$ . In some cases, especially for the exit and entrance ramps the observed net error was over 5%. For purposes of establishing overall traffic counts, a phantom and a miss will cancel each other out and the net error is the figure of interest. In Table 31 the multiplication factors found for all lanes at each trailer location for each site are given. Further information on phantom and misses along with the net errors for each site for each location and for each lane is given in Appendix C which is available in electronic format from the ORITE Human Factors Laboratory.

**Table 31: Multiplication Factors generated from the Phantoms & Misses Analysis**

<b>Site</b>	<b>Location</b>	<b>Lane</b>	<b>Multiplication Factor</b>
I-76 Westbound	Location 1 (Mainline)	Right Lane (Lane 1)	1.01
		Lane 2	0.97
	Location 2 (Mainline)	Right Lane (Lane 1)	0.99
		Lane 2	0.97
	Location 3	Exit Ramp	0.99
	Location 4	Entrance Ramp	1.20
	Location 5 (Mainline)	Right Lane (Lane 1)	1.00
		Lane 2	1.03
	Location 6 (Mainline)	Right Lane (Lane 1)	1.00
		Lane 2	0.90
Location 7 (Mainline)	Lane 1	1.02	
Location 8 (Mainline)	Right Lane (Lane 1)	1.02	
	Lane 2	1.04	
I-270 Westbound	Location 1 (Mainline)	Right Lane (Lane 1)	1.11
		Lane 2	1.10
	Location 2 (Exit Ramp)	Right Lane (Lane 1)	1.02
		Lane 2	0.68
		Lane 3	1.24
	Location 3	Entrance Ramp	1.00
	Location 4 (Mainline)	Right Lane (Lane 1)	1.00
		Lane 2	1.04
	Location 5 (Mainline)	Right Lane (Lane 1)	1.08
		Lane 2	1.12
	Location 6	Exit Ramp	1.02
	Location 7	Entrance Ramp	1.01
	Location 8 (Mainline)	Right Lane (Lane 1)	1.00
Lane 2		1.08	
Location 9 (Mainline)	Right Lane (Lane 1)	0.99	
	Lane 2	1.01	
	Lane 3	1.02	

**Table 31: Multiplication Factors generated from the Phantoms & Misses Analysis (continued)**

I-270 Eastbound	Location 1 (Mainline)	Right Lane (Lane 1)	0.99
		Lane 2	1.05
		Lane 3	1.02
	Location 2 (Mainline)	Right Lane (Lane 1)	0.98
		Lane 2	0.98
	Location 3 (Mainline)	Right Lane (Lane 1)	1.04
		Lane 2	1.03
	Location 4 (Mainline)	Right Lane (Lane 1)	1.06
		Lane 2	1.08
	Location 5	Entrance Ramp	1.04
	Location 6 (Mainline)	Right Lane (Lane 1)	1.07
		Lane 2	1.13
	Location 7	Exit Ramp	1.18
		Right Lane (Lane 1)	0.99
		Lane 2	1.11
	Location 8 (Entrance Ramp)	Right Lane (Lane 1)	1.00
Lane 2		1.01	
Location 9 (Mainline)	Right Lane (Lane 1)	1.02	
	Lane 2	0.97	
I-90 Westbound	Location 1 (Mainline)	Right Lane (Lane 1)	1.04
		Lane 2	1.01
		Lane 3	1.03
		Lane 4	1.08
	Location 2	Exit Ramp	1.38
	Location 3 (Mainline)	Right Lane (Lane 1)	1.00
		Lane 2	1.00
		Lane 3	1.00
	Location 4	Entrance Ramp	1.03
	Location 5	Exit Ramp	1.14
	Location 6 (Mainline)	Right Lane (Lane 1)	1.04
		Lane 2	1.02
Lane 3		1.02	
Lane 4		1.09	



**Table 31: Multiplication Factors generated from the Phantoms & Misses Analysis (continued)**

I-90 Eastbound	Location 1 (Mainline)	Right Lane (Lane 1)	1.03
		Lane 2	1.02
		Lane 3	0.99
	Location 2 (Entrance Ramp)	Right Lane (Lane 1)	1.08
		Lane 2	1.25
	Location 3	Exit Ramp	1.00
	Location 4 (Mainline)	Right Lane (Lane 1)	1.09
		Lane 2	1.04
		Lane 3	1.01
	Location 5	Entrance Ramp	1.00
	Location 6 (Mainline)	Right Lane (Lane 1)	1.13
		Lane 2	1.06
		Lane 3	1.11
	Location 7	Exit Ramp	1.01
	Location 8	Exit Ramp	1.36
		Right Lane (Lane 1)	1.03
		Lane 2	1.02
		Lane 3	1.07
	Location 9	Entrance Ramp	1.16
Location 10 (Mainline)	Right Lane (Lane 1)	1.08	
	Lane 2	0.99	
	Lane 3	1.03	
	Lane 4	1.03	
I-75 Southbound	Location 1 (Mainline)	Right Lane (Lane 1)	1.00
		Lane 2	1.02
		Lane 3	1.10

### ***3.4.2. Traffic Volumes***

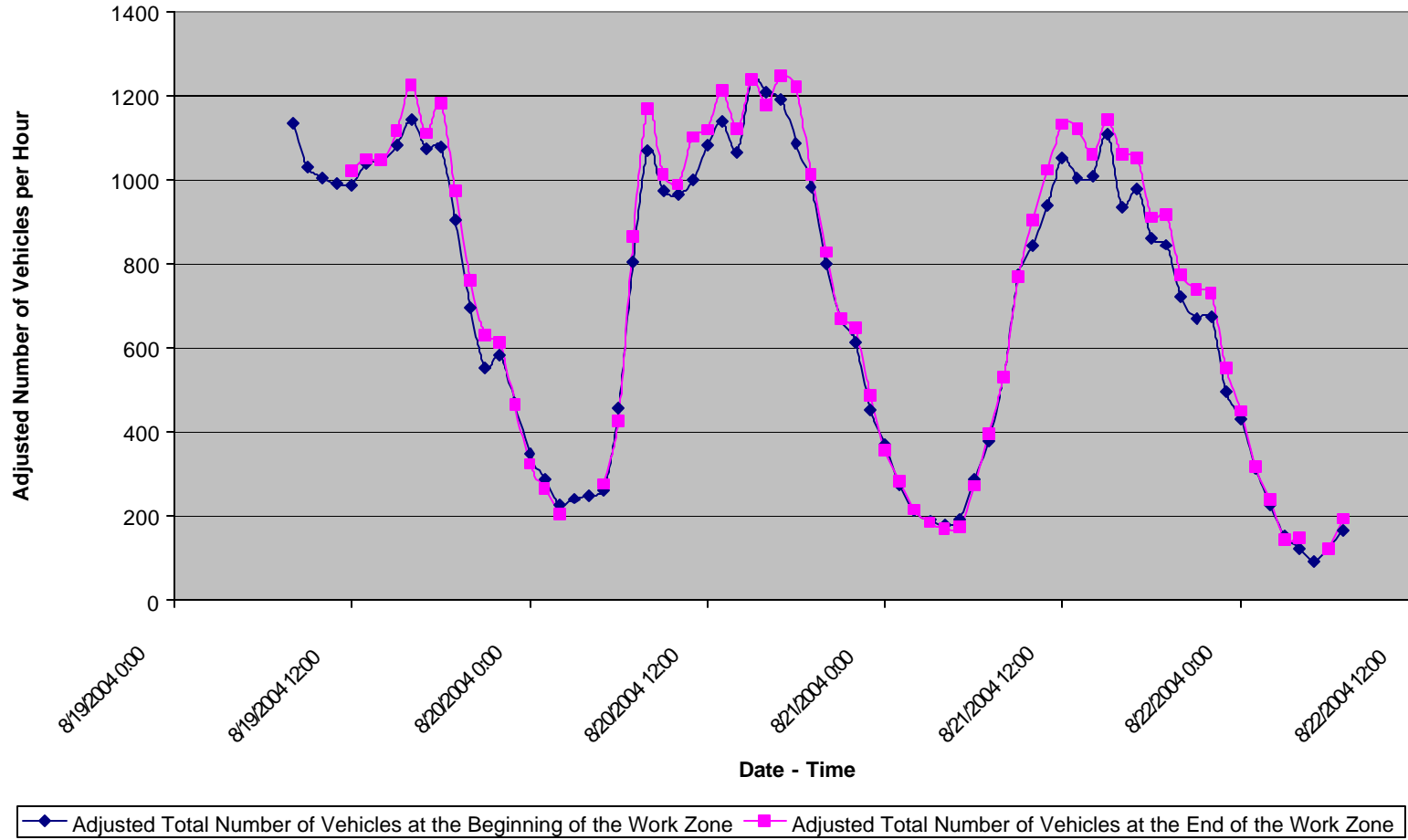
The net error correction factors for the microwave radar trailers were used to generate the adjusted vehicle counts. The three days of data for each site were separated according to the lane of travel and then split into 15-minute time intervals. The vehicle counts for each 15-minute time period were multiplied by 4 to obtain hourly vehicle counts. A correction factor obtained from phantoms and misses analysis was used to multiply the hourly vehicle counts to obtain the adjusted hourly traffic counts. This number indicated the best estimate of the actual number of vehicles per hour per lane (vphpl). The average hourly traffic volumes for the work zone data collection sites are given in Table 32.

**Table 32: Summary of Adjusted Average Vehicle Counts per Hour for Approximately 3 Days of Data**

	Total Average Number of Vehicles at the Beginning of the Work Zone	Total Average Number of Vehicles Entering through Entrance Ramps to the Work Zone	Total Average Number of Vehicles Exiting through Exit Ramps from the Work Zone	Net Average Number of Vehicles Entering Zone through Ramps (Entrance Ramp - Exit Ramp)	Overall Average Number of Vehicles Entering the Work Zone	Total Average Number of Vehicles at the End of the Work Zone
I-76 Westbound	700.31	109.78	98.55	11.23	711.54	737.25
I-270 Westbound	1206.44	793.12	953.66	-160.54	1045.9	1134.44
I-270 Eastbound	1342.05	1236.17	796.8	439.37	1781.42	1729.39
I-90 Eastbound	1892.11	1693.79	500.27	1193.52	3085.63	2952.14
I-90 Westbound	2659.19	316.89	525.68	-208.79	2450.4	2119.25
I-75 Southbound	1992.78					

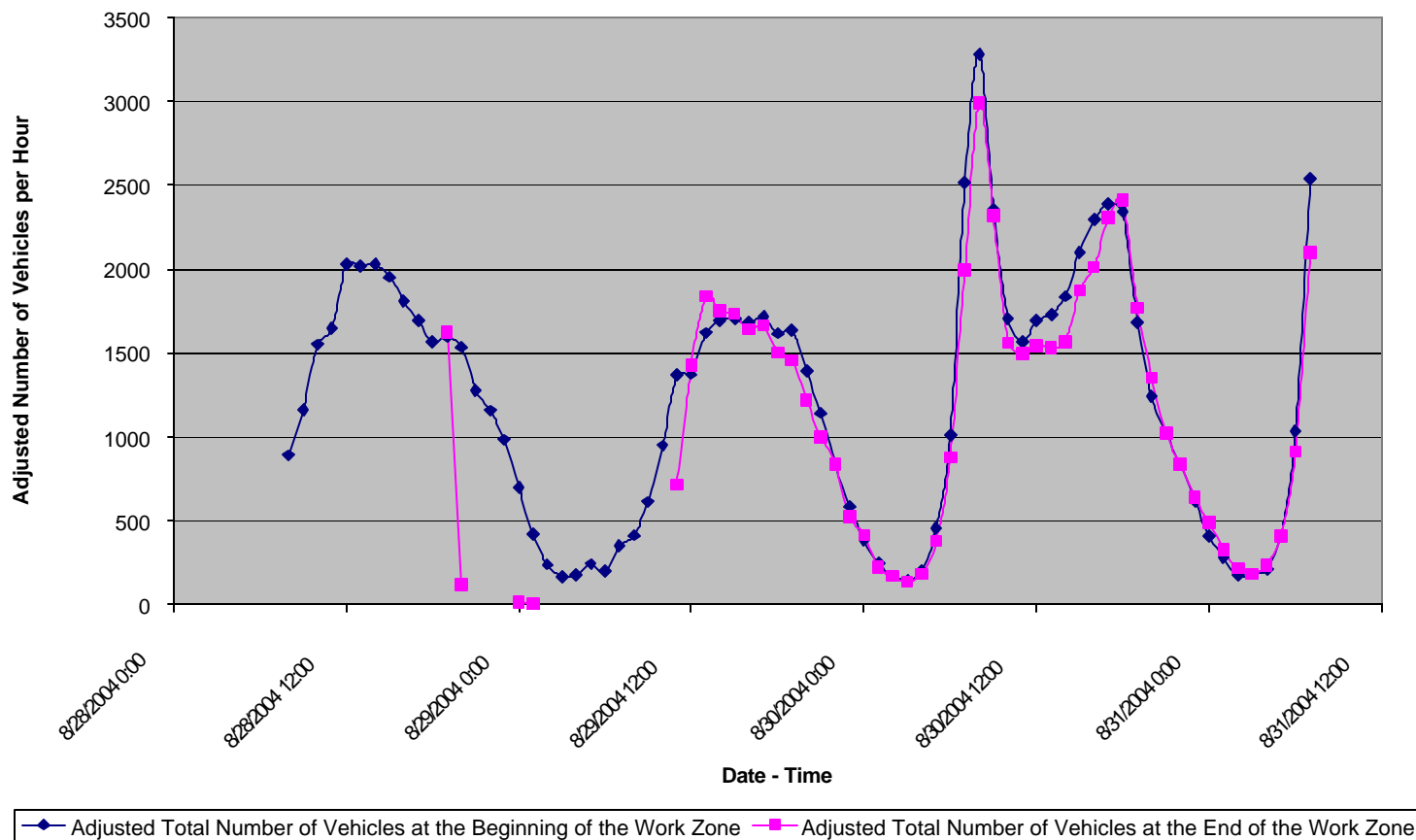
Further information on the hourly traffic counts for the vehicles entering the work zone through the mainline and the exit ramps and for the vehicles leaving the work zone through the mainline and exit ramps for each site is given in Appendix D which is available in electronic format from the ORITE Human Factors Laboratory. In Figure 57 through Figure 62 the hourly traffic volumes at the beginning of the work zone and at the end of the work zone for approximately 3 days of data are plotted for each site. Note that only one trailer was used to collect data at the I-75 Southbound work zone, which was at the beginning of the work zone. As it can be observed the traffic volumes observed at the beginning of the work zones and at the end of work zones are quite close. In some cases the data collection times at the beginning of the work zone and at the end of the work zone did not match for 3 days and some discrepancies were observed.

**Comparison of Adjusted Total Number of Vehicles at the Beginning of the Work Zone and at the End of the Work Zone**



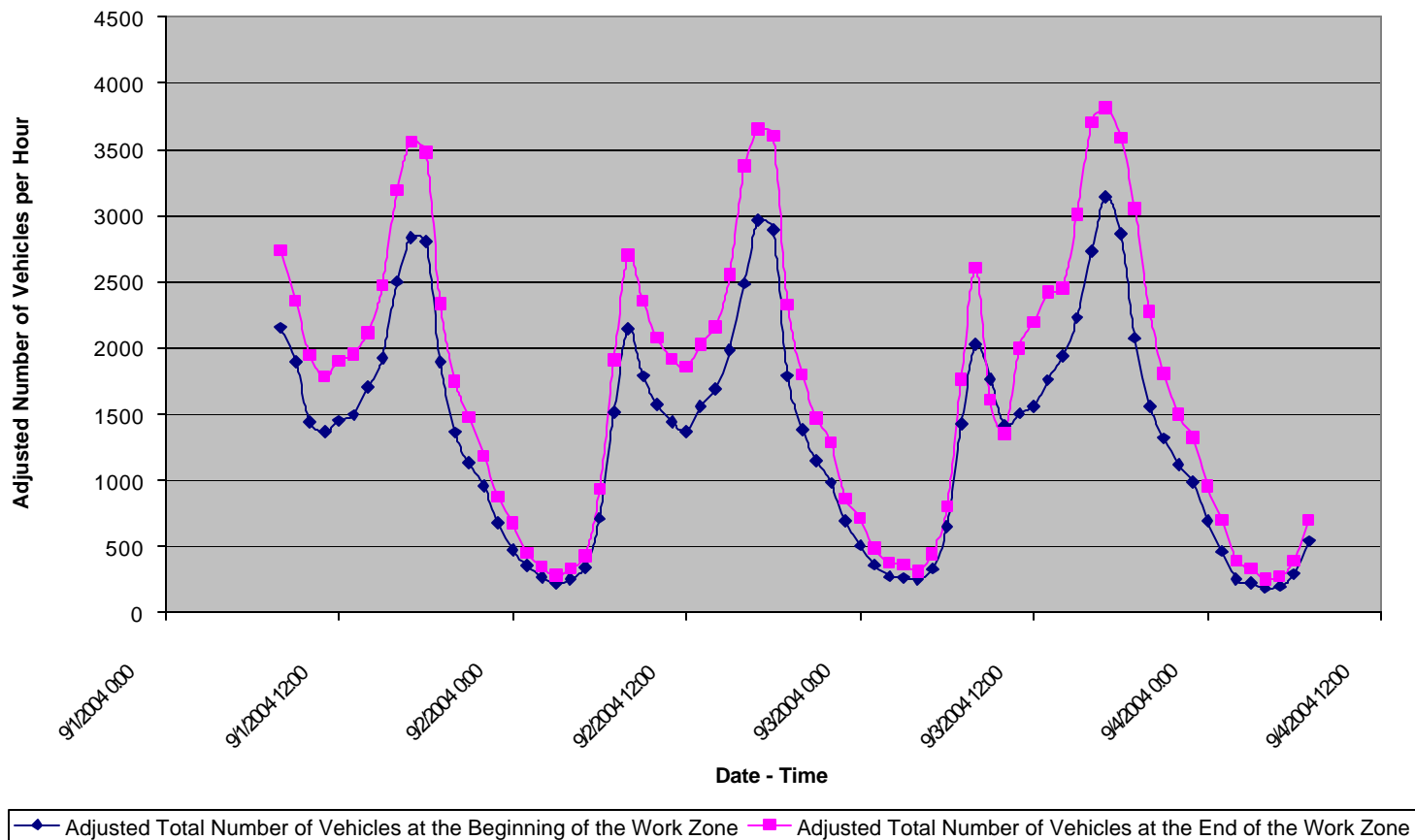
**Figure 57: Comparison of Adjusted Total Number of Vehicles at the Beginning and at the End of I-76 Westbound Work Zone**

**Comparison of Adjusted Total Number of Vehicles at the Beginning of the Work Zone and at the End of the Work Zone**



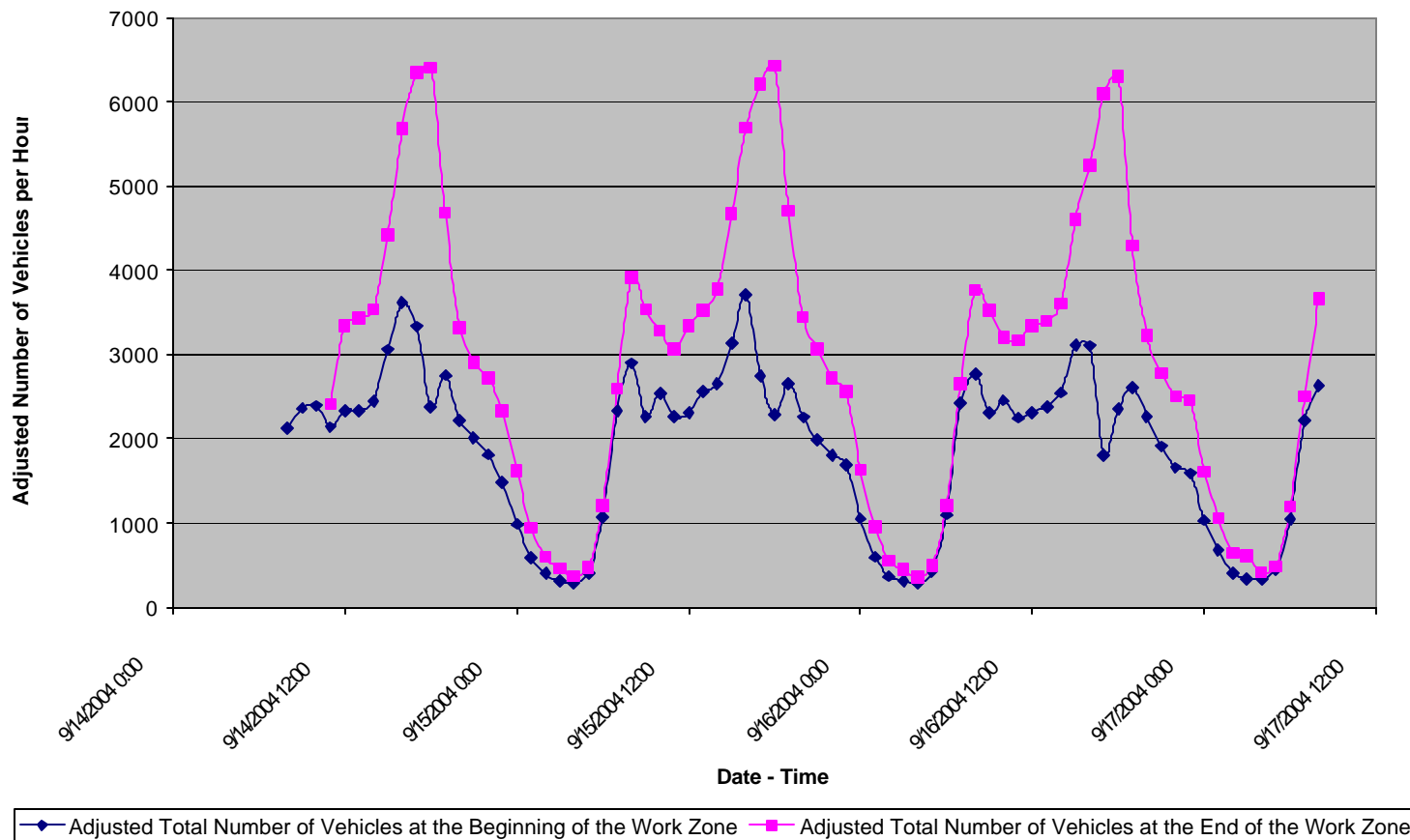
**Figure 58: Comparison of Adjusted Total Number of Vehicles at the Beginning and at the End of I-270 Westbound Work Zone**

**Comparison of Adjusted Total Number of Vehicles at the Beginning of the Work Zone and at the End of the Work Zone**



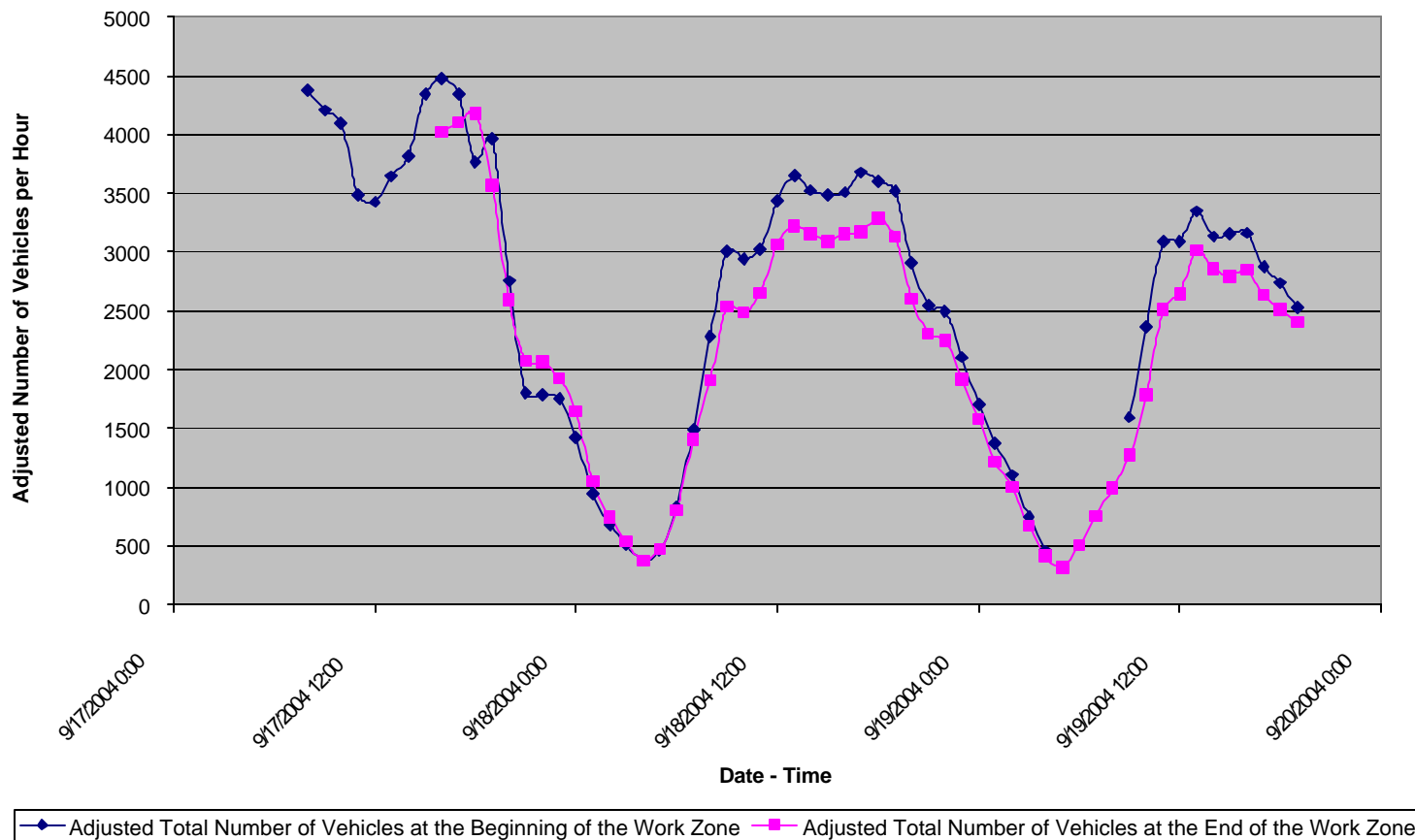
**Figure 59: Comparison of Adjusted Total Number of Vehicles at the Beginning and at the End of I-270 Eastbound Work Zone**

**Comparison of Adjusted Total Number of Vehicles at the Beginning of the Work Zone and at the End of the Work Zone**

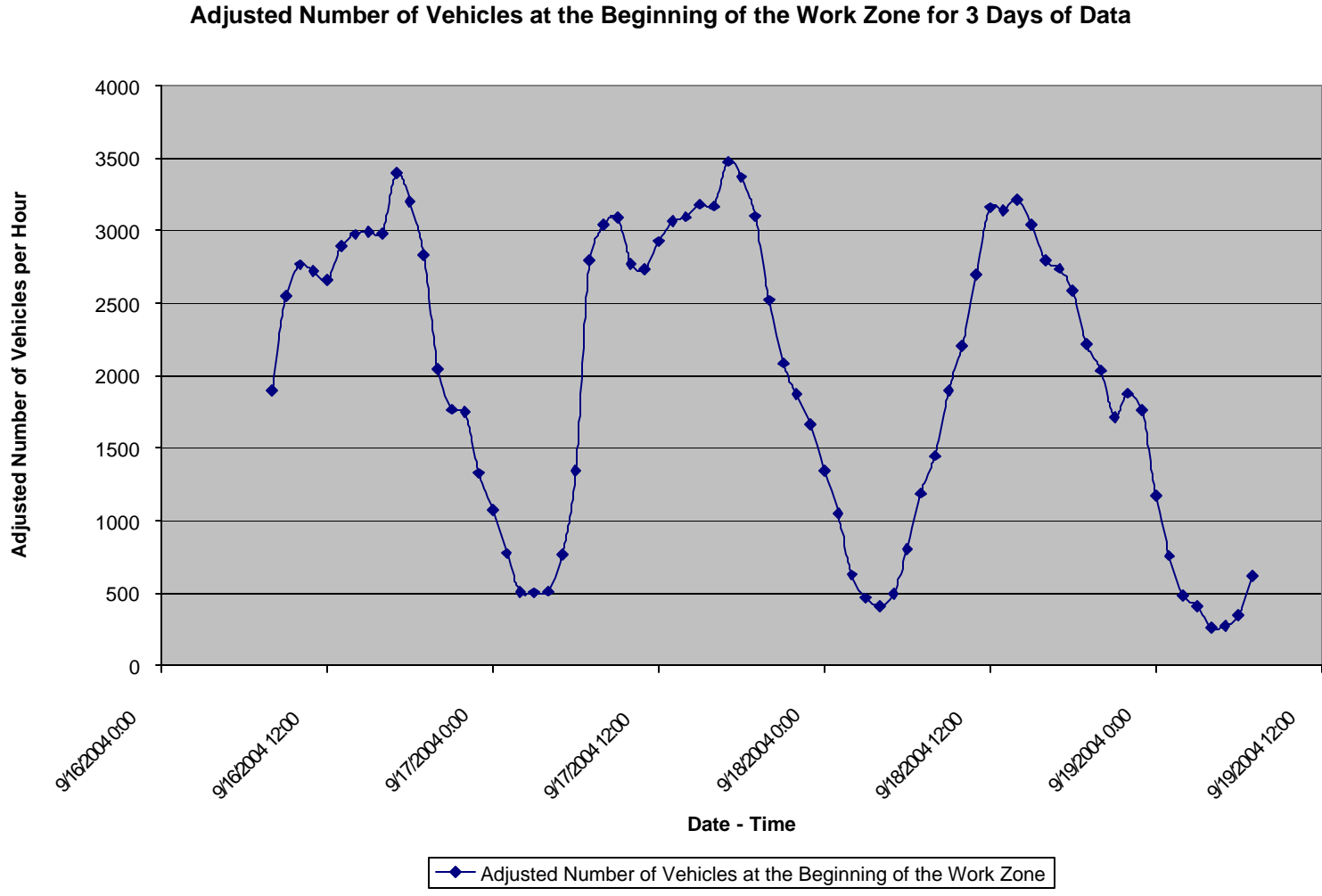


**Figure 60: Comparison of Adjusted Total Number of Vehicles at the Beginning and at the End of I-90 Eastbound Work Zone**

**Comparison of Adjusted Total Number of Vehicles at the Beginning of the Work Zone and at the End of the Work Zone**



**Figure 61: Comparison of Adjusted Total Number of Vehicles at the Beginning and at the End of I-90 Westbound Work Zone**



**Figure 62: Comparison of Adjusted Total Number of Vehicles at the Beginning of I-75 Southbound Work Zone**



### ***3.4.3.Speed and Classification Analysis***

Speed and classification measurements collected by the trailers were compared with the ORITE time-stamped video records and ORITE radar for accuracy. Due to the large speed variability in the side-fire mode, the system does not report individual vehicle speeds, but only moving average speeds of 16 vehicles. This means that the presence of exceptionally fast or slow moving vehicles is not well indicated by the system.

The running average speed is also used to determine the length of a vehicle, so inaccuracies in the speed propagate into the length measurement. For instance, a fast-moving vehicle will have a measured length that is shorter than its actual length because the moving average speed will be less than the vehicle's actual speed.

The trailer provides three classification measures – the length in feet and a length class (0, 1, 2) from each sensor. Trailer data records on classification were compared with the time-stamped ORITE video records. In the analysis of the video records the vehicles were classified into two groups – vehicles less than or equal 40 feet (12 meters) (cars and small trucks) and vehicles greater than 40 feet (12 meters) (large trucks, buses, and tractor-trailers) – since it was not possible to differentiate the vehicles nearly 20 feet (6.1 meters) long from those just over 20 feet (6.1 meters) by visual inspection. ORITE records were then compared with the trailer records for the accuracy of the trailer measurements. In Table 33 the summary of the classification comparison analysis is given. It can be observed that the classification results are fairly accurate when the vehicles are divided into two groups. In almost all cases the difference between the classification results of the ORITE data and trailer data is less than 5%. The details of the classification analysis can be found in Appendix E which is available in electronic format from the ORITE Human Factors Laboratory.

**Table 33: Classification Data from ORITE Video Record and Trailer Data (40ft = 12 m).**

Site	Location	Lane	ORITE Video Record		Trailer Record	
			<= 40 feet	> 40 feet	<= 40 feet	> 40 feet
I-76 Westbound	Location 1 (Mainline)	Right Lane (Lane 1)	95.68%	4.32%	97.47%	2.53%
		Lane 2	63.17%	36.83%	63.46%	36.54%
	Location 2 (Mainline)	Right Lane (Lane 1)	60.61%	39.39%	87.46%	12.54%
		Lane 2	94.46%	5.54%	87.14%	12.86%
	Location 3	Exit Ramp	76.34%	23.66%	75.97%	24.03%
	Location 4	Entrance Ramp	93.72%	6.28%	96.38%	3.62%
	Location 5 (Mainline)	Right Lane (Lane 1)	60.50%	39.50%	66.11%	33.89%
		Lane 2	91.29%	8.71%	96.72%	3.28%
	Location 6 (Mainline)	Right Lane (Lane 1)	84.78%	15.22%	81.64%	18.36%
		Lane 2	95.45%	4.55%	97.51%	2.49%
	Location 7 (Mainline)	Lane 1	92.38%	7.62%	91.30%	8.70%
	Location 8 (Mainline)	Right Lane (Lane 1)	92.75%	7.25%	88.20%	11.80%
		Lane 2	98.79%	1.21%	99.01%	0.99%
	I-270 Westbound	Location 1 (Mainline)	Right Lane (Lane 1)	95.35%	4.65%	91.78%
Lane 2			91.57%	8.43%	97.98%	2.02%
Location 2 (Exit Ramp)		Right Lane (Lane 1)	96.24%	3.76%	96.66%	3.34%
		Lane 2	100.00%	0.00%	93.75%	6.25%
		Lane 3	95.46%	4.54%	95.62%	4.38%
Location 3		Entrance Ramp	99.08%	0.92%	94.41%	5.59%
Location 4 (Mainline)		Right Lane (Lane 1)	95.02%	4.98%	95.75%	4.25%
		Lane 2	94.33%	5.67%	96.07%	3.93%
Location 5 (Mainline)		Right Lane (Lane 1)	95.76%	4.24%	99.07%	0.93%
		Lane 2	94.63%	5.37%	98.05%	1.95%
Location 6		Exit Ramp	89.45%	10.55%	87.76%	12.24%
Location 7		Entrance Ramp	96.42%	3.58%	97.60%	2.40%
Location 8 (Mainline)		Right Lane (Lane 1)	82.99%	17.01%	97.40%	2.60%
		Lane 2	81.77%	18.23%	88.10%	11.90%
Location 9 (Mainline)	Right Lane (Lane 1)	89.24%	10.76%	90.53%	9.47%	
	Lane 2	87.32%	12.68%	86.27%	13.73%	
	Lane 3	98.36%	1.64%	99.64%	0.36%	
I-270 Eastbound	Location 1 (Mainline)	Right Lane (Lane 1)	76.17%	23.83%	72.21%	27.79%
		Lane 2	79.24%	20.76%	81.05%	18.95%
		Lane 3	97.38%	2.62%	97.87%	2.13%
	Location 2 (Mainline)	Right Lane (Lane 1)	82.25%	17.75%	86.54%	13.46%
		Lane 2	74.52%	25.48%	89.93%	10.07%
	Location 3 (Mainline)	Right Lane (Lane 1)	77.80%	22.20%	81.37%	18.63%
		Lane 2	81.03%	18.97%	81.23%	18.77%
	Location 4 (Mainline)	Right Lane (Lane 1)	89.42%	10.58%	92.74%	7.26%
		Lane 2	81.31%	18.69%	87.48%	12.52%
	Location 5	Entrance Ramp	91.03%	8.97%	93.96%	6.04%
	Location 6 (Mainline)	Right Lane (Lane 1)	89.44%	10.56%	92.54%	7.46%
		Lane 2	76.10%	23.90%	82.83%	17.17%
	Location 7	Exit Ramp	88.80%	11.20%	96.24%	3.76%
		Right Lane (Lane 1)	86.41%	13.59%	87.76%	12.24%
Lane 2		81.13%	18.87%	82.74%	17.26%	
Location 8 (Entrance Ramp)	Right Lane (Lane 1)	85.96%	14.04%	87.31%	12.69%	
	Lane 2	86.93%	13.07%	94.54%	5.46%	
Location 9 (Mainline)	Right Lane (Lane 1)	89.82%	10.18%	86.71%	13.29%	
	Lane 2	96.88%	3.13%	97.05%	2.95%	

**Table 33: Classification Data from ORITE Video Record and Trailer Data (continued) (40 ft = 12 m)**

Site	Location	Lane	ORITE Video Record		Trailer Record	
			<= 40 feet	> 40 feet	<= 40 feet	> 40 feet
I-90 Westbound	Location 1 (Mainline)	Right Lane (Lane 1)	97.86%	2.14%	98.79%	1.21%
		Lane 2	92.76%	7.24%	96.90%	3.10%
		Lane 3	94.24%	5.76%	93.94%	6.06%
		Lane 4	99.49%	0.51%	99.42%	0.58%
	Location 2	Exit Ramp	100.00%	0.00%	100.00%	0.00%
	Location 3 (Mainline)	Right Lane (Lane 1)	97.90%	2.10%	98.52%	1.48%
		Lane 2	94.67%	5.33%	95.57%	4.43%
		Lane 3	99.67%	0.33%	99.24%	0.76%
	Location 4	Entrance Ramp	98.63%	1.37%	99.38%	0.62%
	Location 5	Exit Ramp	96.50%	3.50%	99.68%	0.32%
	Location 6 (Mainline)	Right Lane (Lane 1)	97.27%	2.73%	98.39%	1.61%
		Lane 2	94.50%	5.50%	94.37%	5.63%
		Lane 3	88.83%	11.17%	90.48%	9.52%
		Lane 4	97.73%	2.27%	99.61%	0.39%
I-90 Eastbound	Location 1 (Mainline)	Right Lane (Lane 1)	85.58%	14.42%	86.79%	13.21%
		Lane 2	90.02%	9.98%	88.18%	11.82%
		Lane 3	98.13%	1.87%	98.27%	1.73%
	Location 2 (Entrance Ramp)	Right Lane (Lane 1)	97.51%	2.49%	98.91%	1.09%
		Lane 2	95.31%	4.69%	96.55%	3.45%
	Location 3	Exit Ramp	99.32%	0.68%	99.37%	0.63%
	Location 4 (Mainline)	Right Lane (Lane 1)	98.26%	1.74%	99.78%	0.22%
		Lane 2	94.84%	5.16%	97.08%	2.92%
		Lane 3	96.11%	3.89%	96.76%	3.24%
	Location 5	Entrance Ramp	99.37%	0.63%	98.43%	1.57%
	Location 6 (Mainline)	Right Lane (Lane 1)	97.19%	2.81%	99.55%	0.45%
		Lane 2	94.33%	5.67%	97.20%	2.80%
		Lane 3	95.63%	4.37%	97.06%	2.94%
	Location 7	Exit Ramp	100.00%	0.00%	97.86%	2.14%
	Location 8	Exit Ramp	99.31%	0.69%	100.00%	0.00%
		Right Lane (Lane 1)	91.83%	8.17%	95.42%	4.58%
		Lane 2	75.90%	24.10%	86.91%	13.09%
		Lane 3	93.89%	6.11%	93.90%	6.10%
	Location 9	Entrance Ramp	100.00%	0.00%	99.78%	0.22%
Location 10 (Mainline)	Right Lane (Lane 1)	96.66%	3.34%	99.67%	0.33%	
	Lane 2	91.69%	8.31%	96.61%	3.39%	
	Lane 3	91.67%	8.33%	92.02%	7.98%	
	Lane 4	96.26%	3.74%	95.52%	4.48%	
I-75 Southbound	Location 1 (Mainline)	Right Lane (Lane 1)	82.76%	17.24%	96.11%	3.89%
		Lane 2	76.50%	23.50%	84.67%	15.33%
		Lane 3	96.24%	3.76%	96.97%	3.03%

The average ORITE radar speed and the average trailer speeds were compared for the sites I-90 Eastbound, I-90 Westbound, I-270 Eastbound, and I-270 Westbound in free flowing traffic conditions and in restricted traffic conditions. As mentioned earlier, no speed data were collected for I-76 Westbound and no restricted traffic data were collected for I-75 Southbound. Comparing the moving average speeds recorded with those derived from ORITE measured data, the overall average values and the variability were fairly close. The difference between the average radar and trailer speeds is about 5 mph (8 km/h) and the difference between the average standard deviations between the radar and the trailer is about 3 mph (5 km/h) as it can be observed in Table 34. Since the 16-vehicle moving averages are provided by the trailer, short-term changes in traffic speed were not very visible. However longer term values, such as hourly averages, were reasonably accurate.

In what follows, a distinction is generally made between “free flow” and “restricted” conditions. Free flow conditions occur in areas where there all lanes of traffic are open and restricted conditions are where there is the work zone proper, including lane closures, lane shifts, or reduced lane widths.

**Table 34: Summary of Average Speeds and Standard Deviations in mph Measured by the Trailer and the ORITE Radar and the Adjustment Factors Calculated (a=adjustment factor for average speed, b=adjustment factor for standard deviation)**

Site	Lane	N	ORITE Radar Average Speed	Trailer Average Speed	?=ORITE Radar Average Speed - Trailer Average Speed	a = ORITE Radar Average Speed / Trailer Average Speed	ORITE Radar Standard Deviation of Speeds	Trailer Standard Deviation of Speeds	?=ORITE Radar Standard Deviation of Speeds - Trailer Standard Deviation of Speeds	b = ORITE Radar Standard Deviation / Trailer Standard Deviation
			(mph)	(mph)	(mph)	(mph)	(mph)	(mph)	(mph)	(mph)
I - 90 Eastbound	Lane 1(Right) - Freeflow	73	47.9041	51.8767	-3.9726	0.9234	5.8170	3.7967	2.0203	1.5321
I - 90 Eastbound	Lane 2 - Freeflow	70	49.1429	54.0429	-4.9000	0.9093	5.1253	4.0982	1.0271	1.2506
I - 90 Eastbound	Lane 3 - Freeflow	22	50.9545	61.9545	-11.0000	0.8225	6.7997	3.2875	3.5122	2.0684
I - 90 Eastbound	Lane 1(Right) - Restricted	232	32.2586	33.9956	-1.7370	0.9489	8.8123	9.9516	-1.1394	0.8855
I - 90 Eastbound	Lane 2 - Restricted	76	33.9868	36.7105	-2.7237	0.9258	8.5751	11.4715	-2.8963	0.7475
I - 90 Eastbound	Lane 3 - Restricted	61	36.9016	43.0328	-6.1311	0.8575	6.0792	8.7711	-2.6919	0.6931
I - 90 Westbound	Lane 1(Right) - Freeflow	252	53.0000	58.8056	-5.8056	0.9013	5.4576	3.1670	2.2906	1.7233
I - 90 Westbound	Lane 2 - Freeflow	470	57.4596	62.8745	-5.4149	0.9139	5.4100	3.8638	1.5462	1.4002
I - 90 Westbound	Lane 3 - Freeflow	66	63.4625	65.8188	-2.3563	0.9642	5.3692	2.6156	2.7537	2.0528
I - 90 Westbound	Lane 1(Right) - Restricted	189	52.4656	58.8624	-6.3968	0.8913	5.7478	4.1375	1.6103	1.3892
I - 90 Westbound	Lane 2 - Restricted	232	55.6638	64.8793	-9.2155	0.8580	5.6437	3.5362	2.1075	1.5960
I - 90 Westbound	Lane 3 - Restricted	160	60.5303	68.6364	-8.1061	0.8819	4.4522	2.9853	1.4669	1.4914
I - 270 Eastbound	Lane 1(Right) - Freeflow	171	59.6374	59.3567	0.2807	1.0047	4.6079	4.0997	0.5082	1.1240
I - 270 Eastbound	Lane 2 - Freeflow	154	61.0195	67.7792	-6.7597	0.9003	5.0455	3.0599	1.9857	1.6489
I - 270 Eastbound	Lane 1(Right) - Restricted	410	54.3488	55.8317	-1.4829	0.9734	4.7395	3.8503	0.8891	1.2309
I - 270 Eastbound	Lane 2 - Restricted	333	55.0541	53.4144	1.6396	1.0307	4.7640	3.5950	1.1690	1.3252
I - 270 Westbound	Lane 1(Right) - Freeflow	187	58.8663	66.4492	-7.5829	0.8859	5.2042	3.9813	1.2229	1.3072
I - 270 Westbound	Lane 2 - Freeflow	66	62.3333	69.6667	-7.3333	0.8947	5.3847	4.7242	0.6605	1.1398
I - 270 Westbound	Lane 1(Right) - Restricted	577	56.6360	62.4315	-5.7955	0.9072	4.6911	4.1824	0.5087	1.1216
I - 270 Westbound	Lane 2 - Restricted	314	57.7580	60.9682	-3.2102	0.9473	5.8402	4.0428	1.7974	1.4446
N			20	20	20	20	20	20	20	20
Average			52.9692	57.8694	-4.9002	0.9171	5.6783	4.6609	1.0174	1.3586
Standard Deviation			9.0644	10.0729	3.1999	0.0503	1.1756	2.4210	1.6204	0.3662
Minimum			32.2586	33.9956	-11.0000	0.8225	4.4522	2.6156	-2.8963	0.6931
Maximum			63.4625	69.6667	1.6396	1.0307	8.8123	11.4715	3.5122	2.0684

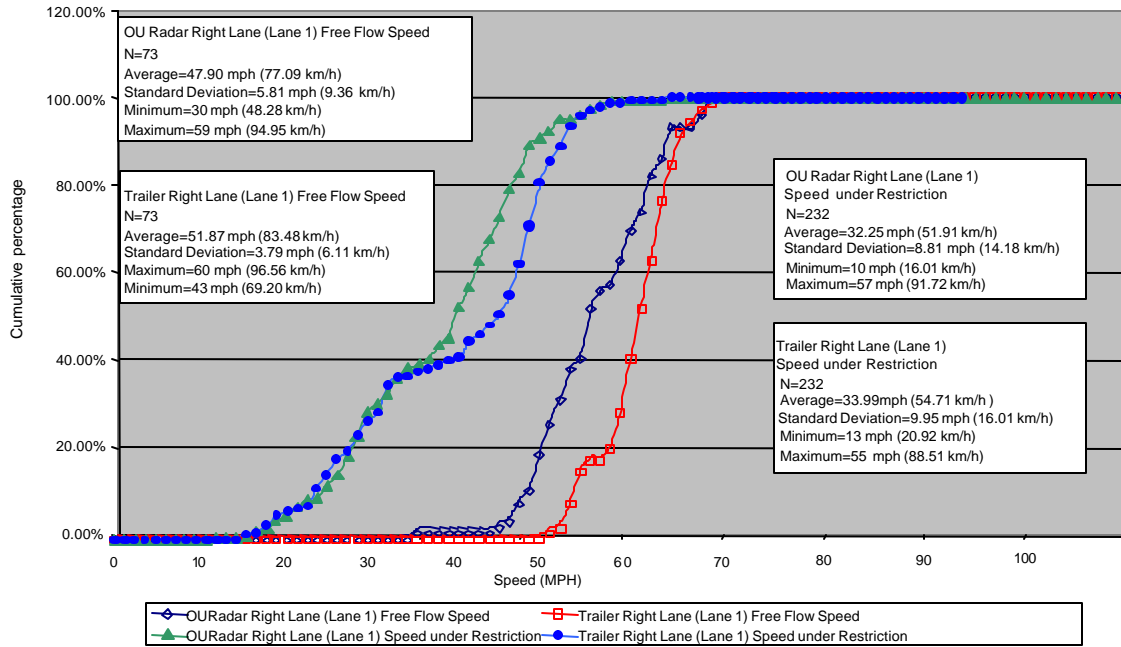
**Table 35: Summary of Average Speeds and Standard Deviations in km/h Measured by the Trailer and the ORITE Radar and the Adjustment Factors Calculated (a=adjustment factor for average speed, b=adjustment factor for standard deviation)**

Site	Lane	N	ORITE Radar Average Speed	Trailer Average Speed	?=ORITE Radar Average Speed - Trailer Average Speed	a = ORITE Radar Average Speed / Trailer Average Speed	ORITE Radar Standard Deviation of Speeds	Trailer Standard Deviation of Speeds	?=ORITE Radar Standard Deviation of Speeds - Trailer Standard Deviation of Speeds	b = ORITE Radar Standard Deviation / Trailer Standard Deviation
			(km/h)	(km/h)	(km/h)	(km/h)	(km/h)	(km/h)	(km/h)	(km/h)
I- 90 Eastbound	Lane 1(Right) - Freeflow	73	77.0777	83.4696	-6.3919	1.4858	9.3596	6.1089	3.2507	2.4651
I- 90 Eastbound	Lane 2 - Freeflow	70	79.0709	86.9550	-7.8841	1.4631	8.2466	6.5940	1.6526	2.0122
I- 90 Eastbound	Lane 3 - Freeflow	22	81.9858	99.6848	-17.6990	1.3234	10.9407	5.2896	5.6511	3.3281
I- 90 Eastbound	Lane 1(Right) - Restricted	232	51.9041	54.6989	-2.7948	1.5268	14.1790	16.0121	-1.8333	1.4248
I- 90 Eastbound	Lane 2 - Restricted	76	54.6848	59.0672	-4.3824	1.4896	13.7973	18.4576	-4.6601	1.2027
I- 90 Eastbound	Lane 3 - Restricted	61	59.3747	69.2398	-9.8649	1.3797	9.7814	14.1127	-4.3313	1.1152
I- 90 Westbound	Lane 1(Right) - Freeflow	252	85.2770	94.6182	-9.3412	1.4502	8.7813	5.0957	3.6856	2.7728
I- 90 Westbound	Lane 2 – Freeflow	470	92.4525	101.1651	-8.7126	1.4705	8.7047	6.2169	2.4878	2.2529
I- 90 Westbound	Lane 3 – Freeflow	66	102.1112	105.9024	-3.7913	1.5514	8.6390	4.2085	4.4307	3.3030
I- 90 Westbound	Lane 1(Right) - Restricted	189	84.4172	94.7096	-10.2925	1.4341	9.2482	6.6572	2.5910	2.2352
I- 90 Westbound	Lane 2 - Restricted	232	89.5631	104.3908	-14.8277	1.3805	9.0807	5.6897	3.3910	2.5680
I- 90 Westbound	Lane 3 - Restricted	160	97.3933	110.4360	-13.0427	1.4190	7.1636	4.8033	2.3602	2.3997
I- 270 Eastbound	Lane 1(Right) - Freeflow	171	95.9566	95.5049	0.4516	1.6166	7.4141	6.5964	0.8177	1.8085
I- 270 Eastbound	Lane 2 – Freeflow	154	98.1804	109.0567	-10.8764	1.4486	8.1182	4.9234	3.1950	2.6531
I- 270 Eastbound	Lane 1(Right) - Restricted	410	87.4472	89.8332	-2.3860	1.5662	7.6259	6.1951	1.4306	1.9805
I- 270 Eastbound	Lane 2 - Restricted	333	88.5820	85.9438	2.6381	1.6584	7.6653	5.7844	1.8809	2.1322
I- 270 Westbound	Lane 1(Right) - Freeflow	187	94.7159	106.9168	-12.2009	1.4254	8.3736	6.4059	1.9676	2.1033
I- 270 Westbound	Lane 2 – Freeflow	66	100.2943	112.0937	-11.7993	1.4396	8.6640	7.6012	1.0627	1.8339
I- 270 Westbound	Lane 1(Right) - Restricted	577	91.1273	100.4523	-9.3250	1.4597	7.5480	6.7295	0.8185	1.8047
I- 270 Westbound	Lane 2 - Restricted	314	92.9326	98.0978	-5.1652	1.5242	9.3969	6.5049	2.8920	2.3244
N			20	20	20	20	20	20	20	20
Average			85.2274	93.1119	-7.8844	1.4756	9.1364	7.4994	1.6370	2.1860
Standard Deviation			14.5846	16.2073	5.1486	0.0809	1.8915	3.8954	2.6072	0.5892
Minimum			51.9041	54.6989	-17.6990	1.3234	7.1636	4.2085	-4.6601	1.1152
Maximum			102.1112	112.0937	2.6381	1.6584	14.1790	18.4576	5.6511	3.3281

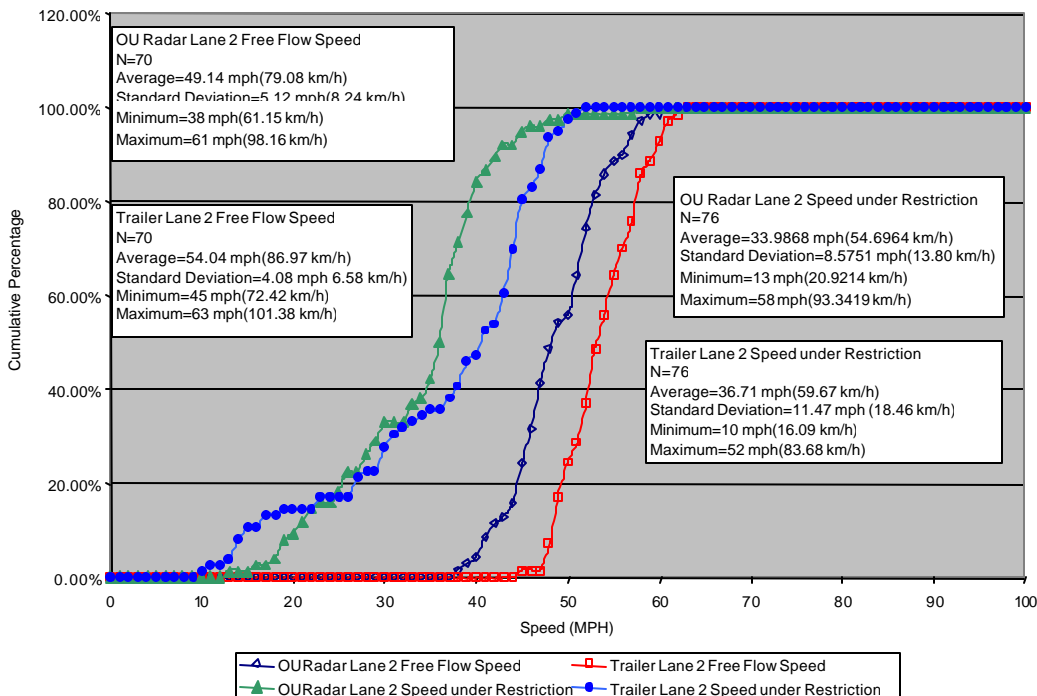
The average speeds for 15 minute time intervals in the free flow zone at the beginning of the work zone were also compared with the 15-minute average speeds in the restriction. Slower traffic speeds were observed for all lanes in the restriction area. The cumulative distributions were generated for ORITE radar and trailer average speeds in free-flowing and restricted conditions.

Figure 63 through

Figure 72 show the cumulative speed distributions for each lane for the sites I-90 Eastbound, I-90 Westbound, I-270 Westbound, and I-270 Eastbound in free-flowing and restricted driving conditions. As expected the difference of speeds between free-flowing conditions and restricted conditions is higher for the left lane (Lane 2) and lower for the right lane (Lane 1). Right lane (lane 1) speed dropped about 3 mph (4.8 km/h) and Lane 2 speed decreased about 15 mph (24 km/h) for the I-270 Westbound and Eastbound work zones. For the I-90 Eastbound and I-90 Westbound work zones a small increase of about 2 mph (3.2 km/h) was observed in the restricted traffic conditions instead of the expected reduction in speed.

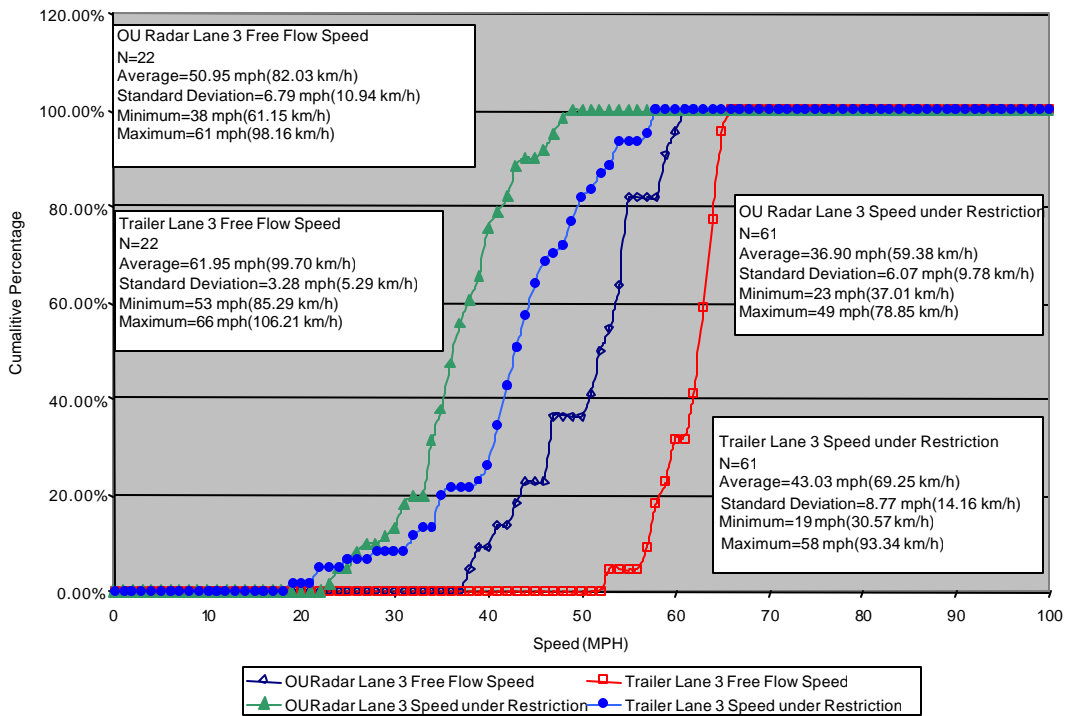


**Figure 63: Comparison of ORITE Radar and Trailer Cumulative Right Lane (Lane 1) Speed Distributions in Free Flow and Restricted Conditions for I-90 Eastbound (1 mph = 1.6 km/h)**

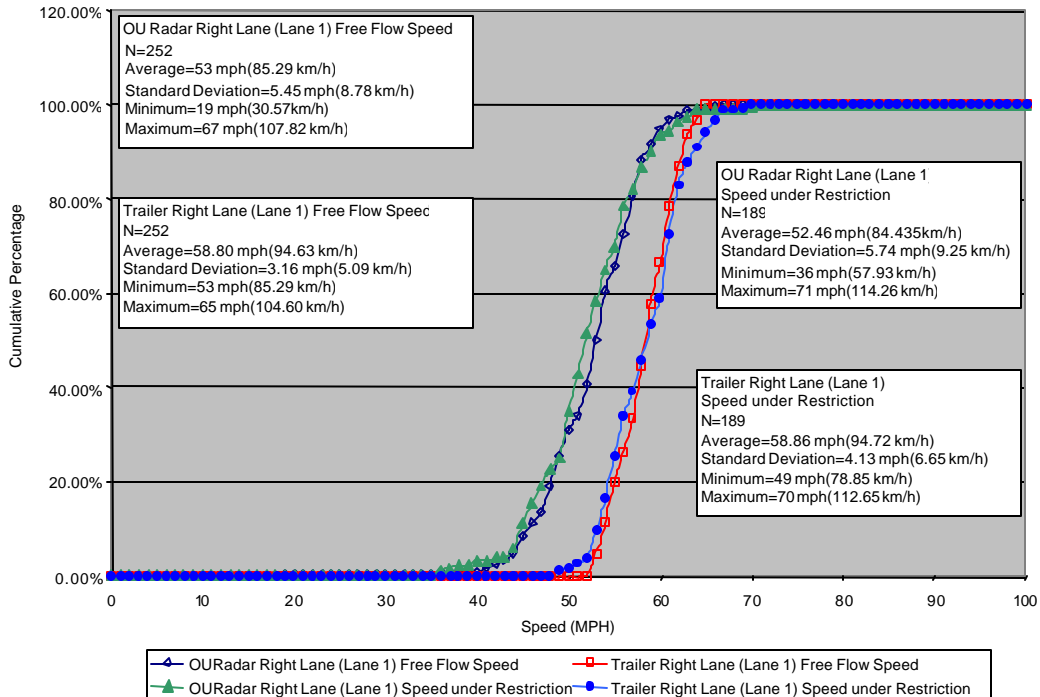


**Figure 64: Comparison of ORITE Radar and Trailer Cumulative Lane 2 Speed Distributions in Free Flow and Restricted Conditions for I-90 Eastbound (1 mph = 1.6 km/h)**

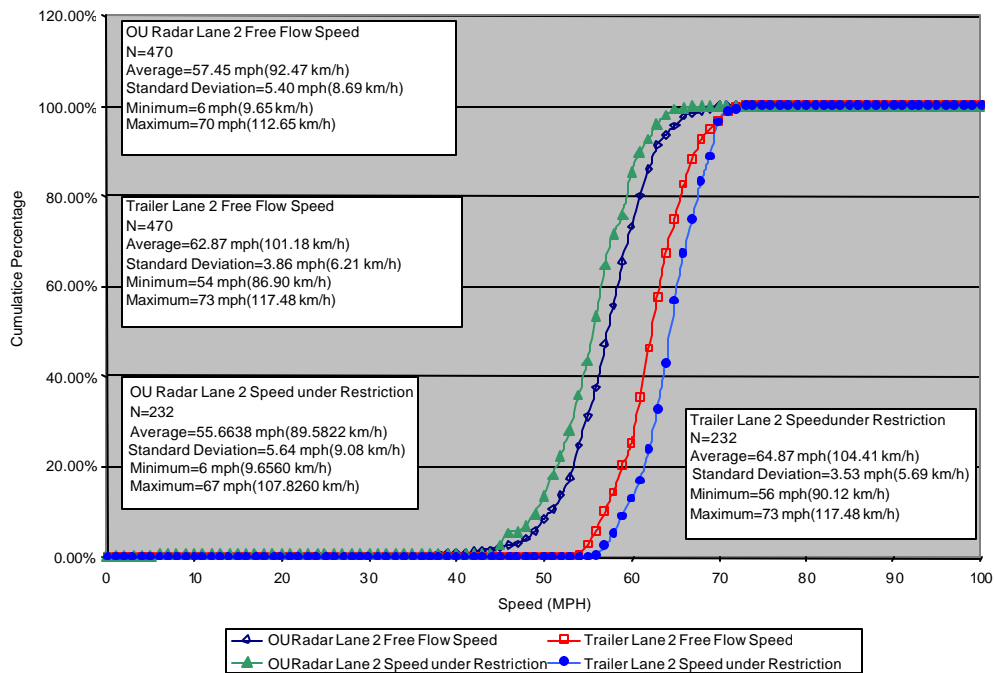




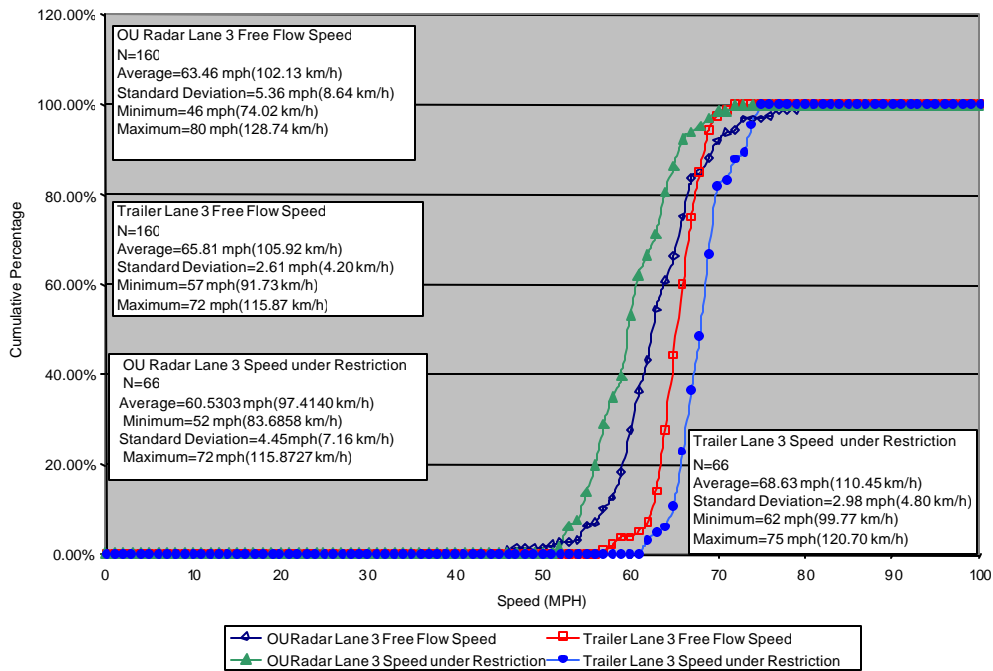
**Figure 65: Comparison of ORITE Radar and Trailer Cumulative Lane 3 Speed Distributions in Free Flow and Restricted Conditions for I-90 Eastbound (1 mph = 1.6 km/h)**



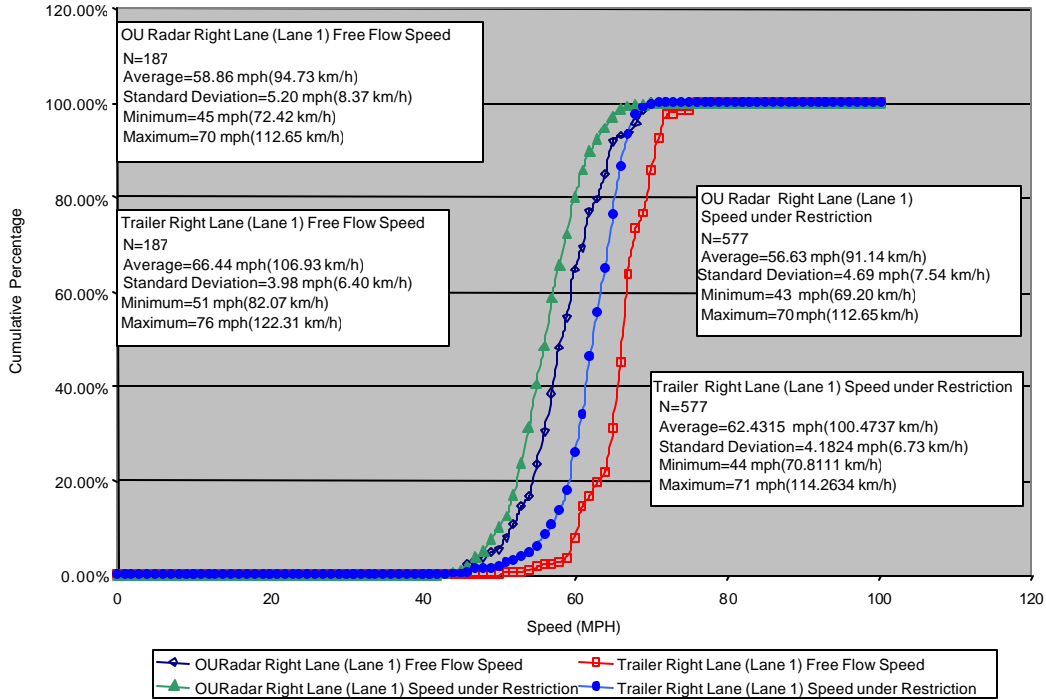
**Figure 66: Comparison of ORITE Radar and Trailer Cumulative Right Lane (Lane 1) Speed Distributions in Free Flow and Restricted Conditions for I-90 Westbound (1 mph = 1.6 km/h)**



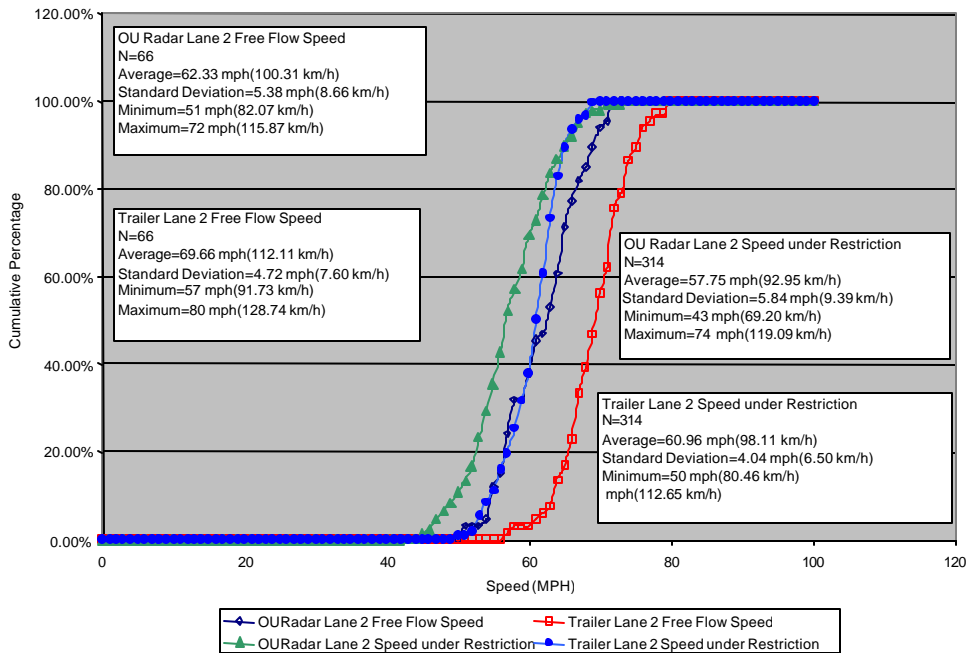
**Figure 67: Comparison of ORITE Radar and Trailer Cumulative Lane 2 Speed Distributions in Free Flow and Restricted Conditions for I-90 Westbound (1 mph = 1.6 km/h)**



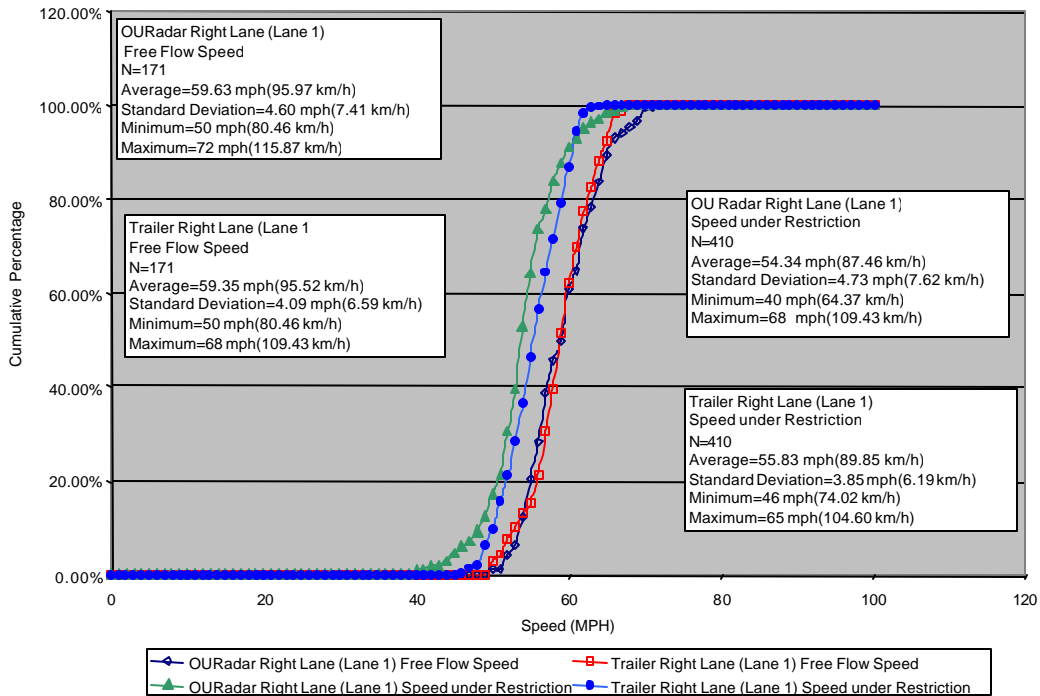
**Figure 68: Comparison of ORITE Radar and Trailer Cumulative Lane 3 Speed Distributions in Free Flow and Restricted Conditions for I-90 Westbound (1 mph = 1.6 km/h)**



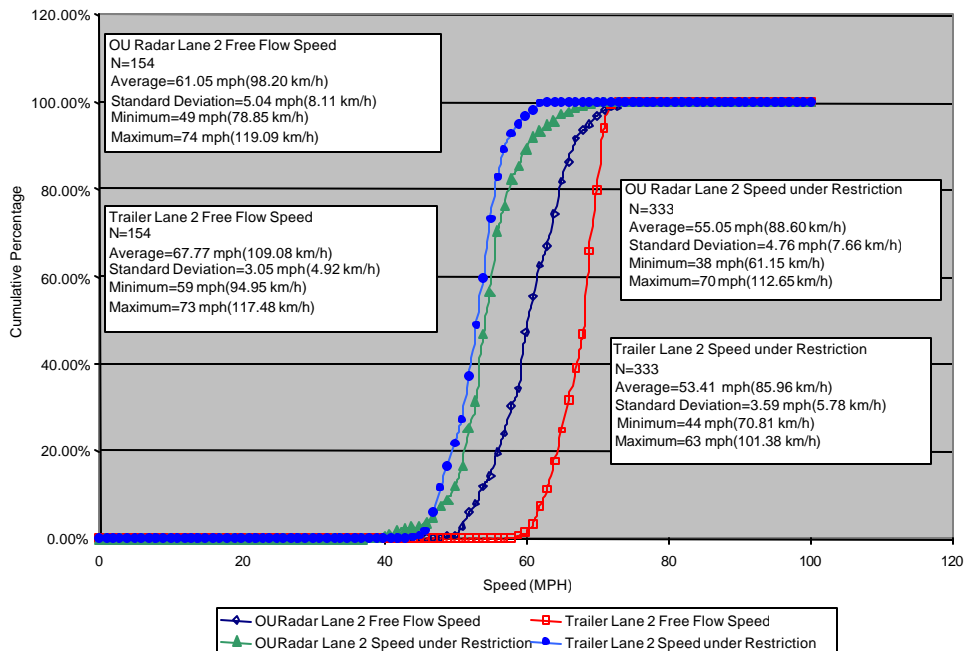
**Figure 69: Comparison of ORITE Radar and Trailer Cumulative Right Lane (Lane 1) Speed Distributions in Free Flow and Restricted Conditions for I-270 Westbound (1 mph = 1.6 km/h)**



**Figure 70: Comparison of ORITE Radar and Trailer Cumulative Lane 2 Speed Distributions in Free Flow and Restricted Conditions for I-270 Westbound (1 mph = 1.6 km/h)**



**Figure 71: Comparison of ORITE Radar and Trailer Cumulative Right Lane (Lane 1) Speed Distributions in Free Flow and Restricted Conditions for I-270 Eastbound (1 mph = 1.6 km/h)**



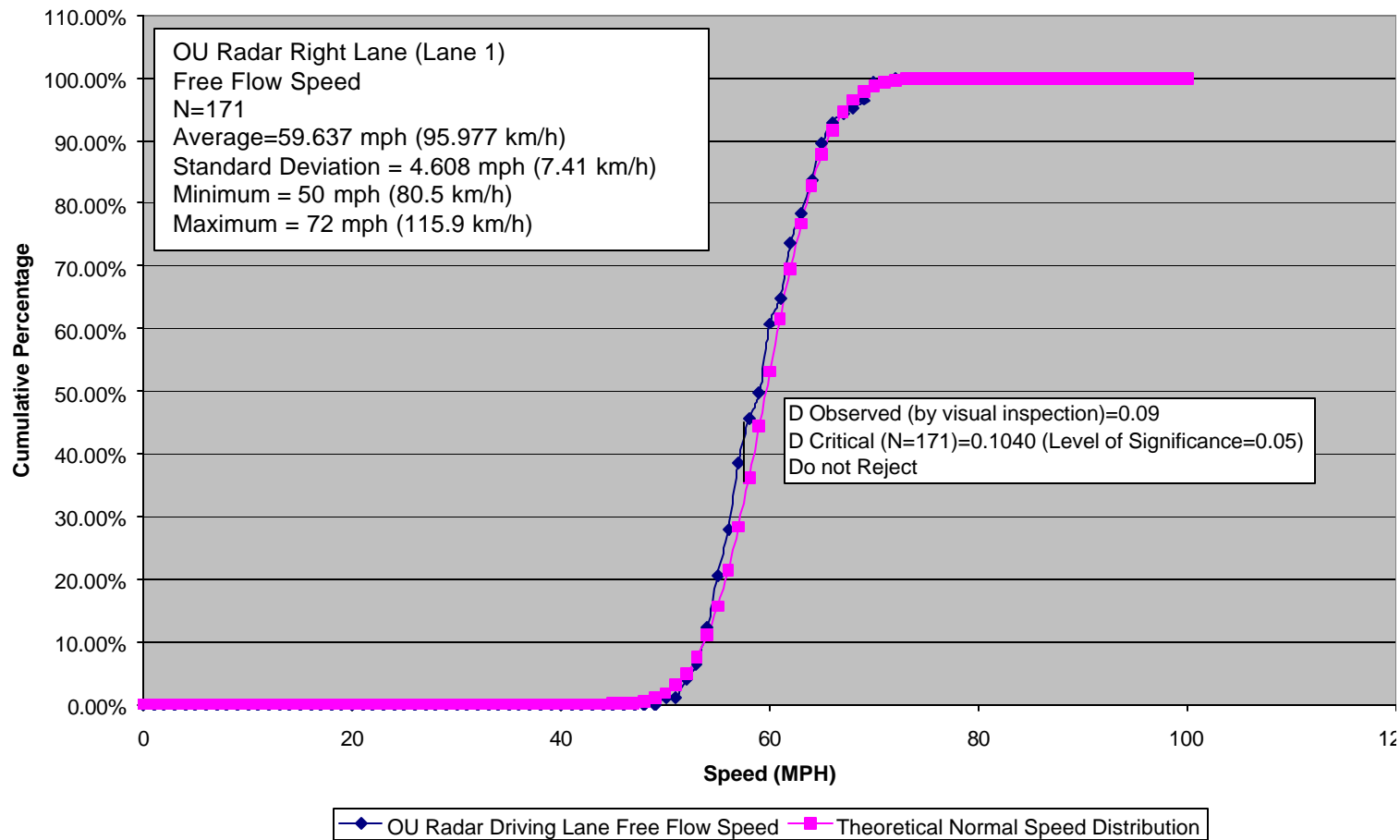
**Figure 72: Comparison of ORITE Radar and Trailer Cumulative Lane 2 Speed Distributions in Free Flow and Restricted Conditions for I-270 Eastbound (1 mph = 1.6 km/h)**

Another analysis performed in the analysis of the speed distributions, which are related to the service time distributions, was the test of normality. The literature revealed that the speed distribution has the pattern of a normal distribution. In order to test normality we calculated theoretical normal distributions for the observed mean and standard deviation values and used Kolmogorov-Smirnov Goodness of Fit Test [116] to compare actual and theoretical distributions. The analysis showed that the speed distributions are very similar to the normal distribution. Table 36 shows the summary results of the Kolmogorov-Smirnov Goodness of Fit Test results. Total of forty tests were performed and in 90% of the tests, the null hypothesis, stating that the speed distribution is coming from a normal distribution, could not be rejected at significance level of 0.05. In Figure 73, the comparison graph for the Kolmogorov-Smirnov test is given as an example. Therefore it can be assumed that the speed distribution can be represented by a normal distribution. Further information on the test of normality can be found in Appendix F which is available in electronic format from the ORITE Human Factors Laboratory.

**Table 36: Summary Results of Kolmogorov-Smirnov Goodness-of-Fit Test used to Compare Speed Distributions**

<b>Comparisons of Observed D Values and Calculated Critical D (Level of significance = 0.05)</b>	
Do not Reject (Observed D < Calculated Critical D)	Reject (Observed D > Calculated Critical D)
36 (90.00%)	4 (10.00%)

**Comparison of Actual OU Radar Free Flow Speed and Computed Theoretical Normal OU Radar Free Flow Speed for I-270 Eastbound Right Lane (Lane 1)**



**Figure 73: Comparison of Actual ORITE Radar Free-Flowing Speed and Computed Theoretical Normal ORITE Radar Free-Flowing Speed for I-270 Eastbound Right Lane (Lane 1) Data (1 mph = 1.6 km/h)**

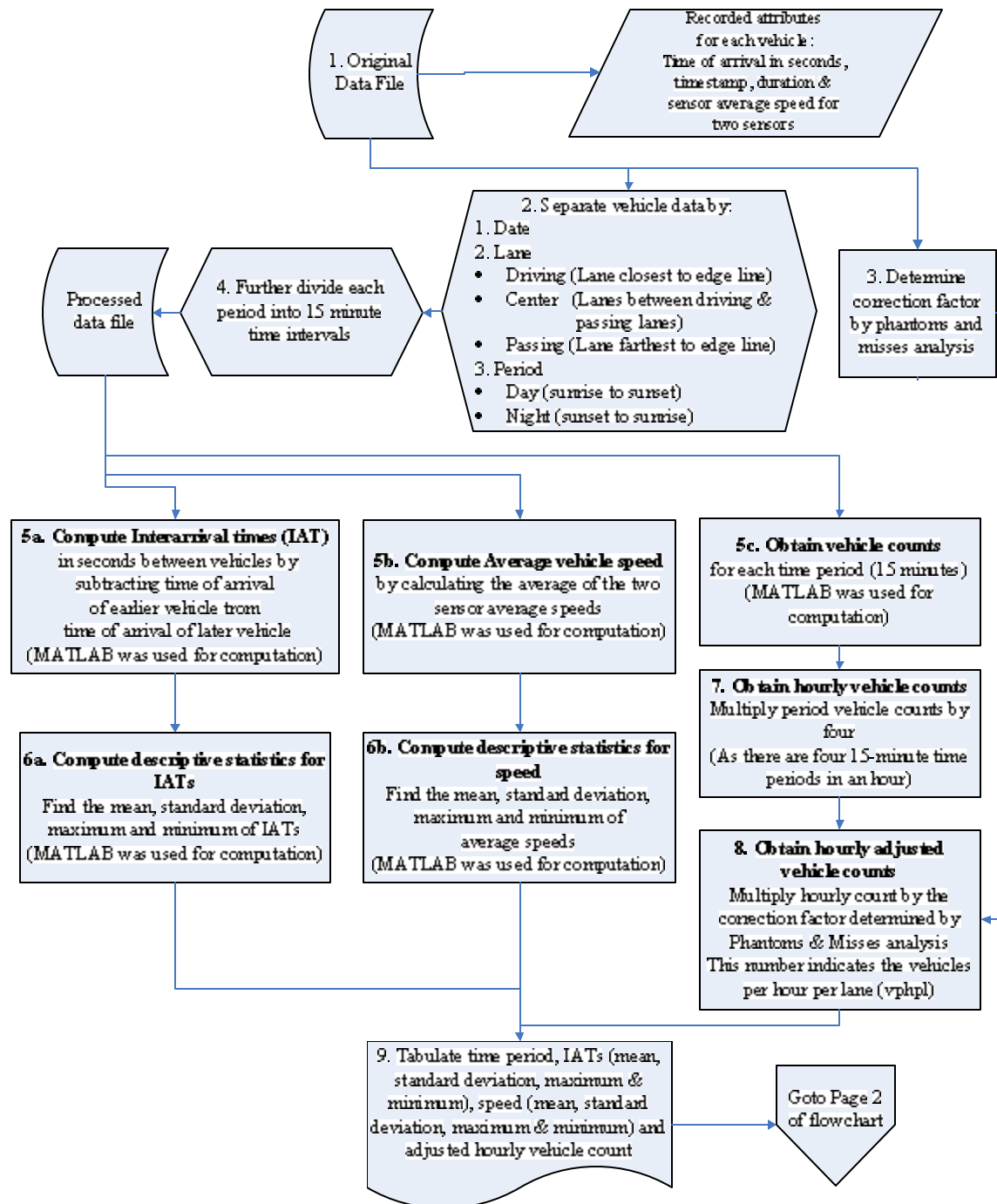
#### **3.4.4. Scalability Analysis**

Scalability means that the IAT pdfs can be generated with reasonable accuracy from hourly traffic volumes. The scalability method should be applicable for a wide range of hourly traffic volumes and IAT distributions could then be generated automatically by the computer.

IAT distributions are absolutely necessary for use in a Monte Carlo Computer Simulation for obtaining accurate queue length and delay time information for work zones subjected to high hourly traffic volumes where the number of traffic lanes is being reduced and traffic queues are expected.

The method to estimate cumulative interarrival times from hourly traffic counts is described in this section and depicted in the flowchart in Figure 74. The end product of this process is a spreadsheet which allows the user to enter the number of vehicles per hour per lane (vphpl) to automatically extract the corresponding cumulative interarrival time distribution. Since the IAT probability distribution function (pdf) is built for a range of traffic volumes based on the collected data, some adjustment is needed to use it for a specific hourly traffic volume within the volume range of the original data. Scalability means that the IAT pdfs can be generated with reasonable accuracy from hourly traffic volumes. If an IAT pdf is scalable, it means that IAT pdfs at 400 and 500 vphpl could be used to estimate the IAT pdf for any vphpl in the interval from 400 to 500 by linear interpolation. Extrapolation beyond the observed hourly volume range is not recommended.

The output data file from the microwave radar trailer records the following main attributes: time of arrival in seconds, timestamp, duration, and sensor average speed. This is the starting point for the flowchart (step 1). The data collected by the system, as previously illustrated in Table 30, include time to the nearest millisecond, (the system is configured to use 2.477-ms time increments), lane of traffic, then a set of data from the first sensor: a timestamp in 2.5-ms time increments, duration of the radar image in 2.477-ms time increments, a moving average speed based on the last 16 vehicles in mph, and a vehicle class. Next, the same set of data from the second sensor, then an average of the two running average speeds in mph, vehicle length in feet, and per vehicle speeds for each sensor in mph. All speeds are rounded to whole mph values, and all lengths to even foot values.



**Figure 74: Flowchart illustrating the generation of a scalable IAT pdf**

Note: The off-page references in this flowchart begin from this page



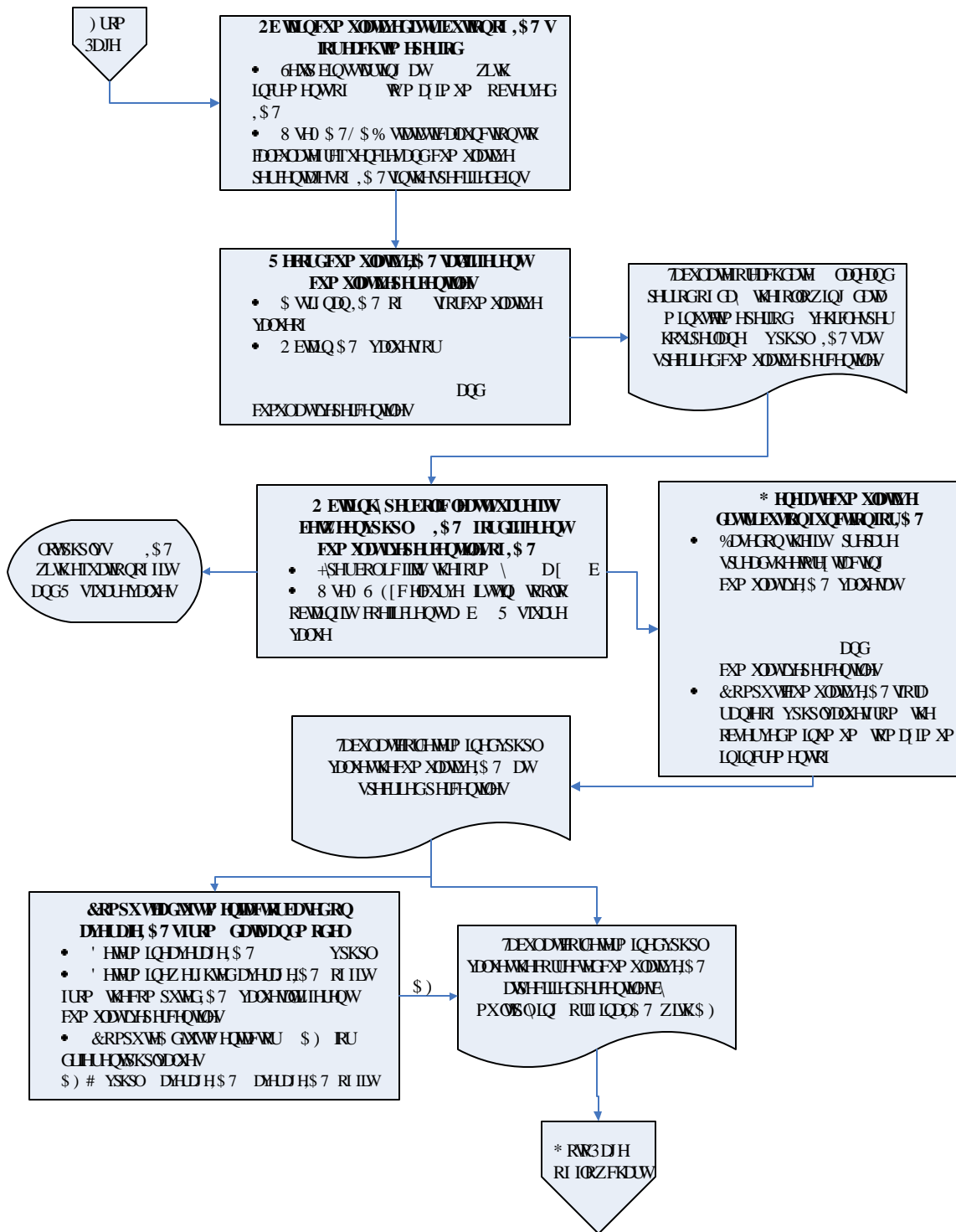
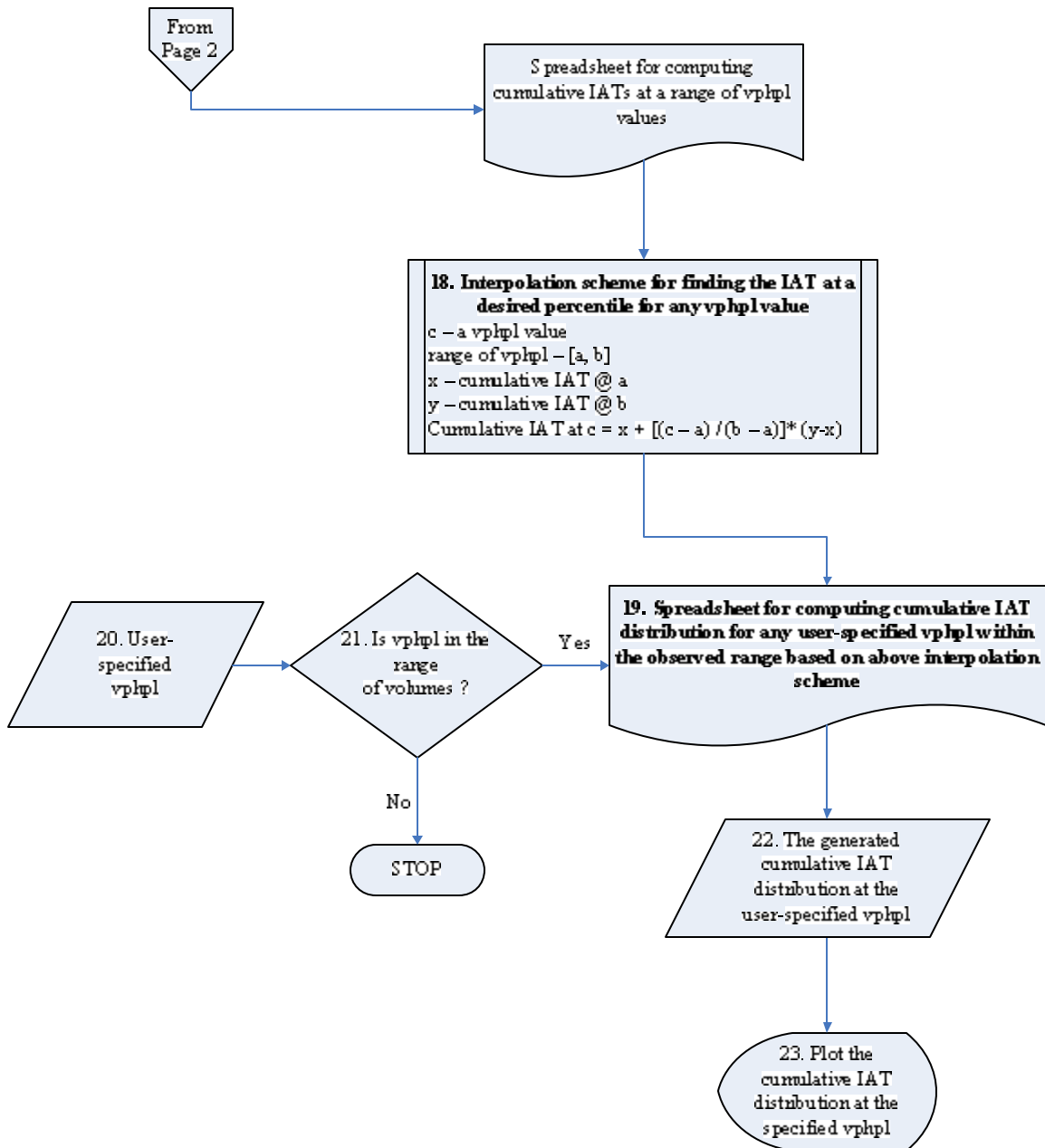


Figure 74: Flowchart illustrating the generation of a scalable IAT pdf (continued)



**Figure 74: Flowchart illustrating the generation of a scalable IAT pdf (continued)**

This data were then separated by lane (right lane (lane 1), lane 2, and lane 3) as given in step 2 of the flowchart. The data set was further separated by the period of day (day and night), where day corresponds to the period between sunrise and sunset and night between sunset and sunrise. The exact times of sunrise and sunset for each day and each location in the study were obtained from [117]. Thus, data sets were obtained for each lane and period of day. In every such data set, there were summary points marked at fifteen minute intervals. These points were used to further segment the data set in 15 minute time intervals as indicated in step 4 of the flow chart. The computation of interarrival time (IAT), average vehicle speed and vehicle counts for the data

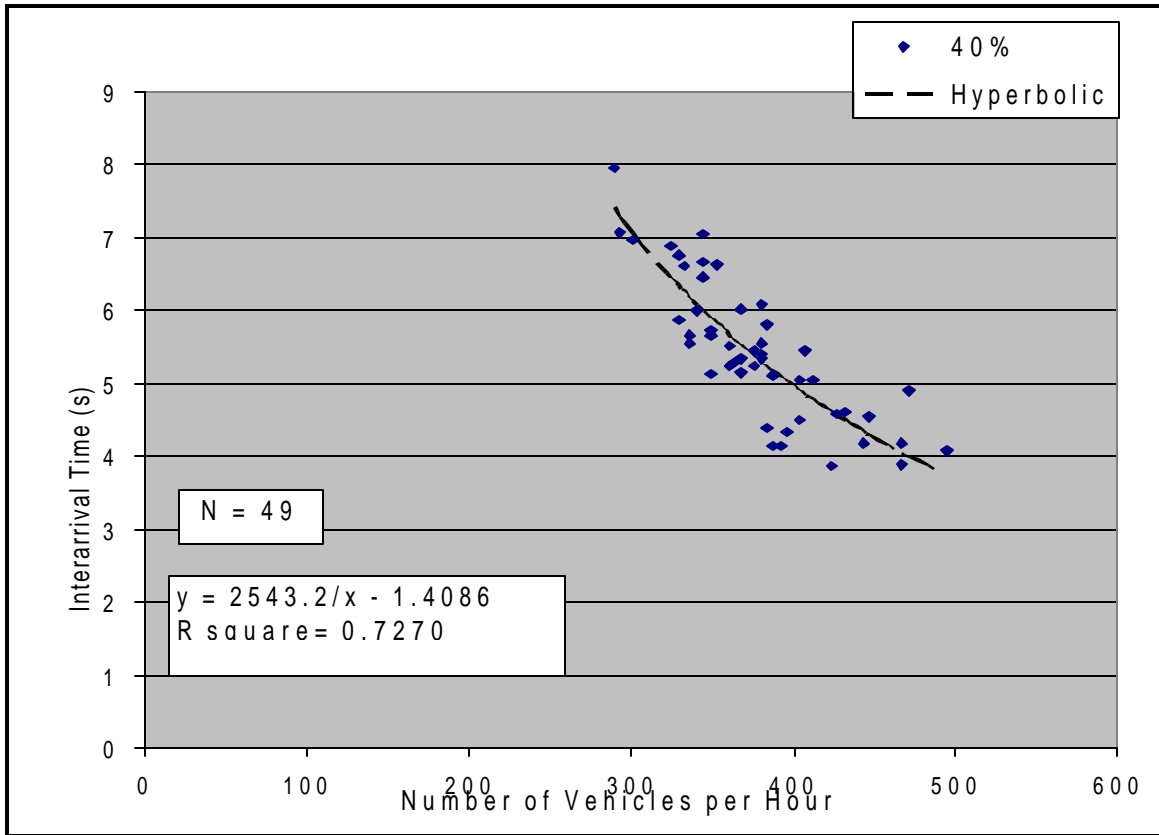
records in each time interval correspond to step 5 in the flowchart. The IAT is computed in seconds as the difference between the timestamps of  $j^{\text{th}}$  vehicle and  $j-1^{\text{th}}$  vehicle (step 5a). The average vehicle speed is obtained by calculating the average of the reported sensor speeds (step 5b). Also, a count of the number of vehicles is obtained (step 5c) by summing up the number of data records. The mean, standard deviation, minimum and maximum of IATs and average speeds are computed from the data records (step 6a & 6b). Matlab [118] scripts were employed for computations in steps 5 and 6. The vehicle count in each time period is multiplied by 4 (an hour has four 15 minute time periods) to obtain hourly vehicle counts as indicated by step 7 in the flowchart. These hourly vehicle counts are based on the trailer data and need some correction based on the independent (ORITE video and radar gun) phantoms and misses analysis (Step 3). A correction factor obtained from this analysis is multiplied to the hourly vehicle counts to obtain the adjusted hourly traffic counts (step 8). This number indicates the vehicles per hour per lane (vphpl). At this stage as illustrated by step 9 in the flowchart, a spreadsheet is tabulated where for each time period, the mean, standard deviation, maximum and minimum values of the IATs, speeds and the adjusted hourly vehicle counts are provided. These tables can be found in Appendix G which is available in electronic format from the ORITE Human Factors Laboratory.

For each time period, a histogram of the interarrival times (IATs) was prepared by using the MATLAB [118] statistical functions (step 10 of flowchart). Bins were set up from 0.01 seconds to the maximum observed IAT in the time interval in increments of 0.01 seconds. An interarrival time of 0.1 seconds was assigned for the cumulative value of 0%, as this value was expected to be well below the lower bound of the IAT distribution. At the next step (step 11), values for interarrival times were extracted from the histogram data for the following 16 percentiles: 1%, 2%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, 98%, 99%, and 100% (taken as the maximum interarrival time recorded). For each date, lane, and period of day, the following data were tabulated: 15 minute time period, vehicles per hour per lane (vphpl), and IATs on the extracted cumulative percentiles.

At each percentile, interarrival times versus flow rate (vphpl) graphs were drawn using Microsoft Excel [119]. On each graph, the data were fitted using a hyperbolic fit of the form:  $y = (a/x) + b$ . Microsoft Excel curve-fitting tools were utilized to estimate the coefficients  $a$  and  $b$  and the  $R^2$  value (correlation coefficient). This corresponds to step 13 in the flow chart. Figure 75 shows the graph where these data points are plotted along with the obtained hyperbolic fit. Also, shown on the graph is the equation of fit and the corresponding  $R^2$  value. The regression statistics for the fit are shown in Table 37. The corresponding analysis of variance (ANOVA) table is summarized in Table 38. The next task (steps 14 & 15) is to prepare a spreadsheet for extracting cumulative IAT values at different percentiles. These values are obtained for a range of vphpl values from the observed minimum to the maximum in increments of 50.

The average IAT can be determined for a vphpl by dividing the number of seconds in an hour (3600) by vphpl. The average IAT of fit is computed as a weighted average of the IATs at different cumulative percentiles. Since the IATs at different percentiles are calculated from the hyperbolic models, the average IAT of fit differs from the average IAT determined from vphpl by a factor. Hence, an adjustment factor is needed to correct the cumulative IATs at different percentiles (step 16). This is computed by dividing the average IAT from vphpl by the weighted average IAT of fit. In each row of Table 39, the vphpl, average IAT determined from vphpl, average IAT determined from fit are shown. The final column shows the adjustment factor. As

an example, for a vphpl of 400, the average IAT should be  $3600/400 = 9$ . The weighted average of fit in this case was 8.382. The adjustment factor is  $9/8.382 = 1.074$ . The IATs at different percentiles are multiplied by the adjustment factor to obtain adjusted IATs which are tabulated in Table 38 (step 17).



**Figure 75: Interarrival time as a function of volume (vphpl) at 40 percentile**

**Table 37: Regression statistics for fit**

Regression Statistics	
Multiple R	0.8527
R Square	0.7271
Adjusted R Square	0.7213
Standard Error	0.5071
Observations	49

**Table 38: Analysis of variance table for fit**

ANOVA					
Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F	Significance F
Regression	1	32.1991	32.1991	125.2197	0.0000
Residual	47	12.0856	0.2571		
Total	48	44.2848			
	Coefficients	Standard Error	t Stat	P-value	
Intercept	-1.4086	0.6149	-2.2909	0.0265	
X Variable	2543.2088	227.2719	11.1902	0.0000	

**Table 39: Adjusted IAT, hyperbolic model and R<sup>2</sup> of fit at different cumulative percentiles**

I-270 Eastbound Location 1 (Trailer 003) Data, 09/01/04 - Day – Right Lane (Lane 1)																	
Number of vehicles per hour per lane	Adjusted cumulative IAT at different percentages (s)																
	0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
250	0.10	0.88	1.25	1.76	2.35	4.26	6.94	9.63	11.91	14.21	17.17	22.85	30.89	41.83	55.94	62.77	73.22
300	0.10	0.76	1.07	1.52	2.10	3.60	5.61	7.71	9.65	11.79	14.58	19.17	26.43	34.95	45.33	51.15	60.61
350	0.10	0.68	0.94	1.35	1.92	3.12	4.67	6.34	8.04	10.06	12.72	16.53	23.24	30.04	37.77	42.87	51.61
400	0.10	0.62	0.84	1.22	1.78	2.77	3.96	5.31	6.83	8.76	11.33	14.56	20.83	26.36	32.11	36.67	44.86
450	0.10	0.57	0.77	1.12	1.68	2.49	3.41	4.52	5.89	7.75	10.24	13.02	18.96	23.49	27.72	31.86	39.62
500	0.10	0.53	0.70	1.04	1.59	2.27	2.98	3.89	5.15	6.95	9.37	11.79	17.45	21.20	24.22	28.02	35.43
Model	0.1	$y = 150.26/x + 0.1972$	$y = 237.76/x + 0.1904$	$y = 310.42/x + 0.3588$	$y = 314.31/x + 0.8767$	$y = 866.12/x + 0.4105$	$y = 1747.49/x - 0.6799$	$y = 2543.2/x - 1.4086$	$y = 2983.54/x - 1.0973$	$y = 3175.81/x + 0.2203$	$y = 3378.94/x + 2.1013$	$y = 4818.53/x + 1.5118$	$y = 5794.22/x + 4.9178$	$y = 9000.84/x + 2.0460$	$y = 13989.8/x - 5.0687$	$y = 15294.07/x - 4.08139$	$y = 16549.8/x + 0.4079$
R-Square		0.03	0.07	0.13	0.07	0.25	0.55	0.73	0.71	0.74	0.68	0.72	0.40	0.56	0.44	0.39	0.30

The next task is to obtain the IAT distribution for any given vphpl value in the observed range of traffic. In Table 39 the IATs at various percentiles were determined for a range of vphpl values. The vphpl values spread from the minimum to maximum observed volume in increments of 50. To obtain the IAT distribution at any intermediate volume in the interval between two vphpl values in the table, we need to interpolate between the IATs at these points. The linear interpolation scheme (step 18) is explained below:

- 1) Let  $c$  be the desired vphpl value for which the IAT distribution needs to be determined. Identify vphpl values  $a$  and  $b$  from the Table 38, such that  $c$  is in the interval  $(a, b)$ .
- 2) Let  $x$  be the cumulative IAT at volume  $a$  and  $y$  be the cumulative IAT at volume  $b$ . The IAT at  $c$  can be calculated as  $x + [(c - a) / (b - a)] * (y - x)$ .

A Microsoft Excel spreadsheet was prepared to compute the scaled IAT distribution for any user-specified volume of traffic (vphpl) in the observed range of traffic, based on the above interpolation scheme (step 19). This spreadsheet for the I-270 Eastbound during day time in the right lane (lane 1) is reproduced in Table 40. A vphpl value is entered in the second column of this sheet after determining a suitable interval from the first column. Cumulative IATs at 1%, 2%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, 98%, 99%, and 100% are computed by built-in formulas in the remaining columns. For example in the second row of this table (Table 40) for a vphpl of 325, the IAT distribution is shown.

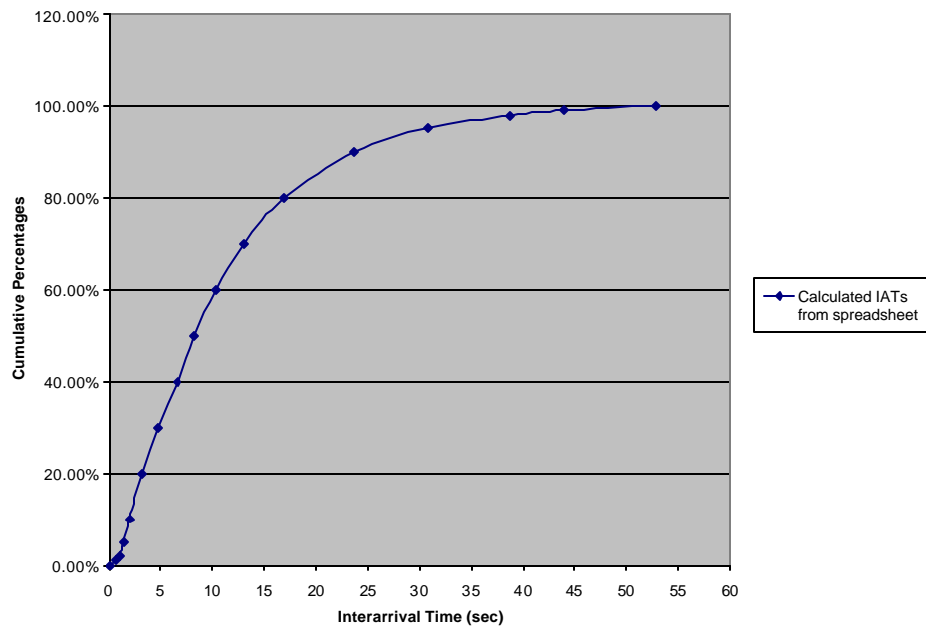
As an example, suppose the user desires to obtain the cumulative IAT distribution for 343 vehicles per hour per lane (step 20). First, it needs to be determined if the user-specified vphpl is the observed range as indicated in step 21 of the flowchart. If so, the particular interval the user-specified vphpl belongs to is determined from the spreadsheet (Table 40). For 343 vphpl, the corresponding interval is (300-350). By putting in the value of 343 in the spreadsheet, we obtain the cumulative IAT distribution (step 22), as shown in Table 41. A plot of the cumulative IAT distribution obtained is shown in Figure 76 (step 23). Thus, this spreadsheet can automatically compute the IAT distribution at any user-specified volume (vphpl) within the range of applicability based on interpolating between IATs at determined volumes (step 20).

**Table 40: Spreadsheet for determining IAT distribution for any vphpl value based on interpolation**

I-270 Eastbound Location 1 (Trailer 003) Data, 09/01/04 - Day – Right Lane (Lane 1)																		
INTERPOLATION																		
Range	Number of vehicles (vphpl)	Cumulative IAT at different percentages (s)																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
<b>250-300</b>	275	0.10	0.82	1.16	1.64	2.22	3.93	6.27	8.67	10.78	13.00	15.87	21.01	28.66	38.39	50.64	56.96	66.92
<b>300-350</b>	325	0.10	0.72	1.01	1.43	2.01	3.36	5.14	7.02	8.84	10.92	13.65	17.85	24.83	32.50	41.55	47.01	56.11
<b>350-400</b>	375	0.10	0.65	0.89	1.28	1.85	2.94	4.31	5.83	7.43	9.41	12.02	15.55	22.03	28.20	34.94	39.77	48.24
<b>400-450</b>	425	0.10	0.59	0.80	1.17	1.73	2.63	3.69	4.92	6.36	8.26	10.78	13.79	19.90	24.92	29.92	34.27	42.24
<b>450-500</b>	475	0.10	0.55	0.73	1.08	1.63	2.38	3.19	4.20	5.52	7.35	9.80	12.40	18.20	22.34	25.97	29.94	37.52

**Table 41: Cumulative IAT distribution obtained from the spreadsheet**

vphpl = 343	
Cumulative percentage	Interarrival time (seconds)
0.00%	0.10
1.00%	0.65
2.00%	0.90
5.00%	1.30
10.00%	1.87
20.00%	2.99
30.00%	4.40
40.00%	5.95
50.00%	7.58
60.00%	9.56
70.00%	12.19
80.00%	15.78
90.00%	22.32
95.00%	28.64
98.00%	35.62
99.00%	40.51
100.00%	49.04



**Figure 76: Cumulative IAT distribution obtained from spreadsheet for 343 vphpl**



The interpolation tables are generated as a result of the scalability analysis. Overall a methodology was developed to generate cumulative IAT distributions using hourly traffic volumes (vphpl) within the range of observed number of vehicles. The interpolation tables were generated for each lane, for each site, for daytime and nighttime, and for weekday and weekend data for the selected sites. A summary of the interpolation tables generated along with acceptable hourly traffic volume ranges for interpolation are given in Table 42 for daytime and in Table 43 for nighttime. Further information on the interpolation tables for each site for the first locations and for each lane can be found in Appendix H which is available in electronic format from the ORITE Human Factors Laboratory.

**Table 42: Minimum and Maximum Traffic Volumes (vphpl) that can be used to Generate Cumulative IAT Distribution during Daytime**

Site	Date	Day	Right Lane (Lane 1)		Lane 2		Lane 3		Lane 4	
			Min	Max	Min	Max	Min	Max	Min	Max
I-76 Westbound	8/19/2004	Weekday	400	750	100	650	-	-	-	-
I-76 Westbound	8/20/2004	Weekday	300	750	-	-	-	-	-	-
I-76 Westbound	8/21/2004	Weekend	250	750	200	500	-	-	-	-
I-76 Westbound	8/22/2004	Weekend	150	850	250	650	-	-	-	-
I-270 Westbound	8/28/2004	Weekend	500	1450	250	700	-	-	-	-
I-270 Westbound	8/29/2004	Weekend	250	1300	150	650	-	-	-	-
I-270 Westbound	8/30/2004	Weekday	700	2000	350	1700	-	-	-	-
I-270 Eastbound	9/1/2004	Weekday	250	500	550	1300	200	1600	-	-
I-270 Eastbound	9/2/2004	Weekday	250	500	600	1300	250	1600	-	-
I-270 Eastbound	9/3/2004	Weekday	250	500	650	1400	250	1600	-	-
I-90 Eastbound	9/14/2004	Weekday	550	1350	250	1450	550	1550	-	-
I-90 Westbound	9/18/2004	Weekend	400	950	600	1100	650	1200	400	900
I-90 Westbound	9/19/2004	Weekend	300	850	450	1000	350	1100	200	700
I-75 Southbound	9/18/2004	Weekend	250	850	700	1550	350	1150	-	-
I-75 Southbound	9/19/2004	Weekend	150	800	300	1550	150	1200	-	-

**Table 43: Minimum and Maximum Traffic Volumes (vphpl) that can be used to Generate Cumulative IAT Distribution during Nighttime**

Site	Date	Day	Right Lane (Lane 1)		Lane 2		Lane 3		Lane 4	
			Min	Max	Min	Max	Min	Max	Min	Max
I-76 Westbound	8/19/2004	Weekday	400	750	100	650	-	-	-	-
I-76 Westbound	8/20/2004	Weekday	300	750	-	-	-	-	-	-
I-76 Westbound	8/21/2004	Weekend	250	750	200	500	-	-	-	-
I-76 Westbound	8/22/2004	Weekend	150	850	250	650	-	-	-	-
I-270 Westbound	8/28/2004	Weekend	500	1450	250	700	-	-	-	-
I-270 Westbound	8/29/2004	Weekend	250	1300	150	650	-	-	-	-
I-270 Westbound	8/30/2004	Weekday	700	2000	350	1700	-	-	-	-
I-270 Eastbound	9/1/2004	Weekday	250	500	550	1300	200	1600	-	-
I-270 Eastbound	9/2/2004	Weekday	250	500	600	1300	250	1600	-	-
I-270 Eastbound	9/3/2004	Weekday	250	500	650	1400	250	1600	-	-
I-90 Eastbound	9/14/2004	Weekday	550	1350	250	1450	550	1550	-	-
I-90 Westbound	9/18/2004	Weekend	400	950	600	1100	650	1200	400	900
I-90 Westbound	9/19/2004	Weekend	300	850	450	1000	350	1100	200	700
I-75 Southbound	9/18/2004	Weekend	250	850	700	1550	350	1150	-	-
I-75 Southbound	9/19/2004	Weekend	150	800	300	1550	150	1200	-	-

### 3.4.5. Portability Analysis

Portability of interarrival time (IAT) distributions implies that observed IAT distributions are similar in different geographical locations or conditions. For instance, if IAT distributions for work zones are portable, it implies that vehicles arrive at work zones in Cleveland in distributions similar to those that would be observed in Cincinnati or elsewhere in Ohio. The method for comparing the portability of IAT distributions is illustrated as a flowchart in Figure 77.

In portability analysis, the free flow traffic (before the crossover or lane reduction in the work zone) data were analyzed to answer the following questions about portability:

- Do we need different cumulative IAT distributions for different sites for right lane (lane 1) during daytime?
- Do we need different cumulative IAT distributions for different sites for right lane (lane 1) during nighttime?
- Do we need different cumulative IAT distributions for different sites for lane 2 during daytime?
- Do we need different cumulative IAT distributions for different sites for lane 2 during nighttime?
- Do we need different cumulative IAT distributions for different sites for lane 3 during daytime?
- Do we need different cumulative IAT distributions for different sites for lane 3 during nighttime?
- Do we need different cumulative IAT distributions for daytime and nighttime data?

- Do we need different cumulative IAT distributions for different days of the week?
- Do we need different cumulative IAT distributions for weekends as opposed to weekdays?
- Do we need different cumulative IAT distributions for different lanes?

The data used for the portability analysis are the cumulative IAT distributions for different lanes (Lane 1, Lane 2, and Lane 3), period of day (daytime & nighttime), and sites at the first trailer location (free flow traffic). These can be obtained from prepared spreadsheets (step 1). This spreadsheet is capable of automatically extracting the cumulative IAT distribution for any user-specified number of vehicles per hour per lane (vphpl) in the observed range of traffic. The next step (step 2) is to determine suitable IAT distribution pairs for comparison. IAT distribution pairs can be compared at only common volume ranges. Hence, it is necessary to determine if there is an overlap in volume ranges for a possible IAT distribution pair. As indicated in step 2-1 of the flowchart, if there is an overlap in volume ranges, the IAT distributions are compared. Otherwise, they cannot be compared. In step 2-2, the IAT distribution pairs are tabulated as a matrix with the elements indicating comparability. In a pair of comparable IAT distributions, two volumes in vphpl are selected for comparison (step 3). The first vphpl for comparison is chosen closer to the beginning of the region of overlap and the second vphpl is selected closer to the end of the overlap (step 3-2). As an example, consider the daytime right lane (lane 1) distributions for I-75 southbound whose observed volume range is (450, 750) and the I-76 westbound whose observed volume range is (400, 750). The region of overlap is (450, 750) and the two selected volumes (vphpl) for comparing these IAT distributions are 475 and 725. In step 3-3, the selected volumes are tabulated for all comparable IAT distribution pairs.

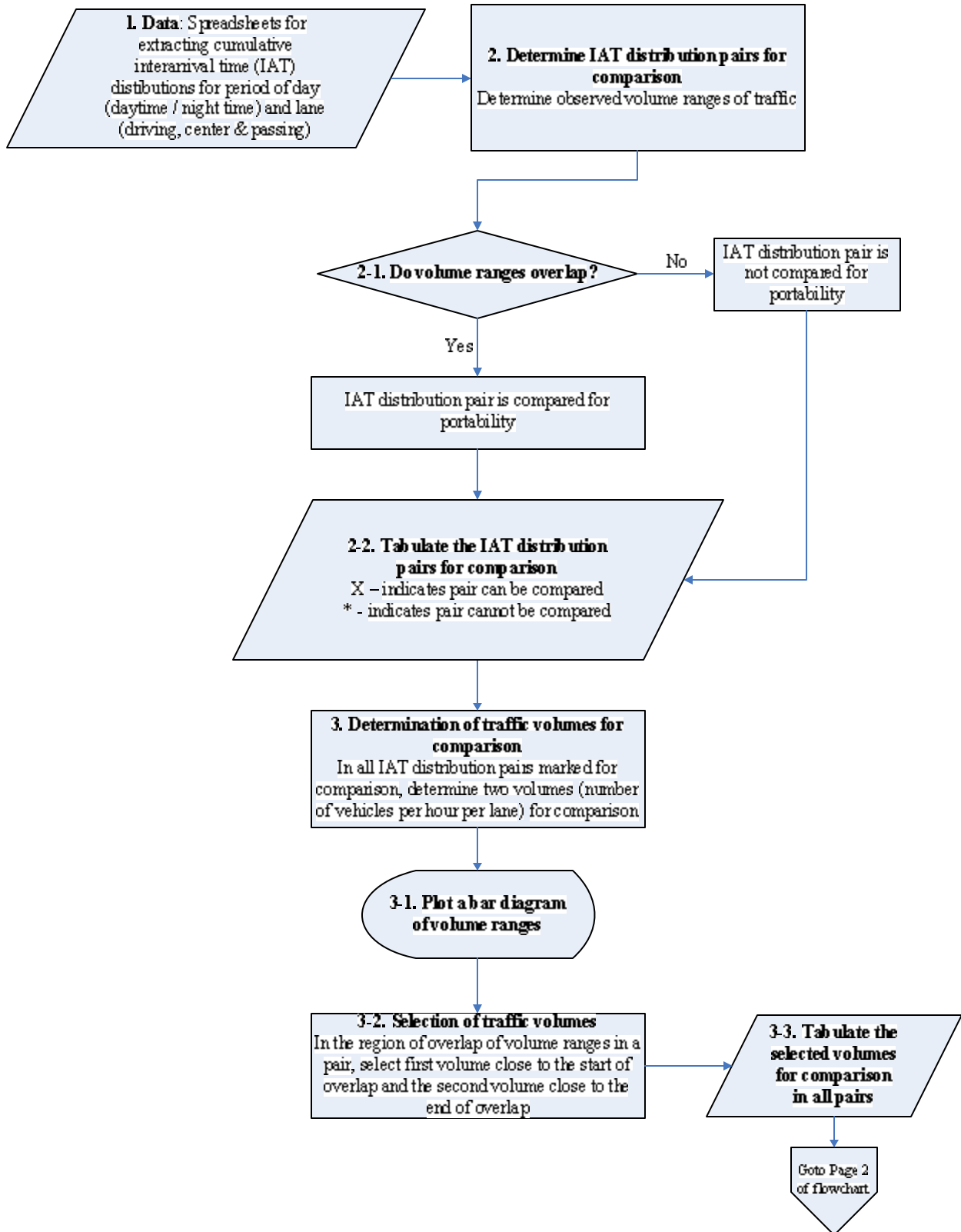


Figure 77: Flowchart for portability analysis of daytime right lane (lane 1) at all locations

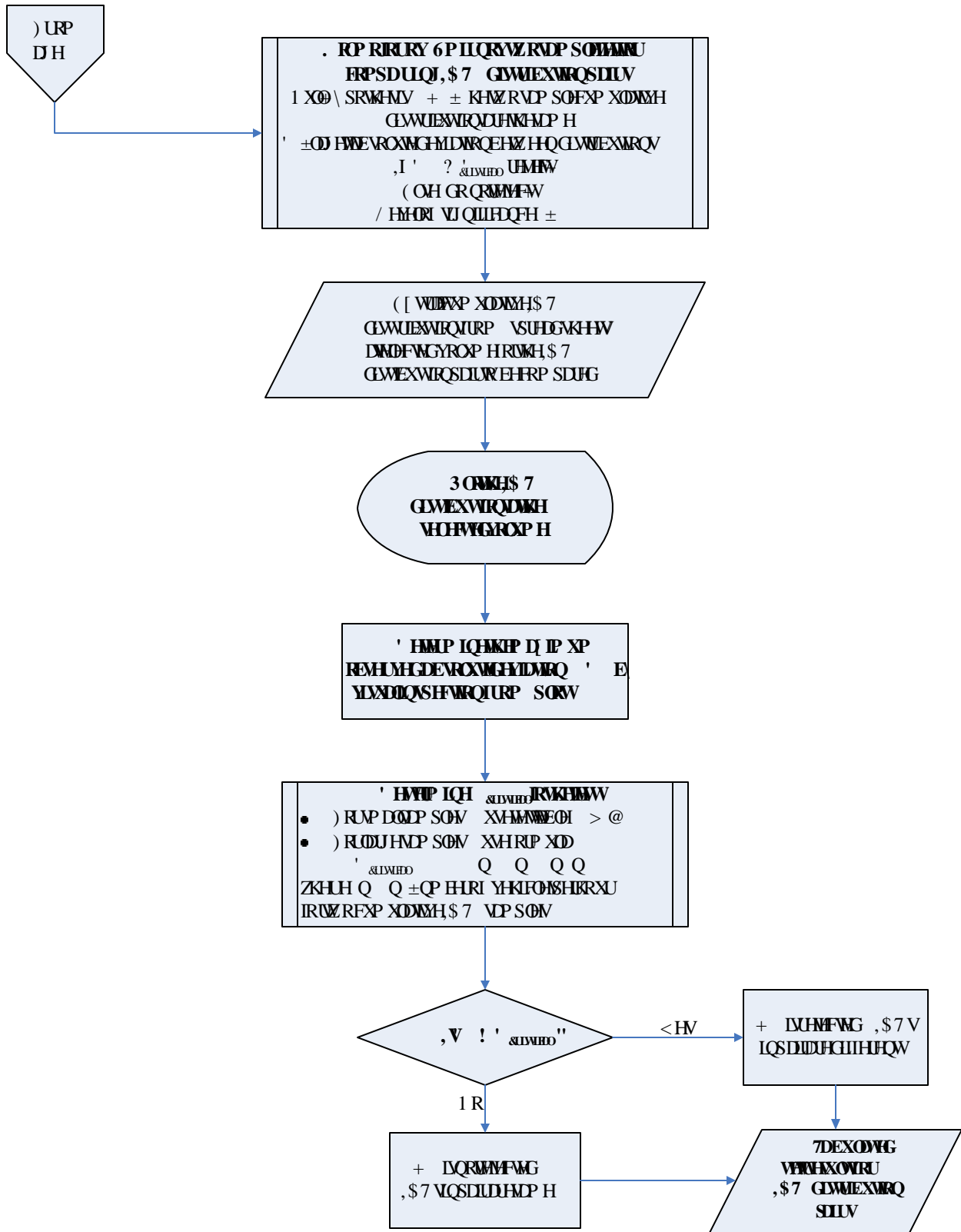


Figure 77: Flowchart for portability analysis of daytime right lane (lane 1) at all locations (continued)

For comparing IAT distributions, the Kolmogorov-Smirnov two sample test was used (step 4). This test can determine whether or not the two sample distributions come from different population distributions. The null hypothesis for this test,  $H_0$ , is that the two distributions are the same (two sample distributions come from the same population). The test statistic,  $D$  is the maximum observed absolute deviation between the two distributions. This is compared to the critical value,  $D_{Critical}$ . If  $D > D_{Critical}$ , then the null hypothesis  $H_0$  is rejected. Otherwise, we conclude that the IAT distributions are effectively the same. For a small sample size ( $= 40$ ), the  $D_{Critical}$  value was determined from the test table [116]. For larger samples, the value is determined from the formula shown below (for  $\alpha = 0.05$ ) [116]:

$$D_{Critical} = 1.36 \sqrt{\frac{n_1 + n_2}{n_1 n_2}}$$

In the above equation,  $n_1$  and  $n_2$  are the sample sizes of the two IAT distributions. If the IAT distributions being compared are generated at  $N$  vphpl, then  $n_1 = n_2 = N/4$ . This division by 4 is because the IAT distributions are for 15-minute time intervals.

Next, from the plot the maximum absolute deviation  $D$  is determined by visual inspection (step 4-2). In step 4-3, we determine the critical value of the test from the table given in [116], if the sample size is less than or equal to 40 or from the equation above if the sample size is greater (step 4-3). Then the  $D_{Critical}$  value is computed using the formula and if  $D < D_{Critical}$ , we conclude that the null hypothesis cannot be rejected at the significance level  $\alpha=0.05$  and that the IAT distributions compared are nearly the same. We then tabulate the test results for all IAT pairs being compared as indicated in step 4-5 of the flowchart. Portability analysis of IAT distributions was conducted for the following categories:

- For all lanes (right lane (lane 1), lane 2, and lane 3) and period of day (day time and night time), the IAT distributions were compared for six sites. An exception to this was I-90 Westbound which had four lanes and hence lane 4 was omitted from the comparisons.
- The IAT distributions for each lane during day time and night time conditions were compared for the following three sites: I-270 Eastbound, I-90 Eastbound and I-75 Southbound.
- The IAT distributions for weekdays (Monday-Friday) and weekends (Saturday-Sunday) were compared for two sites: I-76 Westbound and I-75 Southbound. For all lanes and period of day (day time & night time), the IAT distributions were compared in this category.

Table 44 through Table 48 show the experimentation performed for the portability investigation. Further information on the portability analysis can be found in Appendix I which is also available in electronic format from the ORITE Human Factors Laboratory.

**Table 44: Portability Results for Daytime and Nighttime Driving Conditions for Right Lane (Lane 1) for All Sites - Comparison of Observed D Values and Calculated Critical D Values for Daytime and Nighttime Right Lane (Lane 1) Data (Level of significance = 0.05)**

	I-76 Westbound	I-75 Southbound		I-90 Eastbound		I-90 Westbound		I-270 Eastbound		I-270 Westbound	
I-76 Westbound	-	N= 525 vph, DNR N= 725 vph, DNR	N= 225 vph, DNR N= 425 vph, DNR	N= 575 vph, DNR N= 725 vph, DNR	N= 225 vph, DNR N= 425 vph, DNR	N= 625 vph, R N= 725 vph, R	N= 175 vph, DNR N= 425 vph, DNR	N= 425 vph, DNR N= 475 vph, DNR	N= 175 vph, DNR N= 275 vph, DNR	N= 725 vph, DNR	N= 225 vph, DNR N= 425 vph, DNR
I-75 Southbound	-			N= 625 vph, DNR N= 725 vph, DNR	N= 175 vph, DNR N= 625 vph, DNR	N= 675 vph, DNR N= 725 vph, DNR	N= 225 vph, DNR N= 725 vph, DNR	N= 475 vph, DNR	N= 175 vph, DNR N= 225 vph, DNR	N= 725 vph, DNR	N= 175 vph, DNR N= 675 vph, DNR
I-90 Eastbound				-		N= 725 vph, DNR N= 1275 vph, DNR	N= 225 vph, DNR N= 625 vph, R	*	N= 175 vph, DNR N= 225 vph, DNR	N= 775 vph, DNR N= 1225 vph, DNR	N= 225 vph, DNR N= 675 vph, DNR
I-90 Westbound						-		*	N= 175 vph, DNR N= 275 vph, DNR	N= 725 vph, DNR N= 1475 vph, DNR	N= 175 vph, DNR N= 625 vph, DNR
I-270 Eastbound								-		*	N= 175 vph, DNR N= 225 vph, DNR
I-270 Westbound											-
	Daytime	Nighttime									

\* Volume ranges do not overlap  
(DNR = Do not Reject , R= Reject)

**Table 45: Portability Results for Daytime and Nighttime Driving Conditions for Lane 2 for All Sites - Comparison of Observed D Values and Calculated Critical D Values for Daytime and Nighttime Lane 2 Data (Level of significance = 0.05)**

	I-76 Westbound	I-75 Southbound		I-90 Eastbound		I-90 Westbound		I-270 Eastbound		I-270 Westbound	
I-76 Westbound	-	N= 525 vph, R N= 625 vph, R	N= 225 vph, DNR N= 425 vph, DNR	N= 275 vph, DNR N= 625 vph, R	N= 175 vph, DNR	N= 525 vph, R N= 625 vph, R	N= 125 vph, DNR N= 175 vph, DNR	N= 575 vph, R N= 625 vph, R	N= 125 vph, DNR N= 175 vph, DNR	N= 375 vph, DNR N= 625 vph, DNR	N= 125 vph, DNR N= 175 vph, DNR
I-75 Southbound	-			N= 525 vph, DNR N= 1425 vph, R	N= 325 vph, DNR N= 975 vph, DNR	N= 525 vph, DNR N= 1375 vph, DNR	N= 275 vph, DNR N= 625 vph, DNR	N= 575 vph, R N= 1275 vph, R	N= 375 vph, DNR N= 775 vph, DNR	N= 525 vph, DNR N= 1425 vph, R	N= 275 vph, DNR N= 325 vph, DNR
I-90 Eastbound				-		N= 525 vph, DNR N= 1375 vph, DNR	N= 275 vph, DNR N= 625 vph, R	N= 575 vph, DNR N= 1275 vph, DNR	N= 325 vph, DNR N= 825 vph, DNR	N= 375 vph, DNR N= 1425 vph, R	N= 225 vph, DNR N= 325 vph, DNR
I-90 Westbound						-		N= 575 vph, R N= 1275 vph, R	N= 275 vph, DNR N= 625 vph, DNR	N= 525 vph, R N= 1375 vph, R	N= 175 vph, DNR N= 325 vph, DNR
I-270 Eastbound										N= 575 vph, DNR N= 1275 vph, R	N= 175 vph, DNR N= 325 vph, DNR
I-270 Westbound										-	

Daytime    Nighttime  
(DNR = Do not Reject , R= Reject)



**Table 46: Portability Results for Daytime and Nighttime Driving Conditions for Lane 3 for All Sites - Comparison of Observed D Values and Calculated Critical D Values for Daytime and Nighttime Lane 3 Data (Level of significance = 0.05)**

	I-75 Southbound	I-90 Eastbound		I-90 Westbound		I-270 Eastbound	
I-75 Southbound	-	N= 825 vph , R N= 1475 vph, DNR	N= 325 vph , DNR N= 525 vph , DNR	N= 1025 vph, R N= 1475 vph, DNR	N= 275 vph , DNR N= 625 vph , DNR	N= 825 vph , DNR N= 1475 vph, R	N= 175 vph , DNR N= 225 vph , DNR
I-90 Eastbound		-		N= 1025 vph, DNR N= 1475 vph, DNR	N= 375 vph , DNR N= 725 vph , R	N= 825 vph , R N= 1475 vph, R	N= 125 vph , DNR N= 225 vph , DNR
I-90 Westbound				-		N= 1025 vph, R N= 1425 vph, R	N= 125 vph , DNR N= 225 vph , DNR
I-270 Eastbound						-	

Daytime	Nighttime
---------	-----------

(DNR = Do not Reject , R= Reject)

**Table 47: Portability Results for Daytime and Nighttime Driving Conditions for Right Lane (Lane 1), Lane 2, and Lane 3 for I-270 Eastbound, I-90 Eastbound, and I-75 Southbound - Comparison of Observed D Values and Calculated Critical D Values for Daytime and Nighttime Right Lane (Lane 1), Lane 2, and Lane 3 Data (Level of significance = 0.05).**

	Night – Right Lane (Lane 1)			Night – Lane 2			Night – Lane 3		
Day – Right Lane (Lane 1)	N= 275 vph, DNR	N= 575 vph, DNR N= 725 vph, DNR	N= 575 vph, DNR N= 675 vph, DNR						
Day – Lane 2				N= 625 vph, DNR N= 875 vph, R	N= 325 vph, DNR N= 1025 vph, DNR	N= 625 vph, DNR N= 1025 vph, DNR			
Day – Lane 3							N= 225 vph, DNR N= 275 vph, DNR	N= 625 vph, DNR N= 925 vph, DNR	*
I-270 Eastbound	I-90 Eastbound	I-75 Southbound							

\* Volume ranges do not overlap  
(DNR = Do not Reject , R= Reject)

**Table 48: Portability Results for Weekday and Weekend Driving Conditions for I-76 Westbound and I-75 Southbound during Daytime and Nighttime - Comparison of Observed D Values and Calculated Critical D Values for Weekday and Weekend Right Lane (Lane 1), Lane 2, and Lane 3 Data during Daytime and Nighttime (Level of significance = 0.05)**

	Saturday – Right Lane 1		Saturday – Lane 2		Saturday – Lane 3		Sunday – Right Lane		Sunday – Lane 2		Sunday – Lane 3	
Weekday – Right Lane (Lane 1)	N= 475 vph, DNR	N= 325 vph, DNR					N= 525 vph, DNR	N= 275 vph, DNR				
	N= 675 vph, DNR	N= 425 vph, DNR					N= 625 vph, DNR	N= 375 vph, DNR				
	N= 575 vph, DNR	N= 325 vph, DNR					N= 575 vph, DNR	N= 275 vph, DNR				
	N= 625 vph, DNR	N= 425 vph, DNR					N= 675 vph, DNR	N= 475 vph, DNR				
Weekday – Lane 2			***	***					***	***		
			N= 825 vph, DNR	N= 325 vph, DNR					N= 625 vph, DNR	N= 375 vph, DNR		
			N= 1325 vph, DNR	N= 925 vph, DNR					N= 1375 vph, DNR	N= 975 vph, DNR		
Weekday – Lane 3					N= 475 vph, DNR	N= 125 vph, DNR					N= 375 vph, DNR	N= 125 vph, DNR
					N= 675 vph, DNR	N= 175 vph, DNR					N= 525 vph, DNR	N= 175 vph, DNR
					N= 875 vph, DNR	N= 325 vph, DNR					N= 875 vph, DNR	N= 325 vph, DNR
					N= 1025 vph, DNR	N= 475 vph, DNR					N= 1025 vph, DNR	N= 525 vph, DNR
Saturday – Right Lane (Lane 1)							N= 375 vph, DNR	N= 325 vph, DNR				
							N= 625 vph, DNR	N= 525 vph, DNR				
							N= 325 vph, DNR	N= 275 vph, DNR				
							N= 675 vph, DNR	N= 425 vph, DNR				
Saturday – Lane 2									***	***		
									N= 825 vph, DNR	N= 375 vph, DNR		
									N= 1375 vph, DNR	N= 875 vph, DNR		
Saturday – Lane 3											N= 325 vph, DNR	N= 125 vph, DNR
											N= 425 vph, DNR	N= 225 vph, DNR
											N= 525 vph, DNR	N= 375 vph, DNR
											N= 975 vph, DNR	N= 425 vph, DNR
I-76 Westbound – Daytime		I-76 Westbound – Nighttime		I-75 Southbound – Daytime		I-75 Southbound – Nighttime		*** I-76 Westbound has only 2 Lanes				

The portability analysis showed that the vehicles arrive to a work zone in much the same way in different places in Ohio.

- Daytime Right Lane (Lane 1) Data have similar cumulative IAT distributions for all of the 6 sites.
- Nighttime Right Lane (Lane 1) Data have similar cumulative IAT distributions for all of the 6 sites.
- Daytime Lane 2 Data have similar cumulative IAT distributions for all of the 6 sites.
- Nighttime Lane 2 Data have similar cumulative IAT distributions for all of the 6 sites.
- Daytime Lane 3 Data have similar cumulative IAT distributions for all of the 6 sites.
- Nighttime Lane 3 Data have similar cumulative IAT distributions for all of the 6 sites.
- Daytime and nighttime data have similar cumulative IAT for the sites for right lane (lane 1) (I-270 eastbound, I-90 eastbound, and I-75 southbound data, which has three lanes, was chosen for the investigation of daytime and nighttime portability analysis).
- Daytime and nighttime data have similar cumulative IAT for the sites for lane 2 (I-270 eastbound, I-90 eastbound and I-75 southbound data, which has three lanes, was chosen for the investigation of daytime and nighttime portability analysis).
- Daytime and nighttime data have similar cumulative IAT for the sites for lane 3 (I-270 eastbound, I-90 eastbound, and I-75 southbound data, which has three lanes, was chosen for the investigation of daytime and nighttime portability analysis).
- Weekday and Weekend-Saturday data have similar cumulative IAT distribution for right lane (lane 1), lane 2, and lane 3 during daytime and nighttime for the randomly selected sites I-76 westbound and I-75 southbound.
- Weekday and Weekend-Sunday data have similar cumulative IAT distribution for right lane (lane 1), lane 2, and lane 3 during daytime and nighttime for the randomly selected sites I-76 westbound and I-75 southbound.

#### ***3.4.6. Universal Interarrival Time Distributions***

The portability analysis showed that all the sites have similar cumulative IAT distribution for weekday and weekend data during daytime and nighttime. The data from the sites can be combined together to get a universal cumulative IAT distribution applicable in Ohio for 2-lane freeways, 3-lane freeways, and 4-lane freeways. A set of cumulative IAT distribution spreadsheets may be downloaded at

<http://webce.ent.ohiou.edu/orite/cumulativeIATdistributions.html>.

A total of nine Universal Cumulative IAT Distribution spreadsheets to compute the cumulative IAT distributions for any user-specified hourly traffic volume (vphpl) in the observed range of traffic volumes were generated. These IAT Distributions and their applicable volume ranges are as follows:

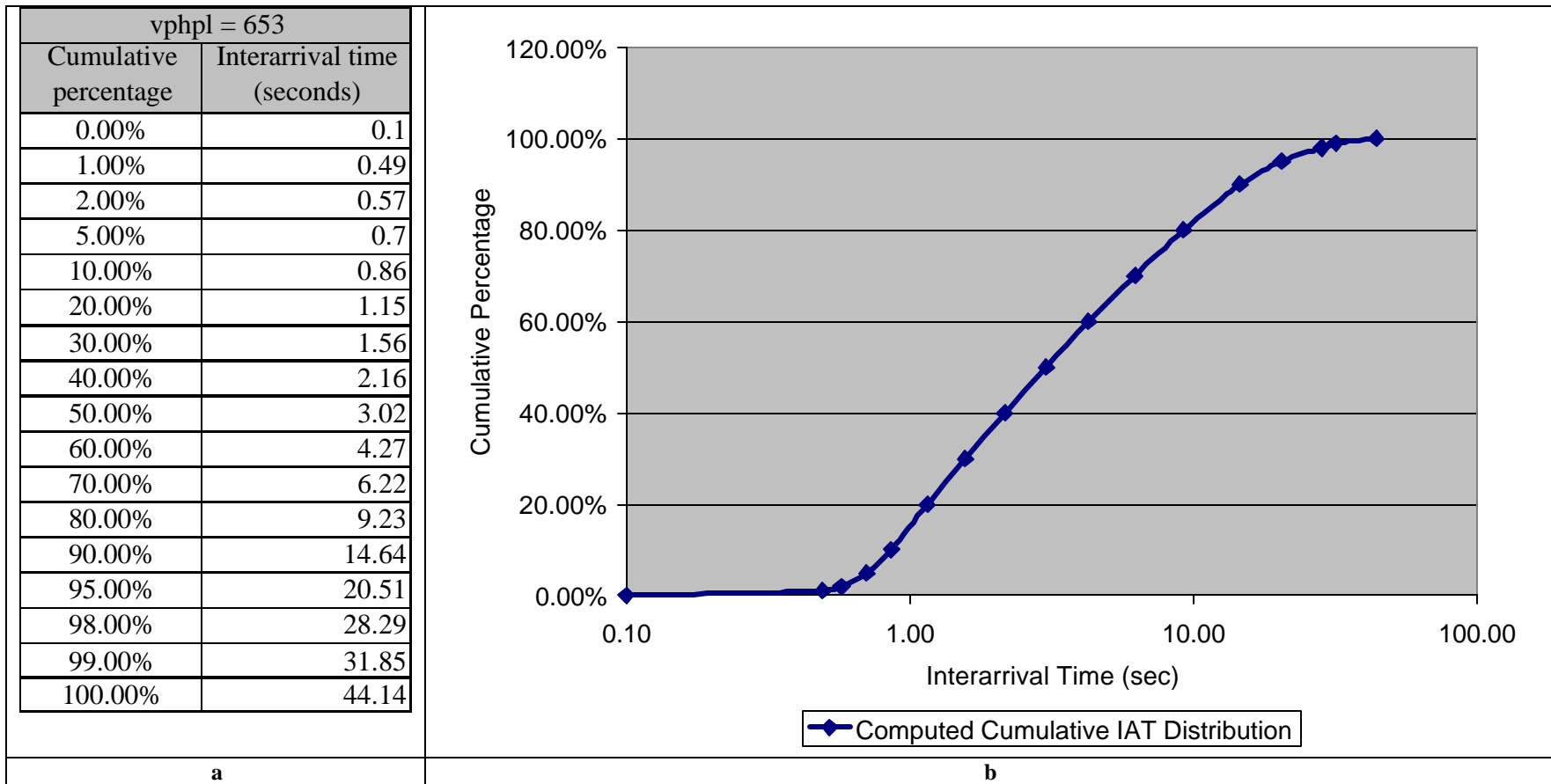
- 2-Lane Freeway-Right Lane (Lane 1), 200-1600 vphpl;
- 2-Lane Freeway-Lane 2, 150-1450 vphpl;
- 3-Lane Freeway- Right Lane (Lane 1), 200-1800 vphpl;
- 3-Lane Freeway-Lane 2, 200-1550 vphpl;
- 3-Lane Freeway-Lane 3, 150-1650 vphpl;
- 4-Lane Freeway- Right Lane (Lane 1), 100-1150 vphpl;
- 4-Lane Freeway-Lane 2, 150-1400 vphpl;
- 4-Lane Freeway-Lane 3, 100-1400 vphpl;
- 4-Lane Freeway-Lane 4, 100-1300 vphpl.

In Table 49, a Universal IAT Distribution spreadsheet for a 2-lane freeway for lane 2 is given as an example for how to determine the IAT distribution for a given hourly traffic volume. In the spreadsheet the user enters only the observed number of vehicles per hour per lane in the corresponding interval into the shaded cell on the left and the IATs for the corresponding cumulative probabilities are generated according to the linear interpolation formula and displayed in the cells to the right of the shaded cell. For example, to compute the IAT distribution for an hourly volume of 653 vphpl, one first determines that 653 is in the range 650-700, which is in the 11<sup>th</sup> row down in the table. One then enters 653 in the second column of the 11<sup>th</sup> row (the shaded square) in place of the default value of 675, at which point the IAT distribution appears in columns 3-19 of row 11. The default values entered in the shaded column at the midpoint of the ranges in column 1 are the midpoints of the ranges. Note that hourly volumes outside the range 150-1450 vphpl lie outside the domain of this table. We obtain the cumulative IAT distribution values as shown in Figure 78a for the traffic volume of 653 vphpl. For illustration purposes only Figure 78b shows the generated cumulative IAT distribution.

**Table 49: Cumulative IAT Distribution Spreadsheet for 2-Lane Freeways – Lane 2**

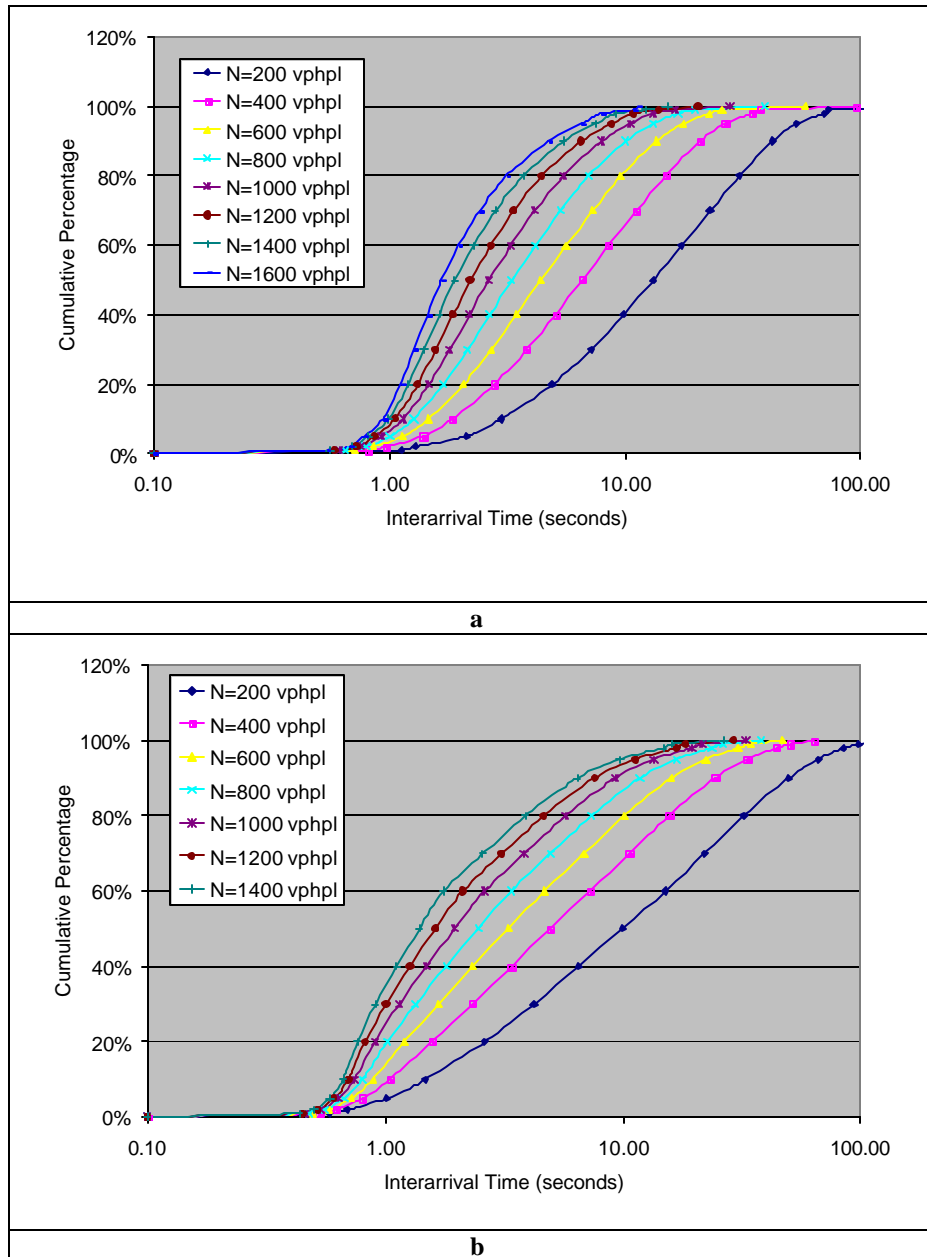
Cumulative Interarrival Time Distribution in seconds - Table for 2-Lane Freeways - Lane 2 for Traffic Volume of 150-1450 vehicles per hour per lane																		
Interval for the hourly traffic volume	Number of vehicles per hour	Cumulative Percentage																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
150-200	175	0.10	0.60	0.71	1.08	1.62	2.97	4.85	7.56	11.64	17.69	25.79	37.80	58.22	77.25	97.98	114.14	130.29
201-250	225	0.10	0.57	0.68	0.97	1.39	2.41	3.84	5.89	8.96	13.52	19.71	28.93	44.70	59.67	76.44	88.67	103.80
251-300	275	0.10	0.55	0.65	0.90	1.25	2.06	3.20	4.85	7.30	10.92	15.92	23.39	36.26	48.69	62.96	72.76	87.21
301-350	325	0.10	0.54	0.64	0.85	1.15	1.82	2.77	4.13	6.15	9.14	13.32	19.60	30.47	41.15	53.71	61.83	75.79
351-400	375	0.10	0.53	0.62	0.82	1.08	1.65	2.45	3.61	5.32	7.83	11.42	16.83	26.24	35.65	46.95	53.85	67.42
401-450	425	0.10	0.52	0.61	0.79	1.02	1.51	2.20	3.21	4.68	6.84	9.98	14.72	23.03	31.46	41.80	47.77	61.03
451-500	475	0.10	0.51	0.60	0.76	0.97	1.40	2.01	2.89	4.18	6.07	8.85	13.06	20.50	28.16	37.73	42.98	55.98
501-550	525	0.10	0.51	0.59	0.74	0.93	1.32	1.86	2.64	3.78	5.44	7.93	11.72	18.45	25.49	34.44	39.10	51.87
551-600	575	0.10	0.50	0.58	0.73	0.90	1.24	1.73	2.43	3.44	4.92	7.17	10.62	16.77	23.29	31.73	35.90	48.47
601-650	625	0.10	0.50	0.58	0.71	0.87	1.18	1.62	2.25	3.16	4.48	6.54	9.70	15.35	21.44	29.44	33.21	45.60
651-700	675	0.10	0.49	0.57	0.70	0.85	1.13	1.53	2.10	2.92	4.12	6.01	8.91	14.15	19.87	27.50	30.92	43.14
701-750	725	0.10	0.49	0.56	0.69	0.83	1.08	1.45	1.97	2.72	3.80	5.54	8.23	13.12	18.52	25.82	28.94	41.02
751-800	775	0.10	0.48	0.56	0.68	0.81	1.04	1.37	1.86	2.54	3.52	5.14	7.65	12.22	17.34	24.35	27.22	39.15
801-850	825	0.10	0.48	0.55	0.67	0.79	1.00	1.31	1.76	2.38	3.28	4.79	7.13	11.43	16.30	23.06	25.71	37.50
851-900	875	0.10	0.47	0.55	0.66	0.78	0.97	1.26	1.67	2.25	3.07	4.48	6.68	10.74	15.39	21.92	24.37	36.05
901-950	925	0.10	0.47	0.54	0.65	0.76	0.94	1.21	1.59	2.12	2.88	4.20	6.27	10.12	14.57	20.90	23.17	34.73
951-1000	975	0.10	0.46	0.54	0.64	0.75	0.92	1.16	1.52	2.01	2.71	3.95	5.91	9.55	13.83	19.97	22.08	33.52
1001-1050	1025	0.10	0.46	0.53	0.63	0.74	0.89	1.12	1.46	1.91	2.55	3.73	5.58	9.05	13.17	19.14	21.11	32.43
1051-1100	1075	0.10	0.46	0.53	0.62	0.72	0.87	1.09	1.40	1.82	2.41	3.53	5.28	8.60	12.57	18.38	20.23	31.44
1101-1150	1125	0.10	0.45	0.52	0.62	0.71	0.85	1.05	1.34	1.74	2.29	3.34	5.01	8.18	12.02	17.69	19.42	30.53
1151-1200	1175	0.10	0.45	0.52	0.61	0.70	0.83	1.02	1.29	1.66	2.17	3.17	4.77	7.80	11.52	17.05	18.68	29.70
1201-1250	1225	0.10	0.45	0.52	0.60	0.69	0.81	0.99	1.25	1.59	2.07	3.02	4.54	7.46	11.06	16.47	18.00	28.92
1251-1300	1275	0.10	0.44	0.51	0.60	0.69	0.80	0.96	1.21	1.53	1.97	2.88	4.33	7.14	10.63	15.93	17.37	28.20
1301-1350	1325	0.10	0.44	0.51	0.59	0.68	0.78	0.94	1.17	1.47	1.88	2.75	4.14	6.84	10.24	15.43	16.79	27.53
1351-1400	1375	0.10	0.44	0.50	0.59	0.67	0.77	0.92	1.13	1.41	1.80	2.63	3.97	6.57	9.88	14.96	16.25	26.90
1401-1450	1425	0.10	0.43	0.50	0.58	0.66	0.75	0.89	1.10	1.36	1.72	2.52	3.80	6.31	9.54	14.53	15.75	26.32

Enter the Hourly Traffic Volume into column 2 (shaded area) next to the interval in column 1 that includes the hourly traffic volume, then press enter to compute the Cumulative Interarrival Time Distribution (in seconds) in the rows to the right.



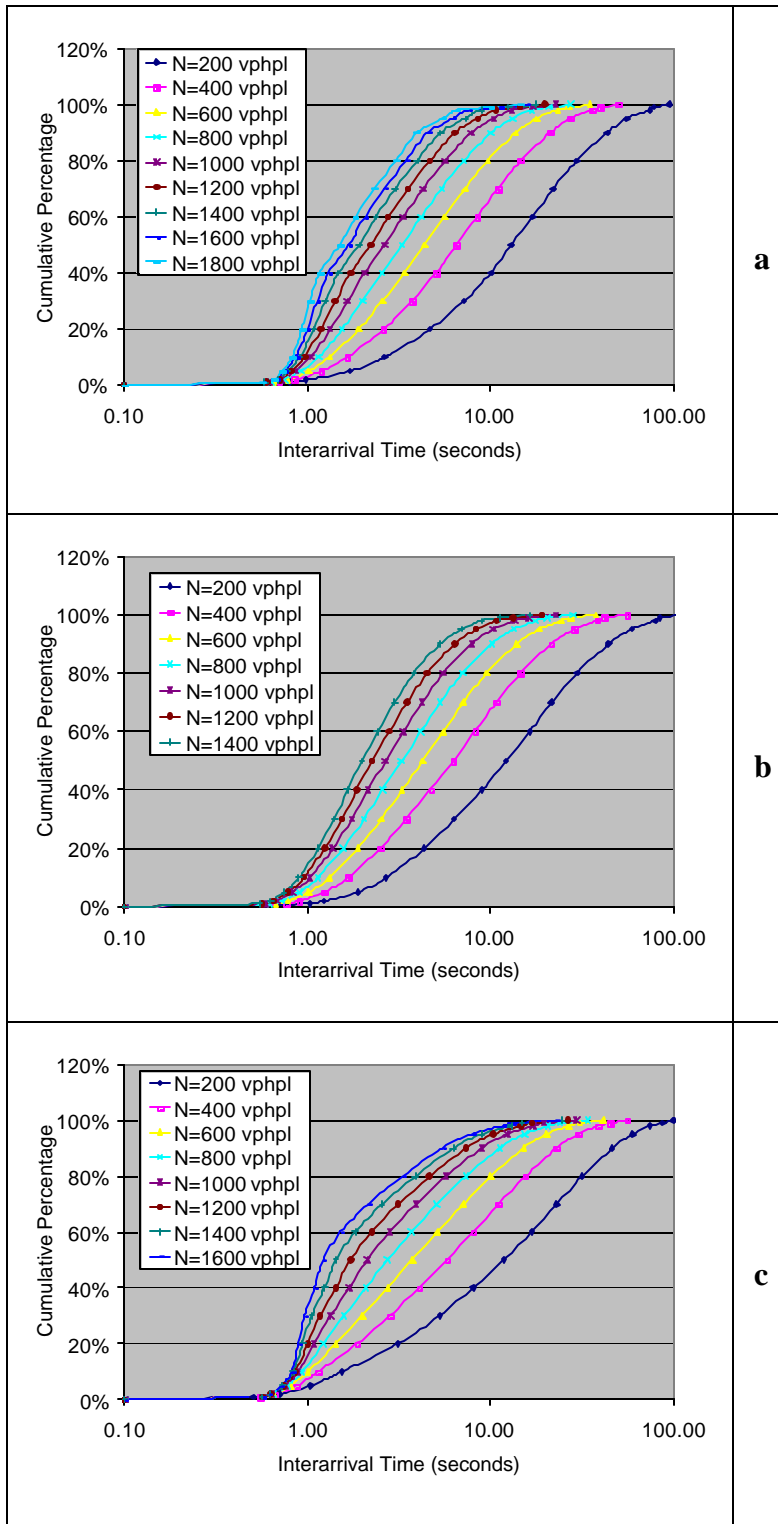
**Figure 78: Cumulative IAT Distribution for N=653 vphpl for 2-Lane Freeway Lane 2 Traffic a) IATs at given cumulative percentages b) Plot of the IATs vs. cumulative percentage**

In Figure 79, Figure 80, Figure 81, and Figure 82 the graphs for the generated universal cumulative IAT distributions for different freeway configurations for different lanes are given for selected traffic volumes within the observed ranges of traffic. The IAT scale along the abscissa is given in a logarithmic scale to magnify the difference between lower IATs at higher traffic volumes.

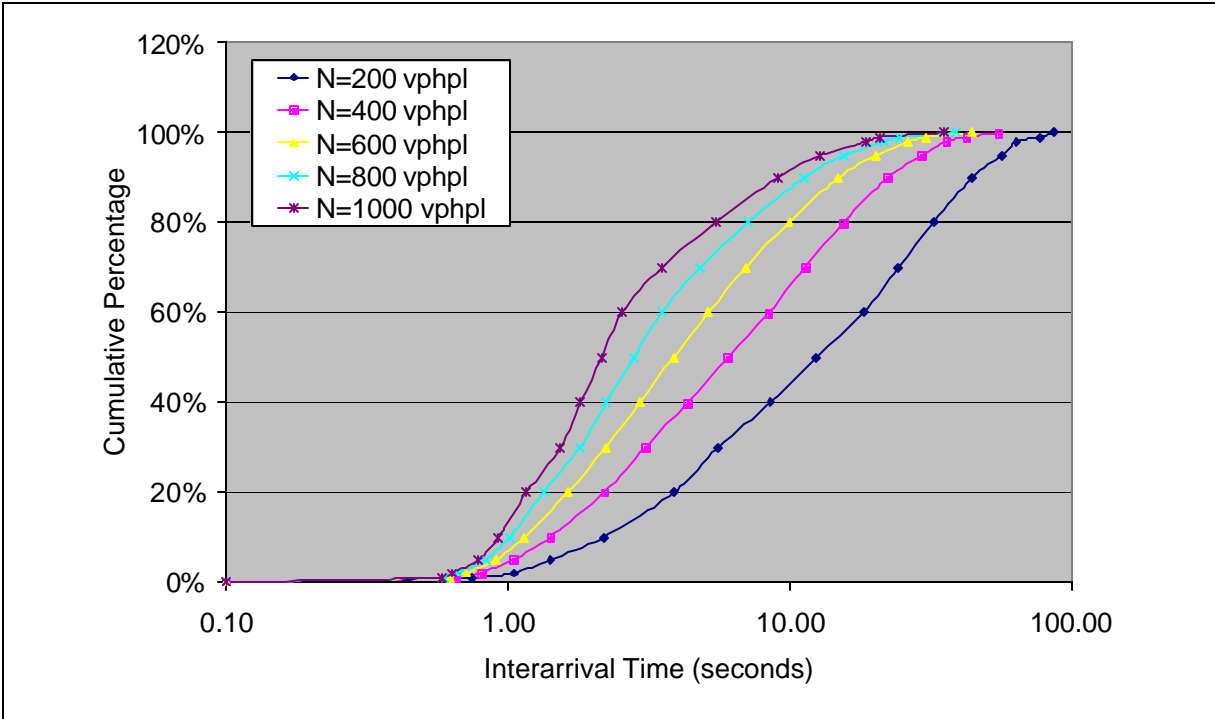


**Figure 79: Comparison of Universal Cumulative Interarrival Time Distributions for 2-Lane Freeways for a) Right Lane (Lane 1) (Cumulative IAT Distribution Range= 200-1600 vphpl) and b) Lane 2 (Cumulative IAT Distribution Range= 150-1450 vphpl)**

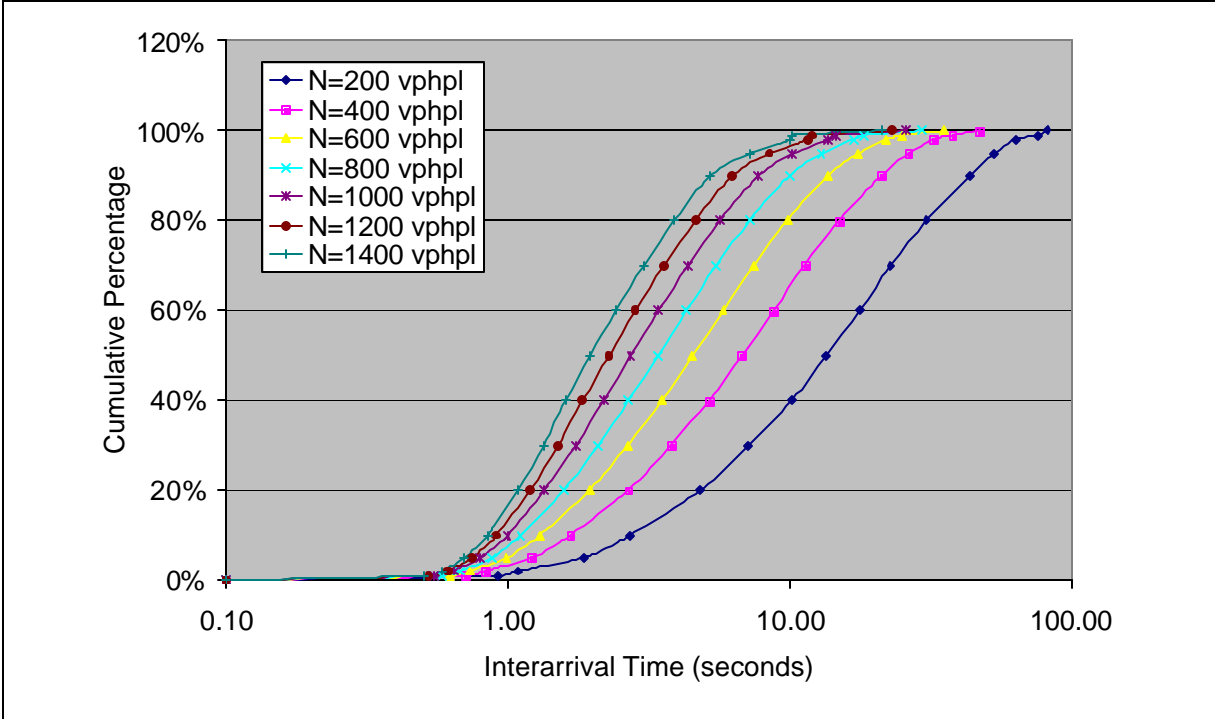




**Figure 80: Comparison of Universal Cumulative Interarrival Time Distributions for 3-Lane Freeways for a) Right Lane (Lane 1) (Cumulative IAT Distribution Range= 200-1800 vphpl), b) Lane 2 (Cumulative IAT Distribution Range= 200-1550 vphpl), and c) Lane 3 (Cumulative IAT Distribution Range= 150-1650 vphpl)**

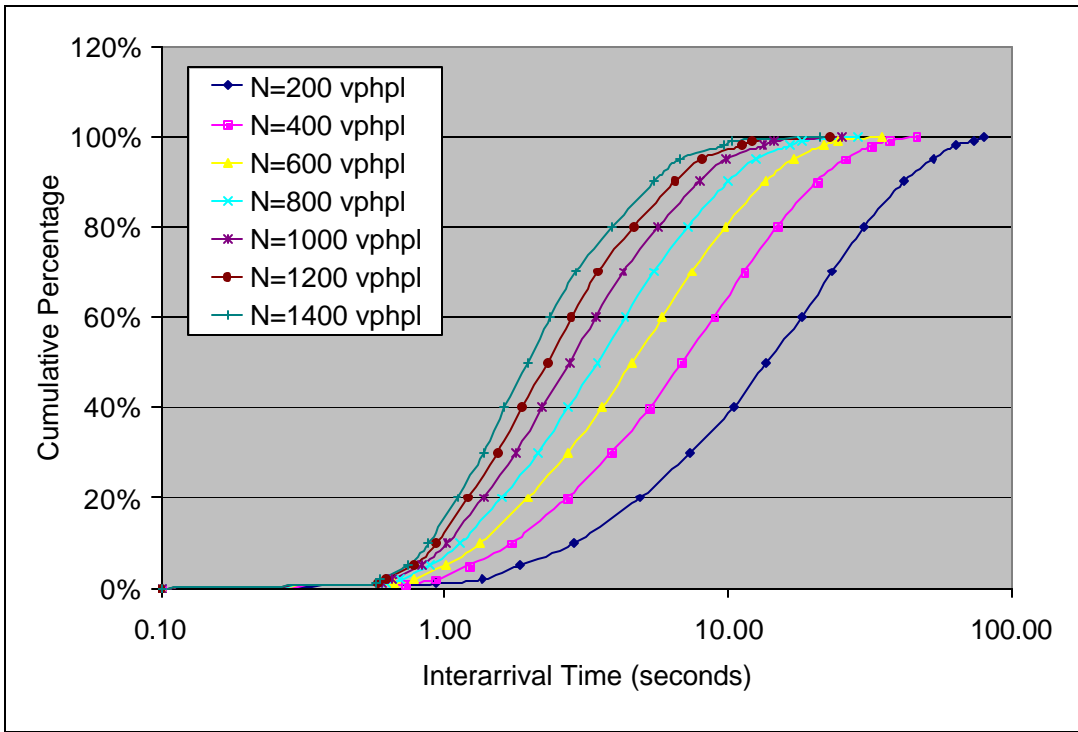


a

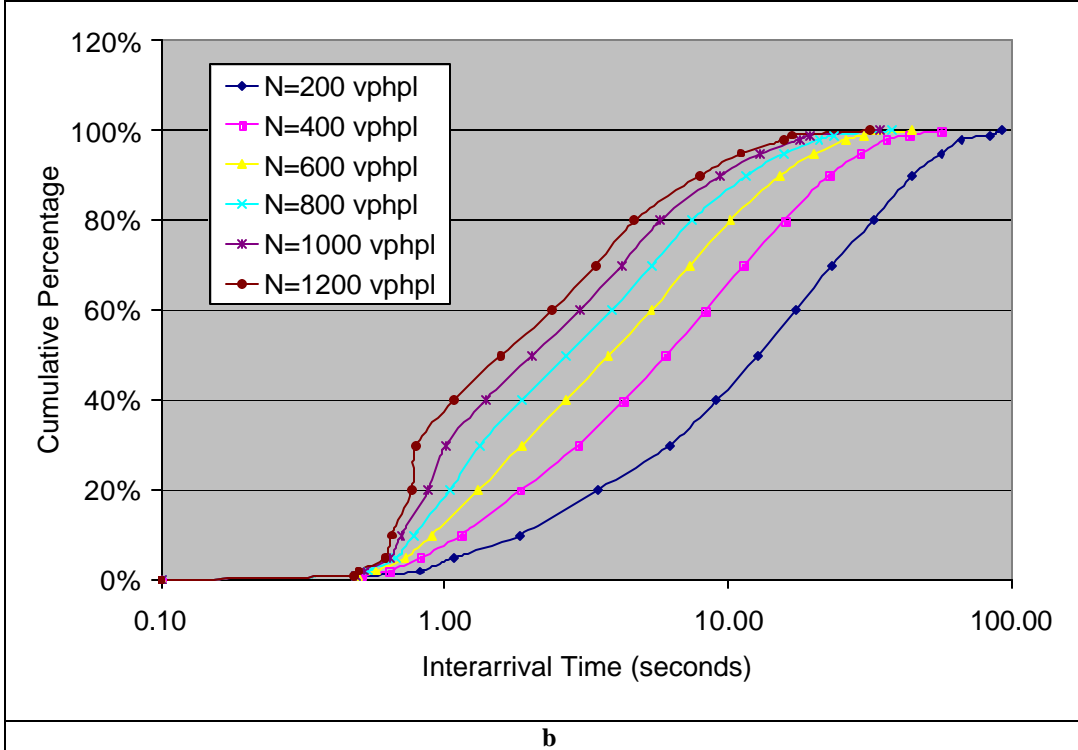


b

**Figure 81: Comparison of Universal Cumulative Interarrival Time Distributions for 4-Lane Freeways for a) Right Lane (Lane 1) (Cumulative IAT Distribution Range= 100-1150 vphpl) b) Lane 2 (Cumulative IAT Distribution Range= 150-1400 vphpl)**



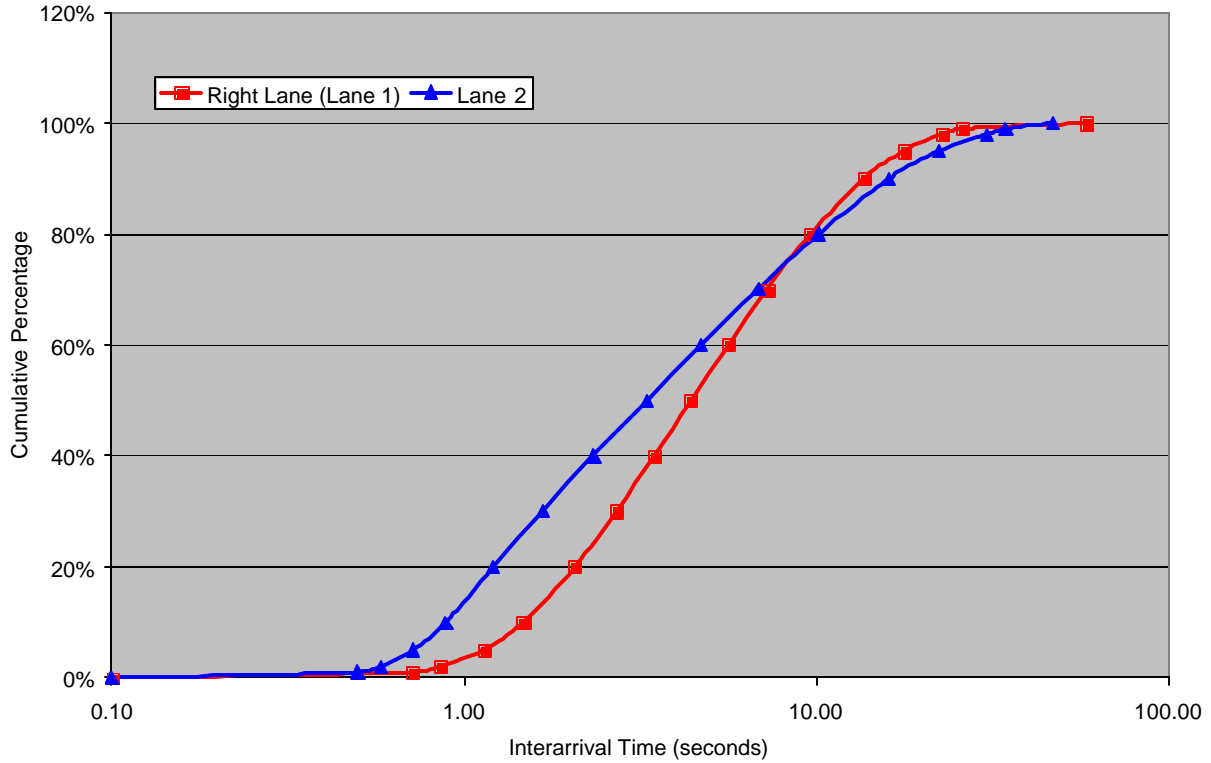
a



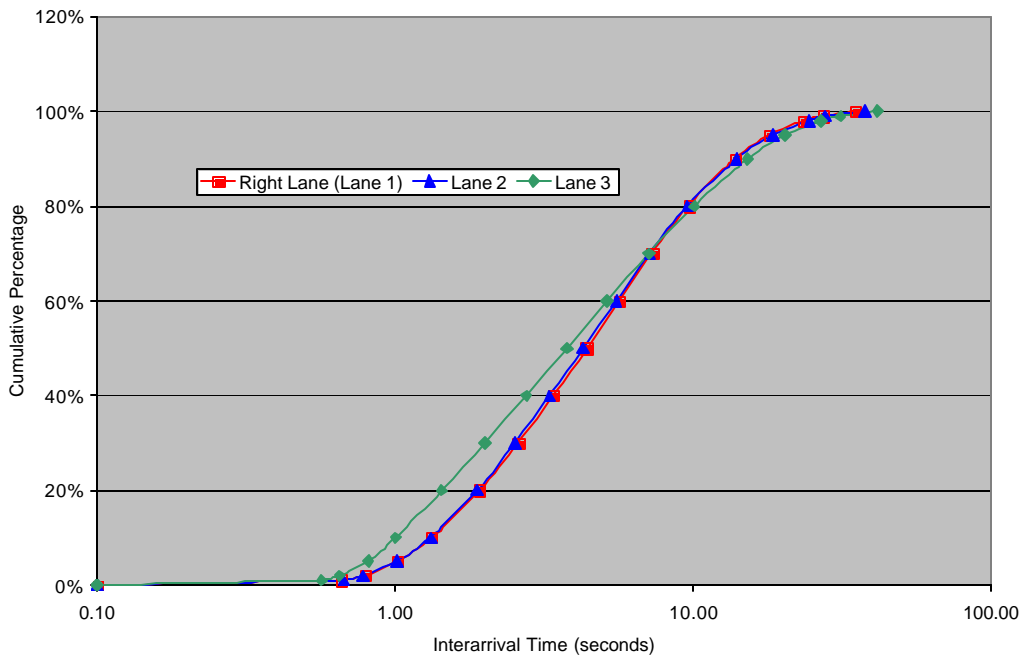
b

**Figure 82: Comparison of Universal Cumulative Interarrival Time Distributions for 4-Lane Freeways for a) Lane 3 (Cumulative IAT Distribution Range= 100-1400 vphpl) b) Lane 4 (Cumulative IAT Distribution Range= 100-1300 vphpl)**

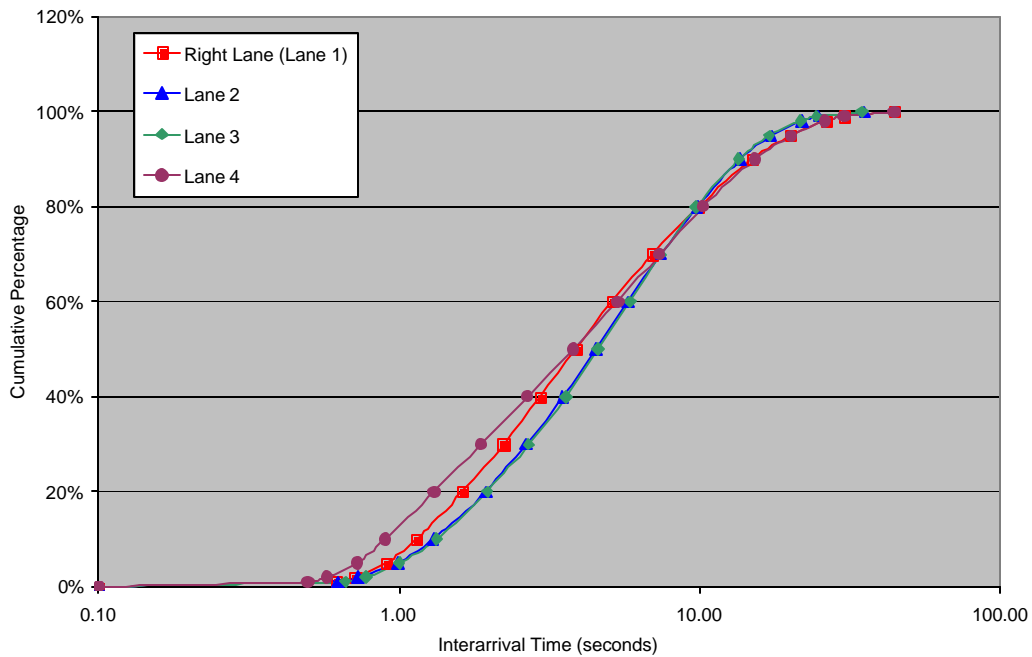
In Figure 83, Figure 84, and Figure 85, cumulative IAT distributions generated with the universal distributions for freeways with different number of lanes are compared according to the lane of travel for a selected hourly traffic volume of 600 vphpl.



**Figure 83: Comparison of Universal Cumulative Interarrival Time Distributions for 2-Lane Freeways for Right Lane (Lane 1) and Lane 2 (N=600 vphpl)**



**Figure 84: Comparison of Universal Cumulative Interarrival Time Distributions for 3-Lane Freeways for Right Lane (Lane 1), Lane 2, and Lane 3 (N=600 vphpl)**



**Figure 85: Comparison of Universal Cumulative Interarrival Time Distributions for 4-Lane Freeways for Right Lane (Lane 1), Lane 2, Lane 3, and Lane 4 (N=600 vphpl)**

## 4. CONCLUSIONS

### 4.1. Work Zone Design Guidelines

In this study we have reviewed ODOT work zone design guidelines and the literature to investigate and improve work zone safety. We have also performed nationwide and ODOT District surveys to evaluate work zone design guidelines and find out innovative work zone safety improvement applications. Based on the evaluation of ODOT work zone guidelines contained in the OMUTCD, TEM, CMS, and SCD and the comparison of these specifications with the practices of other state DOTs, literature and product reviews, and anecdotal evidence, the following recommendations can be made to improve the work zone guidelines:

**General:** it would be more convenient for practitioners to have all guidelines and specifications gathered into a single work zone practices handbook. Perhaps an electronic version on the world wide web would be the most flexible in terms of cross-linking references to appropriate contexts. Updates can be performed on a quarterly basis as is currently done for the TEM. A set of road construction clip art may be useful in the place of some of the standard construction drawings. It is also recommended that ODOT guidelines should reflect the federal Manual of Uniform Traffic Control Devices except where scientific research has proven the MUTCD guidelines to be inadequate and more restrictive standards are needed.

**Signing materials:** The use of fluorescent orange sheeting materials for work zone traffic control devices is not sufficiently emphasized in the guidelines. These materials have a higher conspicuity and make TCDs more effective in communicating their information. Therefore the existing guidelines have to be modified to indicate that fluorescent orange sheeting materials are 'preferable' for all TCDs used in work zones. It has also been found through research that Type IX reflective sheeting material is best when higher legibility is required at a shorter distance. Using Type IX material with other types of reflective sheeting materials will enhance the effectiveness of the TCDs by making them legible from both long and short distances. Therefore it would be beneficial to include this material in the list of reflective materials specified for TCDs. Research has indicated that due to the asymmetrical nature of prismatic retroreflective materials, orientation and rotation angles affect performance; the present ODOT specifications for reflective materials only include the observation and entrance angles. Including specifications for orientation and rotation angles will help increase the effectiveness of the retroreflective traffic signs and other TCDs used in work zones.

**Portable changeable message signs** (variable message signs): PCMSs can be used for many applications in addition to those outlined in the ODOT guidelines to improve operations in construction zones. Using PCMSs to provide real time driver delay and alternate route information (in addition to using for route diversion) ahead of a work zone will ensure efficient flow of work zone traffic and minimize the delay for motorists as some of them may choose the alternate route(s) suggested. PCMSs can also be used to provide drivers information on weather related road conditions to assure the highest possible safety of drivers and construction workers. PCMSs are also used in many states with radar units for speed control by displaying warning messages. They have also been used together with photo-radar techniques. Units with photo-radar PCMSs may be perceived as more threatening to drivers because vehicle license plate

numbers could be identified and displayed with the warning message. These are several other applications of PCMSs that can be considered for use in work zones and for possible inclusion in the ODOT guidelines.

**Arrow panels:** ODOT guidelines for arrow panels contained in the 1999 OMUTCD and the TEM contradicted each other with respect to the modes of operation. The modes indicated in the TEM are compliant with those in the Federal MUTCD. It was recommended that corrections be made to the OMUTCD so that the specifications are consistent with these other documents. ODOT should consider minimizing the use of flashing caution modes for arrow signs, simply leaving signs off when no lanes are closed. This revision was incorporated into the current 2003 OMUTCD. A minimum spacing of 1000 ft (305 m) between arrow panels on freeways was recommended for use in Ohio; the revised 2003 OMUTCD includes guidance that states where speed meets or exceeds 50 mph that the minimum taper length L should be 300 ft (90 m), making the separation between arrow panels at least 900 ft (270 m), which is probably adequate.

**Drums:** The ODOT specifications for drum spacing are consistent with those recommended by the MUTCD and used by many other states. However to ensure that they are effective as channelization devices in a work zone, these distances must always be maintained. The guidelines also ought to emphasize that drums shall be clean and free from dust or other work zone debris to ensure conspicuity at all times. Placing directional arrows on the drums or using direction indicator barricades could further enhance guidance through a work zone.

**Rumble strips:** Continuous shoulder rumble strips are often used to reduce drift-off-road accidents by getting driver attention. Extending the application of rumble strips to the roadway edge lines and centerlines in construction zones would help provide a distinct warning sound and vibration when the drivers drift away from the lane. Rumble strips would ensure increased driver and worker safety, and they could be considered for inclusion in the ODOT work zone guidelines.

**Regulatory, warning and guide signs:** There are several signs that can be included in the ODOT guidelines in order to make work zones safer. These include innovative signs such as “Thank You for Your Patience”, signs with website where up-to-date project information can be found, signs with a 1-800 number for driver comments, and other signs to ensure driver compliance with work zone regulations, particularly reduced speed limits. One sign that is found in Ohio work zones, but which is not very effective, is the “Resume Legal Speed” sign. In order to be effective this sign should be either re-phrased or erected together with (or substituted with) a speed limit sign. The “Fines Doubled” signs are often ineffective in regulating speed in work zones due to fines not being properly imposed. Using PCMSs with photo-radar units is a more effective means of speed regulation because the fine as well as information such as the vehicle license plate number can be displayed immediately. All work zone traffic signs with worded legends should be increased by 6” so that they are easily readable. Therefore signs that are 30”x30”, 36”x36”, and 48”x48” should be increased to 36”x36”, 42”x42”, and 54”x54” respectively. It is also recommended that word messages be made simpler where possible. Ohio law may have to be changed to enable the usage of these sign suggestions.

**Dynamic late merge:** An innovative merge technique, such as the late merge or Indiana lane merge should be evaluated for its potential to reduce queue lengths and/or delays in Ohio.

**Speed control:** Speed control can be improved with one of three levels of increased awareness. Level one consists of a statistics board indicating how many drivers obey the speed limit, tripling fines, and increased enforcement. Level two includes active feedback through fixed radar reporting the motorist's speed to the motorist. Level three includes automatic camera enforcement. A second pair of speed limit signs, one on each side of the road, could be placed one-half mile downstream from the first set of speed limit signs. Speed limit signs longitudinally spaced on both sides of the road throughout the work zone could be combined with transverse rumble strips. A speed limit sign equipped with amber flashers at the top and bottom may be used for the speed control in work zone. These flashers would be operated only when there is actually construction work going on and the reduced speed limit is effective.

**Worker safety and clothing:** Work zones could be equipped with an infrared intrusion device to provide advance warning of errant drivers. We recommend that all workers wear clothing made from florescent yellow-green retroreflective material that is visible at a minimum distance of 1,000 feet (305 m). The retroreflective clothing shall be designed to identify clearly the wearer as a person and be visible through the full range of body motions. To make the full range of body visible, the motion of worker's arms and legs should be visible, for instance by including elastic forearm and lower leg sleeves. The clothing should also be designed for use in both dry weather and wet weather, and for use in both daytime and nighttime conditions. Retroreflective hard hats should be required at all times and the hard hats should be clearly visible from all sides. Workers shall receive extensive training in the use of the clothing. Furthermore, construction equipment should include conspicuous retroreflective markings on all sides for enhanced daytime and nighttime visibility.

**Flaggers:** In advance of a flagger, signs must be placed at the right distance, at most 600 feet (183 m), in advance of a flagger at night. The flagger must be visible from the last flagger symbol sign. A graphic stopped traffic sign similar to that used in Switzerland could also be adopted. In addition to ODOT guidelines, STOP/SLOW sign paddles must have flashing lights at the top and bottom. This makes them more visible and ensures immediate recognition by drivers. The signs might be equipped with rechargeable gel batteries, which can be switched on when necessary. The batteries might be located at the rigid handle.

**Glare and visibility screens:** To shield 95% of large van and bus drivers from the glare of headlights of oncoming large vans and buses, the total height of the separator should be 70 inches (178 cm). This height will also protect drivers of other types of vehicles from all normal headlight configurations, e.g. compact car from large van or bus. This height may be obtained by adding a 20-inch (51 cm) glare screen onto a 50-inch (127 cm) portable concrete barrier or a 38-inch (97 cm) glare screen onto a 32-inch (81 cm) portable concrete barrier. However a 32-inch (81 cm) portable concrete barrier along with 38-inch glare (97 cm) screens are less effective in preventing large SUV's, pick-ups, trucks, buses, and other large vehicles from running over the barriers. Temporary concrete barriers are recommended to be 50 inches (127 cm) high in order to be effective for large vehicles. In addition to reducing headlight glare from oncoming motor vehicle traffic, glare screens can improve the delineation. To achieve this purpose glare screens



should be equipped with reflective stripes as well as with prismatic reflectors. These glare screens will also shield work activities from drivers, reducing rubbernecking and associated accidents. Furthermore the screens used in the work zone can also help contain the work area and reduce the accumulation of dust and debris on the pavement and passing vehicles.

**Work zone illumination:** One suggestion that could be used to cut down on glare for drivers from work site illumination is to have the contractor or a state official drive through the work zone in both directions at night, and then report their findings back by email immediately to the ODOT Office of Traffic Engineering. Work zone illumination should always be directed towards the work area and away from traffic in both directions.

**Materials and hardware:** AASHTO's *Quality Standards for Work Zone Traffic Control Devices* should be strictly adhered to in work zones.

**Ramp closures and metering:** It is necessary to develop a methodology that can be used to determine if and when a ramp can be closed to facilitate work zone operations. Ramp meters can be evaluated for their use in work zones. Guidelines for ramp closures and metering will be more fully investigated in Phase II of this research project.

**Entrance ramp configurations:** It is important to design ramp and side street entrances to work zones so that drivers can easily see mainline traffic, either with a 90 degree approach angle or a parallel merge lane sufficient to accommodate two tractor-trailers. Minimum acceleration lane lengths are discussed separately below.

**Pavement markings:** Nothing is related specifically to crossover sections where driver guidance at night under wet weather conditions is especially important. The specifications indicate general use materials rather than special wet weather materials. There are new wet weather pavement marking materials available today such as 3M 750 Tape which may be used to assure that the intended vehicle path is clearly defined during nighttime wet weather conditions. In the lane shift sections of construction work zones, regular paint and beaded pavement marking (for daytime visibility) plus raised pavement markers should be used in order to provide better guidance to drivers through the work zone. Raised pavement markers with larger entrance and observation angles would be better for entrance and exit ramps or curves with small radii since the markers are not required to be seen at distance up to 1000 ft (305 m) or more. ODOT should prepare an evaluation plan and the evaluation modification has to have the objective to determine which among a number of selected pavement marking and/or RPM treatments (up to five) would most effectively provide night time wet weather delineation. Maybe if wearability can be improved, bendable vertical plastic yellow or white surface markers with a retroreflective horizontal stripe spaced at 10 feet (3.0 m) intervals may be also usable in lieu of paint and beads and rigid plastic RPMs. When raised pavement markings are used, it is imperative that the contractor inspect RPMs and replace broken markings on a daily basis. Directional arrows on pavement in the center of lanes in work zones should enhance traffic flow; half-size arrows may be considered to save on material costs and wear.

**Curve radii:** The curve radii standards in the ODOT manuals appear to be adequate for present use.

**Public Education:** It is recommended that the treatment of work zones in the *Digest of Ohio Motor Vehicle Laws* be substantially increased, including information on the nature of hazards to workers and drivers in a construction zone and the law that fines are doubled (or tripled if another recommendation of this report is implemented). Drivers should be informed of the necessity to choose safety over speed in work zones.

It should be noted that some of these recommendations may eventually be modified depending on the results of the computer simulations performed in Phase II of this research project. Also, some of these recommendations may require evaluation in future research studies prior to implementation to verify their effectiveness.

#### **4.2. Work Zone Data Collection and Analysis**

The system developed to collect work zone data is intended for four uses: traffic counts, timestamped vehicle arrival records, speed measurements, and vehicle classification. Traffic counts can be determined by counting vehicles from the timestamped vehicle record. The timestamp for each arriving vehicle is highly accurate and reliable. The system values agree very well with the times recorded on the video tape, and the arrival times matching quite well. The only problem is the number of phantoms and misses which are seen, and if the trailer is properly set up and calibrated these are generally under 5%, and often well under. Some misses are inevitable since a large truck in a near lane can conceal a small car in a far lane. The timestamped data allow a reasonably accurate cumulative interarrival time distribution to be measured. Comparing the moving average speeds recorded with those derived from ORITE measured data, the overall average values are fairly close. The running average speed is also used to determine the length of a vehicle, so inaccuracies in the speed propagate into the length measurement. However the comparison of percentages of vehicles under or equal to 40 feet (12.2 m) and over 40 feet (12.2 m) with the ORITE video record showed fairly accurate results, in which the difference was less than 5% in most cases. The system developed in this project has the advantage of providing a portable and flexible non-intrusive traffic measurement option.

We have developed an easy to use and nearly automatic method to convert hourly traffic volumes into corresponding cumulative IAT distributions for 2, 3, and 4 lane freeways in Ohio. One might ask whether or not the conversion method developed in this study is important and useful? Most existing mathematical models for headways, such as the ones based on the Poisson or Erlang distributions, do not model IAT distributions observed on freeways very closely. The conversion approach presented here, using a least squares fit approach to get the best relationship between the cumulative IATs and the hourly traffic volumes has been implemented in an easy-to-use Excel spreadsheet which works quite well and appears to provide reasonably accurate cumulative IAT distributions which can then be used in stochastic queuing model simulations to investigate traffic bottlenecks in work zones with lane closures. The Cumulative IAT Distribution spreadsheets for freeways with different number of lanes may be downloaded at <http://webce.ent.ohiou.edu/orite/CumulativeIATDistributions.html>. The study also investigated the portability of the cumulative IAT distributions for a given traffic volume, traffic lane, and freeway configuration for different freeway locations in Ohio. The IAT distribution comparison included 2-lane freeways and 3-lane freeways at different freeway locations in Ohio and found

that the IAT or headway distributions for different freeway locations in Ohio are nearly the same for similar hourly traffic volumes. The analysis showed that we have established sufficient portability and scalability method to convert hourly traffic volumes into interarrival time distributions applicable within the given volume ranges on freeways in Ohio.

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## **Appendix A. Surveys of Ohio Districts and of States and Canadian Provinces and Territories**

Includes

ODOT District Survey cover letter

ODOT District Survey Questionnaire

List of contacts in each ODOT District

State and Canadian Provinces and Territory Survey cover letter

State and Canadian Provinces and Territory Survey Questionnaire

State DOT contacts

Canadian Province and Territory contacts

## Email Questionnaire for the Survey of ODOT Districts

### Cover Letter:

Dear Sir/Madam,

Your name was referred to us by Mack Braxton from Office of Traffic Engineering at the Central ODOT office in Columbus as the Work zone Manager in your district. We at the Ohio Research Institute for Transportation and the Environment (ORITE) Human Factors and Ergonomics Laboratory at Ohio University are conducting a research project " **Improved Work Zone Design Guidelines and Enhanced Model of Travel Delays in Work Zones** " for the Ohio Department of Transportation (ODOT) and we have a few questions we would like to ask you.

We are considering the development of a Monte Carlo computer simulation program to simulate the traffic, vehicle queues and delay times in work zones. Your input will help us in setting up the parameters for the simulation program.

We will really appreciate your inputs.

### Questionnaire:

#### ODOT Districts Survey Questions

1. Looking at the next 5 to 10 years what is the maximum and most typical number of traffic lanes where you would expect a reduction in the number of lanes or a reduction in the width of the lanes in the work zone?

Maximum number of lanes \_\_\_\_\_

Most typical number of lanes \_\_\_\_\_

2. Looking at the next 5 to 10 years please indicate the frequency of the following reduction in number of lanes in a work zone for extended periods of time (weeks, months) based on the key provided below. Select only the most appropriate for each line.

1. Frequently   2. Often   3. Sometimes   4. Rarely   5. Never

2 lanes reduced down to 1 lane \_\_\_

3 lanes reduced down to 2 lanes \_\_\_

3 lanes reduced down to 1 lane \_\_\_

4 lanes reduced down to 3 lanes \_\_\_

4 lanes reduced down to 2 lanes \_\_\_

4 lanes reduced down to 1 lane \_\_\_

5 lanes reduced down to 4 lanes \_\_\_

5 lanes reduced down to 3 lanes \_\_\_

5 lanes reduced down to 2 lanes \_\_\_

6 lanes reduced down to 5 lanes \_\_\_

6 lanes reduced down to 4 lanes \_\_\_

6 lanes reduced down to 3 lanes \_\_\_

3. Looking at the next 5 to 10 years please indicate the frequency of the following for extended periods of time (weeks, months) based on the key provided below. Select only the most appropriate for each line.

1. Frequently 2. Often 3. Sometimes 4. Rarely 5. Never

- 2 lanes with crossover (No number of lane reduction)\_\_\_\_
- 2 lanes (No number of lane reduction) with reduction in width of lanes \_\_\_\_
- 3 lanes with crossover (No number of lane reduction)\_\_\_\_
- 3 lanes (No number of lane reduction) with reduction in width of lanes \_\_\_\_
- 4 lanes with crossover (No number of lane reduction)\_\_\_\_
- 4 lanes (No number of lane reduction) with reduction in width of lanes \_\_\_\_
- 5 lanes with crossover (No number of lane reduction)\_\_\_\_
- 5 lanes (No number of lane reduction) with reduction in width of lanes \_\_\_\_
- 6 lanes with crossover (No number of lane reduction)\_\_\_\_
- 6 lanes (No number of lane reduction) with reduction in width of lanes \_\_\_\_

4. Looking at the next 5 to 10 years what is the maximum and typical number of exit ramps that you would expect in a work zone in your district?

Maximum number of exit ramps \_\_\_\_\_  
Most typical number of exit ramps \_\_\_\_\_

5. Looking at the next 5 to 10 years what is the maximum and typical number of entrance ramps that you would expect in a work zone in your district?

Maximum number of entrance ramps \_\_\_\_\_  
Most typical number of entrance ramps \_\_\_\_\_

6. Looking at the next 5 to 10 years what do you expect would be the maximum and typical length of a work zone where a reduction in the number of lanes or a crossover exists?

Maximum length \_\_\_\_\_ miles  
Typical length \_\_\_\_\_ miles

7. Looking at the next 5 to 10 years what do you expect would be the minimum and most typical width of a reduced lane in a work zone?

Minimum width of the reduced lane \_\_\_\_\_ feet  
Typical width of the reduced lane \_\_\_\_\_ feet

8. Looking at the next 5 to 10 years do you have any criteria in your district for closing entrance ramps? If yes please explain.

9. Looking at the next 5 to 10 years do you have any criteria in your district for closing exit ramps? If yes please explain.

10. Looking at the next 5 to 10 years would you recommend opening the entrance ramp access during periods of low mainline traffic in work zone areas?

11. What can be done to improve entrance and exit ramp operations in work zones? Please explain.

## List of Personnel Contacted – ODOT District Contacts

District #	Name	Designation	E-mail	Phone
1	Eric Pfenning	Work Zone manager	<a href="mailto:Eric.Pfenning@dot.state.oh.us">Eric.Pfenning@dot.state.oh.us</a>	2-8025 Ext 281
2	Joe Rutherford	Work Zone manager	<a href="mailto:Joe.rutherford@dot.state.oh.us">Joe.rutherford@dot.state.oh.us</a>	2-4660 Ext 4471
3	Larry Stormer	Work Zone manager	<a href="mailto:Larry.Stormer@dot.state.oh.us">Larry.Stormer@dot.state.oh.us</a>	(419) 207-7092
4	Lisa Jaynes	Work Zone manager	<a href="mailto:Lisa.jaynes@dot.state.oh.us">Lisa.jaynes@dot.state.oh.us</a>	(330) 786-4817
5	Brain Bosch	Work Zone manager	<a href="mailto:Brain.bosch@dot.state.oh.us">Brain.bosch@dot.state.oh.us</a>	2-8290 Ext 5186
6	Lisa Zigmund	Work Zone manager	<a href="mailto:Lisa.zigmund@dot.state.oh.us">Lisa.zigmund@dot.state.oh.us</a>	2-2590 Ext 340
7	Phil Stormer	Work Zone manager	<a href="mailto:Phil.stormer@dot.state.oh.us">Phil.stormer@dot.state.oh.us</a>	(937) 497-6887
8	Walter Bernau	Work Zone manager	<a href="mailto:Walter.bernau@dot.state.oh.us">Walter.bernau@dot.state.oh.us</a>	(513) 933-6518
9	Greg Baird	Work Zone manager	<a href="mailto:Greg.baird@dot.state.oh.us">Greg.baird@dot.state.oh.us</a>	2-3999 Ext 208
10	Gregory Wright	Work Zone manager	<a href="mailto:Gregory.wright@dot.state.oh.us">Gregory.wright@dot.state.oh.us</a>	(740) 373-0212 Ext 402
11	Mark Davis	Work Zone manager	<a href="mailto:Mark.davis@dot.state.oh.us">Mark.davis@dot.state.oh.us</a>	(330) 339-6633 Ext 7809
	Bobby Taylor	Work Zone manager	<a href="mailto:Bobby.taylor@dot.state.oh.us">Bobby.taylor@dot.state.oh.us</a>	Ext 3974
12	Dennis O*Neil	Work Zone manager	<a href="mailto:dennis.oneil@dot.state.oh.us">dennis.oneil@dot.state.oh.us</a>	(216) 581-2100 Ext 373

## States and Canadian Provinces and Territories Email Questionnaire

### Cover Letter:

Dear Sir/Madam,

We at the Ohio Research Institute for Transportation and the Environment are currently engaged in a research project to propose improved work zone guidelines for the Ohio DOT. As part of this research, we are conducting a survey of work zone best practices to investigate the design guidelines, present research/evaluations on the subject, reports and other publications etc.

A questionnaire with a few questions that we would like to have answers for is attached to this email.

We would appreciate if you could assist us by answering these questions, as they apply to your agency.

**The questionnaire itself appears on next page:**

**Ohio Research Institute for Transportation and the Environment**  
**Survey of Work Zone Best Practices**

We are searching for innovation measures that used to ensure that drivers are properly guided as they approach and travel through work zones.

What type of night illumination in addition to the pre-existing roadside lighting is used?

What types of delineation devices are used? How effective are they during the daytime and nighttime?

Do you use directional pavement arrows in the center of the lane? If not, do you think placing directional pavement arrows in the center of the lane would help to guide drivers better through the work zone?

What measures, if any, have you taken to improve the visibility of construction barrels at night? What is the spacing between the barrels? What do you think of placing additional directional arrows on barrels to guide drivers?

What type of retroreflective sheeting material is used on traffic control devices (TCDs) in work zones?

Has your state used or experimented with any innovative TCDs for work zones? Which, if any, were successful in work zone traffic control? If not, why were they unsuccessful?

How do you ensure that drivers abide by traffic or speed regulations in work zones? Is the 'Fines Doubled' policy in work zones strictly enforced? Have implementation and enforcement of double fines succeeded in making work zones safer? What other regulatory and/or enforcement measures have you implemented in work zones and did they succeed or fail?

What TCDs have you found to be most effective during the daytime? What are most effective during the nighttime?

We are also interested in determining how to best provide for the maximum safety of drivers traveling through a work zone.

Do you use glare screens to limit automobile and/or construction glare? What is the height of the Jersey barrier used in your state (if any)? What is the height of the glare screen above the Jersey barrier? Have you considered using glare screens to obscure construction activities from passing traffic?

What acceleration lane lengths are used for entrance ramps within work zones? Do they depend on the work zone speed limit?



What are your criteria for closing or maintaining an entrance ramp within a work zone? How does this relate to your policies on maintenance of traffic?

Are the pavement markings (PMs) used visible during nighttime and wet weather conditions? If so, how do you ensure that they remain visible under these conditions? Do you use paint or tape for PMs? What is the width of the PMs used in work zones?

We are interested in how to ensure the most efficient setup of TCDs within a work zone.

Do you use standard work zone drawings to describe the setup of TCDs in a work zone?

How do you ensure that the placement of TCDs provides for the efficient flow of traffic through the construction zone?

Do you use any automated/computerized system for standard deployment of TCDs? If so, what do you use? If not do you think such a system would be useful?

We appreciate your cooperation in conducting this survey.  
Thank You!

### List of Personnel Contacted – State Departments of Transportation

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