Phase II – Improved Work Zone Design Guidelines and Enhanced Model of Traffic Delays in Work Zones

Part I: Development of Digital Computer Simulation Model
Part II: Baseline Free-Flow Measurements for Diversion Analysis after Construction
Part III: Development of Design Guidelines for Entrance (including Ramp Metering) and Exit Ramps

Helmut T. Zwahlen and Erdinc Oner

for the
Ohio Department of Transportation
Office of Research and Development

and the
Federal Highway Administration

State Job Number 134270

Final Report – March 2009

OHIO UNIVERSITY
Ohio Research Institute for Transportation and the Environment

1. **Report No.**
FHWA/OH-2009/2

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Phase II - Improved Work Zone Design Guidelines and Enhanced Model of Travel Delays in Work Zones

5. Report Date
March 2009

6. Performing Organization Code

8. Performing Organization Report No.

7. Author(s)
Helmut T. Zwahlen and Erdinc Oner

9. Performing Organization Name and Address
Ohio University
Human Factors and Ergonomics Laboratory
Ohio Research Institute for Transportation and the Environment
Russ College of Engineering & Technology
Athens, Ohio 45701-2979

10. Work Unit No. (TRAIS)

11. Contact or Grant No.
State Job No.134270

12. Sponsoring Agency Name and Address
Ohio Department of Transportation
1980 West Broad Street
Columbus, OH 43223

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract
This project contains three major parts. In the first part a digital computer simulation model was developed with the aim to model the traffic through a freeway work zone situation.
The model was based on the Arena simulation software and used cumulative interarrival times as the input. Its aim was to determine the traffic volumes through the work zone and the queue lengths in advance of lane restrictions. The program was designed to handle up to 15 miles in length, up to six lanes, and up to 20 entrance and exit ramps. The developed program has not been validated due to the lack of reliable field data and the program appears to produce unreasonably short queue lengths and low exit ramp traffic counts compared to the input traffic data for cases where the exit ramps are spaced closely together.
In the second part a diversion analysis was performed to determine the effects of closed ramps. The work zone sites were assigned by Ohio Department of transportation and the diversion effects for these situations were in one case very minimal and in the other case as expected (traffic shifted to the next open exit ramp).
In the third part guidelines for ramp management and ramp metering were established on a 24/7 basis giving special considerations to freeway mainline throughput and local traffic access to freeway.

17. Key Words
Work zone, digital traffic simulation, headways, interarrival times, diversion analysis, ramp management strategies, ramp metering strategies, entrance and exit ramps, local traffic access, freeway mainline throughput, traffic volumes,

18. Distribution Statement
No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	201	

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

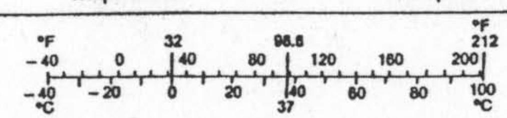
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

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



* SI is the symbol for the International System of Measurement

(Revised April 1989)

Phase II – Improved Work Zone Design Guidelines and Enhanced Model of Traffic Delays in Work Zones

Part I: Development of Digital Computer Simulation Model
Part II: Baseline Free-Flow Measurements for Diversion Analysis after Construction
Part III: Development of Design Guidelines for Entrance (including Ramp Metering) and Exit Ramps

Prepared in cooperation with the

Ohio Department of Transportation
Office of Traffic Engineering

Prepared by

Human Factors and Ergonomics Laboratory
Ohio Research Institute for Transportation and the Environment
Russ College of Engineering and Technology
Ohio University
Athens, Ohio 45701-2979

Final Report
March 2009

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 graduate students Kiran Suravaram and Housila Tiwari who worked on the work zone data collection, work zone data analysis.

We also thank David Holstein, Administrator of the Office of Traffic Engineering, and Mack Braxton, Ken Linger, Reynaldo Stargell, Jennifer Gallagher, Marian Thompson, and George Saylor of the ODOT Office of Traffic Engineering for their technical and logistical support. We also thank Monique Evan s, Administrator of the Office of Research and Development, and Vicky Fout and Wendy Snyder of the ODOT Office of Research and Development for their administrative support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Work zones on heavily traveled divided highways or freeways may present problems to motorists in the form of traffic queues, 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.

In Phase I of this project sufficient portability and scalability was established to convert hourly traffic volumes into interarrival time (IAT) distributions (Phase I - Improved Work Zone Design Guidelines and Enhanced Model of Travel Delays in Work Zones [1]). Scalability means that the IAT distributions can be generated with reasonable accuracy from hourly traffic volumes. Portability implies that IAT distributions have a similar form for different locations in Ohio. The IAT distributions were used in a Monte Carlo simulation model to provide information on queue lengths and delay times for work zones with reductions in the number of traffic lanes or lane width restrictions. Open exit ramps may help traffic flow by reducing traffic in the rest of the work zone, though a widely announced closure of an exit ramp may reduce traffic through the work zone to destinations through that closed exit ramp, which may also reduce traffic into the work zone.

Part I of this project outlines development of the digital computer simulation model with the aim to simulate the effects of various work zone configurations and ramp access schemes to determine the flow of traffic through the work zone and to determine the queue length and delay times.

Part II of this project outlines the measurement of the free-flow traffic after construction and the diversion analysis. Data collection methods and equipment were the same as that was used in Phase I of this project. The data analysis was limited to analyzing the traffic volumes as a function of time. Traffic data was collected for three days in Phase I (construction, some ramps closed) and in Phase II (no construction) and traffic volumes were analyzed based on 1-hour time intervals. Traffic volumes collected in Phase II were compared with the traffic data collected in Phase I and the diversion effects of the closed ramps in the construction work zones on traffic volumes were determined.

In Part III, the third part of the project a set of criteria and guidelines that can be used to determine when a ramp should be closed or metered in order to promote both adequate safety and efficient traffic operations within the work zone are provided. Two separately developed microscopic Arena traffic modeling program were used to evaluate and refine these criteria and guidelines.

2 PART I: DEVELOPMENT OF DIGITAL COMPUTER SIMULATION MODEL

The Ohio Research Institute for Transportation and the Environment (ORITE) agreed with Rockwell Automation, 2000 Ericsson Drive Warrendale, PA 15086 (www.arenasimulation.com), to develop a microscopic traffic simulation software using Arena to examine traffic flow before and through construction work zones.

ORITE has contracted Rockwell Automation to develop a reusable simulation model with animation of traffic flow before and through different construction work zone configurations to help in evaluating:

- overall throughput (counts) of traffic through the construction merge point,
- waiting time for vehicles before the merge,
- queue length of traffic, and
- the impact of ramp metering.

The Rockwell Automation was contracted to deliver functional specification, user interface, verified model, and model documentation for the digital simulation model.

The first Arena simulation program was delivered by Rockwell Automation on October 31, 2007 and the last and the seventh modified arena simulation program was delivered on June 25, 2008.

2.1 General Specifications of the ARENA Traffic Simulation Software Package Initially Prepared by ORITE

The Arena traffic simulation software package consists of fully documented users' manual and the program. The general properties of the program are listed below;

1. Fully documented source code and user manual, Beta tested.
2. Ready to implement on a fast PC (2.4 or higher MHz, more than 512 KB RAM memory)
3. Up to 6 lanes with lane reductions in work zone and/or reduced number of lanes in crossovers;
    - 2 lanes with restrictions (crossovers, narrow lanes, etc.)
    - 2 lanes down to 1 lane with restrictions
    - 3 lanes with restrictions (crossovers, narrow lanes, etc.)
    - 3 lanes down to 2 lane with restrictions
    - 3 lanes down to 1 lane with restrictions
    - 4 lanes with restrictions (crossovers, narrow lanes, etc.)
    - 4 lanes down to 3 lane with restrictions
    - 4 lanes down to 2 lane with restrictions
    - 4 lanes down to 1 lane with restrictions
    - 5 lanes with restrictions (crossovers, narrow lanes, etc.)
    - 5 lanes down to 4 lane with restrictions
    - 5 lanes down to 3 lane with restrictions
    - 5 lanes down to 2 lane with restrictions
    - 6 lanes with restrictions (crossovers, narrow lanes, etc.)
    - 6 lanes down to 5 lane with restrictions
    - 6 lanes down to 4 lane with restrictions
    - 6 lanes down to 3 lane with restrictions
4. Up to 20 entrance and exit ramps in work zone.
5. Up to 15 miles of work zone length.

6. 2 vehicle types (different acceleration and deceleration attributes for cars and trucks).
7. Capability of ramp metering analysis on mainline traffic flow.
8. Starts with free flow conditions before work zone.
9. Hourly change in arrival rates and IAT distributions for each lane

The outputs of the traffic simulation package are;

- Mainline throughput for each lane through work zone
- Queue length during the day
- Delay time during the day

Batch processing, the simulation runs for a given situation 24 hours with variable hourly vehicle volumes for each lane (ex. 100 or more times) to get mainline throughput, queue and delay results in form of a histogram.

.

2.2 Input Variables Initially Developed by ORITE

Number of traffic data variables was entered into the microscopic traffic simulation software to define the traffic system. The output of the program was generated according to these input variables. The following variables were entered in order to get the output variables. The input variables are given along with an example below.

2.2.1 Work Zone Configuration

Physical characteristics of the work zone are entered to the simulation program at this stage. The user defines the number of lanes to be simulated, the points where there might be merging, the points where traffic signs are related to traffic and affecting traffic, the points where the tapers are located. The following is an example for three-lane work zone reduced to two-lanes with five entrance and exit ramps configuration input for the simulation program.

Sample Work Zone Configuration Input:

- The length of the roadway for simulation is 10 miles.
- There are 3 lanes at the beginning of the road, no restrictions.
- At mile 0.7 first exit ramp appears.
- At mile 0.9 first entrance ramp appears with ramp metering possibility.
- At mile 2.2 second exit ramp appears.
- At mile 2.5 second entrance ramp appears with ramp metering possibility.
- At mile 2.7 first warning sign “Right Lane Closed” appears.
- At mile 2.8 second warning sign “Right Lane Closed” appears.
- At mile 2.9 third warning sign “Right Lane Closed” appears.
- At mile 3.0 transition taper begins.
- At mile 3.05 transition taper ends and the road becomes 2 lanes.
- At mile 5.6 third exit ramp appears
- At mile 6.0 third entrance ramp appears with ramp metering possibility
- At mile 8.1 fourth exit ramp appears
- At mile 8.3 fourth entrance ramp appears with ramp metering possibility.
- At mile 9.0 transition taper begins
- At mile 9.05 transition taper ends and road becomes 3 lanes again
- At mile 9.5 fifth exit ramp appears
- At mile 9.7 fifth entrance ramp appears with ramp metering possibility.
- The simulation ends at mile 10.

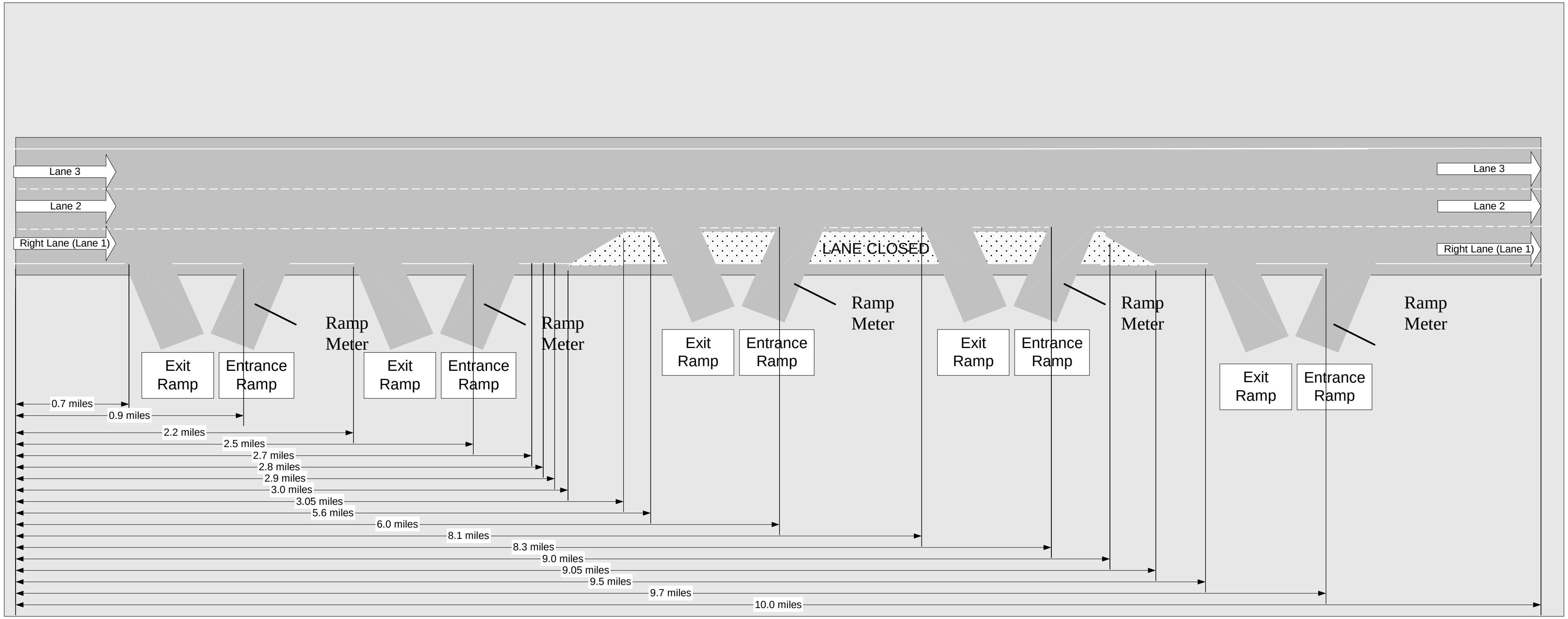


Figure 1. Typical 3-Lane Work Zone Configuration Reduced to 2 Lanes

2.2.2 Vehicle Arrival

Hourly vehicle counts for each lane for mainline before work zone, entrance ramps, and exit ramps (in percentages of the mainline traffic count) are entered by the user. The cumulative IAT distributions are then calculated using the Microsoft Excel Spreadsheets. The spreadsheets generate cumulative interarrival time distributions for given hourly traffic volumes per lane. Separate spreadsheets are used for the cumulative IAT distributions for 2-lane, 3-lane, 4-lane freeways and entrance ramps. The cumulative IAT distributions for lane 3 of 3-lane freeways can be used for non-signalized freeway entrance ramp vehicle arrivals and cumulative IAT distributions for signalized entrance ramps can be used for the signalized entrance rams as given at the URL given below. The Microsoft Excel Spreadsheets for the computation of the cumulative (IAT) distributions for a given hourly traffic volume (number of vehicles per hour per lane) within the specified traffic volume range is given at URL: http://webce.ent.ohiou.edu/orite/cumulativeIATdistributions.html. As an example the traffic volumes for 3-lane freeway and calculated cumulative IAT distributions are given in Table 1 through Table 4.

Table 1 Hourly vehicle counts for mainline before work zone

Mainline			
Time	Lane 1	Lane 2	Lane 3
0:00 - 1:00	213	378	155
1:00 - 2:00	186	300	108
2:00 - 3:00	105	166	35
3:00 - 4:00	233	277	81
4:00 - 5:00	129	199	56
5:00 - 6:00	308	435	296
6:00 - 7:00	577	839	879
7:00 - 8:00	667	970	1149
8:00 - 9:00	593	911	881
9:00 - 10:00	593	860	644
10:00 - 11:00	589	889	627
11:00 - 12:00	615	944	693
12:00 - 13:00	604	937	752
13:00 - 14:00	721	996	806
14:00 - 15:00	810	1158	1064
15:00 - 16:00	968	1299	1386
16:00 - 17:00	1088	1471	1630
17:00 - 18:00	1041	1423	1483
18:00 - 19:00	696	1049	925
19:00 - 20:00	561	942	650
20:00 - 21:00	469	765	427
21:00 - 22:00	439	689	414
22:00 - 23:00	349	589	329
23:00 - 24:00	291	468	221

Table 2 Cumulative IAT distribution table for 3-lane freeways – rightmost lane before work zone

Time	Number of vehicles per hour	Cumulative Percentage																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
0:00 - 1:00	213	0.10	0.79	0.98	1.66	2.55	4.49	6.80	9.56	12.29	16.17	20.96	28.00	41.16	52.45	70.04	73.73	90.00
1:00 - 2:00	186	0.10	0.82	1.01	1.77	2.76	4.94	7.54	10.65	13.69	18.02	23.37	31.23	45.98	58.53	78.27	81.92	99.67
2:00 - 3:00	105	0.10	0.88	1.10	2.11	3.39	6.29	9.77	13.90	17.87	23.59	30.60	40.91	60.46	76.76	102.98	106.50	128.69
3:00 - 4:00	233	0.10	0.78	0.96	1.58	2.39	4.15	6.25	8.76	11.26	14.80	19.18	25.61	37.59	47.94	63.94	67.66	82.83
4:00 - 5:00	129	0.10	0.86	1.07	2.01	3.20	5.89	9.11	12.94	16.63	21.94	28.46	38.04	56.17	71.36	95.66	99.21	120.09
5:00 - 6:00	308	0.10	0.74	0.89	1.36	1.96	3.25	4.77	6.59	8.47	11.08	14.35	19.14	27.93	35.77	47.44	51.25	63.45
6:00 - 7:00	577	0.10	0.67	0.80	1.04	1.36	1.97	2.68	3.54	4.56	5.87	7.58	10.08	14.39	18.70	24.34	28.21	36.20
7:00 - 8:00	667	0.10	0.65	0.78	0.98	1.26	1.77	2.36	3.07	3.95	5.07	6.54	8.68	12.30	16.07	20.78	24.63	31.96
8:00 - 9:00	593	0.10	0.66	0.79	1.03	1.34	1.93	2.61	3.45	4.44	5.71	7.37	9.79	13.96	18.16	23.60	27.47	35.33
9:00 - 10:00	593	0.10	0.66	0.79	1.03	1.34	1.93	2.61	3.45	4.44	5.71	7.37	9.79	13.96	18.16	23.60	27.47	35.33
10:00 - 11:00	589	0.10	0.67	0.79	1.03	1.34	1.94	2.63	3.47	4.47	5.75	7.42	9.86	14.07	18.30	23.79	27.65	35.54
11:00 - 12:00	615	0.10	0.66	0.79	1.01	1.31	1.88	2.53	3.33	4.28	5.50	7.10	9.43	13.43	17.49	22.70	26.56	34.25
12:00 - 13:00	604	0.10	0.66	0.79	1.02	1.32	1.90	2.57	3.38	4.35	5.60	7.23	9.60	13.68	17.81	23.13	26.99	34.76
13:00 - 14:00	721	0.10	0.65	0.77	0.96	1.21	1.68	2.20	2.85	3.66	4.68	6.04	8.01	11.30	14.81	19.07	22.92	29.93
14:00 - 15:00	810	0.10	0.64	0.76	0.92	1.15	1.54	1.99	2.54	3.27	4.16	5.35	7.09	9.94	13.09	16.75	20.58	27.15
15:00 - 16:00	968	0.10	0.62	0.74	0.87	1.06	1.37	1.71	2.14	2.75	3.47	4.46	5.89	8.16	10.83	13.71	17.51	23.49
16:00 - 17:00	1088	0.10	0.61	0.72	0.84	1.01	1.27	1.55	1.91	2.45	3.08	3.95	5.21	7.15	9.56	11.99	15.77	21.40
17:00 - 18:00	1041	0.10	0.62	0.73	0.85	1.03	1.31	1.61	1.99	2.56	3.22	4.14	5.46	7.52	10.02	12.61	16.40	22.16
18:00 - 19:00	696	0.10	0.65	0.77	0.97	1.23	1.72	2.27	2.95	3.79	4.85	6.25	8.30	11.74	15.35	19.81	23.66	30.81
19:00 - 20:00	561	0.10	0.67	0.80	1.05	1.38	2.01	2.75	3.64	4.69	6.04	7.80	10.37	14.82	19.25	25.08	28.94	37.07
20:00 - 21:00	469	0.10	0.69	0.82	1.12	1.52	2.31	3.23	4.35	5.59	7.25	9.37	12.47	17.96	23.21	30.44	34.30	43.41
21:00 - 22:00	439	0.10	0.69	0.83	1.15	1.58	2.43	3.43	4.64	5.97	7.75	10.02	13.34	19.26	24.84	32.65	36.50	46.03
22:00 - 23:00	349	0.10	0.72	0.87	1.28	1.81	2.92	4.23	5.81	7.47	9.75	12.61	16.82	24.45	31.39	41.51	45.35	56.48
23:00 - 24:00	291	0.10	0.74	0.90	1.40	2.04	3.41	5.04	6.98	8.98	11.75	15.22	20.31	29.67	37.97	50.43	54.22	66.96

Table 3 Cumulative IAT distribution table for 3-lane freeways – lane 2 before work zone

Time	Number of vehicles per hour	Cumulative Percentage																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
0:00 - 1:00	378	0.10	0.78	0.92	1.28	1.73	2.63	3.67	5.00	6.63	8.76	11.44	15.60	22.98	30.58	40.84	44.62	59.70
1:00 - 2:00	300	0.10	0.86	1.01	1.46	2.01	3.13	4.44	6.16	8.25	10.97	14.38	19.72	29.15	38.85	52.01	56.25	74.73
2:00 - 3:00	166	0.10	1.10	1.32	2.06	2.97	4.87	7.12	10.16	13.84	18.62	24.55	33.97	50.53	67.50	90.72	96.51	126.76
3:00 - 4:00	277	0.10	0.89	1.05	1.53	2.14	3.36	4.79	6.68	8.98	11.97	15.70	21.58	31.94	42.59	57.06	61.50	81.51
4:00 - 5:00	199	0.10	1.03	1.24	1.89	2.70	4.38	6.37	9.03	12.26	16.47	21.69	29.96	44.51	59.44	79.82	85.17	112.11
5:00 - 6:00	435	0.10	0.75	0.87	1.19	1.59	2.36	3.26	4.40	5.79	7.61	9.91	13.46	19.77	26.28	35.04	38.59	51.89
6:00 - 7:00	839	0.10	0.62	0.71	0.89	1.12	1.52	1.97	2.49	3.13	3.97	5.08	6.71	9.65	12.72	16.73	19.50	27.17
7:00 - 8:00	970	0.10	0.60	0.68	0.84	1.04	1.40	1.78	2.21	2.75	3.45	4.38	5.74	8.19	10.77	14.10	16.74	23.60
8:00 - 9:00	911	0.10	0.60	0.70	0.86	1.07	1.45	1.86	2.33	2.91	3.67	4.67	6.14	8.80	11.58	15.19	17.88	25.08
9:00 - 10:00	860	0.10	0.61	0.71	0.88	1.10	1.50	1.94	2.44	3.06	3.88	4.95	6.53	9.39	12.37	16.25	18.99	26.52
10:00 - 11:00	889	0.10	0.61	0.70	0.87	1.09	1.47	1.89	2.37	2.97	3.75	4.79	6.30	9.04	11.91	15.63	18.35	25.68
11:00 - 12:00	944	0.10	0.60	0.69	0.85	1.06	1.42	1.82	2.26	2.81	3.54	4.50	5.91	8.45	11.11	14.56	17.22	24.22
12:00 - 13:00	937	0.10	0.60	0.69	0.85	1.06	1.43	1.83	2.27	2.83	3.57	4.54	5.95	8.52	11.21	14.69	17.36	24.40
13:00 - 14:00	996	0.10	0.59	0.68	0.83	1.03	1.38	1.75	2.16	2.68	3.36	4.26	5.57	7.95	10.44	13.65	16.27	22.99
14:00 - 15:00	1158	0.10	0.57	0.66	0.79	0.97	1.27	1.59	1.92	2.34	2.90	3.65	4.72	6.68	8.74	11.36	13.87	19.86
15:00 - 16:00	1299	0.10	0.56	0.64	0.76	0.92	1.19	1.47	1.75	2.12	2.59	3.25	4.15	5.83	7.61	9.84	12.26	17.77
16:00 - 17:00	1471	0.10	0.54	0.62	0.73	0.88	1.12	1.36	1.60	1.90	2.30	2.86	3.61	5.02	6.53	8.38	10.73	15.77
17:00 - 18:00	1423	0.10	0.55	0.63	0.74	0.89	1.14	1.39	1.64	1.95	2.37	2.96	3.75	5.23	6.81	8.75	11.12	16.29
18:00 - 19:00	1049	0.10	0.59	0.67	0.82	1.01	1.34	1.69	2.08	2.56	3.19	4.04	5.26	7.49	9.83	12.82	15.40	21.86
19:00 - 20:00	942	0.10	0.60	0.69	0.85	1.06	1.42	1.82	2.26	2.82	3.55	4.51	5.92	8.47	11.14	14.60	17.26	24.27
20:00 - 21:00	765	0.10	0.63	0.73	0.92	1.17	1.61	2.11	2.69	3.41	4.35	5.58	7.41	10.70	14.13	18.63	21.48	29.74
21:00 - 22:00	689	0.10	0.65	0.75	0.96	1.23	1.72	2.28	2.94	3.75	4.82	6.21	8.29	12.01	15.89	21.00	23.96	32.96
22:00 - 23:00	589	0.10	0.68	0.79	1.03	1.33	1.91	2.56	3.36	4.35	5.63	7.28	9.79	14.26	18.90	25.07	28.20	38.45
23:00 - 24:00	468	0.10	0.73	0.85	1.14	1.52	2.24	3.07	4.12	5.40	7.08	9.20	12.47	18.29	24.29	32.35	35.78	48.26

Table 4 Cumulative IAT distribution table for 3-lane freeways – lane 3 before work zone

Time	Number of vehicles per hour	Cumulative Percentage																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
0:00 - 1:00	155	0.10	0.48	0.72	1.14	1.77	3.89	6.76	10.44	15.60	22.07	30.21	41.63	60.43	77.95	96.14	113.04	125.95
1:00 - 2:00	108	0.10	0.44	0.74	1.25	2.02	4.68	8.30	12.92	19.44	27.56	37.70	51.85	75.07	96.60	118.59	139.58	153.28
2:00 - 3:00	35	0.10	0.39	0.77	1.41	2.40	5.91	10.69	16.78	25.39	36.07	49.33	67.73	97.81	125.57	153.46	180.80	195.74
3:00 - 4:00	81	0.10	0.43	0.75	1.31	2.16	5.14	9.18	14.35	21.64	30.71	42.00	57.73	83.48	107.32	131.48	154.83	168.98
4:00 - 5:00	56	0.10	0.41	0.76	1.37	2.29	5.56	10.00	15.67	23.68	33.62	45.99	63.16	91.27	117.24	143.42	168.94	183.52
5:00 - 6:00	296	0.10	0.54	0.68	0.93	1.28	2.31	3.70	5.49	7.97	11.17	15.32	21.31	31.30	40.85	51.47	60.25	71.55
6:00 - 7:00	879	0.10	0.57	0.64	0.77	0.92	1.16	1.48	1.92	2.47	3.31	4.58	6.64	10.26	14.05	19.17	22.07	32.06
7:00 - 8:00	1149	0.10	0.57	0.63	0.75	0.87	1.02	1.21	1.49	1.81	2.37	3.30	4.89	7.76	10.85	15.30	17.50	27.27
8:00 - 9:00	881	0.10	0.57	0.64	0.77	0.92	1.16	1.48	1.91	2.46	3.30	4.57	6.62	10.24	14.02	19.13	22.03	32.01
9:00 - 10:00	644	0.10	0.57	0.65	0.80	0.99	1.38	1.89	2.58	3.48	4.76	6.56	9.34	14.15	19.00	25.15	29.13	39.40
10:00 - 11:00	627	0.10	0.57	0.65	0.81	1.00	1.40	1.93	2.65	3.59	4.91	6.77	9.63	14.56	19.52	25.77	29.87	40.17
11:00 - 12:00	693	0.10	0.57	0.65	0.79	0.97	1.32	1.78	2.40	3.21	4.37	6.03	8.63	13.12	17.69	23.56	27.26	37.46
12:00 - 13:00	752	0.10	0.57	0.65	0.79	0.95	1.26	1.67	2.22	2.94	3.97	5.49	7.88	12.05	16.33	21.93	25.33	35.45
13:00 - 14:00	806	0.10	0.57	0.64	0.78	0.93	1.22	1.58	2.08	2.72	3.66	5.07	7.30	11.22	15.27	20.64	23.81	33.87
14:00 - 15:00	1064	0.10	0.57	0.64	0.75	0.88	1.06	1.28	1.60	1.98	2.62	3.63	5.35	8.41	11.68	16.31	18.69	28.52
15:00 - 16:00	1386	0.10	0.57	0.63	0.73	0.84	0.94	1.06	1.25	1.45	1.86	2.60	3.93	6.37	9.07	13.14	14.95	24.58
16:00 - 17:00	1630	0.10	0.57	0.62	0.72	0.82	0.89	0.95	1.08	1.19	1.48	2.09	3.23	5.36	7.78	11.57	13.10	22.60
17:00 - 18:00	1483	0.10	0.57	0.62	0.73	0.83	0.92	1.01	1.18	1.34	1.69	2.37	3.62	5.93	8.50	12.45	14.15	23.72
18:00 - 19:00	925	0.10	0.57	0.64	0.77	0.91	1.14	1.42	1.83	2.33	3.11	4.31	6.27	9.73	13.37	18.35	21.11	31.05
19:00 - 20:00	650	0.10	0.57	0.65	0.80	0.99	1.37	1.87	2.55	3.45	4.70	6.49	9.24	14.00	18.82	24.92	28.87	39.13
20:00 - 21:00	427	0.10	0.56	0.67	0.86	1.12	1.79	2.68	3.84	5.43	7.54	10.36	14.54	21.60	28.49	36.59	42.66	53.39
21:00 - 22:00	414	0.10	0.55	0.67	0.87	1.13	1.82	2.75	3.96	5.61	7.79	10.71	15.01	22.27	29.35	37.63	43.88	54.66
22:00 - 23:00	329	0.10	0.54	0.68	0.91	1.23	2.15	3.37	4.97	7.17	10.02	13.75	19.15	28.21	36.92	46.74	54.66	65.78
23:00 - 24:00	221	0.10	0.51	0.70	1.02	1.47	2.92	4.87	7.39	10.90	15.35	21.03	29.10	42.47	55.08	68.60	80.50	92.42

The cumulative IAT distributions for entrance ramps were calculated using Microsoft Excel Spreadsheets. The entrance ramps were assumed to be non-signalized entrance ramps therefore cumulative IAT distributions for lane 3 of 3-lane freeways were used. Table 5 through Table 10 shows the traffic volumes at entrance ramps and the cumulative IAT distributions for these ramps.

Table 5 Hourly vehicle counts for entrance ramps

Time	Entrance Ramp 1	Entrance Ramp 2	Entrance Ramp 3	Entrance Ramp 4	Entrance Ramp 5
0:00 - 1:00	47	35	96	104	33
1:00 - 2:00	30	23	73	73	30
2:00 - 3:00	30	13	33	45	21
3:00 - 4:00	31	25	73	49	19
4:00 - 5:00	25	17	22	142	34
5:00 - 6:00	83	27	62	317	130
6:00 - 7:00	192	60	192	544	280
7:00 - 8:00	320	127	301	525	340
8:00 - 9:00	252	110	419	444	282
9:00 - 10:00	216	124	383	448	308
10:00 - 11:00	171	89	296	556	346
11:00 - 12:00	206	95	309	599	388
12:00 - 13:00	211	50	254	675	421
13:00 - 14:00	207	104	307	909	570
14:00 - 15:00	258	115	303	1289	677
15:00 - 16:00	218	151	318	1496	827
16:00 - 17:00	212	131	341	1587	934
17:00 - 18:00	157	109	309	882	420
18:00 - 19:00	123	135	287	774	263
19:00 - 20:00	104	79	250	708	214
20:00 - 21:00	96	47	146	616	182
21:00 - 22:00	86	43	146	399	141
22:00 - 23:00	79	49	99	376	118
23:00 - 24:00	59	43	123	232	75

(20% of the vehicles entering to the road travel on Lane 3, 30% of the vehicles entering to the road travel on Lane 2, 50% of the vehicles entering to the road travel on Right Lane (Lane 1)). Lane 1 is the rightmost lane, lane 2 is the middle lane, and lane 3 is the leftmost lane.

Table 6 Cumulative IAT distribution table for entrance ramp 1

Time	Number of vehicles per hour	Cumulative Percentage																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
0:00 - 1:00	47	0.10	0.67	0.82	1.41	2.34	4.74	8.08	12.89	20.18	31.03	45.22	66.18	101.47	133.48	166.88	195.57	214.95
1:00 - 2:00	30	0.10	0.68	0.84	1.46	2.43	4.98	8.51	13.60	21.31	32.80	47.80	69.95	107.21	140.95	176.04	206.38	226.20
2:00 - 3:00	30	0.10	0.68	0.84	1.46	2.43	4.98	8.51	13.60	21.31	32.80	47.80	69.95	107.21	140.95	176.04	206.38	226.20
3:00 - 4:00	31	0.10	0.68	0.84	1.45	2.43	4.96	8.48	13.55	21.25	32.70	47.65	69.73	106.87	140.51	175.50	205.75	225.54
4:00 - 5:00	25	0.10	0.69	0.84	1.47	2.46	5.05	8.64	13.80	21.65	33.33	48.56	71.06	108.90	143.15	178.73	209.57	229.51
5:00 - 6:00	83	0.10	0.65	0.79	1.32	2.13	4.24	7.17	11.39	17.78	27.28	39.76	58.20	89.30	117.67	147.51	172.67	191.14
6:00 - 7:00	192	0.10	0.59	0.70	1.03	1.52	2.73	4.42	6.85	10.50	15.92	23.21	34.03	52.47	69.78	88.83	103.32	119.05
7:00 - 8:00	320	0.10	0.54	0.64	0.86	1.16	1.84	2.80	4.19	6.25	9.29	13.54	19.91	30.95	41.78	54.49	62.75	76.75
8:00 - 9:00	252	0.10	0.56	0.66	0.93	1.30	2.19	3.43	5.23	7.91	11.88	17.31	25.43	39.36	52.72	67.91	78.60	93.31
9:00 - 10:00	216	0.10	0.57	0.68	0.98	1.42	2.49	3.97	6.11	9.33	14.09	20.53	30.13	46.52	62.05	79.35	92.11	107.38
10:00 - 11:00	171	0.10	0.60	0.72	1.09	1.64	3.02	4.95	7.72	11.90	18.11	26.39	38.69	59.57	79.01	100.14	116.68	132.94
11:00 - 12:00	206	0.10	0.58	0.69	1.00	1.46	2.57	4.12	6.36	9.73	14.71	21.44	31.46	48.55	64.68	82.58	95.94	111.37
12:00 - 13:00	211	0.10	0.58	0.69	0.99	1.44	2.53	4.05	6.24	9.53	14.40	20.99	30.80	47.54	63.37	80.97	94.02	109.38
13:00 - 14:00	207	0.10	0.58	0.69	1.00	1.45	2.56	4.11	6.34	9.69	14.65	21.35	31.33	48.35	64.42	82.26	95.55	110.97
14:00 - 15:00	258	0.10	0.56	0.66	0.92	1.29	2.16	3.37	5.13	7.75	11.63	16.95	24.90	38.55	51.67	66.62	77.08	91.72
15:00 - 16:00	218	0.10	0.57	0.68	0.98	1.42	2.47	3.94	6.06	9.25	13.96	20.35	29.86	46.12	61.52	78.70	91.35	106.59
16:00 - 17:00	212	0.10	0.58	0.69	0.99	1.44	2.52	4.03	6.21	9.49	14.34	20.90	30.66	47.34	63.10	80.64	93.64	108.98
17:00 - 18:00	157	0.10	0.61	0.73	1.12	1.72	3.22	5.30	8.31	12.84	19.57	28.52	41.79	64.30	85.16	107.67	125.59	142.20
18:00 - 19:00	123	0.10	0.63	0.76	1.21	1.91	3.69	6.16	9.72	15.11	23.11	33.68	49.33	75.79	100.10	125.97	147.22	164.69
19:00 - 20:00	104	0.10	0.64	0.78	1.26	2.02	3.95	6.64	10.51	16.37	25.09	36.57	53.54	82.21	108.44	136.20	159.31	177.25
20:00 - 21:00	96	0.10	0.64	0.78	1.28	2.06	4.06	6.84	10.85	16.91	25.93	37.78	55.32	84.91	111.96	140.51	164.40	182.54
21:00 - 22:00	86	0.10	0.65	0.79	1.31	2.12	4.20	7.09	11.26	17.58	26.97	39.30	57.54	88.29	116.35	145.89	170.76	189.16
22:00 - 23:00	79	0.10	0.65	0.80	1.33	2.16	4.30	7.27	11.55	18.04	27.70	40.36	59.09	90.65	119.42	149.66	175.21	193.79
23:00 - 24:00	59	0.10	0.67	0.81	1.38	2.27	4.57	7.78	12.39	19.38	29.78	43.40	63.52	97.41	128.21	160.42	187.93	207.02

Table 7 Cumulative IAT distribution table for entrance ramp 2

Time	Number of vehicles per hour	Cumulative Percentage																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
0:00 - 1:00	35	0.10	0.68	0.84	1.44	2.40	4.91	8.38	13.39	20.98	32.28	47.04	68.84	105.52	138.75	173.34	203.20	222.89
1:00 - 2:00	23	0.10	0.69	0.85	1.48	2.47	5.07	8.69	13.89	21.78	33.53	48.87	71.50	109.57	144.03	179.80	210.84	230.83
2:00 - 3:00	13	0.10	0.69	0.85	1.50	2.53	5.21	8.94	14.30	22.45	34.58	50.38	73.72	112.95	148.42	185.19	217.20	237.44
3:00 - 4:00	25	0.10	0.69	0.84	1.47	2.46	5.05	8.64	13.80	21.65	33.33	48.56	71.06	108.90	143.15	178.73	209.57	229.51
4:00 - 5:00	17	0.10	0.69	0.85	1.49	2.51	5.16	8.84	14.14	22.18	34.16	49.78	72.83	111.60	146.66	183.03	214.65	234.80
5:00 - 6:00	27	0.10	0.68	0.84	1.47	2.45	5.02	8.58	13.72	21.51	33.12	48.26	70.62	108.22	142.27	177.65	208.29	228.18
6:00 - 7:00	60	0.10	0.66	0.81	1.38	2.26	4.56	7.75	12.35	19.31	29.68	43.25	63.30	97.07	127.77	159.89	187.30	206.36
7:00 - 8:00	127	0.10	0.62	0.76	1.20	1.89	3.63	6.06	9.56	14.84	22.70	33.07	48.45	74.44	98.34	123.82	144.67	162.04
8:00 - 9:00	110	0.10	0.63	0.77	1.25	1.98	3.87	6.49	10.26	15.97	24.47	35.66	52.21	80.18	105.81	132.97	155.49	173.28
9:00 - 10:00	124	0.10	0.63	0.76	1.21	1.90	3.67	6.13	9.68	15.04	23.01	33.53	49.11	75.45	99.66	125.44	146.58	164.02
10:00 - 11:00	89	0.10	0.65	0.79	1.30	2.10	4.16	7.02	11.14	17.38	26.66	38.84	56.87	87.28	115.03	144.28	168.85	187.17
11:00 - 12:00	95	0.10	0.64	0.78	1.29	2.07	4.08	6.87	10.89	16.98	26.03	37.93	55.54	85.25	112.40	141.05	165.03	183.21
12:00 - 13:00	50	0.10	0.67	0.82	1.40	2.32	4.70	8.00	12.76	19.98	30.72	44.77	65.52	100.45	132.16	165.27	193.66	212.97
13:00 - 14:00	104	0.10	0.64	0.78	1.26	2.02	3.95	6.64	10.51	16.37	25.09	36.57	53.54	82.21	108.44	136.20	159.31	177.25
14:00 - 15:00	115	0.10	0.63	0.77	1.23	1.96	3.80	6.36	10.06	15.64	23.95	34.90	51.11	78.49	103.61	130.28	152.31	169.98
15:00 - 16:00	151	0.10	0.61	0.73	1.14	1.75	3.30	5.45	8.56	13.24	20.19	29.43	43.12	66.33	87.79	110.90	129.40	146.17
16:00 - 17:00	131	0.10	0.62	0.75	1.19	1.87	3.58	5.96	9.39	14.57	22.28	32.47	47.56	73.08	96.58	121.67	142.13	159.39
17:00 - 18:00	109	0.10	0.64	0.77	1.25	1.99	3.88	6.51	10.31	16.04	24.57	35.81	52.44	80.52	106.25	133.51	156.12	173.95
18:00 - 19:00	135	0.10	0.62	0.75	1.18	1.84	3.52	5.86	9.22	14.31	21.86	31.86	46.67	71.73	94.82	119.51	139.58	156.75
19:00 - 20:00	79	0.10	0.65	0.80	1.33	2.16	4.30	7.27	11.55	18.04	27.70	40.36	59.09	90.65	119.42	149.66	175.21	193.79
20:00 - 21:00	47	0.10	0.67	0.82	1.41	2.34	4.74	8.08	12.89	20.18	31.03	45.22	66.18	101.47	133.48	166.88	195.57	214.95
21:00 - 22:00	43	0.10	0.67	0.83	1.42	2.36	4.80	8.18	13.05	20.45	31.45	45.83	67.07	102.82	135.24	169.04	198.11	217.60
22:00 - 23:00	49	0.10	0.67	0.82	1.41	2.33	4.71	8.03	12.80	20.05	30.82	44.92	65.74	100.79	132.60	165.81	194.30	213.63
23:00 - 24:00	43	0.10	0.67	0.83	1.42	2.36	4.80	8.18	13.05	20.45	31.45	45.83	67.07	102.82	135.24	169.04	198.11	217.60

Table 8 Cumulative IAT distribution table for entrance ramp 3

Time	Number of vehicles per hour	Cumulative Percentage																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
0:00 - 1:00	96	0.10	0.64	0.78	1.28	2.06	4.06	6.84	10.85	16.91	25.93	37.78	55.32	84.91	111.96	140.51	164.40	182.54
1:00 - 2:00	73	0.10	0.66	0.80	1.34	2.19	4.38	7.42	11.80	18.44	28.32	41.27	60.42	92.68	122.06	152.89	179.03	197.76
2:00 - 3:00	33	0.10	0.68	0.84	1.45	2.42	4.94	8.43	13.47	21.11	32.49	47.35	69.29	106.20	139.63	174.42	204.48	224.21
3:00 - 4:00	73	0.10	0.66	0.80	1.34	2.19	4.38	7.42	11.80	18.44	28.32	41.27	60.42	92.68	122.06	152.89	179.03	197.76
4:00 - 5:00	22	0.10	0.69	0.85	1.48	2.48	5.09	8.71	13.93	21.85	33.64	49.02	71.72	109.91	144.47	180.34	211.47	231.49
5:00 - 6:00	62	0.10	0.66	0.81	1.37	2.25	4.53	7.70	12.26	19.18	29.47	42.94	62.86	96.40	126.89	158.81	186.03	205.03
6:00 - 7:00	192	0.10	0.59	0.70	1.03	1.52	2.73	4.42	6.85	10.50	15.92	23.21	34.03	52.47	69.78	88.83	103.32	119.05
7:00 - 8:00	301	0.10	0.55	0.64	0.87	1.19	1.92	2.94	4.42	6.61	9.85	14.36	21.12	32.79	44.17	57.43	66.22	80.38
8:00 - 9:00	419	0.10	0.52	0.61	0.79	1.02	1.52	2.23	3.25	4.75	6.95	10.13	14.94	23.36	31.90	42.34	48.41	61.70
9:00 - 10:00	383	0.10	0.53	0.62	0.81	1.07	1.62	2.40	3.53	5.20	7.66	11.16	16.45	25.66	34.89	46.02	52.75	66.27
10:00 - 11:00	296	0.10	0.55	0.65	0.88	1.20	1.95	2.99	4.50	6.74	10.05	14.65	21.54	33.42	45.00	58.44	67.42	81.64
11:00 - 12:00	309	0.10	0.54	0.64	0.87	1.18	1.89	2.88	4.32	6.46	9.61	14.01	20.61	32.01	43.17	56.19	64.76	78.85
12:00 - 13:00	254	0.10	0.56	0.66	0.92	1.30	2.18	3.41	5.19	7.86	11.79	17.19	25.25	39.09	52.37	67.48	78.09	92.78
13:00 - 14:00	307	0.10	0.55	0.64	0.87	1.18	1.89	2.90	4.34	6.50	9.67	14.10	20.74	32.21	43.42	56.50	65.12	79.24
14:00 - 15:00	303	0.10	0.55	0.64	0.87	1.19	1.91	2.93	4.39	6.57	9.79	14.27	20.99	32.59	43.92	57.12	65.85	80.00
15:00 - 16:00	318	0.10	0.54	0.64	0.86	1.16	1.85	2.82	4.21	6.29	9.34	13.62	20.04	31.14	42.03	54.80	63.11	77.13
16:00 - 17:00	341	0.10	0.54	0.63	0.84	1.12	1.76	2.65	3.94	5.85	8.66	12.62	18.58	28.92	39.14	51.24	58.91	72.73
17:00 - 18:00	309	0.10	0.54	0.64	0.87	1.18	1.89	2.88	4.32	6.46	9.61	14.01	20.61	32.01	43.17	56.19	64.76	78.85
18:00 - 19:00	287	0.10	0.55	0.65	0.89	1.22	2.00	3.08	4.65	6.98	10.42	15.19	22.33	34.64	46.58	60.38	69.70	84.02
19:00 - 20:00	250	0.10	0.56	0.66	0.93	1.31	2.20	3.46	5.26	7.96	11.96	17.43	25.60	39.63	53.07	68.34	79.11	93.84
20:00 - 21:00	146	0.10	0.61	0.74	1.15	1.78	3.37	5.58	8.76	13.57	20.72	30.19	44.23	68.02	89.99	113.59	132.59	149.47
21:00 - 22:00	146	0.10	0.61	0.74	1.15	1.78	3.37	5.58	8.76	13.57	20.72	30.19	44.23	68.02	89.99	113.59	132.59	149.47
22:00 - 23:00	99	0.10	0.64	0.78	1.28	2.05	4.02	6.77	10.72	16.71	25.61	37.33	54.65	83.90	110.64	138.89	162.49	180.56
23:00 - 24:00	123	0.10	0.63	0.76	1.21	1.91	3.69	6.16	9.72	15.11	23.11	33.68	49.33	75.79	100.10	125.97	147.22	164.69

Table 9 Cumulative IAT distribution table for entrance ramp 4

Time	Number of vehicles per hour	Cumulative Percentage																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
0:00 - 1:00	104	0.10	0.64	0.78	1.26	2.02	3.95	6.64	10.51	16.37	25.09	36.57	53.54	82.21	108.44	136.20	159.31	177.25
1:00 - 2:00	73	0.10	0.66	0.80	1.34	2.19	4.38	7.42	11.80	18.44	28.32	41.27	60.42	92.68	122.06	152.89	179.03	197.76
2:00 - 3:00	45	0.10	0.67	0.83	1.42	2.35	4.77	8.13	12.97	20.31	31.24	45.52	66.63	102.14	134.36	167.96	196.84	216.28
3:00 - 4:00	49	0.10	0.67	0.82	1.41	2.33	4.71	8.03	12.80	20.05	30.82	44.92	65.74	100.79	132.60	165.81	194.30	213.63
4:00 - 5:00	142	0.10	0.62	0.74	1.16	1.80	3.42	5.68	8.93	13.84	21.13	30.80	45.12	69.37	91.75	115.75	135.13	152.12
5:00 - 6:00	317	0.10	0.54	0.64	0.86	1.16	1.85	2.83	4.23	6.31	9.37	13.67	20.10	31.24	42.16	54.95	63.29	77.32
6:00 - 7:00	544	0.10	0.51	0.59	0.74	0.92	1.29	1.80	2.55	3.64	5.22	7.62	11.26	17.75	24.58	33.32	37.77	50.46
7:00 - 8:00	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
8:00 - 9:00	444	0.10	0.52	0.61	0.78	1.00	1.46	2.12	3.07	4.47	6.52	9.50	14.02	21.96	30.06	40.08	45.75	58.90
9:00 - 10:00	448	0.10	0.52	0.61	0.78	0.99	1.46	2.11	3.05	4.42	6.45	9.40	13.87	21.73	29.77	39.72	45.32	58.45
10:00 - 11:00	556	0.10	0.50	0.59	0.73	0.91	1.27	1.77	2.50	3.56	5.10	7.44	11.00	17.35	24.05	32.67	37.00	49.65
11:00 - 12:00	599	0.10	0.50	0.58	0.72	0.89	1.21	1.67	2.34	3.30	4.69	6.85	10.14	16.03	22.33	30.54	34.50	46.98
12:00 - 13:00	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
13:00 - 14:00	909	0.10	0.47	0.54	0.65	0.77	0.95	1.22	1.62	2.16	2.94	4.29	6.40	10.31	14.83	21.22	23.54	35.14
14:00 - 15:00	1289	0.10	0.44	0.51	0.60	0.68	0.79	0.96	1.20	1.51	1.94	2.84	4.28	7.05	10.52	15.78	17.20	28.00
15:00 - 16:00	1496	0.10	0.43	0.49	0.57	0.65	0.74	0.87	1.06	1.29	1.62	2.36	3.58	5.97	9.08	13.94	15.06	25.52
16:00 - 17:00	1587	0.10	0.42	0.49	0.56	0.64	0.71	0.83	1.00	1.21	1.48	2.17	3.29	5.53	8.49	13.19	14.19	24.49
17:00 - 18:00	882	0.10	0.47	0.55	0.65	0.77	0.97	1.25	1.66	2.23	3.04	4.44	6.62	10.65	15.27	21.78	24.20	35.86
18:00 - 19:00	774	0.10	0.48	0.56	0.68	0.81	1.04	1.38	1.86	2.54	3.53	5.15	7.66	12.24	17.36	24.38	27.25	39.18
19:00 - 20:00	708	0.10	0.49	0.57	0.69	0.84	1.10	1.47	2.01	2.78	3.90	5.69	8.45	13.45	18.95	26.35	29.57	41.69
20:00 - 21:00	616	0.10	0.50	0.58	0.71	0.88	1.19	1.64	2.28	3.21	4.56	6.65	9.85	15.59	21.75	29.82	33.65	46.07
21:00 - 22:00	399	0.10	0.53	0.62	0.80	1.04	1.57	2.32	3.39	4.97	7.30	10.64	15.69	24.50	33.38	44.17	50.56	63.98
22:00 - 23:00	376	0.10	0.53	0.62	0.82	1.07	1.64	2.44	3.60	5.30	7.81	11.39	16.78	26.17	35.55	46.83	53.71	67.28
23:00 - 24:00	232	0.10	0.57	0.67	0.96	1.37	2.35	3.73	5.71	8.68	13.09	19.07	28.00	43.28	57.82	74.17	85.99	101.01

Table 10 Cumulative IAT distribution table for entrance ramp 5

Time	Number of vehicles per hour	Cumulative Percentage																
		0%	1%	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%	99%	100%
0:00 - 1:00	33	0.10	0.68	0.84	1.45	2.42	4.94	8.43	13.47	21.11	32.49	47.35	69.29	106.20	139.63	174.42	204.48	224.21
1:00 - 2:00	30	0.10	0.68	0.84	1.46	2.43	4.98	8.51	13.60	21.31	32.80	47.80	69.95	107.21	140.95	176.04	206.38	226.20
2:00 - 3:00	21	0.10	0.69	0.85	1.48	2.48	5.10	8.74	13.97	21.91	33.74	49.17	71.95	110.25	144.90	180.88	212.11	232.15
3:00 - 4:00	19	0.10	0.69	0.85	1.49	2.49	5.13	8.79	14.05	22.05	33.95	49.47	72.39	110.93	145.78	181.96	213.38	233.47
4:00 - 5:00	34	0.10	0.68	0.84	1.45	2.41	4.92	8.41	13.43	21.05	32.39	47.19	69.06	105.86	139.19	173.88	203.84	223.55
5:00 - 6:00	130	0.10	0.62	0.75	1.19	1.87	3.59	5.98	9.43	14.64	22.38	32.62	47.78	73.42	97.02	122.21	142.76	160.06
6:00 - 7:00	280	0.10	0.55	0.65	0.90	1.24	2.03	3.15	4.76	7.16	10.71	15.62	22.95	35.58	47.81	61.89	71.48	85.88
7:00 - 8:00	340	0.10	0.54	0.63	0.84	1.12	1.76	2.66	3.95	5.87	8.69	12.67	18.64	29.02	39.26	51.39	59.09	72.92
8:00 - 9:00	282	0.10	0.55	0.65	0.89	1.23	2.02	3.13	4.73	7.11	10.63	15.49	22.77	35.31	47.46	61.46	70.98	85.35
9:00 - 10:00	308	0.10	0.54	0.64	0.87	1.18	1.89	2.89	4.33	6.48	9.64	14.06	20.67	32.11	43.29	56.34	64.94	79.04
10:00 - 11:00	346	0.10	0.54	0.63	0.84	1.11	1.74	2.61	3.88	5.75	8.51	12.41	18.26	28.43	38.51	50.46	58.00	71.78
11:00 - 12:00	388	0.10	0.53	0.62	0.81	1.06	1.61	2.38	3.49	5.13	7.54	11.00	16.21	25.30	34.42	45.44	52.07	65.55
12:00 - 13:00	421	0.10	0.52	0.61	0.79	1.02	1.52	2.22	3.24	4.73	6.91	10.08	14.87	23.25	31.75	42.16	48.19	61.48
13:00 - 14:00	570	0.10	0.50	0.59	0.73	0.90	1.25	1.74	2.45	3.47	4.97	7.24	10.72	16.92	23.49	31.97	36.19	48.78
14:00 - 15:00	677	0.10	0.49	0.57	0.70	0.85	1.13	1.52	2.10	2.92	4.10	5.99	8.88	14.11	19.82	27.43	30.84	43.05
15:00 - 16:00	827	0.10	0.48	0.55	0.66	0.79	1.00	1.31	1.75	2.38	3.27	4.78	7.11	11.40	16.27	23.01	25.65	37.44
16:00 - 17:00	934	0.10	0.47	0.54	0.65	0.76	0.94	1.20	1.58	2.10	2.85	4.15	6.20	10.01	14.43	20.72	22.97	34.50
17:00 - 18:00	420	0.10	0.52	0.61	0.79	1.02	1.52	2.23	3.24	4.74	6.93	10.11	14.90	23.31	31.82	42.25	48.30	61.59
18:00 - 19:00	263	0.10	0.56	0.66	0.91	1.28	2.13	3.32	5.05	7.62	11.42	16.65	24.45	37.87	50.79	65.55	75.81	90.39
19:00 - 20:00	214	0.10	0.57	0.68	0.99	1.43	2.50	4.00	6.16	9.41	14.21	20.71	30.40	46.93	62.57	80.00	92.88	108.18
20:00 - 21:00	182	0.10	0.59	0.71	1.06	1.58	2.87	4.67	7.26	11.17	16.96	24.72	36.25	55.85	74.18	94.22	109.68	125.66
21:00 - 22:00	141	0.10	0.62	0.74	1.17	1.81	3.44	5.71	8.97	13.91	21.24	30.95	45.34	69.71	92.19	116.29	135.77	152.78
22:00 - 23:00	118	0.10	0.63	0.76	1.23	1.94	3.76	6.29	9.93	15.44	23.63	34.44	50.44	77.48	102.29	128.67	150.40	167.99
23:00 - 24:00	75	0.10	0.66	0.80	1.34	2.18	4.35	7.37	11.72	18.31	28.12	40.97	59.97	92.01	121.18	151.81	177.76	196.43

The percentages of total mainline traffic shown in Table 11 determine the number of vehicles exiting the freeway through the exit ramps.

Table 11 Percentage of total mainline traffic before the work zone exiting at a given exit ramp

Time	Exit Ramp 1	Exit Ramp 2	Exit Ramp 3	Exit Ramp 4	Exit Ramp 5
0:00 - 1:00	10.4%	4.3%	27.0%	7.5%	2.7%
1:00 - 2:00	10.1%	7.2%	22.8%	11.6%	5.3%
2:00 - 3:00	7.9%	3.3%	16.0%	5.6%	3.3%
3:00 - 4:00	7.1%	2.7%	14.6%	9.1%	12.4%
4:00 - 5:00	4.8%	4.1%	10.9%	7.7%	7.6%
5:00 - 6:00	5.1%	3.4%	10.1%	13.5%	11.5%
6:00 - 7:00	9.7%	4.5%	17.2%	15.3%	13.8%
7:00 - 8:00	11.4%	3.0%	16.7%	15.1%	14.4%
8:00 - 9:00	14.4%	4.9%	19.2%	16.2%	12.3%
9:00 - 10:00	15.1%	5.3%	18.2%	16.8%	10.0%
10:00 - 11:00	17.1%	4.8%	21.5%	14.5%	11.1%
11:00 - 12:00	16.7%	4.8%	21.3%	13.9%	11.9%
12:00 - 13:00	16.0%	3.1%	20.8%	13.8%	8.8%
13:00 - 14:00	18.8%	5.2%	21.2%	10.0%	9.5%
14:00 - 15:00	16.6%	5.8%	26.0%	9.1%	8.3%
15:00 - 16:00	16.6%	6.3%	28.6%	6.9%	11.4%
16:00 - 17:00	18.9%	5.5%	31.9%	5.4%	10.6%
17:00 - 18:00	13.3%	5.6%	30.5%	10.3%	6.0%
18:00 - 19:00	12.3%	5.2%	26.7%	12.3%	6.1%
19:00 - 20:00	9.2%	5.2%	30.3%	16.5%	6.3%
20:00 - 21:00	10.7%	6.8%	27.3%	12.1%	6.4%
21:00 - 22:00	9.1%	4.7%	24.2%	18.2%	5.9%
22:00 - 23:00	10.0%	3.1%	28.6%	14.3%	4.5%
23:00 - 24:00	10.8%	4.3%	29.5%	12.2%	5.2%

(Assumption: 10% of the vehicles exiting the road leave from Lane 3, 20% of the vehicles exiting the road leave from Lane 2, 70% of the vehicles exiting the road leave from Right Lane (Lane 1)).

2.2.3 Vehicle Type

Two types of vehicles were used in the simulation program. The use of small vehicles (cars, SUVs, etc.) and large vehicles (busses, semi-trucks, etc) provided enough information to simulate the freeway traffic adequately. Vehicle lengths are entered by the users of the simulation program. In the example typical length for small vehicles is 20 feet and typical length for large vehicles is 60 feet. These values are also the default values for vehicle lengths in the simulation program.

The user of the simulation program enters the percentages for large vehicles after defining the length of the vehicles. The user enters the large vehicle percentages for all lanes of the mainline, for all entrance and exit ramps. The percentages of large vehicles are given as an example in Table 12 below.

Table 12 Percentage of large vehicles (trucks) for each lane in the mainline, entrance ramps, and exit ramps (user specified)

	Percentage of Large Vehicles (Trucks)
Right Lane (Lane 1)	15.2%
Lane 2	10.3%
Lane 3	2.7%
Entrance Ramp 1	4.6%
Entrance Ramp 2	1.2%
Entrance Ramp 3	4.7%
Entrance Ramp 4	9.5%
Entrance Ramp 5	4.2%
Exit Ramp 1	1.2%
Exit Ramp 2	1.6%
Exit Ramp 3	1.9%
Exit Ramp 4	5.7%
Exit Ramp 5	2.8%

Another important information used in the simulation program according to the vehicle type is the acceleration and deceleration rates of the vehicles. Typical acceleration and deceleration rates for small and large vehicles were given by the program as default values. However the user may change these values according to observed values. The default values are given in Table 13.

Table 13 Typical acceleration and deceleration rates for small and large vehicles on level roads (user specified, default values are given below)[1]

	Typical Maximum Acceleration Rate on Level Road (ft/sec^2)					Typical Acceleration Rate (not speed dependent)	Typical Maximum Deceleration Rate on Level Road (ft/sec^2)
Vehicle Type	0 to 20 mph	20 to 30 mph	30 to 40 mph	40 to 50 mph	50 to 60 mph		
Small Vehicle	7.54	6.56	5.9	5.25	4.59	6.0	10
Large Vehicle	1.31	0.98	0.66	0.66	0.33	0.7	7

2.2.4 Speed Profile

The average speeds of the vehicles are another important input for the simulation program. Speed is used to determine the vehicle travel times through the work zone and it determines the gap acceptance and car following behaviors. The user enters the average speeds and standard deviations for each average for all lanes on the mainline and for the entrance ramps. Table 14 shows the mainline average speeds and standard deviations for each lane as an example.

Table 14 Average speeds and standard deviations for each lane in the mainline at the beginning and for entrance ramps (user specified)

	Average Speed (mph)	Standard Deviation (mph)
Right Lane (Lane 1)	51	4
Lane 2	54	4
Lane 3	61	3

The average speeds for the vehicles entering the work zone are assumed to be the same as the vehicle speeds on Right Lane (Lane 1) given in Table 14..

2.2.5 Car Following Behavior

In the paper by Rothery, the basic concepts in car following models are explained and the common car following models were compared [3].

In the paper by Rakha and Crowther, three car following models were compared. The Greenshields single regime model, Pipes two regime model, and Van Aerde four parameter single regime model which combines both Greenshields and Pipes model [4].

Constant car following distances were used for the car following behavior in the thesis by Oner. Safe car following spaces were determined for free-flow condition, jam density condition, and stopped conditions for different types of vehicles [5].

2.2.6 Lane Changing Behavior

Lane Changing will be perpendicular to the traffic flow. In the paper by Hidas, lane changing and merging behavior in microsimulation traffic model is modeled [6]

Kanaris et al., determined a model to compute the minimum safe lane changing distances [7]. Oner determined the required gap for lane changing using the differences in the merging vehicle speed and the desired lane speed. Minimum required gaps for lane changing were also calculated for stopped conditions dependent on the number of vehicles waiting in the queue.

2.3 Users' Manual for ARENA Traffic Simulation Software Package Developed by Rockwell Automation

The ORITE – ODOT Construction Zone Traffic Simulation supports the analysis of traffic backups at construction work zones along the interstate highways within the state of Ohio. The purpose of this simulation is to stochastically model traffic flow before and through construction work zones. The simulation model links to a Microsoft Excel interface spreadsheet (ORITE – ODOT Construction Zone Traffic Sim Interface.xls) to facilitate the entry of key input parameters for various construction work zone scenarios.

This document is to be used as a reference tool to help with setting up scenarios using the ORITE – ODOT Construction Zone Traffic Simulation. It walks-through and describes the key worksheets for setting up a simulation scenario in the ORITE – ODOT Construction Zone Traffic Sim Interface, the animation screens in the simulation model, and the results worksheets in the interface.

ORITE – ODOT Construction Zone Traffic Simulation.doe and ORITE – ODOT Construction Zone Traffic Sim Interface.xls files are required to run the simulation program. In addition, Rockwell Software Arena® 11.00 or newer and Microsoft® Excel 2002 or newer software programs are required.

2.3.1 User's Guide for Running the Simulation

1. *Installing Arena & the ORITE – ODOT Construction Zone Traffic Simulation*

Insert the Rockwell Software Arena Version 11.00.00 (CPR 7) installation CD. Follow the prompts to install Arena. If you need help installing Arena, the CD includes installation notes.

To install the ORITE – ODOT Construction Zone Traffic Simulation model, create a folder on your computer's hard-drive or shared network drive to store the required simulation files. It is recommended that you use your computer's hard-drive for running the simulation. Copy or Unzip(if the files are included in a ZIP file) the ORITE – ODOT Construction Zone Traffic Simulation files to your new folder.

Your New Folder \ ORITE – ODOT Construction Zone Traffic Simulation.doe
Your New Folder \ ORITE – ODOT Construction Zone Traffic Sim Interface.xls
Your New Folder \ ORITE – ODOT Construction Zone Traffic Sim Users Guide.pdf

2. *Opening the Simulation Interface Spreadsheet*

Open the interface spreadsheet in Microsoft Excel by double-clicking on **ORITE – ODOT Construction Zone Traffic Sim Interface.xls** file (as shown in Figure 2) in Your New Folder or by clicking on the Open button or choosing the menu File -> Open in Microsoft Excel.

Figure 2. Screenshot of the interface spreadsheet in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

If you are prompted about the spreadsheet's use of macros, choose the **Enable Macros** button (as shown in Figure 3).

Figure 3. Screenshot of the enabling macros in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

3. Setting up a Simulation Scenario

To setup a simulation scenario, you are going to have to enter the scenario parameters in the interface spreadsheet as shown in Figure 4. First, enter the ending lane percentage for vehicles in the model. The percentage must add up to 100%.

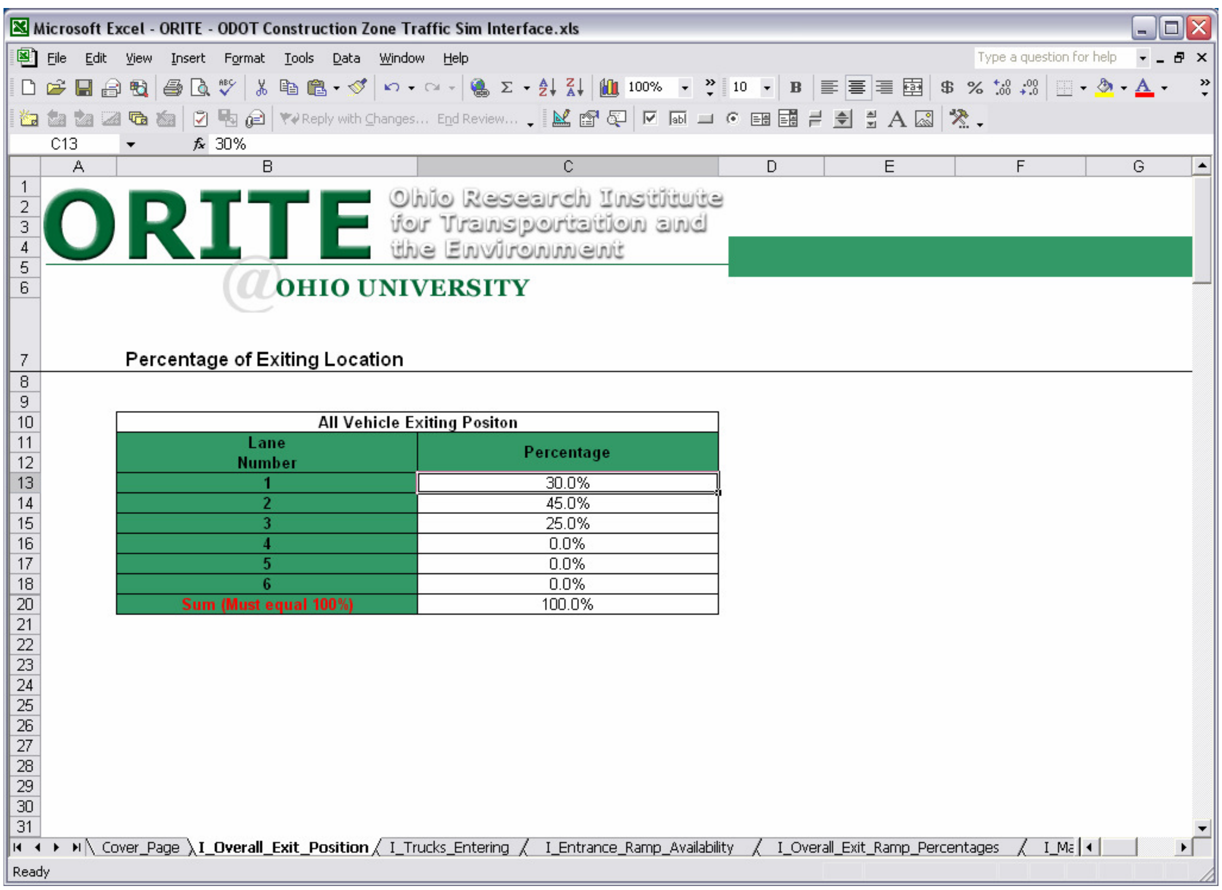


Figure 4. Screenshot of the ending lane percentage of vehicles in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need the weighted percentage of vehicles exiting the system for each lane in the model. The simulation will assign a target lane for vehicles exiting the modeled highway segment based on the percentages in this input worksheet. Do not enter a value for lanes not used in the model. Since lanes 4 through 6 are not used in this model scenario above, the value of 0% is entered for those lanes. Percent Vehicles Exiting Location Parameters:

- Exiting Position – the percentage of vehicles exiting the system in each lane.

Second, enter the percentage of vehicles that are trucks entering the system at each lane start and entrance ramp as shown in Figure 5.

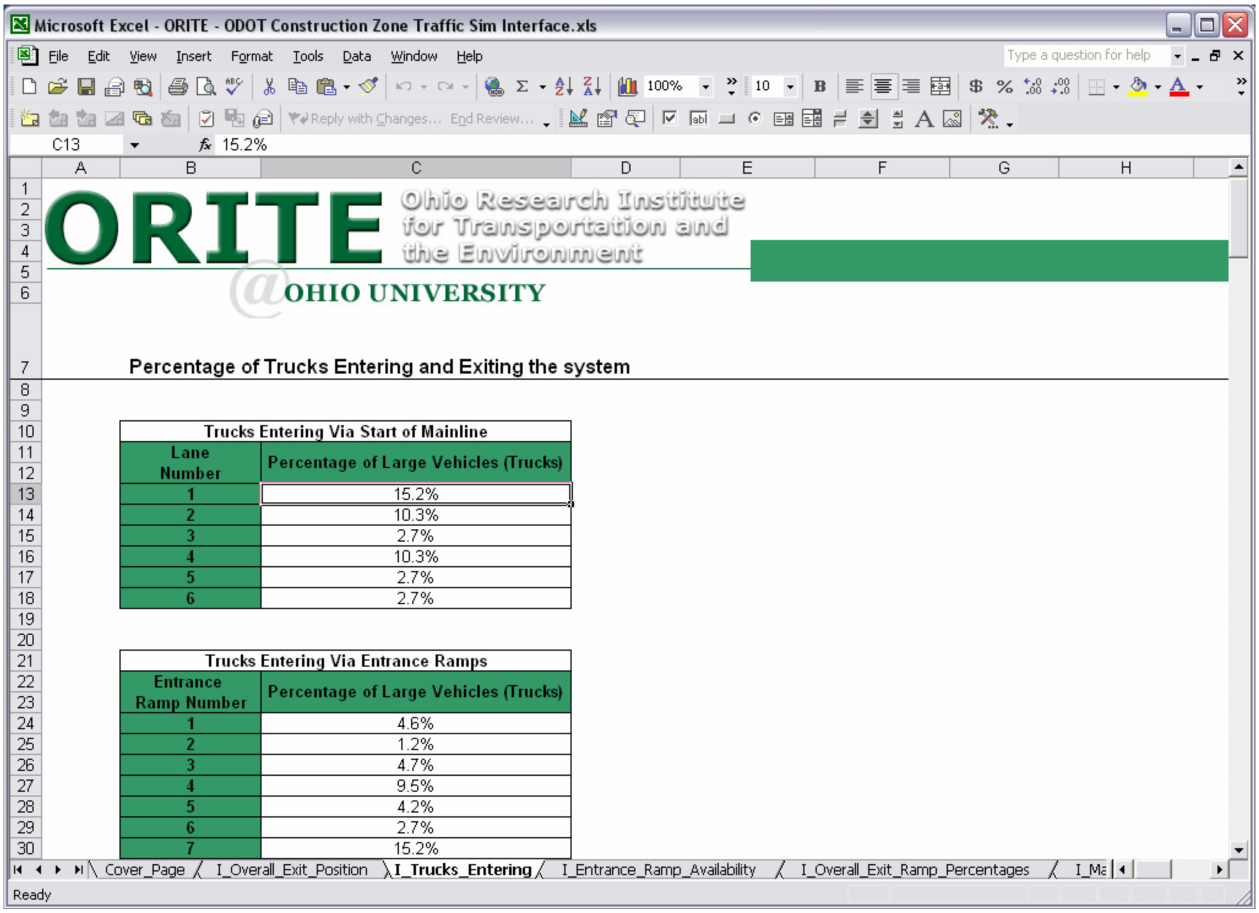
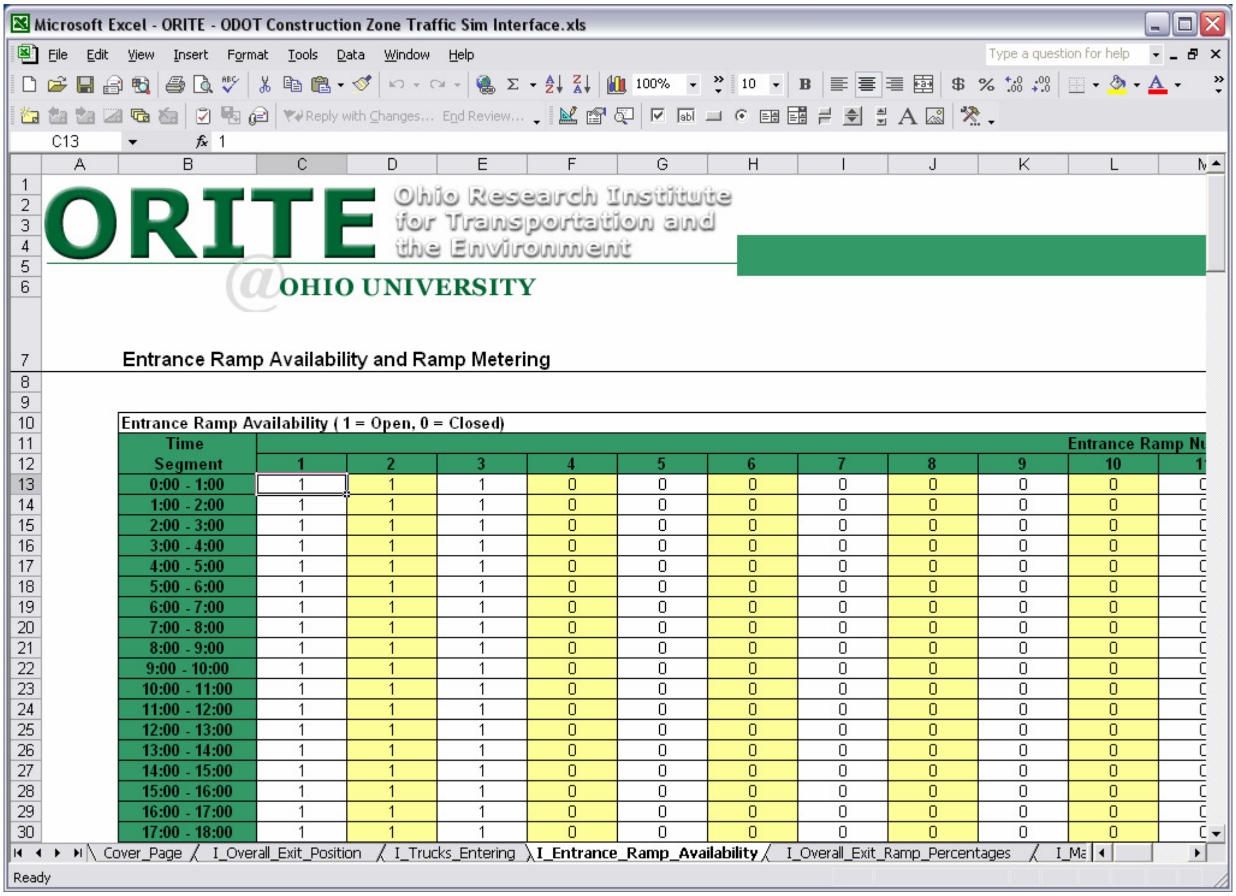


Figure 5. Screenshot of the percentage of vehicles exiting the system in each lane in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need to enter the percentage of trucks entering the system at each lane start and at each entrance ramp modeled in the simulation. The percentage for each lane must be between 0% and 100%. Trucks Entering the System Parameters:

- Trucks Entering at Mainline Start – the percentage of trucks entering the highway at the start of each mainline lane
- Trucks Entering Via Entrance Ramps – the percentage of trucks entering the highway at each entrance ramp in the model

Third, enter the parameters for entrance ramp availability and ramp metering for each ramp as shown in Figure 6.



Time Segment	1	2	3	4	5	6	7	8	9	10
0:00 - 1:00	1	1	1	0	0	0	0	0	0	0
1:00 - 2:00	1	1	1	0	0	0	0	0	0	0
2:00 - 3:00	1	1	1	0	0	0	0	0	0	0
3:00 - 4:00	1	1	1	0	0	0	0	0	0	0
4:00 - 5:00	1	1	1	0	0	0	0	0	0	0
5:00 - 6:00	1	1	1	0	0	0	0	0	0	0
6:00 - 7:00	1	1	1	0	0	0	0	0	0	0
7:00 - 8:00	1	1	1	0	0	0	0	0	0	0
8:00 - 9:00	1	1	1	0	0	0	0	0	0	0
9:00 - 10:00	1	1	1	0	0	0	0	0	0	0
10:00 - 11:00	1	1	1	0	0	0	0	0	0	0
11:00 - 12:00	1	1	1	0	0	0	0	0	0	0
12:00 - 13:00	1	1	1	0	0	0	0	0	0	0
13:00 - 14:00	1	1	1	0	0	0	0	0	0	0
14:00 - 15:00	1	1	1	0	0	0	0	0	0	0
15:00 - 16:00	1	1	1	0	0	0	0	0	0	0
16:00 - 17:00	1	1	1	0	0	0	0	0	0	0
17:00 - 18:00	1	1	1	0	0	0	0	0	0	0

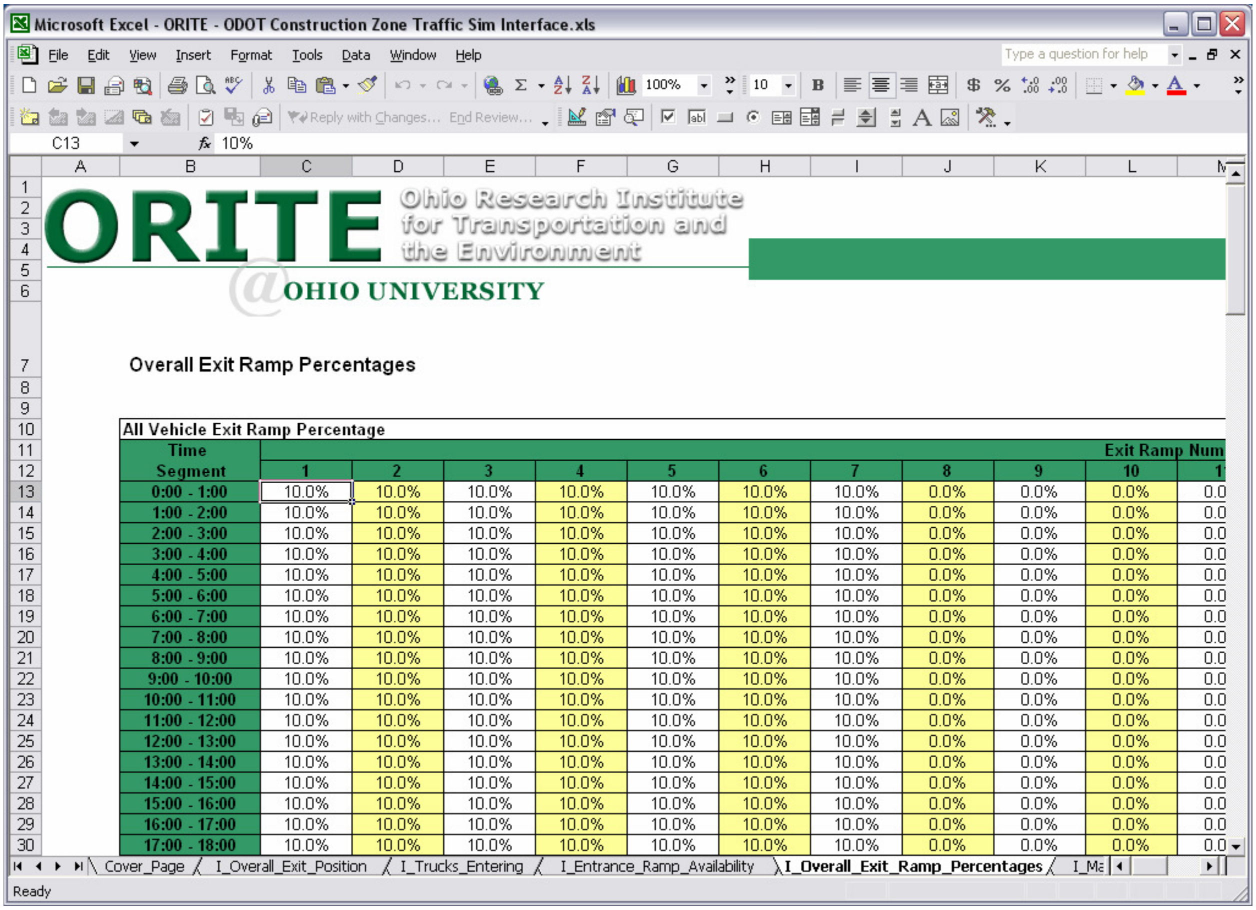
Figure 6. Screenshot of the parameters for entrance ramp availability and ramp metering in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need to enter the entrance ramp availability by lane for each hour of the day. Also, you will need to enter in entrance ramp metering in seconds.

Entrance Ramp Parameters:

- Availability – the hourly availability of each entrance ramp in the simulation. The value of 1 means the ramp is open (available) and 0 means the ramp is closed.
- Metering – the smallest time period between vehicles entering at an entrance ramp. A value of 0 means that the ramp has no metering.

Fourth, enter the percentage of vehicles exiting the highway at each exit ramp as shown in Figure 7.



Time Segment	Exit Ramp Num 1	2	3	4	5	6	7	8	9	10	1
0:00 - 1:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
1:00 - 2:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
2:00 - 3:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
3:00 - 4:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
4:00 - 5:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
5:00 - 6:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
6:00 - 7:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
7:00 - 8:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
8:00 - 9:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
9:00 - 10:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
10:00 - 11:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
11:00 - 12:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
12:00 - 13:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
13:00 - 14:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
14:00 - 15:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
15:00 - 16:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
16:00 - 17:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0
17:00 - 18:00	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0

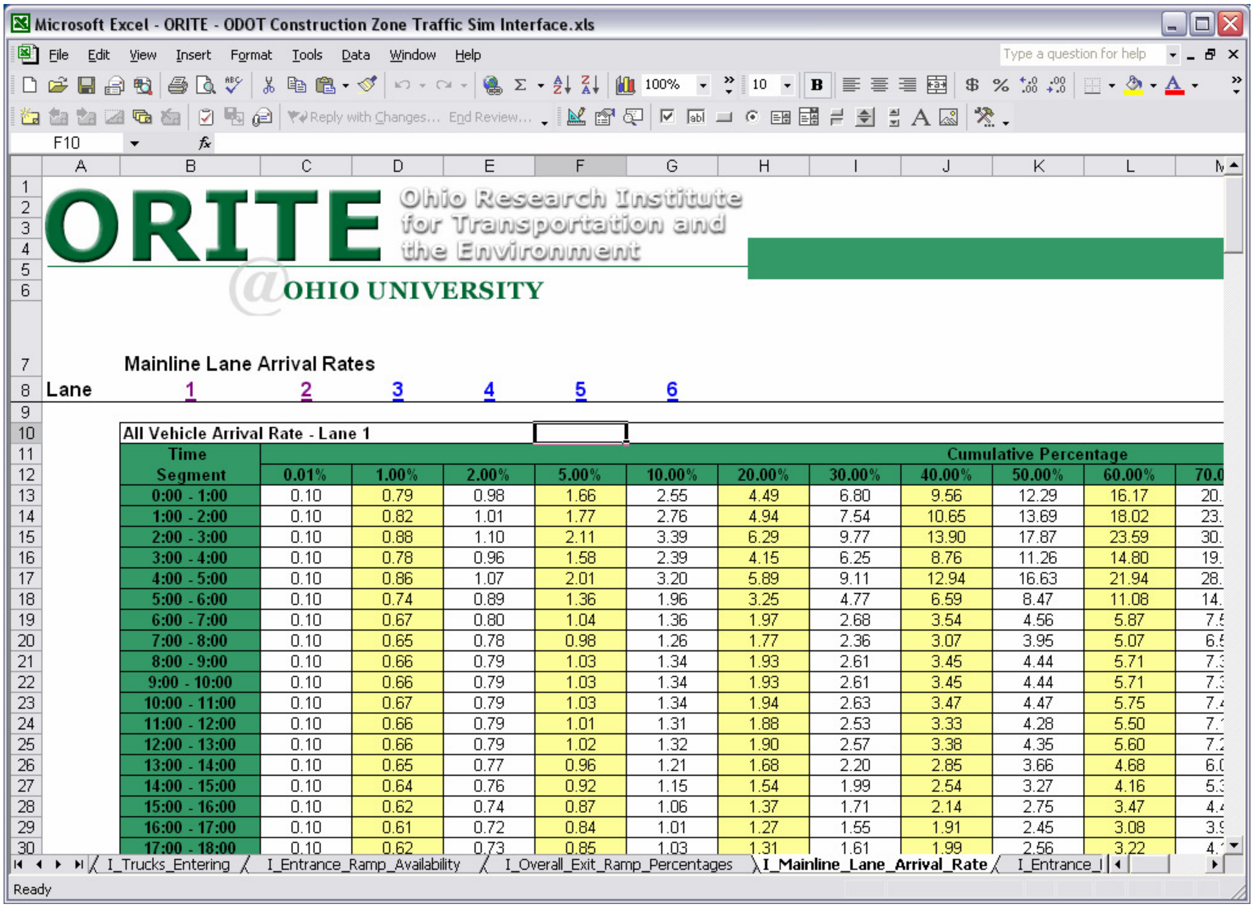
Figure 7. Screenshot of the percentage of vehicles exiting the highway at each exit ramp in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need to enter the percentage of vehicles exiting the system at each ramp for each hour of the day.

Exit Ramp Parameters:

- Exit Ramp Percentage – hourly percentage of vehicles exiting the highway at each exit ramp in the model. A value of 10% means that on average 10 out of 100 vehicles passing an exit ramp will take that exit.

Fifth, enter the inter-arrival times for vehicles starting in each lane as shown in Figure 8.



All Vehicle Arrival Rate - Lane 1

Time Segment	Cumulative Percentage 0.01%	1.00%	2.00%	5.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.0
0:00 - 1:00	0.10	0.79	0.98	1.66	2.55	4.49	6.80	9.56	12.29	16.17	20.
1:00 - 2:00	0.10	0.82	1.01	1.77	2.76	4.94	7.54	10.65	13.69	18.02	23.
2:00 - 3:00	0.10	0.88	1.10	2.11	3.39	6.29	9.77	13.90	17.87	23.59	30.
3:00 - 4:00	0.10	0.78	0.96	1.58	2.39	4.15	6.25	8.76	11.26	14.80	19.
4:00 - 5:00	0.10	0.86	1.07	2.01	3.20	5.89	9.11	12.94	16.63	21.94	28.
5:00 - 6:00	0.10	0.74	0.89	1.36	1.96	3.25	4.77	6.59	8.47	11.08	14.
6:00 - 7:00	0.10	0.67	0.80	1.04	1.36	1.97	2.68	3.54	4.56	5.87	7.5
7:00 - 8:00	0.10	0.65	0.78	0.98	1.26	1.77	2.36	3.07	3.95	5.07	6.5
8:00 - 9:00	0.10	0.66	0.79	1.03	1.34	1.93	2.61	3.45	4.44	5.71	7.3
9:00 - 10:00	0.10	0.66	0.79	1.03	1.34	1.93	2.61	3.45	4.44	5.71	7.3
10:00 - 11:00	0.10	0.67	0.79	1.03	1.34	1.94	2.63	3.47	4.47	5.75	7.4
11:00 - 12:00	0.10	0.66	0.79	1.01	1.31	1.88	2.53	3.33	4.28	5.50	7.1
12:00 - 13:00	0.10	0.66	0.79	1.02	1.32	1.90	2.57	3.38	4.35	5.60	7.2
13:00 - 14:00	0.10	0.65	0.77	0.96	1.21	1.68	2.20	2.85	3.66	4.68	6.0
14:00 - 15:00	0.10	0.64	0.76	0.92	1.15	1.54	1.99	2.54	3.27	4.16	5.3
15:00 - 16:00	0.10	0.62	0.74	0.87	1.06	1.37	1.71	2.14	2.75	3.47	4.4
16:00 - 17:00	0.10	0.61	0.72	0.84	1.01	1.27	1.55	1.91	2.45	3.08	3.9
17:00 - 18:00	0.10	0.62	0.73	0.85	1.03	1.31	1.61	1.99	2.56	3.22	4.1

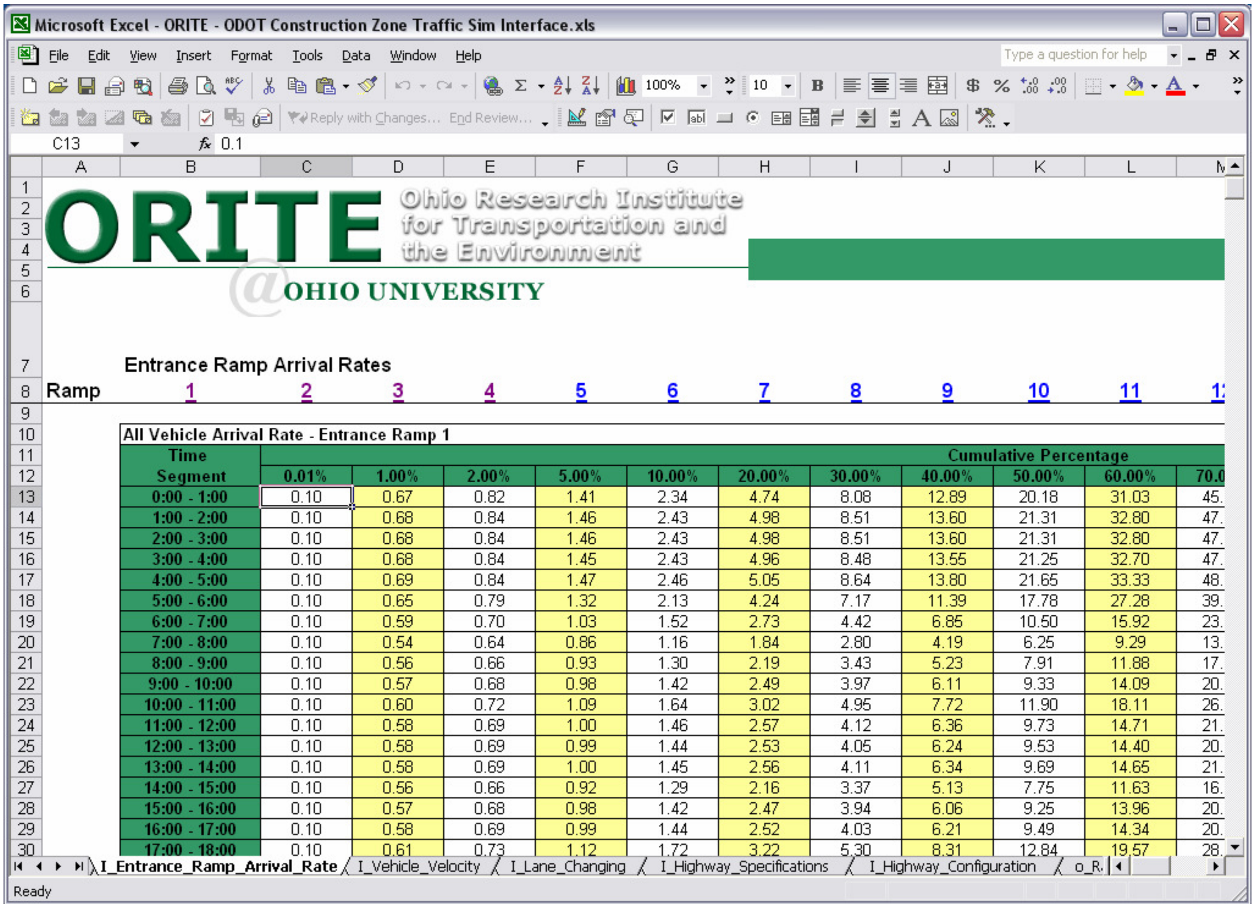
Figure 8. Screenshot of the interarrival times for vehicles starting in each lane in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need to enter the inter-arrival times for each lane of the model by hour. The model uses a cumulative distribution for the arrival rates. The cumulative distribution has 17 arrival rates for each hour period.

Mainline Lane Arrival Rates Parameters:

- Arrival Rate – hourly inter-arrival times for vehicles entering the highway in each mainline lane. The initial cumulative distributions are based on data provided by the Ohio Research Institute for Transportation and the Environment.

Sixth, enter the inter-arrival times for vehicles entering the highway at each entrance ramp as shown in Figure 9.



Entrance Ramp Arrival Rates

Ramp 1 2 3 4 5 6 7 8 9 10 11

All Vehicle Arrival Rate - Entrance Ramp 1											
Time	Cumulative Percentage										
Segment	0.01%	1.00%	2.00%	5.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.0
0:00 - 1:00	0.10	0.67	0.82	1.41	2.34	4.74	8.08	12.89	20.18	31.03	45.
1:00 - 2:00	0.10	0.68	0.84	1.46	2.43	4.98	8.51	13.60	21.31	32.80	47.
2:00 - 3:00	0.10	0.68	0.84	1.46	2.43	4.98	8.51	13.60	21.31	32.80	47.
3:00 - 4:00	0.10	0.68	0.84	1.45	2.43	4.96	8.48	13.55	21.25	32.70	47.
4:00 - 5:00	0.10	0.69	0.84	1.47	2.46	5.05	8.64	13.80	21.65	33.33	48.
5:00 - 6:00	0.10	0.65	0.79	1.32	2.13	4.24	7.17	11.39	17.78	27.28	39.
6:00 - 7:00	0.10	0.59	0.70	1.03	1.52	2.73	4.42	6.85	10.50	15.92	23.
7:00 - 8:00	0.10	0.54	0.64	0.86	1.16	1.84	2.80	4.19	6.25	9.29	13.
8:00 - 9:00	0.10	0.56	0.66	0.93	1.30	2.19	3.43	5.23	7.91	11.88	17.
9:00 - 10:00	0.10	0.57	0.68	0.98	1.42	2.49	3.97	6.11	9.33	14.09	20.
10:00 - 11:00	0.10	0.60	0.72	1.09	1.64	3.02	4.95	7.72	11.90	18.11	26.
11:00 - 12:00	0.10	0.58	0.69	1.00	1.46	2.57	4.12	6.36	9.73	14.71	21.
12:00 - 13:00	0.10	0.58	0.69	0.99	1.44	2.53	4.05	6.24	9.53	14.40	20.
13:00 - 14:00	0.10	0.58	0.69	1.00	1.45	2.56	4.11	6.34	9.69	14.65	21.
14:00 - 15:00	0.10	0.56	0.66	0.92	1.29	2.16	3.37	5.13	7.75	11.63	16.
15:00 - 16:00	0.10	0.57	0.68	0.98	1.42	2.47	3.94	6.06	9.25	13.96	20.
16:00 - 17:00	0.10	0.58	0.69	0.99	1.44	2.52	4.03	6.21	9.49	14.34	20.
17:00 - 18:00	0.10	0.61	0.73	1.12	1.72	3.22	5.30	8.31	12.84	19.57	28.

Figure 9. Screenshot of the interarrival times for vehicles starting in each entrance ramp in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need to enter the inter-arrival times for each entrance ramp in the model by hour. The model uses a cumulative distribution for the arrival rates. The cumulative distribution has 17 arrival rates for each hour period. Entrance Ramp Arrival Rates Parameters:

- Arrival Rate – hourly inter-arrival times for vehicles entering the highway at each entrance ramp. The initial cumulative distributions are based on data provided by the Ohio Research Institute for Transportation and the Environment.

Seventh, enter the velocities for cars and trucks as shown in Figure 10.

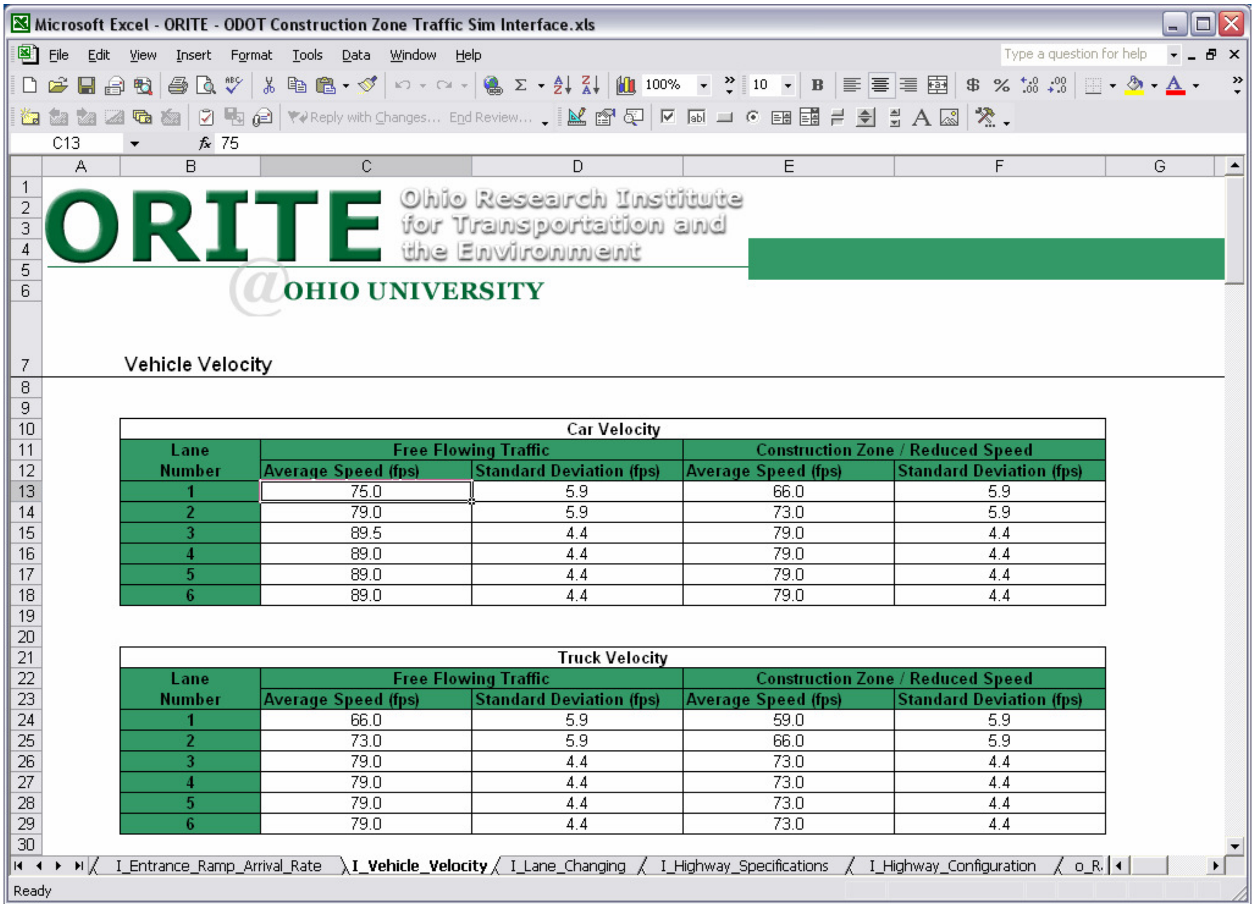


Figure 10. Screenshot of the vehicle velocities in each lane in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need to enter the maximum velocities for cars and trucks for each lane. The velocity (speed) inputs include a standard deviation for each lane to add variability to traffic in the system.

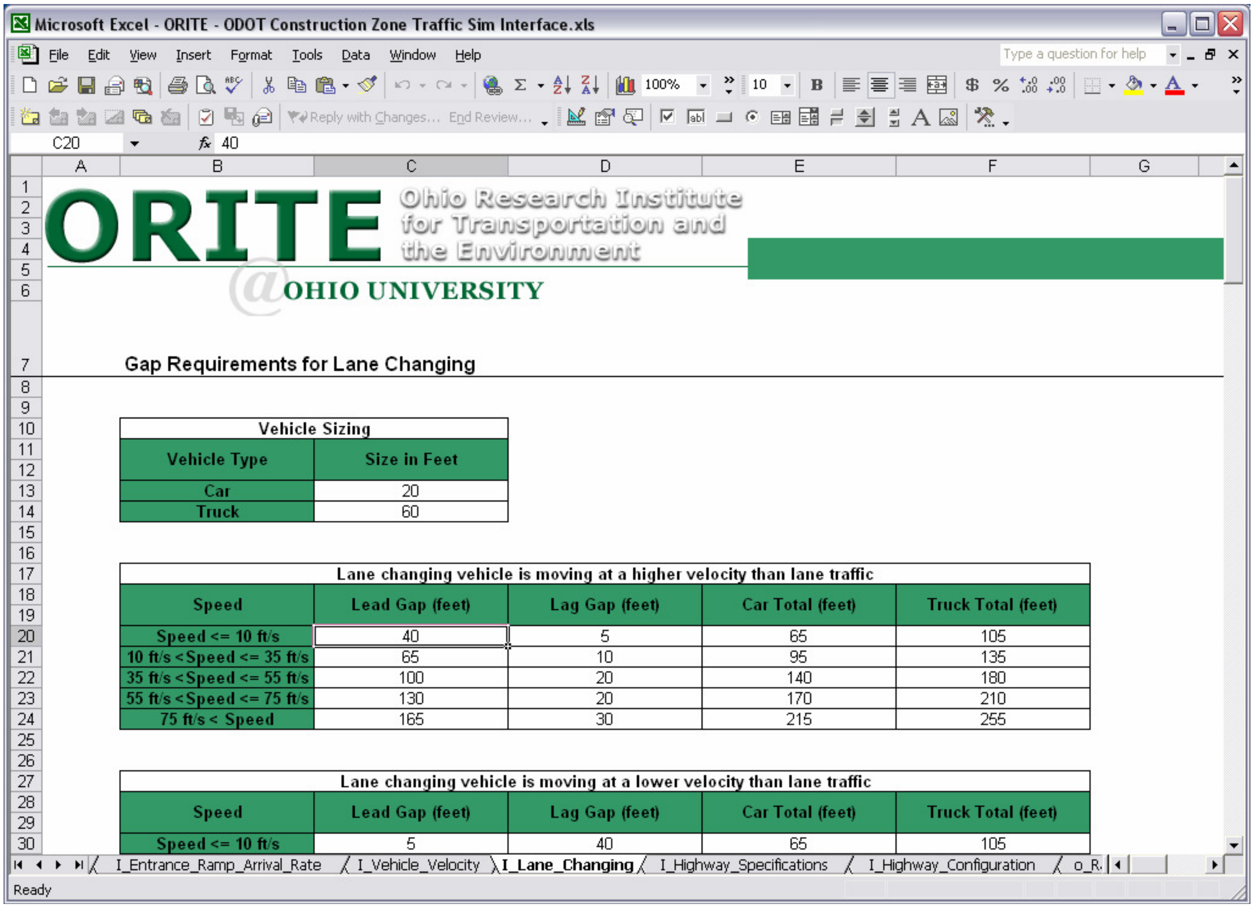
Car Velocity Parameters:

- Free Flowing Traffic – the average velocity and standard deviation in feet per second for cars moving in lanes with no restrictions.
- Construction Zone – the average velocity and standard deviation in feet per second for cars moving through a construction/reduced speed zone.

Truck Velocity Parameters:

- Free Flowing Traffic – the average velocity and standard deviation in feet per second for trucks moving in lanes with no restrictions.
- Construction Zone – the average velocity and standard deviation in feet per second for trucks moving through a construction/reduced speed zone.

Eighth, enter the lane changing characteristics of the model as shown in Figure 11.



Vehicle Sizing	
Vehicle Type	Size in Feet
Car	20
Truck	60

Lane changing vehicle is moving at a higher velocity than lane traffic				
Speed	Lead Gap (feet)	Lag Gap (feet)	Car Total (feet)	Truck Total (feet)
Speed <= 10 ft/s	40	5	65	105
10 ft/s < Speed <= 35 ft/s	65	10	95	135
35 ft/s < Speed <= 55 ft/s	100	20	140	180
55 ft/s < Speed <= 75 ft/s	130	20	170	210
75 ft/s < Speed	165	30	215	255

Lane changing vehicle is moving at a lower velocity than lane traffic				
Speed	Lead Gap (feet)	Lag Gap (feet)	Car Total (feet)	Truck Total (feet)
Speed <= 10 ft/s	5	40	65	105

Figure 11. Screenshot of the lane changing characteristics in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need to enter the size of each vehicle in feet and the lead and lag gaps for a vehicle to change lanes. The spreadsheet uses the vehicle size, lead gap, and lag gap to calculate the total gap required to change lanes for cars and trucks. Vehicles moving from a slower speed to a faster lane require larger lag gap, and vehicles moving from a faster speed to a slower lane require a larger lead gap.

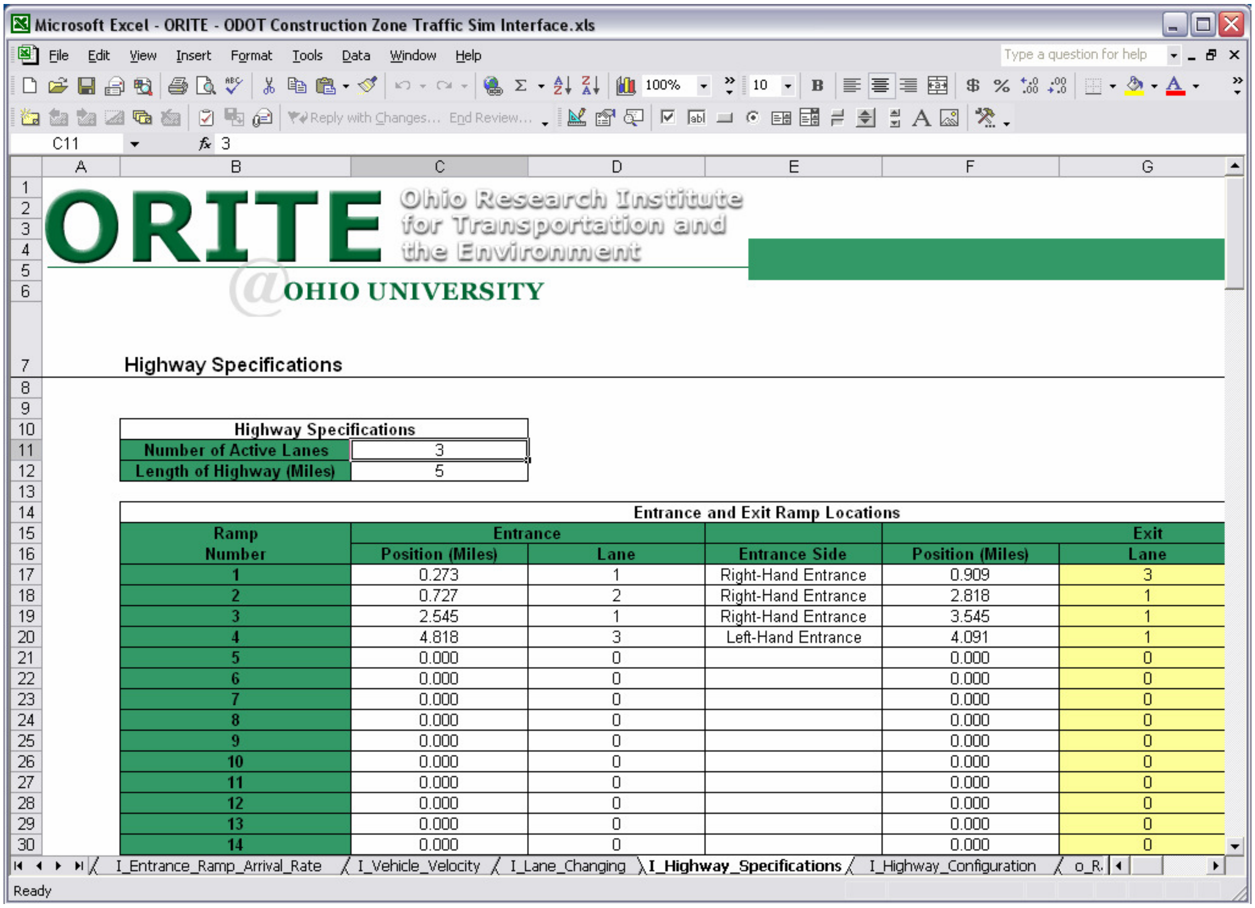
Vehicle Size Parameters:

- Car – the size of a car in feet.
- Truck – the size of a truck in feet.

Lane Changing Parameters:

- Lead Gap – the amount of open distance in feet required in front of a vehicle to change lanes at a given speed differential.
- Lag Gap – the amount of open distance in feet required behind a vehicle to change lanes at a given speed differential.
- Total – the total amount of open space required to change lanes at a given speed differential. This input is calculated from the other input values for lane changing.

Ninth, enter the highway configuration parameters as shown in Figure 12.



Highway Specifications	
Number of Active Lanes	3
Length of Highway (Miles)	5

Entrance and Exit Ramp Locations					
Ramp Number	Entrance			Exit	
	Position (Miles)	Lane	Entrance Side	Position (Miles)	Lane
1	0.273	1	Right-Hand Entrance	0.909	3
2	0.727	2	Right-Hand Entrance	2.818	1
3	2.545	1	Right-Hand Entrance	3.545	1
4	4.818	3	Left-Hand Entrance	4.091	1
5	0.000	0		0.000	0
6	0.000	0		0.000	0
7	0.000	0		0.000	0
8	0.000	0		0.000	0
9	0.000	0		0.000	0
10	0.000	0		0.000	0
11	0.000	0		0.000	0
12	0.000	0		0.000	0
13	0.000	0		0.000	0
14	0.000	0		0.000	0

Figure 12. Screenshot of the highway configuration parameters in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need to enter the number of active lanes, length of the highway in miles, and the entrance and exit ramp locations in the simulation. The entrances and exits can be either right or left-hand entrance.

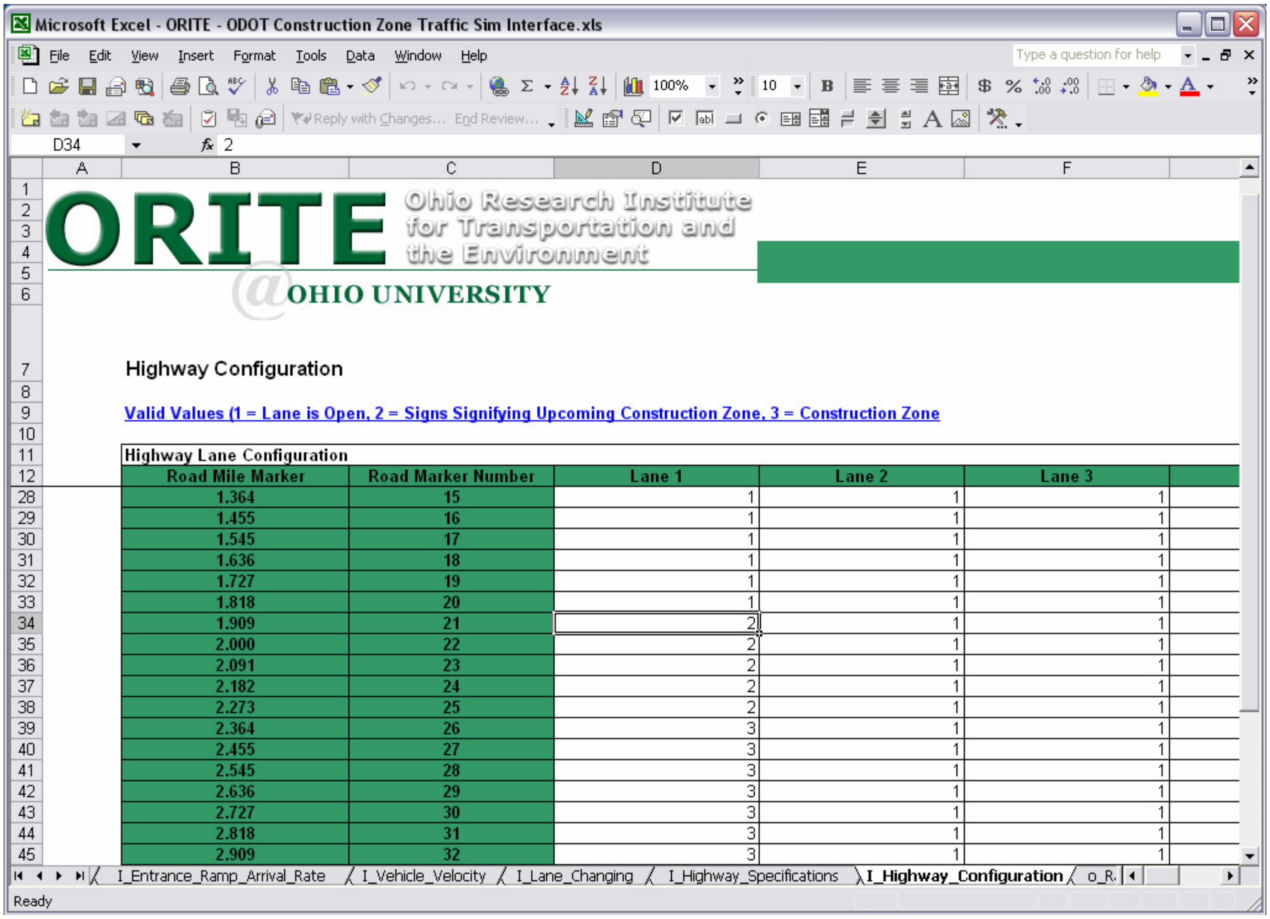
Highway Specification Parameters:

- Number of Active Lanes – the number of active lanes in the simulation model. There can be 2 to 6 lanes in the model.
- Length of Highway – the length of the highway segment in miles modeled in the simulation.

Entrance/Exit Ramp Location Parameters:

- Position – the position of the entrance/exit ramp in miles from the beginning of the highway segment modeled. The positions for each ramp must be entered in ascending order.
- Lane – the lane of the entrance/exit ramp. The entrance/exit ramp must be connected to an open lane. The ramp cannot enter/exit in a lane closed for construction.
- Side – the side of the highway for the entrance/exit ramp. This is for animation purposes. Right-hand ramps are located in the lower lane numbers (depending on construction closures), and left-hand ramps are located in the higher lane numbers.

Finally, enter the highway lane configuration as shown in Figure 13.



Road Mile Marker	Road Marker Number	Lane 1	Lane 2	Lane 3
1.364	15	1	1	1
1.455	16	1	1	1
1.545	17	1	1	1
1.636	18	1	1	1
1.727	19	1	1	1
1.818	20	1	1	1
1.909	21	2	1	1
2.000	22	2	1	1
2.091	23	2	1	1
2.182	24	2	1	1
2.273	25	2	1	1
2.364	26	3	1	1
2.455	27	3	1	1
2.545	28	3	1	1
2.636	29	3	1	1
2.727	30	3	1	1
2.818	31	3	1	1
2.909	32	3	1	1

Figure 13. Screenshot of the highway lane configuration in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

You will need to enter the highway configuration for each active lane in the model. Enter the value of 1 for open lanes, 2 to signal an upcoming closure of a lane, and 3 for the lane area closed by the construction zone.

Highway Configuration Parameters:

- Lane Configuration – the configuration of each active lane is determined by the values 1 through 3.
  1 – Lane is open to traffic
  2 – Lane is open to traffic with signs signaling that the lane will be closed ahead
  3 – Lane is closed to traffic in a construction zone

It is recommended that you save your scenario with a different file name before continuing.

4. Saving and Closing the Interface Spreadsheet

To save the simulation scenario inputs to a different file name, click on File -> Save As. Then, enter the name of the scenario file name as shown in Figure 14.

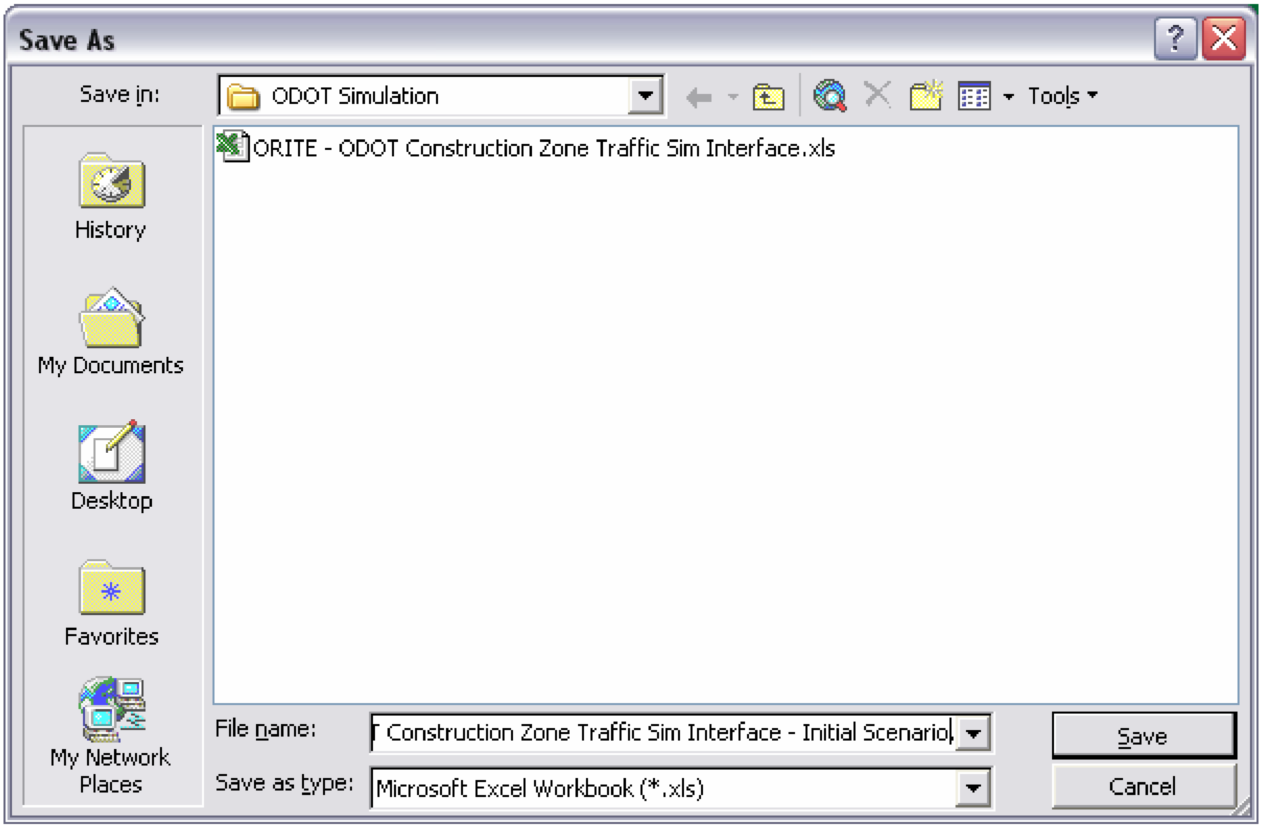


Figure 14. Screenshot of the save as function in Microsoft Excel for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

To close the interface spreadsheet, click on the Close button in the top right corner of the window, or click on File -> Exit. If you have not saved the scenario run already, click on the **Yes** button when prompted to save changes as shown in Figure 15.

Figure 15. Screenshot of the Microsoft Excel prompt for saving the file for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

5. Opening and Running the Simulation Model

Open the ORITE – ODOT Construction Zone Traffic Simulation model in Rockwell Software Arena by double-clicking on **ORITE – ODOT Construction Zone Traffic Simulation.doe** file as shown in Figure 16 in Your New Folder or by clicking on the Open button or choosing the menu File -> Open in Arena.

Figure 16. Screenshot of the Arena& the ORITE - ODOT Construction Zone Traffic simulation Program icon.

The simulation will open as shown in Figure 17.

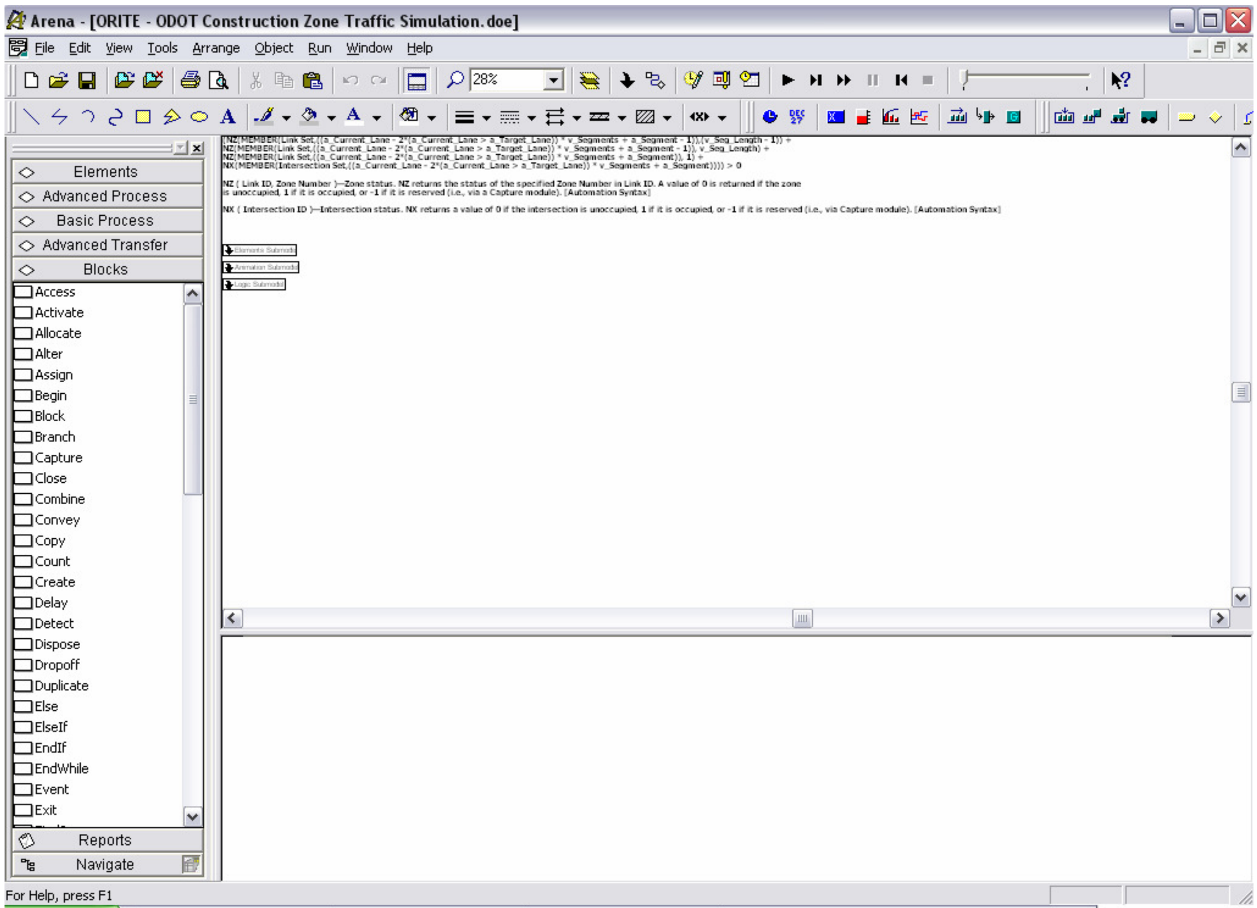


Figure 17. Screenshot of the Arena& the ORITE - ODOT Construction Zone Traffic simulation Program.

Before you start the simulation, you will need to select your populated interface spreadsheet file as the Excel Read File. Click on the button to the right of the Operating System File Name of the Excel Read File, and choose the scenario interface spreadsheet that you saved earlier. Then, click the **OK** Button as shown in Figure 18.

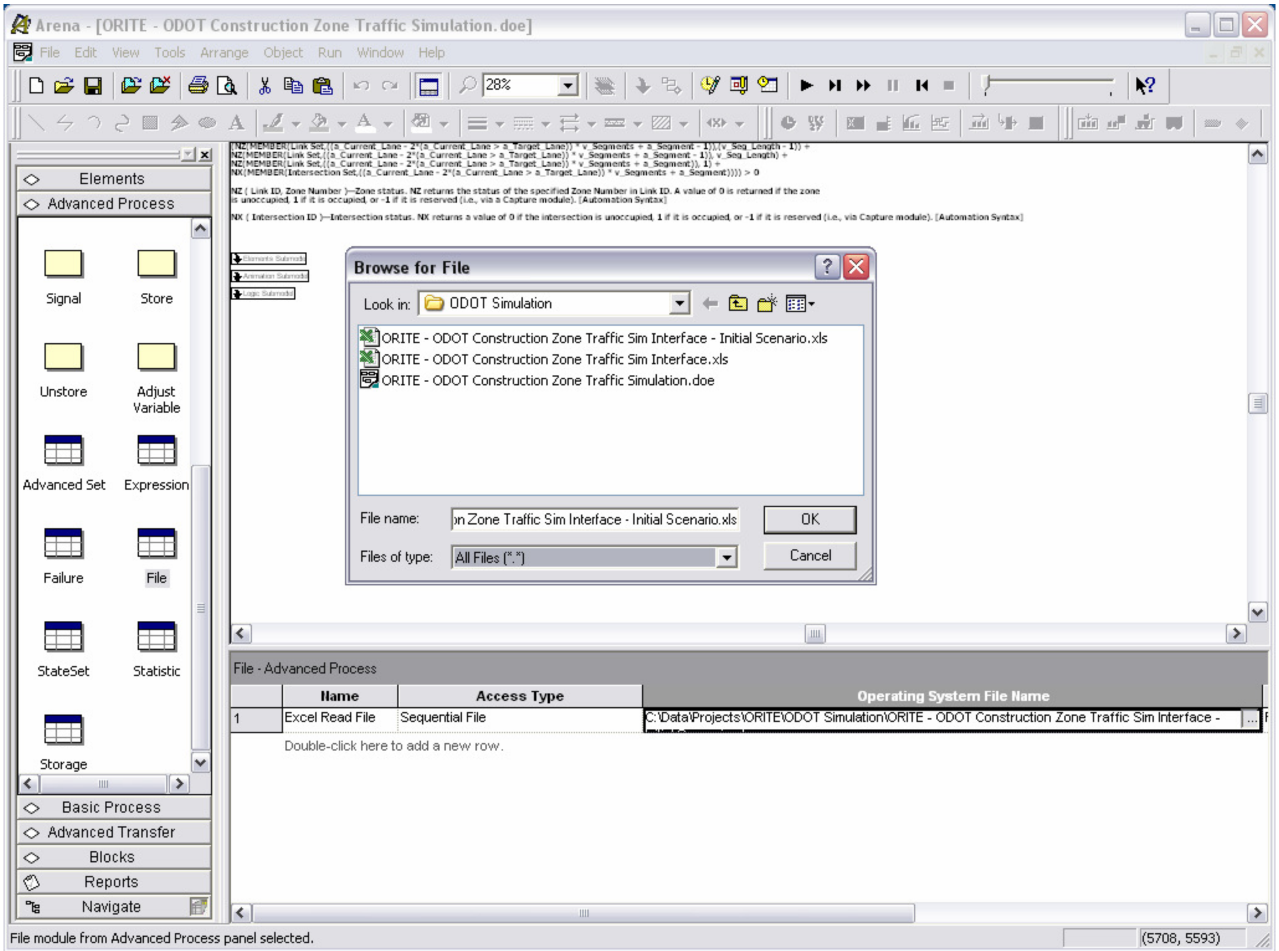


Figure 18. Screenshot of the read file browser for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program icon.

Before the simulation starts running, you will need to choose whether or not you want the model to run with animation. To run the model without animation, choose (check) menu Run -> Run Control -> Batch Run (No Animation). To run the model with animation, make sure that Batch Run is unchecked as shown in Figure 19.

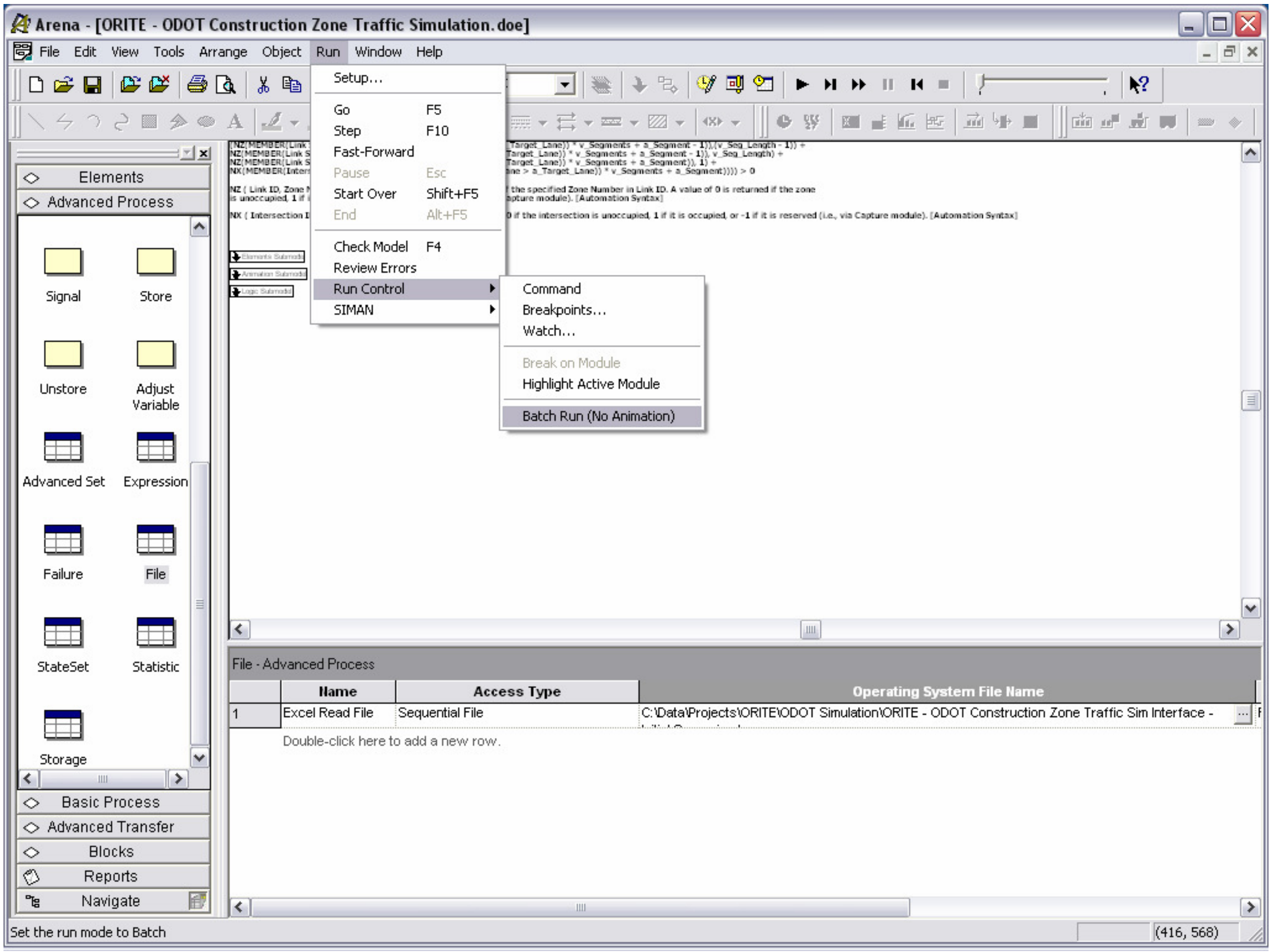


Figure 19. Screenshot of the animation option for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program icon.

When you are ready to run the simulation model, click on the Go button (►) on the Action Toolbar, Run -> Go, or the F5 key.

The simulation animation depicts traffic moving through the construction zone. You can zoom in to specific areas of the highway by using the eyeglass or by increasing the zoom percentage to the right of the eyeglass as shown in Figure 20.

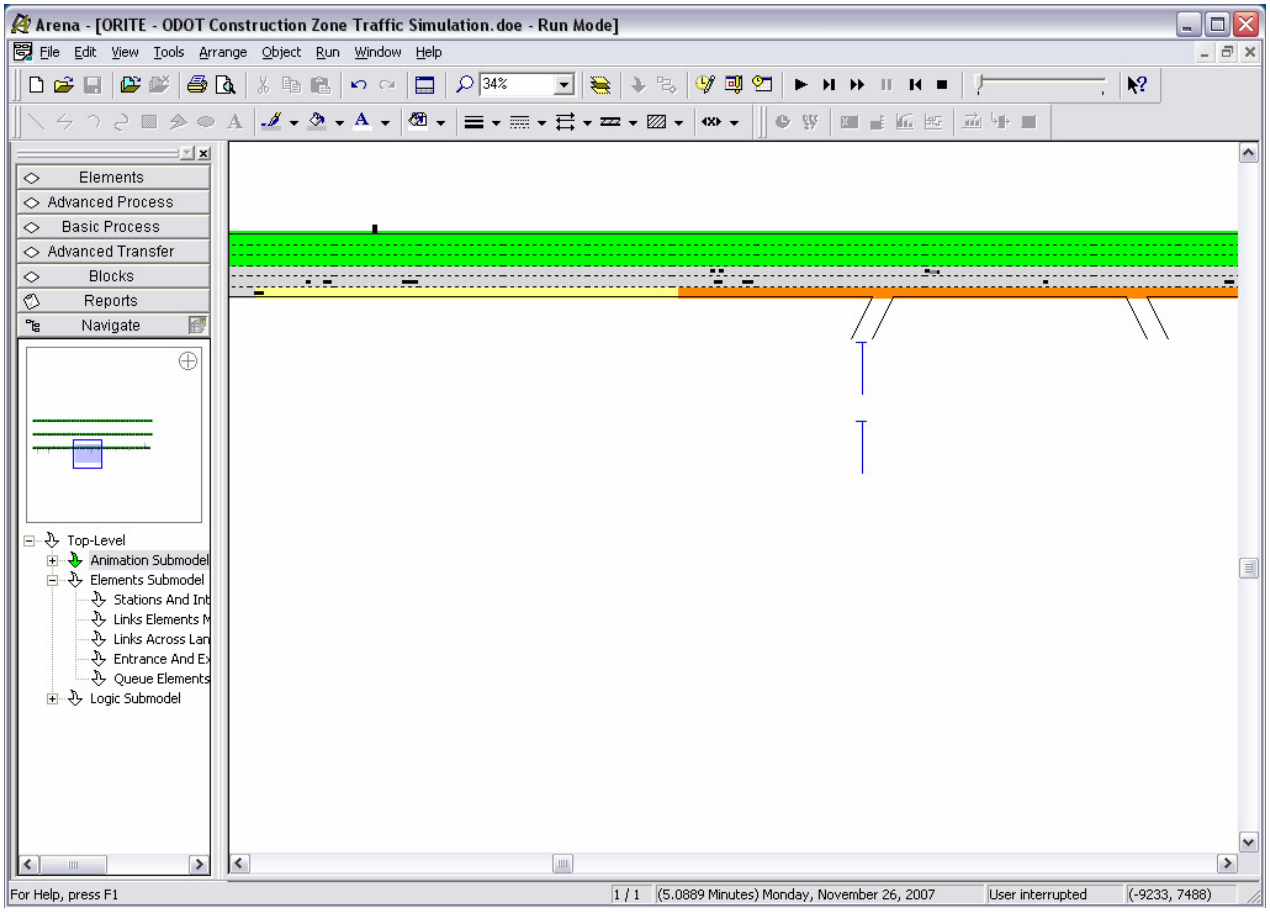


Figure 20. Screenshot of the animation for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program icon.

Once the simulation model has completed running (Replication Number will be N/N and an *End of run* will appear in the System Status), you will be prompted to examine the simulation results in Crystal Ball as shown in Figure 21. If you would like to review all of the output statistics from the simulation, click the **Yes** button. The key performance indicators from the simulation are also outputted to the Results worksheet of the interface spreadsheet.

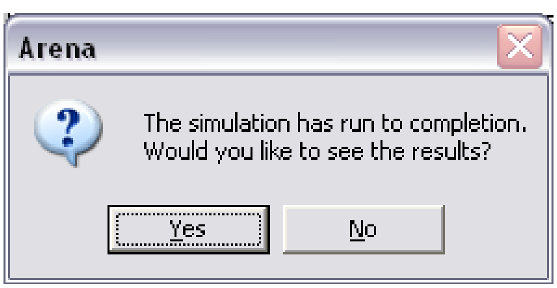


Figure 21. Screenshot of the results option for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program icon.

Close Arena and return to your interface spreadsheet. If prompted, you do not need to save any changes in Arena.

6. Reviewing the Simulation Scenario Results

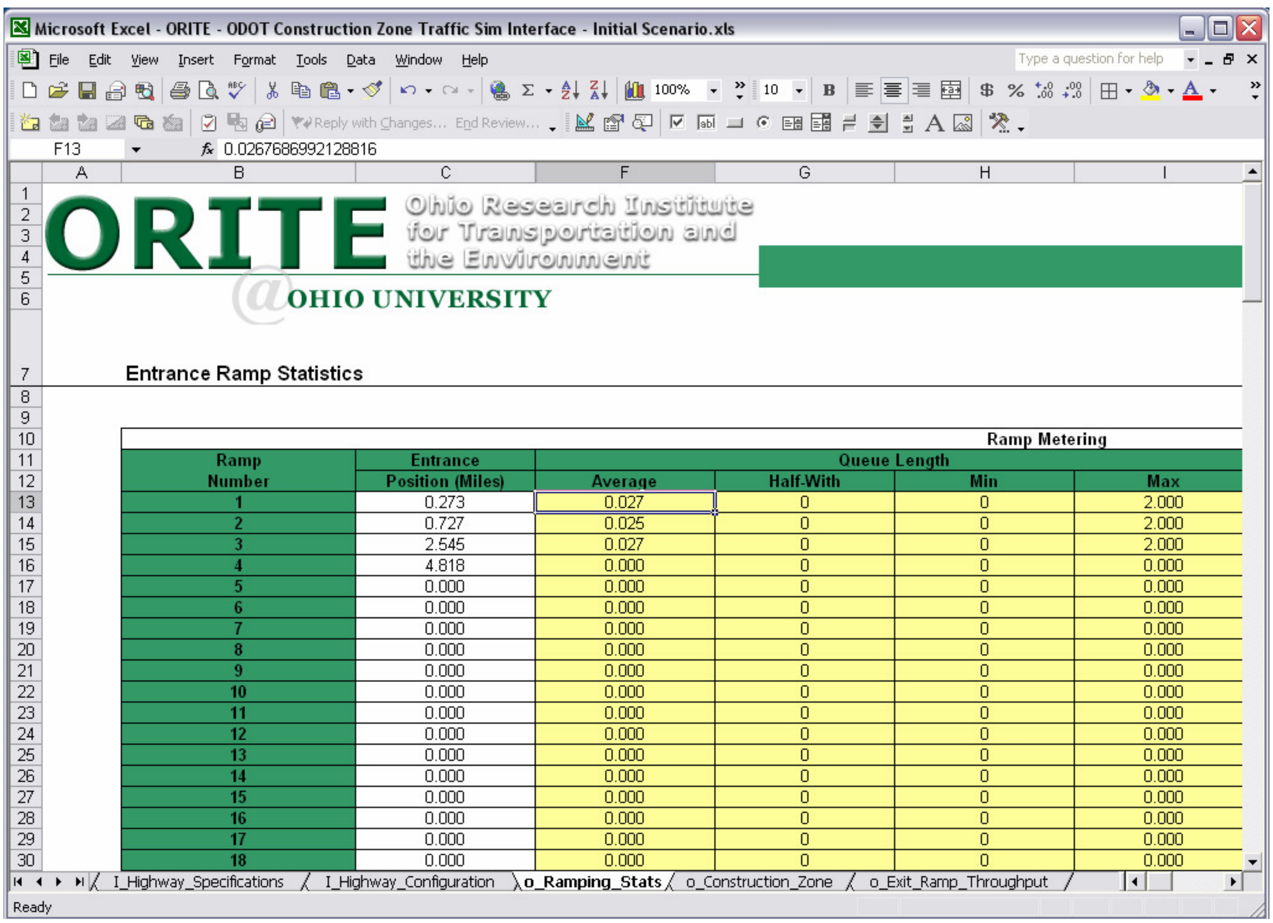
When you return to your scenario interface spreadsheet, the spreadsheet will be populated with model results. There are three results worksheets with aggregated model data for the key performance indicators for the ORITE – ODOT Construction Zone Traffic Simulation model.

The first results worksheet is the Entrance Ramp Statistics worksheet. It presents the queue statistics for each of the entrance ramps.

Entrance Ramp Statistics:

- Queue Length – the average, half-width, minimum, and maximum queue lengths in vehicles for each ramp
- Queue Waiting Time – the average, half-width, minimum, and maximum queue waiting time in minutes for each ramp

The second results worksheet focuses on construction zones queue statistics as shown in Figure 22.



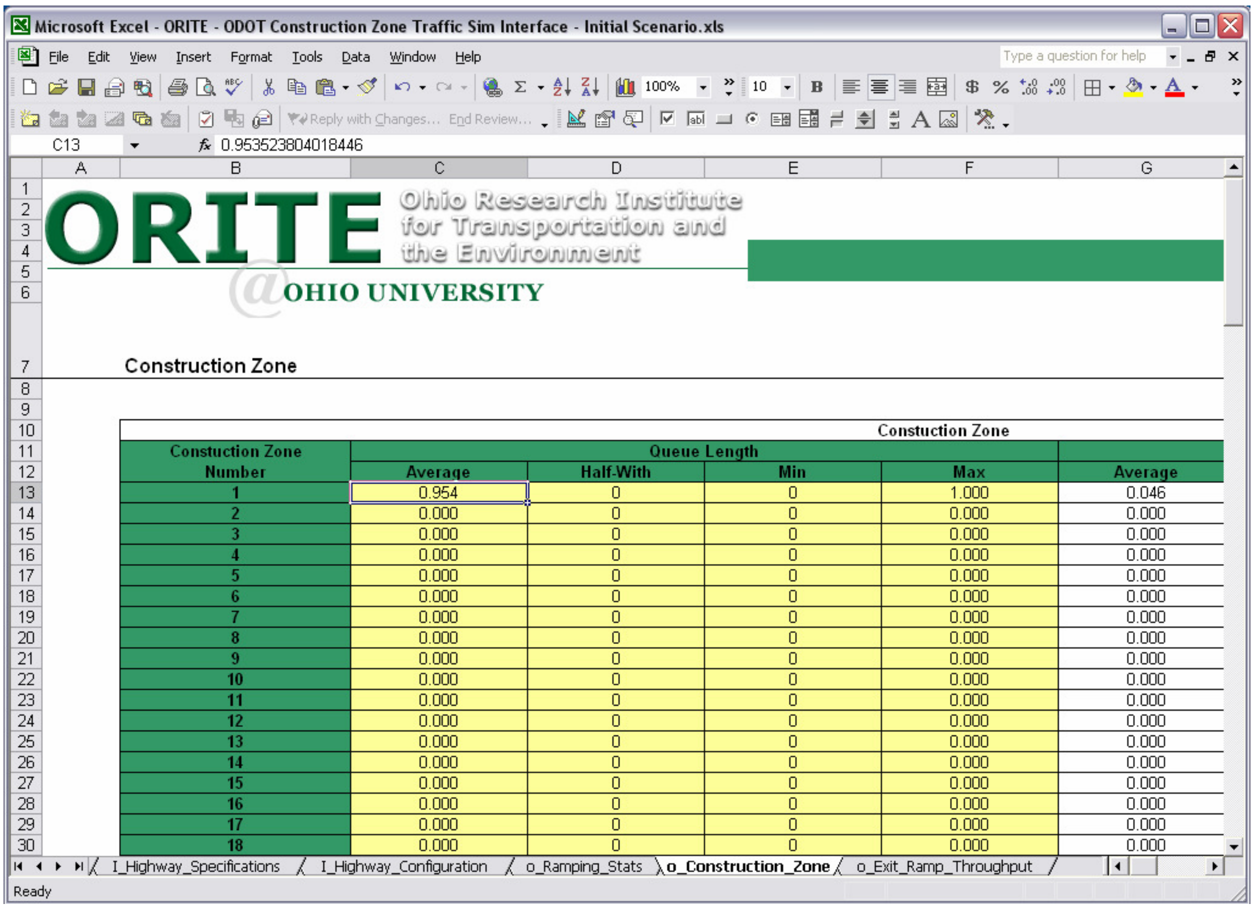
		Ramp Metering			
Ramp Number	Entrance Position (Miles)	Queue Length			
		Average	Half-With	Min	Max
1	0.273	0.027	0	0	2.000
2	0.727	0.025	0	0	2.000
3	2.545	0.027	0	0	2.000
4	4.818	0.000	0	0	0.000
5	0.000	0.000	0	0	0.000
6	0.000	0.000	0	0	0.000
7	0.000	0.000	0	0	0.000
8	0.000	0.000	0	0	0.000
9	0.000	0.000	0	0	0.000
10	0.000	0.000	0	0	0.000
11	0.000	0.000	0	0	0.000
12	0.000	0.000	0	0	0.000
13	0.000	0.000	0	0	0.000
14	0.000	0.000	0	0	0.000
15	0.000	0.000	0	0	0.000
16	0.000	0.000	0	0	0.000
17	0.000	0.000	0	0	0.000
18	0.000	0.000	0	0	0.000

Figure 22. Screenshot of the entrance ramp statistics worksheet for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program icon.

The second results worksheet is the Construction Zone Statistics worksheet. It presents the queue statistics for each of the construction zones in the model (up to 20) as shown in Figure 23.

Construction Zone Statistics:

- Queue Length – the average, half-width, minimum, and maximum queue lengths in vehicles for each construction zone
- Queue Waiting Time – the average, half-width, minimum, and maximum queue waiting time in minutes for each construction zone



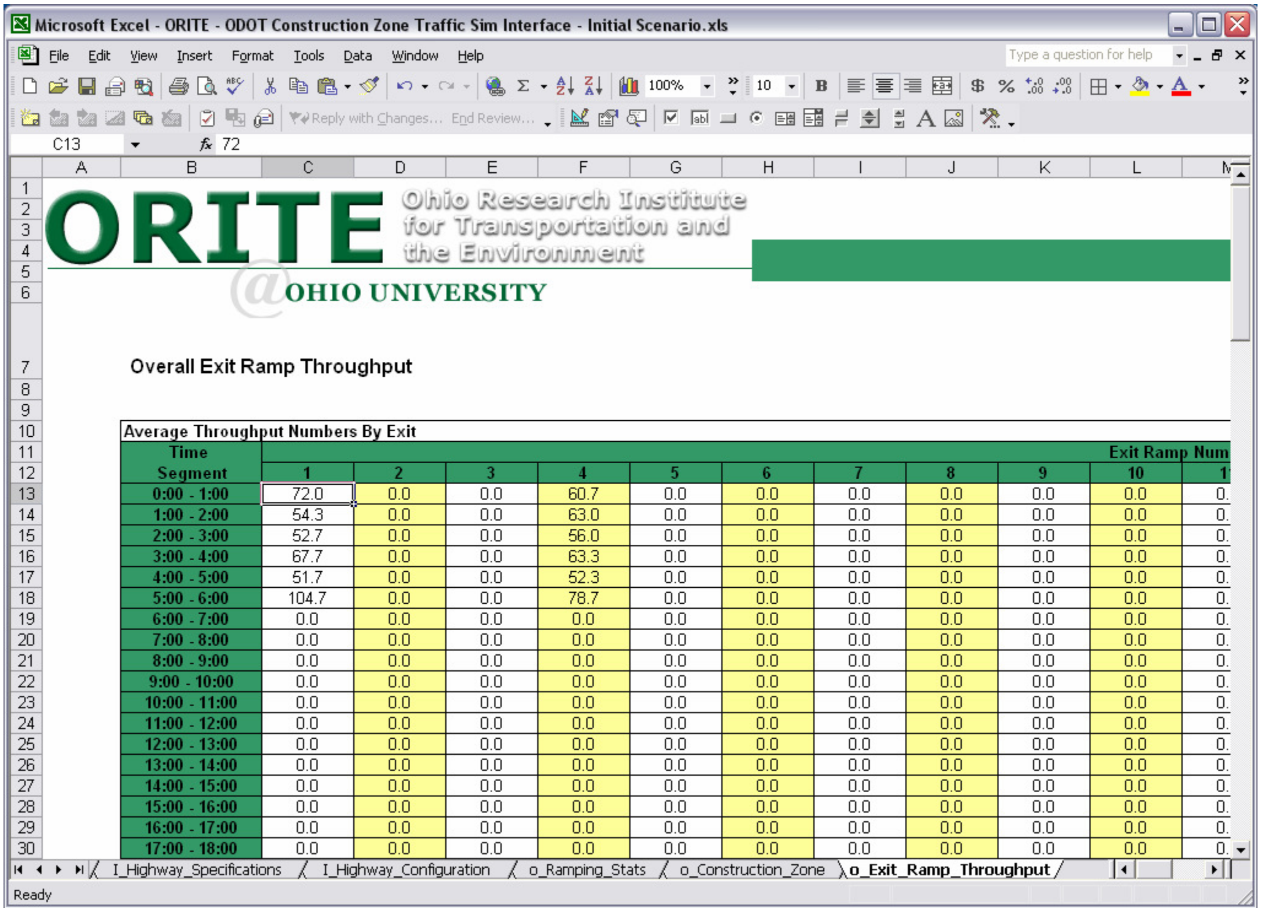
Constuction Zone Number	Queue Length				Constuction Zone
	Average	Half-With	Min	Max	Average
1	0.954	0	0	1.000	0.046
2	0.000	0	0	0.000	0.000
3	0.000	0	0	0.000	0.000
4	0.000	0	0	0.000	0.000
5	0.000	0	0	0.000	0.000
6	0.000	0	0	0.000	0.000
7	0.000	0	0	0.000	0.000
8	0.000	0	0	0.000	0.000
9	0.000	0	0	0.000	0.000
10	0.000	0	0	0.000	0.000
11	0.000	0	0	0.000	0.000
12	0.000	0	0	0.000	0.000
13	0.000	0	0	0.000	0.000
14	0.000	0	0	0.000	0.000
15	0.000	0	0	0.000	0.000
16	0.000	0	0	0.000	0.000
17	0.000	0	0	0.000	0.000
18	0.000	0	0	0.000	0.000

Figure 23. Screenshot of the construction zone statistics worksheet for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program icon.

The third results worksheet focuses on exit ramp throughput. The third results worksheet is the Exit Ramp Throughput Statistics worksheet. It presents the average throughput by exit ramp for each hour of the day as shown in Figure 24.

Exit Ramp Statistics:

- Average Throughput – the average throughput in vehicles per hour for each exit ramp



Average Throughput Numbers By Exit

Time Segment	1	2	3	4	5	6	7	8	9	10	1[illegible]
0:00 - 1:00	72.0	0.0	0.0	60.7	0.0	0.0	0.0	0.0	0.0	0.0	0.
1:00 - 2:00	54.3	0.0	0.0	63.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
2:00 - 3:00	52.7	0.0	0.0	56.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
3:00 - 4:00	67.7	0.0	0.0	63.3	0.0	0.0	0.0	0.0	0.0	0.0	0.
4:00 - 5:00	51.7	0.0	0.0	52.3	0.0	0.0	0.0	0.0	0.0	0.0	0.
5:00 - 6:00	104.7	0.0	0.0	78.7	0.0	0.0	0.0	0.0	0.0	0.0	0.
6:00 - 7:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
7:00 - 8:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
8:00 - 9:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
9:00 - 10:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
10:00 - 11:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
11:00 - 12:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
12:00 - 13:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
13:00 - 14:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
14:00 - 15:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
15:00 - 16:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
16:00 - 17:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.
17:00 - 18:00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.

Figure 24. Screenshot of the average throughput statistics worksheet for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program icon.

7. Closing the Interface Spreadsheet

To close the interface spreadsheet, click on the Close button in the top right corner of the window, or click on File -> Exit. If you have not saved the scenario run already, it is recommended that you click on the **Yes** button when prompted to save changes as shown in Figure 25. This will allow you to review your scenario's results again without re-running the model.

Figure 25. Screenshot of the save function for the Microsoft Excel worksheet for Arena& the ORITE - ODOT Construction Zone Traffic simulation Program icon.

2.4 Arena & the ORITE – ODOT Construction Zone Simulation Program Runs and Comparison of Results with Actual Queues

Arena simulation program was evaluated after each modification made by Rockwell Automation. Total of 93 simulation runs were performed for typical 3-lane work zone situation and 99 simulation runs were performed for 2-lane freeway work zone situations based on the Chitturi and Benekohal [8] and Schnell data [9]. The simulations were run for hourly traffic volumes based on the typical 3-lane work zone example, increased hourly traffic volumes (original traffic volumes multiplied by 1.19), original lead and lag gaps, revised lead and lag gaps, 50% and 25% of the original lead and lag gaps, original vehicle lengths, 1.5, 2, 2.5, 2.63, 2.7, 2.75, 3, and 3.5 times the original vehicle lengths, original vehicle speeds and 50% of the original vehicle speeds. In addition different input parameters were used for the Chitturi and Benekohal [8] and Schnell data [9] in order to replicate the actual queue length results as shown in Table 26.

2.4.1 Arena & the ORITE – ODOT Construction Zone Simulation Program Runs using Typical 3-Lane Work Zone Situation

Arena & the ORITE – ODOT Construction Zone Simulation Program was run for a typical 3-lane work zone situation. The Arena program queue lengths at the lane closure transition taper were compared with the Quickzone program queue length results for a typical 3-lane freeway work zone situation.

In addition to the comparison of the queue lengths, the number of vehicles generated by the Arena program was compared with the input data, the number of vehicles at the beginning of the work zone, number of vehicles at the end of the work zone, number of vehicles at the entrance ramps, and number of vehicles at the exit ramps were compared for each hour of the typical 3-lane freeway work zone situation for the input variables.

2.4.1.1 Construction zone configuration for typical 3-lane work zone reduced to 2 lanes

The Arena simulation program input parameters were configured as given in Section 2.2.1 work zone configuration to establish the typical 3-lane freeway work zone situation.

The original vehicle speeds and the vehicle lengths along with the required lead gaps and lag gaps for merging are given in Table 15 and Table 16 for the typical 3-lane freeway work zone situation used in the Arena simulation program evaluation. Number of Arena simulation runs was performed in order to identify the effects of the changes in the vehicle speeds and vehicle lengths on the queue length and the vehicle numbers.

Table 15. Original Vehicle Speeds used for Typical 3-lane Freeway Work Zone Situation

Car Velocity				
Lane Number	Free Flowing Traffic		Construction Zone / Reduced speed	
	Average Speed (feet/second)	Standard Deviation (feet/second)	Average Speed (feet/second)	Standard Deviation (feet/second)
1	74.8	5.9	74.8	5.9
2	79.0	5.9	79.0	5.9
3	89.5	4.4	89.5	4.4
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
Truck Velocity				
Lane Number	Free Flowing Traffic		Construction Zone / Reduced speed	
	Average Speed (feet/second)	Standard Deviation (feet/second)	Average Speed (feet/second)	Standard Deviation (feet/second)
1	74.8	5.9	74.8	5.9
2	79.0	5.9	79.0	5.9
3	89.5	4.4	89.5	4.4
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
Maximum speed difference per lane (number of standard deviations)				3

Table 16. Original Lead and Lag Gaps used for Typical 3-lane Freeway Work Zone Situation

Vehicle Sizing				
Vehicle Type	Size in feet			
Car	20			
Truck	60			
Lane changing vehicle is moving at a higher velocity than lane traffic				
Speed	Lead Gap (feet)	Lag Gap (feet)	Car Total (feet)	Truck Total (feet)
Speed<=10 ft/s	40	5	65	105
10 ft/s<Speed<=35 ft/s	65	10	95	135
35 ft/s<Speed<=55 ft/s	100	20	140	180
55 ft/s<Speed<=75 ft/s	130	20	170	210
75 ft/s<Speed	165	30	215	255
Lane changing vehicle is moving at a lower velocity than lane traffic				
Speed	Lead Gap (feet)	Lag Gap (feet)	Car Total (feet)	Truck Total (feet)
Speed<=10 ft/s	5	40	65	105
10 ft/s<Speed<=35 ft/s	10	65	95	135
35 ft/s<Speed<=55 ft/s	20	100	140	180
55 ft/s<Speed<=75 ft/s	20	130	170	210
75 ft/s<Speed	30	165	215	255

2.4.1.2 Analysis of Arena & the ORITE – ODOT Construction Zone Simulation Results

The results of the Arena simulation program for a typical 3-lane freeway work zone situation are given in Table 17 through Table 21 after running an extensive number of ARENA and Quickzone simulations (each Arena replication for the 3- lane work zone example takes more than 300 minutes and for the 2-lane example more than 30 to 60 minutes).

The comparison of the maximum queue length results of the Arena simulation program and the Quickzone program showed that the Arena program always generates shorter queue lengths than the Quickzone program. Table 17 shows the maximum queue length results for the Arena simulation program and the Quickzone program for different vehicle lengths, different vehicle speeds, different lead and lag gaps, and increased hourly traffic volumes. It appears that changing the vehicle lengths, lead and lag gaps, and vehicle speeds can really not account for generating longer and more reasonable queues because in all cases Arena simulation program generated very short maximum queues compared to Quickzone simulation program maximum queue output. Arena program generated queue lengths 51.8 to 6.6 times shorter than the Quickzone queue lengths.

The comparison of the number of the vehicles at the beginning of the work zone is given in Table 18. The number of vehicles at the beginning of the work zone input was compared with the Arena simulation program output for the number of vehicles at the beginning of the work zone. The difference between the number of vehicles at the beginning input and the Arena output were very small changing between -1.04% to 1.05% for different vehicle lengths, different vehicle speeds, different lead and lag gaps, and increased hourly traffic volumes. It appears that Arena generates the vehicles at the beginning of the simulation run according to the input data used.

The comparison of the number of the vehicles at the end of the work zone for a typical 3-lane work zone situation is given in Table 19. The number of vehicles at the end of the work zone input was compared with the Arena simulation program output for the number of vehicles at the end of the work zone. The difference between the number of vehicles at the end input and the Arena output were between -1.10% to 8.88% for different vehicle lengths, different vehicle speeds, different lead and lag gaps, and increased hourly traffic volumes. It appears that Arena output for number of vehicles at the end of the work zone is not as accurate as it is for the number of vehicles at the beginning of the work zone.

The comparison of the number of the vehicles at the entrance ramps for a typical 3-lane work zone situation is given in Table 20. The number of vehicles at the entrance ramp input was compared with the Arena simulation program output for the number of vehicles at the entrance ramp. The difference between the number of vehicles at the entrance ramp input and the Arena output were between -14.85% to 1.28% for different vehicle lengths, different vehicle speeds, different lead and lag gaps, and increased hourly traffic volumes. It appears that Arena output for number of vehicles at the entrance ramp is smaller than the expected output values and is not as accurate as it is for the number of vehicles at the beginning of the work zone.

The comparison of the number of the vehicles at the exit ramps for a typical 3-lane work zone situation is given in Table 21. The number of vehicles at the exit ramp input was compared with the Arena simulation program output for the number of vehicles at the exit ramp. The difference between the number of vehicles at the exit ramp input and the Arena output were between -40.37% to 2.55% for different vehicle lengths, different vehicle speeds, different lead and lag gaps, and increased hourly traffic volumes. It appears that Arena output for number of vehicles at the exit ramp is not very accurate especially when the exit ramps are located closely.

The Arena simulation program always generates shorter queues than the Quickzone program and there appears to be a problem with the Arena program in terms of queue lengths.

The Arena simulation program generates fairly accurate number of vehicles at the beginning of the work zone and at the entrance ramps when the input and output vehicle numbers are compared. However there appears to be a problem in the number of vehicles at the exit ramps and at the end of the work zone when the input and output vehicle numbers are compared. It appears that the vehicles cannot exit according to the input variables when the exit ramps are located closely (less than 1.5 miles), which results in fairly large differences between the input and output vehicle numbers at the end of the work zone and at the exit ramps.

It also appears that changing lead and lag gaps, vehicle lengths, and vehicle speeds can really not account for getting longer and more reasonable queue lengths. They would further increase the vehicle number percentage differences for vehicles exiting when there are short distances between the ramps.

Table 17. ARENA and Quickzone Maximum Queue Simulation Results

Multiplication Factor for Vehicle Lengths (Original Car Length = 20 feet, Truck Length = 60 feet)	Maximum Queue Length (feet) - Average of Replications	Replication 1	Replication 2	Replication 3	QuickZone Max Queue (Miles/feet)
Vehicle Length Multiplication Factor = 1	187	180	160	220	1.44(7603)
Vehicle Length Multiplication Factor = 2	1040				2.88(15206)
Vehicle Length Multiplication Factor = 2.5	1750	1950	900	2400	3.58(18902)
Vehicle Length Multiplication Factor = 2.63	9297	9577	9210	9105	3.8(20064)
Vehicle Length Multiplication Factor = 2.7	8892	10476	8262	7938	3.87(20434)
Vehicle Length Multiplication Factor = 2.75	8580				3.96(20909)
Vehicle Length Multiplication Factor = 3	10260				4.32(22810)
Vehicle Length Multiplication Factor = 3.5	10710	10570	9870	11690	5.06(26717)
½ times the Original Speeds (average speed , standard deviation) – Vehicle Length Multiplication Factor = 1	380	640	240	260	1.44(7603)
Vehicle Length Multiplication Factor = 1 (Revised lead and lag gaps)	200	240	160	200	1.44(7603)
½ times the Original Merging Gaps (lead gap, lag gap) – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	153	180	140	140	*
½ times the Original Speeds in Construction Zone – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	227	260	180	240	1.44(7603)
½ times the Original Speeds in Construction Zone and Gaps – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	187	200	180	180	*
Merging Gaps Changed- Rockwell Suggested (lead gap, lag gap) (N = 3 Replications) – (Speed not changed, same as before)	833	840	1020	640	*
Speeds Changed - Rockwell Suggested – Vehicle Length Multiplication Factor = 1 (N = 3 Replications) - (Merging gaps not changed, same as before)	147	180	120	140	1.44(7603)
Merging Gaps and Speeds Changed - Rockwell Suggested (N = 3 Replications)	1147	1620	640	1200	*
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 1	227	180	240	260	6.06(31997)
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 2.5	6917	6500	7650	6600	15.08(79622)

* Simulation cannot be run with Quickzone due to input data entry limitations of Quickzone.

Table 18. Comparison of ARENA Input and ARENA Output for Mainline Hourly Traffic Volumes at the Beginning of the 3-lane Work Zone Situation for 19 hrs (5:00 AM to 12:00 AM)

	Mainline at the Beginning ARENA Output			Mainline at the Beginning (Expected Output			Percent Difference ((Output - Input)/Input)		
Multiplication Factor for Vehicle Lengths (Original Car Length = 20 feet, Truck Length = 60 feet)	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3	Lane 1	Lane 2	Lane 3
Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	11973	17636	15376	11979	17634	15256	-0.05%	0.01%	0.79%
Vehicle Length Multiplication Factor = 2 (N = 1 Replication)	11972	17547	15400	11979	17634	15256	-0.06%	-0.49%	0.94%
Vehicle Length Multiplication Factor = 2.5 (N = 3 Replications)	11932	17690	15300	11979	17634	15256	-0.40%	0.32%	0.29%
Vehicle Length Multiplication Factor = 2.63 (N = 3 Replications)	11882	17558	15195	11979	17634	15256	-0.81%	-0.43%	-0.40%
Vehicle Length Multiplication Factor = 2.7 (N = 3 Replications)	11878	17773	15235	11979	17634	15256	-0.85%	0.79%	-0.14%
Vehicle Length Multiplication Factor = 2.75 (N = 1 Replication)	11920	17727	15160	11979	17634	15256	-0.49%	0.53%	-0.63%
Vehicle Length Multiplication Factor = 3 (N = 1 Replication)	11904	17558	15098	11979	17634	15256	-0.63%	-0.43%	-1.04%
Vehicle Length Multiplication Factor = 3.5 (N = 3 Replications)	11904	17612	15278	11979	17634	15256	-0.63%	-0.12%	0.14%
½ times the Original Speeds (average speed , standard deviation) – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	11914	17645	15132	11979	17634	15256	-0.54%	0.06%	-0.81%
Vehicle Length Multiplication Factor = 1 (Revised lead and lag gaps)	11977	17612	15182	11979	17634	15256	-0.01%	-0.12%	-0.48%

Table 18. Comparison of ARENA Input and ARENA Output for Mainline Hourly Traffic Volumes at the Beginning of the 3-lane Work Zone Situation for 19 hrs (5:00 AM to 12:00 AM) (cont.)

	Mainline at the Beginning ARENA Output			Mainline at the Beginning (Expected Output			Percent Difference ((Output - Input)/Input)		
½ times the Original Merging Gaps (lead gap, lag gap) – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	11973	17712	15385	11979	17634	15256	-0.05%	0.44%	0.85%
½ times the Original Speeds in Construction Zone – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	12005	17613	15175	11979	17634	15256	0.22%	-0.12%	-0.53%
½ times the Original Speeds in Construction Zone and Gaps – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	11952	17700	15309	11979	17634	15256	-0.23%	0.37%	0.35%
Merging Gaps - Rockwell Suggested (lead gap, lag gap) (N = 3 Replications)	11905	17689	15269	11979	17634	15256	-0.62%	0.31%	0.08%
Speeds - Rockwell Suggested – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	11990	17818	15234	11979	17634	15256	0.09%	1.05%	-0.15%
Merging Gaps and Speeds - Rockwell Suggested (N = 3 Replications)	12003	17590	15242	11979	17634	15256	0.20%	-0.25%	-0.09%
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	14248	20943	18195	14255	20984	18155	-0.05%	-0.20%	0.22%
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 2.5 (N = 3 Replications)	14310	20989	18172	14255	20984	18155	0.38%	0.02%	0.10%

Table 19. Comparison of ARENA Input and ARENA Output for Mainline Hourly Traffic Volumes at the End of the 3-lane Work Zone Situation for 19 hrs (5:00 AM to 12:00 AM)

	Mainline at the End ARENA Output				Mainline at the End (Expected Output)	Percent Difference ((Output - Input)/Input)
Multiplication Factor for Vehicle Lengths (Original Car Length = 20 feet, Truck Length = 60 feet)	Lane 1	Lane 2	Lane 3	Total	Total	Total
Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	15143	25229	8321	48693	47682	2.12%
Vehicle Length Multiplication Factor = 2 (N = 1 Replication)	15047	25248	9131	49426	47682	3.66%
Vehicle Length Multiplication Factor = 2.5 (N = 3 Replications)	14992	25930	9526	50448	47682	5.80%
Vehicle Length Multiplication Factor = 2.63 (N = 3 Replications)	15082	26164	9804	51050	47682	7.06%
Vehicle Length Multiplication Factor = 2.7 (N = 3 Replications)	15129	26322	9921	51372	47682	7.74%
Vehicle Length Multiplication Factor = 2.75 (N = 1 Replication)	15048	26147	9922	51117	47682	7.20%
Vehicle Length Multiplication Factor = 3 (N = 1 Replication)	15124	26190	9948	51262	47682	7.51%
Vehicle Length Multiplication Factor = 3.5 (N = 3 Replications)	15143	25229	8321	48693	47682	2.12%
Vehicle Length Multiplication Factor = 1 (Revised lead and lag gaps)	15006	25540	8558	49105	47682	2.98%
½ times the Original Speeds (average speed , standard deviation) – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	14529	25931	9695	50155	47682	5.19%

Table 19. Comparison of ARENA Input and ARENA Output for Mainline Hourly Traffic Volumes at the End of the 3-lane Work Zone Situation for 19 hrs (5:00 AM to 12:00 AM) (cont.)

	Mainline at the End ARENA Output				Mainline at the End (Expected Output)	Percent Difference ((Output - Input)/Input)
½ times the Original Merging Gaps (lead gap, lag gap) – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	15411	24936	7865	48212	47682	-1.10%
½ times the Original Speeds in Construction Zone – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	15312	24757	8049	48118	47682	0.91%
½ times the Original Speeds in Construction Zone and Gaps – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	15643	24664	7705	48012	47682	0.69%
Merging Gaps - Rockwell Suggested (lead gap, lag gap) (N = 3 Replications)	15310	25491	8545	49346	47682	3.49%
Speeds - Rockwell Suggested – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	15394	25479	8118	48992	47682	2.75%
Merging Gaps and Speeds - Rockwell Suggested (N = 3 Replications)	15302	25784	8625	49711	47682	4.26%
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	17860	30065	10209	58134	56741	2.45%
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 2.5 (N = 3 Replications)	18198	31547	12036	61781	56741	8.88%

Table 20. Comparison of ARENA Input and ARENA Output for Entrance Ramp Hourly Traffic Volumes for 3-lane Work Zone Situation for 19 hrs (5:00 AM to 12:00 AM)

	Entrance Ramp ARENA Output					Entrance Ramp (Expected Output)					Percent Difference ((Output - Input)/Input)				
Multiplication Factor for Vehicle Lengths (Original Car Length = 20 feet, Truck Length = 60 feet)	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5
Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	3292	1658	4782	13359	6848	3250	1688	4845	13376	6916	1.28%	-1.76%	-1.29%	-0.13%	-0.98%
Vehicle Length Multiplication Factor = 2 (N = 1 Replication)	3164	1675	4710	13172	6935	3250	1688	4845	13376	6916	-2.65%	-0.77%	-2.79%	-1.53%	0.27%
Vehicle Length Multiplication Factor = 2.5 (N = 3 Replications)	3243	1671	4873	13417	6973	3250	1688	4845	13376	6916	-0.21%	-0.99%	0.57%	0.31%	0.82%
Vehicle Length Multiplication Factor = 2.63 (N = 3 Replications)	3235	1661	4853	13385	6847	3250	1688	4845	13376	6916	-0.45%	-1.60%	0.17%	0.06%	-0.99%
Vehicle Length Multiplication Factor = 2.7 (N = 3 Replications)	3218	1690	4857	13383	6855	3250	1688	4845	13376	6916	-0.98%	0.14%	0.24%	0.05%	-0.88%
Vehicle Length Multiplication Factor = 2.75 (N = 1 Replication)	3255	1667	4822	13150	6703	3250	1688	4845	13376	6916	0.15%	-1.24%	-0.47%	-1.69%	-3.08%
Vehicle Length Multiplication Factor = 3 (N = 1 Replication)	3105	1701	4799	13348	6872	3250	1688	4845	13376	6916	-4.46%	0.77%	-0.95%	-0.21%	-0.64%
Vehicle Length Multiplication Factor = 3.5 (N = 3 Replications)	3196	1656	4815	11389	6041	3250	1688	4845	13376	6916	-1.65%	-1.90%	-0.61%	-14.85%	-12.65%
Vehicle Length Multiplication Factor = 1 (Revised lead and lag gaps)	3194	1670	4767	13430	6926	3250	1688	4845	13376	6916	-1.73%	-1.07%	-1.61%	0.41%	0.14%

Table 20. Comparison of ARENA Input and ARENA Output for Entrance Ramp Hourly Traffic Volumes for 3-lane Work Zone Situation for 19 hrs (5:00 AM to 12:00 AM) (cont.)

	Entrance Ramp ARENA Output					Entrance Ramp (Expected Output)					Percent Difference ((Output - Input)/Input)				
	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5
½ times the Original Speeds (average speed , standard deviation) – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	3192	1644	4716	13297	6864	3250	1688	4845	13376	6916	-1.78%	-2.59%	-2.66%	-0.59%	-0.76%
½ times the Original Merging Gaps (lead gap, lag gap) – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	3179	1652	4783	13340	6881	3250	1688	4845	13376	6916	-2.19%	-2.13%	-1.27%	-0.27%	-0.51%
½ times the Original Speeds in Construction Zone – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	3258	1611	4736	13345	6829	3250	1688	4845	13376	6916	0.25%	-4.54%	-2.26%	-0.23%	-1.26%
½ times the Original Speeds in Construction Zone and Gaps – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	3158	1699	4786	13291	6950	3250	1688	4845	13376	6916	-2.82%	0.63%	-1.22%	-0.64%	0.49%
Merging Gaps - Rockwell Suggested (lead gap, lag gap) (N = 3 Replications)	3245	1685	4787	13331	6921	3250	1688	4845	13376	6916	-0.14%	-0.20%	-1.19%	-0.34%	0.08%
Speeds - Rockwell Suggested – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	3194	1652	4861	13395	6930	3250	1688	4845	13376	6916	-1.72%	-2.11%	0.32%	0.14%	0.20%
Merging Gaps and Speeds - Rockwell Suggested (N = 3 Replications)	3256	1692	4761	13385	6866	3250	1688	4845	13376	6916	0.18%	0.22%	-1.73%	0.07%	-0.72%
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	3859	1948	5669	15883	8107	3868	2009	5766	15917	8230	-0.21%	-3.04%	-1.67%	-0.22%	-1.50%
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 2.5 (N = 3 Replications)	3840	1986	5739	15959	8084	3868	2009	5766	15917	8230	-0.70%	-1.13%	-0.46%	0.26%	-1.78%

Table 21. Comparison of ARENA Input and ARENA Output for Exit Ramp Hourly Traffic Volumes for 3-lane Work Zone Situation for 19 hrs (5:00 AM to 12:00 AM)

	Exit Ramp ARENA Output					Exit Ramp (Expected Output)					Percent Difference ((Output - Input)/Input)				
Multiplication Factor for Vehicle Lengths (Original Car Length = 20 feet, Truck Length = 60 feet)	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5
Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	5807	2108	10002	4520	3696	6334	2072	10034	4534	4288	-8.31%	1.74%	-0.32%	-0.30%	-13.81%
Vehicle Length Multiplication Factor = 2 (N = 1 Replication)	5276	2066	9652	4464	3575	6334	2072	10034	4534	4288	-16.70%	-0.30%	-3.81%	-1.53%	-16.63%
Vehicle Length Multiplication Factor = 2.5 (N = 3 Replications)	4955	2021	9501	4447	3616	6334	2072	10034	4534	4288	-21.77%	-2.46%	-5.32%	-1.91%	-15.68%
Vehicle Length Multiplication Factor = 2.63 (N = 3 Replications)	4462	1762	9228	4424	3617	6334	2072	10034	4534	4288	-29.55%	-14.95%	-8.04%	-2.42%	-15.66%
Vehicle Length Multiplication Factor = 2.7 (N = 3 Replications)	4325	1709	9303	4488	3589	6334	2072	10034	4534	4288	-31.71%	-17.51%	-7.29%	-1.01%	-16.31%
Vehicle Length Multiplication Factor = 2.75 (N = 1 Replication)	4278	1718	9183	4460	3541	6334	2072	10034	4534	4288	-32.46%	-17.09%	-8.49%	-1.62%	-17.43%
Vehicle Length Multiplication Factor = 3 (N = 1 Replication)	4156	1661	9195	4511	3499	6334	2072	10034	4534	4288	-34.39%	-19.84%	-8.37%	-0.50%	-18.40%
Vehicle Length Multiplication Factor = 3.5 (N = 3 Replications)	3777	1476	8953	4397	3522	6334	2072	10034	4534	4288	-40.37%	-28.76%	-10.78%	-3.02%	-17.86%
Vehicle Length Multiplication Factor = 1 (Revised lead and lag gaps)	5711	2098	9655	4512	3572	6334	2072	10034	4534	4288	-9.83%	1.23%	-3.78%	-0.47%	-16.71%
½ times the Original Speeds (average speed , standard deviation) – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	5065	2073	8907	4465	3536	6334	2072	10034	4534	4288	-20.04%	0.05%	-11.23%	-1.52%	-17.54%
½ times the Original Merging Gaps (lead gap, lag gap) – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	6021	2125	9954	4551	3944	6334	2072	10034	4534	4288	-4.95%	2.55%	-0.80%	0.39%	-8.04%

Table 21. Comparison of ARENA Input and ARENA Output for Exit Ramp Hourly Traffic Volumes for 3-lane Work Zone Situation for 19 hrs (5:00 AM to 12:00 AM) (cont.)

	Exit Ramp ARENA Output					Exit Ramp (Expected Output)					Percent Difference ((Output - Input)/Input)				
Multiplication Factor for Vehicle Lengths (Original Car Length = 20 feet, Truck Length = 60 feet)	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5	Ramp 1	Ramp 2	Ramp 3	Ramp 4	Ramp 5
½ times the Original Speeds in Construction Zone – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	5737	2023	10099	4559	3898	6334	2072	10034	4534	4288	-9.42%	-2.39%	0.64%	0.56%	-9.10%
½ times the Original Speeds in Construction Zone and Gaps – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	5985	2071	10082	4508	4050	6334	2072	10034	4534	4288	-5.50%	-0.06%	0.47%	-0.56%	-5.56%
Merging Gaps - Rockwell Suggested (lead gap, lag gap) (N = 3 Replications)	5537	2079	9523	4387	3873	6334	2072	10034	4534	4288	-12.58%	0.34%	-5.10%	-3.23%	-9.69%
Speeds - Rockwell Suggested – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	5719	2102	9863	4462	3846	6334	2072	10034	4534	4288	-9.70%	1.45%	-1.71%	-1.58%	-10.31%
Merging Gaps and Speeds - Rockwell Suggested (N = 3 Replications)	5479	2083	9153	4379	3895	6334	2072	10034	4534	4288	-13.49%	0.54%	-8.78%	-3.42%	-9.18%
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 1 (N = 3 Replications)	6710	2503	11742	5382	4267	7537	2466	11941	5395	5103	-10.98%	1.52%	-1.67%	-0.23%	-16.38%
1.19 times the Original Vehicle Counts – Vehicle Length Multiplication Factor = 2.5 (N = 3 Replications)	4778	1866	10985	5355	4213	7537	2466	11941	5395	5103	-36.61%	-24.34%	-8.01%	-0.75%	-17.45%

The Arena simulation program was also run for 2-lane freeway work zone situations based on the data from the literature [8, 9], where actual queue lengths were recorded by the researchers.

The Arena simulation program was run according to the traffic conditions given in the study by Chitturi and Benekohal [8] and the Arena program output for maximum queue lengths were compared with the actual queue lengths observed in the field by Chitturi and Benekohal.

In Table 22, the Arena simulation program queue lengths using the same average speed before the work zone and in the work zone situations and for the given hourly traffic volumes and truck percentages in Chitturi and Benekohal [8] were compared with the actual queue lengths observed in the field by Chitturi and Benekohal. The Arena queue lengths were 85.15% to 93.87% shorter than the observed queue lengths in the field.

In Table 23, the Arena simulation program queue lengths using different average speed before the work zone and in the work zone situations and for the given hourly traffic volumes and truck percentages in Chitturi and Benekohal [8] were compared with the actual queue lengths observed in the field by Chitturi and Benekohal. The Arena queue lengths were 97.45% to 98.74% shorter than the observed queue lengths in the field.

In Table 24, the Arena simulation program queue lengths using different average speed before the work zone and in the work zone situations and for the given hourly traffic volumes and truck percentages in Chitturi and Benekohal [8] were compared with the actual queue lengths observed in the field by Chitturi and Benekohal. In addition, the lead and lag gaps were revised in the Arena simulation program based on the critical gap acceptance values from a study by Lee [10]. The Arena queue lengths were 98.11% to 98.91% shorter than the observed queue lengths in the field.

In Table 25, the Arena simulation program queue lengths using different average speed before the work zone and in the work zone situations and for the given hourly traffic volumes and truck percentages in Chitturi and Benekohal [8] were compared with the actual queue lengths observed in the field by Chitturi and Benekohal. In addition, the lead and lag gaps were revised in the Arena simulation program based on the critical gap acceptance values from a study by Lee [10] and 1.5 times the original vehicles lengths (original vehicle lengths; car=20 ft, truck=60 ft) were used. The Arena queue lengths were 97.14% to 98.39% shorter than the observed queue lengths in the field.

In Table 26, the Arena simulation program queue lengths for the Chitturi and Benekohal [8] site 1, 2nd hour data were compared with the actual queue length data for different vehicle lengths and lead and lag gaps. The Arena queue lengths were 92.01% to 98.39% shorter than the observed queue lengths in the field.

Table 22. Comparison of Queue Lengths generated using ARENA with the same Approach and Work Zoe Speeds with the Queue Lengths Observed in the Field (From [8])

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (Approach and Work Zone (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Site 1 - 1st Hour	24.04	1.47	784	Lane 1=13.1, Lane 2=13.1	987/ 0.1869 (1st Rep. =780, 2nd Rep. = 1120, 3rd Rep. = 1060)	-87.29%
Site 1 - 2nd Hour	26.44	1.09	488	Lane 1=13.1, Lane 2=13.1	500/ 0.0946 (1st Rep. =620, 2nd Rep. = 320, 3rd Rep. = 560)	-91.32%
Site 2	19.18	1.99	660	Lane 1=18.1, Lane 2=18.1	1560/ 0.2955 (1st Rep. =1840, 2nd Rep. = 1160, 3rd Rep. = 1680)	-85.15%
Site 3	20.88	1.4	930	Lane 1=3.9, Lane 2=3.9	453/ 0.0858 (1st Rep. =380, 2nd Rep. = 220, 3rd Rep. = 760)	-93.87%

Table 23. Comparison of Queue Lengths generated using ARENA with Different Approach and Work Zone Speeds with the Queue Lengths Observed in the Field (From [8])

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Site 1 - 1st Hour	Approach Mean = 63 Approach St. Dev. = 1 Work Zone Mean = 24.04 Work Zone St. Dev. = 2	1.47	784	Lane 1=13.1, Lane 2=13.1	120/ 0.0227 (1st Rep. =140, 2nd Rep. = 80, 3rd Rep. = 140)	-98.45%
Site 1 - 2nd Hour	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 26.44 Work Zone St. Dev. = 2	1.09	488	Lane 1=13.1, Lane 2=13.1	147/ 0.0278 (1st Rep. =120, 2nd Rep. = 180, 3rd Rep. = 140)	-97.45%
Site 2	Approach Mean = 64 Approach St. Dev. = 1 Work Zone Mean = 19.18 Work Zone St. Dev. = 2	1.99	660	Lane 1=18.1, Lane 2=18.1	167/ 0.0316 (1st Rep. =180, 2nd Rep. = 180, 3rd Rep. = 140)	-98.41%
Site 3	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 20.88 Work Zone St. Dev. = 2	1.4	930	Lane 1=3.9, Lane 2=3.9	93/ 0.0176 (1st Rep. =80, 2nd Rep. = 120, 3rd Rep. = 80)	-98.74%

Table 24. Comparison of Estimated Queue Lengths using ARENA with the Queue Lengths Observed in the Field (From [8]) – Revised Lead and Lag Gaps

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Site 1 - 1st Hour	Approach Mean = 63 Approach St. Dev. = 1 Work Zone Mean = 24.04 Work Zone St. Dev. = 2	1.47	784	Lane 1=13.1, Lane 2=13.1	147/ 0.0278 (1st Rep. =140, 2nd Rep. = 120, 3rd Rep. = 180)	-98.11%
Site 1 - 2nd Hour	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 26.44 Work Zone St. Dev. = 2	1.09	488	Lane 1=13.1, Lane 2=13.1	93/ 0.0176 (1st Rep. =120, 2nd Rep. = 80, 3rd Rep. = 80)	-98.39%
Site 2	Approach Mean = 64 Approach St. Dev. = 1 Work Zone Mean = 19.18 Work Zone St. Dev. = 2	1.99	660	Lane 1=18.1, Lane 2=18.1	187/ 0.0354 (1st Rep. =180, 2nd Rep. = 140, 3rd Rep. = 240)	-98.22%
Site 3	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 20.88 Work Zone St. Dev. = 2	1.4	930	Lane 1=3.9, Lane 2=3.9	80/ 0.0152 (1st Rep. =80, 2nd Rep. = 80, 3rd Rep. = 80)	-98.91%

Table 25. Comparison of Estimated Queue Lengths ARENA with the Queue Lengths Observed in the Field – 1.5 times the Vehicle Lengths (From [8]) – Revised Lead and Lag Gaps

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Site 1 - 1st Hour	Approach Mean = 63 Approach St. Dev. = 1 Work Zone Mean = 24.04 Work Zone St. Dev. = 2	1.47	784	Lane 1=13.1, Lane 2=13.1	210/ 0.0398 (1st Rep. =210, 2nd Rep. = 210, 3rd Rep. = 210)	-97.29%
Site 1 - 2nd Hour	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 26.44 Work Zone St. Dev. = 2	1.09	488	Lane 1=13.1, Lane 2=13.1	93/ 0.0176 (1st Rep. =180, 2nd Rep. = 120, 3rd Rep. = 210)	-98.39%
Site 2	Approach Mean = 64 Approach St. Dev. = 1 Work Zone Mean = 19.18 Work Zone St. Dev. = 2	1.99	660	Lane 1=18.1, Lane 2=18.1	300/ 0.0568 (1st Rep. =180, 2nd Rep. = 480, 3rd Rep. = 240)	-97.14%
Site 3	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 20.88 Work Zone St. Dev. = 2	1.4	930	Lane 1=3.9, Lane 2=3.9	150/ 0.0152 (1st Rep. =150, 2nd Rep. = 150, 3rd Rep. = 150)	-97.97%

Table 26. Comparison of Estimated Queue Lengths using ARENA with the Queue Lengths Observed in the Field for Site 1 2nd Hour Traffic Data (From [8])

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Original Lead and Lag Gaps –Original Vehicle Lengths	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 26.44 Work Zone St. Dev. = 2	1.09	488	Lane 1=13.1, Lane 2=13.1	147/ 0.0278 (1st Rep. =120, 2nd Rep. = 180, 3rd Rep. = 140)	-97.45%
Revised Lead and Lag Gaps –Original Vehicle Lengths	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 26.44 Work Zone St. Dev. = 2	1.09	488	Lane 1=13.1, Lane 2=13.1	93/ 0.0176 (1st Rep. =120, 2nd Rep. = 80, 3rd Rep. = 80)	-98.39%
Revised Lead and Lag Gaps – 1.5 times the Original Vehicle Lengths	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 26.44 Work Zone St. Dev. = 2	1.09	488	Lane 1=13.1, Lane 2=13.1	170/ 0.0322 (1st Rep. =180, 2nd Rep. = 120, 3rd Rep. = 210)	-97.05%
25% of the Revised Lead and Lag Gaps – 1.5 times the Original Vehicle Lengths	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 26.44 Work Zone St. Dev. = 2	1.09	488	Lane 1=13.1, Lane 2=13.1	190/ 0.036 (1st Rep. =210, 2nd Rep. = 180, 3rd Rep. = 180)	-96.7%
200% of the Revised Lead and Lag Gaps – 1.5 times the Original Vehicle Lengths	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 26.44 Work Zone St. Dev. = 2	1.09	488	Lane 1=13.1, Lane 2=13.1	460/ 0.0871 (1st Rep. =300, 2nd Rep. = 300, 3rd Rep. = 780)	-92.01%
Rockwell Suggested Lead and Lag Gaps and Vehicle Lengths	Approach Mean = 62 Approach St. Dev. = 1 Work Zone Mean = 26.44 Work Zone St. Dev. = 2	1.09	488	Lane 1=13.1, Lane 2=13.1	433/ 0.0820 (1st Rep. =300, 2nd Rep. = 320, 3rd Rep. = 680)	-92.47%

The Arena simulation program was run according to the traffic conditions given in the study by Schnell et al. [9] and the Arena program output for maximum queue lengths were compared with the actual queue lengths observed in the field by Schnell et al.

In Table 27, the Arena simulation program queue lengths using different average speed before the work zone and in the work zone situations and for the given hourly traffic volumes and truck percentages in Schnell et al. [9] were compared with the actual queue lengths observed in the field by Schnell et al. The Arena queue lengths were 50.6%, 43.7%, and 1.25% shorter than the observed queue lengths in the field. The third site in the Schnell study was the closest to actual queue length observed in the field.

In Table 28, the Arena simulation program queue lengths using different average speed before the work zone and in the work zone situations and for the given hourly traffic volumes and truck percentages in Schnell et al. [9] were compared with the actual queue lengths observed in the field by Schnell et al. In addition, 2 times the original vehicle lengths (original vehicle lengths; car=20 ft, truck=60 ft) were used. The Arena queue lengths were 58.59%, 28.83%, and 276.89% longer than the observed queue lengths in the field.

In Table 29, the Arena simulation program queue lengths using different average speed before the work zone and in the work zone situations and for the given hourly traffic volumes and truck percentages in Schnell et al. [9] were compared with the actual queue lengths observed in the field by Schnell et al. In addition, 2 times the original lead and lag gaps were used. The difference between the Arena queue length results and the actual queue lengths were -37%, -41.33%, and 34.32%.

In Table 30, the Arena simulation program queue lengths using different average speed before the work zone and in the work zone situations and for the given hourly traffic volumes and truck percentages in Schnell et al. [9] were compared with the actual queue lengths observed in the field by Schnell et al. In addition, 1.5 the original vehicle lengths (original vehicle lengths; car=20 ft, truck=60 ft) were used. The difference between the Arena queue length results and the actual queue lengths were 36.67%, 1.17%, and 192.02%. The second site in the Schnell study was the closest to actual queue length observed in the field.

In Table 31, the Arena simulation program queue lengths for Schnell et al. [9] site 1 data was compared with the actual queue length data for different vehicle lengths and different lead and lag gaps. The difference between the Arena queue length output and the actual queue length for the given site was between -50.61% and 58.59%.

Table 27. Comparison of Queue Lengths generated using Arena Simulation Program with the Queue Lengths Observed in the Field (From [9])

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Cambridge – 10 ft	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	13020 / 2.47 (1st Rep. =12880, 2nd Rep. = 10920, 3rd Rep. = 15260)	-50.6%
Cambridge – 12 ft	Approach Mean = 55.8 Approach Stand. Dev. = 16.9 Work Zone Mean = 20.6 Work Zone Stand. Dev. = 11	6.0	1480	Lane 1=28, Lane 2=28	17853 / 3.38 (1st Rep. =19800, 2nd Rep. = 15660, 3rd Rep. = 18100)	-43.7%
Sandusky	Approach Mean = 68.1 Approach Stand. Dev. = 8.2 Work Zone Mean = 17.8 Work Zone Stand. Dev. = 8.2	1.6	1460	Lane 1=19, Lane 2=19	8360/ 1.58 (1st Rep. =10140, 2nd Rep. = 7640, 3rd Rep. = 7300)	-1.25%

Table 28. Comparison of Queue Lengths generated using Arena Simulation Program with the Queue Lengths Observed in the Field – 2 times the Original Vehicle Lengths (Car = 40 ft, Truck = 120 ft) (From [9])

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Cambridge – 10 ft	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	41867 / 7.93 (1st Rep. = 41880, 2nd Rep. = 41840, 3rd Rep. = 41880)	%58.59
Cambridge – 12 ft	Approach Mean = 55.8 Approach Stand. Dev. = 16.9 Work Zone Mean = 20.6 Work Zone Stand. Dev. = 11	6.0	1480	Lane 1=28, Lane 2=28	40827 / 7.73 (1st Rep. = 41880, 2nd Rep. = 40080, 3rd Rep. = 40520)	%28.83
Sandusky	Approach Mean = 68.1 Approach Stand. Dev. = 8.2 Work Zone Mean = 17.8 Work Zone Stand. Dev. = 8.2	1.6	1460	Lane 1=19, Lane 2=19	31840 / 6.03 (1st Rep. = 33160, 2nd Rep. = 30020, 3rd Rep. = 32240)	%276.89

Table 29. Comparison of Queue Lengths generated using Arena Simulation Program with the Queue Lengths Observed in the Field – 2 times the Original Lead and Lag Gaps (From [9])

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Cambridge – 10 ft	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	16613 / 3.15 (1st Rep. = 18640, 2nd Rep. = 14940, 3rd Rep. = 16260)	-%37
Cambridge – 12 ft	Approach Mean = 55.8 Approach Stand. Dev. = 16.9 Work Zone Mean = 20.6 Work Zone Stand. Dev. = 11	6.0	1480	Lane 1=28, Lane 2=28	18567 / 3.52 (1st Rep. = 20200, 2nd Rep. = 16200, 3rd Rep. = 19300)	-%41.33
Sandusky	Approach Mean = 68.1 Approach Stand. Dev. = 8.2 Work Zone Mean = 17.8 Work Zone Stand. Dev. = 8.2	1.6	1460	Lane 1=19, Lane 2=19	11347 / 2.15 (1st Rep. = 12220, 2nd Rep. = 10080, 3rd Rep. = 11740)	%34.32

Table 30. Comparison of Queue Lengths generated using Arena Simulation Program with the Queue Lengths Observed in the Field – 1.5 times the Original Vehicle Lengths (Car = 40 ft, Truck = 120 ft) (From [9])

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Cambridge – 10 ft	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	36080 / 6.83 (1st Rep. = 37530, 2nd Rep. = 34200, 3rd Rep. = 36510)	%36.67
Cambridge – 12 ft	Approach Mean = 55.8 Approach Stand. Dev. = 16.9 Work Zone Mean = 20.6 Work Zone Stand. Dev. = 11	6.0	1480	Lane 1=28, Lane 2=28	32050 / 6.07 (1st Rep. = 32940, 2nd Rep. = 32960, 3rd Rep. = 30750)	%1.17
Sandusky	Approach Mean = 68.1 Approach Stand. Dev. = 8.2 Work Zone Mean = 17.8 Work Zone Stand. Dev. = 8.2	1.6	1460	Lane 1=19, Lane 2=19	24670 / 4.67 (1st Rep. = 23820, 2nd Rep. = 24720, 3rd Rep. = 25470)	%192.02

Table 31. Comparison of Queue Lengths generated using Arena Simulation Program with the Queue Lengths Observed in the Field for Cambridge 10-ft Traffic Data (From [9])

	Paper		ARENA Input		ARENA Output (N= 3 Replications	Percent Difference
	Average Speed (mph)	Actual Queue Length in Field (mi)	Traffic Volume (vphpl)	% Heavy Vehicle	Max Queue Length (ft/mi)	(ARENA - Actual)/ Actual
Original Lead and Lag Gaps –Original Vehicle Lengths	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	13020 / 2.47 (1st Rep. =12880, 2nd Rep. = 10920, 3rd Rep. = 15260)	-50.6%
Revised Lead and Lag Gaps –Original Vehicle Lengths	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	14440 / 2.73 (1st Rep. =17560, 2nd Rep. = 12980, 3rd Rep. = 12780)	-45.3%
Revised Lead and Lag Gaps – 1.2 times the Original Vehicle Lengths	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	27224 / 5.16 (1st Rep. = 27408, 2nd Rep. = 26568, 3rd Rep. = 27696)	%3.12
Revised Lead and Lag Gaps – 1.3 times the Original Vehicle Lengths	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	29475 / 5.58 (1st Rep. = 29640, 2nd Rep. = 29536, 3rd Rep. = 29250)	%11.64
Revised Lead and Lag Gaps – 1.5 times the Original Vehicle Lengths	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	36080 / 6.83 (1st Rep. = 37530, 2nd Rep. = 34200, 3rd Rep. = 36510)	%36.67
Revised Lead and Lag Gaps – 2 times the Original Vehicle Lengths	Approach Mean = 57 Approach Stand. Dev. = 19.1 Work Zone Mean = 17 Work Zone Stand. Dev. = 8.3	5.0	1020	Lane 1=32, Lane 2=32	41867 / 7.93 (1st Rep. = 41880, 2nd Rep. = 41840, 3rd Rep. = 41880)	%58.59

2.5 Part I Conclusions

The evaluation of the Arena & the ORITE – ODOT Construction Zone Simulation Program showed that the Arena simulation program always generates shorter queues than the Quickzone program and there appears to be a problem with the Arena program in terms of queue lengths.

The Arena simulation program generates fairly accurate number of vehicles at the beginning of the work zone and at the entrance ramps when the input and output vehicle numbers are compared. However there appears to be a problem in the number of vehicles at the exit ramps and at the end of the work zone when the input and output vehicle numbers are compared. It appears that the vehicles cannot exit according to the input variables when the exit ramps are located closely together (less than 1.5 miles), which results in fairly large differences between the input and output vehicle numbers at the end of the work zone and at the exit ramps. It appears that the lane changing mechanisms are not sufficient to let enough vehicles exit.

It also appears that changing lead and lag gaps, vehicle lengths, and vehicle speeds can really not account for getting longer and more reasonable queue lengths. They would further increase the vehicle number percentage differences for vehicles exiting when there are short distances between the ramps.

The comparison of the Arena simulation program queue lengths output with the observed queue lengths in the field from the studies by Chitturi and Benekohal [8] and Schnell [9] showed that Arena simulation program does not provide accurate queue lengths except one case in Schnell study, where the difference in queue lengths was -1.25%.

Figure 26 shows the only real world queue validation data available for comparison with the Arena simulation program queue length output. It should be noted that for both studies (Chitturi & Benekohal and Schnell et al.) only have one queue length observation per site per traffic volume and situation is available. The validations and conclusions based on these two studies based on a single real world data point are highly questionable. In order to do a more scientific validation a minimum of 3 independent queue length observations for each site under similar traffic volumes and conditions is required. The variability in the actual queue lengths shown in Figure 26 is considerable and only 31% of the variability (least squares regression) can be explained using a linear relationship. The variability between the different traffic volumes can also not be explained by the percentage of trucks.

For the reasons stated above with regard to queue lengths, the ARENA program appear not to produce accurate queue results especially in the Chitturi and Benekohal cases where Arena produces almost no queues. The Arena simulation program generated a reasonably accurate queue length for only one case of the Schnell data (matching one real world data point only) using the actual vehicle lengths and original merging gaps. However, the Arena simulation program queue lengths were way too short when compared with the Chitturi and Benekohal data in all cases even when vehicle length, merging gap adjustments and speed changes were made.

In conclusion, at this point in time the use of the Arena simulation program cannot be recommended as a reliable tool to determine queue lengths and correct exit ramp traffic volumes in cases where exit ramps are closely spaced together. Additional field data collection would be required for a more adequate queue length validation and the lane changing mechanisms need to be improved to obtain more correct exit percentage values especially for cases where multiple lanes and close spacings (less than 1.5 miles apart) between two adjacent exits exist.

Rockwell Automation was not able to rectify the queue length problem and the exit percentage problem and has terminated and completed their development work on the Arena simulation program after submitting the seventh modification (received June 25, 2008).

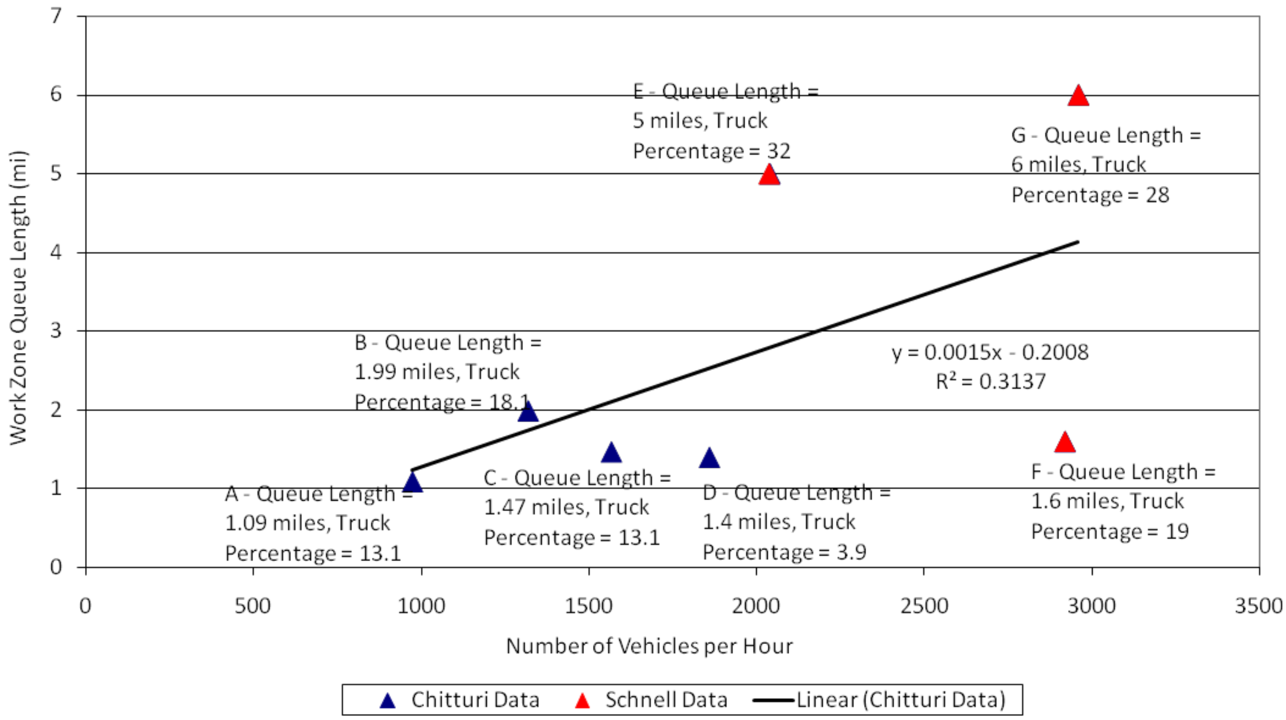


Figure 26. Comparison of Actually Observed Work Zone Maximum Queue Lengths by Chitturi & Benekohal [8] and Schnell et al. [9]

3 PART II: BASELINE FREE-FLOW MEASUREMENTS FOR DIVERSION ANALYSIS AFTER CONSTRUCTION

Traffic data was collected during construction and after construction on I-90 Eastbound, I-90 Westbound, I-270 Eastbound, and I-270 Westbound. The free flow measurements were used for diversion analysis. The hourly traffic volumes on the mainline, entrance ramps, and exit ramps were compared to determine the effects of construction on traffic.

3.1 Data Collection after Construction

Traffic data was collected for baseline (all entrance and exit ramps open, no traffic restrictions) free-flow measurements for diversion analysis after construction. The same data collection methods and equipment were used as that was used in Phase I of this project. Traffic data was collected for three days and traffic volumes were analyzed based on 1-hour intervals.

Traffic data was not collected on I-76 Westbound construction work zone and I-75 Southbound since no ramps were closed in I-76 Westbound in Phase I and we only measured traffic at the beginning of the I-75 Southbound construction work zone. No ramps were closed on I-270 Westbound either, however exit ramp to US 62 on I-270 Eastbound was closed during the construction and it might have affected I-270 Westbound traffic.

The traffic data was collected on I-90 Eastbound, I-90 Westbound, I-270 Eastbound, and I-270 Westbound.

Microwave radar detectors such as those used in Phase I of this project were used to collect traffic data nonintrusively beside the road [1].

3.1.1 Description of Data Collection Sites

Total of 4 sites were chosen for this study. Data had been collected at these four sites during the construction period. The sites were I-90 Eastbound and I-90 Westbound in Cleveland and I-270 Eastbound and I-270 Westbound in Columbus. The brief description of the data collection sites are given below.

3.1.1.1 <u>I-90 Eastbound / Westbound in Cleveland</u>

Microwave radar trailers as described above were set up at the site. The data was collected separately for the eastbound and westbound traffic. The time periods of data collection and the number of microwave radar trailers used are given in Table 32. The traffic at the site was monitored for at least for 3 days at each location. The vehicles entering and exiting the mainline traffic through the ramps were also recorded. In Table 33 the trailer locations are given for I-90 Eastbound. The location numbers refers to the numbers given in Figure 27 and Figure 28. In Figure 27 the location of the trailers were marked on aerial view of the Microsoft Live Search Map and in Figure 28 the trailer locations and highway configuration is given.

Table 32. Trailer Data Collection Dates for I-90 Eastbound/Westbound in Cleveland after Construction

Site	Number of Trailers	Data Collection Period
I-90 Eastbound	10	10/09/2005 – 10/12/2005
I-90 Westbound	8	10/14/2005 – 10/16/2005

Table 33. Trailer Locations on I-90 Eastbound after Construction

Location 1	I-90 Eastbound – Mainline
Location 2	SR 2 to I-90 Eastbound Entrance Ramp
Location 3	I-90 Eastbound to 55th Street Exit Ramp
Location 4	55th Street to I-90 Eastbound Entrance Ramp
Location 5	I-90 Eastbound Mainline
Location 6	I-90 Eastbound to 72nd Street Exit Ramp
Location 7	72nd Street to I-90 Eastbound Entrance Ramp
Location 8	I-90 Eastbound to Martin Luther King Drive Exit Ramp
Location 9	Martin Luther King Drive to I-90 Eastbound Entrance Ramp
Location 10	I-90 Eastbound – Mainline

Figure 27. Trailer Locations on I-90 Eastbound after Construction

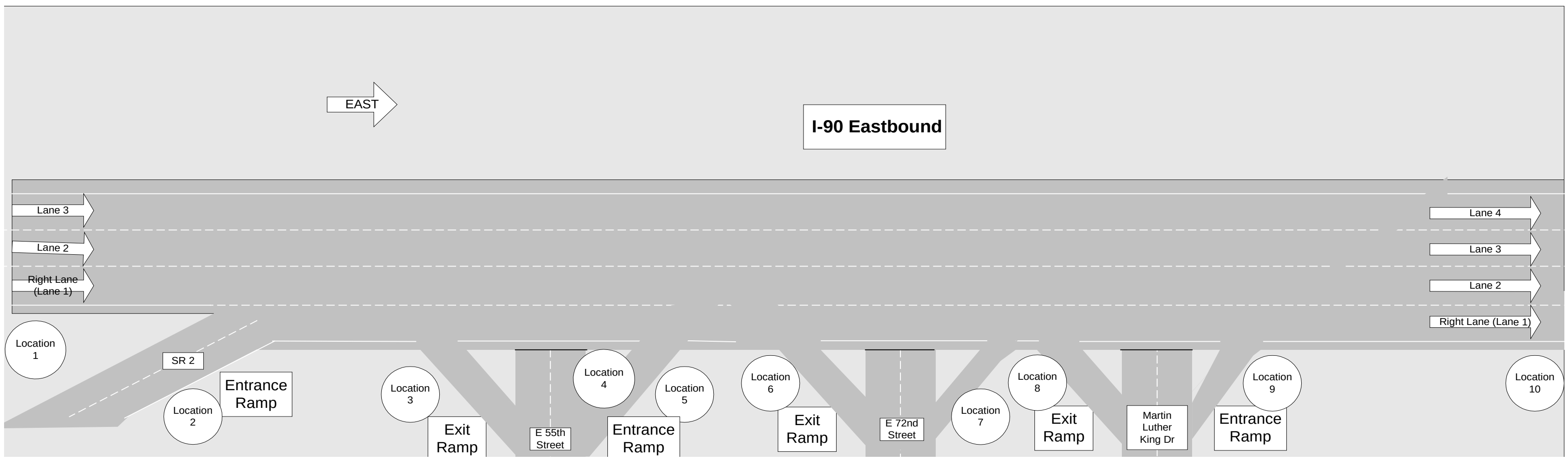


Figure 28. Drawing of Trailer Locations on I-90 Eastbound after Construction

In Table 34the trailer locations are given for I-90 Westbound. The location numbers refers to the numbers given in Figure 29and Figure 30. In Figure 29the location of the trailers were marked on aerial view of the Microsoft Live Search Map and in Figure 30 the trailer locations and highway configuration is given.

Table 34. Trailer Locations on I-90 Westbound after Construction

Location 1	I-90 Westbound – Mainline
Location 2	I-90 Westbound to Martin Luther King Drive Exit Ramp
Location 3	I-90 Westbound - Mainline
Location 4	Martin Luther King Drive to I-90 Westbound Entrance Ramp
Location 5	I-90 Westbound to 72^{nd} Street Exit Ramp
Location 6	72^{nd} Street to I-90 Westbound Entrance Ramp
Location 7	I-90 Westbound to 55^{th} Street Exit Ramp
Location 8	I-90 Westbound - Mainline

Figure 29. Trailer Locations on I-90 Westbound after Construction

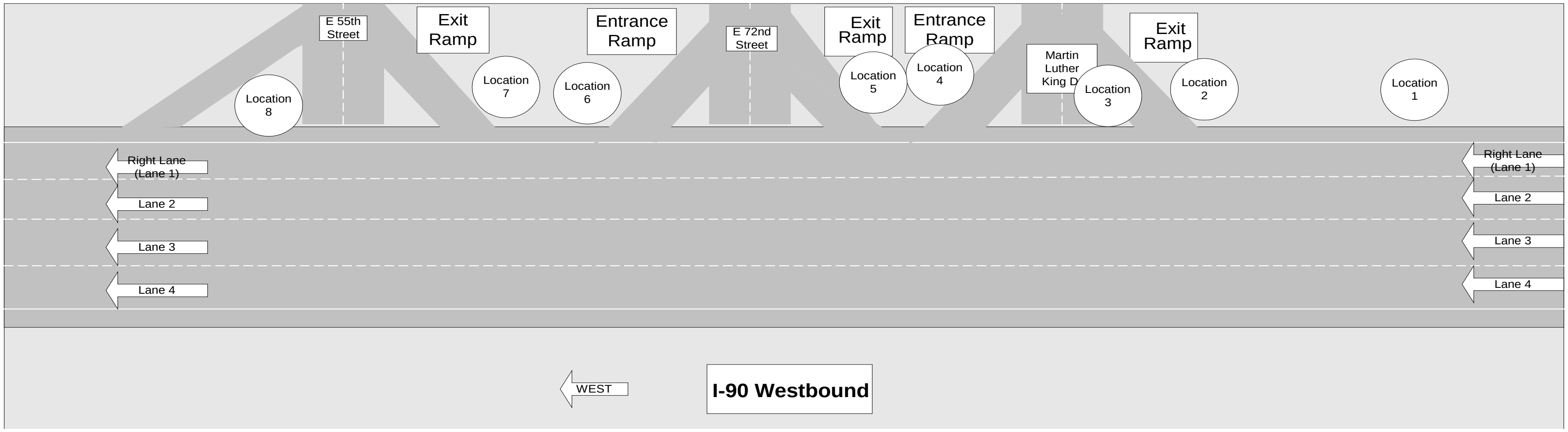


Figure 30. Drawing of Trailer Locations on I-90 Westbound after Construction

3.1.1.2 I-270 Eastbound / Westbound in Columbus

Microwave radar trailers were set up at the site. The data was collected separately for the eastbound and westbound traffic. The time periods of data collection and the number of microwave radar trailers used are given in Table 35. The traffic at the site was monitored for at least for 3 days at each location. The vehicles entering and exiting the mainline traffic through the ramps were also recorded. In Table 36the trailer locations are given for I-270 Eastbound. The location numbers refers to the numbers given in Figure 31 and Figure 32. In Figure 31 the location of the trailers were marked on aerial view of the Microsoft Live Search Map and in Figure 32 the trailer locations and highway configuration is given.

Table 35. Trailer Data Collection Dates for I-270 Eastbound/Westbound in Cleveland after Construction

Site	Number of Trailers	Data Collection Period
I-270 Eastbound	10	06/27/2006 – 06/30/2006
I-270 Westbound	10	06/23/2006 – 06/25/2006

Table 36. Trailer Locations on I-270 Eastbound after Construction

Location 1	I-270 Eastbound – Mainline
Location 2	SR 62 North to I-270 Eastbound Entrance Ramp and I-270 Eastbound to SR 62 Exit Ramp
Location 3	SR 62 South to I-270 Eastbound Entrance Ramp
Location 4	I-270 Eastbound – Mainline
Location 5	I-270 Eastbound – Mainline
Location 6	I-270 Eastbound to I-71 South Exit Ramp
Location 7	I-270 Eastbound to I-71 North Exit Ramp
Location 8	I-71 North to I-270 Eastbound Entrance Ramp
Location 9	I-71 South to I-270 Eastbound Entrance Ramp
Location 10	I-270 Eastbound - Mainline

Figure 31. Trailer Locations on I-270 Eastbound after Construction

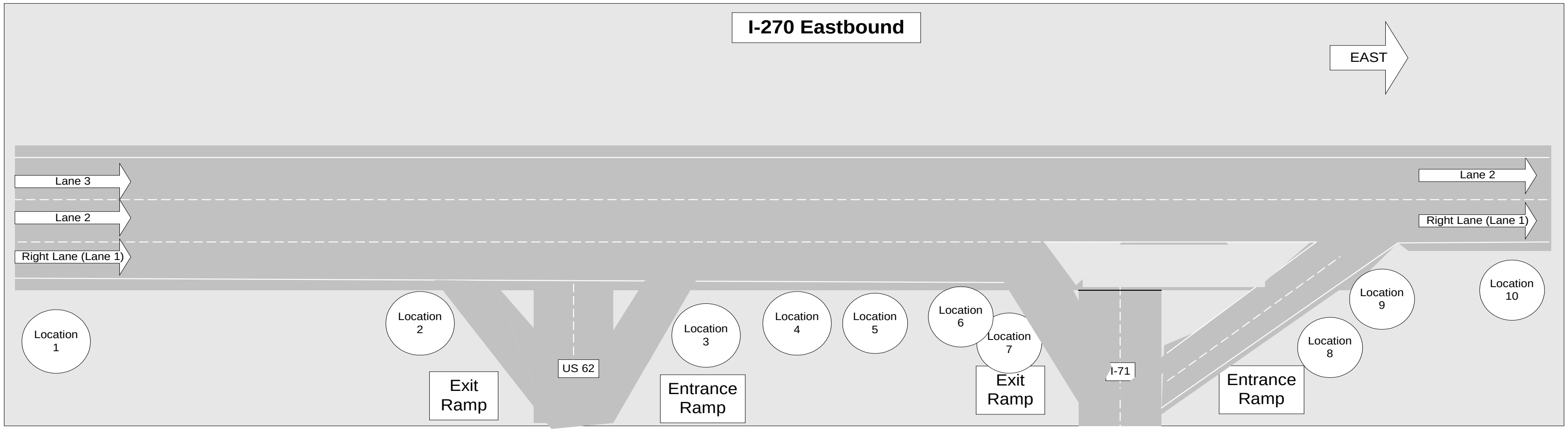


Figure 32. Drawing of Trailer Locations on I-270 Eastbound after Construction

In Table 37 the trailer locations are given for I-270 Westbound. The location numbers refers to the numbers given in Figure 33and Figure 34. In Figure 33 the location of the trailers were marked on aerial view of the Microsoft Live Search Map and in Figure 34 the trailer locations and highway configuration is given.

Table 37. Trailer Locations on I-270 Westbound after Construction

Location 1	I-270 Westbound – Mainline
Location 2	I-270 Westbound to I-71 North Exit Ramp
Location 3	I-71 North to I-270 Westbound Entrance Ramp
Location 4	I-270 Westbound to I-71 South Exit Ramp
Location 5	I-71 South to I-270 Westbound Entrance Ramp
Location 6	I-270 Westbound – Mainline
Location 7	I-270 Westbound – Mainline
Location 8	I-270 Westbound to SR 62 Exit Ramp
Location 9	SR 62 to I-270 Westbound Entrance Ramp
Location 10	I-270 Westbound - Mainline

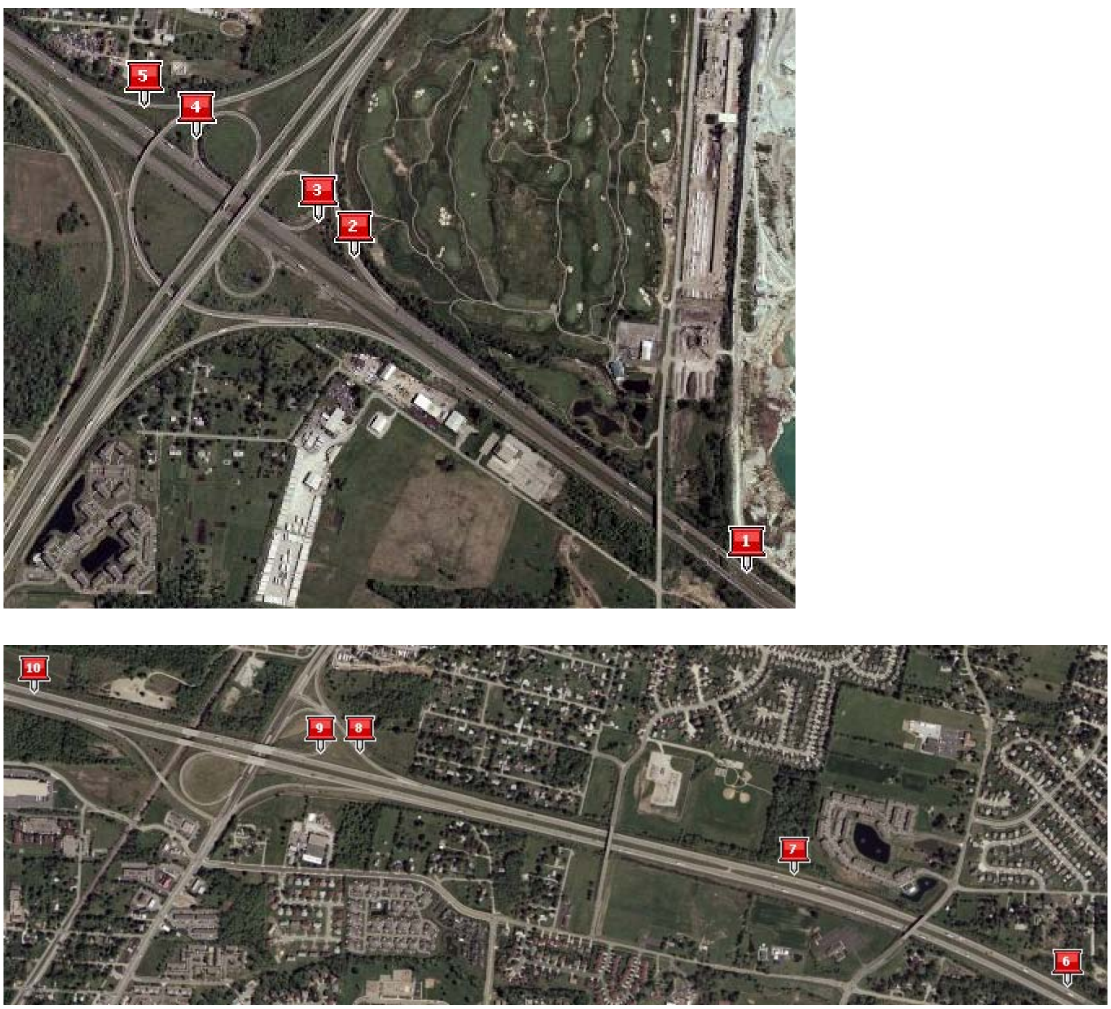


Figure 33. Trailer Locations on I-270 Westbound after Construction

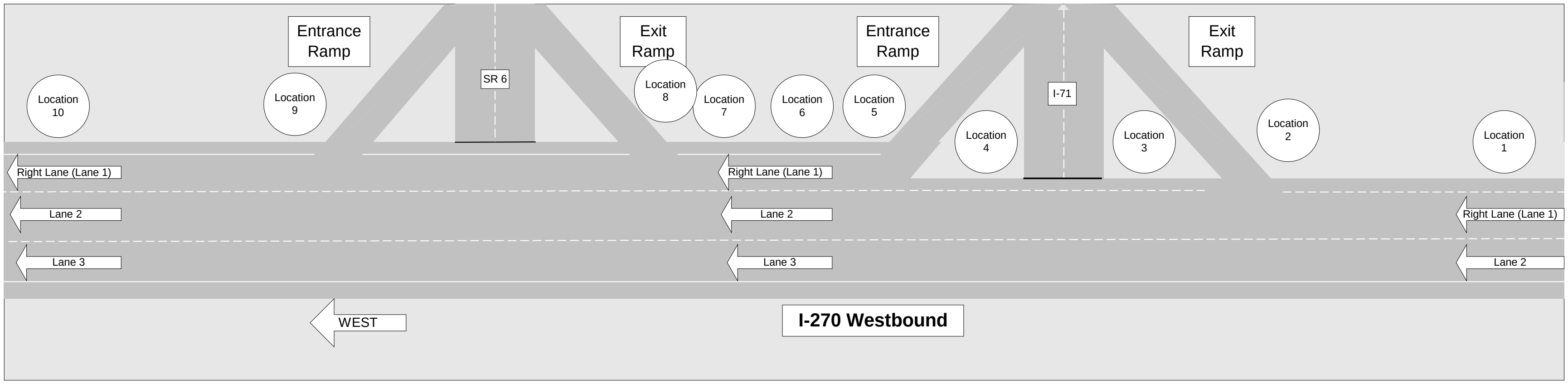


Figure 34. Drawing of Trailer Locations on I-270 Westbound after Construction

3.2 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.

3.2.1 Phantoms and Misses Analysis

Using the microwave radar trailers in side fire mode a phantom could occur when a truck in a farther away lane produces such a strong signal that the system records another vehicle in a closer in lane. A miss could occur if a truck in a closer in lane obstructs and hides a vehicle in a farther away lane. 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 ±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 38 through Table 41 the multiplication factors found for all lanes at each trailer location for each site are given (adapted from 1).

Table 38. Multiplication Factors found for I-90 Eastbound Data

Site	Location	Lane	Multiplication Factor
I90 Eastbound	Location 1	Lane 1	0.9687
		Lane 2	0.991
		Lane 3	0.9863
	Location 2	Lane 1	1.0053
		Lane 2	0.914
	Location 3	Lane 1	1.0883
	Location 4	Lane 1	0.9932
	Location 5	Lane 1	0.9197
		Lane 2	1.052
		Lane 3	1.0758
		Lane 4	1.1033
	Location 6	Lane 1	1.0372
	Location 7	Lane 1	1.0202
	Location 8	Lane 1	1.5517
	Location 9	Lane 1	1.0127
	Location 10	Lane 1	1.1685
		Lane 2	0.9718
		Lane 3	0.9733
		Lane 4	1.0528

Table 39. Multiplication Factors found for I-90 Westbound Data

Site	Location	Lane	Multiplication Factor
I90 Westbound	Location 1	Lane 1	1.158
		Lane 2	1.0703
		Lane 3	1.061
		Lane 4	1.0785
	Location 2	Lane 1	1.3659
	Location 3	Lane 1	0.9782
		Lane 2	1.0069
		Lane 3	1.0147
		Lane 4	0.9575
	Location 4	Lane 1	1.2477
	Location 5	Lane 1	1.0479
	Location 6	Lane 1	1.234
	Location 7	Lane 1	0.9497
	Location 8	Lane 1	0.6304
		Lane 2	0.9234
		Lane 3	1.8902
		Lane 4	*

* Multiplication factor could not be determined. The values given in the trailer data was taken as the corrected values.

Table 40. Multiplication Factors found for I-270 Eastbound Data

Site	Location	Lane	Multiplication Factor
I270 Eastbound	Location 1	Lane 1	1.015
		Lane 2	0.989
		Lane 3	1.031
	Location 2	Lane 1	1.061
		Lane 2	1.269
	Location 3	Lane 1	1.345
	Location 4	Lane 1	0.987
		Lane 2	1.019
		Lane 3	1.111
	Location 5	Lane 1	0.99
		Lane 2	0.981
		Lane 3	0.99
	Location 6	Lane 1	1.276
	Location 7	Lane 1	0.955
	Location 8	Lane 1	1.124
	Location 9	Lane 1	1.093
	Location 10	Lane 1	0.956
		Lane 2	1.023

Table 41. Multiplication Factors found for I-270 Westbound Data

Site	Location	Lane	Multiplication Factor
I270 Westbound	Location 1	Lane 1	1.023
		Lane 2	0.974
	Location 2	Lane 1	0.71
		Lane 2	1.004
	Location 3	Lane1	1.013
	Location 4	Lane1	1.038
	Location 5	Lane1	0.945
	Location 6	Lane1	0.933
		Lane 2	0.939
		Lane 3	0.938
	Location 7	Lane 1	0.983
		Lane 2	0.939
		Lane 3	0.879
	Location 8	Lane1	0.995
	Location 9	Lane1	0.966
	Location 10	Lane1	0.918
		Lane2	1.024
		Lane3	0.835

3.2.2 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. 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).

3.3 Diversion Analysis

The diversion analysis was performed for the four sites where entrance and/or exit ramps were closed and where the traffic data was collected during construction and after construction. The data collection sites were the I-90 Eastbound/Westbound in Cleveland and I-270 Eastbound/Westbound in Columbus. A number of entrance and exit ramps were closed in the data collection sites except on I-270 Eastbound. None of the entrance and exit ramps were closed on I-270 Eastbound; however the exit ramp on I-270 Westbound was closed during construction, which would have affected the traffic on I-270 Eastbound and therefore it was included in diversion analysis. In Table 42 and Table 43 the data collection dates for each site during construction and after the construction along with the number of microwave radar trailers used are given.

Table 42. Trailer Data Collection Dates for the Sites after Construction – Phase II (No Work Zone)

Site	Number of Trailers	Data Collection Period
I-90 Eastbound	10	10/09/2005 – 10/12/2005
I-90 Westbound	8	10/14/2005 – 10/16/2005
I-270 Eastbound	10	06/27/2006 – 06/30/2006
I-270 Westbound	10	06/23/2006 – 06/25/2006

Table 43. Trailer Data Collection Dates for the Sites during Construction – Phase I (Work Zone)

Site	Number of Trailers	Data Collection Period
I-90 Eastbound	10	09/14/2004 – 09/17/2004
I-90 Westbound	6	09/17/2004 – 09/19/2004
I-270 Eastbound	9	09/01/2004 – 09/04/2004
I-270 Westbound	9	08/29/2004 – 08/31/2004

The data was collected for at least a three day period of time at each site; however only one day of data was used in the diversion analysis. The same weekdays of the data collection dates were selected for comparing traffic counts at the sites after construction and during construction. The dates, days of the week, and times for the data used in the diversion analysis are given in Table 44.

Table 44. Trailer Data Collection Dates used in Diversion Analysis

Site	**Phase I (Work Zone)**		**Phase II (No Work Zone)**
	Date	**Start & End Time**	**Date**
I-270 Westbound	08/29/2004 Sunday	12:00 AM to 8:00 PM (20 hrs)	06/25/2006 Sunday
I-270 Eastbound	09/01/2004 Wednesday and 09/02/2004 Thursday	9:00 AM to 12:00 AM 12:00 AM to 12:00 AM (39 hrs)	06/28/2006 Wednesday and 06/29/2006 Thursday
	09/02/2004 Thursday	12:00 AM to 12:00 AM (24 hrs)	06/29/2006 Thursday
I-90 Eastbound	09/15/2004 Wednesday	1:00 AM to 12:00 AM (23 hrs)	10/12/2005 Wednesday
I-90 Westbound	09/18/2004 Saturday	1:00 AM to 12:00 AM (23 hrs)	10/15/2005 Saturday

In order to eliminate the day of the week variability the data for the same weekday for each site and direction were compared for Phase I and Phase II.

In Table 45, the total numbers of vehicles at the beginning of the data collection sites (work zone) are given for Phase I and Phase II. The seasonal and annual adjustment factors (see ODOT webpage http://www.dot.state.oh.us/techservsite/offceorg/traffmonit/CountInformation/) are used to compare the traffic volumes. The table given shows that the number of vehicles at the beginning of the freeway data collection location have increased in Phase II (no work zone situation) at all sites.

The smallest increase in number of vehicles at the beginning was observed at the I-90 Eastbound in Cleveland site (0.63 % increase) and the maximum increase was observed at I-270 Westbound in Columbus site (10.74 % increase).

The differences in number of vehicle counts were analyzed for the daily time periods of 20 hours to 39 hours. The individual analysis of increases in the number of vehicles for each hour of the day is given in the report. The analysis of the number of vehicles for the hourly time periods showed that there was no trend in the differences for Phase I and Phase II. The hourly vehicle counts were higher for Phase I in some cases and higher for Phase II in other cases.

Table 45. Total Number of Vehicles Observed at the Beginning of the Data Collection Sites (Work Zone)

Site	Phase I (Work Zone)			Phase II (No Work Zone)		Difference in the Observed Number of Vehicles (Phase II - Phase I) (Difference in Percent (Phase II – Phase I)/Phase II))
	Date	Start & End Time	Total Number of Vehicles at the Beginning of the Site	Date	Total Number of Vehicles at the Beginning of the Site	
I-270 Westbound	08/29/2004 Sunday	12:00 AM to 8:00 PM (20 hrs)	22390 (22369*)	06/25/2006 Sunday	25061	2692 (10.74%)
I-270 Eastbound	09/01/2004 Wednesday and 09/02/2004 Thursday	9:00 AM to 12:00 AM 12:00 AM to 12:00 AM (39 hrs)	56137 (58194*)	06/28/2006 Wednesday and 06/29/2006 Thursday	63247	5052 (7.99%)
	09/02/2004 Thursday	12:00 AM to 12:00 AM (24 hrs)	32107 (33284*)	06/29/2006 Thursday	36111	2828 (7.83%)
I-90 Eastbound	09/15/2004 Wednesday	1:00 AM to 12:00 AM (23 hrs)	45638 (46451*)	10/12/2005 Wednesday	46747	297 (0.63%)
I-90 Westbound	09/18/2004 Saturday	1:00 AM to 12:00 AM (23 hrs)	55771 (56764*)	10/15/2005 Saturday	58050	1286 (2.22%)

* The adjusted traffic counts according to the Seasonal Adjustment Factors and Annual adjustment Factors. The numbers represents the vehicle counts for the same month and year as the dates given in Phase II data collection. (Example: Traffic Volume on I-90E on 09/15/2004 = 45608, from the Table for seasonal adjustment factors, it is multiplied by September weekday factor and then divided by October weekday factor. 45638/0.938*0.890). For the Annual adjustment the number is multiplied by the percentage value given in the Annual Adjustment Factors table for 2004-2005. (44627-44627*1.8%)

In Table 47 through Table 58, the hourly vehicle counts for each site during construction and after construction are given. For each site the hourly vehicle counts at the beginning of the work zone, at the entrance ramps, at the exit ramps, and at the end of the work zone are given based on the microwave radar trailer data.

The microwave radar trailer data on vehicle counts at the end of the work zone is compared with the calculated number of vehicles at the end of the work zone. The calculated number of vehicles at the end of the work zone is calculated by adding the entrance ramp vehicle count to the vehicle counts at the beginning of the work zone and then subtracting the exit ramp vehicle counts. The differences in percentages were calculated for the microwave radar vehicle data (observed data) and the calculated vehicle count data. The hourly differences between the observed and the calculated at the end of the work zone in vehicle counts varied from -39.69 % to 31.49 %. The vehicle count comparison on the hourly basis did not provide close results for the microwave radar data. However the comparison of vehicle counts on a daily basis (duration for the diversion analysis) provided a somewhat closer result. The difference between the microwave radar data (observed data) and the calculated data based on 9 to 48 hour periods varied from -26.21% to 13.55% as given in Table 46.

Table 46. Vehicle Count Differences at the End of the Work Zone on a Daily Basis in Percentages for all Sites and all Phases

Site	Phase (Phase I-Work Zone, Phase II-No Work Zone)	Difference between the Observed and the Calculated Vehicle Counts at the End on a Daily Basis
I-90 Eastbound	I	-4.43%
I-90 Eastbound	II	3.78%
I-90 Westbound	I	-4.09%
I-90 Westbound	II	13.55% ?No Explanation
I-270 Westbound	I	6.28%
I-270 Westbound	II	-26.21% ?No Explanation
I-270 Eastbound	I	-3.70%
I-270 Eastbound	II	-1.44%

Since the daily analysis of vehicle counts provided somewhat better results than the hourly analysis, the diversion analysis was performed using the daily traffic count data only.

Looking at the Table 47 through Table 58, the hourly differences between the observed and the calculated vehicle numbers are in most cases very big.

The daily differences between the observed and the calculated vehicle numbers are also very big in some cases (Table 46). Two cases (I-90 Eastbound and I-270 Eastbound) with the relatively small differences were selected for diversion analysis based on the comparison of observed and calculated vehicle numbers.

It should also be noted that in some cases the hourly differences between the observed and the calculated vehicle numbers can change from a relatively large negative difference to a relatively large positive difference from one hour to the next hour. Since no vehicles can be added or lost between freeway entrances and exits there is no explanation other than equipment inaccuracy for the differences in vehicle counts at the end of the work zone.

Table 47. Hourly Vehicle Counts in Percentages for I-90 Eastbound for Phase I (Work Zone)

Date	Time		At the Beginning	Entrance Ramps	Exit Ramps	At the End	At the End Calculated	Percent Difference
	Start	End	Observed Count	Observed Count (Total of 3 Entrance Ramps)	Observed Count (Total of 3 Exit Ramps)	Observed Count	(Obs. At the Beginning + Obs. Entrance Ramps – Obs. Exit Ramps)	(Observed At the End - At the End Calculated)/ Observed at the End
9/15/2004	12:00 AM	1:00 AM	***	***	***	***	***	***
9/15/2004	1:00 AM	2:00 AM	397	254	70	597	581	2.68%
9/15/2004	2:00 AM	3:00 AM	308	198	61	461	445	3.47%
9/15/2004	3:00 AM	4:00 AM	289	123	60	361	352	2.49%
9/15/2004	4:00 AM	5:00 AM	403	140	94	472	449	4.87%
9/15/2004	5:00 AM	6:00 AM	1072	371	182	1200	1261	-5.08%
9/15/2004	6:00 AM	7:00 AM	2327	1166	664	2594	2829	-9.06%
9/15/2004	7:00 AM	8:00 AM	2898	2400	938	3909	4360	-11.54%
9/15/2004	8:00 AM	9:00 AM	2268	2427	828	3542	3867	-9.18%
9/15/2004	9:00 AM	10:00 AM	2543	1643	741	3280	3445	-5.03%
9/15/2004	10:00 AM	11:00 AM	2271	1600	669	3068	3202	-4.37%
9/15/2004	11:00 AM	12:00 PM	2304	1769	682	3337	3391	-1.62%
9/15/2004	12:00 PM	1:00 PM	2556	1961	671	3530	3846	-8.95%
9/15/2004	1:00 PM	2:00 PM	2654	2007	678	3784	3983	-5.26%
9/15/2004	2:00 PM	3:00 PM	3136	2545	705	4671	4976	-6.53%
9/15/2004	3:00 PM	4:00 PM	3713	3600	738	5693	6575	-15.49%
9/15/2004	4:00 PM	5:00 PM	2754	4225	776	6208	6203	0.08%
9/15/2004	5:00 PM	6:00 PM	2283	4316	631	6429	5968	7.17%
9/15/2004	6:00 PM	7:00 PM	2661	2636	605	4704	4692	0.26%
9/15/2004	7:00 PM	8:00 PM	2256	1874	508	3447	3622	-5.08%
9/15/2004	8:00 PM	9:00 PM	1985	1556	434	3068	3107	-1.27%
9/15/2004	9:00 PM	10:00 PM	1810	1434	351	2722	2893	-6.28%
9/15/2004	10:00 PM	11:00 PM	1694	1227	347	2556	2574	-0.70%
10/15/2005	11:00 PM	12:00 AM	1056	978	234	1628	1800	-10.57%
Total Number of Vehicles for 23 hours			45638	40450	11667	71261	74421	-4.43%

*** Data not available due to equipment malfunction.
Note: Observed data is the measured data adjusted by phantoms and misses factors.

Table 48. Hourly Vehicle Counts in Percentages for I-90 Eastbound for Phase II (No Work Zone)

Date	Time		At the Beginning	Entrance Ramps	Exit Ramps	At the End	At the End Calculated	Percent Difference
	Start	End	Observed Count	Observed Count (Total of 4 Entrance Ramps)	Observed Count (Total of 3 Exit Ramps)	Observed Count	(Obs. At the Beginning + Obs. Entrance Ramps – Obs. Exit Ramps)	(Observed At the End - At the End Calculated)/ Observed at the End
10/12/2005	12:00 AM	1:00 AM	***	***	***	***	***	***
10/12/2005	1:00 AM	2:00 AM	595	338	103	990	807	18.49%
10/12/2005	2:00 AM	3:00 AM	306	185	63	528	415	21.36%
10/12/2005	3:00 AM	4:00 AM	592	184	104	848	647	23.68%
10/12/2005	4:00 AM	5:00 AM	384	116	47	478	436	8.69%
10/12/2005	5:00 AM	6:00 AM	1039	294	145	1250	1161	7.12%
10/12/2005	6:00 AM	7:00 AM	2296	690	384	2822	2541	9.95%
10/12/2005	7:00 AM	8:00 AM	2787	1679	621	4226	3719	12.00%
10/12/2005	8:00 AM	9:00 AM	2384	1491	671	3751	3095	17.50%
10/12/2005	9:00 AM	10:00 AM	2097	1151	599	3155	2524	20.01%
10/12/2005	10:00 AM	11:00 AM	2105	1144	467	3103	2692	13.24%
10/12/2005	11:00 AM	12:00 PM	2253	1217	515	3491	2860	18.07%
10/12/2005	12:00 PM	1:00 PM	2293	1669	465	3526	3446	2.25%
10/12/2005	1:00 PM	2:00 PM	2522	1898	514	3749	3802	-1.42%
10/12/2005	2:00 PM	3:00 PM	3033	2464	561	4659	4821	-3.46%
10/12/2005	3:00 PM	4:00 PM	3653	3270	536	6001	6235	-3.89%
10/12/2005	4:00 PM	5:00 PM	4189	4323	553	7464	7828	-4.88%
10/12/2005	5:00 PM	6:00 PM	3948	4474	466	7674	7847	-2.27%
10/12/2005	6:00 PM	7:00 PM	2671	2632	410	4640	4758	-2.56%
10/12/2005	7:00 PM	8:00 PM	2153	1652	354	3372	3373	-0.01%
10/12/2005	8:00 PM	9:00 PM	1661	1270	242	2672	2643	1.10%
10/12/2005	9:00 PM	10:00 PM	1542	1191	232	2458	2458	-0.01%
10/12/2005	10:00 PM	11:00 PM	1267	912	178	1974	1952	1.13%
10/12/2005	11:00 PM	12:00 AM	979	764	182	1559	1519	2.53%
Total Number of Vehicles for 23 hours			46747	35009	8412	74389	71580	3.78%

*** Data not available due to equipment malfunction.

Note: Observed data is the measured data adjusted by phantoms and misses factors

Table 49. Hourly Traffic Counts for 72nd Street to I-90 Eastbound Entrance Ramp after Construction

Date	Time		Location 7 - 72nd to I90E
	Start	End	Count (vehicles/hour)
10/12/2005	1:00 AM	2:00 AM	24
10/12/2005	2:00 AM	3:00 AM	20
10/12/2005	3:00 AM	4:00 AM	19
10/12/2005	4:00 AM	5:00 AM	7
10/12/2005	5:00 AM	6:00 AM	40
10/12/2005	6:00 AM	7:00 AM	65
10/12/2005	7:00 AM	8:00 AM	98
10/12/2005	8:00 AM	9:00 AM	81
10/12/2005	9:00 AM	10:00 AM	73
10/12/2005	10:00 AM	11:00 AM	100
10/12/2005	11:00 AM	12:00 PM	95
10/12/2005	12:00 PM	1:00 PM	86
10/12/2005	1:00 PM	2:00 PM	84
10/12/2005	2:00 PM	3:00 PM	166
10/12/2005	3:00 PM	4:00 PM	180
10/12/2005	4:00 PM	5:00 PM	242
10/12/2005	5:00 PM	6:00 PM	212
10/12/2005	6:00 PM	7:00 PM	130
10/12/2005	7:00 PM	8:00 PM	103
10/12/2005	8:00 PM	9:00 PM	86
10/12/2005	9:00 PM	10:00 PM	88
10/12/2005	10:00 PM	11:00 PM	48
10/12/2005	11:00 PM	12:00 AM	33
		N=	23
		Total=	2080
		Average =	90.4
		Minimum=	7
		Maximum=	242

Table 50. Hourly Vehicle Counts in Percentages for I-90 Westbound for Phase I (Work Zone)

Date	Time		At the Beginning	Entrance Ramps	Exit Ramps	At the End	At the End Calculated	Percent Difference
	Start	End	Observed Count	Observed Count (Total of 1 Entrance Ramps)	Observed Count (Total of 2 Exit Ramps)	Observed Count	(Obs. At the Beginning + Obs. Entrance Ramps – Obs. Exit Ramps)	(Observed At the End - At the End Calculated)/ Observed at the End
9/18/2004	12:00 AM	1:00 AM	940	147	202	1050	885	15.72%
9/18/2004	1:00 AM	2:00 AM	683	122	133	749	672	10.25%
9/18/2004	2:00 AM	3:00 AM	514	96	111	537	498	7.29%
9/18/2004	3:00 AM	4:00 AM	372	72	76	374	368	1.55%
9/18/2004	4:00 AM	5:00 AM	468	63	73	475	458	3.41%
9/18/2004	5:00 AM	6:00 AM	829	72	148	804	753	6.29%
9/18/2004	6:00 AM	7:00 AM	1493	133	396	1406	1230	12.56%
9/18/2004	7:00 AM	8:00 AM	2285	173	419	1910	2039	-6.72%
9/18/2004	8:00 AM	9:00 AM	3008	243	563	2533	2688	-6.13%
9/18/2004	9:00 AM	10:00 AM	2942	312	628	2483	2625	-5.72%
9/18/2004	10:00 AM	11:00 AM	3025	371	641	2653	2754	-3.80%
9/18/2004	11:00 AM	12:00 PM	3438	403	668	3069	3173	-3.41%
9/18/2004	12:00 PM	1:00 PM	3646	458	688	3217	3417	-6.22%
9/18/2004	1:00 PM	2:00 PM	3526	480	776	3159	3230	-2.26%
9/18/2004	2:00 PM	3:00 PM	3483	494	715	3089	3263	-5.62%
9/18/2004	3:00 PM	4:00 PM	3508	496	636	3152	3369	-6.87%
9/18/2004	4:00 PM	5:00 PM	3678	469	720	3168	3427	-8.17%
9/18/2004	5:00 PM	6:00 PM	3603	471	565	3291	3509	-6.62%
9/18/2004	6:00 PM	7:00 PM	3519	416	590	3131	3346	-6.87%
9/18/2004	7:00 PM	8:00 PM	2906	368	533	2604	2741	-5.25%
9/18/2004	8:00 PM	9:00 PM	2541	328	422	2306	2446	-6.06%
9/18/2004	9:00 PM	10:00 PM	2499	335	414	2245	2419	-7.75%
9/18/2004	10:00 PM	11:00 PM	2105	283	340	1918	2048	-6.74%
9/18/2004	11:00 PM	12:00 AM	1701	261	335	1577	1626	-3.09%
Total Number of Vehicles for 24 hours			55771	7065	10792	50900	52983	-4.09%

Note: Observed data is the measured data adjusted by phantoms and misses factors

Table 51. Hourly Vehicle Counts in Percentages for I-90 Westbound for Phase II (No Work Zone)

Date	Time		At the Beginning	Entrance Ramps	Exit Ramps	At the End	At the End Calculated	Percent Difference
	Start	End	Observed Count	Observed Count (Total of 2 Entrance Ramps)	Observed Count (Total of 3 Exit Ramps)	Observed Count	(Obs. At the Beginning + Obs. Entrance Ramps – Obs. Exit Ramps)	(Observed At the End - At the End Calculated)/ Observed at the End
10/15/2005	12:00 AM	1:00 AM	***	***	***	***	***	***
10/15/2005	1:00 AM	2:00 AM	1159	213	305	1339	1067	20.37%
10/15/2005	2:00 AM	3:00 AM	807	158	218	934	747	19.99%
10/15/2005	3:00 AM	4:00 AM	1129	190	290	1367	1029	24.76%
10/15/2005	4:00 AM	5:00 AM	552	60	130	627	481	23.26%
10/15/2005	5:00 AM	6:00 AM	1019	78	188	1121	910	18.82%
10/15/2005	6:00 AM	7:00 AM	1817	146	538	1715	1425	16.92%
10/15/2005	7:00 AM	8:00 AM	2153	182	461	2190	1873	14.45%
10/15/2005	8:00 AM	9:00 AM	3026	251	749	3038	2528	16.80%
10/15/2005	9:00 AM	10:00 AM	3134	262	852	3092	2544	17.71%
10/15/2005	10:00 AM	11:00 AM	3097	244	789	3166	2553	19.38%
10/15/2005	11:00 AM	12:00 PM	3455	426	852	3540	3029	14.44%
10/15/2005	12:00 PM	1:00 PM	3626	477	812	3763	3290	12.55%
10/15/2005	1:00 PM	2:00 PM	3520	466	867	3639	3119	14.29%
10/15/2005	2:00 PM	3:00 PM	3571	533	819	3810	3285	13.78%
10/15/2005	3:00 PM	4:00 PM	3415	536	684	3734	3268	12.49%
10/15/2005	4:00 PM	5:00 PM	3408	537	703	3609	3243	10.14%
10/15/2005	5:00 PM	6:00 PM	3548	522	836	3702	3235	12.62%
10/15/2005	6:00 PM	7:00 PM	3575	436	831	3562	3180	10.72%
10/15/2005	7:00 PM	8:00 PM	3004	431	642	3050	2793	8.44%
10/15/2005	8:00 PM	9:00 PM	2457	366	364	2699	2459	8.89%
10/15/2005	9:00 PM	10:00 PM	2367	312	381	2470	2297	6.97%
10/15/2005	10:00 PM	11:00 PM	2284	361	349	2512	2296	8.60%
10/15/2005	11:00 PM	12:00 AM	1927	270	308	2092	1889	9.70%
Total Number of Vehicles for 23 hours			58050	7458	12968	60772	52541	13.55%

*** Data not available due to equipment malfunction.

Note: Observed data is the measured data adjusted by phantoms and misses factors

Table 52. Hourly Vehicle Counts for I-270 Westbound for Phase I (Work Zone)

Date	Time		At the Beginning	Entrance Ramps	Exit Ramps	At the End	At the End Calculated	Percent Difference
	Start	End	Observed Count	Observed Count (Total of 2 Entrance Ramps)	Observed Count (Total of 2 Exit Ramps)	Observed Count	(Obs. At the Beginning + Obs. Entrance Ramps – Obs. Exit Ramps)	(Observed At the End - At the End Calculated)/ Observed at the End
8/29/2004	12:00 AM	1:00 AM	517	304	343	***	478	***
8/29/2004	1:00 AM	2:00 AM	310	189	217	***	282	***
8/29/2004	2:00 AM	3:00 AM	223	175	182	***	216	***
8/29/2004	3:00 AM	4:00 AM	186	122	139	***	169	***
8/29/2004	4:00 AM	5:00 AM	274	106	222	***	158	***
8/29/2004	5:00 AM	6:00 AM	381	122	135	***	368	***
8/29/2004	6:00 AM	7:00 AM	615	201	245	***	571	***
8/29/2004	7:00 AM	8:00 AM	821	288	331	***	778	***
8/29/2004	8:00 AM	9:00 AM	1073	329	501	***	901	***
8/29/2004	9:00 AM	10:00 AM	1430	583	765	***	1248	***
8/29/2004	10:00 AM	11:00 AM	1522	800	1026	***	1296	***
8/29/2004	11:00 AM	12:00 PM	1881	1060	1081	1429	1860	-30.18%
8/29/2004	12:00 PM	1:00 PM	1875	1396	1386	1841	1885	-2.39%
8/29/2004	1:00 PM	2:00 PM	1877	1343	1422	1755	1798	-2.46%
8/29/2004	2:00 PM	3:00 PM	1813	1272	1330	1733	1755	-1.24%
8/29/2004	3:00 PM	4:00 PM	1678	1228	1433	1640	1473	10.17%
8/29/2004	4:00 PM	5:00 PM	1565	1238	1454	1665	1349	18.98%
8/29/2004	5:00 PM	6:00 PM	1452	1054	1476	1503	1030	31.49%
8/29/2004	6:00 PM	7:00 PM	1477	1059	1412	1459	1124	22.98%
8/29/2004	7:00 PM	8:00 PM	1420	853	1193	1223	1080	11.66%
8/29/2004	8:00 PM	9:00 PM	***	740	1003	1002	***	***
8/29/2004	9:00 PM	10:00 PM	***	555	713	841	***	***
8/29/2004	10:00 PM	11:00 PM	***	406	552	523	***	***
8/29/2004	11:00 PM	12:00 AM	***	310	387	414	***	***
Total Number of Vehicles for 9 hours			22390	15733	18948	17028	19819	6.28%

*** Data not available due to equipment malfunction.

Note: Observed data is the measured data adjusted by phantoms and misses factors

Table 53. Hourly Vehicle Counts for I-270 Westbound for Phase II (No Work Zone)

Date	Time		At the Beginning	Entrance Ramps	Exit Ramps	At the End	At the End Calculated	Percent Difference
	Start	End	Observed Count	Observed Count (Total of 3 Entrance Ramps)	Observed Count (Total of 3 Exit Ramps)	Observed Count	(Obs. At the Beginning + Obs. Entrance Ramps – Obs. Exit Ramps)	(Observed At the End - At the End Calculated)/ Observed at the End
6/25/2006	12:00 AM	1:00 AM	730	391	479	555	643	-15.82%
6/25/2006	1:00 AM	2:00 AM	457	232	320	311	369	-18.61%
6/25/2006	2:00 AM	3:00 AM	280	220	212	252	288	-14.50%
6/25/2006	3:00 AM	4:00 AM	186	129	133	131	182	-38.79%
6/25/2006	4:00 AM	5:00 AM	293	124	220	146	197	-35.11%
6/25/2006	5:00 AM	6:00 AM	288	116	171	185	233	-25.70%
6/25/2006	6:00 AM	7:00 AM	469	175	260	288	385	-33.68%
6/25/2006	7:00 AM	8:00 AM	580	271	400	372	451	-21.15%
6/25/2006	8:00 AM	9:00 AM	906	361	531	527	736	-39.69%
6/25/2006	9:00 AM	10:00 AM	1174	569	727	746	1016	-36.13%
6/25/2006	10:00 AM	11:00 AM	1401	758	935	969	1223	-26.27%
6/25/2006	11:00 AM	12:00 PM	1740	952	1108	1268	1584	-24.93%
6/25/2006	12:00 PM	1:00 PM	2176	1150	1277	1609	2049	-27.32%
6/25/2006	1:00 PM	2:00 PM	2222	1181	1486	1552	1917	-23.49%
6/25/2006	2:00 PM	3:00 PM	2082	1188	1369	1533	1901	-24.02%
6/25/2006	3:00 PM	4:00 PM	1983	1028	1260	1388	1751	-26.10%
6/25/2006	4:00 PM	5:00 PM	2169	1088	1410	1463	1847	-26.23%
6/25/2006	5:00 PM	6:00 PM	2236	1023	1471	1418	1787	-26.07%
6/25/2006	6:00 PM	7:00 PM	1958	890	1258	1266	1590	-25.61%
6/25/2006	7:00 PM	8:00 PM	1730	834	1108	1139	1456	-27.85%
6/25/2006	8:00 PM	9:00 PM	***	***	***	***	***	***
6/25/2006	9:00 PM	10:00 PM	***	***	***	***	***	***
6/25/2006	10:00 PM	11:00 PM	***	***	***	***	***	***
6/25/2006	11:00 PM	12:00 AM	***	***	***	***	***	***
Total Number of Vehicles for 20 hours			25061	12679	16135	17118	21605	-26.21%

*** Data not available due to equipment malfunction.

Note: Observed data is the measured data adjusted by phantoms and misses factors

Table 54. Hourly Vehicle Counts for I-270 Eastbound for Phase I (Work Zone)

Date	Time		At the Beginning	Entrance Ramps	Exit Ramps	At the End	At the End Calculated	Percent Difference
	Start	End	Observed Count	Observed Count (Total of 2 Entrance Ramps)	Observed Count (Total of 1 Exit Ramps)	Observed Count	(Obs. At the Beginning + Obs. Entrance Ramps – Obs. Exit Ramps)	(Observed At the End - At the End Calculated)/ Observed at the End
9/1/2004	12:00 AM	1:00 AM	***	***	***	***	***	***
9/1/2004	1:00 AM	2:00 AM	***	***	***	***	***	***
9/1/2004	2:00 AM	3:00 AM	***	***	***	***	***	***
9/1/2004	3:00 AM	4:00 AM	***	***	***	***	***	***
9/1/2004	4:00 AM	5:00 AM	***	***	***	***	***	***
9/1/2004	5:00 AM	6:00 AM	***	***	***	***	***	***
9/1/2004	6:00 AM	7:00 AM	***	***	***	***	***	***
9/1/2004	7:00 AM	8:00 AM	2155	***	1647	2740	***	***
9/1/2004	8:00 AM	9:00 AM	1898	***	1423	2357	***	***
9/1/2004	9:00 AM	10:00 AM	1438	1103	1024	1947	***	***
9/1/2004	10:00 AM	11:00 AM	1366	1408	964	1784	***	***
9/1/2004	11:00 AM	12:00 PM	1450	1454	999	1902	***	***
9/1/2004	12:00 PM	1:00 PM	1494	1571	1081	1950	1984	-1.74%
9/1/2004	1:00 PM	2:00 PM	1702	1584	1152	2118	2134	-0.76%
9/1/2004	2:00 PM	3:00 PM	1928	1805	1253	2474	2480	-0.24%
9/1/2004	3:00 PM	4:00 PM	2502	2240	1428	3189	3314	-3.92%
9/1/2004	4:00 PM	5:00 PM	2838	2272	1606	3560	3504	1.57%
9/1/2004	5:00 PM	6:00 PM	2809	2243	1572	3477	3480	-0.09%
9/1/2004	6:00 PM	7:00 PM	1895	1580	1143	2334	2332	0.09%
9/1/2004	7:00 PM	8:00 PM	1364	1196	769	1751	1791	-2.28%
9/1/2004	8:00 PM	9:00 PM	1130	1039	723	1481	1446	2.36%
9/1/2004	9:00 PM	10:00 PM	956	826	607	1187	1175	1.01%
9/1/2004	10:00 PM	11:00 PM	681	586	386	880	881	-0.11%
9/1/2004	11:00 PM	12:00 AM	477	485	277	678	685	-1.03%
9/2/2004	12:00 AM	1:00 AM	357	308	203	455	462	-1.54%
9/2/2004	1:00 AM	2:00 AM	271	231	133	350	369	-5.43%
9/2/2004	2:00 AM	3:00 AM	225	193	158	280	260	7.14%
9/2/2004	3:00 AM	4:00 AM	257	221	138	334	340	-1.80%
9/2/2004	4:00 AM	5:00 AM	344	281	162	434	463	-6.68%
9/2/2004	5:00 AM	6:00 AM	715	667	409	933	973	-4.29%
9/2/2004	6:00 AM	7:00 AM	1514	1559	1037	1906	2036	-6.82%
9/2/2004	7:00 AM	8:00 AM	2149	2276	1555	2698	2870	-6.38%
9/2/2004	8:00 AM	9:00 AM	1787	1862	1251	2354	2398	-1.87%
9/2/2004	9:00 AM	10:00 AM	1575	1603	984	2075	2194	-5.73%
9/2/2004	10:00 AM	11:00 AM	1440	1437	859	1914	2018	-5.43%
9/2/2004	11:00 AM	12:00 PM	1374	1433	815	1857	1992	-7.27%
9/2/2004	12:00 PM	1:00 PM	1558	1543	929	2031	2172	-6.94%

*** Data not available due to equipment malfunction.

Table 54. Hourly Vehicle Counts for I-270 Eastbound for Phase I (Work Zone) (continued)

9/2/2004	1:00 PM	2:00 PM	1692	1575	942	2158	2325	-7.74%
9/2/2004	2:00 PM	3:00 PM	1984	1844	1089	2551	2739	-7.37%
9/2/2004	3:00 PM	4:00 PM	2488	2413	1348	3372	3553	-5.37%
9/2/2004	4:00 PM	5:00 PM	2967	2164	1427	3656	3704	-1.31%
9/2/2004	5:00 PM	6:00 PM	2891	2771	1430	3602	4232	-17.49%
9/2/2004	6:00 PM	7:00 PM	1789	1656	1022	2323	2423	-4.30%
9/2/2004	7:00 PM	8:00 PM	1387	1286	802	1801	1871	-3.89%
9/2/2004	8:00 PM	9:00 PM	1153	1057	728	1473	1482	-0.61%
9/2/2004	9:00 PM	10:00 PM	984	881	571	1284	1294	-0.78%
9/2/2004	10:00 PM	11:00 PM	693	586	440	865	839	3.01%
9/2/2004	11:00 PM	12:00 AM	513	535	295	720	753	-4.58%
Total Number of Vehicles for 36 hours			56137	51774	33711	72138	68968	-3.70%

Note: Observed data is the measured data adjusted by phantoms and misses factors

Table 55. Hourly Vehicle Counts for I-270 Eastbound for Phase II (No Work Zone)

Date	Time		At the Beginning	Entrance Ramps	Exit Ramps	At the End	At the End Calculated	Percent Difference
	Start	End	Observed Count	Observed Count (Total of 3 Entrance Ramps)	Observed Count (Total of 3 Exit Ramps)	Observed Count	(Obs. At the Beginning + Obs. Entrance Ramps – Obs. Exit Ramps)	(Observed At the End - At the End Calculated)/ Observed at the End
6/28/2006	12:00 AM	1:00 AM	418	275	311	446	397	11.04%
6/28/2006	1:00 AM	2:00 AM	250	185	156	319	287	9.82%
6/28/2006	2:00 AM	3:00 AM	223	216	145	323	302	6.43%
6/28/2006	3:00 AM	4:00 AM	252	153	138	309	277	10.38%
6/28/2006	4:00 AM	5:00 AM	350	229	215	424	381	10.14%
6/28/2006	5:00 AM	6:00 AM	729	596	440	945	962	-1.79%
6/28/2006	6:00 AM	7:00 AM	1546	1324	1100	1899	1915	-0.84%
6/28/2006	7:00 AM	8:00 AM	2294	2020	1617	2796	2885	-3.19%
6/28/2006	8:00 AM	9:00 AM	1958	1682	1421	2398	2326	3.02%
6/28/2006	9:00 AM	10:00 AM	1598	1325	1174	1955	1834	6.20%
6/28/2006	10:00 AM	11:00 AM	1444	1339	1065	1838	1814	1.28%
6/28/2006	11:00 AM	12:00 PM	1581	1435	1173	1995	1937	2.89%
6/28/2006	12:00 PM	1:00 PM	1715	1529	1242	2033	2084	-2.48%
6/28/2006	1:00 PM	2:00 PM	1806	1428	1286	2172	2077	4.35%
6/28/2006	2:00 PM	3:00 PM	1970	1635	1454	2469	2266	8.24%
6/28/2006	3:00 PM	4:00 PM	2803	2148	1420	3200	3667	-14.62%
6/28/2006	4:00 PM	5:00 PM	3223	2208	1542	3678	4018	-9.24%
6/28/2006	5:00 PM	6:00 PM	3409	1599	1214	3453	3954	-14.49%
6/28/2006	6:00 PM	7:00 PM	2261	1571	1377	2602	2583	0.74%
6/28/2006	7:00 PM	8:00 PM	1530	1167	1031	1693	1736	-2.56%
6/28/2006	8:00 PM	9:00 PM	1304	884	975	1405	1291	8.14%
6/28/2006	9:00 PM	10:00 PM	1117	776	800	1203	1136	5.57%
6/28/2006	10:00 PM	11:00 PM	804	643	538	959	939	2.03%
6/28/2006	11:00 PM	12:00 AM	570	505	355	784	739	5.69%
6/29/2006	12:00 AM	1:00 AM	386	289	252	460	438	4.88%
6/29/2006	1:00 AM	2:00 AM	279	193	149	360	332	7.82%
6/29/2006	2:00 AM	3:00 AM	265	215	179	339	307	9.44%
6/29/2006	3:00 AM	4:00 AM	253	182	165	326	284	12.90%
6/29/2006	4:00 AM	5:00 AM	330	233	195	406	384	5.46%
6/29/2006	5:00 AM	6:00 AM	728	620	441	949	987	-4.04%
6/29/2006	6:00 AM	7:00 AM	1457	1406	1059	1868	1974	-5.69%
6/29/2006	7:00 AM	8:00 AM	2263	2016	1605	2734	2885	-5.53%
6/29/2006	8:00 AM	9:00 AM	1903	1697	1449	2283	2275	0.36%
6/29/2006	9:00 AM	10:00 AM	1598	1384	1173	1745	1892	-8.46%
6/29/2006	10:00 AM	11:00 AM	1480	1430	1110	1904	1897	0.39%
6/29/2006	11:00 AM	12:00 PM	1573	1451	1095	2014	2042	-1.38%
6/29/2006	12:00 PM	1:00 PM	1772	1550	1277	2126	2137	-0.52%

Table 55. Hourly Vehicle Counts for I-270 Eastbound for Phase II (No Work Zone) (continued)

6/29/2006	1:00 PM	2:00 PM	1898	1394	1266	2158	2142	0.71%
6/29/2006	2:00 PM	3:00 PM	2215	1635	1373	2493	2595	-4.10%
6/29/2006	3:00 PM	4:00 PM	2795	2133	1450	3241	3598	-10.99%
6/29/2006	4:00 PM	5:00 PM	3042	1788	1463	3674	3514	4.36%
6/29/2006	5:00 PM	6:00 PM	3443	1701	1486	3696	3813	-3.16%
6/29/2006	6:00 PM	7:00 PM	2500	1529	1384	2749	2754	-0.18%
6/29/2006	7:00 PM	8:00 PM	1684	1202	1094	1929	1883	2.36%
6/29/2006	8:00 PM	9:00 PM	1404	953	920	1513	1522	-0.63%
6/29/2006	9:00 PM	10:00 PM	1279	822	821	1316	1360	-3.30%
6/29/2006	10:00 PM	11:00 PM	923	657	580	1085	1058	2.55%
6/29/2006	11:00 PM	12:00 AM	642	431	395	751	737	1.82%
Total Number of Vehicles for 48 hours			71267	53784	44571	83418	84619	-1.44%

Note: Observed data is the measured data adjusted by phantoms and misses factors

Table 56. Hourly Vehicle Counts for I-270 Eastbound to I71Exit Ramp during and after Construction

Phase II - Date	Time		Location 6 - I270E to I71S	Location 7 - I270E to I71N	Phase I - Date	Time		Location 7 - I270E to I71
	Start	End	Count	Count		Start	End	Count
6/28/2006	12:00 AM	1:00 AM	94	39	**9/1/2004**	12:00 AM	1:00 AM	***
6/28/2006	1:00 AM	2:00 AM	61	26	**9/1/2004**	1:00 AM	2:00 AM	***
6/28/2006	2:00 AM	3:00 AM	63	21	**9/1/2004**	2:00 AM	3:00 AM	***
6/28/2006	3:00 AM	4:00 AM	72	9	**9/1/2004**	3:00 AM	4:00 AM	***
6/28/2006	4:00 AM	5:00 AM	109	28	**9/1/2004**	4:00 AM	5:00 AM	***
6/28/2006	5:00 AM	6:00 AM	146	134	**9/1/2004**	5:00 AM	6:00 AM	***
6/28/2006	6:00 AM	7:00 AM	313	469	**9/1/2004**	6:00 AM	7:00 AM	***
6/28/2006	7:00 AM	8:00 AM	492	646	**9/1/2004**	7:00 AM	8:00 AM	1647
6/28/2006	8:00 AM	9:00 AM	481	495	**9/1/2004**	8:00 AM	9:00 AM	1423
6/28/2006	9:00 AM	10:00 AM	449	319	**9/1/2004**	9:00 AM	10:00 AM	1024
6/28/2006	10:00 AM	11:00 AM	380	269	**9/1/2004**	10:00 AM	11:00 AM	964
6/28/2006	11:00 AM	12:00 PM	452	240	**9/1/2004**	11:00 AM	12:00 PM	999
6/28/2006	12:00 PM	1:00 PM	445	300	**9/1/2004**	12:00 PM	1:00 PM	1081
6/28/2006	1:00 PM	2:00 PM	476	272	**9/1/2004**	1:00 PM	2:00 PM	1152
6/28/2006	2:00 PM	3:00 PM	550	285	**9/1/2004**	2:00 PM	3:00 PM	1253
6/28/2006	3:00 PM	4:00 PM	627	289	**9/1/2004**	3:00 PM	4:00 PM	1428
6/28/2006	4:00 PM	5:00 PM	652	307	**9/1/2004**	4:00 PM	5:00 PM	1606
6/28/2006	5:00 PM	6:00 PM	723	314	**9/1/2004**	5:00 PM	6:00 PM	1572
6/28/2006	6:00 PM	7:00 PM	521	250	**9/1/2004**	6:00 PM	7:00 PM	1143
6/28/2006	7:00 PM	8:00 PM	336	198	**9/1/2004**	7:00 PM	8:00 PM	769
6/28/2006	8:00 PM	9:00 PM	365	133	**9/1/2004**	8:00 PM	9:00 PM	723
6/28/2006	9:00 PM	10:00 PM	280	108	**9/1/2004**	9:00 PM	10:00 PM	607
6/28/2006	10:00 PM	11:00 PM	181	89	**9/1/2004**	10:00 PM	11:00 PM	386
6/28/2006	11:00 PM	12:00 AM	131	47	**9/1/2004**	11:00 PM	12:00 AM	277
6/29/2006	12:00 AM	1:00 AM	74	39	**9/2/2004**	12:00 AM	1:00 AM	203
6/29/2006	1:00 AM	2:00 AM	57	26	**9/2/2004**	1:00 AM	2:00 AM	133
6/29/2006	2:00 AM	3:00 AM	59	39	**9/2/2004**	2:00 AM	3:00 AM	158
6/29/2006	3:00 AM	4:00 AM	76	20	**9/2/2004**	3:00 AM	4:00 AM	138
6/29/2006	4:00 AM	5:00 AM	88	32	**9/2/2004**	4:00 AM	5:00 AM	162
6/29/2006	5:00 AM	6:00 AM	125	139	**9/2/2004**	5:00 AM	6:00 AM	409
6/29/2006	6:00 AM	7:00 AM	293	449	**9/2/2004**	6:00 AM	7:00 AM	1037
6/29/2006	7:00 AM	8:00 AM	474	655	**9/2/2004**	7:00 AM	8:00 AM	1555
6/29/2006	8:00 AM	9:00 AM	471	527	**9/2/2004**	8:00 AM	9:00 AM	1251
6/29/2006	9:00 AM	10:00 AM	396	351	**9/2/2004**	9:00 AM	10:00 AM	984
6/29/2006	10:00 AM	11:00 AM	413	266	**9/2/2004**	10:00 AM	11:00 AM	859
6/29/2006	11:00 AM	12:00 PM	419	226	**9/2/2004**	11:00 AM	12:00 PM	815
6/29/2006	12:00 PM	1:00 PM	487	281	**9/2/2004**	12:00 PM	1:00 PM	929
6/29/2006	1:00 PM	2:00 PM	450	297	**9/2/2004**	1:00 PM	2:00 PM	942
6/29/2006	2:00 PM	3:00 PM	494	284	**9/2/2004**	2:00 PM	3:00 PM	1089
6/29/2006	3:00 PM	4:00 PM	605	302	**9/2/2004**	3:00 PM	4:00 PM	1348
6/29/2006	4:00 PM	5:00 PM	616	278	**9/2/2004**	4:00 PM	5:00 PM	1427

*** Data not available due to equipment malfunction.

Table 56. Hourly Vehicle Counts for I-270 Eastbound to I71Exit Ramp during and after Construction (cont.)

Phase II - Date	Time		Location 6 - I270E to I71S	Location 7 - I270E to I71N	Phase I - Date	Time		Location 7 - I270E to I71
	Start	End	Count	Count		Start	End	Count
6/29/2006	5:00 PM	6:00 PM	706	339	**9/2/2004**	5:00 PM	6:00 PM	1430
6/29/2006	6:00 PM	7:00 PM	546	261	**9/2/2004**	6:00 PM	7:00 PM	1022
6/29/2006	7:00 PM	8:00 PM	455	145	**9/2/2004**	7:00 PM	8:00 PM	802
6/29/2006	8:00 PM	9:00 PM	434	***	**9/2/2004**	8:00 PM	9:00 PM	728
6/29/2006	9:00 PM	10:00 PM	357	***	**9/2/2004**	9:00 PM	10:00 PM	571
6/29/2006	10:00 PM	11:00 PM	266	***	**9/2/2004**	10:00 PM	11:00 PM	440
6/29/2006	11:00 PM	12:00 AM	191	***	**9/2/2004**	11:00 PM	12:00 AM	295
		N=	48	44			N=	41
		Total=	16951	10243			Total=	36781
		Average =	368.6	258.8			Average =	805.4
		Minimum=	57	9			Minimum=	133
		Maximum=	723	655			Maximum=	1647

*** Data not available due to equipment malfunction.

Table 57. Hourly Vehicle Counts for I71 to I-270 Eastbound Entrance Ramp during Construction – Phase I

Date	Time		Location 8 - I71 to I270E		
	Start	End	Lane 1	Lane 2	Total
			Count	Count	Count
9/1/2004	12:00 AM	1:00 AM	***	***	***
9/1/2004	1:00 AM	2:00 AM	***	***	***
9/1/2004	2:00 AM	3:00 AM	***	***	***
9/1/2004	3:00 AM	4:00 AM	***	***	***
9/1/2004	4:00 AM	5:00 AM	***	***	***
9/1/2004	5:00 AM	6:00 AM	***	***	***
9/1/2004	6:00 AM	7:00 AM	***	***	***
9/1/2004	7:00 AM	8:00 AM	***	***	***
9/1/2004	8:00 AM	9:00 AM	***	***	***
9/1/2004	9:00 AM	10:00 AM	384	261	645
9/1/2004	10:00 AM	11:00 AM	637	430	1067
9/1/2004	11:00 AM	12:00 PM	626	445	1071
9/1/2004	12:00 PM	1:00 PM	656	480	1136
9/1/2004	1:00 PM	2:00 PM	661	488	1149
9/1/2004	2:00 PM	3:00 PM	676	649	1325
9/1/2004	3:00 PM	4:00 PM	776	872	1648
9/1/2004	4:00 PM	5:00 PM	789	956	1745
9/1/2004	5:00 PM	6:00 PM	804	940	1744
9/1/2004	6:00 PM	7:00 PM	589	547	1136
9/1/2004	7:00 PM	8:00 PM	470	398	868
9/1/2004	8:00 PM	9:00 PM	411	325	736
9/1/2004	9:00 PM	10:00 PM	358	234	592
9/1/2004	10:00 PM	11:00 PM	263	170	433
9/1/2004	11:00 PM	12:00 AM	235	140	375
9/2/2004	12:00 AM	1:00 AM	156	83	239

*** Data not available due to equipment malfunction.

Table 57. Hourly Vehicle Counts for I71 to I-270 Eastbound Entrance Ramp during Construction (cont.)

Date	Time		Location 8 - I71 to I270E		
	Start	End	Lane 1	Lane 2	Total
			Count	Count	Count
9/2/2004	1:00 AM	2:00 AM	126	44	170
9/2/2004	2:00 AM	3:00 AM	73	38	111
9/2/2004	3:00 AM	4:00 AM	101	60	161
9/2/2004	4:00 AM	5:00 AM	120	73	193
9/2/2004	5:00 AM	6:00 AM	250	161	411
9/2/2004	6:00 AM	7:00 AM	495	432	927
9/2/2004	7:00 AM	8:00 AM	698	619	1317
9/2/2004	8:00 AM	9:00 AM	621	565	1186
9/2/2004	9:00 AM	10:00 AM	633	525	1158
9/2/2004	10:00 AM	11:00 AM	622	458	1080
9/2/2004	11:00 AM	12:00 PM	614	452	1066
9/2/2004	12:00 PM	1:00 PM	643	490	1133
9/2/2004	1:00 PM	2:00 PM	630	521	1151
9/2/2004	2:00 PM	3:00 PM	722	695	1417
9/2/2004	3:00 PM	4:00 PM	830	997	1827
9/2/2004	4:00 PM	5:00 PM	727	962	1689
9/2/2004	5:00 PM	6:00 PM	1404	877	2281
9/2/2004	6:00 PM	7:00 PM	698	582	1280
9/2/2004	7:00 PM	8:00 PM	569	408	977
9/2/2004	8:00 PM	9:00 PM	470	302	772
9/2/2004	9:00 PM	10:00 PM	405	271	676
9/2/2004	10:00 PM	11:00 PM	286	171	457
9/2/2004	11:00 PM	12:00 AM	246	136	382
		N=	39	39	39
		Total=	20474	17257	37731
		Average =	524.9	442.5	967.5
		Minimum=	73	38	111
		Maximum=	1404	997	2281

Table 58. Hourly Vehicle Counts for I71 to I-270 Eastbound Entrance Ramp after Construction – Phase II

Date	Time		Location 8 - I71N to I270E	Location 9 - I71S to I270E		
	Start	End	Lane 1	Lane 1	Lane 2	Total
			Count	Count	Count	Count
6/28/2006	12:00 AM	1:00 AM	127	9	63	72
6/28/2006	1:00 AM	2:00 AM	82	9	45	53
6/28/2006	2:00 AM	3:00 AM	90	8	43	51
6/28/2006	3:00 AM	4:00 AM	75	4	45	49
6/28/2006	4:00 AM	5:00 AM	107	10	53	63
6/28/2006	5:00 AM	6:00 AM	238	18	138	156
6/28/2006	6:00 AM	7:00 AM	424	51	306	357
6/28/2006	7:00 AM	8:00 AM	746	90	406	496
6/28/2006	8:00 AM	9:00 AM	705	82	358	440

Table 58. Hourly Vehicle Counts for I71 to I-270 Eastbound Entrance Ramp after Construction – Phase II (cont.)

Date	Time		Location 8 - I71N to I270E	Location 9 - I71S to I270E		
	Start	End	Lane 1	Lane 1	Lane 2	Total
			Count	Count	Count	Count
6/28/2006	9:00 AM	10:00 AM	570	76	324	399
6/28/2006	10:00 AM	11:00 AM	593	74	349	423
6/28/2006	11:00 AM	12:00 PM	667	86	384	470
6/28/2006	12:00 PM	1:00 PM	663	82	359	441
6/28/2006	1:00 PM	2:00 PM	637	74	397	471
6/28/2006	2:00 PM	3:00 PM	708	71	468	539
6/28/2006	3:00 PM	4:00 PM	837	140	674	814
6/28/2006	4:00 PM	5:00 PM	845	158	788	947
6/28/2006	5:00 PM	6:00 PM	413	177	581	758
6/28/2006	6:00 PM	7:00 PM	694	79	461	540
6/28/2006	7:00 PM	8:00 PM	548	68	303	371
6/28/2006	8:00 PM	9:00 PM	287	51	285	336
6/28/2006	9:00 PM	10:00 PM	275	54	229	283
6/28/2006	10:00 PM	11:00 PM	316	26	185	211
6/28/2006	11:00 PM	12:00 AM	259	23	125	148
6/29/2006	12:00 AM	1:00 AM	154	14	72	86
6/29/2006	1:00 AM	2:00 AM	91	4	46	51
6/29/2006	2:00 AM	3:00 AM	70	4	39	44
6/29/2006	3:00 AM	4:00 AM	104	7	36	43
6/29/2006	4:00 AM	5:00 AM	108	10	54	64
6/29/2006	5:00 AM	6:00 AM	257	15	157	172
6/29/2006	6:00 AM	7:00 AM	441	63	328	391
6/29/2006	7:00 AM	8:00 AM	725	74	461	536
6/29/2006	8:00 AM	9:00 AM	633	82	414	496
6/29/2006	9:00 AM	10:00 AM	607	83	355	438
6/29/2006	10:00 AM	11:00 AM	673	80	367	447
6/29/2006	11:00 AM	12:00 PM	693	82	370	452
6/29/2006	12:00 PM	1:00 PM	693	84	417	501
6/29/2006	1:00 PM	2:00 PM	605	79	389	468
6/29/2006	2:00 PM	3:00 PM	675	126	449	575
6/29/2006	3:00 PM	4:00 PM	806	143	707	851
6/29/2006	4:00 PM	5:00 PM	502	161	682	843
6/29/2006	5:00 PM	6:00 PM	537	158	596	754
6/29/2006	6:00 PM	7:00 PM	627	95	420	515
6/29/2006	7:00 PM	8:00 PM	541	65	354	419
6/29/2006	8:00 PM	9:00 PM	299	58	282	340
6/29/2006	9:00 PM	10:00 PM	282	34	246	280
6/29/2006	10:00 PM	11:00 PM	263	30	185	215
6/29/2006	11:00 PM	12:00 AM	193	14	110	124
		N=	48	48	48	48
		Total=	21485	3085	14905	17993
		Average =	447.6	64.3	310.5	374.8
		Minimum=	70	4	36	43
		Maximum=	845	177	788	947

3.4 Conclusions

The sites used in this study were assigned by ODOT. The traffic volume at the end of the work zone can be obtained in two ways. The first way is to actually measure the traffic volume at the end of the work zone using a microwave radar trailer. The other way is to measure the traffic volume at the beginning of the work zone and at each of the entrance and exit ramps in the work zone and then adding the entrance ramp traffic volume to the beginning traffic volume and subtracting the exit ramp traffic volume from the sum. Using accurate traffic measurement equipment there should be a very small difference between these two traffic volumes at the end. Based on the analysis of the traffic volumes for each hour the differences obtained for some of the work zone situations were quite large indicating that there were large equipment inaccuracies involved. Therefore, an analysis of the diversions due to ramp closings based on hourly traffic volumes was not considered as a feasible method and an analysis based on daily traffic volumes which showed a somewhat better accuracy was done for two of the four work zone sites which showed differences between the observed and the calculated daily traffic volumes of less than 5%.

It is observed that in a 23 hours period (Wednesday) an average of only 90.4 vehicles/hour (total 2080 vehicles per 23 hours) entered the 72nd Street to I-90 Eastbound entrance ramp in Phase II (no work zone) as given in Table 49. Compared to the other average entrance ramp, exit ramp, mainline at the beginning, and mainline at the end hourly vehicle counts, the 90.4 vehicles/hour or the total of 2080 vehicles per 23 hours is a very small number {total of vehicle counts for 23 hours at the 72nd street to I-90 Eastbound entrance ramp / total of vehicle counts for 23 hours calculated at the end of the mainline – [(2080/71580)*100 = 2.9%], given in Table 48 and Table 49}. Considering the small volume of only 2.9% at the 72nd Street to I-90 Eastbound entrance ramp, the variability and the limited accuracy of the measurement equipment one would not expect to find any significant diversion effects in this case.

With regard to I-270 Eastbound where the exit ramp to US62 was closed in Phase I (work zone) we observed that the traffic volume for the exit ramp to I-71 [northbound and southbound combined, average hourly traffic volume in Phase I = 805.4 vehicles/hour, in Phase II = 627.4 vehicles/hour (368.6+258.8=627.4), see Table 56] decreased by 28.4% [(627.4-805.4)* 100/627.4] in Phase II (no work zone) which indicates that most drivers diverted to the I71exit ramp since the previous exit ramp (US62) was closed.

The mainline traffic volume at the end of the work zone in Phase II (no work zone) is about 8.4% less than in Phase I (work zone) {(average hourly vehicle count for 48 hours in Phase II – average hourly vehicle count for 36 hours in Phase I) / average hourly vehicle count for 48 hours in Phase II, [(84619/48)-(68968/36)]*100/(84619/48) = 8.4%, from Table 54 and Table 55} mainly due to a smaller traffic volume entering from I-71 {17.6% less in Phase II (no work zone) [(447.6+374.9)-967.5]*100/(447.6+374.9)= -17.6%, data given in Table 57 and Table 58}. The decrease in the traffic volume entering from I-71 cannot be explained.

The diversion analysis for the two sites (I-90 Eastbound in Cleveland and I-270 Eastbound in Columbus) and the average vehicle counts for the mainline, and entrance and exit ramps are given in Figure 35 and Figure 36. More detailed information on the Diversion Analysis can be found in Appendix A Interim Report on Diversion analysis, which is stored in ORITE Human Factors and Ergonomics Laboratory and available in electronic form upon request.

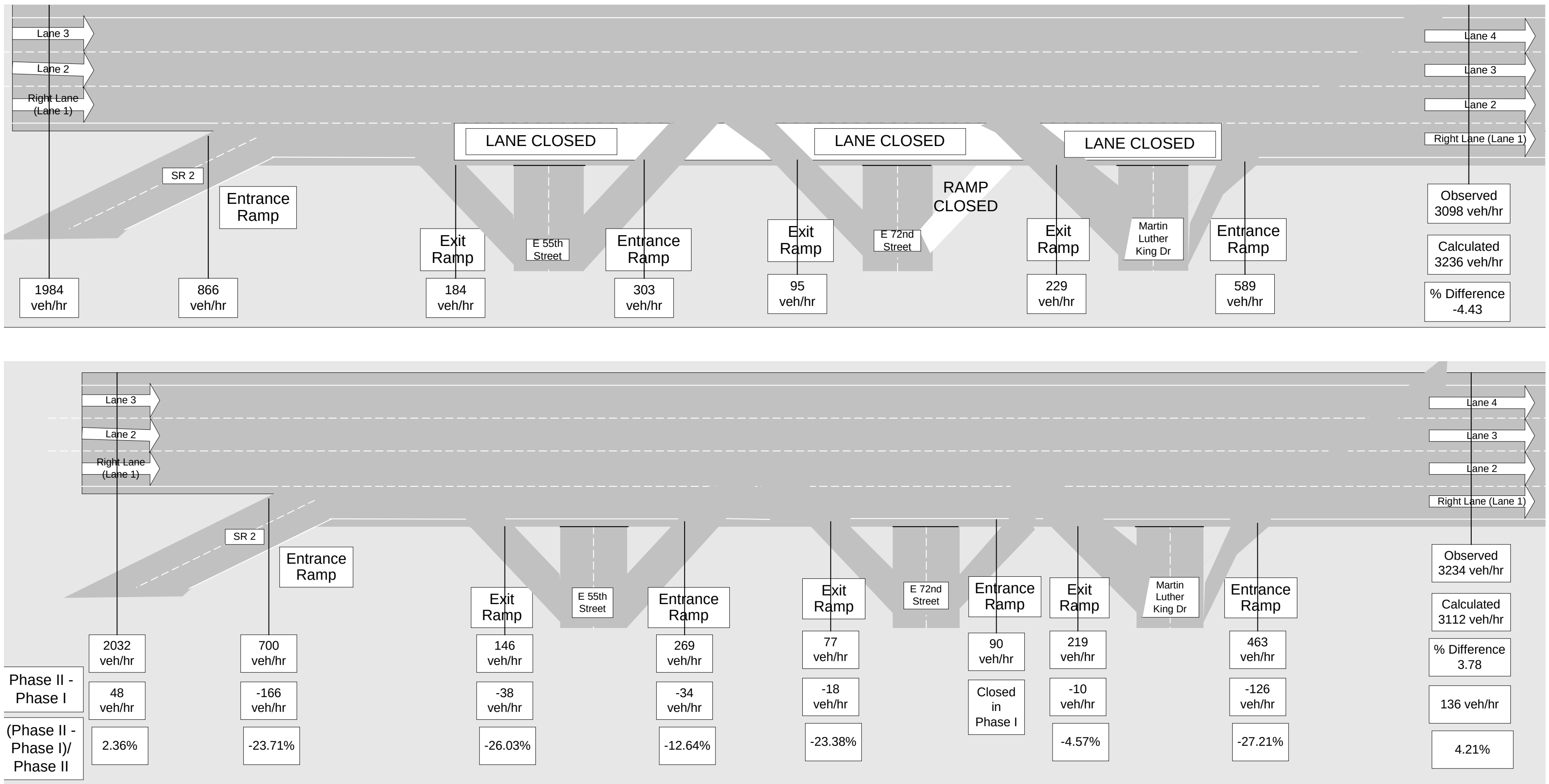
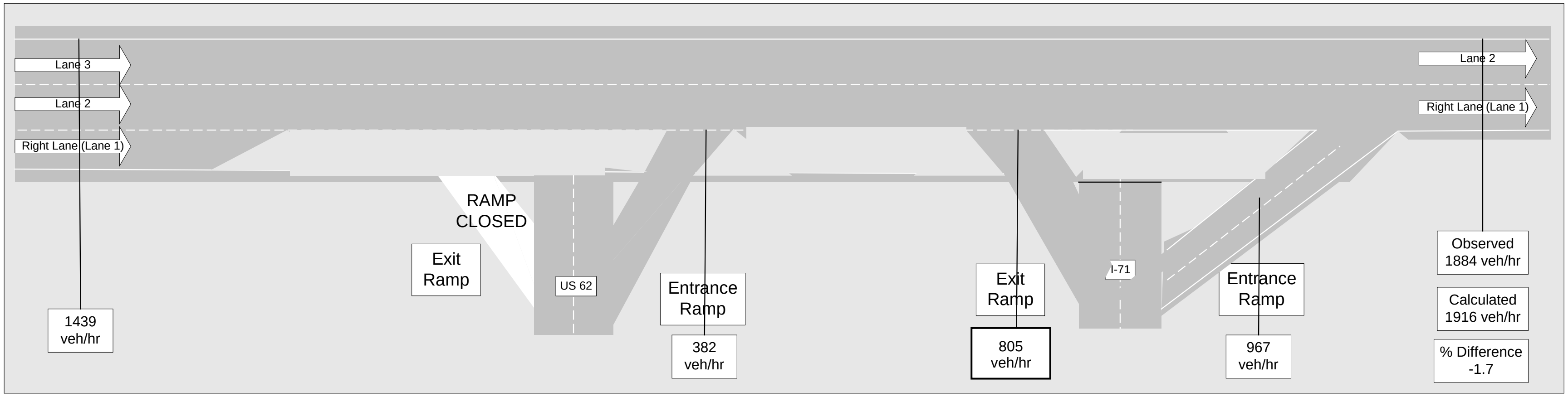


Figure 35. Diversion Analysis for I-90 Eastbound [Phase I (Work Zone – 72nd Street Entrance Ramp Closed) and Phase II (No Work Zone)] using average vehicle counts per hour.



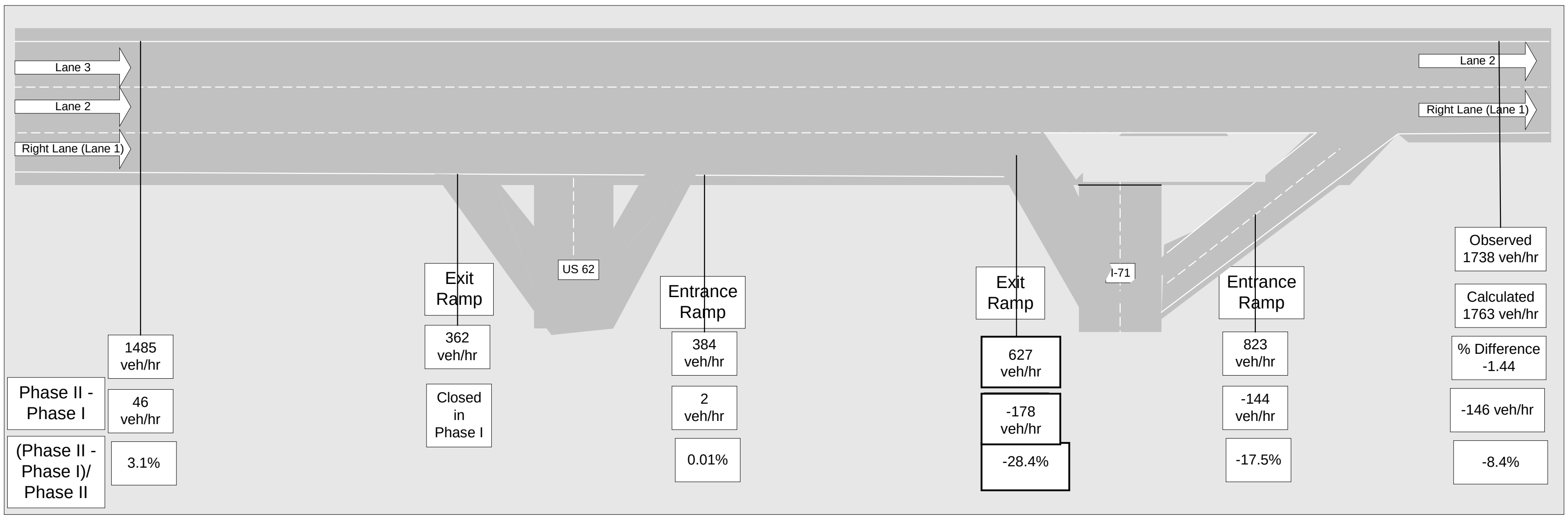


Figure 36. Diversion Analysis for I-270 Eastbound [Phase I (Work Zone – US 62 Exit Ramp Closed) and Phase II (No Work Zone)] using average vehicle counts per hour.

4 PART III: DEVELOPMENT OF DESIGN GUIDELINES FOR ENTRANCE (INCLUDING RAMP METERING) AND EXIT RAMPS

In Part III of this project the design guidelines for entrance (including ramp metering) and exit ramps were developed.

4.1 Ramp Management and Ramp Metering

Ramp management is a part of freeway management system to maximize use and benefit of transportation systems. Ramp management is a set of strategies to provide fast, efficient, and convenient means of travel to the public [12]. Ramp management strategies can be grouped in four main categories; ramp metering, ramp closure, special use treatments, and ramp terminal treatments. Ramp management may be applied to either entrance ramps or exit ramps.

Before and after studies of appropriately implemented and operated ramp management strategies showed the benefits of ramp management.

Ramp management strategies can improve the safety of the drivers on freeways and on the arterials trying to merge into the freeway traffic. The drivers on the arterials often have difficulty in merging to the mainline traffic. In congested traffic conditions, the drivers on the ramps cannot access the freeway since there is not enough gap for them to merge. The difficulty in merging often causes accidents. On the other hand, the drivers in the mainline are also disturbed by the incoming vehicles through the ramps. They need to adjust their speeds and gap acceptance according to incoming vehicles. In a study performed by Piotrowicz and Robinson [13], the summary of safety benefits of ramp metering are given. Table 59 shows the safety benefits of ramp metering.

Table 59. Summary of Ramp Metering Safety Benefits (adapted from [13])

Location	Benefit
Portland, OR	43% reduction in peak period collisions.
Minneapolis, MN	24% reduction in peak period collisions.
Seattle, WA	39% reduction in collision rate.
Denver, CO	50% reduction in rear-end and side-swipe collisions.
Detroit, MI	50% reduction in total collisions and 71% reduction in injury collisions.
Long Island, NY	15% reduction in collision rate.

Ramp management may also improve the mobility of the drivers and productivity. The operational objectives may be achieved by limiting the access of excessive number of vehicles to the freeway [13]. In Table 60 the mobility and productivity benefits of ramp metering are given.

Table 60 Summary of Ramp Metering Mobility and Productivity Benefits (adapted from 13)

Location	Benefit
Portland, OR	A 173% increase in average travel speed.
Minneapolis, MN	A 16% increase in average peak hour travel speed and a 25% increase in peak period volume.
Seattle, WA	A 52% reduction in average travel time and a 74% increase in traffic volume.
Denver, CO	A 57% increase in average peak period travel speed and a 37% decrease in average travel time.
Detroit, MI	An 8% increase in average travel speed and a 14% increase in traffic volume.
Long Island, NY	A 9% increase in average travel speed.

The potential benefits of ramp metering are dependent on the traffic and geometric conditions. Pearson summarized the potential benefits of ramp metering in [14]. Ramp metering may improve the efficient use of freeway capacity by diverting some mainline traffic to arterial roads and by diverting the local traffic and encouraging them to use alternative roads. In addition, by using ramp meters during peak hours the local traffic is discouraged to enter the congested freeways and the arrival of local traffic through the entrance ramps is spread out over longer time periods resulting in better utilization of freeway capacity. Ramp metering may also improve safety by reducing the platoons of vehicles entering the mainline traffic, which would decrease the sideswipe and rear-end crashes in freeway merge areas. In addition, by reducing the platoons of vehicles entering the mainline, the variance in mainline speed distributions may be reduced and safer conditions can be provided for drivers. Ramp metering may also reduce vehicle emissions and improve fuel savings by providing less speed variation on the mainline traffic. Ramp metering may also improve travel times. The travel time for the vehicles at ramps may increase; however the system-wide travel times may be reduced by increased mainline traffic speeds.

Ramp metering may also have negative impacts on the traffic dependent on the traffic conditions, geometric conditions, and the ramp metering system [14]. One of the negative impacts of ramp metering is the potential for traffic diversion when local routes cannot support diverted traffic. The operations on local routes may be negatively affected and increased crash rates may be observed. Another negative impact of ramp metering is its effects on motorists who live closer to downtown. Ramp metering promotes longer trips. Motorists living closer to downtown may observe increased travel times compared to their travel distances. Ramp metering may also have socio-economic effects in the neighborhood where they are implemented. The increased delay on the entrance ramps may negatively affect the surrounding businesses. However these negative impacts are for the long term implementation of ramp metering. The ramp metering in work areas in freeway work zones are limited for the duration of the construction therefore fewer negative impacts of ramp metering in freeway work zones may be expected. The potential benefits and negative impacts of ramp metering are summarized in Table 61 (adapted from [17]).

Table 61. Potential benefits and negative impacts of ramp metering.

Potential Benefits	Potential Negative Impacts
More efficient use of freeway capacity [14, 15, 16]	Limited space before ramp metering signals (queue spill over from signals back into arterials) [14, 15, 16]
Improved safety [14, 15, 16]	Limited space for enforcement between ramp metering signal and merge area [14]
Reduced vehicle emissions and fuel consumption [14, 15, 16]	Queue build up at mainline merging area due to few merging gaps [14]
Increased mainline throughput and travel times [14, 15, 16]	Limited acceleration lane lengths for merging [14, 16]
	Traffic diversion to local traffic, when the capacity of arterials is limited, may cause increased accident rates [14, 16]
	Equity: Ramp metering favors through traffic and promotes longer trips for local traffic. Motorists living closer to downtown may observe increased travel times compared to their travel distances. [14, 15, 16]

The typical ramp metering layout based on the ODOT Ramp Meter Design Manual [18] with the required traffic control devices are given in Figure 37 for signalized freeway entrance ramps and in Figure 38 for non-signalized freeway entrance ramps.

In signalized freeway entrance ramps the vehicles on the local (arterial) roads access the freeway mainline through the entrance ramp. The entry of the vehicles to the entrance ramp is based on the traffic signals at the intersection. The traffic on local roads is controlled by the traffic signals for all directions. The required traffic control devices for ramp metering at the signalized freeway entrance ramp are the ramp metering signals, ramp metering regulatory and warning signs, and the flashing beacons.

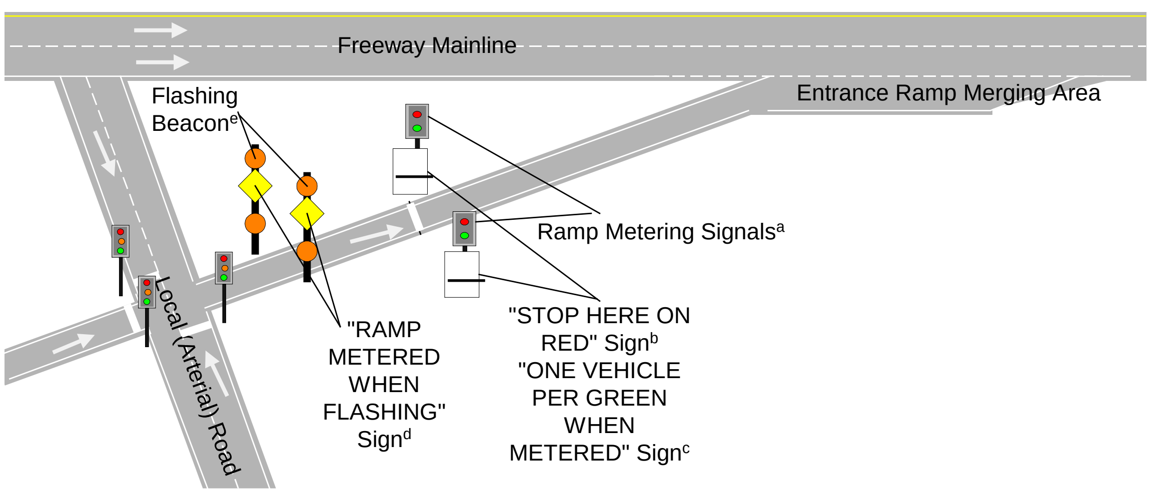
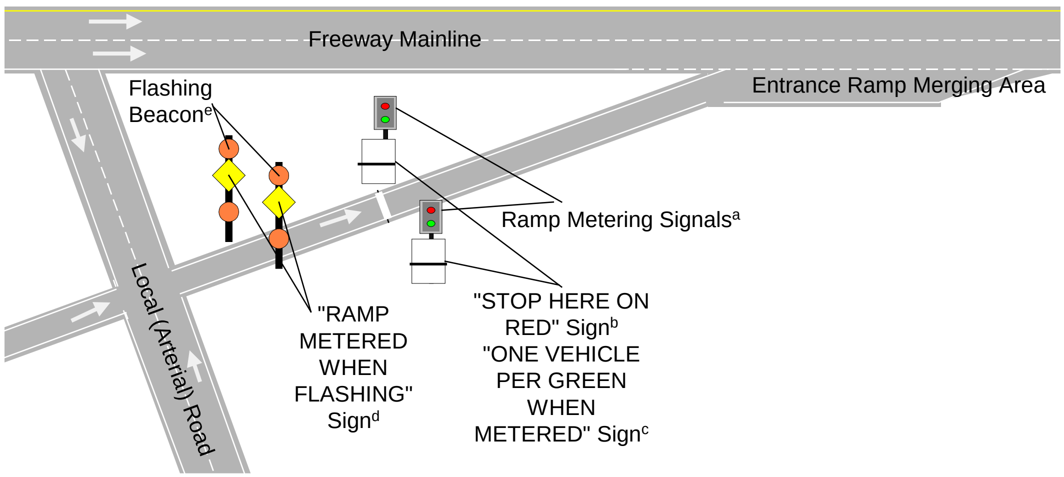
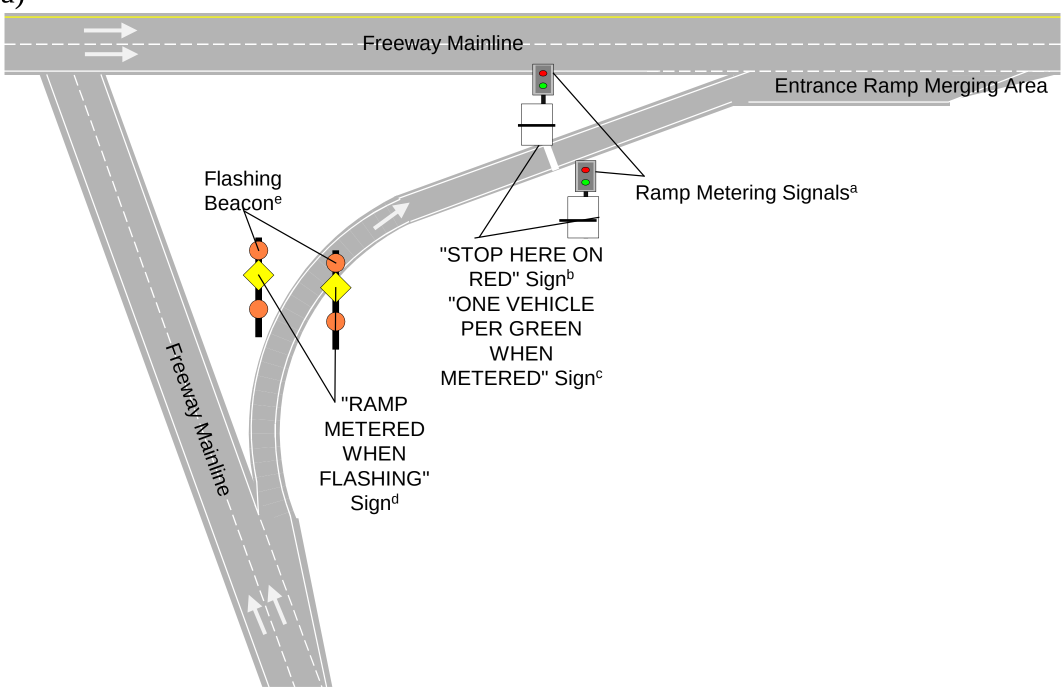


Figure 37. Layout of signalized freeway entrance ramp with advance ramp metering signs and ramp metering signals (traffic control devicesa,b,c,d,e are based on ODOT manuals).

The configuration of the non-signalized freeway entrance ramps investigated in this study is given in Figure 38. In this situation, the freeway entrance ramp may be connecting a local (arterial) road to the freeway as in Figure 38a or two different freeways as in Figure 38b. The exit ramp for one freeway becomes the entrance ramp for another freeway in connecting two freeways situation. The same traffic control devices for ramp metering at the non-signalized freeway entrance ramp are required as in the signalized freeway entrance ramp.



a)



b)

Figure 38. Layout of non-signalized freeway entrance ramp with advance ramp metering signs and ramp metering signals a) entrance ramp from a non-signalized intersection, b) entrance ramp connecting two different freeways (traffic control devices[a,b,c,d,e] are based on ODOT manuals).

The traffic control devices required for ramp metering based on the Ohio Manual of Uniform Traffic Control Devices (OMUTCD) [19] and Sign Design Manual [20] are given below.

Ramp Metering Signals: Section 4H of the OMUTCD [19] provides the standards and guidelines for the use of ramp metering signals. Ramp metering signals may be installed at the entrance ramp along with the regulatory signs. The ramp metering signal consists of two or three signal heads red and green or red, yellow, and green. The ramp metering signal may be installed on both sides of the roadway. The ramp metering signals should also be located and designed to minimize their viewing by freeway mainline traffic. The ramp metering signals should be supplemented with the stop lines, 12 to 24 in ((30 to 60 cm) wide solid white line extending across the approach lane as defined in Section 3B-16 of OMUTCD [19], at the signal. A sample application and placement of the ramp metering signal at an entrance ramp can be seen in Figure 39.

Figure 39. Sample ramp metering signal application at an entrance ramp (from [18]).

Regulatory Traffic Signs for Ramp Metering: The ramp metering signals should be supplemented with the regulatory traffic signs to inform drivers. The signing needs to alert motorists of the presence, operation of the ramp meter, and instructions that the motorist must follow on the metered ramp. Signing depends on the selected approach to ramp metering on the specific ramp [18]. The single lane freeway entrance ramp metering was investigated in this study. The required signing for single lane freeway entrance ramp metering are the “STOP HERE ON RED” and “ONE VEHICLE PER GREEN” signs. The signs should be placed at the stop line and fastened to the signal assembly. The design specifications (character height, width, spacing, etc.) for the “STOP HERE ON RED” sign is given in section R10-6 of the ODOT Sign Design Manual [20] and the design specifications for the “ONE VEHICLE PER GREEN” sign is given in section R10-H23 of the ODOT Sign Design Manual [20] as shown in Figure 40.

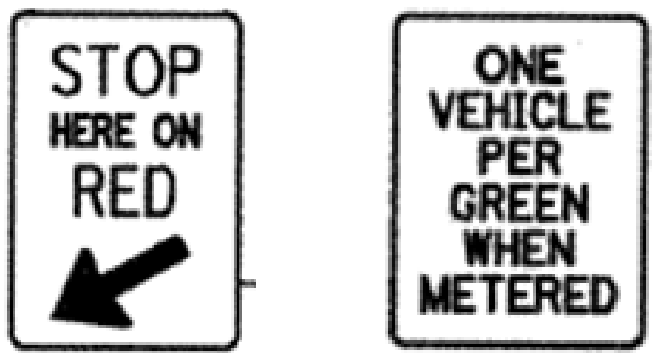


Figure 40. Regulatory traffic signs used in ramp metering (from [20]).

<u>Ramp Metering Signal Advance Warning Signs:</u> A ramp metering signal advance warning sign should be placed on the advance warning sign assemblies and should be accompanied by two yellow flashing beacons [18]. The "RAMP METERED WHEN FLASHING" black on yellow warning sign should be used to inform the drivers on the operation of ramp metering signals as given in Figure 41. The design specifications (character height, width, spacing, etc) for the "RAMP METERED WHEN FLASHING" sign is given in ODOT Sign Design Manual [20]. Section 4K of the OMUTCD [19] provides the standards and guidelines for the use of flashing beacons. The flashing beacons should be flashed at a rate of not less than 50 nor more than 60 times per minute. The flashing beacons should not be facing the freeway mainline traffic. Sign post may be placed on both sides of the road or on one side of the road depending on the entrance ramp geometric considerations. A sample "Ramp Metered When Flashing" advance warning sign for ramp metering is given in Figure 41.

Figure 41. Advance warning sign for ramp metering (from [18]).

<u>Changeable Message Signs (CMSs):</u> In ramp open some of the time and ramp open some of the time and metered temporary ramp control strategies, the ramp is made accessible or closed for the local traffic by the use of CMSs. Portable CMSs are important part of traffic control in freeway work zones and when they are used properly, they can command good attention from

motorists, provide information about roadwork activities, and help drives to make proper driving decisions [21]. The use of portable CMSs to inform local traffic about the ramp situation ("RAMP OPEN" or "RAMP CLOSED") will improve the ability of drivers to make decision to use the ramps in advance of the ramps.

The Section 6F.55 of the Ohio Manual of Uniform Traffic Control Devices (OMUTCD) [19] provides the standards for the CMSs. The OMUTCD requires the CMSs to be consisted of one or two phases for a message with at least 3 seconds phases. A phase may consist of up to three lines of eight characters per line. The letter height should be a minimum of 18 in. (45 cm) for CMSs in order to be visible from 0.5 mile (800 m) under both day and night conditions. Figure 42 shows an example of CMS which may be used to inform drivers about the ramp accessibility.

Figure 42. Changeable message signs informing drivers about the work zone (from [22]).

In a study by Ullman [23], the legibility distances of portable CMSs with different character heights are investigated. The researchers found that the 12-inch (30.5 cm) characters may provide sufficient legibility distances (409.2 ft (124.8 m) during daytime and 283.8 ft (86.6 m) during nighttime for 85% of the drivers) for arterial roads with average speeds of 45 mph (72 km/h) or higher at night with 2 units of information provided. Therefore 12-inch (30.5 cm) high letters may also be used in CMSs before the freeway entrance ramps to inform drivers about the ramp situations.

The location of the CMSs at signalized freeway entrance ramps is another important factor to be considered in ramp metering. The CMSs should not be visible at the same time with the signalized intersection traffic signals. The CMSs should be placed in advance of the intersection traffic signals in order to prevent confusion with the traffic signals. The local traffic will be able to see the CMSs in advance of the signalized freeway entrance ramp and then adjust their lane of travel accordingly. The drivers will continue on their way at the signalized intersection based on the CMSs "RAMP OPEN" or "RAMP CLOSED" message and the intersection traffic signal. The CMSs at non-signalized freeway entrance ramps may be placed near the guide sign providing information on the location of the freeway entrance ramp. The drivers would have enough time to adjust their travel with the advance warning about the entrance ramp condition.

4.2 Ramp Metering Literature Review

Ramp metering strategies have been used to improve freeway safety and efficiency. The literature review for ramp metering included general information on ramp metering and ramp metering strategies, algorithms, evaluation studies, safety studies, best practices, guidelines, and handbooks. The summary of literature reviewed is given in Table 62.

Table 62. List of publications reviewed in the study.

Summary of Literature (List of Publications)	
Manuals	9
Reports	17
Studies (Thesis and Presentations)	11
Papers	44
Books	5
Total	86

All publications are listed either in the references section or in the section after the references section which lists additional publications related to ramp metering not referenced in the text.

4.3 Cumulative Interarrival Time Distributions

Cumulative IAT time distributions for the signalized and non-signalized freeway entrance ramps having different geometric configurations and hourly traffic volume ranges were established. The cumulative IAT graphs for 300, 600, and 900 vph are given in Figure 43, Figure 44, and Figure 45. show that the cumulative IAT distributions for the four non-signalized freeway entrance ramps were similar for the data collection sites and the cumulative IAT distributions for the two signalized freeway entrance ramps were similar for the data collection sites. However it can be observed that there was a difference between the cumulative IAT distributions for non-signalized and signalized freeway entrance ramps.

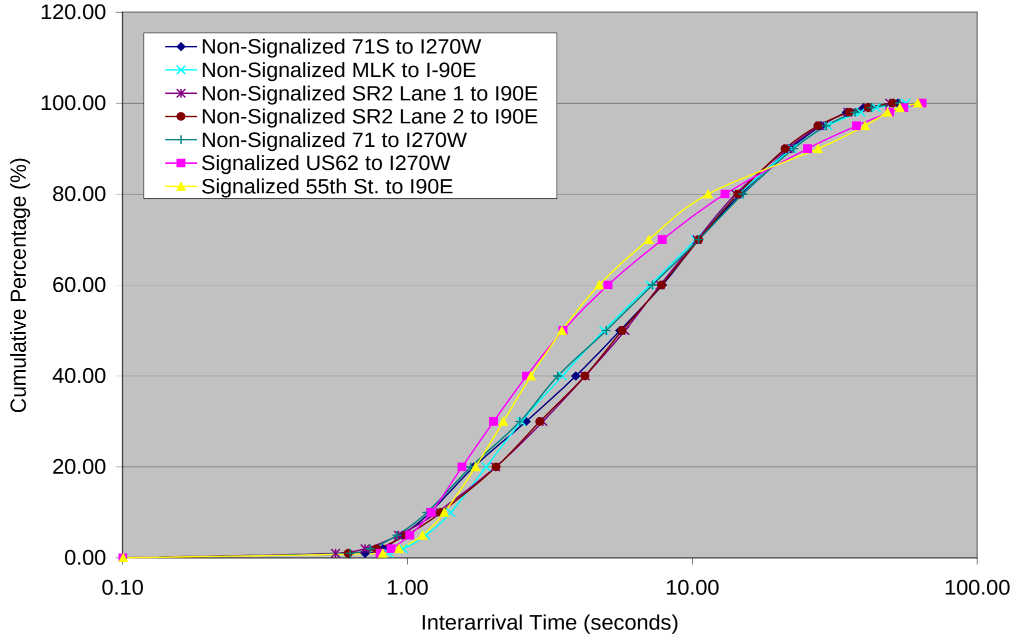


Figure 43. Cumulative IAT distributions for all freeway entrance ramps for 300 vph.

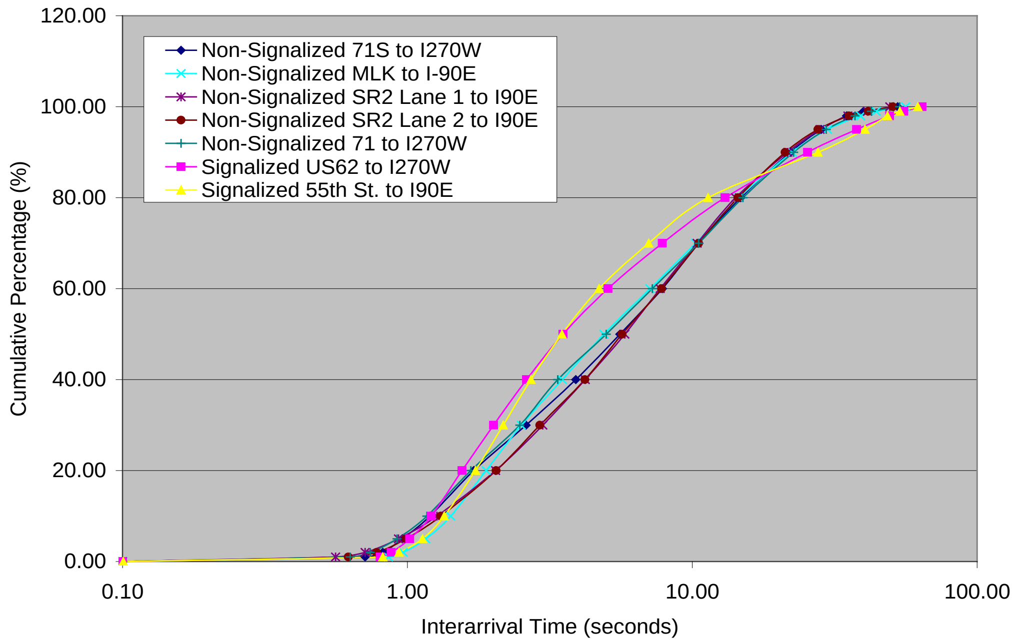


Figure 44. Cumulative IAT distributions for all freeway entrance ramps for 600 vph.

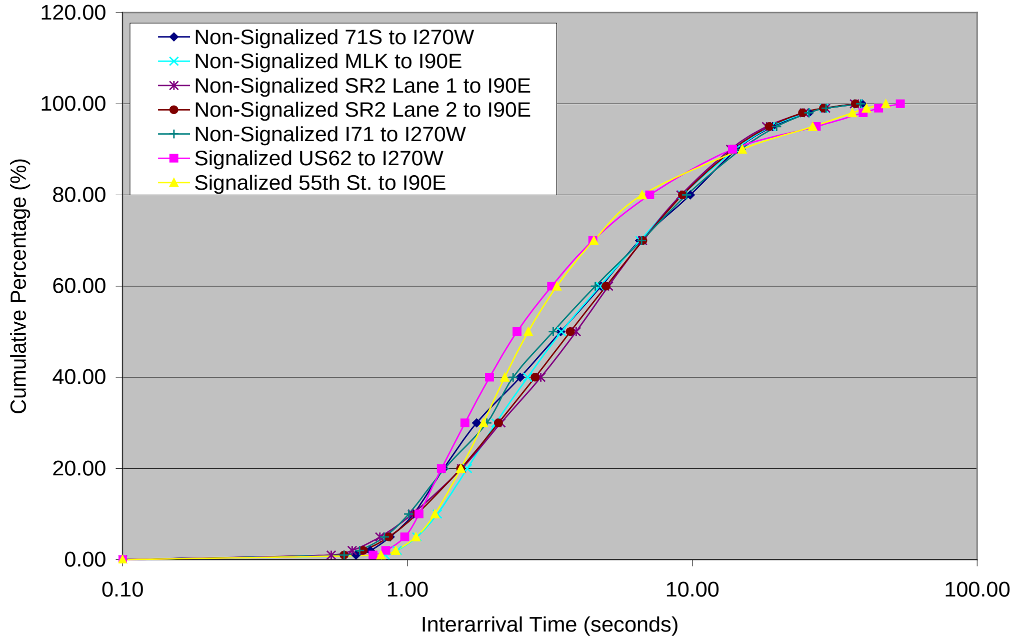
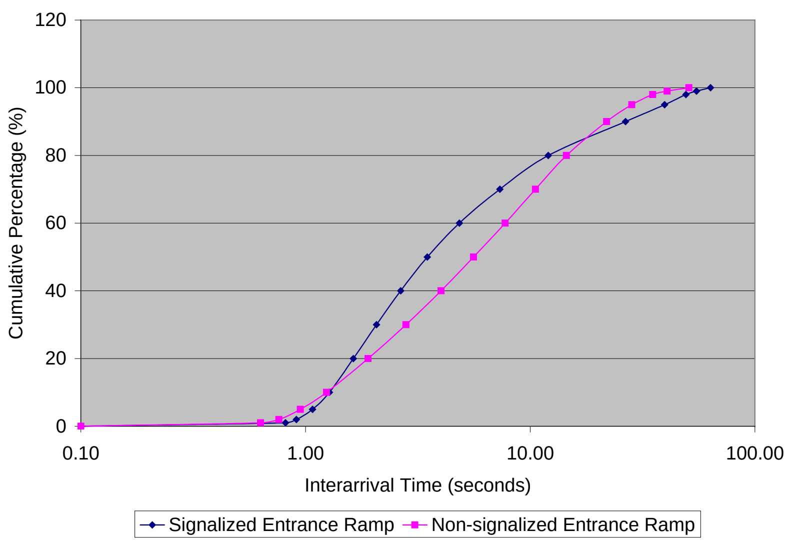


Figure 45. Cumulative IAT distributions for all freeway entrance ramps for 900 vph.

Since there was very little difference between the non-signalized cumulative IAT distributions for different locations, the IAT data for each of the 15-minute intervals were combined for all non-signalized entrance ramps and a universal cumulative IAT distribution for non-signalized freeway entrance ramps was generated using the procedure described for cumulative IAT distributions for signalized freeway entrance ramps above. In addition, a universal cumulative IAT distribution for signalized entrance ramps was generated using the same procedure. As a result one (universal) cumulative IAT distribution for all signalized freeway entrance ramps and one (universal) cumulative IAT distribution for all non-signalized entrance ramps were developed. The extrapolated cumulative IAT distributions for 2-lane, 3-lane, and 4-lane freeways and signalized and non-signalized entrance ramps are available in online at http://www.ent.ohiou.edu/ce/orite/universalIATdistributions.html.

4.3.1 Comparison of Universal IAT Distributions for Signalized and Non-signalized Freeway Entrance Ramps

The developed universal cumulative IAT distributions had larger traffic volume ranges than the individual entrance ramp traffic volume ranges. Therefore the cumulative IAT distributions for signalized and non-signalized entrance ramps were compared and plotted for 400, 600, and 800 vph as given in Figure 46, Figure 47, and Figure 48. The comparison of standard deviations for each traffic volumes showed that the standard deviations for non-signalized entrance ramps were smaller than signalized entrance ramps, resulting in tighter distributions. The maximum differences for the cumulative IAT distributions were also determined for each traffic volume by visual inspection. KS two sample two tailed goodness-of-fit tests for large samples with a significance level of 0.05 were used to determine the similarity of the two universal freeway entrance ramp IAT distributions [24]. The maximum differences were compared with the critical value for the KS two sample goodness of fit test for the low traffic volume sample, medium traffic volume sample, and high traffic volume sample for the universal cumulative IAT distributions for signalized and non-signalized freeway entrance ramps. In all three cases the observed maximum differences were greater than the critical maximum differences at level of significance of 0.05; therefore the null hypothesis that the two distributions are the same was rejected. The maximum absolute differences were 0.16 for 400 vph, 0.1 for 600 vph, and 0.09 for 800 vph, which were all greater than the critical maximum absolute differences calculated for the KS two sample goodness-of-fit test.

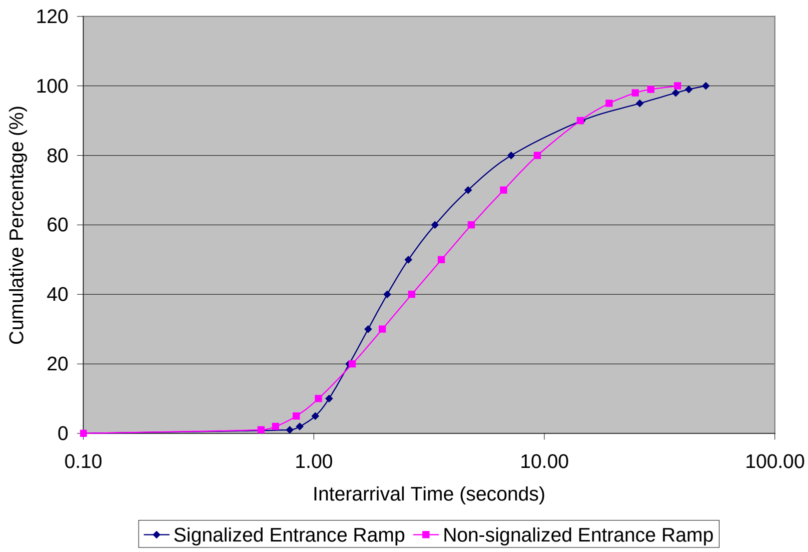


Universal IAT Distribution for Signalized Entrance Ramp
Average= 8.992
Standard Deviation= 12.232
Coefficient of Variation= 1.360

Universal IAT Distribution for Non-Signalized Entrance Ramp
Average= 8.986
Standard Deviation= 9.059
Coefficient of Variation= 1.008

KS Two Sample Goodness of Fit Test
D Observed (by visual inspection)= 0.16
D Critical= 0.096 (Level of Significance=0.05)
Reject

Figure 46. Comparison of signalized and non-signalized freeway entrance ramp universal IAT distributions for 400 vph.

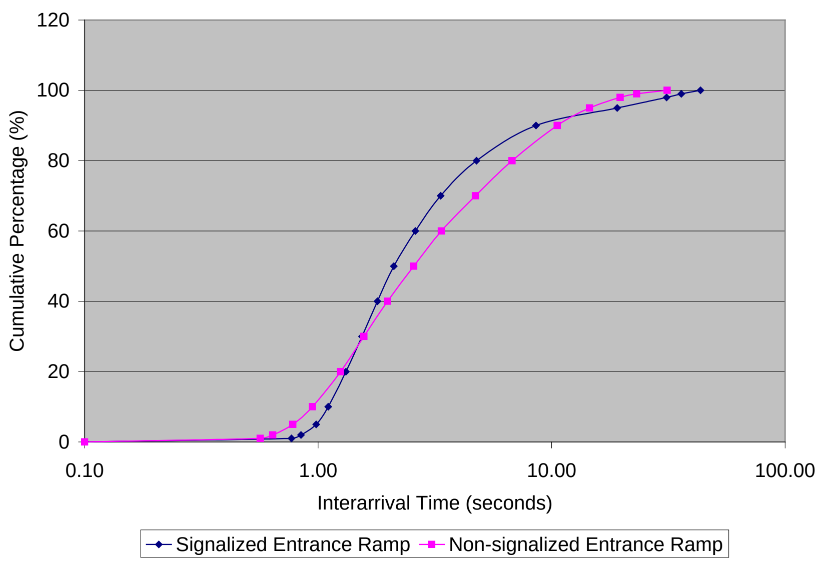


Universal IAT Distribution for Signalized Entrance Ramp
Average= 5.995
Standard Deviation= 8.413
Coefficient of Variation= 1.403

Universal IAT Distribution for Non-Signalized Entrance Ramp
Average= 5.992
Standard Deviation= 6.205
Coefficient of Variation= 1.036

KS Two Sample Goodness of Fit Test
D Observed (by visual inspection)= 0.12
D Critical= 0.078 (Level of Significance=0.05)
Reject

Figure 47. Comparison of signalized and non-signalized freeway entrance ramp universal IAT distributions for 600 vph.



Universal IAT Distribution for Signalized Entrance Ramp
Average= 4.497
Standard Deviation= 6.618
Coefficient of Variation= 1.472

Universal IAT Distribution for Non-Signalized Entrance Ramp
Average= 4.495
Standard Deviation= 4.791
Coefficient of Variation= 1.066

KS Two Sample Goodness of Fit Test
D Observed (by visual inspection)= 0.09
D Critical= 0.068 (Level of Significance=0.05)
Reject

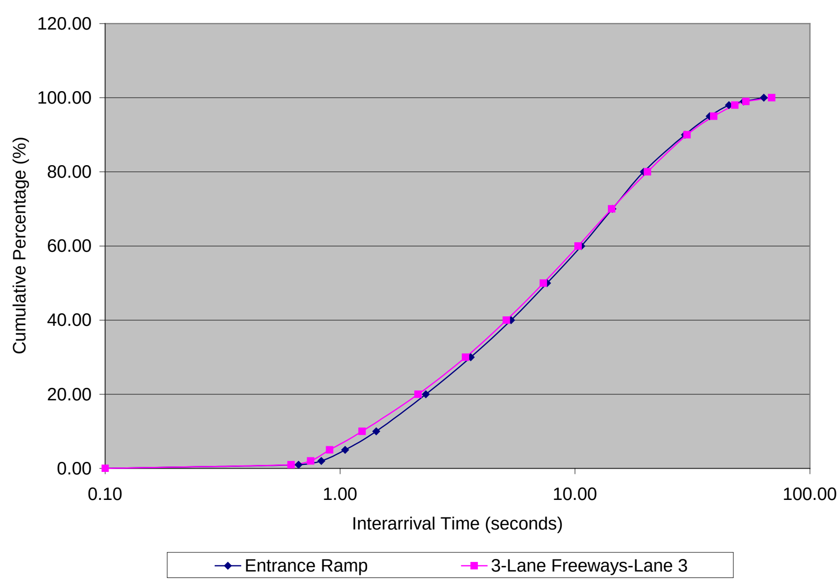
Figure 48. Comparison of signalized and non-signalized freeway entrance ramp universal IAT distributions for 800 vph.

4.3.2 Comparison of Universal IAT Distributions for Signalized and Non-signalized Freeway Entrance Ramps with Universal IAT Distributions for the Mainline

The universal IAT distributions for signalized and non-signalized freeway entrance ramps were also compared with the universal IAT distributions obtained for the freeways in [25]. The comparisons were performed by plotting the cumulative IAT distributions and using the KS two sample goodness of fit test.

The graphical comparisons were made by plotting the cumulative IAT times for both the entrance ramps and the freeways for the same hourly traffic volumes. For each traffic volume, a total of nine cumulative IAT distribution plots were generated for all lanes of 2-lane, 3-lane and 4-lane freeways to compare with the entrance ramp cumulative IATs.

The signalized freeway entrance ramp universal cumulative IAT distribution was also compared with the freeway mainline universal cumulative IAT distributions [25]. The maximum absolute differences in percentages for each distribution were compared for 300, 600, and 900 vph. The maximum absolute differences were compared with the critical difference value calculated using the KS two sample goodness of fit test (D-Critical). The maximum absolute differences were smaller than the critical value for lane 2 of 2-lane freeways and lane 4 of 4-lane freeways only for 300 vph. The results of the KS two sample goodness of fit test showed that the universal cumulative IAT distributions for signalized freeway entrance ramps are not similar to the freeway mainline universal cumulative IAT distributions. Figure 52, Figure 53, and Figure 54 show the comparison of signalized freeway entrance ramp cumulative IAT distribution with the cumulative IAT distribution for lane 3 of 3-lane freeways.

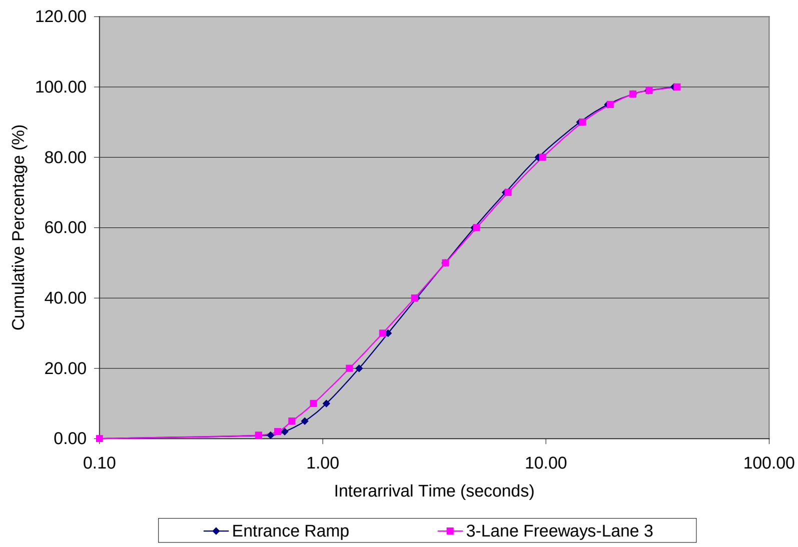


Non-Signalized Freeway Entrance Ramp Universal IAT Distribution
Average= 11.950
Standard Deviation= 11.898
Coefficient of Variation= 0.996

3-Lane Lane 3 Universal IAT Distribution
Average= 12.075
Standard Deviation= 12.495
Coefficient of Variation= 1.035

KS Two Sample Goodness of Fit Test
D Observed (by visual inspection)= 0.03
D Critical= 0.111 (Level of Significance=0.05)
Do Not Reject

Figure 49. Comparison of cumulative IAT distributions for universal non-signalized freeway entrance ramps with universal 3-lane freeway lane 3 - 300 vph.

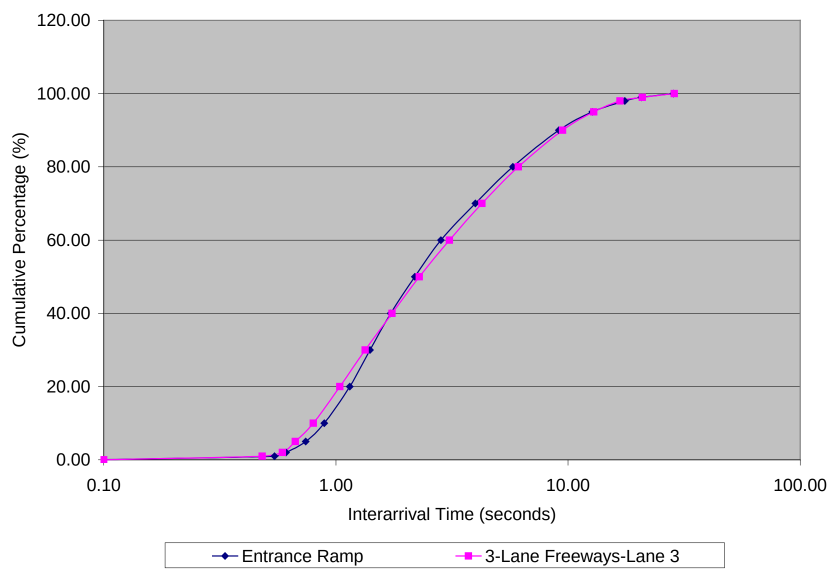


Non-Signalized Freeway Entrance Ramp Universal IAT Distribution
Average= 5.933
Standard Deviation= 6.144
Coefficient of Variation= 1.036

3-Lane Lane 3 Universal IAT Distribution
Average= 6.019
Standard Deviation= 6.315
Coefficient of Variation= 1.049

KS Two Sample Goodness of Fit Test
D Observed (by visual inspection)= 0.02
D Critical= 0.079 (Level of Significance=0.05)
Do Not Reject

Figure 50. Comparison of cumulative IAT distributions for universal non-signalized freeway entrance ramps with universal 3-lane freeway lane 3 - 600 vph.

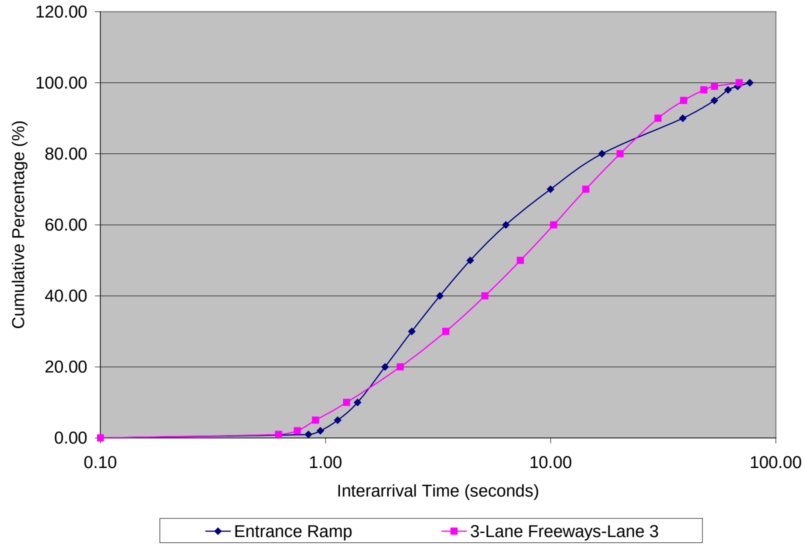


Non-Signalized Freeway Entrance Ramp Universal IAT Distribution
Average= 3.910
Standard Deviation= 4.231
Coefficient of Variation= 1.082

3-Lane Lane 3 Universal IAT Distribution
Average= 4.000
Standard Deviation= 4.276
Coefficient of Variation= 1.069

KS Two Sample Goodness of Fit Test
D Observed (by visual inspection)= 0.02
D Critical= 0.064 (Level of Significance=0.05)
Do Not Reject

Figure 51. Comparison of cumulative IAT distributions for universal non-signalized freeway entrance ramps with universal 3-lane freeway lane 3 - 900 vph.

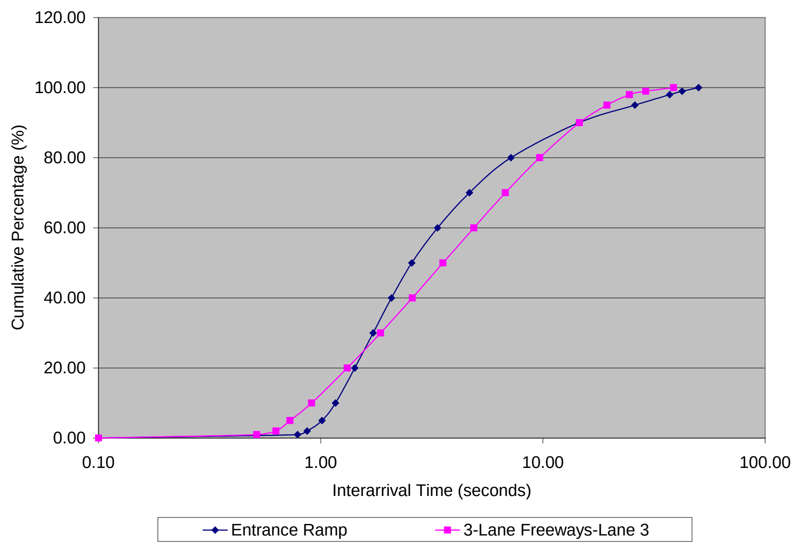


Signalized Freeway Entrance Ramp Universal IAT Distribution
Average= 11.989
Standard Deviation= 16.180
Coefficient of Variation= 1.350

3-Lane Lane 3 Universal IAT Distribution
Average= 12.075
Standard Deviation= 12.495
Coefficient of Variation= 1.035

KS Two Sample Goodness of Fit Test
D Observed (by visual inspection)= 0.12
D Critical= 0.111 (Level of Significance=0.05)
Reject

Figure 52. Comparison of cumulative IAT distributions for universal signalized freeway entrance ramps with universal 3-lane freeway lane 3 - 300 vph.

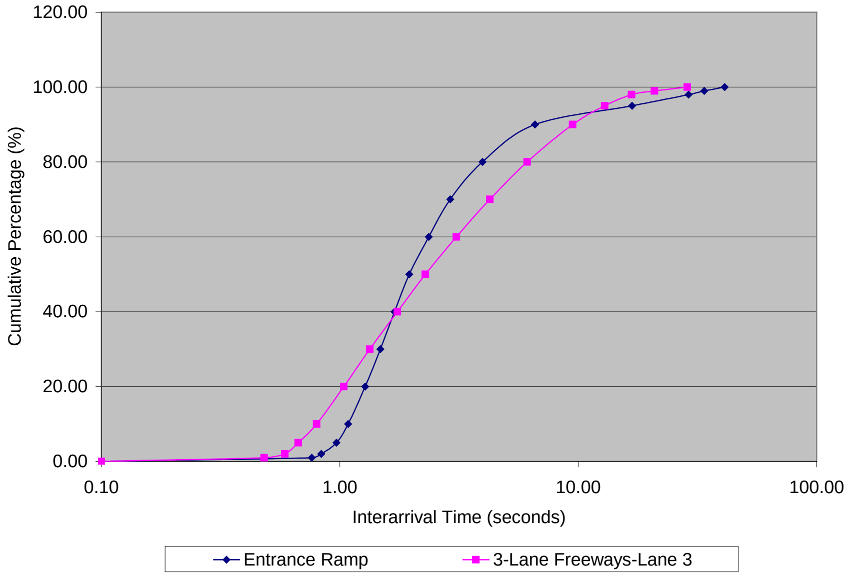


Signalized Freeway Entrance Ramp Universal IAT Distribution
Average= 5.995
Standard Deviation= 8.413
Coefficient of Variation= 1.403

3-Lane Lane 3 Universal IAT Distribution
Average= 6.019
Standard Deviation= 6.315
Coefficient of Variation= 1.049

KS Two Sample Goodness of Fit Test
D Observed (by visual inspection)= 0.11
D Critical= 0.079 (Level of Significance=0.05)
Reject

Figure 53. Comparison of cumulative IAT distributions for universal signalized freeway entrance ramps with universal 3-lane freeway lane 3 - 600 vph.



Signalized Freeway Entrance Ramp Universal IAT Distribution
Average= 3.997
Standard Deviation= 6.052
Coefficient of Variation= 1.514

3-Lane Lane 3 Universal IAT Distribution
Average= 4.000
Standard Deviation= 4.276
Coefficient of Variation= 1.069

KS Two Sample Goodness of Fit Test
D Observed (by visual inspection)= 0.15
D Critical= 0.064 (Level of Significance=0.05)
Reject

Figure 54. Comparison of cumulative IAT distributions for universal signalized freeway entrance ramps with universal 3-lane freeway lane 3 - 600 vph.

4.4 Number of Gaps on Freeway Mainline Rightmost Lane for Merging

The first step for managing the entrance ramp traffic is the analysis of the mainline traffic. The vehicles coming from the entrance ramps may not be able to merge to the mainline during peak hours if the traffic volumes on the rightmost lane of the mainline are very high and the critical gaps for merging of the entrance ramp traffic are not available. This may cause a problem of queue at the mainline merging area from the entrance ramps. Another point to consider when allowing the vehicles from the entrance ramps is the capacity of the mainline rightmost lane. The millennium edition of the highway capacity manual (HCM) [26] defines the capacity of freeways under ideal conditions for multilane highways as 2250 passenger cars per lane per hour (pcplph) for free flow speed of 55 mph (88 km/h), 2300 pcplph for free flow speed of 60 mph (96 km/h), 2350 pcplph for free flow speed of 65 mph (105 km/h), and 2400 pcplph for free flow speed of 70 mph (113 km/h). The free flow speed is defined as the average speed that a motorist would travel in there were no congestion or other adverse effects and the ideal conditions are defined as uninterrupted flow, free from interference, only passenger cars in the stream, 12 foot lanes and adequate shoulders, and a driver population dominated by regular and familiar users of the facility [2].

The capacity information was used to determine the number of vehicles from the entrance ramp that can be accommodated by the mainline traffic, therefore with the addition of the entrance ramp traffic, the traffic volume on the mainline should not be larger than the lane capacity. Zhang and Levinson [27] investigated 27 uniform freeway segments and found that the maximum capacity observed at the study locations ranged from 1772 to 2332 pcplph. They found that a traffic volume within these ranges may cause high speed drops on the mainline traffic. Their finding also corresponds with the HCM definition. In another study Lorenz and Elefteriadou [28] investigated the probability of breakdown based on the hourly traffic flow rate (vph). They found that the hourly traffic flow rates of 1900 vph or more have a probability of at least 0.10 to cause mainline traffic breakdown. In another study Banks [29] analyzed the speed flow relationship on freeways. Figure 55 shows the relationship between the traffic flow (number of vphpl) and the speed (km/hour). The maximum traffic flow Banks observed was near 2500 vphpl. The maximum traffic flow observed in Bank's study was used to identify the number of vehicles that can merge to the mainline traffic from entrance ramps. The entrance ramp traffic will have no problem in finding acceptable required critical gaps for merging into the mainline traffic if the gaps on the mainline are larger than the critical gaps required in high traffic volume freeway mainline traffic situations.

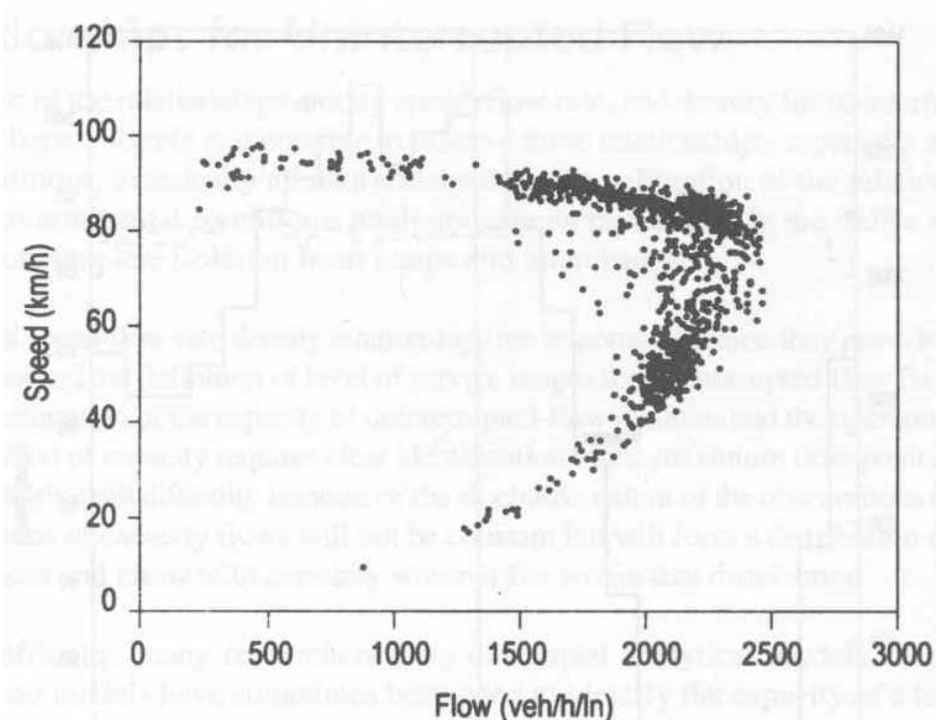


Figure 55. Observed speed flow relationship on a San Diego freeway (from [29]).

The analysis showed that there appears to be sufficient spacing between the freeway mainline rightmost lane vehicles within a period of 1-hour to accommodate 2500 vph (0% trucks) mainline traffic volume where the mainline rightmost lane traffic volume is less than 2500 vph based on the cumulative IAT distributions and critical gap requirements data.

In Figure 56, the hourly traffic volumes generated for each weekday of the week for I270 eastbound near Georgesville Road are given using the data available from ODOT Technical Services [30] in order to show the availability of traffic data from ODOT as an example. Figure 57 received from ODOT Technical Services [31] shows the difference in the traffic flow during a weekday and a weekend day for I70 west of James Road in Columbus, OH derived from ODOT automatic traffic recorder data.

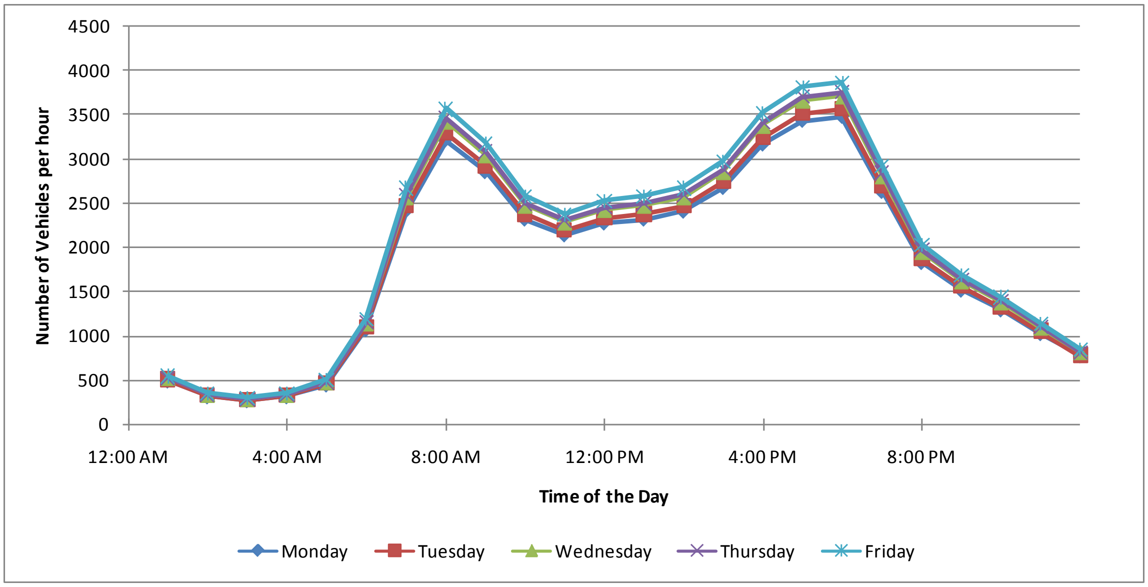


Figure 56. Hourly traffic volumes estimated for each weekday of the week (6/26/2006 – 6/30/2006) for I270 eastbound near Georgesville Road using data available from ODOT (adapted from [30]).

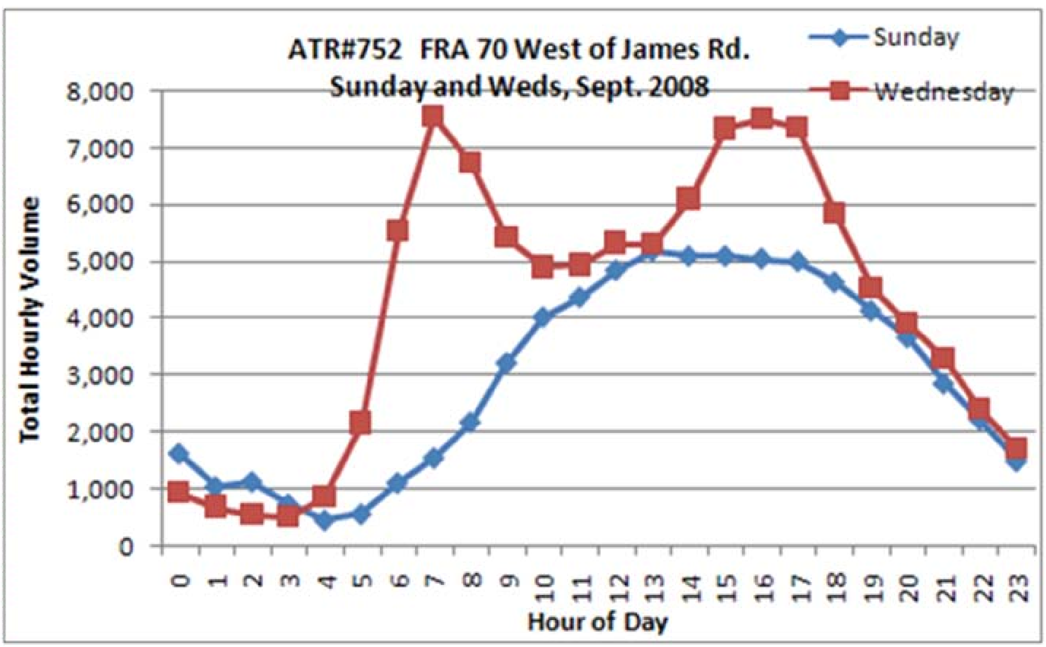


Figure 57. Comparison of hourly traffic volumes for a weekday (Wednesday) and a weekend day (Sunday) for I70 west of James Road – ODOT automatic traffic recorder # =752 (from [31]).

The given information above shows that ODOT has enough information related to traffic counts for Ohio's freeways. The practitioners can identify the hourly traffic volume for a given road section (based on functional classification) using the adjustment factors and data provided by ODOT. The hourly traffic volumes may be found for the total traffic on freeway mainline for all lanes, the freeway mainline rightmost lane hourly traffic volumes may be assumed to be equal to the average number of vehicles per lane per hour on mainline. It should be noted that ODOT do not identify the hourly traffic volume percentages for weekend data. However the weekend data is available at ODOT from the automatic traffic data recorders, the effects of weekend data in ramp control strategies and in ramp metering can be analyzed for the weekend data in detail using the ODOT site specific hourly traffic volumes.

4.5 Spill Back from Ramp Metering Signal back to Local Road

The Arena simulation model was developed for single lane signalized and non-signalized freeway entrance ramps to investigate the spill back queues from ramp metering signals back to local roads. The only difference between the signalized and non-signalized freeway entrance ramps was the cumulative IAT distributions. There was no difference between the non-signalized entrance ramps from non-signalized intersections and from other freeways. The entrance ramp was assumed to be 12 ft. (3.6 m) wide straight ramp with less than 3% grade. The available space for queue storage from ramp metering signal back to the local (arterial) road or freeway was assumed to be infinite. The vehicles (entities) were disposed after they pass the ramp metering signal.

The availability of the critical gaps for freeway mainline rightmost lane merging from the entrance ramps required further analysis of ramp metering for signalized and non-signalized entrance ramps in freeway work zones. Arena simulation model to determine potential spill back from ramp metering signal back to local (arterial) road was developed. The queue from the entrance ramp metering signal to the local (arterial) road was investigated for hourly entrance ramp traffic volumes of 200, 400, 600, 800, 1000, and 1200 vph (with no trucks) at signalized and non-signalized freeway entrance ramps with ramp metering signal timings based on the 80%, 90%, 95%, and 99% of the average arrival times for the given entrance ramp hourly traffic volumes. For instance, 4.8 seconds ((3600/600)*80%), 5.4 seconds((3600/600)*90%), 5.7 seconds ((3600/600)*95%), and 5.94 seconds ((3600/600)*99%) were the 80%, 90%, 95%, and 99% signal timings respectively for hourly traffic volume of600 vph. All combinations investigated using Arena simulation model for spill back were run for 20 replications where one replication was 101 hours including 1 hour of warm up for 90% signal timing percentage combinations and 1001 hours including 1 hour warm-up for 99% signal timing percentage combinations. The entrance ramp hourly traffic volumes did not appear to have an effect on spill back since the queue from ramp metering signal back to local (arterial) road is only dependent on the traffic signal timing percentage (traffic intensity). The signal timing percentage (traffic intensity) was equal the ratio of the average IAT for a given hourly traffic volume to the signal timing, which was based on the arrival rate. The 99% signal timing percentage was used as the maximum ramp metering signal timing percentage since the traffic intensity values equal to or greater than 1 (100% signal timing percentage) cannot be used to calculate average queue lengths in steady state using Queueing Theory formulations, such as Pollaczek-Khintchine formula [32, 33]. The difference in signal timings based on 99% and 100% signal timing percentages are very small and may be considered to be zero in practice. The present practice of ramp metering is to use 100% or higher signal timing percentages to control and restrict local traffic access to freeways [14]. Therefore, the ramp metering rates that are equal to or less than the entrance ramp traffic volumes are used.

The average of the average queue lengths and the maximum of the maximum queue lengths for 20 replications (101 hours including 1 hour of warm up for 90% signal timing percentage and 1001 hours including 1 hour warm-up for 99% signal timing percentage for each replication) were compared for signalized and non-signalized freeway entrance ramps. the average of average queue lengths at signalized freeway entrance ramps were 21.31% and 28.52% greater than the average of average queue lengths at non-signalized freeway entrance ramps using 99% and 90% signal timing percentages respectively. The comparison of the average of maximum queue lengths at signalized and non-signalized freeway entrance ramps also showed that the signalized freeway entrance ramps generated 12.93% and 16.94% larger queues than non-signalized freeway entrance ramps.

The comparison of the average of the average queue lengths output for spill back showed that the average queue lengths for spill back were 9.67 times smaller for 90% signal timing compared to 99% signal timing for signalized freeway entrance ramps and 10.26 times smaller for 90% signal timing compared to 99% signal timing for non-signalized freeway entrance ramps. The comparison of average of maximum queue lengths for spill back at signalized and non-signalized freeway entrance ramps using 90% and 99% signal timings showed that the queue from the ramp metering signal back to local (arterial) road was 6.04 times smaller for 90% signal timing compared to 99% signal timing for signalized freeway entrance ramps and 6.25 times smaller for 90% signal timing compared to 99% signal timing for non-signalized freeway entrance ramps. The comparison of the 99% and 90% signal timing percentages showed that 90% signal timing percentages provides much smaller average and maximum queues than 99% signal timing percentage for signalized and non-signalized entrance ramps as shown in Table 63. There appears to be very little difference between signalized and non-signalized freeway entrance ramp queues based on the comparison of the 90% and 99% signal timing percentages.

Therefore, based on the comparison of the average and the maximum queue lengths it appears that 90% signal timing reduces the potential for spill back from ramp metering signals to the local (arterial) roads considerably and should be preferred in cases where short queue storage spaces are available from ramp metering signals to local (arterial) roads both for signalized and non-signalized freeway entrance ramps.

Table 63. Arena simulation model for spill back results for averages and maximums for 20 replications* for entrance ramp hourly traffic volumes of 200, 400, 600, 800, 1000, and 1200 vph.

Entrance Ramp	Percentage of Trucks on Entrance Ramp (%)	Ramp Metering Signal Timing Percentage (%)	Average of Averages for 20 Replications (ft (m))	Maximum of Maximums for 20 Replications (ft (m))
Non-signalized	0%	90%	114.52 (34.93)	1462.5 (446.08)
Non-signalized	0%	99%	1175.55 (358.54)	9933 (3029.67)
Signalized	0%	90%	147.20 (44.89)	1750 (533.75)
Signalized	0%	99%	1426.04 (434.94)	10866.7 (3314.34)
Non-signalized	10%	90%	132.84 (40.52)	1696.50 (517.45)
Non-signalized	10%	99%	1363.64 (415.91)	11552 (3515)
Signalized	10%	90%	170.75 (52.07)	2030 (619)
Signalized	10%	99%	1654.21 (504.53)	12606 (3844)

*(1 replication = 101 hours including 1 hours warm-up for 90% signal timing percentage, 1 replication = 1000 hours including 1 hours warm-up period for 99% signal timing percentage)

An attempt to validate Arena simulation model for spill back was performed by using negative exponential distribution for vehicle arrivals in Arena simulation model for spill back and by using Pollaczek-Khintchine formula to calculate the expected average queue lengths. The average queue lengths for 99% signal timing percentage and 90% signal timing percentage were calculated using Pollaczek-Khintchine formula and compared with the Arena simulation model for spill back average queue length results for 20 replications (101 hours including 1 hours of warm up for 90% signal timing percentage and 1001 hours including 1 hours warm-up for 99% signal timing percentage for each replication) based on negative exponential IATs, signalized freeway entrance ramps cumulative IATs, and non-signalized freeway entrance ramp cumulative IATs for hourly traffic volumes of 200, 400, 600, 800, 1000, and 1200 vph. The average queue lengths were very close for all IAT distributions except the signalized freeway entrance ramp cumulative IAT distribution, which was the result of the difference between signalized and non-signalized freeway entrance ramp cumulative IAT distributions. The average queue lengths were much closer for 90% signal timing when compared to 99% signal timing because of the reduced variability. The comparisons showed that Arena simulation model for spill back appears to provide accurate queue length results.

4.6 Queue Backup from Freeway Mainline Merge Area back to Ramp Metering Signal

The Arena simulation model was developed for single lane signalized and non-signalized freeway entrance ramps. The entrance ramp merging to the freeway rightmost lane in the work area in a freeway work zone was simulated. A typical 3-lane freeway work zone with lane reduction situation was taken as an example in the simulation. The work zone was assumed to require the closure of the rightmost lane of the 3-lane freeway in the work area. Therefore the freeway became a 2-lane freeway in the work area and cumulative IAT distribution for rightmost lane of 2-lane freeways was used to create vehicles on the mainline. The freeway mainline average speed was assumed to be 55 mph (88 km/h) in the work zone, which is the typical speed limit application on Ohio freeways. Section 1203 of ODOT Traffic Engineering Manual [34] specifies the typical speed limit on freeways as 65 mph (104 km/h) and determined that 10 mph (16 km/h) speed reduction in the speed limit would be appropriate for work zones. Figure 58 shows the configuration of the entrance ramp merging to the mainline area. There were no differences between non-signalized entrance ramps where traffic enters through a non-signalized intersection or another freeway. The 55 mph (88 km/h) freeway mainline speed limit in the work zone requires 960 ft (263 m) of acceleration lane length from stop condition from the ramp metering signal to the mainline merge area [18]. The vehicles started merging into the freeway mainline rightmost lane at 285 ft. (87 m) from the entrance ramp metering signal. The simulation model then allowed vehicles to merge into the mainline rightmost lane at 485 ft. (148 m), 660 ft. (201 m), 810 ft. (247 m), which were the remaining distances for critical gap acceptance values determined based on Lee's data [10], and at the end of the entrance ramp acceleration lane for merging at 960 ft. (293 m). The acceleration lane length used in the simulation was for grades less than 3%. The acceleration lane lengths have to be adjusted for grades greater than 3%. The entrance ramp was assumed to be 12 ft. (3.6 m) wide straight single lane ramp with less than 3% grade. The vehicles (entities) were disposed after they merged into the mainline.

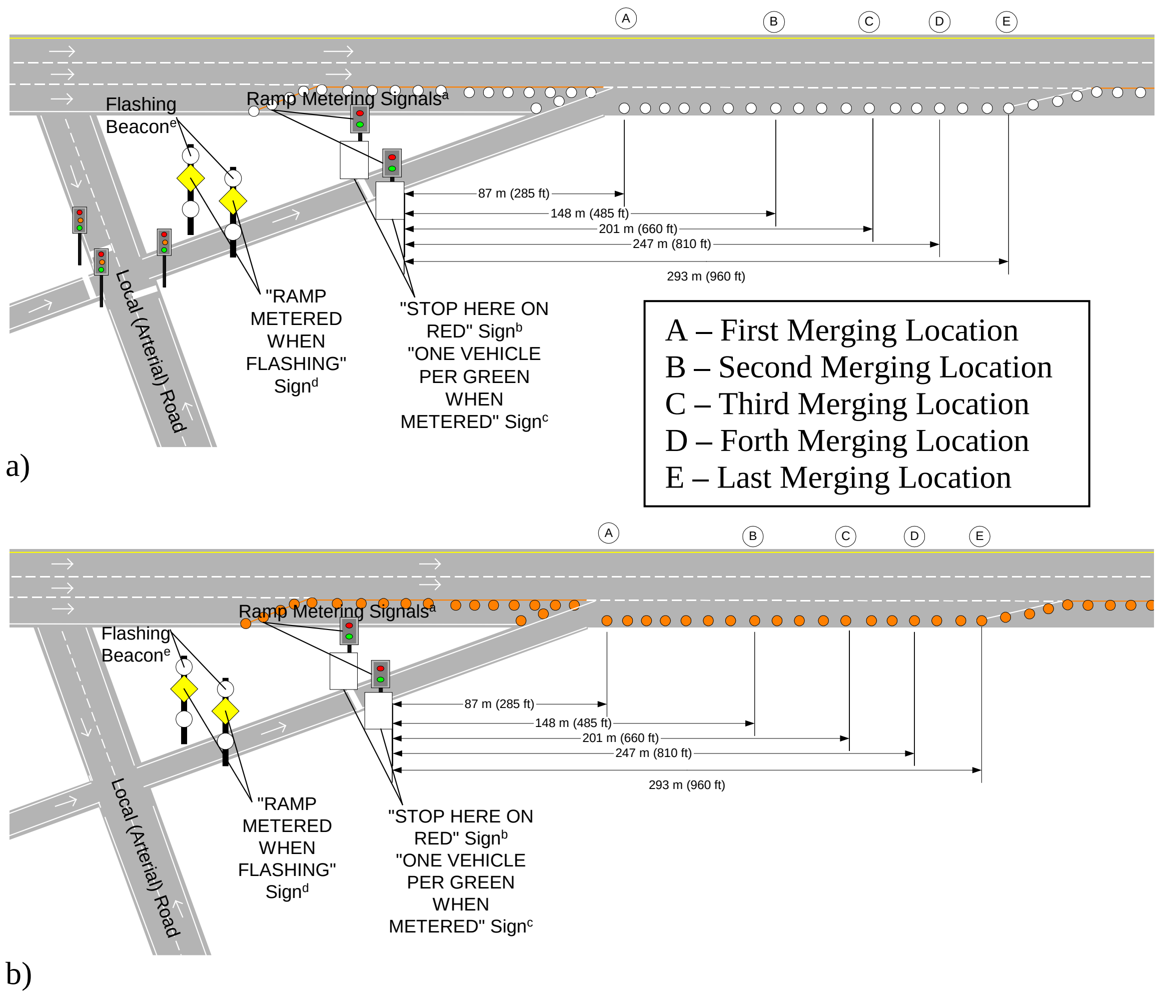


Figure 58. Entrance ramp traffic merging into the freeway mainline rightmost lane configurations used in the Arena simulation model for a) signalized freeway entrance ramp, b) non-signalized freeway entrance ramp (not to scale) (traffic control devicesa,b,c,d,e are based on ODOT manuals).

Arena simulation model for merging was developed to investigate queue back up from freeway mainline rightmost lane merge area to ramp metering signal. The simulation model was run for signalized and non-signalized freeway entrance ramps for low (300 vph) and high (1900 vph) entrance ramp and mainline hourly traffic volume pair with 0% and 10% trucks and high (900 vph) and low (1300 vph) entrance ramp and mainline hourly traffic volume pair with 0% and 10% trucks, and for ramp metering signal timing percentages of 90% and 99%. All combinations investigated using Arena simulation model for merging were run for 20 replications where one replication was 105 hours including 5 hours of warm up for 90% signal timing percentage combinations and 1010 hours including 10 hour warm-up for 99% signal timing percentage combinations. The hourly traffic volume pairs had a significant effect on the queue lengths at freeway mainline rightmost lane merge area as expected since the arrival rate of entrance ramp traffic was tripled in the high traffic volume case. The 0% (low) and 10% (high) trucks on the freeway entrance ramp and freeway mainline rightmost lane was investigated. The same truck percentages were assigned to the freeway entrance ramp traffic and freeway mainline rightmost lane traffic in simulation runs. The percentage of trucks on the entrance ramp and the freeway mainline rightmost lane also had significant effect on the queue lengths since the queue length was dependent on the number of vehicles in queue and vehicle lengths.

The Arena simulation model for merging queue lengths for vehicle arrivals from signalized and non-signalized freeway entrance ramps were compared for low-high and high-low entrance ramp and freeway mainline rightmost lane hourly traffic volumes pairs, truck percentages of 0% and 10% on the entrance ramp and freeway mainline rightmost lane traffic, and 90% and 99% ramp metering signal timing percentages. The average of the average queue lengths and the maximum of the maximum queue lengths for 20 replications (105 hours including 5 hours of warm up for 90% signal timing percentage and 1010 hours including 10 hours warm-up for 99% signal timing percentage for each replication) were compared. The average of the average queue lengths for merging was found to be slightly larger for signalized freeway entrance ramps. The average difference between signalized and non-signalized freeway entrance ramps was found to be -1.5% ranging from 0.18% to -3.72%. It appears that the freeway entrance ramp configuration has very small effect on the queues at freeway mainline merge area when the averages of the average queue lengths were compared. The maximums of the maximum queue lengths were compared and signalized entrance ramp merging queue was found to be slightly larger than the non-signalized freeway entrance ramp merging queue. The average difference between the merging queue for signalized and non-signalized freeway entrance ramps was found to be 5.5% ranging from -12.50% to 26.96%. The maximum queue lengths compared for signalized and non-signalized freeway entrance ramps were based on 20 replications where each replication was 105 hours (including 5-hour warm-up period) for 90% signal timing percentage and 1010 hours (including 10-hour warm-up period) for 99% signal timing percentage, therefore high variability in the maximum queue lengths were the cause of the differences observed when comparing signalized and non-signalized freeway entrance ramps. It appears that the freeway entrance ramp configuration has no considerable effect on the queues at freeway mainline merge area when the entrance ramp is metered.

The Arena simulation model for merging queue lengths for 90% and 99% ramp metering signal timing percentages were compared for vehicle arrivals from signalized and non-signalized freeway entrance ramps, low-high and high-low entrance ramp and freeway mainline rightmost lane hourly traffic volumes pairs, and truck percentages of 0% and 10% on the entrance ramp and freeway mainline rightmost lane traffic. It appears that 90% signal timing percentage provides -11.63% to -30.96% shorter maximum queues for the low-high traffic volume pair and 17.92% to 32.89% longer maximum queues for high-low traffic volume pair. It appears that when the entrance ramp hourly traffic volume was low the 90% signal timing percentage generated smaller maximum queues than 99% signal timing percentage and when the entrance ramp hourly traffic volume was high the 90% signal timing percentage generated larger maximum queues than 99% signal timing percentage. The maximum queue lengths were based on 20 replications where each replication was 105 hours (including 5-hour warm-up period) for 90% signal timing percentage and 1010 hours (including 10-hour warm-up period) for 99% signal timing percentage; therefore high variability may occur in the maximum comparisons. The percent differences in averages of average queue lengths were high; however the averages of average queue lengths were very small as given in Table 64. Therefore the use of 90% signal timing instead of 99% signal timing appears to have no negative impact on the average of the average queue lengths.

Table 64. Arena simulation model for merging results for averages and maximums for 20 replications* and freeway entrance ramp and freeway mainline rightmost lane hourly traffic volumes pair of 900 – 1300 vph.

Entrance Ramp	Percentage of Trucks on Freeway Mainline and Entrance Ramp (%)	Ramp Metering Signal Timing Percentage (%)	Average of Averages for 20 Replications (ft (m))	Maximum of Maximums for 20 Replications (ft (m))
Non-signalized	0%	90%	86.96 (26.52)	1350 (411.75)
Non-signalized	0%	99%	58.42 (17.82)	1025 (312.63)
Signalized	0%	90%	88.7 (27.05)	1200 (366)
Signalized	0%	99%	58.31 (17.78)	975(297.38)
Non-signalized	10%	90%	327.14 (99.78)	4470 (1363.35)
Non-signalized	10%	99%	188.81 (57.59)	3000 (915)
Signalized	10%	90%	327.21 (99.80)	3265 (993.85)
Signalized	10%	99%	189.1 (57.68)	2680 (817.40)

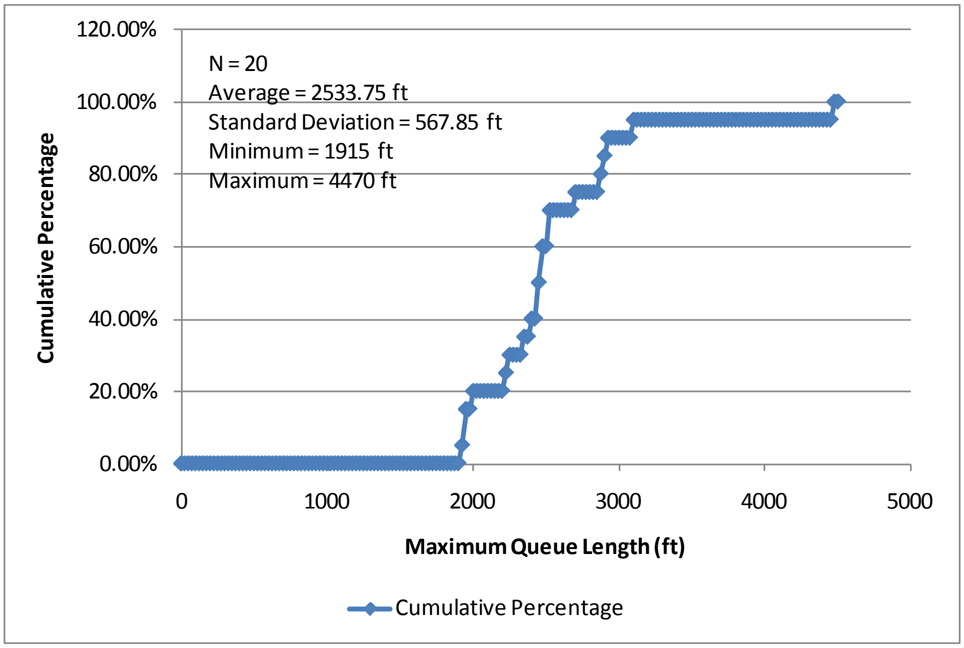
*(1 replication = 105 hours including 5 hours warm-up for 90% signal timing percentage, 1 replication = 1010 hours including 10 hours warm-up period for 99% signal timing percentage)

However the maximum of maximum queue lengths had to be considered in order to investigate the effects of queue backup from freeway mainline rightmost lane merge area to ramp metering signal. The maximum queue lengths were based on 20 replications where each replication was 105 hours (including 5-hour warm-up period) for 90% signal timing percentage and 1010 hours (including 10-hour warm-up period) for 99% signal timing percentage; therefore high variability was observed for the maximum queue lengths. Two hour (including 1-hour warm-up period) replications were run in order to determine the probability of maximum queue length occurrence which was greater than the available space between the freeway mainline rightmost lane merge area and the ramp metering signal 960 ft (293 m).

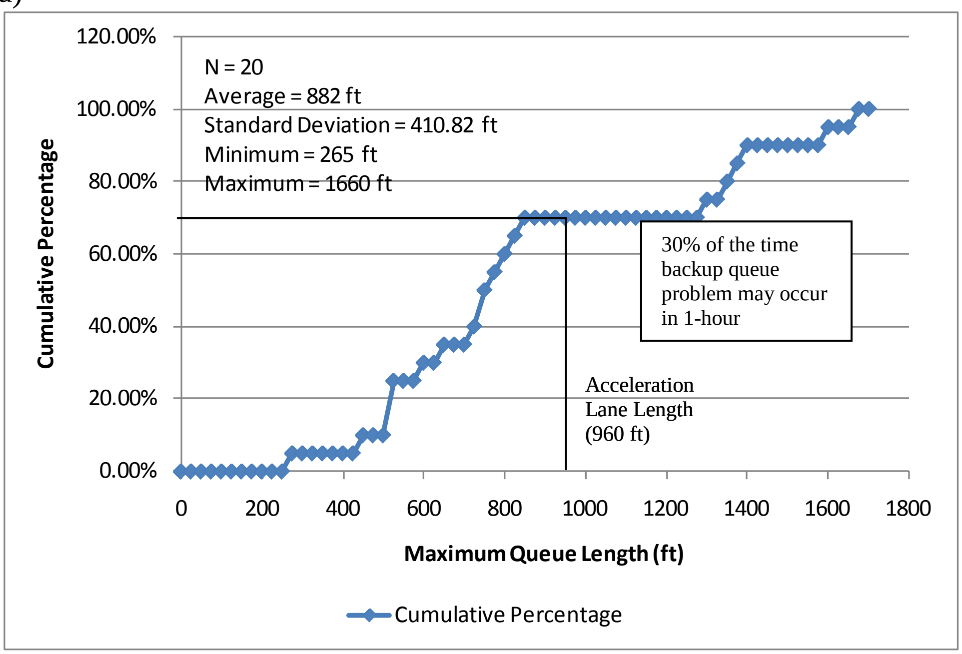
Figure 59 shows the cumulative probability distribution for the maximum queue lengths for non-signalized freeway entrance ramp with freeway entrance ramp hourly traffic volume of 900 (high) and freeway mainline rightmost lane hourly traffic volume of 1900 (high) pair, 10% trucks, and 90% entrance ramp metering signal timing for 20-1 hour replications and for 20-100 hours replications. The maximum of the maximum queues for 20-100 hours replication was 4470 ft (1363 m) which was larger than the maximum available distance 960 ft (293 m) between the entrance ramp metering signal and the last location for merging into freeway mainline rightmost lane and caused backup problem at the freeway entrance ramp. The maximum of the maximum queues for 20-1 hour replication was 1660 ft (506 m) which was also larger than the maximum available distance 960 ft (293 m). The probability of maximum queue length occurrence at the freeway mainline merge area which was larger than the maximum available distance 960 ft (293 m) was found to be 30%.

The probability of maximum queue length occurrence at the freeway mainline merge area which was larger than the maximum available distance 960 ft (293 m) was also investigated when 99% signal timing percentage was used at non-signalized freeway entrance ramp with freeway entrance ramp hourly traffic volume of 900 (high) and freeway mainline rightmost lane hourly traffic volume of 1900 (high) pair and 10% trucks. The analysis of maximum queue length cumulative probability distribution for 20-1 hour replications for 99% signal timing percentage at non-signalized freeway entrance ramp with freeway entrance ramp hourly traffic volume of 900 (high) and freeway mainline rightmost lane hourly traffic volume of 1900 (high) pair and 10% trucks as given in Figure 60 showed that the probability of maximum queue length occurrence at the freeway mainline merge area which was larger than the maximum available distance 960 ft (293 m) was 25%.

Therefore the use of 90% or 99% entrance ramp metering signal timing percentage appears to have nearly the same probability for the occurrence of backup from freeway mainline rightmost lane merge area to entrance ramp metering signal. Moreover 90% ramp metering signal timing percentage appears to be a better alternative compared to 99% signal timing at non-signalized freeway entrance ramp with high freeway entrance ramp hourly traffic volumes with 10% trucks since 90% signal timing percentage considerably improves spill back from entrance ramp metering signal to local (arterial) roads problem and does not cause a larger problem with queue backup from the freeway mainline rightmost lane merge area to entrance ramp metering signal compared to 99% signal timing queue backup problem.

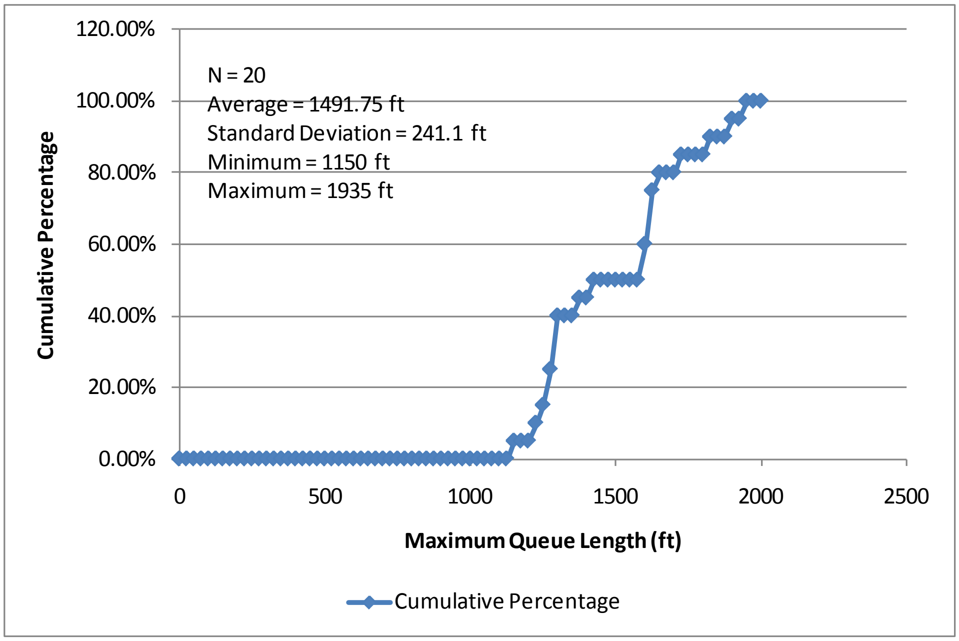


a)

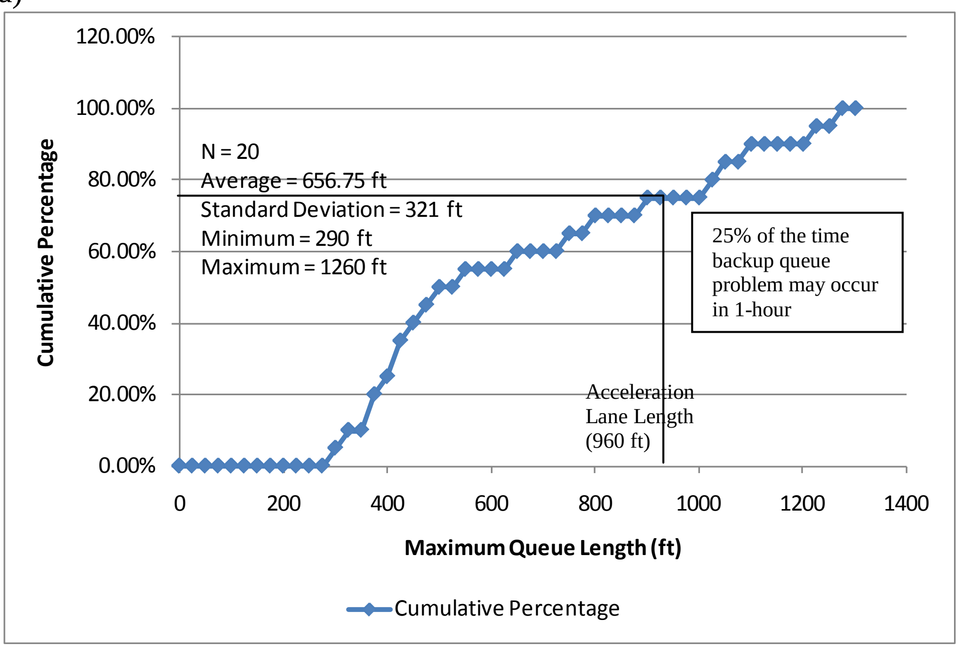


b)

Figure 59. Cumulative probability distributions for maximum queue lengths for 20 replications for non-signalized freeway entrance ramp with freeway entrance ramp hourly traffic volume of 900 (high) and freeway mainline rightmost lane hourly traffic volume of 1900 (high) pair with 10% trucks and 90% entrance ramp metering signal timing a) for 1 Replication = 105 hours (including 5 hours of warm-up period), b) 1 Replication = 2 hour (including 1 hour of warm-up period).



a)



b)

Figure 60. Cumulative probability distributions for maximum queue lengths for 20 replications for non-signalized freeway entrance ramp with freeway entrance ramp hourly traffic volume of 900 (high) and freeway mainline rightmost lane hourly traffic volume of 1900 (high) pair with 10% trucks and 99% entrance ramp metering signal timing a) for 1 Replication = 105 hours (including 5 hours of warm-up period), b) 1 Replication = 2 hour (including 1 hour of warm-up period.

An attempt to validate Arena simulation model for merging was performed by analyzing the input and output vehicle counts and number of vehicles merged for the Arena simulation model for merging.

The vehicles entering the system were generated using the cumulative IAT distributions for signalized and non-signalized freeway entrance ramps and the freeway mainline rightmost lane cumulative IAT distributions in the Arena simulation model for merging. The number of vehicles generated by the cumulative IAT distributions was nearly the same as the number of vehicles exit the system at the end of the simulation duration (105 hours including 5 hours warm-up for 90% signal timing percentage, 1010 hours including 10 hours warm-up period for 99% signal timing percentage). The Arena simulation model for merging appears to be providing correct number of vehicles in compared to the number of vehicles input using the cumulative IAT distributions and Arena modules. The number of vehicles exit the system at the end of the simulation run also appears to be correct considering the number of vehicles remains in the system at the end of a replication.

4.7 Guidelines for Temporary Entrance Ramp Control in Freeway Work Zones

The information gathered from the literature, analysis of the data, and the results of the simulations were used to develop the guidelines for temporary entrance ramp traffic control before the work area and in the work area in the freeway work zones. The rules and recommendations on “when to” and “how to” ramp meter were developed. The list of information used to develop the guidelines for temporary ramp control may be summarized as follows:

1. Literature on freeway capacity: The millennium edition of the highway capacity manual [26] defines the capacity of freeways with free flow speed of 55 mph (88 km/h) as 2250 pcplph under ideal conditions; uninterrupted flow, free from side interference, only passenger cars in traffic stream, 12-foot (3.6 m) lanes, adequate shoulders, regular and familiar users of the facility. Therefore with the addition of the entrance ramp traffic, the traffic volume on the mainline where the entrance ramp traffic merges should not be larger than this level.
2. Literature on ramp metering: The literature review showed that no ramp metering strategy included partial ramp metering (ramp open some of the time and metered) where the access to the freeway entrance ramp is limited for a given time period in an hour or partial ramp closure (ramp open some of the time) where the access to the freeway entrance ramp is limited for a given time in an hour without ramp metering.
3. Number of vehicles that can merge into the mainline rightmost lane based on the number and length of critical gaps available (based on information from the literature on critical gap acceptance for the merging of the entrance ramp traffic into mainline) and the cumulative IAT distribution for the mainline rightmost lane.
4. Cumulative IAT distributions for freeway mainline rightmost lane traffic. The cumulative IAT distributions for a few vehicles up to 2500 vph were developed to identify the gaps between vehicles on the mainline. The gap information along with the critical gap requirement was used to identify the number of vehicles that can merge into the mainline.
5. Cumulative IAT distributions for signalized and non-signalized freeway entrance ramps. The cumulative IAT distributions for a few vehicles up to 2500 vph were developed to identify the headways between vehicle arrivals at the freeway entrance ramps.

6. Geometric information for the freeway entrance ramp and the freeway mainline.
    a. The location of entrance ramps; before the work area or in the work area.
    b. Type of freeway entrance ramps; signalized or non-signalized.
    c. Number of lanes on the freeway mainline.
    d. Typical distances; acceleration lane lengths for the entrance ramp traffic, lane widths, available space for storage of vehicles waiting at the ramp metering signals.
    e. Number of lanes at the entrance ramps, lane width, percent grade.
7. Available traffic data from ODOT: The hourly traffic volumes and the percent of trucks for the mainline (hourly traffic volume for the rightmost lane assumed to be equal to the average hourly traffic volume per lane) and entrance ramp for 24 hours a day for weekdays.
8. The maximum queue length estimates from ramp metering signal back to local road to investigate spill back and the maximum queue length estimates from mainline merge area back to ramp metering signal to investigate queue backup (more detailed information is given in Chapter 7 and Chapter 8).
9. Importance of mainline traffic flow and local traffic access to the freeway. The importance of the local traffic access to the mainline should be determined based on public acceptance, effects on local businesses, distance to the alternative access points to the freeway, locations of the entrance ramps, and political consideration in addition to the importance of the mainline traffic flow.
10. Availability of resources to install temporary equipment at the freeway entrance ramps including labor for the temporary entrance ramp traffic control.

Each of the points given above can be prioritized in the selection of the optimal freeway entrance ramp control strategy before or in the work areas in work zones. The importance of mainline traffic flow and local traffic access to the freeway have the highest priority in decision making followed by traffic data available from ODOT, geometric information available, number of critical gaps based on the cumulative IAT distributions for mainline rightmost lane and entrance ramp, the maximum queue lengths to investigate spill back and backup, and available resources for the temporary freeway entrance ramp control implementation.

4.7.1 Importance of Freeway Mainline Traffic Throughput and Local Traffic Access to the Freeway

The decision making process starts with establishing the importance of the mainline traffic throughput and the importance of the local traffic access to the freeway, which is the most important factor in the selection of the temporary ramp control strategy in freeway work zones. The inclusion of the importance considerations for freeway mainline traffic throughput and the local traffic access to freeway is in the spirit of the ODOT mission statement and the core and departmental values [35]. The effects of allowing local traffic to access the freeway at the given entrance ramp or the closure of the entrance ramp have to be determined based on the political considerations, local business considerations, location of the entrance ramp and its distance to other freeway ramp access locations, economical impacts (increased time of travel for local traffic and increased fuel consumption), environmental impacts (increased traffic volumes on local roads, congestion on local roads, and increased emissions), freeway mainline traffic flow, freeway mainline traffic disturbance from the entrance ramp traffic, freeway mainline capacity and speeds, effects on the construction work, and safety of the workers in the work area [36]. Two levels of importance were assumed for local traffic access to the freeway and for freeway mainline traffic throughput; not that important (low importance) and very important (high importance). In the design of experiments the two level (high, low) factorial designs are found to be the most efficient method to investigate the effects of all possible combinations [37]. Therefore, the importance decision is based on the two factors; freeway mainline traffic throughput and local traffic access with two levels of importance each. Two levels of importance appear to be sufficient to identify the possible affects and interactions for each factor from a design of experiments point of view. Therefore, a total of four situations may be observed in this situation with two factors for a given entrance ramp in a freeway work zone; 1) local traffic access to the freeway is not that important - freeway mainline traffic throughput is not that important, 2) local traffic access to the freeway is very important - freeway mainline traffic throughput is not that important, 3) local traffic access to the freeway is not that important - freeway mainline traffic throughput is very important, and 4) local traffic access to the freeway is very important -freeway mainline traffic throughput is very important. The temporary entrance ramp control strategies can be ordered based on the severity of the local traffic and mainline traffic throughput importance from 1 (least critical) to 4 (most critical). More detailed information for each situation is given below in order of their severity.

a) Local Traffic Access to the Freeway Not that Important - Freeway Mainline Traffic Throughput Not that Important

Local traffic access to the freeway and the freeway mainline traffic throughput are both not that important in this situation, which has the least severe conditions out of the four situations. The freeway entrance ramps may be located near rural areas where very few businesses and residences are present. Fairly busy freeway mainline traffic and entrance ramp traffic may be observed both for signalized and non-signalized freeway entrance ramps. The freeway mainline traffic congestion and local traffic demand to access the freeway do not cause any problems.

In this situation, the temporary ramp control strategies appear not to have an important effect on local traffic and freeway mainline traffic. Therefore the freeway entrance ramp control strategies which require minimal control, equipment, and maintenance should be selected in this situation.

b) Local Traffic Access to the Freeway Very Important - Freeway Mainline Traffic Throughput Not that Important

Local traffic access to the freeway is very important and the freeway mainline traffic throughput is not that important in this situation, which has the second least severe conditions out of the four situations. The entrance ramps may be located near highly populated areas or business areas. Fairly busy freeway mainline traffic and high local traffic demand to access the freeway may be observed both for signalized and non-signalized freeway entrance ramps. The freeway mainline traffic congestion appear not to cause any concerns or problems, however the local traffic demand to access the freeway should be thoroughly investigated for potential problems.

In this situation, the temporary entrance ramp control strategies should maintain the accessibility of the freeway by the local traffic. The mainline traffic throughput appears not to be affected negatively by the temporary entrance ramp control strategies most of the time.

c) Local Traffic Access to the Freeway Not that Important - Freeway Mainline Traffic Throughput Very Important

Local traffic access to the freeway is not that important and the freeway mainline traffic throughput is very important in this situation, which has the second most severe conditions out of the four situations. The freeway mainline traffic has higher priority than the local traffic access to the freeway in this situation. Highly busy freeway mainline traffic and fair local traffic demand to access the freeway may be observed both for signalized and non-signalized freeway entrance ramps. The local traffic accessibility to the freeway appear not to cause any concerns or problems; however the freeway mainline traffic should be thoroughly investigated for potential problems.

In this situation, the temporary entrance ramp control strategies must satisfy the needs of the freeway mainline traffic and prevent or reduce the disturbance caused by the local traffic access to the freeway.

d) Local Traffic Access to the Freeway Very Important - Freeway Mainline Traffic Throughput Very Important

Local traffic access to the freeway and the freeway mainline traffic throughput both are very important in this situation, which has the most severe conditions out of the four situations. The freeway mainline traffic may be congested some of the time and may be highly disturbed by the entrance ramp traffic, but the local traffic accessibility to the freeway is also very important in this situation and the access of local traffic to the freeway should be maintained at all possible times. However the freeway mainline traffic flow and congestion concerns have higher priority than the local traffic access to the freeway all the time.

In this situation, the temporary entrance ramp control strategies must satisfy the needs of the freeway mainline traffic and prevent or reduce the disturbance caused by the local traffic access to the freeway.

The next step in developing the guidelines for temporary entrance ramp control strategies was the analysis of the hourly traffic volumes and the other remaining points of information listed.

4.7.2 Effects of Hourly Traffic Volumes for Freeway Mainline Rightmost Lane and Entrance Ramp

The second set of information required for developing temporary entrance ramp control strategies in freeway work zones was the traffic data for the location in consideration. The hourly traffic volumes for the freeway entrance ramp and the freeway mainline is required for 24 hours a day and 7 days a week in order to be able to select the optimal temporary entrance ramp control strategy. The traffic data required for temporary entrance ramp control strategy decision is available for weekdays and can be gathered from ODOT Technical Services [30]. ODOT also has the traffic data available for weekend days through the data collected with automatic traffic recorders; however they are not available online for public access [31].

The hourly traffic volume information was used to determine the thresholds, where different entrance ramp control strategies may be implemented. As mentioned earlier the millennium edition of the highway capacity manual [26] defines the capacity of freeways with free flow speed of 55mph (88 km/h), which is the typical speed limit in freeway work zones [26], as 2250 pcplph, therefore with the addition of the entrance ramp traffic, the traffic volume on the mainline where entrance ramp traffic merges should not be larger than this level with the consideration of the truck percentages in mainline and entrance ramp. The freeway entrance ramp traffic has to be limited by the use of temporary entrance ramp control strategies when the total of freeway mainline rightmost lane hourly traffic volumes and the freeway entrance ramp traffic hourly traffic volumes is greater than 2250 pcplph, where the freeway mainline rightmost lane traffic volume is less than 2250 pcplph. The freeway entrance ramp may be closed if the freeway mainline traffic volume is at capacity or over the capacity.

The literature review on ramp metering guidelines showed that entrance ramp metering is not recommended for hourly traffic volumes of less than 240 vph and hourly traffic volumes higher than 900 vph for single lane freeway entrance ramps [38] when one vehicle per green strategy is used. Therefore the temporary freeway entrance ramp metering control strategies were developed based on the entrance ramp hourly traffic volumes of 300 vph and 900 vph. The three levels of entrance ramp hourly traffic volumes were used in the guidelines for temporary entrance ramp control strategies in freeway work zones as low (up to 300 vph), medium (between 301 vph to 900 vph), and high (901 vph to 1200). The entrance ramp hourly traffic volume of 1200 vph is the maximum number of vehicles that can be controlled by ramp metering strategies for single lane entrance ramps [38]. The 1200 vph hourly entrance ramp traffic volume was assumed to be the maximum number of vehicles that can be observed in single lane freeway entrance ramps in freeway work zones.

The freeway mainline rightmost lane hourly traffic volumes were also classified into three levels as low, medium and high. The level of service (LOS) criteria as shown in Figure 61 was used to determine the low, medium, and high freeway mainline rightmost lane hourly traffic volume intervals. The typical speed limit in freeway work zones is 55 mph (88 km/h), therefore the maximum service flow rate for LOS F at 55 mph (88 km/h) speed limit determines the capacity of the freeway mainline rightmost lane, which is 2250 pcplph. In traffic engineering the service flow rates for LOS C and LOS D are usually used because they ensure a more acceptable quality of service to facility users [1], therefore the service flow rates for LOS C and LOS D were selected as the medium interval for the freeway mainline rightmost lane hourly traffic volumes when considering the temporary freeway entrance ramp control strategies. The level of service C is observed when hourly traffic volumes are greater than 880 pcplph and the level of service D is observed when the hourly traffic volumes are less than 1744 pcplpl for free flow speed of 55 mph (88 km/h) under ideal conditions [39].

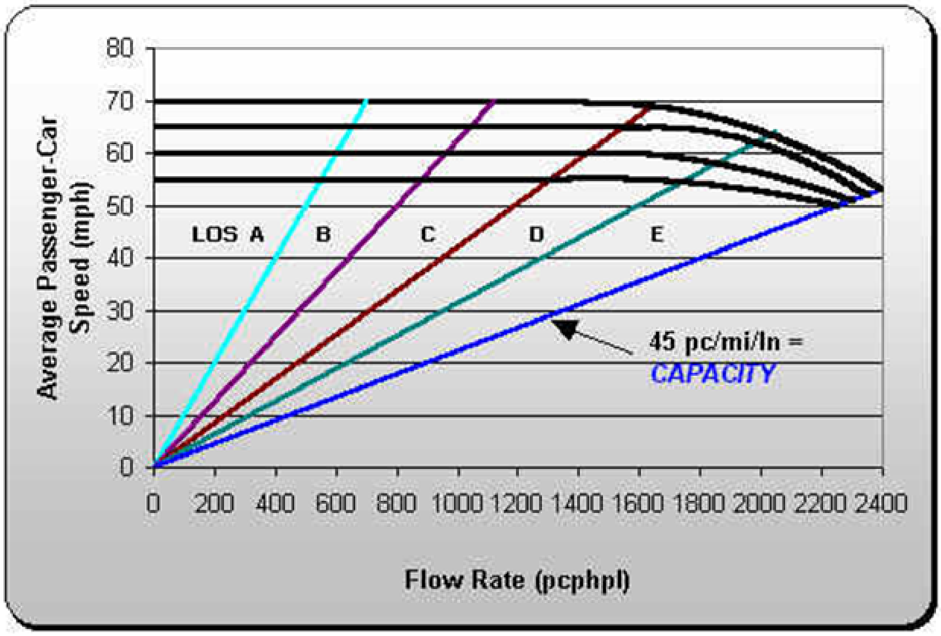


Figure 61. Level of service criteria based on flow rate and free flow speed [39].

Therefore based on the level of service criteria and the capacity of the freeway mainline rightmost lane at 55 mph (88 km/h) speed limit, low hourly traffic volume interval for freeway mainline rightmost lane was assumed to be less than 900 vph, the medium hourly traffic volume interval for freeway mainline rightmost lane was assumed to be from 901 vph up to 1800 vph, and the high hourly traffic volume interval for freeway mainline rightmost lane was assumed to be from 1801 vph up to 2250 vph (capacity).

Table 65 shows the hourly traffic volume classifications used in the guidelines for temporary entrance ramp control strategies for freeway mainline rightmost lane and entrance ramp for the given hourly traffic volume intervals. Three levels of hourly traffic volumes for freeway mainline rightmost lane and freeway entrance ramp traffic appears to be sufficient for analyzing the effects of hourly traffic volumes since all possible numerical values that may be observed are included in the defined intervals.

Table 65. Hourly traffic volume classifications for freeway mainline rightmost lane hourly traffic volumes and entrance ramp hourly traffic volumes based on level of service criteria and ramp metering design guidelines.

Hourly Traffic Volume Ranges	Freeway Mainline Rightmost Lane Hourly Traffic Volume Intervals	Entrance Ramp Hourly Traffic Volume Intervals
Low	up to 900 vph	up to 300 vph
Medium	901 vph to 1800 vph	301 vph to 900 vph
High	1801 vph to 2250 vph	901 vph to 1200 vph

The percentage of trucks in the mainline and entrance ramp is another important factor when considering the hourly traffic volumes. The freeway mainline rightmost lane capacity is assumed to be 2250 pcplph. The low and high percentage of trucks affects the freeway mainline rightmost lane capacity considerations. The hourly traffic volumes given in vehicles per hour (vph), therefore the hourly traffic volumes (vph) need to be converted into passenger cars per lane per hour (pcplph), when trucks are present in the freeway mainline rightmost lane and freeway entrance ramp. The percentage of trucks in the mainline and entrance ramp was assumed to be 0% in the guidelines.

The effects of the traffic volumes on the temporary entrance ramp control decision have to be investigated for low freeway mainline rightmost lane hourly traffic volume – low freeway entrance ramp hourly traffic volume, low freeway mainline rightmost lane hourly traffic volume – medium freeway entrance ramp hourly traffic volume, low freeway mainline rightmost lane hourly traffic volume – high freeway entrance ramp hourly traffic volume, medium freeway mainline rightmost lane hourly traffic volume – low freeway entrance ramp hourly traffic volume, medium freeway mainline rightmost lane hourly traffic volume – medium freeway entrance ramp hourly traffic volume, medium freeway mainline rightmost lane hourly traffic volume – high freeway entrance ramp hourly traffic volume, high freeway mainline rightmost lane hourly traffic volume – low freeway entrance ramp hourly traffic volume, high freeway mainline rightmost lane hourly traffic volume – medium freeway entrance ramp hourly traffic volume, and high freeway mainline rightmost lane hourly traffic volume – high freeway entrance ramp hourly traffic volume pairs. The hourly traffic volumes for the freeway mainline rightmost lane and freeway entrance ramp changes for each hour of the day, therefore the temporary ramp control decisions should be made for each hour of the day based on the hourly traffic volumes. Each of the traffic volume pairs should be investigated for each situation for the freeway mainline traffic throughput importance and local traffic access to the freeway importance situation. Therefore for each of the importance condition, nine different hourly traffic volume conditions should be considered in the selection of the temporary freeway entrance ramp control strategy.

4.7.3 Guidelines for Temporary Entrance Ramp Control Strategies in Freeway Work Zones

Temporary entrance ramp control strategies were developed based on the freeway mainline throughput importance and local traffic access to freeway importance and freeway entrance ramp hourly traffic volumes and freeway mainline rightmost lane hourly traffic volumes. The guidelines are applicable for a total of 36 combinations based on importance levels and hourly traffic volume levels as given in Table 66.

Table 66. Freeway mainline throughput - local traffic access to freeway importance and freeway entrance ramp - freeway mainline rightmost lane hourly traffic volume combinations examined in guidelines for temporary entrance ramp control strategies in freeway work zones.

Freeway Mainline Throughput / Local Traffic Access to Freeway			Not that Important			Very Important		
			Entrance Ramp Hourly Traffic Volume Intervals					
			up to 300 vph	301 vph to 900 vph	901 vph to 1200 vph	up to 300 vph	301 vph to 900 vph	901 vph to 1200 vph
Not that Important	Freeway Mainline Rightmost Lane Hourly Traffic Volume Intervals	up to 900 vph	a1	a2	a3	b1	b2	b3
		901 vph to 1800 vph	a4	a5	a6	b4	b5	b6
		1801 vph to 2250 vph	a7	a8	a9	b7	b8	d9
Very Important		up to 900 vph	c1	c2	c3	d1	d2	d3
		901 vph to 1800 vph	c4	c5	c6	d4	d5	d6
		1801 vph to 2250 vph	c7	c8	c9	d7	d8	d9

(light color to dark color – least critical to most critical)

An example is given for each situation examined to show how the entrance ramp control strategy is selected. The hourly traffic volumes used for the sample decision making process are given in Table 67 for the freeway mainline rightmost lane and the entrance ramp. It should be noted that the hourly traffic volumes are selected arbitrarily near the higher end of the hourly traffic volume intervals given in Table 65 to consider the near critical conditions in the ramp control decision making.

Table 67. Hourly traffic volumes selected arbitrarily for freeway mainline rightmost lane and entrance ramp based on the hourly traffic volume intervals in entrance ramp control strategy selection example.

		Freeway Mainline Rightmost Lane Hourly Traffic Volume		
		Low (up to 900 vph)	Medium (901 to 1800 vph)	High (1801 to 2250 vph)
Entrance Ramp Hourly Traffic Volume	Low (up to 300 vph)	250, 800	250, 1600	250, 2100
	Medium (301 to 900 vph)	800, 800	800, 1600	800, 2100
	High (901 to 1200 vph)	1100, 800	1100, 1600	1100, 2100

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area with no negative effect on the construction work in the example given. The truck percentage is assumed to be zero for both the freeway mainline rightmost lane and freeway entrance ramp in the example given.

a) <u>Local Traffic Access to the Freeway Not that Important - Freeway Mainline Traffic Not that Important</u>

Local traffic access to the freeway mainline and the mainline traffic throughput both are not that important in this situation. The temporary entrance ramp control strategies do not have an important effect on local traffic and freeway mainline traffic throughput.

a1) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low(up to 900 vph) – Entrance Ramp Hourly Traffic Volume Low(up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The local traffic is least affected by the closure of entrance ramp and the mainline traffic throughput is least affected by the entrance ramp traffic.

The entrance ramp may be open all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is before the work area and has no negative impact on the construction work.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is in the work area and if the entrance ramp traffic has negative impact on the construction work. The closure of the entrance ramp would eliminate the distracting traffic from the entrance ramp, speed up construction with full access, provide easier and better construction, improve safety, and reduce congestion.

The ramp open all the time control strategy does not require any additional equipment or labor, whereas the ramp closed all the time control strategy requires the use the use of CMS and traffic signs to warn and inform drivers about the ramp closure. The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The ramps may also be open or closed all the time during the construction duration if the resources for hourly opening and closing adjustments for ramps are not available.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1050 vph with the addition of the entrance ramp traffic volume and the mainline traffic and the construction work are not affected by the freeway entrance ramp traffic. In addition, the ramp open all the time control strategy does not require any additional traffic control devices.

a2) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low (up to 900 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation.

The local traffic and freeway mainline traffic are least affected by the temporary entrance ramp control strategies.

The entrance ramp may be open all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp has no negative impact on the construction work.

The entrance ramp may be closed all the time if the ramp is in the work area and the entrance ramp traffic has negative impact on the construction work both for signalized and non-signalized freeway entrance ramps. The mainline rightmost lane traffic volume capacity and the efficiency of the construction work are the important factors used to determine the ramp control strategies.

In addition, the ramps may be open or closed all the time during the construction duration if the resources for hourly opening and closing adjustments for ramps are not available. The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1600 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity of the freeway mainline rightmost lane. The mainline traffic and the construction work are not affected by the freeway entrance ramp traffic. In addition, the ramp open all the time control strategy does not require any additional traffic control devices.

a3) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low(up to 900 vph) – Entrance Ramp Hourly Traffic Volume High (901 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is high (between 901 vph and 1200 vph) in this situation. The local traffic and freeway mainline traffic are least affected by the temporary entrance ramp control strategies. The entrance ramp may be open all the time or closed all the time during the mainline low, entrance ramp high traffic volume hours.

The entrance ramp may be open all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp has no negative impact on the construction work.

The entrance ramp may be closed all the time if the ramp is in the work area and the entrance ramp traffic has negative impact on the construction work both for signalized and non-signalized freeway entrance ramps. The mainline rightmost lane traffic volume capacity and the efficiency of the construction work are the important factors used to determine the ramp control strategies.

In addition, the ramps may be open or closed all the time during the construction duration if the resources for hourly opening and closing adjustments for ramps are not available. The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1900 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity of the freeway mainline rightmost lane. The mainline traffic and the construction work are not affected by the freeway entrance ramp traffic. In addition, the ramp open all the time control strategy does not require any additional traffic control devices.

a4) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume Low (up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The local traffic and freeway mainline traffic are least affected by the temporary entrance ramp control strategies. The entrance ramp may be open all the time or closed all the time during the mainline medium, entrance ramp low traffic volume hours. The mainline rightmost lane capacity and the efficiency of the construction work are the important factors to determine the ramp control strategies.

The ramp may be open all the time for the given hourly traffic volumes if the ramp is located before the work area of the freeway work zone and entrance ramp traffic does not affect the construction work efficiency when the capacity on mainline rightmost lane is not exceeded.

The ramp may be closed all the time for the given hourly traffic volumes if the ramp is located in the work area of the freeway work zone and affect the construction work efficiency.

In addition, the ramps may be open or closed all the time during the construction duration if the resources for hourly opening and closing adjustments for ramps are not available. The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1850 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity of the freeway mainline rightmost lane. The mainline traffic and the construction work are not affected by the freeway entrance ramp traffic. In addition, the ramp open all the time control strategy does not require any additional traffic control devices.

a5) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The local traffic and freeway mainline traffic are least affected by the temporary entrance ramp control strategies.

The entrance ramp may be open all the time or closed all the time during the mainline medium, entrance ramp medium traffic volume hours. The mainline rightmost lane capacity, available resources for temporary entrance ramp control, and the efficiency of the construction work are the important factors to determine the ramp control strategies.

The ramp may be open all the time during the given hourly traffic volume if the ramp is located before the work area of the freeway work zone and entrance ramp traffic does not affect the construction work efficiency when the capacity on mainline rightmost lane is not exceeded.

The ramp may be closed all the time if the ramp is located in the work area of the freeway work zone and affect the construction work efficiency or when the capacity on mainline rightmost lane is exceeded.

In addition, the ramps may be open or closed all the time during the construction duration if the resources for hourly opening and closing adjustments for ramps are not available. The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the mainline rightmost lane traffic volume will be 2400 vph with the addition of the entrance ramp traffic volume, which is over the capacity (2250 vph) of the freeway mainline rightmost lane. The closure of the freeway entrance ramp does not affect the local traffic since it is not that important in this situation. In addition, the ramp closed all the time control strategy requires the use of CMS [21] for the given hour.

a6) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume High (900 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is high (between 901 vph and 1200 vph) in this situation. The local traffic and freeway mainline traffic are least affected by the temporary entrance ramp control strategies.

The entrance ramp may be open all the time or closed all the time during the mainline medium, entrance ramp high traffic volume hours. The mainline rightmost lane capacity, available resources for temporary entrance ramp control, and the efficiency of the construction work are the important factors to determine the ramp control strategies.

The ramp may be open all the time if the ramp is located before the work area of the freeway work zone and entrance ramp traffic does not affect the construction work efficiency when the capacity on mainline rightmost lane is not exceeded. The freeway entrance ramp hourly traffic volume with the freeway mainline rightmost lane hourly traffic volume should be used to determine whether the capacity on the freeway mainline rightmost lane will be exceeded or not.

The ramp may be closed all the time if the ramp is in the work area and the entrance ramp traffic has negative impact on the construction work or when the capacity on mainline rightmost lane is exceeded.

In addition, the ramps may be open all the time when the hourly traffic volumes over the capacity are not observed or the ramps may be closed all the time when the hourly traffic volumes over the capacity are observed during the construction duration if the resources for hourly opening and closing adjustments for ramps are not available.

The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the mainline rightmost lane traffic volume will be 2700 vph with the addition of the entrance ramp traffic volume, which is over the capacity (2250 vph) of the freeway mainline rightmost lane. The closure of the freeway entrance ramp does not affect the local traffic since it is not that important in this situation. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

a7) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume Low (up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is low (less than 300 vph). The local traffic and freeway mainline traffic are least affected by the temporary entrance ramp control strategies in this situation.

The mainline traffic volumes may exceed the capacity and cannot accommodate much entrance ramp traffic since the freeway mainline traffic volume is high. The entrance ramp may be closed all the time since the local traffic access to the freeway is not that important and there is only a few hundred vehicles requesting to access the freeway. The negative impact of entrance ramp traffic on the construction work is eliminated by the closure of the freeway entrance ramps before or in the work area.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the mainline rightmost lane traffic volume will be 2350 vph with the addition of the entrance ramp traffic volume, which is over the capacity (2250 vph) of the freeway mainline rightmost lane. The closure of the freeway entrance ramp does not affect the local traffic since the freeway entrance ramp hourly traffic volume is low and it is not that important in this situation. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

a8) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The local traffic and freeway mainline traffic are least affected by the temporary entrance ramp control strategies.

The mainline traffic volumes may exceed the capacity and cannot accommodate much entrance ramp traffic since the freeway mainline traffic volume is high. The entrance ramp may be closed all the time since the local traffic access to the freeway is not that important. The negative impact of entrance ramp traffic on the construction work is eliminated by the closure of the freeway entrance ramps before or in the work area.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the mainline rightmost lane traffic volume will be 2900 vph with the addition of the entrance ramp traffic volume, which is over the capacity (2250 vph) of the freeway mainline rightmost lane. The closure of the freeway entrance ramp does not affect the local traffic since the freeway entrance ramp hourly traffic volume is not that important in this situation. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

a9) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume High (900 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is high (between 301 vph and 900 vph) in this situation. The local traffic and freeway mainline traffic are least affected by the temporary entrance ramp control strategies.

The mainline traffic volumes may exceed the capacity and cannot accommodate much entrance ramp traffic since the freeway mainline traffic volume is high. The entrance ramp may be closed all the time since the local traffic access to the freeway is not that important. The negative impact of entrance ramp traffic on the construction work is eliminated by the closure of the freeway entrance ramps before or in the work area.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the mainline rightmost lane traffic volume will be 3200 vph with the addition of the entrance ramp traffic volume, which is over the capacity (2250 vph) of the freeway mainline rightmost lane. The closure of the freeway entrance ramp does not affect the local traffic since the freeway entrance ramp hourly traffic volume is not that important in this situation. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

The freeway mainline traffic flow and the local traffic access to the freeway have been judged to be not that important this situation. The temporary entrance ramp control strategy does not affect the freeway mainline traffic and the local traffic. The least expensive and simple approach for the temporary ramp control strategy in this situation would be leaving the ramps open all the time during construction for all hourly traffic volumes and entrance ramp locations. This temporary entrance ramp control strategy will not require the use of any additional equipment and labor.

b) <u>Local Traffic Access to the Freeway Very Important - Freeway Mainline Traffic Not that Important</u>

Local traffic access to the freeway mainline is very important and the mainline traffic is not that important in this situation. The temporary entrance ramp control strategies should maintain the accessibility of the freeway by the local traffic. The mainline traffic flow is not affected negatively by the temporary entrance ramp control strategies most of the time.

b1) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low(up to 900 vph) – Entrance Ramp Hourly Traffic Volume Low(up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The local traffic to the freeway should be maintained at all possible times.

The entrance ramp may be open all the time during the mainline low, entrance ramp low traffic volume hours both for signalized and non-signalized freeway entrance ramps before or in the work area and has no negative impact on the construction work.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is in the work area and has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy. The ramps may be open all the time during the construction duration if the resources for hourly opening and closing adjustments for ramps are not available and the hourly traffic volumes at the entrance ramp and freeway mainline are fairly low all the time.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1050 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

b2) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low (up to 900 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The local traffic access to the freeway is very important; therefore the temporary entrance ramp control strategies should maintain the accessibility of the freeway by the local traffic. The mainline traffic flow is not affected negatively by the entrance ramp traffic and the temporary entrance ramp control strategies.

The entrance ramp may be open all the time during low freeway mainline traffic volume hours and medium entrance ramp traffic volume hours for signalized and non-signalized freeway entrance ramps before or in the work area. Freeway entrance ramp metering is not used in this situation since the freeway mainline traffic is not that important. The mainline rightmost lane capacity and the efficiency of the construction work are the important factors used to determine the ramp control strategies.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is in the work area and has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy. The ramps may be open all the time during the construction duration if the resources for hourly opening and closing adjustments for ramps are not available and the hourly traffic volumes at the entrance ramp and freeway mainline are fairly low all the time.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1600 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

b3) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low(up to 900 vph) – Entrance Ramp Hourly Traffic Volume High (901 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is high (between 901 vph and 1200 vph) in this situation. The local traffic access to the freeway is very important and the mainline traffic flow is not affected negatively by the entrance ramp traffic.

The entrance ramp may be open all the time during low freeway mainline traffic volume hours and high entrance ramp traffic volume hours for signalized and non-signalized freeway entrance ramps before or in the work area. Freeway entrance ramp metering is not used in this situation since the freeway mainline traffic is not that important. The mainline rightmost lane capacity and the efficiency of the construction work are the important factors used to determine the ramp control strategies.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is in the work area and has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy. The ramps may be open all the time during the construction duration if the resources for hourly opening and closing adjustments for ramps are not available and the hourly traffic volumes at the entrance ramp and freeway mainline are fairly low all the time.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1900 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

b4) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume Low (up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The local traffic access to the freeway is very important and freeway mainline traffic is not that important in this situation.

The entrance ramp may be open all the time during the mainline medium, entrance ramp low traffic volume hours. The mainline rightmost lane traffic volume capacity and the efficiency of the construction work are the important factors to determine the ramp control strategies.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is in the work area and has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1850 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

b5) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The local traffic access to the freeway is very important and freeway mainline traffic is not that important in this situation.

The entrance ramp may be open all the time, open some of the time, or closed all the time during the mainline medium, entrance ramp medium traffic volume hours. The mainline rightmost lane capacity is the important factor to determine the ramp control strategies.

The ramp may be open all the time for the given hourly traffic volumes when capacity on mainline rightmost lane is not exceeded both for signalized and non-signalized freeway entrance ramps before the work area or in the work area.

The ramp may be open some of the time for the given hourly traffic volumes when the capacity on mainline rightmost lane is exceeded both for signalized and non-signalized freeway entrance ramps before the work area or in the work area.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is in the work area and has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be open some of the time for this situation since the mainline rightmost lane traffic volume will be 2400 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane. The freeway mainline can accommodate up to 2250 vph, therefore capacity minus the mainline traffic volume gives the number of vehicles that can be allowed to enter the freeway mainline from the entrance ramp. 650 entrance ramp vehicles (capacity – freeway mainline rightmost lane hourly traffic volume; 2250 vph – 1600 vph) may be allowed to enter the freeway mainline, which means that the entrance ramp may be open for 48.75 minutes ((capacity – freeway mainline rightmost lane hourly traffic volume / freeway entrance ramp hourly traffic volume)*60 minutes; (650/800)*60). Therefore the freeway entrance ramp should be open for 50 minutes (rounded to the nearest 5 minutes) and closed for 10 minutes to allow 650 vehicles in an hour from the entrance ramp. The freeway entrance ramp should be open 5 times (50/10) than it is closed in an hour. Assuming that the CMSs can be programmed for every minute, the ramp may be open for the first 5 minutes than closed for 1 minute and continue with same order for an hour. The entrance ramp open some of the time (ramp open partially) will require the use of changeable message signs (CMSs) to inform and warn drivers for the entrance ramp situation. The CMS needs to be preprogrammed to display "RAMP OPEN" or "RAMP CLOSED" message for the given durations in an hour.

b6) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume High (900 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is high (between 901 vph and 1200 vph) in this situation. The local traffic access to the freeway is very important and freeway mainline traffic is not that important in this situation.

The entrance ramp may be open all the time, open some of the time, or closed all the time during the mainline medium, entrance ramp high traffic volume hours. The mainline rightmost lane capacity is the important factor to determine the ramp control strategies.

The ramp may be open all the time for the given hourly traffic volumes when capacity on mainline rightmost lane is not exceeded both for signalized and non-signalized freeway entrance ramps before the work area or in the work area.

The ramp may be open some of the time for the given hourly traffic volumes when the capacity on mainline rightmost lane is exceeded both for signalized and non-signalized freeway entrance ramps before the work area or in the work area.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is in the work area and has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be open some of the time for this situation since the mainline rightmost lane traffic volume will be 2700 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane. The freeway mainline can accommodate up to 2250 vph, therefore capacity minus the mainline traffic volume gives the number of vehicles that can be allowed to enter the freeway mainline from the entrance ramp. 650 entrance ramp vehicles (capacity – freeway mainline rightmost lane hourly traffic volume; 2250 vph – 1600 vph) may be allowed to enter the freeway mainline, which means that the entrance ramp may be open for 35.45 minutes ((capacity – freeway mainline rightmost lane hourly traffic volume / freeway entrance ramp hourly traffic volume)*60 minutes; (650/1100)*60). Therefore the freeway entrance ramp should be open for 35 minutes (rounded to the nearest 5 minutes) and closed for 25 minutes to allow 650 vehicles in an hour from the entrance ramp. The freeway entrance ramp should be open 1.4 times (35/25) than it is closed in an hour. Assuming that the CMSs can be programmed for every minute, the ramp may be open for the first 3 minutes than closed for 2 minutes and continue with same order for an hour. The entrance ramp open some of the time (ramp open partially) will require the use of changeable message signs (CMSs) to inform and warn drivers for the entrance ramp situation. The CMS needs to be preprogrammed to display “RAMP OPEN” or “RAMP CLOSED” message for the given durations in an hour.

b7) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume Low (up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The local traffic access to the freeway is very important and freeway mainline traffic is not that important in this situation.

The entrance ramp may be open all the time, open some of the time, or closed all the time during the mainline high, entrance ramp low traffic volume hours. The mainline rightmost lane traffic volume capacity is the important factor to determine the ramp control strategies.

The ramp may be open all the time for the given hourly traffic volumes when the capacity on mainline rightmost lane is not exceeded both for signalized and non-signalized freeway entrance ramps before the work area or in the work area.

The ramp may be open some of the time for the given hourly traffic volumes when the capacity on mainline rightmost lane is exceeded both for signalized and non-signalized freeway entrance ramps before the work area or in the work area.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before or in the work area if the ramp has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 2250 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 2250 vph with the addition of the entrance ramp traffic volume, which is at capacity (2250 vph) of the freeway mainline rightmost lane. The ramp open all the time strategy will not require any additional equipment or labor.

b8) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The local traffic access to the freeway is very important and freeway mainline traffic is not that important in this situation.

The entrance ramp may be open all the time and metered, open some of the time and metered, or closed all the time during the mainline high, entrance ramp low traffic volume hours.

The mainline rightmost lane capacity is the important factor to determine the ramp control strategies.

The ramp may be open all the time and metered for the given hourly traffic volumes when capacity on mainline rightmost lane is not exceeded both for signalized and non-signalized freeway entrance ramps before the work area or in the work area. The entrance ramp traffic is regulated by the use of ramp metering since the freeway mainline traffic volume is high and may be easily disturbed.

The ramp may be open some of the time and metered for the given hourly traffic volumes when the capacity on mainline rightmost lane is not exceeded both for signalized and non-signalized freeway entrance ramps before the work area or in the work area. The entrance ramp traffic is regulated by the use of ramp metering since the freeway mainline traffic volume is high and may be easily disturbed.

The 90% ramp metering signal timing may be used for the signalized and non-signalized freeway entrance ramps before or in the work area. The use of the 90% signal timing would result in accommodating all of the entrance ramp traffic and provide the minimum or near minimum queue lengths before the ramp metering signals and will not generate larger queues than 100% signal timing. In addition, the use of 90% ramp metering signal timing will allow the accessibility of the entrance ramps for more vehicles than it is estimated by hourly traffic volumes. The extra number of vehicles that can be accommodated by the use of 90% ramp metering signal timing will provide a buffer for higher entrance ramp traffic volumes.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before or in the work area when it has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp closed all the time control strategy would require the least amount additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be open some of the time and metered for this situation since the mainline rightmost lane traffic volume will be 2900 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane. The freeway mainline can accommodate up to 2250 vph, therefore capacity minus the mainline traffic volume gives the number of vehicles that can be allowed to enter the freeway mainline from the entrance ramp. 150 entrance ramp vehicles (capacity – freeway mainline rightmost lane hourly traffic volume; 2250 vph – 2100 vph) may be allowed to enter the freeway mainline, which means that the entrance ramp may be open for 11.25 minutes ((capacity – freeway mainline rightmost lane hourly traffic volume / freeway entrance ramp hourly traffic volume)*60 minutes; (150/800)*60). Therefore the freeway entrance ramp should be open for 10 minutes (rounded to the nearest 5 minutes) and closed for 50 minutes to allow 150 vehicles in an hour from the entrance ramp. The freeway entrance ramp should be open 0.2 times (10/50) than it should be closed in an hour. Assuming that the CMSs can be programmed for every minute, the ramp may be open for the first 1 minute than closed for 5 minutes and continue with same order for an hour. The entrance ramp open some of the time strategy (ramp open partially) will require the use of changeable message signs (CMSs) to inform and warn drivers for the entrance ramp situation. The CMS needs to be preprogrammed to display “RAMP OPEN” or “RAMP CLOSED” message for the given durations in an hour.

The entrance ramp is open to allow 150 vph to the freeway; therefore the ramp metering signal timing should be programmed to accommodate 150 vph using 90% signal timing as recommended. However the literature recommends not using ramp metering for hourly traffic volumes fewer than 240 vph. Therefore the ramp metering signal timing should be programmed to accommodate 300 vph, which is recommended as the lower limit for ramp metering, using 90% signal timing. The temporary entrance ramp metering signal timing would be 11 seconds (3600 seconds/300 vph *90%) in this situation.

b9) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume High (900 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is high (between 301 vph and 900 vph) in this situation. The local traffic access to the freeway is very important and freeway mainline traffic is not that important in this situation.

The entrance ramp may be open some of the time and metered or closed all the time during the mainline high, entrance ramp low traffic volume hours. The mainline rightmost lane traffic volume capacity is the important factor to determine the ramp control strategies.

The ramp may be open some of the time and metered for the given hourly traffic volumes when the capacity on mainline rightmost lane is not exceeded both for signalized and non-signalized freeway entrance ramps before the work area or in the work area. The entrance ramp traffic is regulated by the use of ramp metering since the freeway mainline traffic volume is high and may be easily disturbed.

The 90% ramp metering signal timing may be used for the signalized and non-signalized freeway entrance ramps before or in the work area. The use of the 90% signal timing would result in accommodating all of the entrance ramp traffic and provide the minimum or near minimum queue lengths before the ramp metering signals. In addition, the use of 90% ramp metering signal timing will allow the accessibility of the entrance ramps for more vehicles than it is estimated by hourly traffic volumes. The extra number of vehicles that can be accommodated by the use of 90% ramp metering signal timing will provide a buffer for higher entrance ramp traffic volumes.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before or in the work area when it has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be open some of the time and metered for this situation since the mainline rightmost lane traffic volume will be 3200 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane. The freeway mainline can accommodate up to 2250 vph, therefore capacity minus the mainline traffic volume gives the number of vehicles that can be allowed to enter the freeway mainline from the entrance ramp. 150 entrance ramp vehicles (capacity – freeway mainline rightmost lane hourly traffic volume; 2250 vph – 2100 vph) may be allowed to enter the freeway mainline, which means that the entrance ramp may be open for 8.18 minutes ((capacity – freeway mainline rightmost lane hourly traffic volume / freeway entrance ramp hourly traffic volume)*60 minutes; (150/1100)*60). Therefore the freeway entrance ramp should be open for 10 minutes (rounded to the nearest 5 minutes) and closed for 50 minutes to allow 150 vehicles in an hour from the entrance ramp. The freeway entrance ramp should be open 0.2 times (10/50) than it should be closed in an hour. Assuming that the CMSs can be programmed for every minute, the ramp may be open for the first 1 minute than closed for 5 minutes and continue with same order for an hour. The entrance ramp open some of the time strategy (ramp open partially) will require the use of changeable message signs (CMSs) to inform and warn drivers for the entrance ramp situation. The CMS needs to be preprogrammed to display "RAMP OPEN" or "RAMP CLOSED" message for the given durations in an hour.

The entrance ramp is open to allow 150 vph to the freeway; therefore the ramp metering signal timing should be programmed to accommodate 150 vph using 90% signal timing as recommended. However the ramp metering signal timing should be programmed to accommodate 300 vph, which is recommended as the lower limit for ramp metering, using 90% signal timing. The temporary entrance ramp metering signal timing would be 11 seconds (3600 seconds/300 vph *90%) in this situation.

The freeway mainline traffic flow has been judged to be not that important and the local traffic access to the freeway has been judged to be very important in this situation. The temporary entrance ramp control strategy does not affect the mainline traffic, but the accessibility of the freeway by the local traffic should be maintained at all times possible. The least expensive and the most simple approach for the temporary entrance ramp control strategy would be leaving the ramps open all the time during construction for all hourly traffic volumes and entrance ramp locations in this situation. This temporary entrance ramp control strategy will not require the use of any additional equipment and labor.

c) <u>Freeway Mainline Traffic Very Important –Local Traffic Access to the Freeway Not that Important</u>

Local traffic access to the freeway mainline is not that important and the mainline traffic flow is very important in this situation. The freeway mainline traffic has higher priority than the local traffic access to the freeway. In this situation, the temporary entrance ramp control strategies must satisfy the needs of the freeway mainline traffic and prevent or reduce the disturbance caused by the local traffic access to the freeway.

c1) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low(up to 900 vph) – Entrance Ramp Hourly Traffic Volume Low(up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The freeway mainline traffic flow is very important and the mainline traffic should not be disturbed by the entrance ramp traffic.

The entrance ramp may be open all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is before or in the work area and has no negative impact on the construction work.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is before or in the work area and has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1050 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

c2) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low (up to 900 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The freeway mainline traffic flow is very important and the mainline traffic should not be disturbed by the entrance ramp traffic.

The entrance ramp may be open all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before or in the work area when entrance ramp traffic has no negative impact on the construction work.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when entrance ramp traffic has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1600 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

c3) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low(up to 900 vph) – Entrance Ramp Hourly Traffic Volume High (901 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is high (between 901 vph and 1200 vph) in this situation. The freeway mainline traffic flow is very important and the mainline traffic should not be disturbed by the entrance ramp traffic.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area since the high hourly traffic volume at the entrance ramp may disturb the freeway mainline traffic. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the high hourly traffic volume at the freeway entrance ramp may disturb the mainline traffic. The closure of the freeway entrance ramp does not affect the local traffic since the local traffic accessibility to the freeway is not that important in this situation. In addition, the ramp closed all the time control strategy requires temporary closure of the ramp by CMS [21] for the given hour.

c4) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume Low (up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The freeway mainline traffic flow is very important and the mainline traffic should not be disturbed by the entrance ramp traffic.

The entrance ramp may be open all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has no negative impact on the construction work.. The entrance ramp traffic would not disturb the mainline traffic since the hourly traffic volumes are low.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1850 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane and the low freeway entrance ramp hourly traffic volume should not disturb the freeway mainline traffic. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

c5) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The freeway mainline traffic flow is very important and the mainline traffic should not be disturbed by the entrance ramp traffic. The entrance ramp may be open all the time and metered, open some of the time and metered, or closed all the time for the given hourly traffic volumes in this situation.

The entrance ramp may be open all the time and metered for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has no negative impact on the construction work. The decision for leaving the ramp open all the time and metered depends on the freeway mainline rightmost lane capacity. The 100% ramp metering signal timing may be used for the signalized and non-signalized freeway entrance ramps before or in the work area. The use of the 100% signal timing would result in accommodating all of the entrance ramp traffic and providing longer durations between the vehicle arrivals to the mainline merging area as shown in Arena simulation results. The Arena simulation results for estimating the queue lengths before the ramp metering signal at the entrance ramp and at the mainline merge area showed that the queues will not cause a problem when the mainline rightmost lane capacity is not exceeded.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp closed all the time control strategy would require the minimum equipment and labor when compared to the ramp metering equipment and labor requirements; therefore it is the least expensive option for freeway entrance ramp control strategy in this situation.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the mainline rightmost lane traffic volume will be 2400 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane and the local traffic access to the freeway is not that important. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

c6) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume High (900 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is high (between 901 vph and 1200 vph) in this situation. The freeway mainline traffic flow is very important and the mainline traffic should not be disturbed by the entrance ramp traffic. The entrance ramp may be closed all the time for the given hourly traffic volumes in this situation.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area since the entrance ramp hourly traffic volumes are high and local traffic access to the freeway is not that important. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp closed all the time control strategy would require the minimum equipment and labor when compared to the ramp metering equipment and labor requirements; therefore it is the least expensive option for freeway entrance ramp control strategy in this situation.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the mainline rightmost lane traffic volume will be 2700 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane. The freeway entrance ramp may be closed all the time for this situation since the high hourly traffic volume at the freeway entrance ramp may disturb the mainline traffic. The closure of the freeway entrance ramp does not affect the local traffic since the local traffic accessibility to the freeway is not that important in this situation. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

c7) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume Low (up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The freeway mainline traffic flow is very important and the mainline traffic should not be disturbed by the entrance ramp traffic. The entrance ramp may be closed all the time for the given hourly traffic volumes in this situation.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work. The mainline traffic volumes may exceed the capacity and cannot accommodate much entrance ramp traffic since the freeway mainline traffic volume is high. In addition the freeway mainline traffic has high importance whereas the local traffic accessibility to the freeway has low importance. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the freeway mainline rightmost lane hourly traffic volume is high and may not accommodate freeway entrance ramp traffic. The closure of the freeway entrance ramp does not affect the local traffic since the local traffic accessibility to the freeway is not that important in this situation. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

c8) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The freeway mainline traffic flow is very important and the mainline traffic should not be disturbed by the entrance ramp traffic. The entrance ramp may be closed all the time for the given hourly traffic volumes in this situation.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area. The mainline traffic volumes may exceed the capacity and cannot accommodate much entrance ramp traffic since the freeway mainline traffic volume is high. In addition the freeway mainline traffic has high importance whereas the local traffic accessibility to the freeway has low importance. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the freeway mainline rightmost lane hourly traffic volume is high and may not accommodate freeway entrance ramp traffic. The closure of the freeway entrance ramp does not affect the local traffic since the local traffic accessibility to the freeway is not that important in this situation. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

c9) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume High (900 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is high (between 301 vph and 900 vph) in this situation. The freeway mainline traffic flow is very important and the mainline traffic should not be disturbed by the entrance ramp traffic. The entrance ramp may be closed all the time for the given hourly traffic volumes in this situation.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area. The mainline traffic volumes may exceed the capacity and cannot accommodate much entrance ramp traffic since the freeway mainline traffic volume is high. In addition the freeway mainline traffic has high importance whereas the local traffic accessibility to the freeway has low importance. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the freeway mainline rightmost lane hourly traffic volume is high and may not accommodate freeway entrance ramp traffic. The closure of the freeway entrance ramp does not affect the local traffic since the local traffic accessibility to the freeway is not that important in this situation. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

The freeway mainline traffic flow has been judged to be important and the local traffic access to the freeway has been judged to be not that important in this situation. The temporary entrance ramp control strategy does not affect the local traffic, but the freeway mainline traffic flow is highly affected by the entrance ramp traffic and the disturbance from the entrance ramp traffic should be eliminated or reduced at all times possible. The entrance ramp may be open all the time, open all the time and metered, open some of the time and metered, or closed all the time during an hour based on the freeway mainline and entrance ramp hourly traffic volumes during construction. The temporary entrance ramp control strategies recommended will require the use of additional equipment and labor for ramp control (timing equipment, additional signage, ramp metering traffic signals, and changeable message signs (CMSs)) to provide partial access to the entrance ramp for the local traffic and smooth the entrance ramp traffic merging to the mainline.

The least expensive and the most simple approach for the temporary entrance ramp control strategy would be closing the ramps all the time during construction for all hourly traffic volumes and entrance ramp locations in this situation.

d) Freeway Mainline Traffic Very Important –Local Traffic Access to the Freeway Very Important

Local traffic access to the freeway mainline and the mainline traffic are both very important in this situation. The freeway mainline traffic may be congested some of the time and may be highly disturbed by the entrance ramp traffic, but the local traffic accessibility to the freeway is also very important in this situation and the access of local traffic to the freeway should be maintained at all possible times. However the freeway mainline traffic flow and congestion concerns have higher priority than the local traffic access to the freeway all the time.

d1) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low(up to 900 vph) – Entrance Ramp Hourly Traffic Volume Low(up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The freeway mainline traffic flow and the local traffic accessibility to the freeway are both very important.

The entrance ramp may be open all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before or in the work area when the entrance ramp traffic has no negative impact on the construction work.

The entrance ramp may be closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps if the ramp is in the work area and has negative impact on the construction work. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and the distracting traffic from the entrance ramp.

The ramp open all the time control strategy does not require any equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1050 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

d2) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low (up to 900 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The freeway mainline traffic flow and the local traffic accessibility to the freeway are both very important.

The entrance ramp may be open all the time or closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area.

The entrance ramp may be open all the time during low freeway mainline traffic volume hours and medium entrance ramp traffic volume hours for signalized and non-signalized freeway entrance ramps before or in the work area. The mainline rightmost lane traffic volume capacity and the efficiency of the construction work are the important factors used to determine the ramp control strategies. The entrance ramp metering is not required in this situation since the mainline traffic volume is low and it is not affected by the entrance ramp traffic.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work and cause hazardous working environment in the work area. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and improve safety.

The ramp open all the time control strategy does not require any additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1600 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

d3) Freeway Mainline Rightmost Lane Hourly Traffic Volume Low(up to 900 vph) – Entrance Ramp Hourly Traffic Volume High (901 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is low (less than 900 vph) and entrance ramp hourly traffic volume is high (between 901 vph and 1200 vph) in this situation. The freeway mainline traffic flow and the local traffic accessibility to the freeway are both very important.

The entrance ramp may be open all the time or closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area.

The entrance ramp may be open all the time during low freeway mainline traffic volume hours and high entrance ramp traffic volume hours for signalized and non-signalized freeway entrance ramps before or in the work area. Freeway entrance ramp metering is not used in this situation since the freeway mainline traffic volume is low and not affected much by the entrance ramp traffic. The mainline rightmost lane traffic volume capacity and the efficiency of the construction work are the important factors used to determine the ramp control strategies.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work and cause hazardous working environment in the work area. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and improve safety.

The ramp open all the time control strategy does not require any additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 800 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1900 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

d4) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume Low (up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The freeway mainline traffic flow and the local traffic accessibility to the freeway are both very important.

The entrance ramp may be open all the time, or closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area.

The entrance ramp may be open all the time if entrance ramp traffic has no negative impact on the construction work since the entrance ramp traffic volume is low.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work and cause hazardous working environment in the work area. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and improve safety.

The ramp open all the time control strategy does not require any additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be open all the time for this situation since the mainline rightmost lane traffic volume will be 1850 vph with the addition of the entrance ramp traffic volume, which is lower than the capacity (2250 vph) of the freeway mainline rightmost lane. In addition, the ramp open all the time control strategy does not require any additional equipment or labor for the temporary freeway entrance ramp control.

d5) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The freeway mainline traffic flow and the local traffic accessibility to the freeway are both very important.

The entrance ramp may be open all the time and metered, open some of the time and metered, or closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area.

The entrance ramp may be open all the time and metered if the entrance ramp traffic has no negative impact on the construction work based on the freeway mainline rightmost lane capacity consideration. The capacity of freeway mainline should be considered for the total of entrance ramp traffic volume and the mainline rightmost lane traffic volume.

The freeway entrance ramp may be open some of the time and metered for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has no negative impact on the construction work based on the freeway mainline rightmost lane capacity consideration.

The 90% ramp metering signal timing may be used for the signalized and non-signalized freeway entrance ramps before or in the work area. The use of the 90% signal timing would result in accommodating all of the entrance ramp traffic and not generate larger queues in the freeway mainline rightmost lane merge area compared to using 100% signal timing as shown in Arena simulation results. The Arena simulation results for estimating the queue lengths before the ramp metering signal at the entrance ramp and at the mainline merge area showed that the queues will not cause a problem when the mainline rightmost lane capacity is not exceeded.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work and cause hazardous working environment in the work area. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and improve safety.

The ramp closed all the time control strategy would require the least amount additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be open some of the time and metered for this situation since the mainline rightmost lane traffic volume will be 2400 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane. The freeway mainline can accommodate up to 2250 vph, therefore capacity minus the mainline traffic volume gives the number of vehicles that can be allowed to enter the freeway mainline from the entrance ramp. 650 entrance ramp vehicles (capacity – freeway mainline rightmost lane hourly traffic volume; 2250 vph – 1600 vph) may be allowed to enter the freeway mainline, which means that the entrance ramp may be open for 48.75 minutes ((capacity – freeway mainline rightmost lane hourly traffic volume / freeway entrance ramp hourly traffic volume)*60 minutes; (650/800)*60). Therefore the freeway entrance ramp should be open for 48 minutes and closed for 12 minutes to allow 650 vehicles in an hour from the entrance ramp. The freeway entrance ramp should be open 4 times (48/12) than it should be closed in an hour. Assuming that the CMSs can be programmed for every minute, the ramp may be open for the first 4 minutes than closed for 1 minutes and continue with the same order for an hour. The entrance ramp open some of the time situation (ramp open partially) will require the use of changeable message signs (CMSs) to inform and warn drivers for the entrance ramp situation. The CMS needs to be preprogrammed to display "RAMP OPEN" or "RAMP CLOSED" message for the given durations in an hour.

The entrance ramp is open to allow 650 vph to the freeway; therefore the ramp metering signal timing should be programmed to accommodate 650 vph using 90% signal timing as recommended. The temporary entrance ramp metering signal timing would be 5 seconds (3600 seconds/650 vph *90%).

d6) Freeway Mainline Rightmost Lane Hourly Traffic Volume Medium (901 vph to 1800 vph) – Entrance Ramp Hourly Traffic Volume High (900 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is medium (between 901 vph and 1800 vph) and entrance ramp hourly traffic volume is high (between 901 vph and 1200 vph) in this situation. The freeway mainline traffic flow and the local traffic accessibility to the freeway are both very important.

The entrance ramp may be open some of the time and metered or closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area.

The freeway entrance ramp may be open some of the time and metered for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has no negative impact on the construction work.

The 90% ramp metering signal timing may be used for the signalized and non-signalized freeway entrance ramps before or in the work area. The use of the 90% signal timing would result in accommodating all of the entrance ramp traffic and not generate larger queues in the freeway mainline rightmost lane merge area compared to using 100% signal timing as shown in Arena simulation results. The Arena simulation results for estimating the queue lengths before the ramp metering signal at the entrance ramp and at the mainline merge area showed that the queues will not cause a problem when the mainline rightmost lane capacity is not exceeded.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work and cause hazardous working environment in the work area. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and improve safety.

The ramp closed all the time control strategy would require the least amount additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 1600 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be open some of the time and metered for this situation since the mainline rightmost lane traffic volume will be 2700 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane.

The freeway mainline can accommodate up to 2250 vph, therefore capacity minus the mainline traffic volume gives the number of vehicles that can be allowed to enter the freeway mainline from the entrance ramp. 650 entrance ramp vehicles (capacity – freeway mainline rightmost lane hourly traffic volume; 2250 vph – 1600 vph) may be allowed to enter the freeway mainline, which means that the entrance ramp may be open for 35.45 minutes ((capacity – freeway mainline rightmost lane hourly traffic volume / freeway entrance ramp hourly traffic volume)*60 minutes; (650/1100)*60). Therefore the freeway entrance ramp should be open for 35 minutes and closed for 25 minutes to allow 650 vehicles in an hour from the entrance ramp. The freeway entrance ramp should be open 1.4 times (35/25) than it should be closed in an hour. Assuming that the CMSs can be programmed for every minute, the ramp may be open for the first 3 minutes than closed for 2 minutes and continue with the same order for an hour. The entrance ramp open some of the time situation (ramp open partially) will require the use of changeable message signs (CMSs) to inform and warn drivers for the entrance ramp situation. The CMS needs to be preprogrammed to display "RAMP OPEN" or "RAMP CLOSED" message for the given durations in an hour.

The entrance ramp is open to allow 650 vph to the freeway; therefore the ramp metering signal timing should be programmed to accommodate 650 vph using 90% signal timing as recommended. The temporary entrance ramp metering signal timing would be 5 seconds (3600 seconds/650 vph *90%).

d7) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume Low (up to 300 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is low (less than 300 vph) in this situation. The freeway mainline traffic flow and the local traffic accessibility to the freeway are both very important.

The entrance ramp may be open all the time or closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area.

The freeway entrance ramp may be open all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has no negative impact on the construction work and the mainline capacity is not exceeded.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work and cause hazardous working environment in the work area. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and improve safety.

The ramp open all the time control strategy would not require any additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 250 vph as an example. The freeway entrance ramp may be closed all the time for this situation since the freeway mainline rightmost lane hourly traffic volume is high and may not accommodate freeway entrance ramp traffic. The closure of the freeway entrance ramp does not affect the local traffic much since the freeway entrance ramp hourly traffic volume is low in this situation. In addition, the ramp closed all the time control strategy requires CMSs to inform drivers for the ramp closure and ramp metering signal in red all the time [21] for the given hour.

d8) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume Medium (301 vph to 900 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is medium (between 301 vph and 900 vph) in this situation. The freeway mainline traffic flow and the local traffic accessibility to the freeway are both very important.

The entrance ramp may be open all the time and metered, open some of the time and metered, or closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area.

The entrance ramp may be open all the time and metered if the entrance ramp traffic has no negative impact on the construction work based on the freeway mainline rightmost lane capacity consideration. The capacity of freeway mainline should be considered for the total of entrance ramp traffic volume and the mainline rightmost lane traffic volume.

The freeway entrance ramp may be open some of the time and metered for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has no negative impact on the construction work based on the freeway mainline rightmost lane capacity consideration.

The 90% ramp metering signal timing may be used for the signalized and non-signalized freeway entrance ramps before or in the work area. The use of the 90% signal timing would result in accommodating all of the entrance ramp traffic and not generate larger queues in the freeway mainline rightmost lane merge area compared to using 100% signal timing as shown in Arena simulation results. The Arena simulation results for estimating the queue lengths before the ramp metering signal at the entrance ramp and at the mainline merge area showed that the queues will not cause a problem when the mainline rightmost lane capacity is not exceeded.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work and cause hazardous working environment in the work area. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and improve safety.

The ramp closed all the time control strategy would require the least amount additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 800 vph as an example. The freeway entrance ramp may be open some of the time and metered for this situation since the mainline rightmost lane traffic volume will be 2900 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane. The freeway mainline can accommodate up to 2250 vph, therefore capacity minus the mainline traffic volume gives the number of vehicles that can be allowed to enter the freeway mainline from the entrance ramp. 150 entrance ramp vehicles (capacity – freeway mainline rightmost lane hourly traffic volume; 2250 vph – 2100 vph) may be allowed to enter the freeway mainline, which means that the entrance ramp may be open for 11.25 minutes ((capacity – freeway mainline rightmost lane hourly traffic volume / freeway entrance ramp hourly traffic volume)*60 minutes; (150/800)*60). Therefore the freeway entrance ramp should be open for 10 minutes and closed for 60 minutes to allow 150 vehicles in an hour from the entrance ramp. The freeway entrance ramp should be open 0.2 times (10/50) than it should be closed in an hour. Assuming that the CMSs can be programmed for every minute, the ramp may be open for the first 1 minute than closed for 5 minutes and continue with the same order for an hour. The entrance ramp open some of the time situation (ramp open partially) will require the use of changeable message signs (CMSs) to inform and warn drivers for the entrance ramp situation. The CMS needs to be preprogrammed to display "RAMP OPEN" or "RAMP CLOSED" message for the given durations in an hour.

The entrance ramp is open to allow 150 vph to the freeway; therefore the ramp metering signal timing should be programmed to accommodate 150 vph using 90% signal timing as recommended. However the ramp metering signal timing should be programmed to accommodate 300 vph, which is recommended as the lower limit for ramp metering, using 100% signal timing. The temporary entrance ramp metering signal timing would be 11 seconds (3600 seconds/300 vph *90%).

d9) Freeway Mainline Rightmost Lane Hourly Traffic Volume High (1801 vph to 2250 vph) – Entrance Ramp Hourly Traffic Volume High (900 vph to 1200 vph)

The freeway mainline rightmost lane hourly traffic volume is high (between 1801 vph and 2250 vph) and entrance ramp hourly traffic volume is high (between 901 vph and 1200 vph) in this situation. The freeway mainline traffic flow and the local traffic accessibility to the freeway are both very important.

The entrance ramp may be open some of the time and metered or closed all the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area.

The freeway entrance ramp may be open some of the time and metered for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has no negative impact on the construction work based on the freeway mainline rightmost lane capacity consideration.

The 90% ramp metering signal timing may be used for the signalized and non-signalized freeway entrance ramps before or in the work area. The use of the 90% signal timing would result in accommodating all of the entrance ramp traffic and not generate larger queues in the freeway mainline rightmost lane merge area compared to using 100% signal timing as shown in Arena simulation results. The Arena simulation results for estimating the queue lengths before the ramp metering signal at the entrance ramp and at the mainline merge area showed that the queues will not cause a problem when the mainline rightmost lane capacity is not exceeded.

The entrance ramp may be closed all of the time for the given hourly traffic volumes both for signalized and non-signalized freeway entrance ramps before the work area and in the work area when the entrance ramp traffic has negative impact on the construction work and cause hazardous working environment in the work area. The closure of the entrance ramp would eliminate the disturbance by the entrance ramp traffic and improve safety.

The ramp closed all the time control strategy would require the least amount additional equipment or labor; therefore it is the least expensive option for freeway entrance ramp control strategy.

The freeway entrance ramp is assumed to be a signalized freeway entrance ramp in the work area and the mainline rightmost lane hourly traffic volume is assumed to be 2100 vph and the freeway entrance ramp traffic volume is assumed to be 1100 vph as an example. The freeway entrance ramp may be open some of the time and metered for this situation since the mainline rightmost lane traffic volume will be 3200 vph with the addition of the entrance ramp traffic volume, which is higher than the capacity (2250 vph) of the freeway mainline rightmost lane. The freeway mainline can accommodate up to 2250 vph, therefore capacity minus the mainline traffic volume gives the number of vehicles that can be allowed to enter the freeway mainline from the entrance ramp. 150 entrance ramp vehicles (capacity – freeway mainline rightmost lane hourly traffic volume; 2250 vph – 2100 vph) may be allowed to enter the freeway mainline, which means that the entrance ramp may be open for 8.18 minutes ((capacity – freeway mainline rightmost lane hourly traffic volume / freeway entrance ramp hourly traffic volume)*60 minutes; (150/1100)*60). Therefore the freeway entrance ramp should be open for 8 minutes and closed for 52 minutes to allow 150 vehicles in an hour from the entrance ramp. The freeway entrance ramp should be open 0.15 times (8/52) than it should be closed in an hour. Assuming that the CMSs can be programmed for every minute, the ramp may be open for the first 1 minute than closed for 6 minutes and continue with the same order for an hour. The entrance ramp open some of the time situation (ramp open partially) will require the use of changeable message signs (CMSs) to inform and warn drivers for the entrance ramp situation. The CMS needs to be preprogrammed to display “RAMP OPEN” or “RAMP CLOSED” message for the given durations in an hour.

The entrance ramp is open to allow 150 vph to the freeway; therefore the ramp metering signal timing should be programmed to accommodate 150 vph using 90% signal timing as recommended. However the ramp metering signal timing should be programmed to accommodate 300 vph, which is recommended as the lower limit for ramp metering, using 100% signal timing. The temporary entrance ramp metering signal timing would be 11 seconds (3600 seconds/300 vph *90%).

The entrance ramp may be open all the time, open all the time and metered, open some of the time and metered, or closed all the time during an hour based on the freeway mainline and entrance ramp hourly traffic volumes during construction for very important freeway mainline traffic and local traffic access to freeway situation. The temporary entrance ramp control strategies recommended will require the use of additional equipment and labor for ramp control (timing equipment, additional signage, ramp metering traffic signals, and changeable message signs (CMSs)) to provide partial access to the entrance ramp for the local traffic and smooth the entrance ramp traffic merging to the mainline.

The least expensive and the most simple approach for the temporary entrance ramp control strategy would be only using the ramps open some of the time strategy during construction duration based on the freeway mainline rightmost lane capacity considerations for all hourly traffic volumes and entrance ramp locations in this situation. The ramp open some of the time control strategy requires temporary closure of the ramp by the use of CMSs [21] for the given hour. The use of additional equipment and labor for ramp control (additional signage and ramp metering traffic signals with timing equipment) to smooth the entrance ramp traffic merging to the mainline will not be required for this strategy.

Table 68 through Table 71 shows the summary of temporary entrance ramp control options that can be used for different freeway mainline traffic throughput and local traffic freeway access importance levels and for different levels of mainline and entrance ramp hourly traffic volumes.

Table 68. The summary of temporary entrance ramp control strategies based on the freeway mainline and entrance ramp hourly traffic volume classifications for freeway mainline traffic throughput is not that important (low) and local traffic access to freeway is not that important situation (low).

Traffic Volume for Freeway Mainline Rightmost Lane	Traffic Volume for Entrance Ramp	Temporary Entrance Ramp Control Options
Low (up to 900 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	Medium (301 vph to 900 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	High (901 vph to 1200 vph)	Ramp Open All the Time*, Ramp Closed All the Time
Medium (901 vph to 1800 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	Medium (301 vph to 900 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	High (901 vph to 1200 vph)	Ramp Open All the Time*, Ramp Closed All the Time
High (1801 vph to 2250 vph)	Low (up to 300 vph)	Ramp Closed All the Time
	Medium (301 vph to 900 vph)	Ramp Closed All the Time
	High (901 vph to 1200 vph)	Ramp Closed All the Time

* Least expensive temporary entrance ramp control strategy

Table 69. The summary of temporary entrance ramp control strategies based on the freeway mainline and entrance ramp hourly traffic volume classifications for freeway mainline traffic throughput is not that important (low) and local traffic access to freeway is very important situation (high).

Traffic Volume for Freeway Mainline Rightmost Lane	Traffic Volume for Entrance Ramp	Temporary Entrance Ramp Control Options
Low (up to 900 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	Medium (300 vph to 900 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	High (900 vph to 1200 vph)	Ramp Open All the Time*, Ramp Closed All the Time
Medium (900 vph to 1800 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	Medium (300 vph to 900 vph)	Ramp Open All the Time*, Ramp Open Some of the Time, Ramp Closed All the Time
	High (900 vph to 1200 vph)	Ramp Open All the Time*, Ramp Open Some of the Time, Ramp Closed All the Time
High (1800 vph to 2250 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Open Some of the Time, Ramp Closed All the Time
	Medium (300 vph to 900 vph)	Ramp Open All the Time and Metered Ramp Open Some of the Time and Metered, Ramp Closed All the Time*
	High (900 vph to 1200 vph)	Ramp Open Some of the Time and Metered Ramp Closed All the Time*

* Least expensive temporary entrance ramp control strategy

Table 70. The summary of temporary entrance ramp control strategies based on the freeway mainline and entrance ramp hourly traffic volume classifications for freeway mainline traffic throughput is very important (high) and local traffic access to freeway is not that important situation (low).

Traffic Volume for Freeway Mainline Rightmost Lane	Traffic Volume for Entrance Ramp	Temporary Entrance Ramp Control Options
Low (up to 900 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	Medium (300 vph to 900 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	High (900 vph to 1200 vph)	Ramp Open All the Time*, Ramp Closed All the Time
Medium (900 vph to 1800 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	Medium (300 vph to 900 vph)	Ramp Open All the Time and Metered, Ramp Closed All the Time*
	High (900 vph to 1200 vph)	Ramp Closed All the Time
High (1800 vph to 2250 vph)	Low (up to 300 vph)	Ramp Closed All the Time
	Medium (300 vph to 900 vph)	Ramp Closed All the Time
	High (900 vph to 1200 vph)	Ramp Closed All the Time

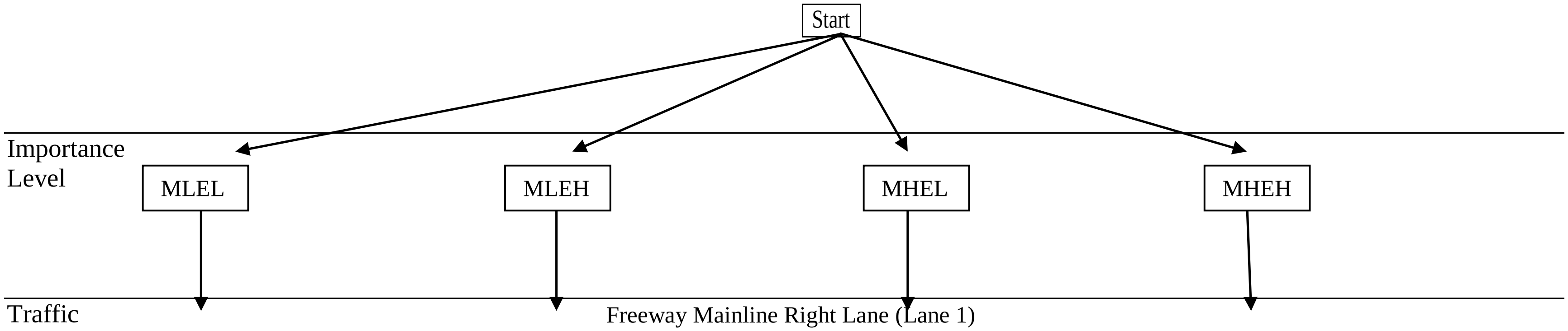
* Least expensive temporary entrance ramp control strategy

Table 71. The summary of temporary entrance ramp control strategies based on the freeway mainline and entrance ramp hourly traffic volume classifications for freeway mainline traffic throughput is very important (high) and local traffic access to freeway is very important situation (high).

Traffic Volume for Freeway Mainline Rightmost Lane	Traffic Volume for Entrance Ramp	Temporary Entrance Ramp Control Options
Low (up to 900 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	Medium (300 vph to 900 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	High (900 vph to 1200 vph)	Ramp Open All the Time*, Ramp Closed All the Time
Medium (900 vph to 1800 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	Medium (300 vph to 900 vph)	Ramp Open All the Time and Metered, Ramp Open Some of the Time and Metered, Ramp Closed All the Time*
	High (900 vph to 1200 vph)	Ramp Open Some of the Time and Metered, Ramp Closed All the Time*
High (1800 vph to 2250 vph)	Low (up to 300 vph)	Ramp Open All the Time*, Ramp Closed All the Time
	Medium (300 vph to 900 vph)	Ramp Open All the Time and Metered Ramp Open Some of the Time and Metered, Ramp Closed All the Time*
	High (900 vph to 1200 vph)	Ramp Open Some of the Time and Metered Ramp Closed All the Time*

* Least expensive temporary entrance ramp control strategy

Figure 62 shows the summary of temporary entrance ramp strategies recommended for different levels of freeway mainline traffic throughput importance and local traffic access to mainline importance for low, medium, and high levels of freeway mainline rightmost lane and entrance ramp hourly traffic volumes.



MLEL:

	FL	FM	FH
EL	ROA*, RCA	ROA*, RCA	RCA
EM	ROA*, RCA	ROA*, RCA	RCA
EH	ROA*, RCA	ROA*, RCA	RCA

MLEH:

	FL	FM	FH
EL	ROA*, RCA	ROA*, RCA	ROA*, ROS, RCA
EM	ROA*, RCA	ROA*, ROS, RCA	ROAM, ROSM, RCA*
EH	ROA*, RCA	ROA*, ROS, RCA	ROSM, RCA*

MHEL:

	FL	FM	FH
EL	ROA*, RCA	ROA*, RCA	RCA
EM	ROA*, RCA	ROAM, RCA*	RCA
EH	ROA*, RCA	RCA	RCA

MHEH:

	EL	EM	EH
EL	ROA*, RCA	ROA*, RCA	ROA*, RCA
EM	ROA*, RCA	ROAM, ROSM, RCA*	ROAM, ROSM, RCA*
EH	ROA*, RCA	ROSM, RCA*	ROSM, RCA*

Importance:	Freeway Mainline Right Lane (Lane 1) Hourly Traffic Volumes:	Entrance Ramp Hourly Traffic Volumes:	Temporary Ramp Control Strategies:
MLEL – freeway mainline traffic is not that important and local traffic access to freeway is not that important MLEH – freeway mainline traffic is not that important and local traffic access to freeway is very important MHEL – freeway mainline traffic is very important and local traffic access to freeway is not that important MHEH – freeway mainline traffic is very important and local traffic access to freeway is very important	FL – up to 900 vph FM – 901 vph to 1800 vph FH – 1801 vph to 2250 vph	EL – up to 300 vph EM – 301 vph to 900 vph EH – 901 vph to 1200 vph	ROA – Ramp open all the time ROS – Ramp open some of the time ROAM – Ramp open all the time and metered ROSM – Ramp open some of the time and metered RCA – Ramp closed all the time

* Least expensive temporary entrance ramp control strategy

Figure 62. Summary of temporary ramp control strategies in freeway work zones based on the hourly traffic volumes for freeway mainline traffic throughput importance and local traffic access to freeway importance.

4.7.4 Recommended Configurations for Temporary Entrance Ramp Control Strategies

The temporary freeway entrance ramp control strategies in freeway work zones consists of ramp open all the time, ramp open some of the time, ramp open all the time and metered, ramp open some of the time and metered, and ramp closed all the time based on the freeway mainline throughput and local traffic access to freeway importance considerations and freeway mainline rightmost lane and freeway entrance ramp hourly traffic volumes. Each of these temporary entrance ramp control strategies may be used over 24-hour period for a ramp. Therefore, for each hour of the day the ramp may be open all the time, open some of the time, open all the time and metered, open some of the time and metered, and closed all the time.

Temporary traffic control devices are required in order to be able to perform temporary ramp control for each hour of the day. Figure 63 and Figure 64 illustrates the required devices and their placements for signalized and non-signalized freeway entrance ramps before the work area and in the work area in freeway work zones. The required devices and their placements for signalized and non-signalized freeway entrance ramps do not differ in before the work area and in the work area in freeway work zones situations. In addition, the required devices and their placements for non-signalized freeway entrance ramps do not change whether they are connecting from another freeway or from a non-signalized intersection to the freeway. In each of these situations the freeway entrance ramp is designed to be controlled by any of the temporary entrance ramp control strategies. Therefore, the traffic control devices are required for all situations when the hourly freeway entrance ramp control strategies are used whether the selected temporary ramp control strategy is ramp open all the time or ramp open some of the time and metered situation. The required traffic control devices for temporary ramp control are the CMSs in addition to the ramp metering signal advance warning signs, ramp metering signals as specified in ODOT Ramp Meter Design Manual [40].

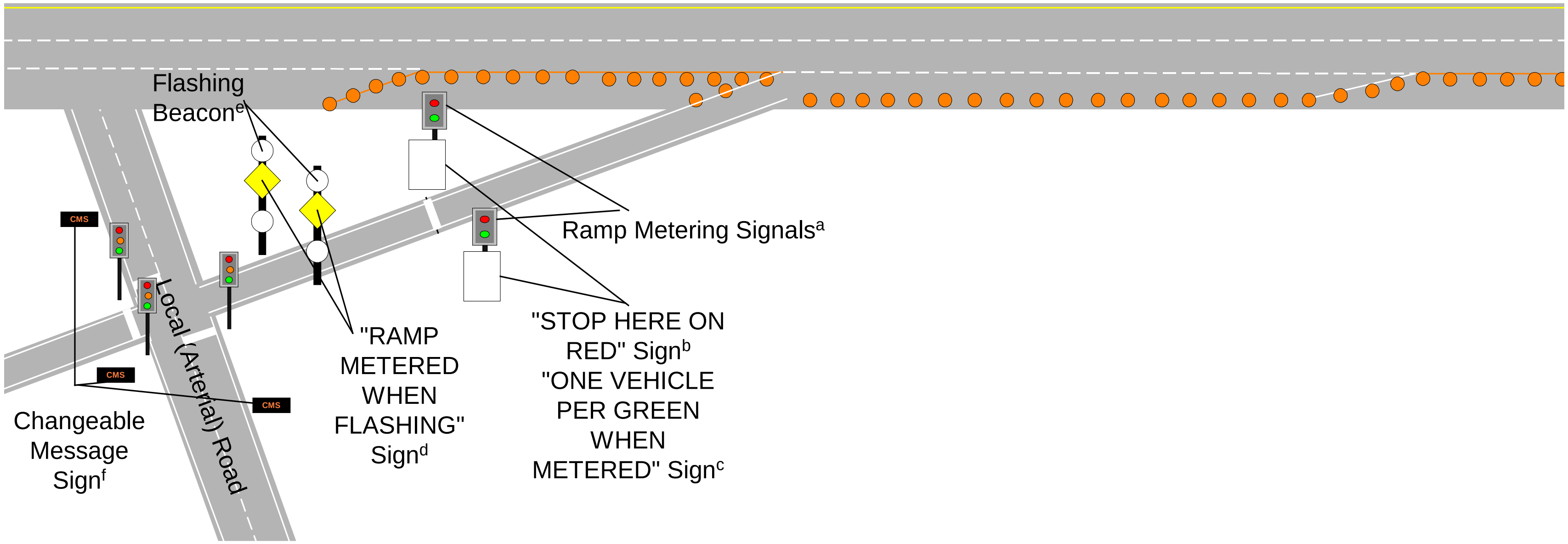


Figure 63. Recommended entrance ramp configuration when the temporary entrance ramp control strategy is variable for every hour of the day for signalized freeway entrance ramps in the work area in the freeway construction work zone (traffic control devices[a,b,c,d,e,f] are based on ODOT manuals).

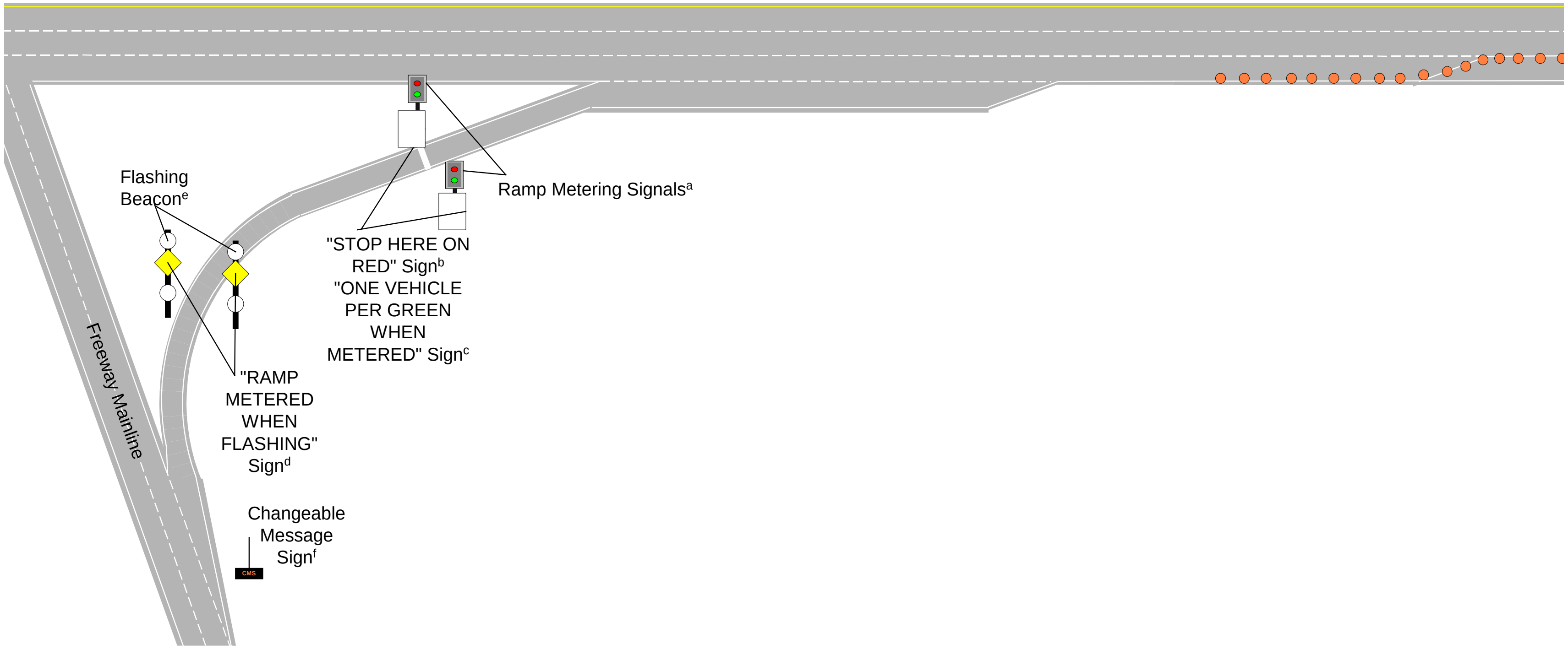


Figure 64. Recommended entrance ramp configuration when the temporary entrance ramp control strategy is variable for every hour of the day for non-signalized freeway entrance ramps before the work area in freeway construction work zone (traffic control devices[a,b,c,d,e,f] are based on ODOT manuals).

4.7.4.1 Ramp Open all the Time Temporary Entrance Ramp Control Strategy

The signalized or non-signalized freeway entrance ramp before the work area or in the work area in a freeway work zone may be open all the time during the given hourly traffic volumes for freeway entrance ramp and freeway mainline rightmost lane and based on the freeway mainline traffic throughput and local traffic accessibility to the freeway importance.

Figure 63 and Figure 64 shows the recommended design for the signalized and non-signalized freeway entrance ramps before the work area or in the work area when the ramp is open all the time as a part of other temporary ramp control strategies such as ramp open some of the time, ramp open all the time and metered, ramp open some of the time and metered, and ramp closed all the time. The local traffic is informed by the condition of the entrance ramp in advance of the ramp entrance by the use of CMSs. The drivers have enough time to make decision whether they can use the entrance ramp or not. The second warning about the ramp situation is provided right after the ramp entrance. Flashing beacons provide information when the ramp is metered. The last information about the ramp situation is given at the ramp metering signal. The ramp metering signal will stay on green all the time when the ramp is open. The local traffic users will be informed of the situation of the ramp and they will decide whether they can use the ramp or not.

Figure 63 and Figure 64 shows the recommended design for the signalized and non-signalized freeway entrance ramps before the work area or in the work area when the ramp is open all the time as a part of other temporary ramp control strategies, therefore the ramp open all the time is specified for 1-hour. However the ramp may be open all the time during construction if the local traffic access to the freeway is important and it has no negative effect on the freeway traffic throughput and the construction work efficiency. In that case the ramp may stay open during construction duration and no additional equipment would be required.

4.7.4.2 Ramp Open Some of the Time Temporary Entrance Ramp Control Strategy

The signalized or non-signalized freeway entrance ramp before the work area or in the work area in a freeway work zone may be open some of the time during the given hourly traffic volumes for freeway entrance ramp and freeway mainline rightmost lane and based on the freeway mainline traffic throughput and local traffic accessibility to the freeway importance.

Figure 63 and Figure 64 show the recommended design for the signalized and non-signalized freeway entrance ramps before the work area or in the work area when the ramp is open some of the time as a part of other ramp control strategies such as ramp open all the time, ramp open all the time and metered, ramp open some of the time and metered, and ramp closed all the time. The local traffic is informed by the condition of the entrance ramp in advance of the ramp entrance by the use of CMSs. The CMSs may display “RAMP OPEN” or “RAMP CLOSED” during the hour for the selected periods of times and intervals based on the hourly traffic volume considerations. The drivers have enough time to make decision whether they can use the entrance ramp or not. The ramp metering signal will stay on red all the time when the ramp is closed. The ramp is closed for some of the time during the given hour in this situation. Some of the drivers may enter the ramp when the CMS shows the “RAMP CLOSED” message. In this situation, the ramp metering signal will stay on red and when the CMS message turns into “RAMP OPEN” the ramp metering signal will return to its programmed intervals for red and green.

4.7.4.3 Ramp Open all the Time and Metered Temporary Entrance Ramp Control Strategy

The signalized or non-signalized freeway entrance ramp before the work area or in the work area in a freeway work zone may be open all the time and metered during the given hourly traffic volumes for freeway entrance ramp and freeway mainline rightmost lane and based on the freeway mainline traffic throughput and local traffic accessibility to the freeway importance.

Figure 63 and Figure 64 show the recommended design for the signalized and non-signalized freeway entrance ramps before the work area or in the work area when the ramp is open all the time and metered as a part of other temporary ramp control strategies such as ramp open some of the time, ramp open all the time, ramp open some of the time and metered, and ramp closed all the time. The local traffic is informed by the condition of the entrance ramp in advance of the ramp entrance by the use of CMSs. The CMS displays “RAMP OPEN” message for the given hour. The drivers have enough time to make decision whether they can use the entrance ramp or not. The second warning about the ramp situation is provided right after the ramp entrance. Flashing beacons inform drivers that the ramp meter is on. The last information about the ramp situation is given at the ramp metering signal. The ramp metering signal will display red and green for the preprogrammed durations and intervals for the given hour and one vehicle per green will pass the ramp metering signal and access the freeway mainline.

4.7.4.4 Ramp Open Some of the Time and Metered Temporary Entrance Ramp Control Strategy

The signalized or non-signalized freeway entrance ramp before the work area or in the work area in a freeway work zone may be open some of the time and metered during the given hourly traffic volumes for freeway entrance ramp and freeway mainline rightmost lane and based on the freeway mainline traffic throughput and local traffic accessibility to the freeway importance.

Figure 63 and Figure 64 shows the recommended design for the signalized and non-signalized freeway entrance ramps before the work area or in the work area when the ramp is open some of the time and metered as a part of other ramp control strategies such as ramp open all the time, ramp open all the time and metered, ramp open some of the time and metered, and ramp closed all the time. The local traffic is informed by the condition of the entrance ramp in advance of the ramp entrance by the use of CMSs. The CMSs may display “RAMP OPEN” or “RAMP CLOSED” during the hour for the selected periods of times and intervals based on the hourly traffic volume considerations. The drivers have enough time to make decision whether they can use the entrance ramp or not. The second warning about the ramp situation is provided right after the ramp entrance. Flashing beacons inform drivers that the ramp meter is on or off. The last information about the ramp situation is given at the ramp metering signal. The ramp metering signal will display red and green for the preprogrammed durations and intervals for the given hour and one vehicle per green will pass the ramp metering signal and access the freeway mainline. The ramp is closed for some of the time during the given hour in this situation. Some of the drivers may enter the ramp when the CMS shows the “RAMP CLOSED” message. In this situation, the ramp metering signal will stay on red and when the CMS message turns into “RAMP OPEN” the ramp metering signal will return to its programmed intervals for red and green.

4.7.4.5 Ramp Closed all the Time Temporary Entrance Ramp Control Strategy

The signalized or non-signalized freeway entrance ramp before the work area or in the work area in a freeway work zone may be closed all the time during the given hourly traffic volumes for freeway entrance ramp and freeway mainline rightmost lane and based on the freeway mainline traffic throughput and local traffic accessibility to the freeway importance.

Figure 63 and Figure 64 show the recommended design for the signalized and non-signalized freeway entrance ramps before the work area or in the work area when the ramp is closed all the time as a part of other ramp control strategies such as ramp open all the time, ramp open all the time and metered, and ramp open some of the time and metered. The local traffic is informed by the condition of the entrance ramp in advance of the ramp entrance by the use of CMSs. The CMSs may display "RAMP CLOSED" during the hour based on the hourly traffic volume considerations. The drivers have enough time to make decision whether they can use the entrance ramp or not.

Figure 63 and Figure 64 show the recommended design for the signalized and non-signalized freeway entrance ramps before the work area or in the work area when the ramp is closed all the time as a part of other temporary ramp control strategies, therefore the ramp closed all the time is specified for 1-hour. However the ramp may be closed all the time during construction if the local traffic access to the freeway is not that important and it has negative effect on the freeway traffic throughput and the construction work efficiency. In that case the ramp may be closed during construction duration and no additional equipment would be required for ramp metering and ramp control.

4.7.4.6 Least Expensive and Most Simple Entrance Ramp Control Strategies

In addition to determining the temporary entrance ramp control strategies for each hour of the day simpler temporary ramp control strategies may be implemented at the entrance ramp in the work zones for the duration of the construction work zones. The importance analysis for an entrance ramp is performed individually, therefore least expensive and most simple temporary entrance ramp control strategies may be used based on the importance of the local traffic access to the freeway and the mainline traffic considerations for the duration of the construction work zone.

The ramp may be open all the time during construction, closed all the time during construction, or open or closed all the time during construction based on the availability of resources for temporary entrance ramp control and the importance of the local traffic access to the freeway and the mainline traffic throughput.

The entrance ramp may be open all the time during construction when the freeway mainline traffic throughput and the local traffic access to the freeway are not that important. The probability of spill back to the local roads and the probability of congestion on the mainline are very low in this situation. The entrance ramp may be open all the time during construction if the entrance ramp traffic has no negative impact on the construction work and does not cause a hazardous environment for the construction crew. The entrance ramp open all the time during construction strategy would not require any additional equipment or labor for implementation.

The entrance ramp may be open all the time during construction when the freeway mainline traffic throughput is not that important and the local traffic access to the freeway is very important. The local traffic access to the freeway should be maintained at all times, therefore ramp open all the time during construction will satisfy this condition. Moreover the freeway mainline traffic will not be disturbed or affected negatively by the entrance ramp traffic since it has low importance. The entrance ramp may be open all the time during construction if the entrance ramp traffic has no negative impact on the construction work and does not cause a hazardous environment for the construction crew. The entrance ramp open all the time during construction strategy would not require any additional equipment or labor for implementation.

The entrance ramp may be closed all the time during construction when the freeway mainline traffic throughput is very important and the local traffic access to the freeway is not that important. The freeway mainline traffic throughput is very important and it should not be disturbed by the entrance ramp traffic. The entrance ramp closed all the time during construction will not have negative effects on the local traffic since the local traffic access to the freeway is not that important. In addition, the effects of entrance ramp traffic on the construction efficiency will be eliminated. The entrance ramp closed all the time strategy would require the use of concrete barriers for closing the ramp entrance for access. In addition, advance warning sign may be required to inform the drivers that the entrance ramp is closed.

The entrance ramp may be open some of the time during construction when the freeway mainline traffic throughput is very important and the local traffic access to the freeway is very important. The freeway mainline traffic throughput is very important and it should not be disturbed by the entrance ramp traffic and the local traffic access to the freeway is very important and maintained at all possible times. In this situation the ramps open some of the time strategy during construction duration is based on the freeway mainline rightmost lane capacity considerations. The entrance ramp may be open all the time for the low traffic volume hours where the freeway mainline rightmost lane capacity is not exceeded with the addition of the entrance ramp hourly traffic volumes or the entrance ramp may be closed all the time for the high traffic volume hours where the freeway mainline rightmost lane capacity is exceeded with the addition of the entrance ramp hourly traffic volumes. The entrance ramp may be open some of the time during construction if the entrance ramp traffic has no negative impact on the construction work and does not cause a hazardous environment for the construction crew. The entrance ramp open some of the time during construction strategy would require the use of CMSs for informing drivers on the entrance ramp availability during the day. The use of additional equipment and labor for ramp control (timing equipment, additional signage, and ramp metering traffic signals) will not be required for this strategy

4.7.4.7 Hypothetical Example for the Application of Temporary Ramp Control Strategies for 24 hours

In this section a sample entrance ramp situation was made up in order to be able to demonstrate the application of temporary ramp control design guidelines.

A non-signalized entrance ramp close to downtown in the work area of a freeway construction work zone was investigated. The entrance ramp traffic did not have any negative effect on the construction work. The hourly traffic volumes in the freeway mainline were high and congestion was a high probability problem for the freeway mainline traffic. The resources for the application of the temporary control strategies were assumed to be available.

The hourly traffic volumes for the freeway mainline rightmost lane and the entrance ramp were given in passenger cars per lane per hour (pcplph). Figure 65 shows the hourly traffic volumes for one day for freeway mainline rightmost lane and freeway entrance ramp.

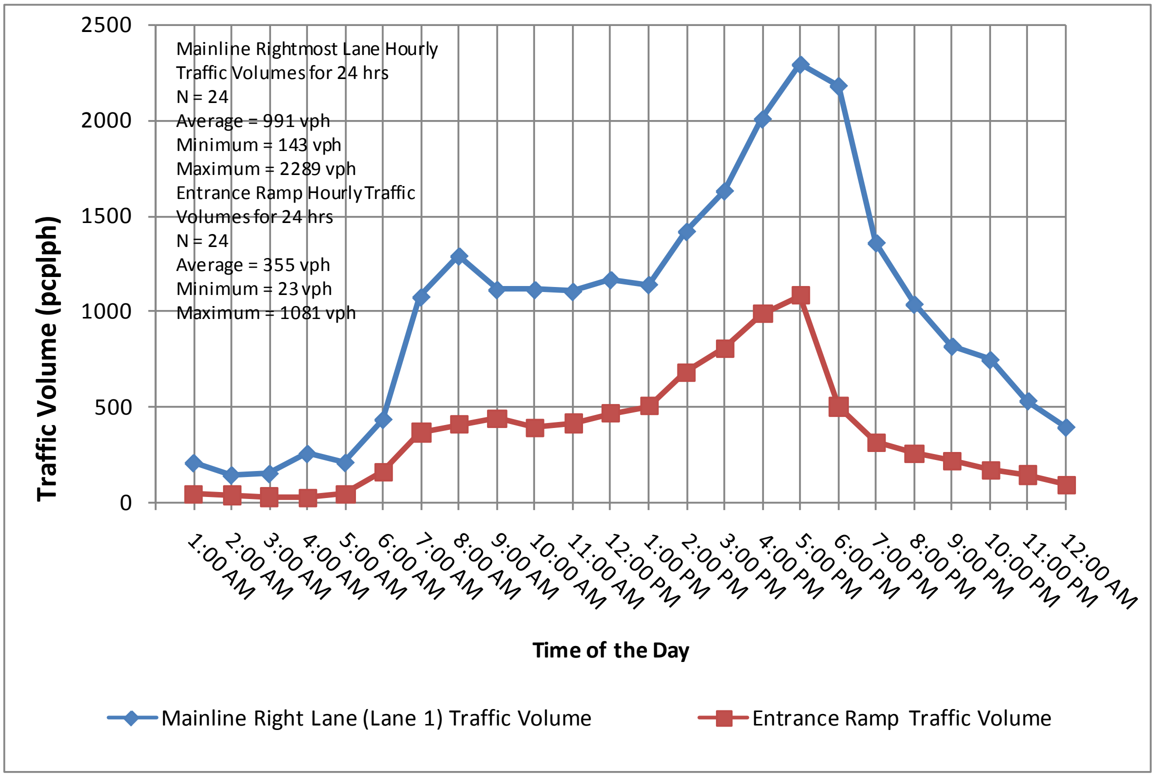


Figure 65. Hourly traffic volumes modified for the mainline rightmost lane and entrance ramp based on the data collected by ORITE on I90 eastbound in Cleveland, OH from 9/13/2004 Monday to 9/16/2004 Thursday (adapted from [1]).

The entrance ramp control strategies were identified for each hour of the day based on the information provided. The first step was to identify the importance of local traffic access to freeway and freeway mainline traffic throughput. The entrance ramp was located near downtown; therefore the local traffic access to freeway was very important, especially during rush hours. The freeway mainline traffic was also important since congestion might be a problem. As a result both the local traffic and the freeway mainline traffic throughput had high importance.

The next step in the analysis was to identify the classification of the hourly traffic volumes for each hour of the day for the freeway mainline and entrance ramp traffic based on the hourly traffic volume intervals given in Table 65. The hourly traffic volumes for freeway mainline rightmost lane and the entrance ramp are given for one day along with the traffic volume classifications in Table 72.

Table 72. Freeway mainline rightmost lane and entrance ramp hourly traffic volumes and classifications for temporary entrance ramp control.

Time Interval	Mainline Rightmost Lane Traffic Volume (vph)	Entrance Ramp Traffic Volume (vph)	Classification of the Traffic Volumes (Mainline – Entrance Ramp)
12:00 AM - 1:00 AM	207	39	Low-Low
1:00 AM - 2:00 AM	143	36	Low-Low
2:00 AM - 3:00 AM	150	25	Low-Low
3:00 AM - 4:00 AM	255	23	Low-Low
4:00 AM - 5:00 AM	208	40	Low-Low
5:00 AM - 6:00 AM	433	155	Low-Low
6:00 AM - 7:00 AM	1073	363	Medium-Medium
7:00 AM - 8:00 AM	1287	405	Medium-Medium
8:00 AM - 9:00 AM	1111	436	Medium-Medium
9:00 AM - 10:00 AM	1111	387	Medium-Medium
10:00 AM - 11:00 AM	1102	412	Medium-Medium
11:00 AM - 12:00 PM	1164	462	Medium-Medium
12:00 PM - 1:00 PM	1138	501	Medium-Medium
1:00 PM - 2:00 PM	1416	678	Medium-Medium
2:00 PM - 3:00 PM	1628	806	Medium-Medium
3:00 PM - 4:00 PM	2004	984	High-High
4:00 PM - 5:00 PM	2289	1111	High-High
5:00 PM - 6:00 PM	2178	500	High-Medium
6:00 PM - 7:00 PM	1356	313	Medium-Medium
7:00 PM - 8:00 PM	1035	255	Medium-Low
8:00 PM - 9:00 PM	816	217	Low-Low
9:00 PM - 10:00 PM	745	168	Low-Low
10:00 PM - 11:00 PM	531	140	Low-Low
11:00 PM - 12:00 AM	393	89	Low-Low

The temporary freeway entrance ramp control strategies were selected using the information provided. At the first hour of the day both traffic volumes were low therefore the entrance ramp could be open all the time during the first hour. The temporary entrance ramp control strategy could be identified for each hour of the day using the data available in Table 68 as given in Table 73. The temporary entrance ramp control strategies identified for each hour of the day are given along with the hourly traffic volumes for the freeway mainline rightmost lane and the entrance ramp, and the total of the mainline and entrance ramp in Figure 66.

Table 73. Selected temporary entrance ramp control strategies based on the hourly traffic volumes for each hour of the day, for 24 hours.

Time Interval	Total of Mainline and entrance Ramp Traffic Volume (vph)	Classification of the Traffic Volumes (Mainline – Entrance Ramp)	Classification of the Traffic Volumes (Mainline – Entrance Ramp)
12:00 AM - 1:00 AM	246	Low-Low	Ramp open all the time
1:00 AM - 2:00 AM	179	Low-Low	Ramp open all the time
2:00 AM - 3:00 AM	175	Low-Low	Ramp open all the time
3:00 AM - 4:00 AM	278	Low-Low	Ramp open all the time
4:00 AM - 5:00 AM	248	Low-Low	Ramp open all the time
5:00 AM - 6:00 AM	588	Low-Low	Ramp open all the time
6:00 AM - 7:00 AM	1436	Medium-Medium	Ramp open all the time and metered
7:00 AM - 8:00 AM	1692	Medium-Medium	Ramp open all the time and metered
8:00 AM - 9:00 AM	1547	Medium-Medium	Ramp open all the time and metered
9:00 AM - 10:00 AM	1498	Medium-Medium	Ramp open all the time and metered
10:00 AM - 11:00 AM	1514	Medium-Medium	Ramp open all the time and metered
11:00 AM - 12:00 PM	1626	Medium-Medium	Ramp open all the time and metered
12:00 PM - 1:00 PM	1639	Medium-Medium	Ramp open all the time and metered
1:00 PM - 2:00 PM	2094	Medium-Medium	Ramp open all the time and metered
2:00 PM - 3:00 PM	2434	Medium-Medium	Ramp open some of the time and metered
3:00 PM - 4:00 PM	2988	High-High	Ramp open some of the time and metered
4:00 PM - 5:00 PM	3400	High-High	Ramp closed all the time
5:00 PM - 6:00 PM	2678	High-Medium	Ramp closed all the time
6:00 PM - 7:00 PM	1669	Medium-Medium	Ramp open all the time and metered
7:00 PM - 8:00 PM	1290	Medium-Low	Ramp open all the time
8:00 PM - 9:00 PM	1033	Low-Low	Ramp open all the time
9:00 PM - 10:00 PM	913	Low-Low	Ramp open all the time
10:00 PM - 11:00 PM	671	Low-Low	Ramp open all the time
11:00 PM - 12:00 AM	482	Low-Low	Ramp open all the time

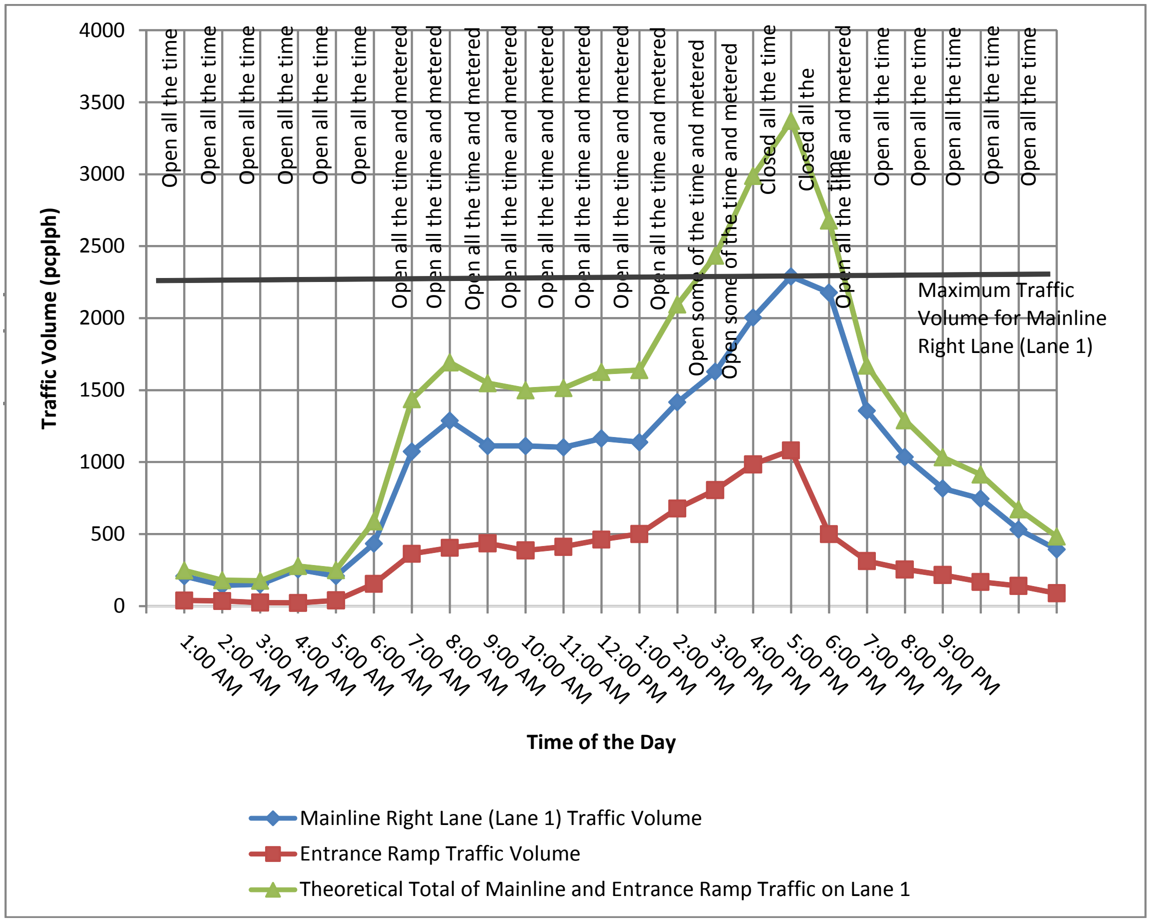


Figure 66. Selected temporary ramp control strategies for each hour of the day for total traffic volumes given in the hypothetical example (mainline rightmost lane + entrance ramp) (based on the modified hourly traffic volume data collected by ORITE on I90 eastbound in Cleveland, OH from 9/13/2004 Monday to 9/16/2004 Thursday (adapted from [1]).

The next step was to identify the entrance ramp metering traffic signal timings for the ramp open all the time and metered and ramp open some of the time and metered situations.

Table 74 shows the sample entrance ramp metering signal timings for “ramp open all the time and metered” situation. The 100% traffic signal timing was used to calculate the intervals by dividing 1-hour (3600 seconds) by the entrance ramp traffic volume. The results are then rounded to the nearest 0.5 seconds. The 100% traffic signal timings were multiplied by 90% signal timing percentage and rounded to the nearest 0.5 seconds to find the 90% entrance ramp metering signal timings. The use of 90% ramp metering signal timing will produce shorter queues at ramp metering signals and will not produce larger queues than 100% signal timings at the freeway mainline rightmost lane merge area.

Table 74. Sample entrance ramp metering traffic signal timings using 90% and 100% signal timing percentages for Ramp Metered Situation.

Time Interval	Entrance Ramp Traffic Volume (pcplph)	90% Entrance Ramp Metering Signal Timing ((3600 seconds /Ent.Ramp Traffic Vol.)*0.90)	100% Entrance Ramp Metering Signal Timing (3600 seconds /Ent.Ramp Traffic Vol.)
6:00 AM - 7:00 AM	363	9	10
7:00 AM - 8:00 AM	405	8	9
8:00 AM - 9:00 AM	436	7.5	8.5
9:00 AM - 10:00 AM	387	8.5	9.5
10:00 AM - 11:00 AM	412	8	8.5
11:00 AM - 12:00 PM	462	7	8
12:00 PM - 1:00 PM	501	6.5	7
1:00 PM - 2:00 PM	678	5	5.5
6:00 PM - 7:00 PM	313	10.5	11.5

Similar procedure as in ramp open all the time and metered situation was used to identify the ramp metering signal timings for the ramp open some of the time and metered situation. There were three instances where ramp was open some of the time and metered; for entrance ramp traffic volumes of 806 vph and 984 vph, and the mainline traffic volumes of 1628 vph and 2004 vph. The number of vehicles that could be allowed to enter to the freeway was found using the capacity consideration for the freeway mainline rightmost lane. The capacity of the freeway mainline rightmost lane was 2250 vph; therefore the number of entrance ramp vehicles that could be allowed to enter to the freeway was equal to capacity minus the freeway mainline hourly traffic volume. 622 vph (2250 – 1628) and 246 vph (2250 – 2004) could be allowed to enter the freeway for the given mainline hourly traffic volumes. The number of vehicles that could be allowed to enter the freeway was then used to calculate the duration of the ramp open situation in an hour. The number of vehicles that could be allowed to enter the freeway was divided by the entrance ramp hourly traffic volume to find the ratio of ramp open situation to ramp closed situation in an hour. The total time in an hour that the freeway entrance ramp would be open was calculated as 50 minutes ((672 / 806)*60 = 50) and 18 minutes ((296 / 984)*60 = 18). Therefore the freeway entrance ramp would be open for 50 minutes and closed for 10 minutes to allow 672 vehicles in an hour when the entrance ramp hourly traffic volume was 806 and the freeway entrance ramp would be open for 18 minutes and closed for 42 minutes to allow 296 vehicles in an hour when the entrance ramp hourly traffic volume was 984. The freeway entrance ramp should be open for of 5 times (50/10) than it should be closed in an hour for entrance ramp hourly traffic volume of 806, therefore the ramp would be open 5 times in an hour and closed 5 times in an hour. The CMS could be programmed to display “RAMP OPEN” message for 5 minutes, and then display “RAMP CLOSED” message for 1 minute for 10 cycles in an hour for the entrance ramp with hourly traffic volume of 806. The entrance ramp with hourly traffic volume of 984 should be open for 0.43 times (18/42) than it should be closed in an hour. Therefore the ramp would be open 20 times in an hour and closed 20 times in an hour. The CMS could be programmed to display “RAMP OPEN” message for 1 minute, and then display “RAMP CLOSED” message for 2 minutes for 20 cycles in an hour for the entrance ramp with hourly traffic volume of 984.The freeway open some of the time (ramp open partially) would require the use of changeable message signs (CMSs) to inform and warn drivers for the entrance ramp situation. The CMS needs to be preprogrammed to display “RAMP OPEN” or “RAMP CLOSED” message for the given durations in an hour.

The entrance ramp is open to allow 672 vph and 296 vph to the freeway; therefore the ramp metering signal timing would be programmed to accommodate these hourly traffic volumes using 90% ramp metering signal timing. Therefore the entrance ramp metering signal timings would be 5 seconds ((3600/672)*90%) for the entrance ramp with the hourly traffic volume of 806 vph and 11 seconds (3600/296) for the entrance ramp with hourly traffic volume of 984 vph. As a result of the analysis of the mainline and entrance ramp traffic volumes and the recommended entrance ramp control strategies; the ramp would be open all the time from 12 AM to 6 AM; ramp would be open all the time and metered from 6 AM to 2 PM; ramp would be open some of the time and metered from 2 PM to 4 PM; ramp would be closed from 4 PM to6 PM; ramp would be open all the time and metered from 6 PM to 7 PM; and ramp would be open all the time from 7 PM to 12 AM according to the ramp metering signal timings given above.

4.8 Exit Ramp Control in Freeway Work zones

The exit ramps in freeway work zones cause less of a problem than the freeway entrance ramps in work zones.

The exit ramps in freeway work zones should be remained open at all possible times. Therefore the traffic destined for local area can exit at closest point and does not have to drive to other exits. Exit ramps open all the time in freeway work zone would help to improve freeway mainline throughput since the exits of vehicles from the mainline reduce the number of vehicles on mainline and congestion.

4.9 Part III Conclusions

A new concept for temporary entrance ramp control including entrance ramp metering for freeway work zones was developed based on two major factors.

The first factor is the importance level of freeway mainline traffic throughput and the importance level of local traffic access to the freeway through the entrance ramp.

Further, the second factor is the hourly traffic volumes of the freeway mainline, specifically the hourly traffic volumes of the rightmost lane, (assumed to be equal to the average mainline hourly traffic volume per lane) and the hourly traffic volumes of the freeway entrance ramp.

The selected importance levels for freeway mainline throughput and the local traffic access to freeway are “very important” (high) and “not that important” (low). The hourly traffic volumes for the freeway mainline rightmost lane are low (0 to 900 vph), medium (901 to 1800 vph), and high (1801 to 2250 vph) and for the freeway entrance ramp are low (0 to 300 vph), medium (301 to 900 vph), and high (901 to 1200 vph).

Guidelines for temporary entrance ramp control and ramp metering in freeway work zones were developed for each of the four importance level combinations (local traffic access to the freeway is not that important - freeway mainline traffic throughput is not that important, local traffic access to the freeway is very important - freeway mainline traffic throughput is not that important, local traffic access to the freeway is not that important - freeway mainline traffic throughput is very important, and local traffic access to the freeway is very important -freeway mainline traffic throughput is very important) and for each of the nine freeway mainline rightmost lane and freeway entrance ramp hourly traffic volume combinations (low– low, low – medium, low – high, medium– low, medium– medium, medium– high, high– low, high – medium, and high – high, where the first level defines the freeway mainline rightmost lane hourly traffic volume and the second level defines the freeway entrance ramp hourly traffic volume).

Temporary freeway entrance ramp control strategies in freeway work zones involve ramp open all the time during the hour, ramp open some of the time (ramp open partially) during the hour, ramp open all the time and metered during the hour, ramp open some of the time and metered (ramp metered partially) during the hour, and ramp closed all the time during the hour for each of the 24 hours of the day.

Historical hourly traffic volumes for each of the 24 hours of the day and for each of the 7 days of the week represent the basic input to determine the temporary freeway entrance ramp control strategy considering the importance levels of freeway mainline traffic throughput and local traffic access to the freeway through the entrance ramp and the hourly traffic volume levels of the freeway mainline rightmost lane and freeway entrance ramp.

The temporary freeway entrance ramp metering control strategy was investigated by using two Arena simulation models. The first Arena simulation model was developed to determine spill back queue from the ramp metering signal back to the local (arterial) road. The second Arena simulation model was developed to determine the queue from freeway mainline rightmost lane merge area back to the ramp metering signal. It was found that a ramp metering signal interval, which is 90% of the ramp metering signal interval that would be equal or just sufficient to process the ramp demand in an hour (entrance ramp hourly traffic volume), will result in much shorter spill back queues from ramp metering signal back to local (arterial) roads while on the other hand not increase the queue lengths from the freeway mainline rightmost lane merge area back to the ramp metering signal considerably for either signalized or non-signalized freeway entrance ramps even when 10% trucks in the mainline and in the entrance ramp are present.

Implementation of the developed temporary freeway entrance ramp control strategies requires hourly historical traffic volume data for each of the 24 hours of the day for each of the 7 days of the week and a computer or a microprocessor capable to program 168 hours (7 days x 24 hours) of ramp control strategies, as well as the temporary hardware for the entrance ramp which could include CMSs, ramp metering signals, and advance traffic signs with or without flashing beacons.

It is tentatively concluded that these guidelines for temporary entrance ramp control in freeway work zones are comprehensive and will make it possible for traffic engineers to design and implement an entrance ramp control strategy including entrance ramp metering in freeway work zones, which may also be applied to freeways without work zone, and consider both freeway mainline traffic throughput and the local traffic access of the driving public to the freeway system.

5 REFERENCES

1. Zwahlen, H.T. and Oner, E., “Improved Work Zone Design Guidelines and Enhanced Model of Travel Delays in Work Zones”, Report No. FHWA/OH-2006/1, January 2006.
2. Pline, James L., Traffic Engineering Handbook, Institute of Transportation Engineers, Fifth Edition, 1999, pp. 62-68.
3. Rothery, Richard W., Car Following Models, Civil Engineering Department, The University of Texas, Austin, Texas
4. Rakha H. and Crowther B., Comparison of Greenshields, Pipes, and Van Aerde Car-following and Traffic Stream Models, *Transportation Research Record* , No. 1802, 2002, pp. 248-262
5. Oner, E., A Simulation Approach to Modeling Traffic in Construction Work Zones, 2004, available online at http://www.ohiolink.edu/etd/send-pdf.cgi?ohiou1108146637
6. Hidas, P., Modelling Lane Changing and Merging in Microscopic Traffic Simulation, Transportation Research, Part-C: Emerging Technologies, Volume 10, Issues 5-6, October-December 2002, Pages 351-371.
7. A. Kanaris, E. Kosmatopoulos and P. Ioannou "Strategies and Spacing Requirements for Lane Changing and Merging in Automated Highway Systems" IEEE Transactions on Vehicular Technology, Vol. 50, No. 6, November 2001, pp 1568-1582.
8. Chitturi M.V. and R.F. Benekohal. Comparison of QUEWZ, FRESIM and QuickZone with Field Data for Work Zones, *83rd Annual TRB Meeting* Compendium of Papers CD ROM, Washington, D.C., Jan 2004.
9. Schnell, T., Aktan, F., Mohror, J., “Evaluation of Traffic Flow Analysis Tools Applied to Work Zones Based on Flow Data Collected in the Field”, Final Report FHWA/HWA-2001/08, prepared for Ohio Department of Transportation, 2001, 109 pages.
10. Lee, G. *Modeling Gap Acceptance at Freeway Merges*. Master’s Thesis, Massachusetts Institute of Technology, 2006.
11. Traffic Monitoring Reports, Seasonal and Annual Adjustment Factors, Ohio Department of Transportation Technical Services Traffic Survey Report, URL: http://www.dot.state.oh.us/techservsite/offceorg/traffmonit/CountInformation/ , accessed on March 02, 2007.
12. Leslie Jacobson ... [et al.]. In Jacobson L. N., Inc P. F. and Administration U. S. F. H. (Eds.), *Ramp management and control: Handbook*. Washington, DC : U.S. Dept. of Transportation, Federal Highway Administration. 2006.
13. Piotrowicz, G. and J. Robinson. *Ramp Metering Status in North America; 1995 Update.* Publication DOT-T-95-17. FHWA, U.S Department of Transportation. June 1995.
14. Jacobson, L., J. Stribiak, L. Nelson, and D. Sallman. *Ramp Management and Control Handbook*, Federal Highway Administration, Report No. FHWA-HOP-06-001, Washington, DC, 2006.
15. Pearson, R. *Ramp Metering*. ITS Decision Report, California Department of Transportation, 2001. Available online at: http://www.calccit.org/itsdecision/serv_and_tech/Ramp_metering/ramp_metering_report.htm#r_meter_system. Accessed Nov. 17, 2008.
16. Papageorgiou, M. and I. Papamichail. European Ramp Metering Project – Handbook of Ramp Metering. Prepared for European Community Information Technology Societies, Contract No. 507645, Report No. IST- 2002-23110, 88 pages, September 2007.

17. Oner, Erdinc. An Evaluation of Entrance Ramp Metering for Freeway Work Zones using Digital Simulation. OU PhD. Dissertation, Ohio University, 2008.
18. *Ramp Meter Design Manual*, Draft, Prepared by Office of Traffic Engineering, Ohio Department of Transportation, May 2007.
19. *Ohio Manual of Uniform Traffic Control Devices*, 2005 Edition, ODOT, Office of Traffic Engineering, Available online at http://www.dot.state.oh.us/Divisions/HighwayOps/Traffic/publications2/OhioMUTCD/Pages/default.aspx. Accessed Nov. 18, 2008.
20. *Sign Design Manual, Section 295-2 of the Traffic Engineering Manual*, Revised Oct. 17, 2008, ODOT, Office of Traffic Engineering, Available online at http://www.dot.state.oh.us/Divisions/HighwayOps/Traffic/publications2/SDM/Pages/default.aspx. Accessed Nov. 18, 2008.
21. Ullman, G.L., C.L. Dudek, B.R. Ullman, A. Williams, and G. Pesti. *Effective Use of Portable Changeable Message Signs in Work Zones.* Final report prepared for the Texas Department of Transportation, Project No. 0-4748, December 2005.
22. Zwahlen, H.T. and A. Russ. Evaluation of Accuracy of Real-Time Travel Time Prediction System in Freeway Construction Work Zone. In *Transportation Research Record 1803*, TRB, National Research Council, Washington, D. C., pp. 87-93, 2002
23. Ullman, G.L., B.R. Ullman, C.L. Dudek, and N.D. Trout. *Legibility Distances of Smaller Character Light-Emitting Diode (LED) Dynamic Message Signs for Arterial Roadways.* Final report prepared for City of Dallas, Transportation management Systems, Project No. 404940, 41 pages, July 2004.
24. Siegel, S. *Nonparametric Statistics for the Behavioral Sciences*. McGraw-Hill Book Company, Inc., New York, 1956, p.131.
25. Zwahlen, H.T. and E. Oner, and K. Suravaram. Approximated Headway Distributions of Free-Flowing Traffic on Ohio Freeways for Work Zone Traffic Simulations. Paper No. 07-1511. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1999*, TRB, National Research Council, Washington, DC, 2007, pp. 131-140.
26. *Highway Capacity Manual*, Transportation Research Board, Washington, D.C., 2000.
27. Zhang , L. and D. Levinson. Some Properties of Flows at Freeway Bottlnecks. In 83rd Annual Meeting of the Transportation Research Board Compendium of Papers CD-ROM. TRB, National Research Council, Washington, DC, 2004.
28. Lorenz, M. R. and L. Elefteriadou. Defining Freeway Capacity as a Function of Breakdown Probability. In *Transportation Research Record 1776*, TRB, National Research Council, Washington, D. C., pp. 43-51, 2001.
29. Banks, J.H. Freeway Speed Flow Concentration Relationships: More Evidence and Interpretations. In *Transportation Research Record 1225*, TRB, National Research Council, Washington, D. C., pp. 53-60, 1989.
30. *Technical Services Products and Services – Traffic Monitoring Section*, Ohio Department of Transportation. Available online at: http://www.dot.state.oh.us/Divisions/Planning/TechServ/Prod_Services/Pages/default.aspx. Accessed Nov. 17, 2008.
31. Manch, T., Ohio Department of Transportation Technical Services, "Hourly Traffic Counts for a Week", E-mail to Helmut T. Zwahlen, October 28, 2008.
32. Gross, D. and Harris, C.M. *Fundamentals of Queueing Theory*, John Wiley & Sons, Inc., Second Edition, 1985, pp. 13-35.

33. Hall, R.W. Queueing Methods for Services and Manufacturing. Prentice-Hall, Inc., New Jersey, 1991, p. 151-153.
34. *Traffic Engineering Manual*, 2002 Edition (including revisions through October 17, 2008), ODOT, Office of Traffic Engineering, Available online at http://www.dot.state.oh.us/Divisions/HighwayOps/Traffic/publications2/TEM/Pages/default.aspx. Accessed Nov. 18, 2008.
35. The Ohio Department of Transportation's Mission, Available online at: http://www.dot.state.oh.us/policy/Pages/ODOTMissionValuesandGoals.aspx. Accessed on Nov. 17, 2008.
36. Traffic Management in Work Zones Interstate and Other Freeways, Ohio Department of Transportation, Policy No: 516-003 (P), effective data July 18, 2000. Available online at http://www.dot.state.oh.us/districts/D01/PlanningPrograms/policies/Documents/516-003p.pdf. Accessed on Nov. 17, 2008.
37. Montgomery, D.C. *Design and Analysis of Experiments*, John Wiley & Sons, Inc., Sixth Edition, 1991, pp. 160-164.
38. *Ramp Design Manual*, California Department of Transportation, January 2000. Available online at: http://www.dot.ca.gov/hq/traffops/systemops/ramp_meter/RMDM.pdf. Accessed on Nov. 17, 2008.
39. Transportation Engineering Online Manual, Available online at http://www.webs1.uidaho.edu/niatt_labmanual/index.htm. Accessed Nov. 17, 2008.
40. *Ramp Meter Design Manual*, Draft, Prepared by Office of Traffic Engineering, Ohio Department of Transportation, May 2007.

List of Additional Publications Related to Ramp Metering not Referenced in Text

1. Sisiopiku, V.P., A. Das, and A. Sullivan. *Applications of Freeway Ramp Metering in Alabama.* University Transportation Center for Alabama, Report No. UTCA Report 04203, 81 pages, 2005.
2. Papageorgiou, M. and A. Kotsialos. Freeway Ramp Metering: An Overview. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 3, No. 4, 2002, pp. 271-281.
3. Papageorgiou, M., H. Hadj-Salem, and F. Middelham. ALINEA Local Ramp Metering – Summary of Field Results. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1603*, TRB, National Research Council, Washington, DC, 1997, pp. 90-98.
4. Scariza, J.R. *Evaluation of Coordinated and Local Ramp Metering Algorithms using Microscopic Traffic Simulation*. Master's Thesis, Massachusetts Institute of Technology, 2003.
5. Hourdakis, J and P.G. Michalopoulos. Evaluation of Ramp Control Effectiveness in Two Twin Cities Freeways. Paper No. 02-2675. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1811*, TRB, National Research Council, Washington, DC, 2002, pp. 21-29.
6. Taylor, C., D. Meldrum, and L. Jacobson. Fuzzy Ramp Metering: Design Overview and Simulation Results. Paper No. 98-0675. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1634*, TRB, National Research Council, Washington, DC, 1998, pp. 10-18.
7. Bogenberger, K. and A.D. May. Advanced coordinated traffic responsive ramp metering Strategies. California PATH Working Paper, UCB-ITS-PWP-99-1, Institute of Transportation Studies, University of California, Berkeley, 1999.
8. Jacobsen, L., K. Henry and O. Mahyar. Real-time Metering Algorithm for Centralized Control. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1232*, TRB, National Research Council, Washington, DC, 1989, pp.17-26.
9. Ahn, S., R.L. Bertini, B. Auffray, and J.H. Ross. Evaluating the Benefits of a System-Wide Adaptive Ramp-Metering Strategy in Portland, Oregon. In 86th Annual Meeting of the Transportation Research Board Compendium of Papers CD-ROM. TRB, National Research Council, Washington, DC, 2007.
10. Chu, L., H.X. Liu, W. Recker, and H.M. Zhang. Performance Evaluation of Adaptive Ramp-Metering Algorithms Using Microscopic Traffic Simulation Model. *Journal of Transportation Engineering*, Vol. 130, No. 3, 2004, pp. 330-338.
11. Smaragdis, E., M. Papageorgiou, and E. Kosmatopoulos. A Flow-Maximizing Adaptive Local Ramp Metering Strategy. *Transportation Research. Part B, Methodological*, Vol. 38B, No. 3, 2004, pp. 251-270.
12. Taylor, J.C., P.G. McKenna, P.C. Young, A. Chotai, and M. MacKinnon. Macroscopic Traffic Flow Modelling and Ramp Metering Control using Matlab/Simulink. *Environmental Modelling and Software*, Vol. 19, No. 10, 2004, pp. 975-988.
13. Stewart, P. *Ramp Metering Study.* Scottish Executive Summary, SIAS Limited, Report No. TPRAMP2/55129, March 2003.
14. Kwon, E., S. Nanduri, R. Lau, and J. Aswegan. Comparative Analysis of Operational Algorithms for Coordinated Ramp Metering. Paper No. 01-3411. In *Transportation Research*

Record: Journal of the Transportation Research Board, No. 1748, TRB, National Research Council, Washington, DC, 2001, pp. 144-152.
15. Bellemans, T., B. De Schutter, and B. De Moor. Model Predictive Control for Ramp Metering of Motorway Traffic: A Case Study. In *Control Engineering Practice*, Vol. 14, 2006, pp. 757-767.
16. Hasan, M., M. Jha, and M. Ben-Akiva. Evaluation of Ramp Control Algorithms using Microscopic Traffic Simulation. *Transportation Research. Part C*, Vol. 10, 2002, pp.229-256.
17. Lee, C., B. Hellinga, and K. Ozbay. Quantifying Effects of Ramp Metering on Freeway Safety. *Accident Analysis and Prevention*, Vol. 38, No. 2, 2006, pp. 279-288.
18. Messer, C.J and M.A. Butorac. *A Dual-Lane Flow Signal Plan for Texas*. Research report prepared for Texas Department of Transportation, Study No. 0-1295, Report No. FHWA/TX-98/1295-2, 102 pages, August 1997.
19. *Ramp Metering Summary Report*, Highways Agency, An Executive Agency of the Department of Transport, Bristol Publications Group SW05303, 20 pages, 2005. Available at:
http://www.highways.gov.uk/knowledge/documents/SW05303_Ramp_metering.pdf, Accessed on January 1, 2008.
20. Persaud, B., S. Yagar, D. Tsui, and H. Look. Breakdown-Related Capacity for Freeway with Ramp Metering. Paper No. 01-2636. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1748*, TRB, National Research Council, Washington, DC, 2001, pp. 110-115.
21. Gordon, R.L. Algorithm for Controlling Spillback from Ramp Meters. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1554*, TRB, National Research Council, Washington, DC, 1996, pp. 162-171.
22. Bertini, R.L. and A. El-Geneidy. Techniques for Evaluating the Performance of Pre-Timed Ramp Meters using Archived ITS Data. In 83rd Annual Meeting of the Transportation Research Board Compendium of Papers CD-ROM. TRB, National Research Council, Washington, DC, 2004.
23. Cassidy M.J. and J. Rudjanakanoknad. On-Ramp Metering Experiments to Increase Freeway Merge Capacity. California PATH Research Report, UCB-ITS-PRR-2005-28, Institute of Transportation Studies, University of California, Berkeley, 2005.
24. Banks, J.H. Are Minimization of Delay and Minimization of Freeway Congestion Compatible Ramp Metering Objective? Paper No. 00-1615. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1727*, TRB, National Research Council, Washington, DC, 2000, pp. 112-119.
25. Janson B.N. Modeling Network Travel Time Impact of Freeway Ramp Metering. Paper No. 98-0871. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1645*, TRB, National Research Council, Washington, DC, 1998, pp. 152-159.
26. Kotsialos, A., M. Papageorgiou, and F. Middelham. Optimal Coordinated Ramp Metering with Advanced Motorway Optimal Control. Paper No. 01-3125. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1748*, TRB, National Research Council, Washington, DC, 2001, pp. 55-65.
27. Kotsialos, A. and M. Papageorgiou. Efficiency and Equity Properties of Freeway Network-Wide Ramp Metering with AMOC. *Transportation Research. Part C*, Vol. 12, 2004, pp.401-420.

28. Wu, J., McDonald, M, and K. Chatterjee. A Detailed Evaluation of Ramp Metering Impacts on Driver Behaviour. *Transportation Research. Part F,* Vol. 10, 2007, pp.61-75.
29. Chaudhary, N.A. and C.J. Messer. *Design Criteria for Ramp Metering: Appendix to TXDOT Roadway Design Manual*. Report prepared for Texas Department of Transportation, Project No. 0-2121, Report No. FHWA/TX-01/2121-3, 12 pages, November 2000.
30. Ahmed, K. *Modeling Drivers' Acceleration and Lane Changing Behavior*. MIT Ph.D. Dissertation, Massachusetts Institute of Technology, 1999.
31. *ASSHTO Green Book: A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials, 5th edition, 2004.
32. Choudhury, C.H. *Modeling Lane Changing Behavior in Presence of Exclusive Lanes*. Master's Thesis, Massachusetts Institute of Technology, 2005.
33. Toledo, T. *Integrating Driver Behavior Modeling*. Ph.D. Thesis, Massachusetts Institute of Technology, 2003.
34. *Ramp Design Manual*, California Department of Transportation, January 2000. Available online at:
http://www.dot.ca.gov/hq/traffops/systemops/ramp_meter/RMDM.pdf. Accessed on Nov. 17, 2008.