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Determining Work Zone Lane Capacities along Multilane Signalized Corridors

By

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April, 2017

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16. Abstract
The existing motor vehicle travel lanes are either narrowed to a single lane or diverted around the work zone, which may lead to disruptions in traffic flow due to reduced capacity. The capacity of the work zone can be estimated from research on the capacity associated with various lane closures on multilane facilities. The purpose of this study was to provide the Delaware Department of Transportation (DelDOT) with a review of the state-of-the-practice tools for managing work zone safety, estimating the traffic mobility impacts at work zones and developing Delaware-specific values much like those found in the DelDOT Work Zone Safety and Mobility Procedures and Guidelines and the 2010 HCM to represent work zone lane capacities on multilane signalized roadways. Since traffic flow on most of multilane signalized roadways in Delaware does not exceed the work zone capacity, it is more difficult to estimate true value of work zone capacity. To this end, we propose a new methodology to determine work zone capacity distribution based on the probabilistic speed-flow-density relationships. Data in terms of the traffic flow, speed, density, lane occupancy in work zones were collected in six work zones on freeways in California and twenty-five work zones on multilane signalized roadways in Delaware. The proposed methodology can be helpful in evaluating the variability of work zone capacity and selecting better the work zone traffic control strategies to improve the capacity and construction staging.

17. Key Words
Capacity, Safety, Work Zone, Lane Closure, Multilane Signalized Corridors, Review, Estimation, Approach

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EXECUTIVE SUMMARY

Safety and mobility for users and personnel on the worksite and efficient flow of traffic through work zones is a major concern to practitioners, researchers, managers, or transportation officials. The Federal Highway Administration (FHWA) requires all the state DOTs to develop a Traffic Management Plan during the design phase of road construction and maintenance projects. Following the FHWA requirement, state DOTs perform work zone traffic analyses to select appropriate lane closure strategies based on predicted capacity, queue lengths, user costs and crash rates for work zones to reduce construction times and minimize impacts on the motoring public. While work zone processes and procedures differ significantly from state to state, they all focus on developing increased capacity and efficiency through the work zone or within the adjacent corridor. The appendix examines most of the state DOT's progress in work zone management.

The determination of appropriate time periods for lane closures is a balance between the needs of the construction crews to complete the work in a timely manner as well as providing the least amount of delay to motorists approaching and traveling through the work zone. The capacity of the work zone can be estimated by establishing a relationship between speed reduction and the primary factors impacting the work zone capacity. Currently, the Delaware Department of Transportation (DelDOT) refers to the Work Zone Safety and Mobility Procedures and Guidelines document, more specifically Table-2 of the Guidelines: "Measured Average Work Zone Capacities" to determine capacity values within work zones on uninterrupted roadway facilities.

The purpose of this study was to provide the Delaware Department of Transportation (DelDOT) with a review of the state-of-the-practice tools for managing work zone safety, estimating the traffic mobility impacts at work zones and developing Delaware-specific values much like those found in the DelDOT Work Zone Safety and Mobility Procedures and Guidelines and the 2010 HCM to represent work zone lane capacities on multilane signalized roadways

Our analysis of the issues is informed by a comprehensive review of the approaches taken by researchers and practitioners for the estimation of capacity in construction work zones to mitigate traffic delays caused by such closures in past research. An annotated bibliography of over 60 references is presented which is concerned primarily with work zone capacity model. A literature search of the 50 state transportation agencies, as well as the District of Columbia were conducted to determine what innovative practices of work zone operations are being utilized to determine the capacity at work zones. However, not all states have formalized a policy that can be used for estimating the traffic impacts of work zone lane closures. Since many traffic flow analysis tools applied to work zones do not consider congestion characteristics such as queue length and delay, we provide a systematic review of software developed to perform the work zone capacity analysis and to help quantify queue length and travel delay times. We also explore how to help mitigate traffic delay problems.

The presentation of analysis methods used to evaluate traffic conditions under work zone operations is separated into two components: freeways and multilane signalized arterial, because performance measures used to characterize these two roadway types are different. Since traffic flow on most of multilane signalized roadways in Delaware does not exceed the work zone capacity, it is more difficult to estimate true value of work zone capacity. To this end, we propose a new methodology to determine work zone capacity distribution based on the probabilistic speed-flow-density relationships. Data in terms of the traffic flow, speed, density, lane occupancy in work zones were collected in six work zones on freeways in California and twenty-five work zones on multilane signalized roadways in Delaware.

The 25-site average capacities were 1475 vphpl. Notably, they were larger than the 1240 vphpl Highway Capacity Manual (HCM) based capacity values and currently used by DelDOT but lower than most values found in the nationwide survey. The proposed methodology can be helpful in evaluating the variability of work zone capacity and selecting better the work zone traffic control strategies to improve the capacity and construction staging.

1 INTRODUCTION

1.1 Problem Statement

Congestion caused or amplified by road or lane closures in areas with significant traffic volumes is often a source of frustration and anxiety of the traveling public as they approach or travel through work zones. Not only can they prove costly in terms of increased delay, travel time, vehicle emissions, and fuel consumption, but they are also associated with substantial number of crashes and injuries. During the 2003 to 2010 period, there were 7,009 fatalities in work zones[1], 962 workers were killed while working at a road construction site. Nearly half of these deaths resulted from a vehicle or mobile equipment striking the worker[2]. There is a disproportionately higher frequency of crashes in work zones than they are on stretches of highway under normal traffic volumes. Therefore, there is an urgent need to reduce the congestion and improve safety in work zones.

Safety and mobility for users and personnel on the worksite and efficient flow of traffic through work zones is a major concern to practitioners, researchers, managers, or transportation officials. The Federal Highway Administration (FHWA) requires all the state DOTs to develop a Traffic Management Plan (TMP) during the design phase of road construction and maintenance projects (FHWA, 2005). Following the FHWA requirement, state DOTs conduct work zone traffic analyses to select appropriate lane closure strategies based on predicted capacity, queue lengths, user costs and crash rates on roads under construction to reduce construction times and minimize impacts on the motoring public. While work zone processes and procedures differ significantly from state to state, they all focus on developing increased capacity and efficiency through the work zone or within the adjacent corridors. Supplemental materials in the appendix examine most of the state DOT's progress in work zone management.

Congestion mitigation in work zones is taking an important role in the construction process. The selection of strategies by State Transportation Agencies (STAs) for Transportation Management Plans (TMPs) varies widespread among different agencies when performing work zone activities such as reconstruction, resurfacing, maintenance, and location of either urban or rural, and facility types of expressways, freeways, two-lane highways. Work zone congestion mitigation strategies are adapted by agencies of Transportation Management Plan to reduce congestion through work zones. At present, strategies including traffic management strategies, demand management strategies, alternative project scheduling and phasing strategies, design alternatives to minimize life cycle congestion cost strategies, and alternative contracting and delivery strategies are used in Transportation Management Plan. Also, each strategy consisting of several micro-strategies is considered to address mobility and safety impacts. However, the strategies benefits in reducing congestion on urban facilities might not provide the same beneficial function to a rural facility.

[1] FARS (Fatality Analysis Reporting System), www-fars.nhtsa.dot.gov

[2] http://www.bls.gov/opub/mlr/2013/article/pdf/an-analysis-of-fatal-occupational-injuries-at-road-construction-sites-2003-2010.pdf

The enforcement of a lane closure policy is crucial for reducing congestion and maintaining the overall integrity of the policy. However, current data indicated that enforcement issues are rare in most states, and that most contractors and other counterparts needing a lane closure understand the importance of reduced congestion (Maze & Wiegand, 2007). The determination of appropriate time periods for lane closures is a balance between the needs of the construction crews to complete the work in a timely manner as well as providing the least amount of delay to motorists approaching and traveling through the work zone. The capacity of the work zone can be estimated by establishing a relationship between speed reduction and the primary factors impacting the work zone capacity. ***Figure** 1* illustrates a typical work zone on a multilane signalized corridor in Delaware.

Figure 1 Work zone at Summit Bridge Road, Delaware
(Photos taken on January 29, 2017 at Summit Bridge Road)

A typical work zone consists of the following elements (as depicted in Figure 2).

- Advance warning area
- Transition area
- Activity area
- Termination area

Currently, the Delaware Department of Transportation (DelDOT) refers to the Work Zone Safety and Mobility Procedures and Guidelines (the Guidelines) document, more specifically Table 2: "Measured Average Work Zone Capacities" (***Table 1* in this report)** to determine capacity values within work zones on uninterrupted roadway facilities only.

Table 1: Measured average work zone capacities

Number of Lanes		**Work Zone Capacity**	
Normal Operations	Open to Traffic in Work Zone	Vehicles Per Hour (VPH)	Vehicles Per Hour Per Lane (VPHPL)
3	1	1,170	1,170
2	1	1,340	1,340
5	2	2,740	1,370
4	2	2,960	1,480
3	2	2,980	1,490
4	3	4,560	1,520

Source: DelDOT Work Zone Safety and Mobility Procedures and Guidelines, Table 2: "Measured Average Work Zone Capacities".

Table 1 reflects observed work zone mixed vehicle flow capacities at several real-world work zones under several lane closure scenarios (Highway Capacity Manual 2010). These values are taken directly from the 1997 update to the Highway Capacity Manual, 1985 version. The HCM has since been updated, including the work zone lane capacity table, and DelDOT is in the process of adjusting recommended lane closure times to accommodate these changes.

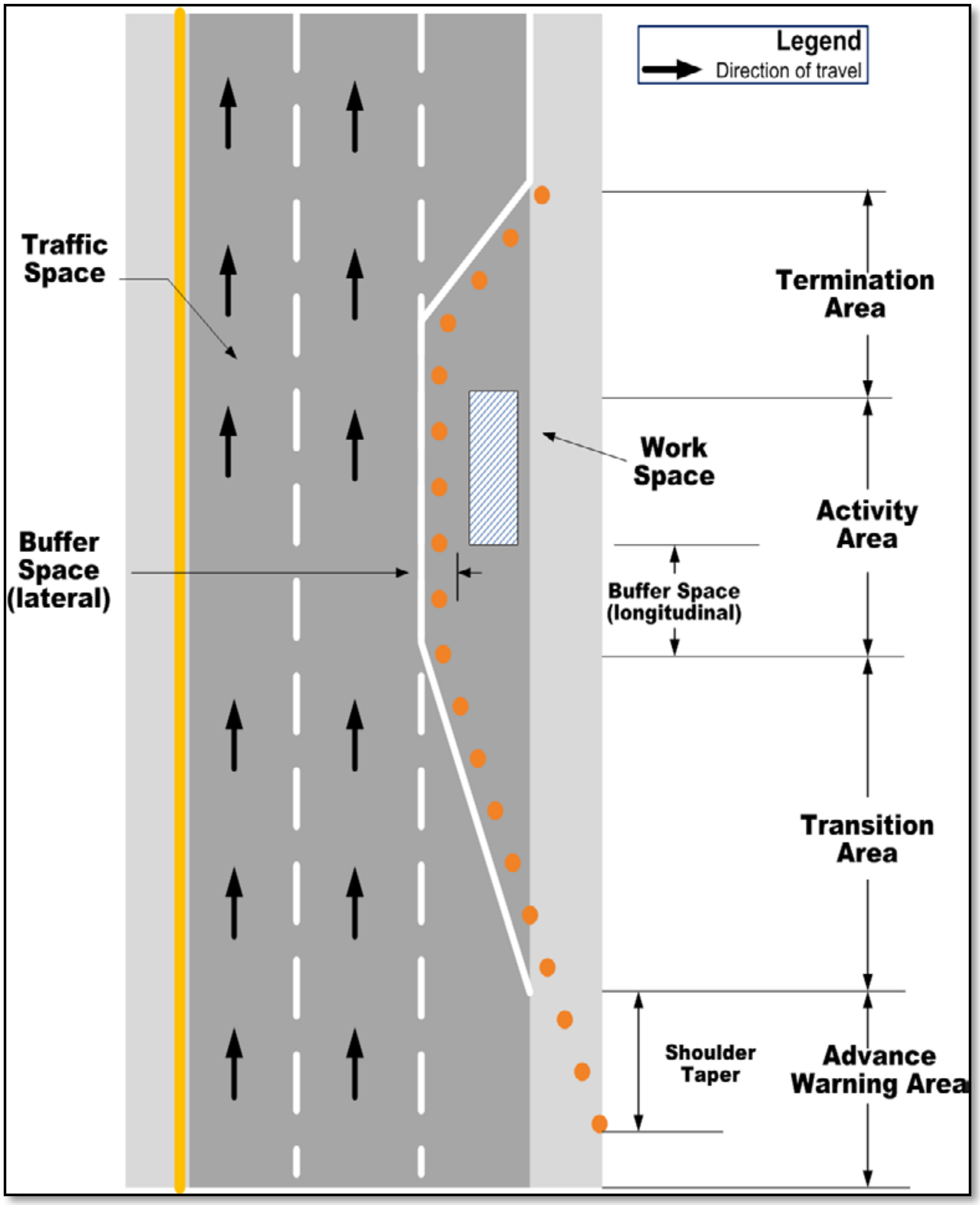

Figure 2: Component parts of a temporary traffic control zone

Multilane signalized arterial corridors generally have four to six lanes (in both directions) and posted speed limits between 40 and 55 mph. These signalized corridors may be undivided (with only a centerline separating the traffic in each direction) or divided (with a physical median for exclusive use of traffic in each direction), or they may or may not have a two-way left-turn lane (TWLTL). DelDOT's current practice for determining work zone lane capacities along interrupted flow facilities is to use the corresponding capacity value from ***Table 1*** in the Guidelines and apply an assumed signal delay factor to account for red time and startup delays at intersections.

Typically, the signal delay factor for a multilane signalized corridor is 40% of the value found in *Table 1* of the Guidelines. Engineering judgment is used for corridors which have a higher or lower density of signals, and the delay factor is adjusted accordingly.

1.2 Motivation

A recent literature review was performed within the DelDOT Traffic Safety section to investigate other states' methods for determining work zone lane capacities, and it was determined that Delaware's values are fairly conservative when compared with those used by several other states. A recommendation from the study was to develop a Delaware-specific table representing these work zone lane capacity values for both interrupted and uninterrupted facilities.

The research presented here faces the following challenging questions:

- What is the expected average speed, hourly volume (*Figure 3*), service capacity (the maximum sustainable flow rate before the breakdown or queue discharge rate after the breakdown), and average queue length for the work zones?
- What is the maximum amount of traffic the highway can handle where traffic is in the "free flow" regime?
- How to develop specific values to represent work zone lane capacities on multilane signalized roadways in Delaware?
- Will a diversion increase throughput or decrease travel time delay?
- How to determine what the work zone impact is if working on an urban road that already experiences heavy congestion?

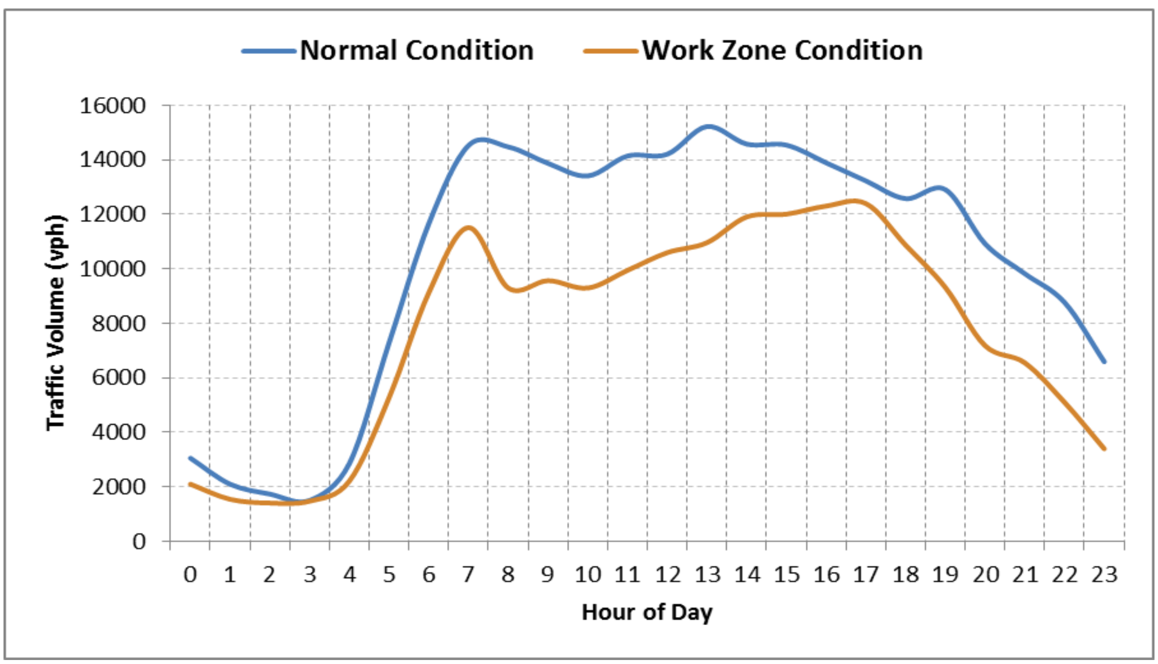

Figure 3: Traffic volumes under normal and work zone conditions

1.3 Report Outline

This report consists of four chapters, which are structured as follows: Chapter 1 gives a brief introduction to our research activities – the problem statement and motivation of our research, the research goal, and our approach.

Chapter 2 provides a comprehensive review of a large amount of previously published evidence about theoretical approaches to predicting traffic queues at work zones, impact from lane closure, capacity analysis tools and available data sets to be used for testing of model alternatives.

Chapter 3 describes data collection activities for our approach. A list of study sites, time and duration of data collection is also given in this chapter. Data in terms of the traffic flow, speed, density, lane occupancy in work zones were collected in six work zones on freeways in California and twenty-five work zones on multilane signalized roadways in Delaware.

Chapter 4 summarizes the findings of the work zone impact assessment. Concluding remarks, recommendations for implementation and future research extensions are given in this chapter.

2. LITERATURE REVIEW

2.1 Introduction

A significant amount of research has been conducted in the general area of estimating capacity and traffic delay in work zones. The objective of this section was to explore the factors affecting work zone capacity, to provide a summary of this literature and to make commendations based on the literature. This section includes a review of the pertinent background, a discussion of current recommendations, and a detailed critical review of recent contributions to the field. The purpose of this section is not just to summarize the results from the literature; rather, we will synthesize some major findings in the literature, discuss the approaches for work zone capacity estimation and prediction, and then make suggestions for future research.

Literature reviews among 50 state DOTs on procedures, techniques used for work zone capacity calculation, queue, delay, and role of ITS in work zones were conducted. The process review involves having a thorough understanding of the work zone safety, policies, and practices which is identified in a problem statement, conducting a critical examination of the state of art and best practice about assessing the safety impact of work zones, and identifying the appropriate level of detail and tools. Evaluations of existing research conducted nationally and internationally will be synthesized for key lessons learned, and serve as a basis for defining user and functional requirements to provide a proven and effective work zone performance management resource for practitioners and researchers. This section also discusses the magnitude of categories like throughput, delays, travel times, travel time reliability, and vehicle queues and how to quantify work zone impacts.

Key National Safety Analysis Resources

- FHWA Work Zone Mobility & Safety Program[3]
- National Highway Work Zone Safety Program[4]
- National Highway Traffic Safety Administration[5]
- FHWA Safety Program[6]
- AASHTO Highway Safety Manual[7]
- Proven Safety Countermeasures[8]
- FHWA Data and Safety Analysis Tools[9]

Key DelDOT Safety Analysis Resources

- Delaware Office of Highway Safety[10]

[3] https://ops.fhwa.dot.gov/wz/index.asp
[4] https://safety.fhwa.dot.gov/wz/wz_natl_pro.cfm
[5] https://www.nhtsa.gov
[6] https://safety.fhwa.dot.gov
[7] http://www.highwaysafetymanual.org/Pages/default.aspx
[8] https://safety.fhwa.dot.gov/provencountermeasures
[9] https://safety.fhwa.dot.gov/rsdp
[10] http://ohs.delaware.gov

- Delaware's Strategic Highway Safety Plan[11]
- DelDOT Road Design Manual[12]
- Delaware Manual on Uniform Traffic Control Devices (DE-MUTCD)[13]

Section 2 presents a thorough and comprehensive literature review focusing on existing numerical and analytical approaches for estimating work zone capacity. Section 3 discusses the treatment of the fundamentals of work zone capacity in the Highway Capacity Manual (2011). Next, an in-depth review of state of the practice in work zone capacity is conducted focusing on empirical studies and methods used to estimate capacity. This includes review of the literature on different lane closure scenarios and used data. Section 5 reviews the current DelDOT lane closure analysis procedure. Since many computer models do not consider congestion characteristics such as queue length and delay, section 6 reviews software developed to perform the work zone capacity analysis and to help quantify queue length and travel delay times. The last section summarizes the literature review findings and provides conclusions and recommendations.

2.2 Existing numerical and analytical approaches for estimating work zone capacity

A large number of studies have been conducted for estimation of the work zone capacity based on measured field data (Dudek & Richards, 1982; Dudash & Bullen, 1983; Michalopoulos & Plum, 1983; Krammes & Lopez, 1994; Dixon, Hummer, & Lorscheider, 1996; Jiang & Adeli, 2004; Benekohal, Kaja-Mohideen, & Chitturi, 2004).

Krammes and Lopez (1994) presented recommendations on short-term freeway work zone lane closure capacity values based on capacity counts at 33 work zones in Texas between 1987 and 1991. Al-Kaisy and Hall (2002) estimated an ideal capacity at freeway reconstruction sites and the individual effect of several important factors that affect the capacity, such as the effect of heavy vehicles, driver population, rain, site configuration, work activity at site, and light condition. They also presented attempts to model work zone capacity. Initially, two types of site-specific capacity models were developed by using different analytical techniques and data from sites with the most extensive and comprehensive capacity observations. Based on the results from the individual investigations and the site-specific models, a generic capacity model for freeway reconstruction sites is proposed. The proposed model indicates a base capacity value of 2,000 pcphpl for reconstruction sites under favorable conditions. Both heavy vehicles and driver population were found having the most significant effect on capacity. This information of generic model presented in this paper can provide valuable guidance to analysis users in estimating freeway capacity on long-term reconstruction sites.

There are many factors that could affect work zone capacity (*Table 2*). Al-Kaisy and Hall (2003) investigated the capacities of six reconstruction sites in Ontario, Canada, and then developed a generic multiplicative site-specific model for estimating the capacity of long-term work zones, which is multiplied by adjustment factors to account for the impact of various variables. The effect of heavy

11 http://www.deldot.gov/information/community_programs_and_services/DSHSP
12 http://deldot.gov/information/pubs_forms/manuals/road_design/index.shtml
13 http://deldot.gov/information/pubs_forms/manuals/de_mutcd

vehicles, driver population, inclement weather, site configuration, activity at site, and light conditions on capacity was investigated; heavy vehicles and driver population were identified to be the most significant factors affecting work zone capacity. The authors found that mean capacity ranges between 1,853 and 2,252 pcphpl, with a suggested base capacity value of 2, 000 pcphpl for reconstruction sites under favorable conditions (Al-Kaisy & Hall, 2003).

Karim and Adeli (2003) proposed an adaptive computational model for estimating the work zone capacity and queue length and delay. Eleven primary factors impacting the work zone capacity were considered in this research: number of lanes, number of open lanes, work zone layout, length, lane width, percentage of trucks, grade, speed, work intensity, darkness factor, and proximity of ramps. Seventeen different factors impacting the work zone capacity are included in an adaptive neuro-fuzzy logic model is presented for estimation of the freeway work zone capacity developed by Adeli and Jiang (2003). Weng and Meng (2012) provide a detailed analysis that incorporates 16 important factors that have an impact on work zone capacity.

Adeli and Jiang (2003) presented a new neuro-fuzzy freeway work zone capacity estimation model is by using fuzzy logic and neuro-computing concepts. A backpropagation neural network is employed to estimate the parameters associated with the bell-shaped Gaussian membership functions in the fuzzy inference mechanism. Compared with the two empirical equations, the new model in general provides a more accurate estimate of the work zone capacity, especially when the data combined the factors impacting the work zone capacity are only partially available. The new model provides two important additional advantages beyond the existing empirical equations. First, it incorporates a quite large number of factors impacting the work zone capacity. Also, unlike the previous empirical equations, the new model does not need to select various adjustment factors by the work zone engineers based on prior experience. The new model can be implemented into an intelligent decision support system for estimating the work zone capacity in a rational way, performing scenario analysis, and studying the impact of various factors influencing the work zone capacity.

Heaslip et al. (2009) developed analytical models and procedures for estimating capacity at freeway work zones by considering reductions. CORSIM was employed in this study to conduct simulation experiments for three work zone configurations: two-to-one, three-to-two, and three to-one lane closures due to various geometric, traffic, and work zone–related parameters. Recommendations were provided regarding possible improvements for CORSIM simulator to enhance its capability to simulate work zones.

Zhang et al. (2012) categorized traffic analysis tools into seven types, in the order of increasing complexity: 1) sketch-planning tools; 2) analytical/deterministic tools (HCM-based); 3) travel demand models; 4) traffic signal optimization tools; 5) macroscopic simulation models; 6)mesoscopic simulation models; and 7) microscopic simulation models. Edara et al. (2012) found that the queue discharge flow (QDF) values were the most conservative estimates of capacity.

Several articles in the literature discuss various methodologies for capacity estimation of freeway work zones. Weng & Meng (2013) present an overall review of parametric, non-parametric, and simulation approaches to increase the work zone capacity and mitigate traffic delay in work zones. Parametric approaches, non-parametric approaches, and simulation approaches are studied to estimate work zone capacity. Current approaches applicable for estimating traffic delay in work zones are mainly classified into macroscopic analytical approaches, macroscopic simulation approaches, and microscopic simulation approaches. By comparison, non-parametric approaches provide a better accuracy of estimation than the parametric approach, unless there is a strong linear relationship between work zone capacity and its influencing factor.

Table 2 Primary factors affecting work zone capacity

	Al-Kaisy and Hall (2003)	Karim and Adeli (2003)	Adeli and Jiang (2003)	Weng and Meng (2012)
Activity at site	√			
Driver composition	√		√	√
Lane closure location (urban or rural)			√	√
Lane width		√	√	√
Lighting condition	√	√		
Number of closed lanes				√
Number of opened lanes		√		√
Number of total lanes		√	√	
Pavement conditions (dry, wet, or icy)			√	
Percentage of heavy vehicle	√	√	√	√
Proximity of ramps		√	√	√
Road type				√
Speed		√	√	√
State/City				√
Weather	√		√	√
Work day (weekday or weekend)			√	
Work intensity		√	√	√
Work time (day or night)			√	√
Work zone duration			√	√
Work zone grade		√	√	√
Work zone layout (lane merging, lane shifting, and crossover)	√	√	√	
Work zone length		√	√	√

2.3 Capacity values of work zone recommended by the Highway Capacity Manual

The Highway Capacity Manual 2000 (HCM 2000) defines capacity as follows: "The maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions; usually expressed as vehicles per hour, passenger cars per hour, or persons per hour. " (Highway Capacity Manual, 2000). Similarly, the Highway Capacity Manual 2010 (HCM 2010) defines capacity as "the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform segment of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions." (Highway Capacity Manual, 2011). The latest Highway Capacity Manual (2016) defines capacity as "the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions".

2.3.1 Work Zone Capacity in HCM 2000

Previous highway capacity manual (HCM) was replaced by HCM 2000 Hybrid Version, which have been developed and tested. HCM Hybrid Version can minimize error in predicting actual maximum queue length (MQL) at the work zones. Its other advantage can minimize a passenger car equivalent (PCE) close to 2.1 error minimized in MQL compared to typical PCE values in the range from 2.0 to 2.5. Actually, the HCM 2000 Hybrid Version has been validated using six work zone cases, three from Alabama and three from North Carolina. However, the tool need be further modified to make it more extensive for mobility impact assessment with a graphical depiction of the queue profile and additional guidance will be offered the special cases of planning work zones without the normal conditions expected by the model.

Short-Term Work Zone Capacity

The HCM 2000 (Chapter 22) suggests that a capacity of 1,600 pcphpl be used as the base capacity for short-term freeway work zones, regardless of the lane closure configurations.

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)}$$

(Equation 1)

where

f_{HV} = heavy-vehicle adjustment factor,
P_T = proportion of trucks and buses in the traffic stream,
E_T = passenger-car equivalent for trucks and buses, and

The resulting reduced capacity in vehicles per hour can be estimated using Eq. 2:

$$c_a = (1,600 + I - R) \times f_{HV} \times N$$

(Equation 2)

where
c_a = adjusted capacity (vph);
f_{HV} = heavy-vehicle adjustment factor;
I = adjustment factor for type, intensity, and location of work activity;
N = number of lanes open through the work zone;
R = adjustment for ramps

Long-Term Work Zone Capacity

The HCM 2000 also provides capacity values for long-term construction zones (***Table 3***):

Table 3 Capacity values for long-term construction zones

No. of Normal Lanes	Lanes Open	Number of Studies	Range of Values (vphpl)	Average per Lane (vphpl)
3	2	7	1780-2060	1860
2	1	3	-	1550

Source: HCM 2000 and Dudek (1984).

2.3.2 Work Zone Capacity in HCM 2010

Short-Term Work Zone Capacity

The HCM 2010 (Chapter 10, Freeway Facilities) recommends that a value of 1600 vphpl be used as the base capacity value for short term freeway work zones., regardless of the lane-closure configuration (e.g., 2-to-1, 3-to-2, and 3-to-1). However, a higher value may be chosen for some types of closures.

Because the base capacity value is given as passenger cars per hour per lane (pc/h/ln), HCM 2010 recommends that the heavy vehicle adjustment factor (f_{HV}) be used (***Eq. 3***).

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)} \quad \text{(Equation 3)}$$

where

f_{HV} = heavy-vehicle adjustment factor,
P_T = proportion of trucks and buses in the traffic stream,
P_R = proportion of RVs in the traffic stream,
E_T = passenger-car equivalent for trucks and buses, and
E_R = passenger-car equivalent for RVs.

The resulting reduced capacity in vehicles per hour can be estimated using equation ***Eq. 4***:

$$c_a = (1{,}600 + I) \times f_{HV} \times N - R \quad \text{(Equation 4)}$$

where
c_a = adjusted capacity (vph);
f_{HV} = heavy-vehicle adjustment factor;
I = adjustment factor for type, intensity, and proximity of work activity;
N = number of lanes open through the work zone;
R = manual adjustment for on-ramps (vph).

Long-Term Work Zone Capacity

The overall base capacity of 1,600 pc/h/ln was suggested for short-term ideal highway work zones (Krammes & Lopez, 1994; Highway Capacity Manual, 2011).

Exhibit 10-14 of the 2010 HCM provides long-term construction zone capacities in terms of vehicles per hour per lane according to the original number of lanes before the establishment of the work zone and number of lanes open through the work zone (***Table 4***).

Table 4: Long-term capacities of freeway work zones (vphpl)

		After		
		1 Lane Work Zone	**2 Lanes Work Zone**	**3 Lanes Work Zone**
Before	**2 Lanes**	1,400		
	3 Lanes	1,450	1,450	
	4 Lanes	1,350	1,450	1,500
Average		1,400	1,450	1,500
Range		950-2,000	1,300-2,100	1,300-1,600

Source: Adapted from Exhibit 10-14 of 2010 HCM and Chatterjee et al. (2009).

Capacity of multilane highway segments

The HCM 2010 also provides capacity values for construction zones on multilane highway segments (***Table 5***):

Table 5: Capacity of multilane highway segments in one direction under base conditions

Free-Flow Speed (mph)	Capacity (pc/h/ln)
60	2,200
55	2,100
50	2,000
45	1,900

Source: Adapted from 2010 HCM (2011) , page 14-4.

2.3.3 Work Zone Capacity in HCM 2016

One of the most significant changes of the new 6th Edition of the Highway Capacity Manual (2016) is equations to explore the effects of work zones based on NCHRP project 03-107: work zone capacity (Schoen, Schroeder, Bonneson, Wang, Burghdoff, & Hajbabaie, 2012).

The new process recommended in HCM 2016 for calculating work zone capacity is performed by using following steps:

Step 1: **Calculate the lane closure severity index, LCSI**

$$LCSI = \frac{1}{OR \times N_o}$$

(Equation 5)

Where

LCSI	=	lane closure severity index;
OR	=	open ratio, the ratio of the number of open lanes during road work to the total (or normal) number of lanes
No	=	number of open lanes in the work zone

Step 2: **Calculate the work zone queue discharge rate**

$$QDR_{WZ} = 2,093 - 154 \times LCSI - 194 \times f_{BT} - 179 \times f_{AT} + 9 \times f_{LAT} - 59 \times f_{DN}$$

(Equation 6)

Where

QDR_{WZ}	=	average 15-min queue discharge rate (pc/h/ln)
f_{BT}	=	indicator variable for barrier type: 0 for concrete and hard barrier separation, and 1 for cone, plastic drum, or other soft barrier separation;
f_{AT}	=	indicator factor for area type: 0 for urban areas, and 1 for rural areas
f_{LAT}	=	lateral distance from the edge of travel lane adjacent to the work zone to the barrier, barricades, or cones
f_{DN}	=	indicator variable for daylight or night: 0 for daylight, and 1 for night

Step 3: **Calculate the** work zone capacity (pc/h/ln)

$$c_{WZ} = \frac{QDR_{WZ}}{100 - a_{WZ}} \times 100$$

(Equation 7)

Where

c_{WZ}	=	work zone capacity (pc/h/ln)
a_{WZ}	=	percentage drop in prebreakdown capacity at the work zone due to queuing conditions

2.4 Scan of state programs for assessing work zone traffic impacts

The Federal Highway Administration requires all the state DOTs to develop a Traffic Management Plan during the design phase of road construction and maintenance projects (FHWA, 2005). As a result, state DOTs conduct work zone traffic analyses to select appropriate lane closure strategies. Many state DOTs decide on which tool would be suitable for estimating work zone capacity based on the size of the project. Literature reviews among 50 state DOTs on procedures, techniques used for work zone capacity calculation, queue, delay, and role of ITS in work zones were conducted in this section (***Figure 4***). The points with varying sizes in ***Figure 4*** representing the number of reviewed documents pertaining to the lane closure policies, processes and procedures for the various state transportation agencies.

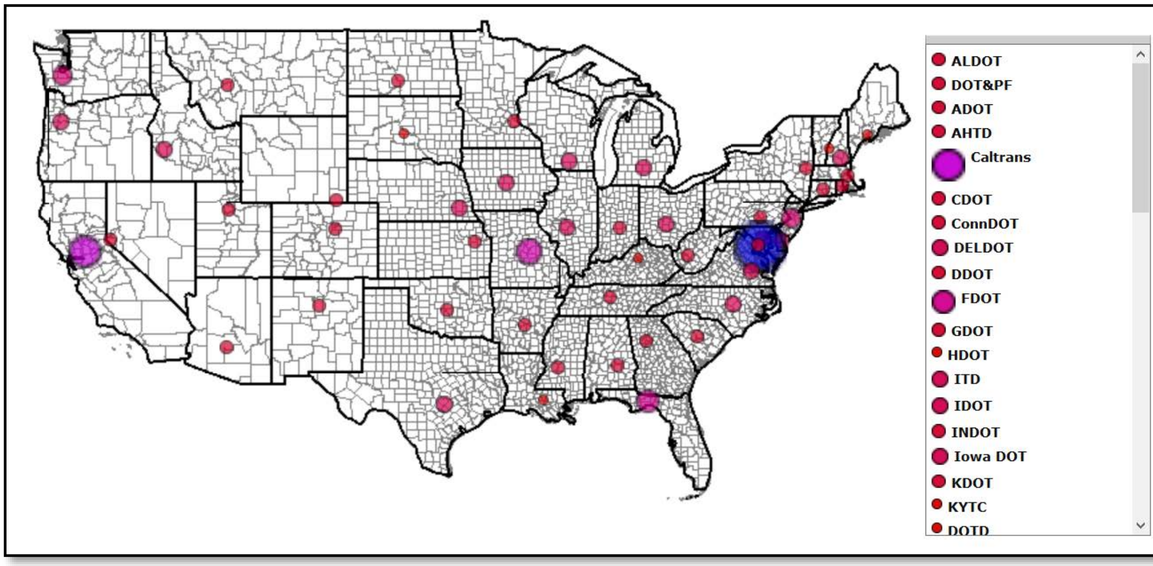

Figure 4: Summary of methodology for estimating work zone capacity

Table 6: Approach for estimating the work zone capacity in each state

Approach for estimating the work zone capacity	State
HCM method	Alabama, California, Delaware, Iowa, Maine, Maryland, Minnesota, Mississippi, Montana, New Jersey, New York, North Carolina, Ohio, Wyoming
Simulation method	Alaska, Connecticut, Colorado, District of Columbia, Idaho, Michigan, Missouri, Nevada, Washington, Wisconsin

Lane closure policies aim to evaluate the safety and mobility by reducing work zone–induced congestion by preventing lane closures when traffic demand would exceed the resulting capacity. The outputs of the lane closure policies have been widespread used in the United States, such as ODOT and Caltrans with an internet based permitted lane closure map and lane closure reporting system, and INDOT with a permitted lane closure times either graphically displayed in charts. Actual hourly breakdowns can provide a more precise beginning and ending time than general time periods when lane closures permitted from graphical representation. Moreover, a weekday closure systems do not be able to accurately record actual conditions as well as weekend closure. Although they have similar processes of lane closure policy development in the United States, they are different from analysis of the congestion created by a lane closure between states.

Alabama Department of Transportation (ALDOT) uses an Excel-based —Lane Rental (LR) Model originally developed by the Oklahoma Department of Transportation (OkDOT) and whose work zone capacity values are the same as the 1994 Highway Capacity Manual (Batson, et al., 2009). Connecticut Department of Transportation (ConnDOT) continues to use typical traffic capacity volumes to determine allowable hours for lane closure. For example, a maximum capacity of 1800 vehicles per hour (vph) for the Route 15 parkway, 1750 vph for ramps, and 1500 vph for all other roadways (2011). District Department of Transportation (DDOT) uses the same table from the HCM to estimate the capacity of a work zone based on the lanes available.

Illinois Department of Transportation (IDOT) uses queue analysis to dictate the capacity of a work zone. The analysis is performed by one or more of the measures, i.e., permitted lane closure maps (PLCM), hourly volume maps, district knowledge and experience, site reviews, highway capacity analysis converted into a predicted queue, and computer simulation programs (e.g., QUEWZ, TSIS – CORSIM, Quickzone). In addition to these, IDOT stresses that experience with similar projects allows the engineer to check the results that these methods produce.

The work zone analysis guide of Maryland Department of Transportation (MDOT) included three different models for determining the capacity in a work zone. The first is the same table (from HCM, 1997) used by DelDOT that simply relates the number of lanes available vs normal to the capacity. The second model is an equation developed by the University of Maryland. The third model included by SHA is the HCM's 2000 update. SHA leaves the decision of which model to use up to the discretion of the engineer responsible for the project. It also includes additional considerations that may necessitate adjustments to the models. These include: lane configurations, traffic volumes, work zone speeds, and simulation factors.

Massachusetts Department of Transportation (MassDOT) employs a simple table to estimate the capacity of a roadway in a work zone. The values are the same as DelDOT's table but include different combinations of open vs. closed lanes. Both DOTs gathered their information for these tables from the same edition of the HCM. Traffic management plans (TMPs) are to report the result of the planning, design, and preparation of contract documents for modification of the normal traffic and pedestrian patterns during construction. In other word, Traffic management plans (TMPs) are the result of work zone traffic control. It was reported that the frequency of crashes in work zones in Massachusetts is disproportionately much higher than at the other locations. Therefore, for Massachusetts, the primary consideration factor in work zone traffic control is the safety of pedestrians, bicyclists, motorists, and personnel on the worksite around work zones. Actually, maintaining the full carrying capacity and accommodation for all users is usually not possible during construction. Improving alternative routes of travel, providing temporary facilities staging work and police officer control during off-peak hours are ways to reduce the effects of construction on roadway operations. Accurate and timeline reporting of project data in public is a valuable component in the overall strategy for supervising a work zone. The resources such as MassHighway's Project information System, newspaper, radio, television, changeable message signs, and traveler information systems of 511, Mass Traveler and SmarTraveler can greatly improve the public's acceptance of occurring delays and inconveniences. Close coordination will be necessary to assure whether plans can be refined as needed or modified to effectively address unanticipated situations. Work zone mainly are categorized road closures, time restrictions, stationary work zones, mobile work zones. If road closure is a corrective option, the designer should tale the following action before closing a road:

The Michigan Department of Transportation (MDOT), much like DelDOT uses a table to determine the average capacity in the lanes available in a work zone. Table relates the number or lanes during normal operation and the number now available. In addition to this table, there are adjustments noted to accommodate specific situations. These situations include a truck percentage of greater than 10%, the inclusion of an entrance ramp in the closure zone, and the presence of above or below average work activities. These adjustments allow for more flexibility in the use of the table to determine capacity.

The Missouri Department of Transportation (MoDOT) uses the Work Zone Impact Analysis Spreadsheet with HCM 2010 Program. This program gives the capacity of the roadway, based on location of work, type of work, lane width, truck percentage, and number of open lanes. To determine work zone capacity, a detailed capacity analysis with the traditional method of maximum sustained flow rate was carried out based on identification of breakdown events. Maximum sustained flow rates were based on 5-, 10-, and 15 minute intervals. the average flow rates were 1406 and 1307 vphpl for the eastbound and westbound direction, respectively, which indicates the average maximum 15-minute sustained flow rate in the eastbound direction was higher than that in the westbound direction. The data collection period in the detailed capacity analysis was divided into uncongested and congested periods based on one-minute intervals at breakdown. Both mean queue discharge and breakdown flow rate can estimate Work zone capacity. The definition of breakdown flow is the traffic flow rate immediately prior to the onset of congestion, and that of mean queue discharge flow is the average traffic flow during congested queued conditions. Breakdown flow rate is a useful measure of capacity for predicting traffic congestion.

The Montana Department of Transportation requires a TMP for significant projects. They outline that a "Traffic Project Engineer if necessary for capacity issues" is suggested for this TMP. They do not outline what constitutes a capacity issue, but it can be assumed that it is when volume is greater than the capacity causing excessive delay. The also do not outline how to estimate the capacity in the work zone.

The Nevada Department of Transportation (NDOT) outlines in their Work Zone Safety & Mobility Implementation Guide that measures must be taken if the projected volume of the work zone exceeds the capacity of the work zone, but gives no way of calculating the capacity of the work zone. With this said, it seems that the method is left up to the engineer to determine, whether it is the HCM or some other method.

The New Jersey Department of Transportation (NJDOT) employs the same table as DelDOT. They also include adjustments that can be made based on the specific work zone and roadway. Their adjustment that is included is that the capacity (veh/lane/hour) can be increased by 100 when a Jersey barrier is protecting the work zone.

The New York State Department of Transportation (NYSDOT) requires analysis of both the capacity of a work zone as well as the queue formed. They do not specify a method for capacity but suggest that the HCM is a very useful tool. They outline how to calculate the queue analysis in referencing Chapter 2 of the FHWA's Publication Work Zone Road User Costs – Concepts and Applications.

To optimize an existing queue prediction spreadsheet tool and evaluate accuracy of metric of queue length prediction, the underlying logistic relationship among principal variables in the Oklahoma Department of Transportation (OkDOT) baseline spreadsheet was analyzed and the availability of a work zone queue prediction tools was examined. The calibration opportunity for improving work zone capacity estimation can better reflect actual conditions from this analysis. And the two other alternatives, the HCM 2000 version and the HCM 2000 hybrid version, are used into different work zone capacity models. However, for some special situations such as urban sites, severe weather, no model with sufficient data is to quantify their effects on work zone capacity and queue formation.

The Oregon Department of Transportation (ODOT) constructed web-based Work Zone Traffic Analysis (WZTA) methodologies to figure out the problem of lane closure restriction recommendations and construction delay estimates in 2010 (Jackson, Siromaskul, & King, 2010). Both lane closure restriction recommendations and construction delay estimates can lead to highway structure, maintenance, public utility work or relative incidence reaction. The idea of determining lane restrictions is directly considered from the following three factors: 1) the volume of traffic expected on the highway; 2) the maximum amount of traffic the highway can handle and still maintain a free flowing situation, also called Free Flow Threshold (FFT); 3) and whether the anticipated traffic volume is larger than the amount of traffic that allows for free flow movement. And then delay estimates are deliverable to the Project Manager and the Regional Mobility Liaison. ODOT uses Free Flow thresholds (FFT) for estimating the capacity of a work zone. The FFT defaults are shown below and the regions refer to different regions within Oregon. The values are based on "decades of experience observing Oregon work zones". ODOT also includes that circumstances specific to an individual project may require adjustments to these default values. Engineering judgment is the deciding factor in these adjustments.

The Rhode Island Department of Transportation (RIDOT) allows for the use of microsimulations software to be used in the estimation of capacity in a work zone. These include HCM-Based Software, QuickZone, and Microscopic simulation model. They consider a delay of over 15 minutes to be unacceptable for a work zone.

The South Carolina Department of Transportation (SCDOT) uses a table that classifies the type of impact that the project will have on the work zone. There are 4 types that range from significant to basic. Within the classifications, there are requirements that must be met for the closing of lanes on specific road classifications. In doing this, SCDOT is "backing into" assigning the capacity of roadways based on the impact of the project on the work zone.

The Tennessee Department of Transportation (TDOT) used the HCM to develop a table that relates the amount of open and closed lanes to the maximum allowable 2-way AADT for a 30 minute additional delay. It is differentiated by type of road. These numbers are averages. TDOT has adjustment factors for work zones that include signalized intersections. These simple adjustment factors allow for the numbers to be more flexible without much more complexity.

Virginia Department of Transportation (VDOT)'s report (2012) includes a table that outlines the number of states that use each method to assess work zones. The performance measures are: average queue length, maximum queue length, average delay, maximum delay, volume to capacity ratio, travel time, subjective rating of delay/congestion, and other. Of these, average queue length, maximum queue length, and volume to capacity ratio are all measures that use capacity to measure performance. VDOT itself acknowledges that within Virginia, there are a wide range of criteria used. The most used is travel times and maximum queue length.

Table 7: Work zone capacity values adopted by state DOTs

State	2 to 1	3 to 1	3 to 2	Two way one lane (TWOL)	TWOL (with median crossover)
Florida	1800 vph		3600 vph	1400 vph	
Wisconsin	1500 pcphpl	1500 vph	1500 pcphpl		1400 pcphpl
Nevada	1500-1600 pcphpl	1500-1600 pcphpl	1500-1600 pcphpl	1500-1600 pcphpl1500-1600 pcphpl	
Massachusetts	1500 vph	1500 vph	3000 vph	850-1100 vph	
Hawaii	1600 pcphpl	1600 pcphpl	1600 pcphpl	600-800 pcphpl	
Iowa	1450 vphpl		1450 vphpl		
New York	1800 pcphpl	1600 pcphpl	1700 pcphpl		
New Jersey	1300-1400 vphpl	1200-1300 vphpl	3000-3200 vphpl	600-750 vphpl	1200-1500 vphpl

Source: Analytical Methods for Deriving Work Zone Capacities from Field Data (Edara, Kianfar, & Sun, 2012)

The Washington State Department of Transportation (WSDOT) uses a table to estimate the "short-term lane closure work zone capacity". The table (Exhibit 1010-1) gives a vehicle per hour per lane based on roadway type (multilane freeways/highways, multilane urban/suburban, two-lane rural highway). The manual published by WSDOT acknowledges that this is a basic technique and that they are simply averages. It refers the reader to the Highway Capacity Manual for more information. For "long-term work zone capacity", WSDOT requires the use of traffic modeling software.

The work zone capacity values of found in the DOT surveys were higher than the field values observed in Missouri. The highest end capacity was Florida (1800 vphpl) and New York (1800 pcphpl) in the United States. Several states ranged around 1450 to 1600 vphpl or pcphpl such as Wisconsin, Nevada, Massachusetts, Hawaii and Iowa. Because truck factors cannot be unified to translate all reported capacity values into a uniform unit of pcphpl, the DOT surveys also exposed a variety of practice in reality among DOTs in estimating work zone capacity. Therefore, some DOTs used simulation with historical data, and some others used analytical tools to estimate work zone capacity.

As shown in ***Table 7*** and ***Appendix A***: Work zone capacity studies by the state DOTs, there is wide variability in the capacity values used for different types of work zone lane closures.

2.5 Overview of DelDOT policies and programs

The methods of estimating facility traffic volumes are variable between states. Even though Automatic Traffic Recorder (ATR) as the most accurate method can continuously count traffic, they are not always located extensively throughout a state. Especially, collecting data of using volumes over a short period of time as a basis for determining lane closure times is not extremely accurate.

Also, spot counts of using a seasonal factor and then an hourly factor are applied to a facility analysis, the resulting volumes generally do not accurately portray true segment volumes. Therefore, the variations to the policy are important to include that the surveyed states were fairly consistent in their identification of the circumstances and events that require identification and subsequent lane closure variation.

The changing for the regulation on “Traffic Safety in Highway and Street Work Zones” in Delaware based on the rule of work zone safety and mobility. The updated rule would address some issues, such as more work zones, growing traffic volumes and congestion, micro growth of roadway capacity, safety concerns of work zone, more performance of traffic and public frustration in work zones. Also, the updated rule would be able to ensure more reliable safety and better mobility around the work zones, and the implementation of management strategies would systemically evaluate their processes. Finally, the updated rule would provide one sufficiently flexible probability applied both current and future work zone issues.

These guidelines apply to all projects that occur on streets and the Department’s highways jurisdiction. This includes existing and new State roads, subdivision streets maintained by the Department. These guidelines should be significantly applied to all the new projects and all existing projects with a preliminary plan since October 12th, 2007. Determining whether a project is significant depends what level of detail is required in a Transportation Management Plan (TMP). Those non-significant projects also are required for a Traffic Control Plan (TCP). When the Capital Transportation Plan is updated each year, significant projects can be identified during its planning phase. Some significant projects will not cause disruption, even though they have involved lengthy closures or other major facilities. Project procedures shall be performed with the statewide planning phase, concept development phase, design phase, construction phase, and post-construction. Specially, the contents of concept development phase mainly perform the preliminary work zone, which impacts assessment, determine TMP needs, and identify stakeholder and begin public outreach. Design phase is to develop TMP, revise TMP, and finalize TMP.

Construction phase is to reevaluate TMP, implement TMP, monitor TMP, and update TMP. Post-construction is to determine TMP needs and Type B TMP components. A Work Zone Impacts assessment would be performed during the concept development and design phases for all projects that require a Type B TMP. The steps of Work Zone Impacts Assessment During the Concept Development Phase (Type B TMP Only) : 1) Compile Project Information; 2) Perform Preliminary Work Zone Impacts Assessment of Alternatives; 3) Analyze Potential Impacts; 4) Identify Potential Work Zone Management Strategies; 5) Compile Preliminary Work Zone Strategy. The steps of Work Zone Impacts Assessment During the Design Phase (Type B TMP Only) : 1) Compile Concept Development Material (Preliminary Plan Stage); 2) Reassess Work Zone Impacts (Semi-Final Plan Stage); 3) Analyze Work Zone Impacts (As Needed) (Semi-Final Plan Stage). 4) Develop/Recommend Final Construction Staging and TMP (Final Plan Stage). Last, work zone will impact the assessment report.

The process review will include the following steps for assembling a multi-disciplinary team with developing review objectives and methods, analyzing and interpreting results, and developing and prioritizing recommendations and lessons learned. Traffic control strategies, devices, and contracting/construction techniques and coordination will be contributed in facilitating traffic flow and safety around the work zones. Control Strategies includes various traffic control approaches of construction phasing, and full roadway closures. Control strategies also consider other factors of Lane shifts/closures, reduced lane widths to maintain number of lanes, one-lane, two-way operation, two-way traffic on crossover, reversible lanes, ramp closures/relocation, night work, weekend work, work hour restrictions for peak travel, pedestrian/bicycle access improvements, business access improvements, and off-site detours/use of alternate routes. Therefore, work zones need special traffic control devices safety devices: 1) temporary signs; 2) changeable message signs; 3) arrow panels; 4) channelizing devices; 5) temporary pavement markings; 6) flaggers and uniformed traffic control officers; 7) temporary traffic signals; 8) lighting devices (DelDOT, 2007).

2.6 A review of software developed to perform the work zone capacity analysis

Since many work zone capacity and analysis tools do not consider congestion characteristics such as queue length and delay, this section reviews software developed to perform the work zone capacity analysis and to help quantify queue length and travel delay times.

1. Spreadsheet-based models

Though microscopic simulation programs (e.g., CORSIM, FRESIM, QUEWZ, Quickzone, TSIS) are chosen for detailed data analysis, some literature shows that the simple, deterministic spreadsheet tools produce more accurate estimates of traffic impacts than the former ones (Edara & Cottrell, 2007).

Spreadsheets use a widely used procedure from the Highway Capacity Manual and analytical performance function equations, e.g., Bureau of Public Road (BPR) function, with calculations carried out in Microsoft Excel (Malaghan, 2014). A spreadsheet application is typically developed with the following input elements: (1) demand, (2) day-dependent capacity generated from a stochastic capacity distribution, and (3) static travel time functions. A wide range of travel time statistics can be derived from the traffic assignment results, such as the mean and variance of day-dependent travel times. *Figure 5* demonstrates how a spreadsheet model is operated for calculating travel time, user cost and user equilibrium. *Figure 6* and *Figure 7* describe two spreadsheet models used by Ohio DOT and MoDOT, respectively.

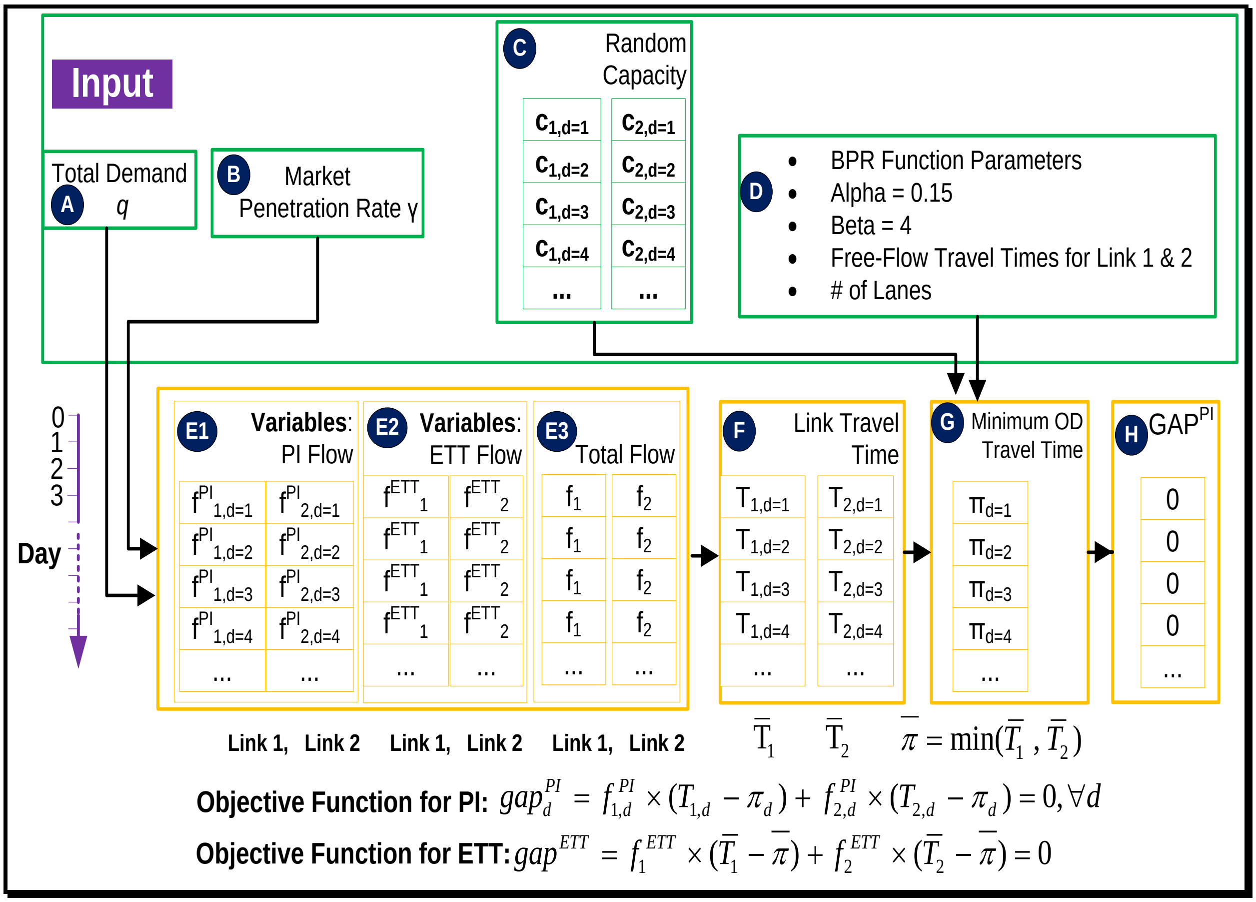

Figure 5: Spreadsheet-based calculation model for calculating user equilibrium

Source: (Li, Zhou, & Rouphail, 2011)

Ohio Department of Transportation

WORK ZONE SPEED ZONE EVALUATION SHEET

FOR HIGH-SPEED (≥55 MPH) MULTI-LANE HIGHWAYS

Rev. 1/16/15

(This form is not intended for use with Variable WZ Speed Zones (VWZSZs) using Digital Speed Limit (DSL) Sign Assemblies.)

Complete all areas in Green

ROUTE:	ww	DATE:		PROJ. NO.:	
COUNTY:		CITY/TWP.		PID:	
BEGIN STUDY AT:		END STUDY AT:			
LENGTH:	Miles	Existing Legal Speed Limit		MPH	

Pick Data From Data List Here		1	2	3	4	5	Factor
Access Points/Mile - Number of ramps intersecting mainline lanes within logical route segment divided by length of section (e.g., I-90 from I-77 to I-271). Includes both on and off ramps and Construction openings in the zone used by project vehicles.		>7	7 - 5	4 - 3	2 - 1	<1	
ADT/lane - Current AADT (weighted)/average number of through lanes in section during construction. Do not count weave or Collector\Distributor lanes. Express lanes are counted as through lanes. The value will be provided by ODOT.		>20K	20K - 14K	14K - 8K	8K - 4K	<4K	
Shoulder Width - Either the left or right, whichever is the narrowest.		< 3'		3' to 6'		> 6'	
Lane Width			9'	10'	11'	12'	
Is Barrier being used?		No				Yes	
Calculated Speed is = Total Factors / 5					**Total Factors**		0

MPH Reduction : ≤1.5 = 15 MPH, >1.5 to <3.6 = 10 MPH, ≥3.6 = 0 MPH)

Calculated Speed = ______ MPH

Restricted geometrics not addressed that may warrant an additional reduction to the "Calculated Speed" (also see the Work Zone Speed Zone Justification Report):

Reduction recommended by:		Date:		**Approved Speed Limit:**	**MPH**
Reviewed by (Speed Zone Coordinator)		Date:			

Figure 6: Ohio Department of Transportation work zone evaluation sheet

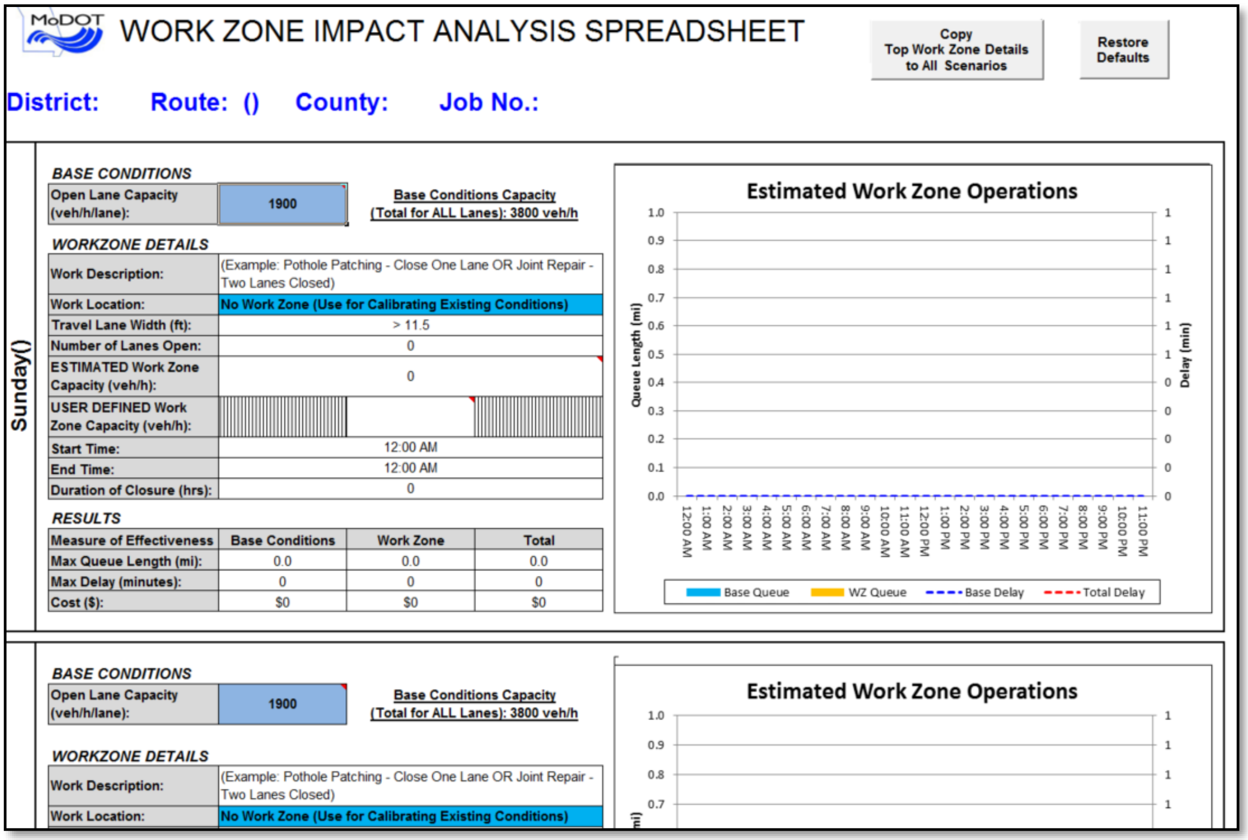

Figure 7: MoDOT Work Zone Impact Analysis Spreadsheet

2. QUEWZ-98

Queue and User Cost Evaluation of Work Zones (QUEWZ) [14] is a microcomputer analysis tool developed by the Texas Transportation Institute. QUEWZ-98 is the most recent version, which has been used by Texas DOT for evaluating capacity, speed, queuing delay and road user cost (RUC) in freeway work zone with or without lane closures.

3. FRESIM

Freeway Simulation (FRESIM) is a microscopic time-stepping simulation model within the CORSIM software for the analysis of incidents on freeways from various sources including lane closures, lane shifts, lane drops, or a shoulder incident. The software can calculate the queue length resulting from a lane closure but it requires calibration based on field data and knowledge of model parameters, process, and problem-solving strategies (Cheu, Jin, Ng, Ng, & Srinivasan, 1998; Chitturi & Benekohal, 2010).

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14 http://mctrans.ce.ufl.edu/test_downloads/free/quewz.zip

4. QUICKZONE

In order to facilitate DOTs to estimate and quantify work zone delays, FHWA has developed the QuickZone program, which is an open-source, comprehensive and highly detailed but data intensive analytical model (Curtis & Funderburg, 2003). QuickZone is composed of four major modules, namely Input Data, Program Controls, Output Data and Open/Save. In contrast to the simple HCM-based spreadsheets QuickZone requires knowledge of the complete network, including network with nodes links with their attributes, a complete description of the various work zone plans and capacity decrease of each affected link (Benekohal, Kaja-Mohideen, & Chitturi, 2003).

5. CA4PRS

CA4PRS[15] (Construction Analysis for Pavement Rehabilitation Strategies) is a knowledge-based computer simulation model designed to estimate road user delay cost due to work zone lane closures. The software was originally used to help highway agencies estimate the maximum probable length of highway pavement, balance construction scheduling, rehabilitation productivity and cost of agencies, as well as migrate traffic inconvenience (Lee & Ibbs, 2005; Lee, Harvey, & Samadian, 2005). CA4PRS can aid transportation departments and agencies in estimating working days, the capacity of work zones with lane closures, Critical Path Method (CPM) schedules, and traffic control plan etc.

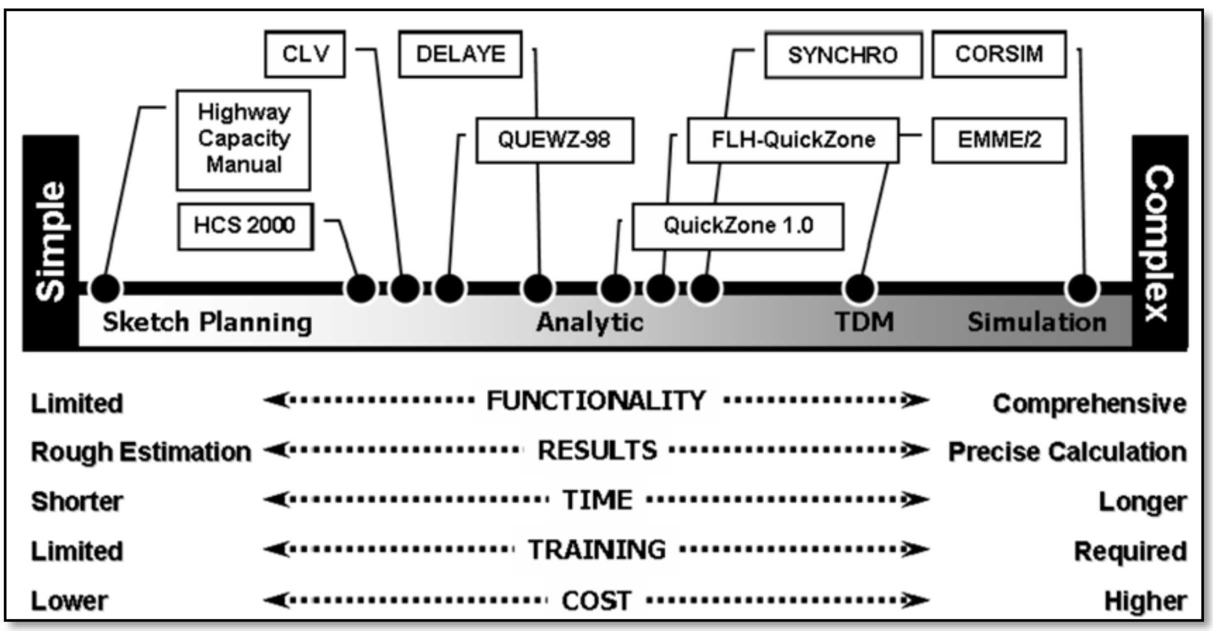

Figure 8: Summary of work zone modelling methods

Source: (Hardy, Larkin, & Wunderlich, QuickZone A Work Zone Delay Estimation and Analysis Tool, 2002; Ozbay & Bartin, 2008)

15 http://www.dot.ca.gov/research/roadway/ca4prs/index.htm

Ten popular tools used by traffic engineers at state DOT and highway agencies for estimating work zone in terms of availability of input data, model flexibility, ease of use and accuracy of estimates are listed in ***Figure 8*** ranging from simple to complex (Hardy, Larkin, & Wunderlich, 2002; Hardy, Larkin, Wunderlich, & Nedzesky, 2007; Ozbay & Bartin, 2008).

Chitturi and Benekohal (2004) compared the performance of FRESIM, QUEWZ 92, and QuickZone software with field data at 14 freeway work zone locations in Illinois. The results of the study showed that none of these models offered an accurate representation of real field conditions. QUEWZ 92 overestimated the capacity but underestimated the queue lengths. FRESIM consistently overestimated the speeds when there was no queuing at the work zones. QuickZone consistently underestimated the total delay since it does not take account of the delay due to slower speeds in the work zones.

Generally, macroscopic analytical approaches, macroscopic simulation approaches, and microscopic simulation approaches have their respective characteristics of both advantages drawbacks in estimating the traffic delay in work zones. Specifically, macroscopic analytical approaches are the simplest but lack of the accuracy of estimation. Compared to the other models, the CA model in the microscopic simulation approaches is more favorable to estimate traffic delay because this method not only can shorten computation time, but also increase the reliability and repeatability of data for estimating work zone traffic delay. However, current CA model does not consider the factor of the behavior to possibly change lanes. Both PARAMICS and VISSIM as the microscopic simulation software also are frequently applied into estimating traffic delay since they provide a better function in desiring the dynamic vehicle and driver behavior. The integration and parallelization of macroscopic analytical models and microscopic simulation software will be studied for improving computation efficiency through a fast dynamic and agent-based traffic simulation.

2.7 Summary of literature review

Considerable effort has been done in the area of work zone capacity estimation. This section presents a thorough and comprehensive literature review focusing on existing numerical and analytical approaches for estimating work zone capacity. Many computer models do not consider congestion characteristics such as queue length and delay (Heaslip, Kondyli, Arguea, Elefteriadou, & Sullivan, 2009; Karim & Adeli, 2003).

Table 8 shows the summary of the survey conducted by the Virginia Transportation Research Council in December 2005 through January 2006 regarding the current practices used by nineteen states for determining the capacity value at work zone bottlenecks and the current practices performed by ten more states compiled by Edara and Cottrell (Edara & Cottrell, 2007). The experience of the DOT staff and HCM-based spreadsheets and highway capacity Software are the most popular tool for determining the capacity at work zone bottlenecks among DOTs.

From this review, it is difficult to establish whether one analysis tool is better than another in terms of estimating the impact of lane closings and reduced capacity of work zones on the traveling public and goods movement, because all have strengths, weaknesses, limitations, scopes and requirements for the various traffic analysis project types and different locations.

Table 8: Current practices for assessing work zone traffic impacts

State	Tools Used for Estimating Capacity	Queues and Delays
Alabama	N/A	Oklahoma DOT Spreadsheet
Arizona	N/A	QUEWZ
Arkansas	N/A	QUEWZ
California	Experience and HCM	Spreadsheet based on HCM
Colorado	Guidelines in the "Lane Closure Policy" document	Synchro/Sim Traffic and HCS
Delaware	HCM	Delaware Transportation Model, HCS, Synchro, CORSIM
Florida	Chapter 10 of FDOT's Plan Preparation Manual and HCS 2000	
Hawaii	HCM	• HCM and experience • QuickZone in the future
Illinois	HCS 2000, SIG/Cinema, HCM, and QUEWZ	HCS 2000, SIG/Cinema, HCM-based Spreadsheet, QuickZone, and QUEWZ
Indiana	HCM	QUEWZ, QuickZone, Synchro, CORSIM
Kansas	None Experience, if any	None
Kentucky	Experience, no formal procedure	• No formal procedure • Rare use of CORSIM
Maine	Experience and HCM 1994	• Spreadsheet and Synchro/SimTraffic for partial closures • TRIPS (Travel Demand Model) for full closures of bridges or highways
Maryland	MD-QuickZone (modified QuickZone) using HCM Value or University of Maryland Model or any user defined value	MD-QuickZone (modified QuickZone)
Massachusetts	Start with base capacity value and apply adjustment factors for lane widths, truck percentages, grades, etc. (similar to HCM)	• Spreadsheet model (BASICQUE) based on 'Planning and Scheduling Work Zone Traffic Control' publication of FHWA (Chapter 2, page 15), published in 1981 • Also use QuickZone, TRANPLAN for complex projects
Montana	No estimation	HCM, if used
Nevada	HCM 2000	• Currently Synchro, CORSIM, HCM • QuickZone in the future
New Jersey	HCM 1994	Spreadsheet based on HCM
Ohio	QUEWZ-98	Ohio DOT Spreadsheet
Oklahoma	N/A	Spreadsheet based on HCM

State	Tools Used for Estimating Capacity	Queues and Delays
Oregon	• Currently experience • Actual traffic counts in future	• Currently CORSIM • Aim to develop graph from CORSIM results and validate it with field data
Pennsylvania	N/A	Actively using QuickZone
Rhode Island	HCM 1997	• Mostly HCM and experience • Occasionally QuickZone
Tennessee	Mix of actual traffic counts and HCM procedures	Web-based Queue/Delay Prediction Model under development
Texas	QUEWZ	QUEWZ and CORSIM
Utah	N/A	DELAY Software for small projects, MINUTP (comprehensive planning model) for large projects
Washington	Mix of actual traffic counts and HCM procedures	• Primarily QUEWZ • Limited use of QuickZone
Wisconsin	Experience and literature	Mainly spreadsheet based on HCM, but occasionally CORSIM and QuickZone
Wyoming	HCM and Synchro	HCM and Synchro

Source: (Edara & Cottrell, 2007). Note: Survey conducted in December 2005 through January 2006 is indicated in bold.

3 METHODOLOGY

3.1 Work zone capacity freeway

Currently, the methods of maximum sustained flow, re-scaled cumulative flow curves, and the 85th percentile traffic flow have used to determine work zone capacity. The maximum sustained flows reduced as the aggregation interval from 5 to 15 minutes. The queue discharge flow (QDF) values were the most conservative method to estimate capacity. The result by the method of 85th percentile flows was usually lower than the 15-min sustained flow values. The pre-queue flow (PQF) values, indicative of near-constant flow prior to breakdown, were not suitable to any of the four work zones tested. When traffic flow does not exceed the work zone capacity, it is more difficult to estimate true value of work zone capacity. Hence we propose a new methodology to determine work zone capacity distribution based on the probabilistic speed-flow-density relationships.

3.1.1 Data collection

As previously mentioned, a constant value does not practically reflect the work zone capacity, the means of a probability distribution will be researched to deliver the true value of work zone capacity. Therefore, one new methodology respectively modeled under the uncongested and congested traffic conditions was proposed to determine work zone capacity distribution based on the probabilistic speed-flow relationships with the lognormal distribution of random variables. In this section, we use a data set for a bottleneck at the I-5 freeway corridor, Los Angeles Area (***Figure 9***) to calibrate statistical distributions of capacity (long-term capacity in the static traffic assignment model and queue discharge rate in the point-queue model) and incoming demand flow rates.

The reason for selecting these particular locations for work zone capacity analysis was that Los Angeles has the worst percentage of bottlenecks, according to Unclogging America's Arteries (2015) released by the American Highway Users Alliance, a study of performance using observed vehicle speed data from 2014. It has 11 of the top 30 worst areas in the United States, six of them among the top 10. The I-5 Freeway in Los Angeles has been rated as California's most congested, according to data analyzed by the California Department of Transportation (California Department of Transportation, 2014).

The California Department of Transportation (Caltrans) implement the closures May 26-30, 2015, as part of a project that is constructing carpool lanes on I-5 between SR-170 and SR-118 and a carpool lane connector at the I-5/SR-170 interchange (***Figure 9***). There were freeway closures for striping and installations of loop detectors from 11:59 p.m. to 4 a.m. Signed detours were provided. Two lanes of Northbound I-5 between Sheldon Street and Paxton Street were closed from 10 p.m. to 5 a.m. To calibrate queue discharge rates, the volume, speed and occupancy data are extracted from the Performance Measurement System (PeMS) (2016) covering from 05/18/2015 to 06/05/2015 (***Figure 10***).

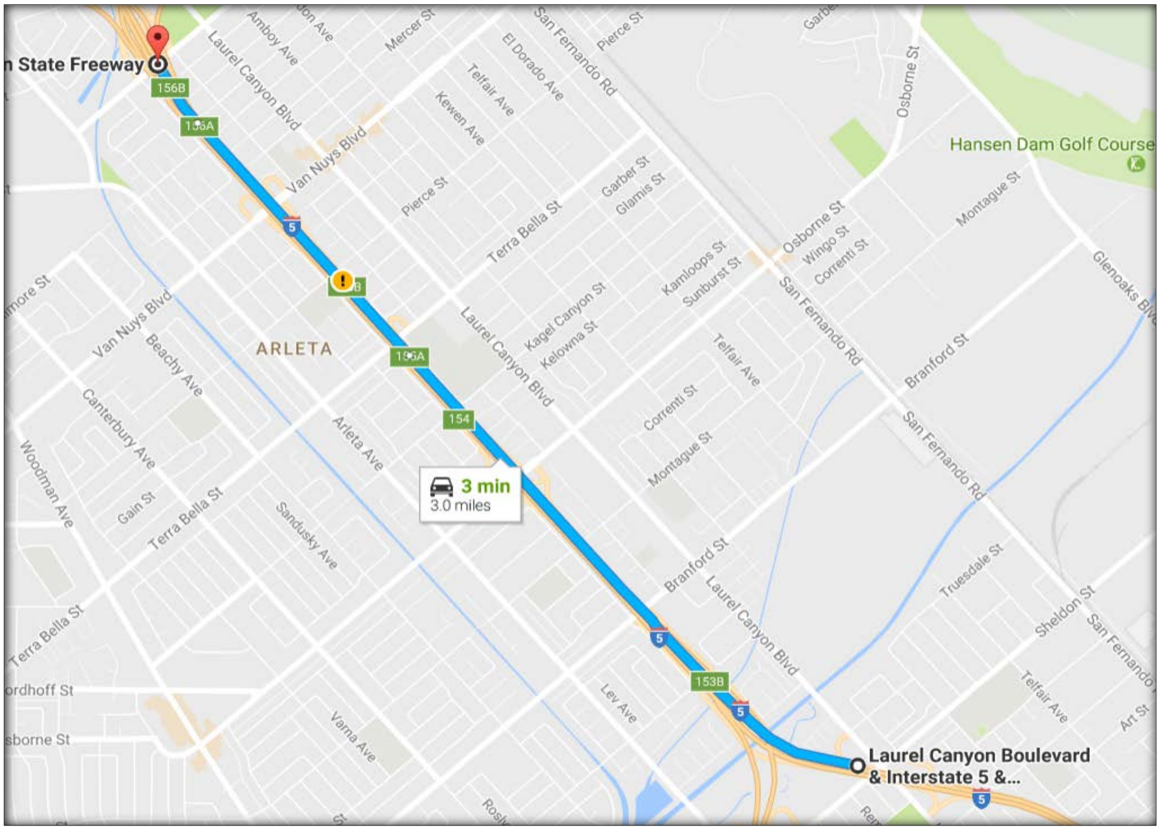

Figure 9: Work zone on the I-5 corridor study site
(Base map source from Google Map at https://maps.google.com)

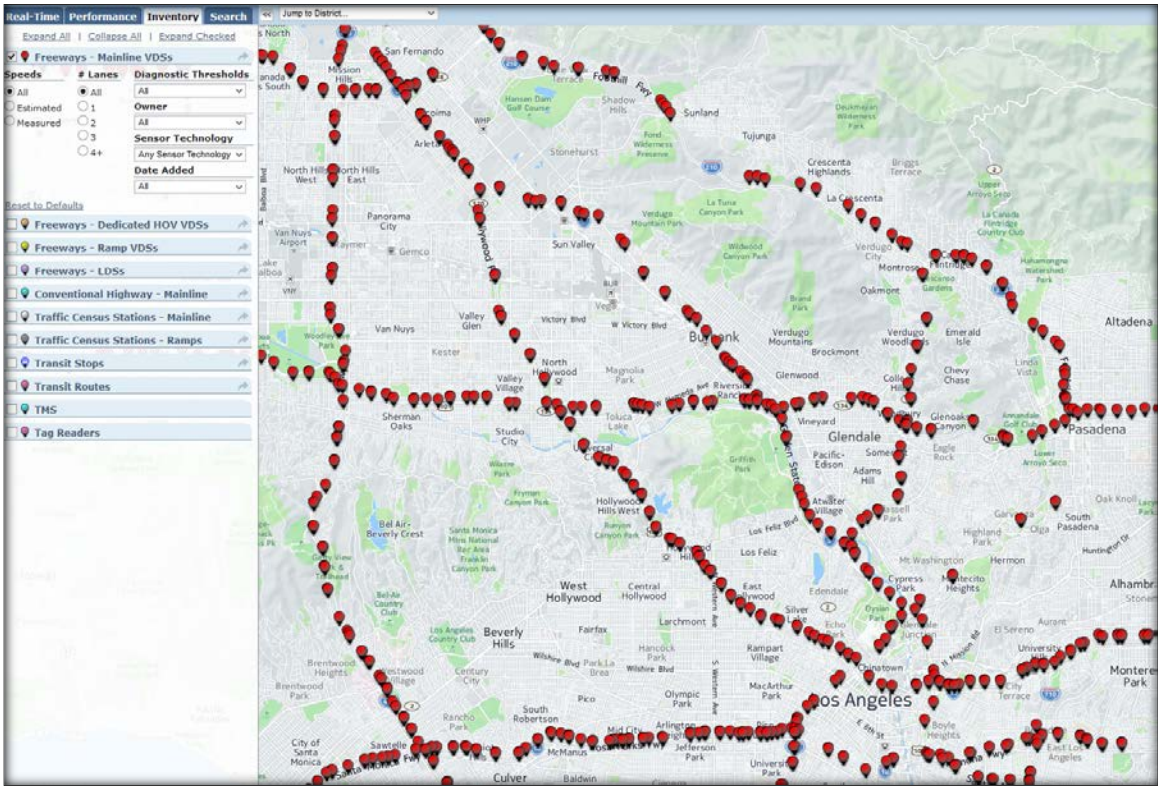

Figure 10: Map of the PEMS traffic monitoring network in Los Angeles Area

The data used for this study consisted of five days of five-minute intervals detector data for seven locations along I-5 work zone between Sheldon Street and Paxton Street, as depicted in ***Figure 11***. The data used for this analysis also covers five-minute intervals for the non-work zone period between 05/18/2015 through 05/25/2015 and between 05/31/2015 through 06/05/2015.

Data processing consists of converting the mixed volumes to passenger car equivalents (PCE) and the calculation of local density using the equation given by (May, 1990):

$$k = \left(\frac{52.8}{L_v + L_d} \right) \times \%OCC \tag{8}$$

Where:
k = density (pc/mile)
L_v = average vehicle length (feet)
L_d = detection zone length (feet)
% OCC = percent occupancy

In this case study, we use a dataset with information about bottlenecks at the Interstate 5 (I-5) freeway corridor to calibrate statistical distributions of capacity (long-term capacity in the static traffic assignment model and queue charge rate in the point-queue model) and incoming demand flow rates. The freeway stretch under consideration is 2.7 miles long and has a total of six detector stations, spaced out at approximately 0.45 mile intervals. Through a mixture of sensors installed at fixed permanent locations, these stations collect and store the following measurements:

a) Volume (Vehicle count categorized by vehicle class in the 5-minute interval).

b) Lane-occupancy (percentage of the 5-minute interval), and

c) Average speed (of all vehicles passing over the sensor in the 5-minute interval).

The data used for this study consisted of five days of detector data for these seven locations along Interstate 5 in Los Angeles Area. ***Figure 11*** shows the location of the sites. More detailed information about each site is given in ***Table 9***. The time series plots for all sites are given in Appendix A.

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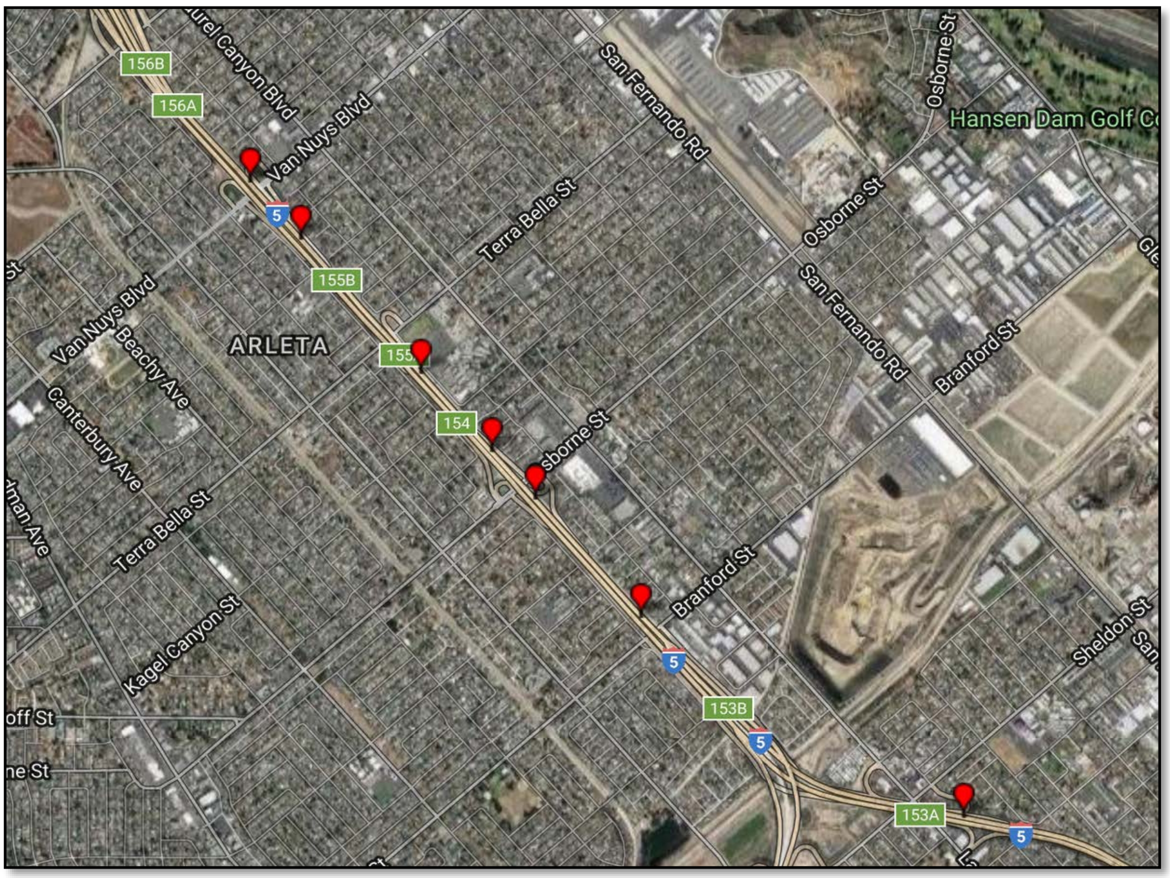


Figure 11: Location of sensors on the I-5 corridor study site [16,17]

16 Work zone schedule: District 7 Planned Lane Closures, http://www.lcswebreports.dot.ca.gov/lcswebreports/SearchPreAction.do?district=7

(Base map source from Google Map at https://maps.google.com)

Table 9: Detailed information about each sensor location

Sensor ID	Latitude	Longitude	URL	# of Lanes
768655	34.257090	-118.435212	http://pems.dot.ca.gov/?station_id=768655&dnode=VDS&content=sta_cfg	4
768664	34.254804	-118.432792	http://pems.dot.ca.gov/?station_id=768664&dnode=VDS&content=sta_cfg	6
768682	34.249318	-118.427068	http://pems.dot.ca.gov/?station_id=768682&dnode=VDS&content=sta_cfg	6
718092	34.246140	-118.423735	http://pems.dot.ca.gov/?station_id=718092&dnode=VDS&content=sta_cfg	6
718389	34.244193	-118.421690	http://pems.dot.ca.gov/?station_id=718389&dnode=VDS&content=sta_cfg	6
764156	34.239405	-118.416632	http://pems.dot.ca.gov/?station_id=764156&dnode=VDS&content=sta_cfg	4
717000	34.231273	-118.401340	http://pems.dot.ca.gov/?station_id=717000&dnode=VDS&content=sta_cfg	4

Table 10: Roadway information

Barrier	Concrete Barrier w/Glare Screen
Design Speed Limit	70 mph
Functional Class	Principal Arterial W/ C/L
Inner Median Type	Paved - No Roadway Use
Inner Median Width	22 ft
Inner Shoulder Treated Width	10 ft
Inner Shoulder Width	10 ft
Lane Width	12.0 ft
Outer Shoulder Treated Width	9 ft
Outer Shoulder Width	9 ft
Population	Urbanized
Road Width	84 ft
Roadway Use	Auxiliary Lane
Surface	Concrete
Terrain	Flat

[17] Sensor location information: http://pems.dot.ca.gov/?fwy=405&dir=N&dnode=search&content=cnt_search&center=33.9700145%2C-118.103278&view=e#34.246273,-118.422446,15

Accurate and reliable traffic data acquisition is still a major concern for transportation practitioners and researchers investigating data on the basis of real cases. To this end, preliminary analysis was first conducted to check the data quality and to make sure that the collected data reveals a consistent and reasonable pattern. One of the most commonly used approached is to investigate the scatter of individual links' fundamental diagram (FD) and the three state road traffic variables (speed, flow, density) to describe the traffic flow dynamics (Edie, 1961; Herman & Prigogine, 1979; Kühne & Gartner, 2011). ***Figure 12*** and ***Figure 13*** show the fundamental diagrams, which reflect the fundamental car-traffic speed-flow-density relationship that are used in this study as an indicator of the data quality.

A numerical experiment is performed according to the following procedure:

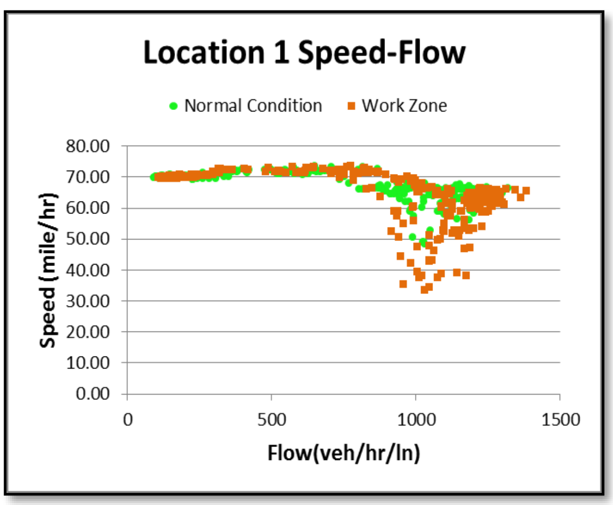
Step 1: Check reasonableness.

Step 2: Estimate capacity, demand, and travel time distributions.

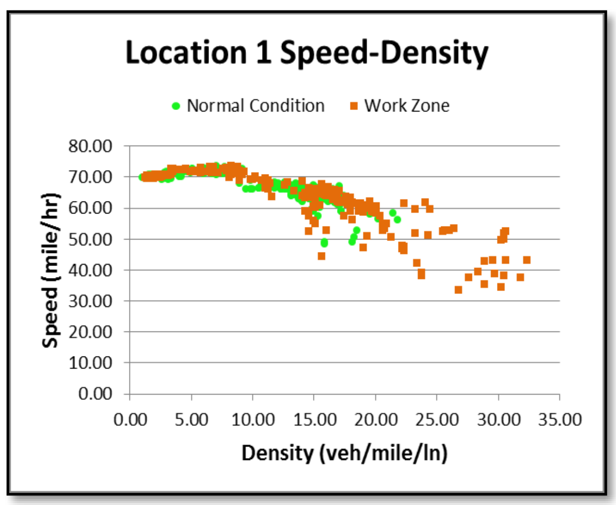
Step 3: Test if the total travel delay can be characterized through statistical distributions (e.g., log-normal distribution, Weibull distribution, etc.) based on stochastic demand and capacity data.

Step 4: Verify the linear relationship between mean travel delay, space headway, queue length and their standard deviations.

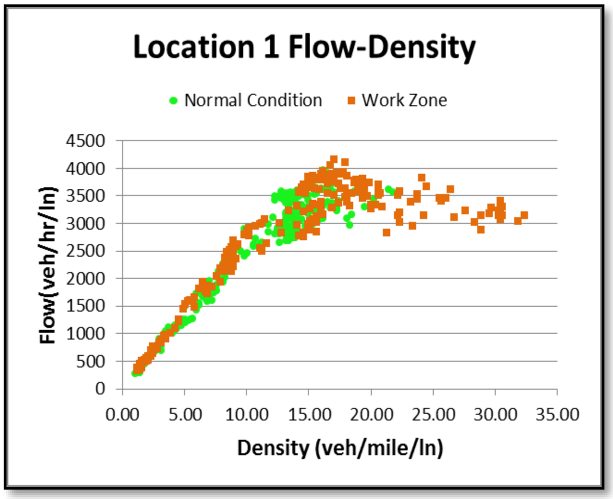
3.1.2 Check the data quality



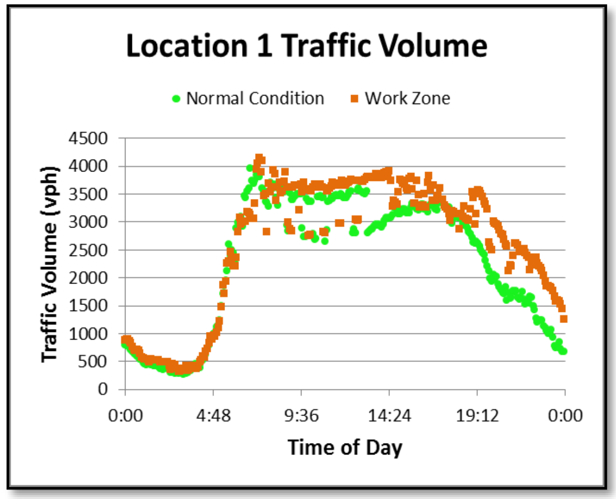
(A)



(B)



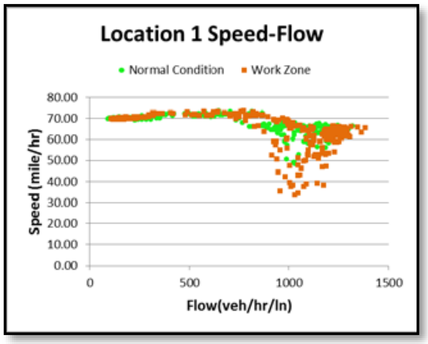
(C)



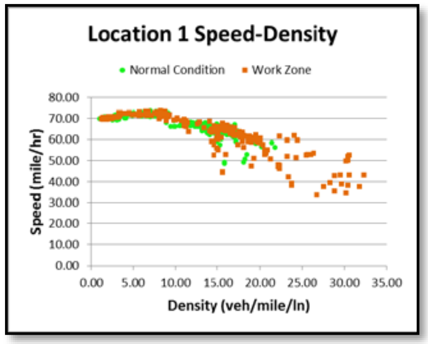
(D)

Figure 12: Field data plots for location 1

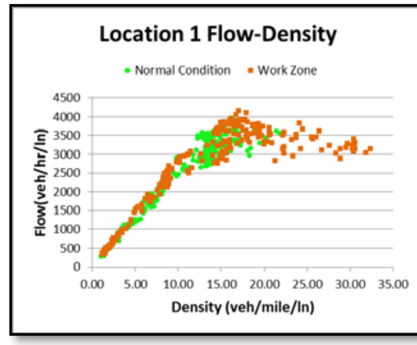
Data quality is a significant concern in traffic data archiving (Turner, Albert, Gajewski, & Eisele, 2000; Weijermars & Van Berkum, 2006). *Figure 13* shows the fundamental diagrams (FD), which reflect the fundamental car-traffic speed-flow-density relationship that are valuable in building confidence in the quality of our analysis data. The complete speed flow time series plots for all 6 sites in LA area are given in Appendix B.



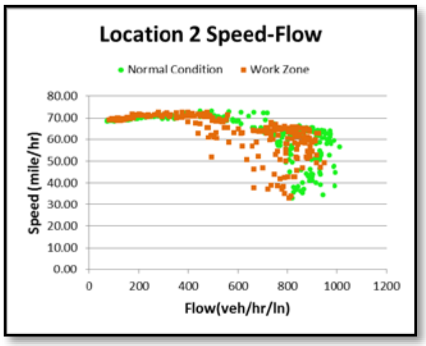
A1



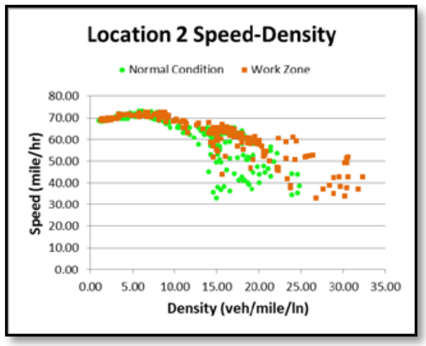
B1



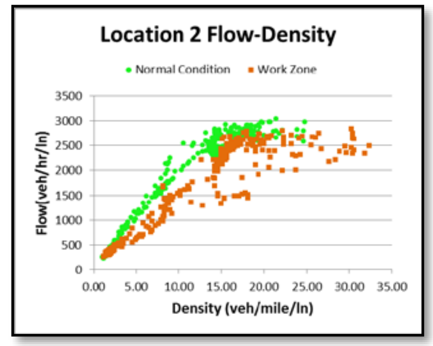
C1



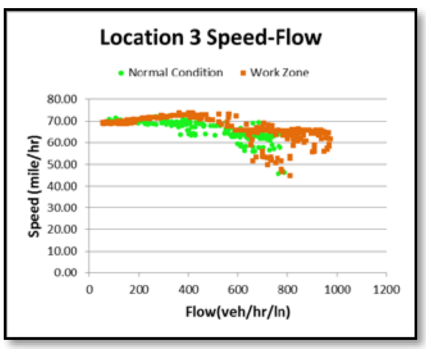
A2



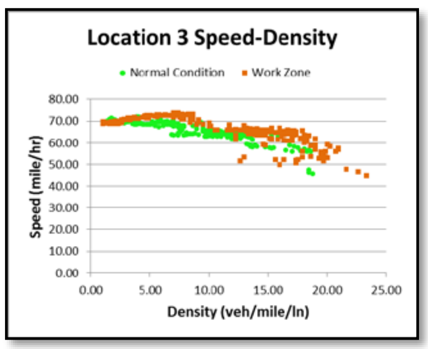
B2



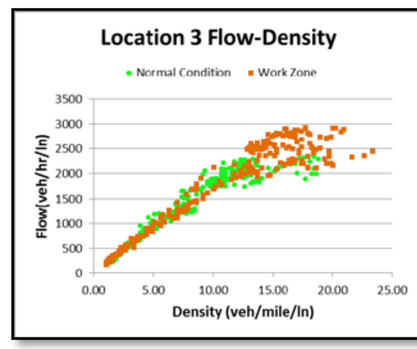
C2



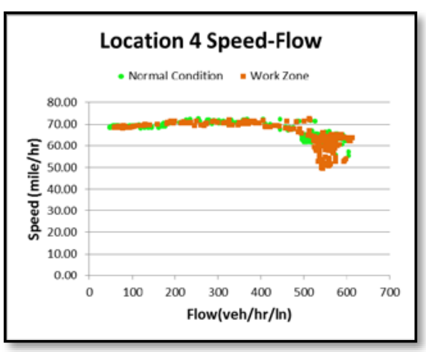
A3



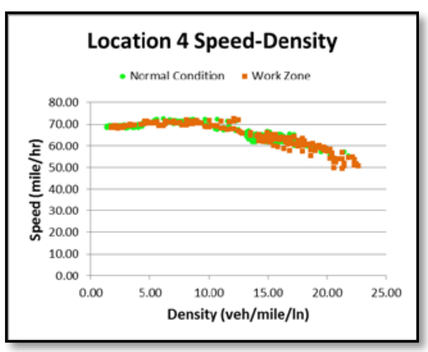
B3



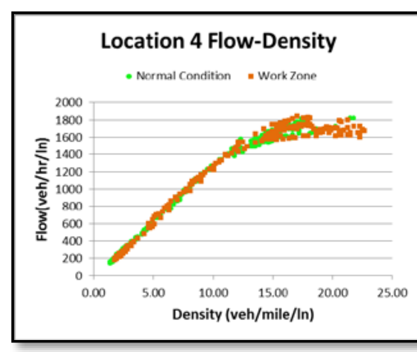
C3



A4



B4



C4

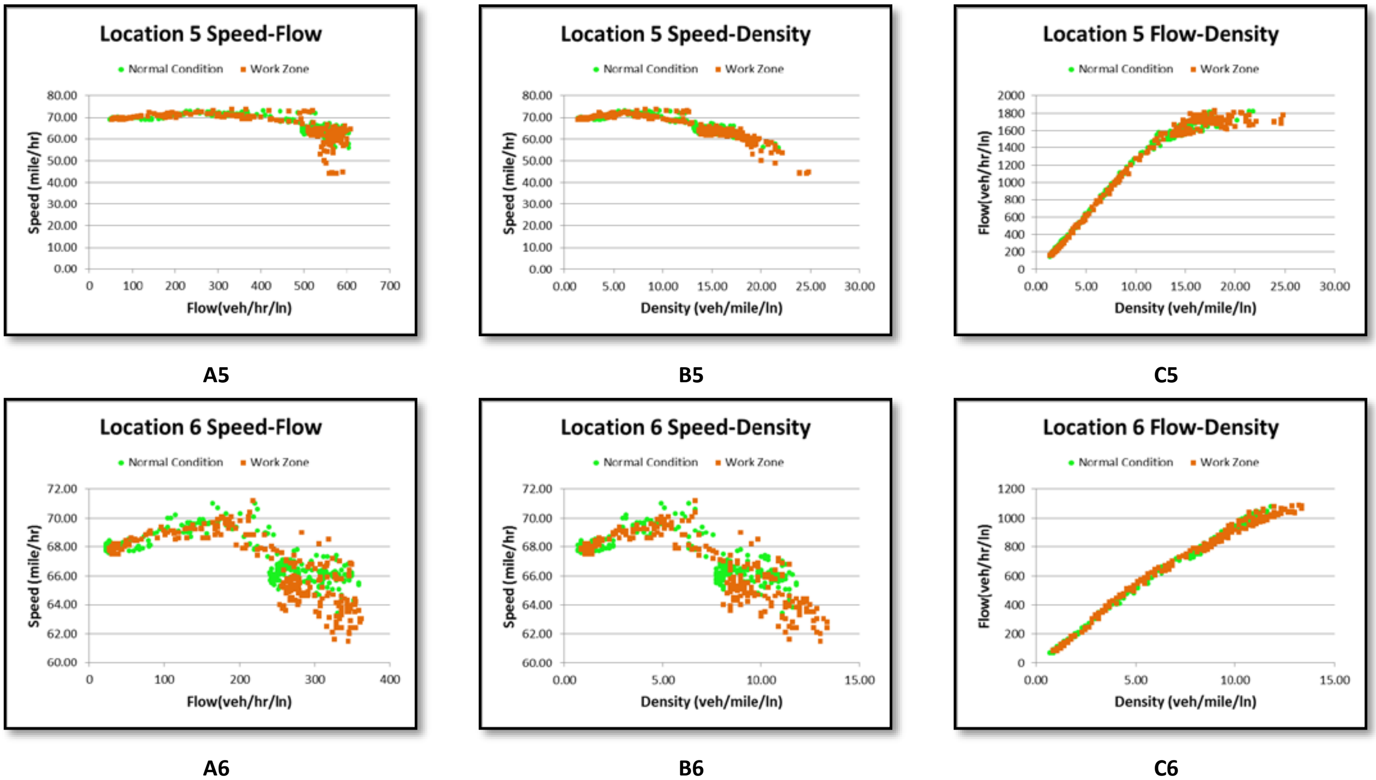


Figure 13: Field data plots showing the fundamental diagrams

3.1.3 Estimate capacity, demand, and travel time distributions

The queue discharge rates after the breakdown are provided by Jia et al. (2010), we can obtain a shifted log-normal distribution with the following probability density function (*Figure 14*). Further, to avoid site specific bias, a probability distribution was estimated independently for each site. *Figure 15* shows the log-normal probability density function for demand flow rate distributions. *Figure 16* illustrates the travel time index (TTI) distribution, which is defined as the measure of travel time index (TTI) is defined as a ratio of travel time /FFTT.

The 15-minute queue discharge rate after the breakdown is described in Jia et al. (2010). We can obtain a shifted log-normal distribution with the following probability density function (Eq. 2). The detailed definitions of pre-breakdown flow rates and queue discharge rates are provided in the paper by Jia et al. (2010).

$$f_X = (r; \mu, \sigma) = \frac{1}{(x-\gamma)\sigma\sqrt{2\pi}} e^{-\frac{[\ln(x-\gamma)-\mu]^2}{2\sigma^2}}, \quad x > 0 \qquad \text{(Equation 9)}$$

where

x = random variable

γ = the shift parameter

μ = the mean of the variable's natural logarithm, and

σ = the standard deviation of the variable's natural logarithm.

The statistical analysis in some existing empirical studies, e.g., (Brilon, Geistefeldt, & Regler, 2005) and (Brilon, Geistefeldt, & Zurlinden, 2007) indicated that the probability of freeway breakdown follow a Weibull distribution (Eq. 3) or lognormal distribution (Zhou, Rouphail, & Li, 2011; Li, Zhou, & Rouphail, 2016; Li, Rouphail, Mahmoudi, Liu, & Zhou, 2017). The Probability density function for stochastic queue discharge rate is illustrated in Figure 8.

$$F(x) = 1 - e^{-\left(\frac{x}{b}\right)^{a}}$$ **(Equation 10)**

where

a = shape parameter

b = scale parameter

x = flow rate (veh/h)

F(x) = (cumulative) probability of freeway breakdown at flow rate x

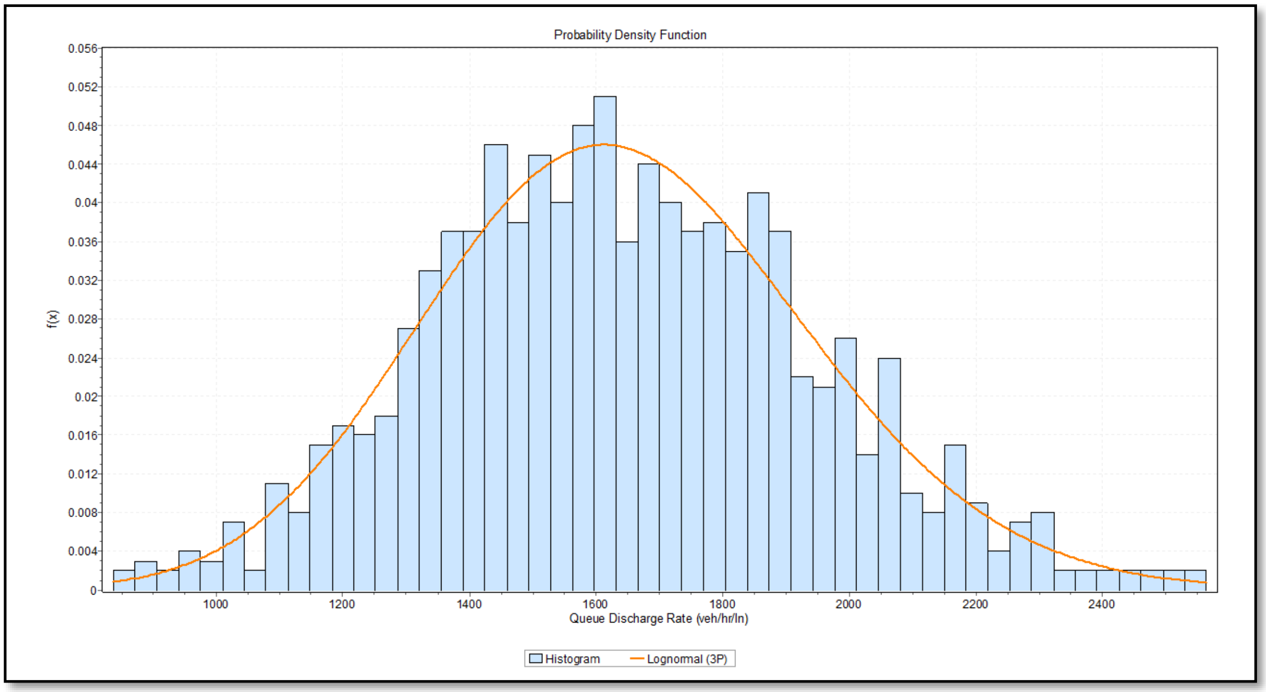


Figure 14: Probability density function for queue discharge rate

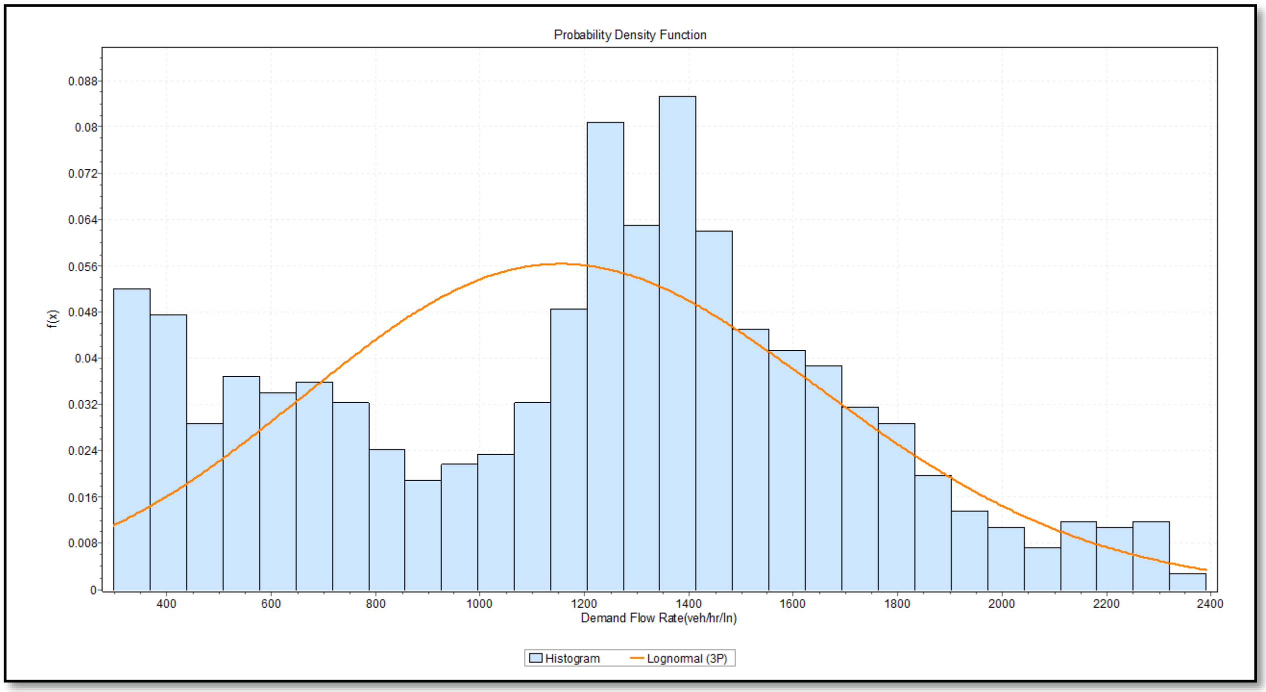


Figure 15: Probability density function for demand flow rate distributions

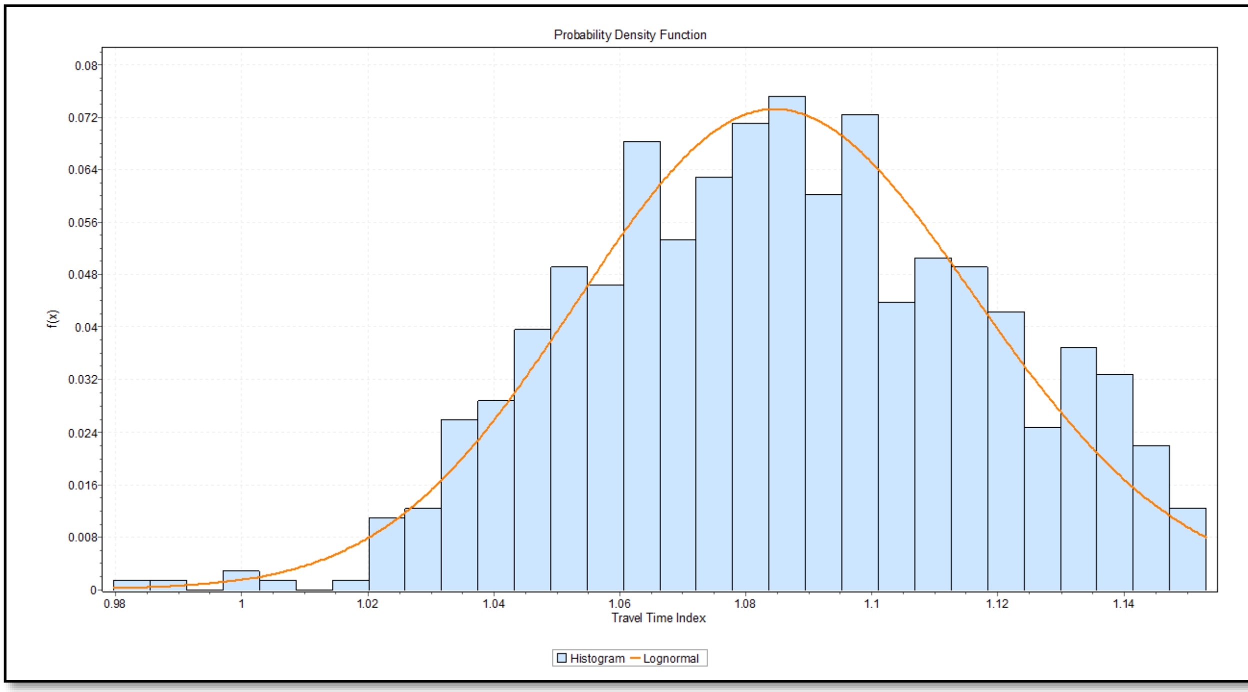


Figure 16: Log-normal probability density function for travel time index

3.1.4 Verify the relationship between the most important MOEs

This section verifies the linear relationship between mean travel delay, space headway, queue length and their standard deviations. The plot of actual versus predicted travel time to all downstream locations is presented in ***Figure 17***, which substantiate visually the linear relationship of the dependent variable with all independent variables (density, queue length and flow rate) that are used in the point queue models. As reported, the R^2 is greater than 80 percent at all locations (ranging from 0.83 to 0.99) and is high enough to explain the linear relationship. Results for all the regression models are statistically significant at a probability <0.05 for all variables.

Note that, instead of using travel time, we use the distance-weighted travel time rate (in minutes per mile), an important measure of traffic performance to exclude the variability caused by trip distance (Richardson & Taylor, 1978; Mahmassani, Hou, & Saberi, 2013). The standard deviation and mean travel time rate are computed for every 5 minute interval based on real-data. ***Figure 18*** shows a robust linear relationship between the mean travel time rate and its standard deviation (R^2 = 0.99 for 10% sample data; R^2 = 0.97 for 100% sample data).

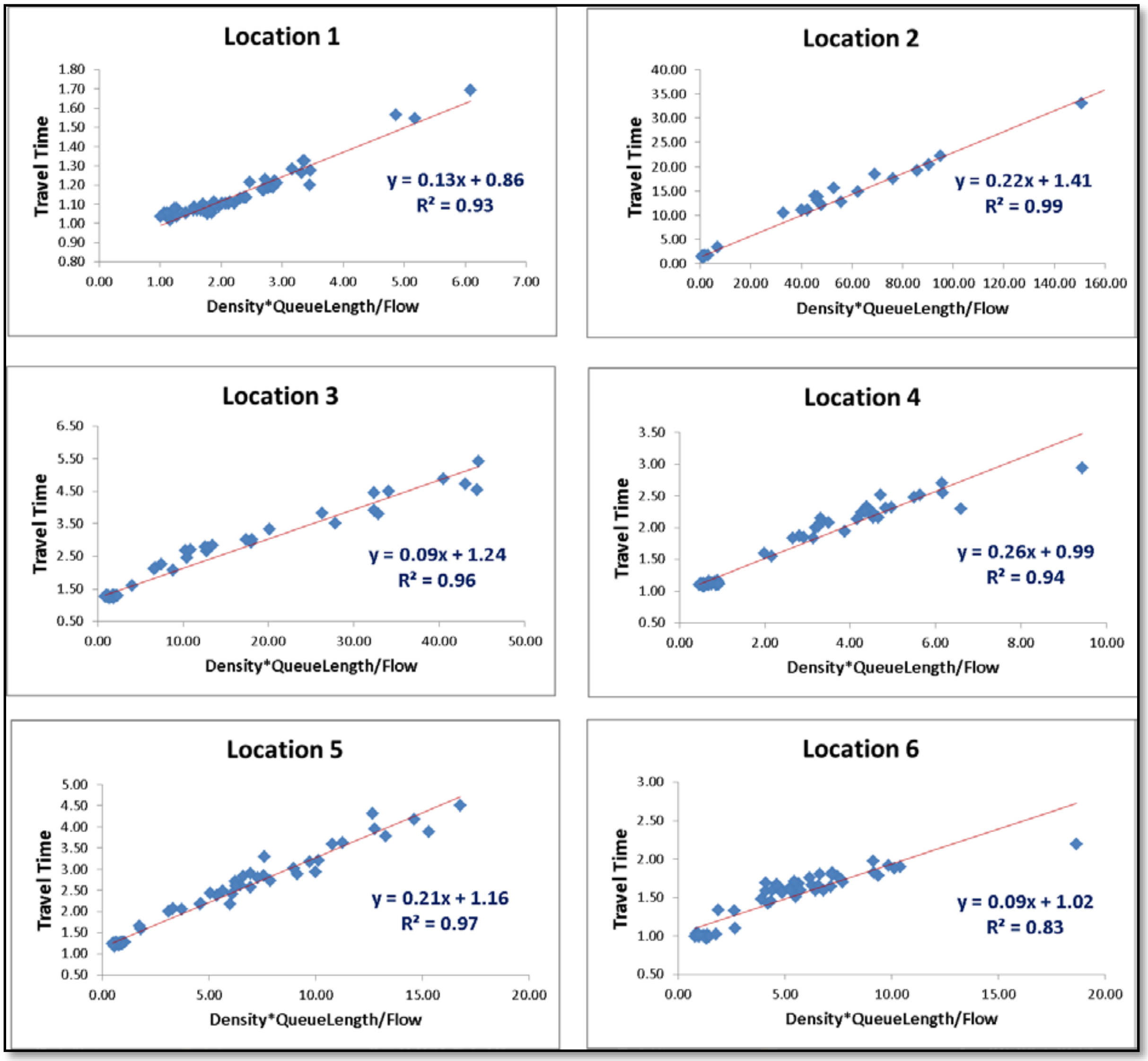


Figure 17: Linear relationship of the travel time based on the point queue model

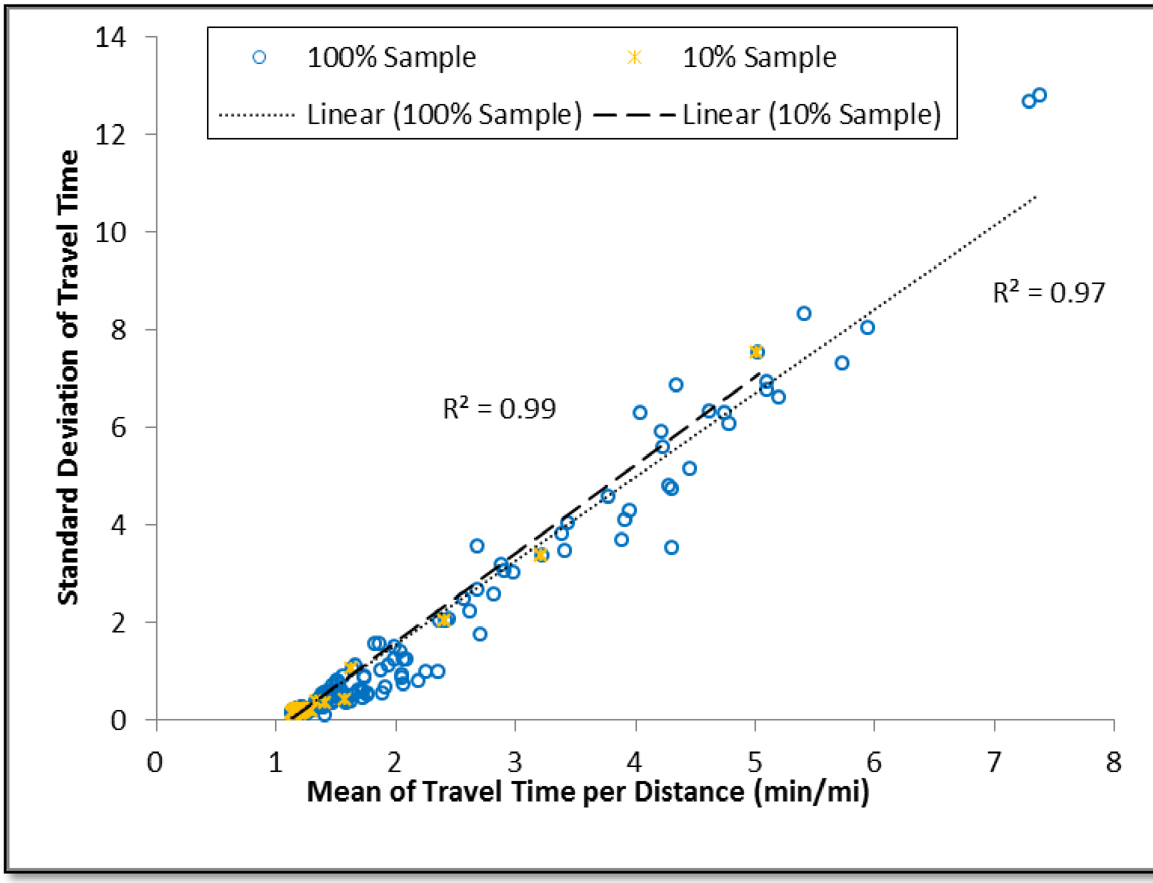


Figure 18: Mean travel time rate and its standard deviation

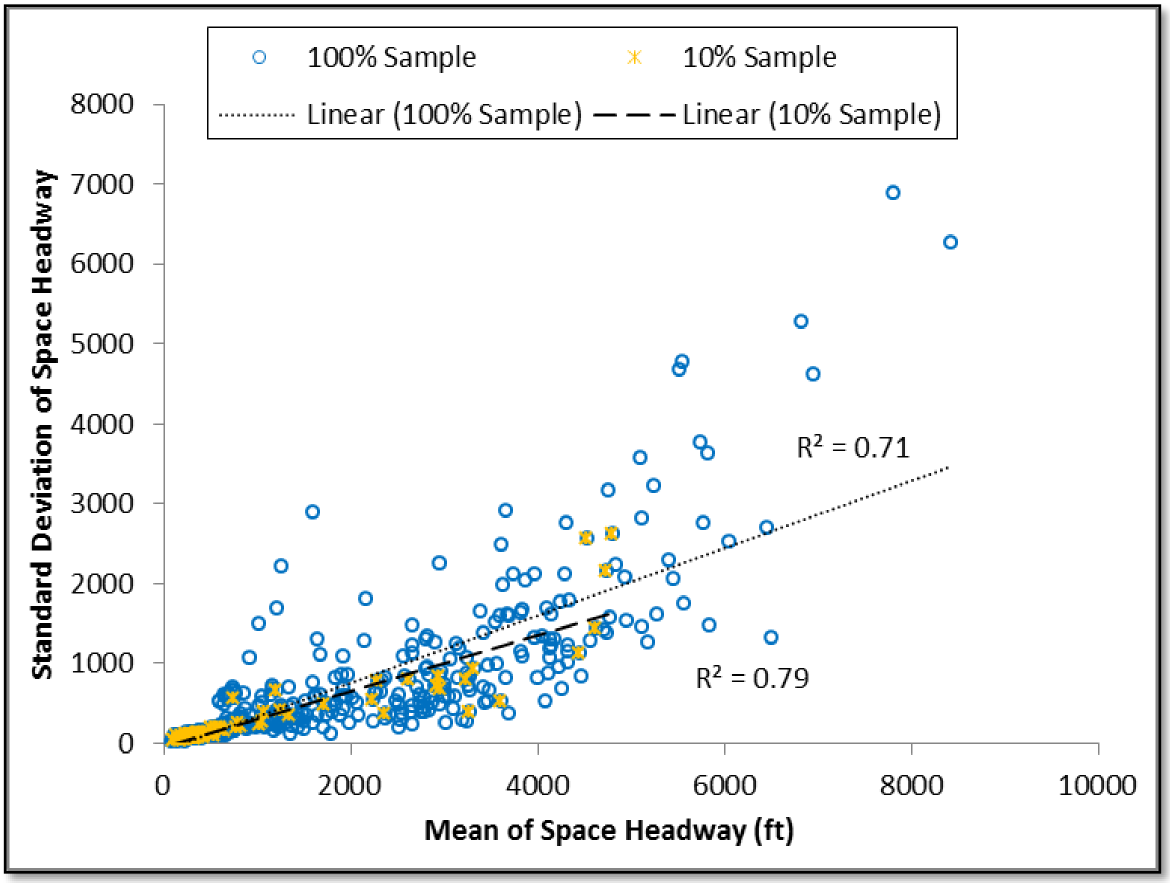


Figure 19: Mean space headway and its standard deviation

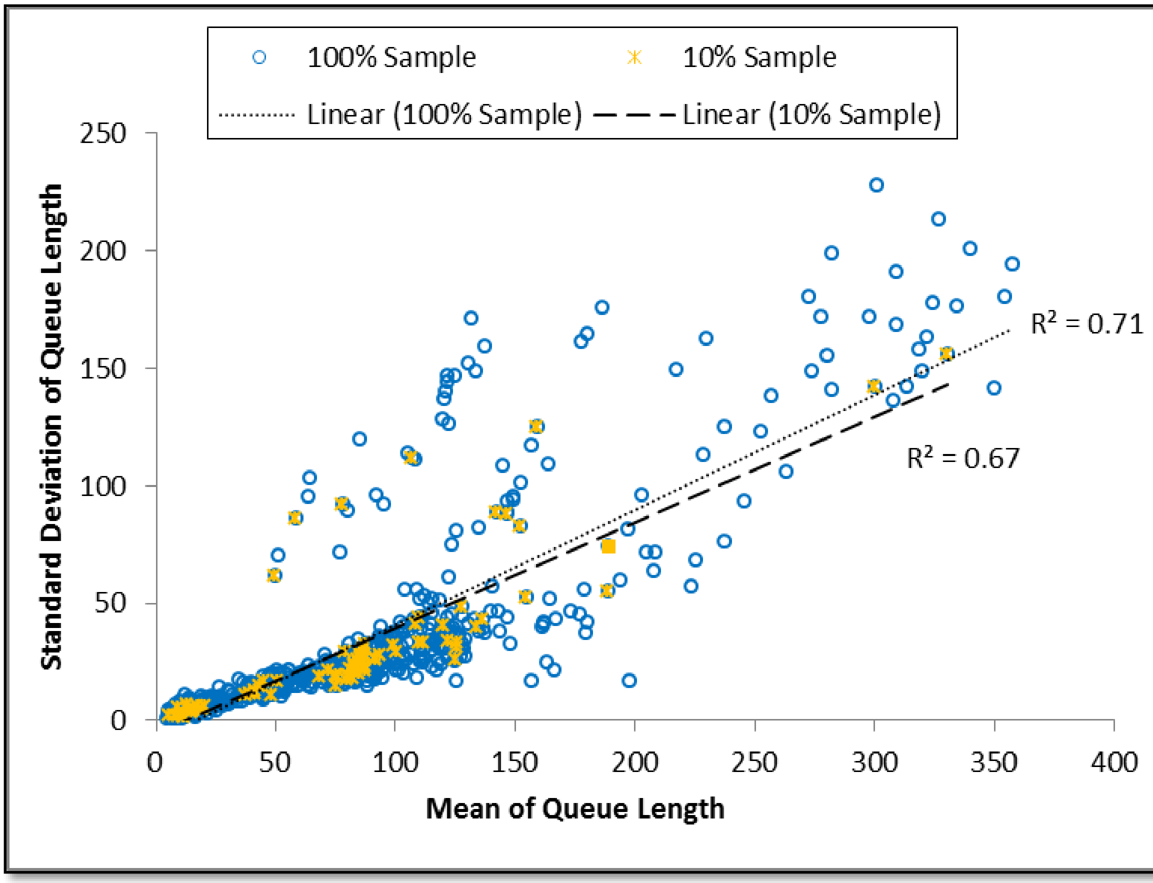


Figure 20: Mean queue length and its standard deviation

Although the relationship between the standard deviation and mean of space headway was apparently linear (*Figure 19*), the coefficient of determination (R^2 = 0.79 for 10% sample data; R^2 = 0.71 for 100% sample data) were both smaller than for standard deviation and mean of travel time per distance. Similarly, the results in *Figure 20* shows that there is a significant linear relationship between standard deviation of queue length ($P < .001$), although the data appear to be more scattered with a lower coefficient of determination in regression (R^2 = 0.67 for 10% sample data; R^2 = 0.71 for 100% sample data).

3.2 Work zone lane capacities along multilane signalized corridors in Delaware

A recent literature review was performed within the DelDOT Traffic Safety section to investigate other states' methods for determining work zone lane capacities, and it was determined that Delaware's values are fairly conservative when compared with those used by several other states. A recommendation from the study was to develop a Delaware-specific table representing these work zone lane capacity values for both interrupted and uninterrupted facilities.

3.2.1 Data collection

Sites selected for evaluation differed on types of roads, traffic volume, section lengths, geometric characteristics, and time lengths of construction activities (***Table 11***). The complete list of multilane signalized corridors in Delaware is given in Appendix C. After collecting the traffic data at work zone, the time series plots of flow, occupancy were studied to find how the presence of lane closure affects the flow. Two groups of plots were studied: time series plots for flow-occupancy scatter plots (***Figure 21***) and traffic flow vs. occupancy scatter plots (***Figure 22***).

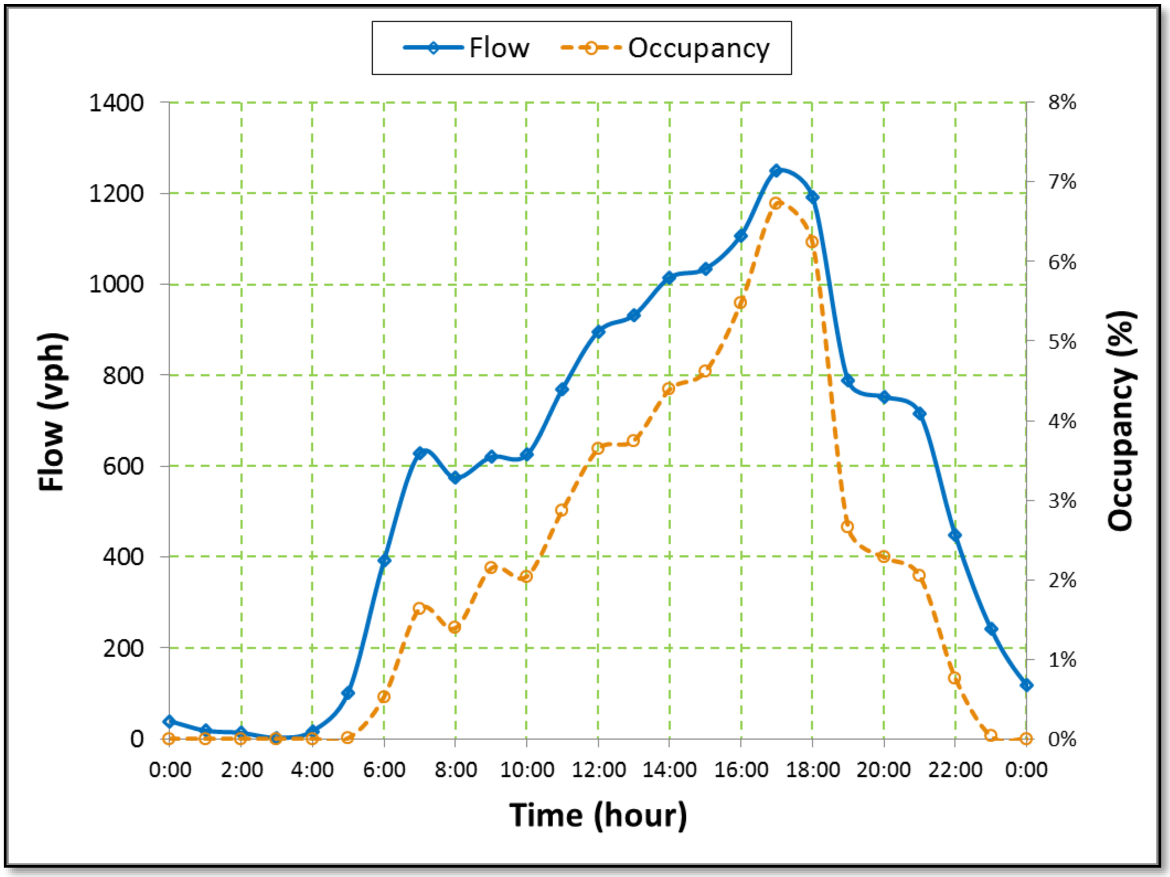


Figure 21: Time series plots for flow-occupancy scatter

Figure 21 and ***Figure 22*** are flow-occupancy scatter time series plots for Naamans Road between Foulk Road and I-95, Eastbound. The complete flow-occupancy time series plots for all 25 sites in Delaware are given in Appendix E. As we can see in Appendix E, there is little or no drop in speed with increasing flow, which indicates that vehicles at most of the work zones remained stable and close to the work zone speed limit, i.e., under uncongested conditions. The linear flow-occupancy relationship represents free flow condition, while the flow-occupancy curve shifts upward when relationships drivers proceed through the work zone with higher flow at given occupancy.

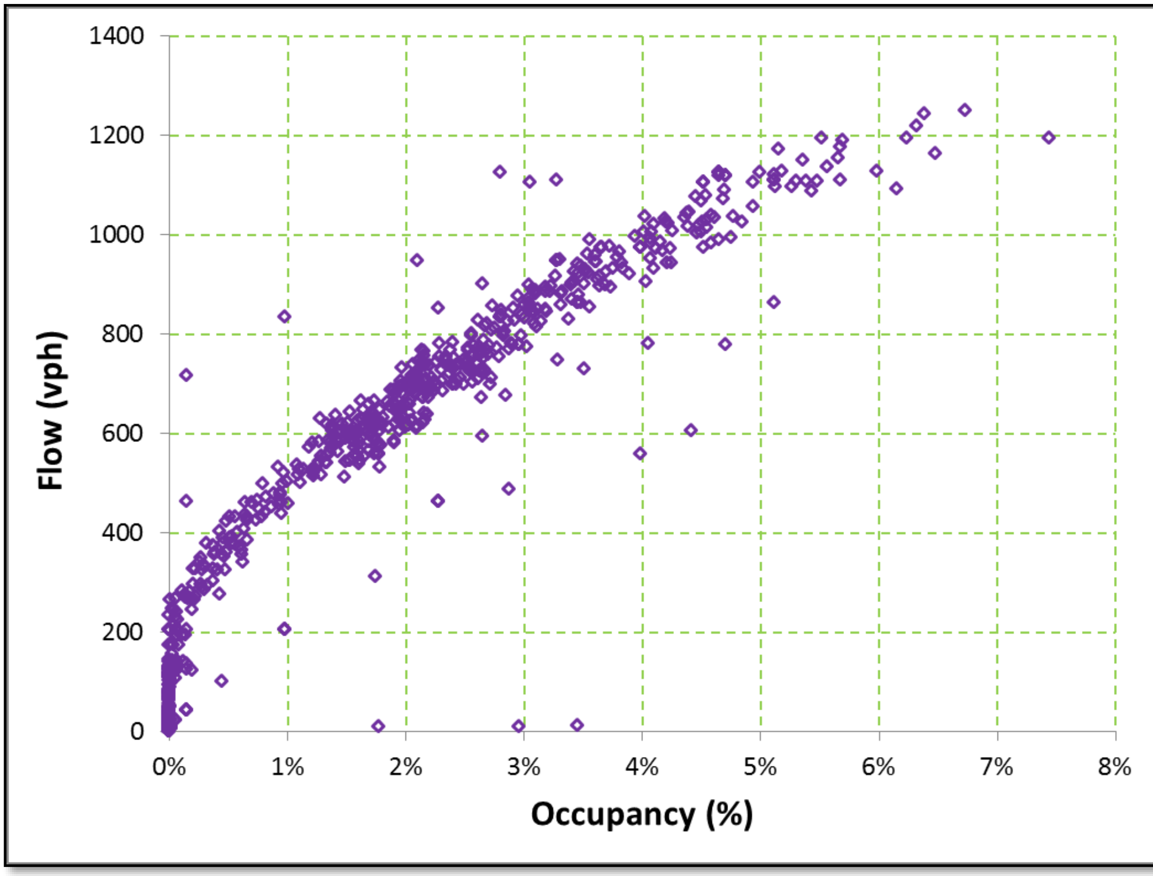


Figure 22: Flow vs. occupancy scatter plots, Naamans Rd., Foulk Rd. to I-95, EB

Table 11: Work zone schedule

New Castle County

1) Naamans Rd., Foulk Rd. to I-95, EB/WB; 6/13/2014 -7/25/2014, 9am - 4pm

2) Kirkwood Hwy, SR 100 to SR 141, WB/EB, 4/20/2015 - 5/8/2015, 24/7

3) SR 273, SR 1 to I-95, WB/EB, 1/16/2015 - 2/27/2015 8am- 3pm

4) SR 273, Rt. 4 to I-95, EB only, 9/15/2014 - 9/19/2014, 9am-3pm

5) DuPont Hwy, 141 to I-295, NB only, 1/6/2014 - 7/6/2015 24/7

6) Foulk Road, PA line to Naamans, SB/NB, 5/20/2013 - 6/28/2013,7am - 5pm

7) Foulk Road, Naamans Rd. to Silverside, SB/NB, 6/25/2012 -11/15/2012, 7am - 5pm

8) Foulk Road, Silverside to Shipley, SB/NB, 6/25/2012 - 11/15/2012, 7am - 5pm

9) I-95, Exit 8 (US 202) to Exit 9, NB/SB, 12/30/2013-12/31/2014, 9am - 3pm

10) I-95, Exit 5 (SR 141/I-295 JCT) to I-495 JCT, NB/SB, 8/6/2012 -10/26/2012, 9am - 5pm

11) I-495, I-95 to Exit 1 (US 13), NB only, 5/5/2013 - 6/28/2013,9am -3pm

12) I-495, Exit 4 (Marsh Rd.) to Exit 5 (Rt. 13), NB/SB,2/16/2014 -7/18/2014,7/24

Kent County

1) Relief Route, Exit 95 to NCC County Line, NB only, 12/14/2012 -12/31/2014, 8am -2pm

2) US 13, Rt 14 to Rt 12, NB, 5/5/2014 -5/30/2014, 9am -2pm

3) US 13, Rt 10a to Rt 10, NB/SB, 11/28/2013 -11/29/2013, 8am - 3pm

4) US 13,Rt 10 to Rt 8, NB/SB,12/2/2013-3/14/2014,8am -3pm

5) US 13,Rt 8 to Scarborough Rd., NB/SB,1/20/2014 -3/14/2014, 9am3pm

6) US 13,Scarborough Rd. to Rt 42,NB/SB, 1/4/2013 - 2/8/2013, 9am -3pm

7) US 13,SR 42 to Exit 114,NB only,1/20/2014 -3/14/2014, 9am-3pm

Sussex County

US 113, US 9 to SR 20 West, SB/NB, 12/4/2014 -2/20/2015,7am -5pm

3.2.2 Findings and results

Table 12: Work zone capacity assessment

#	Road Location	Dir.	Date		Time Interval		Number of Lanes		Estimated Work Zone Capacity		Work Zone Capacity in HCM 1997	Work Zone Capacity in HCM 2010
			From	To	From	To	Normal Operations	Open to Traffic in Work Zone	Vehicles Per Hour (VPH)	Vehicles Per Hour Per Lane (VPHPL)	Vehicles Per Hour Per Lane (VPHPL)	Vehicles Per Hour Per Lane (VPHPL)
1	Naamans Rd., Foulk Rd. to I-95	EB	6/13/2014	7/25/2014	9:00	14:00	2	1	1250	1250	1170	1400
2	Naamans Rd., Foulk Rd. to I-95	WB	6/13/2014	7/25/2014	9:00	14:00	2	1	1291	1291	1170	1400
3	Kirkwood Hwy, SR 100 to SR 141	EB	4/20/2015	5/8/2015	00:00	23:55	2	1	1353	1353	1170	1400
4	Kirkwood Hwy, SR 100 to SR 141	WB	4/20/2015	5/8/2015	00:00	23:55	2	1	1529	1529	1170	1400
5	SR 273, SR 1 to I-95	EB	1/16/2015	2/27/2015	8:00	15:00	2	1	1535	1535	1170	1400
6	SR 273, SR 1 to I-95	WB	1/16/2015	2/27/2015	8:00	15:00	2	1	1977	1977	1170	1400
7	SR 273, Rt. 4 to I-95,	EB	9/15/2014	9/19/2014	9:00	15:00	2	1	1892	1892	1170	1400
8	DuPont Hwy, 141 to I-295	NB	1/6/2014	7/6/2015	00:00	23:55	3	2	2490	2490	1170	1400
9	Foulk Road, PA line to Naamans	NB	5/20/2013	6/28/2013	7:00	17:00	2	1	680	680	1170	1400
10	Foulk Road, PA line to Naamans	SB	5/20/2013	6/28/2013	7:00	17:00	2	1	595	595	1170	1400

#	Road Location	Dir.	Date		Time Interval		Number of Lanes		Estimated Work Zone Capacity		Work Zone Capacity in HCM 1997	Work Zone Capacity in HCM 2010
			From	To	From	To	Normal Operations	Open to Traffic in Work Zone	Vehicles Per Hour (VPH)	Vehicles Per Hour Per Lane (VPHPL)	Vehicles Per Hour Per Lane (VPHPL)	Vehicles Per Hour Per Lane (VPHPL)
11	Foulk Road, Naamans Rd. to Silverside	NB	6/25/2012	11/15/2012	7:00	17:00	2	1	676	676	1170	1400
12	Foulk Road, Naamans Rd. to Silverside	SB	6/25/2012	11/15/2012	7:00	17:00	2	1	785	785	1170	1400
13	Foulk Road, Silverside to Shipley	NB	6/25/2012	11/15/2012	7:00	17:00	2	1	943	943	1170	1400
14	Foulk Road, Silverside to Shipley	SB	6/25/2012	11/15/2012	7:00	17:00	2	1	1037	1037	1170	1400
15	Relief Route, Exit 95 to NCC County Line	NB	12/14/2012	12/31/2014	8:00	14:00	2	1	895	895	1170	1400
16	US 13, Rt 14 to Rt 12	NB	5/5/2014	5/30/2014	9:00	14:00	2	1	274	274	1170	1400
17	US 13, Rt 10a to Rt 10	NB	11/28/2013	11/29/2013	8:00	15:00	2	1	1018	1018	1170	1400
18	US 13, Rt 10a to Rt 10	SB	11/28/2013	11/29/2013	8:00	15:00	2	1	884	884	1170	1400
19	US 13,Rt 10 to Rt 8	NB	12/2/2013	3/14/2014	8:00	15:00	2	1	1205	1205	1170	1400
20	US 13,Rt 10 to Rt 8	SB	12/2/2013	3/14/2014	8:00	15:00	2	1	1284	1284	1170	1400
21	US 13,Rt 8 to Scarborough Rd	NB	1/20/2014	3/14/2014	9:00	15:00	3	2	2258	1129	1490	1450
22	US 13,Rt 8 to Scarborough Rd	SB	1/20/2014	3/14/2014	9:00	15:00	3	2	3456	1728	1490	1450

#	Road Location	Dir.	Date		Time Interval		Number of Lanes		Estimated Work Zone Capacity		Work Zone Capacity in HCM 1997	Work Zone Capacity in HCM 2010
			From	To	From	To	Normal Operations	Open to Traffic in Work Zone	Vehicles Per Hour (VPH)	Vehicles Per Hour Per Lane (VPHPL)	Vehicles Per Hour Per Lane (VPHPL)	Vehicles Per Hour Per Lane (VPHPL)
23	US 13,Scarborough Rd. to Rt 42	NB	1/4/2013	2/8/2013	9:00	15:00	2	1	1555	1555	1170	1400
24	US 13,Scarborough Rd. to Rt 42	SB	1/4/2013	2/8/2013	9:00	15:00	2	1	1324	1324	1170	1400
25	US 13,SR 42 to Exit 114	NB	1/20/2014	3/14/2014	9:00	15:00	3	2	2018	1009	1170	1400

Table 12 and ***Table 13*** report the results of actual work zone capacity values and estimated average work zone capacity values, respectively. Note that the actual values would be dependent on several factors, such as the existing number of lanes, number of lanes closed, the effect of heavy vehicle percentage, driver population, weather, site configuration, work activity at site, light condition, traffic speed, interchanges/intersections, type of work, type of traffic control, etc. For further information, consult ***Table 2*** and ***Figure 24***. The summary statistics of work zone capacity analysis is shown in ***Table 14***.

Table 13 Measured average work zone capacities

Number of Lanes		**Work Zone Capacity**	
Normal Operations	Open to Traffic in Work Zone	Vehicles Per Hour (VPH)	Vehicles Per Hour Per Lane (VPHPL)
3	1	1,170	1,170
2	1	**1,481**	**1,481**
5	2	2,740	1,370
4	2	2,960	1,480
3	2	**2,578**	**1,289**
4	3	4,560	1,520

Note: New estimated average work zone capacity values marked in red.

Table 14: Summary statistics of work zone capacity

Mean	1475
Standard Error	98
Median	1339
Standard Deviation	390
Sample Variance	152333
Kurtosis	2
Skewness	1
Range	1472
Minimum	1018
Maximum	2490
Confidence Level(95.0%)	208

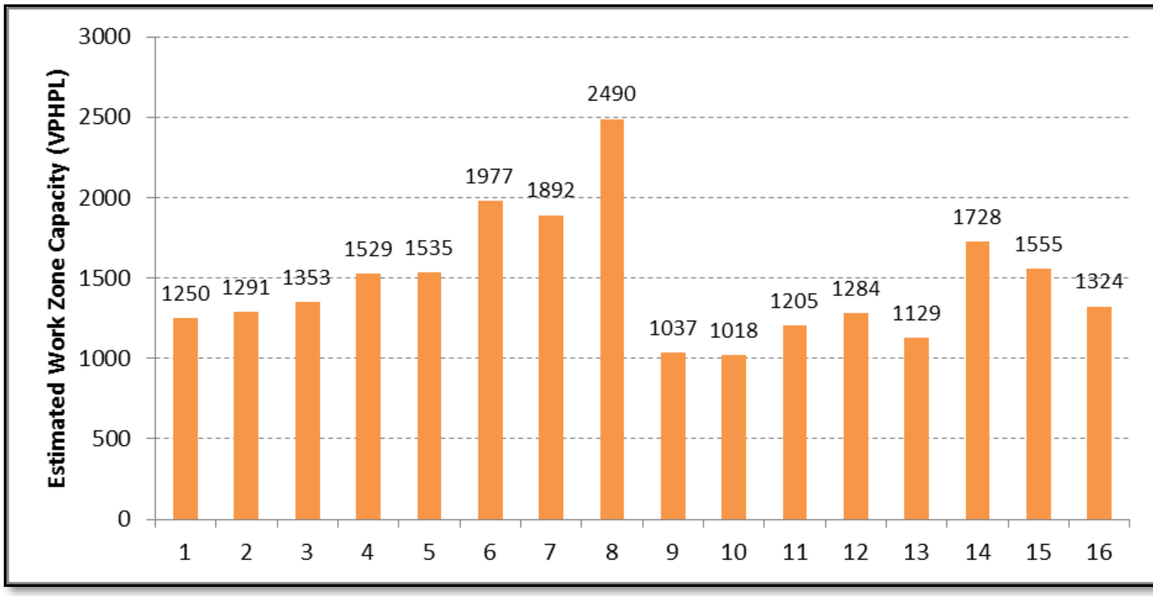


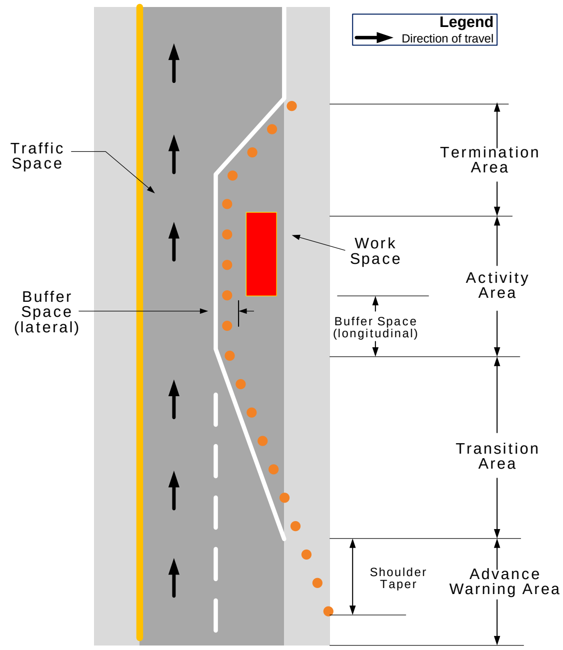
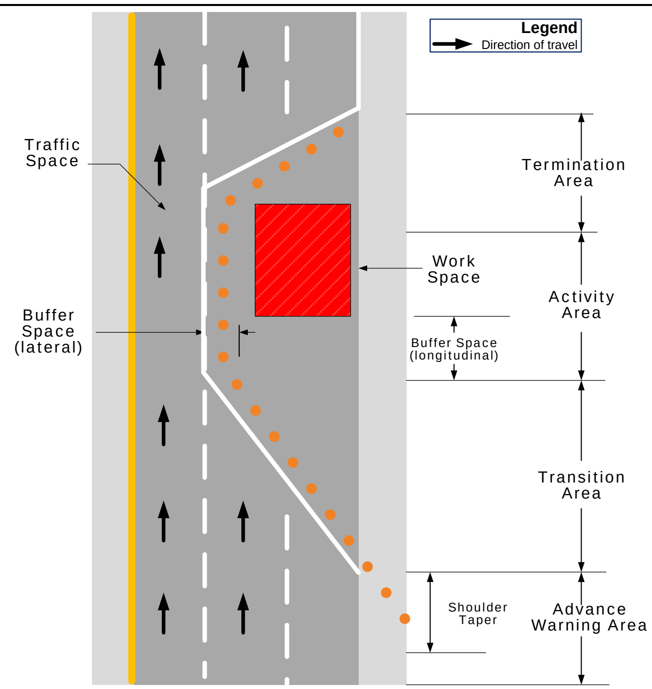
Figure 23: Work zone capacity distribution

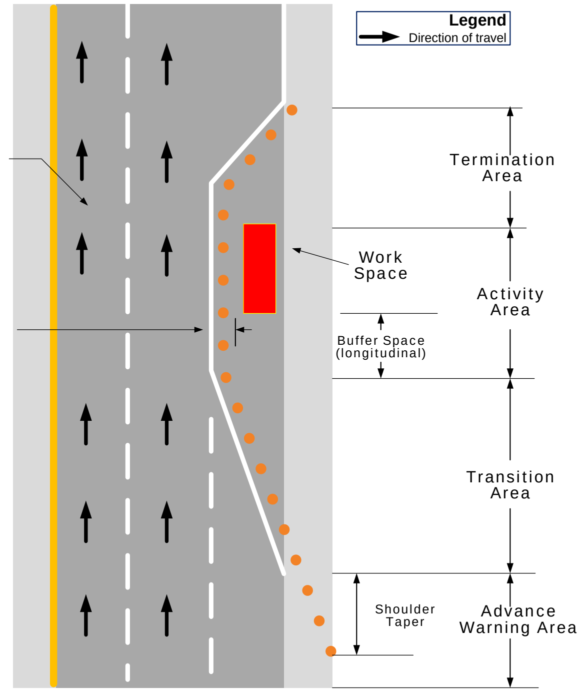
The 25-site average capacities were 1475 vphpl for 15-min sustained flow (***Table 14*** & ***Figure 23***). Notably, they were larger than the 1240 vphpl Highway Capacity Manual (HCM) based capacity values and currently used by DelDOT but lower than most values found in the nationwide survey

The definition of work zone capacity was built on the maximum traffic flows observed over a one-hour period. Throughput values were also compiled over longer periods when traffic was within 90% of the maximum observed one-hour flows, as well as over the multi-hour mid-day period.

The HCM 2010 (Chapter 10, Freeway Facilities) recommends that a value of 1600 vphpl be used as the base capacity value for short term freeway work zones., regardless of the lane-closure configuration, e.g., 2-to-1, 3-to-2, and 3-to-1 (***Table 15***).

Table 15: Lane closure types considered in this study

Lane closure type	Component parts of a temporary traffic control zone
2 To 1	
3 To 1	

Lane closure type	Component parts of a temporary traffic control zone
3 To 2	

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Although extensive research has been conducted on freeway capacity by estimating parameters of the various probability distribution functions that are utilized to represent the probabilistic nature of freeway capacity for specific roadway under prevailing traffic and control conditions, minimal research has been carried out for multilane signalized corridors section capacity estimation, especially sections within work zones. This study attempted to fill that gap for multilane signalized corridors in Delaware, by estimating capacity of multilane signalized corridors work zones in Delaware. Twenty-five work zone locations were randomly selected from a list of work zones for obtaining actual field data and further investigations.

A recent literature review was performed to investigate other states' methods for determining work zone lane capacities, and it was determined that Delaware's values are fairly conservative when compared with those used by several other states. A literature search of the 50 state transportation agencies, as well as the District of Columbia were conducted to determine what innovative practices are being utilized to determine the capacity at work zones.

This research developed one methodology to determine the work zone capacity distribution based on the probabilistic speed-flow relationships in dealing with the variation of factors. In the case of the 7 sites of 5-minutes traffic data from California, the mean of work zone capacity and geometrical alignment were reduced with the increase of construction sites. Also, the work zone with a big geometrical alignment or a low speed limit is associated with a short length of prediction interval, suggesting a low degree of the uncertainty associated with work zone capacity. This methodology can successfully examine the effects of geometrical alignment, number of construction sites per work zone and speed limit on the work zone capacity distribution. However, the case study just focused on the local work zones, not meaning its good fitness for other cities and countries. So, future study will investigate more cities to generate a general distribution model for estimating the work zone capacity. The other limit is that the other factors of work intensity and weather conditions were not taken into account. Last, lognormal distribution will be transformed in the equation to further confirm whether it is the best method to estimate the work zone capacity.

The 25-site average capacities were 1475 vphpl for sustained flow. Notably, they were larger than the 1240 vphpl Highway Capacity Manual (HCM) based capacity values and currently used by DelDOT but lower than most values found in the nationwide survey. There are many factors that could affect work zone capacity. The capacity of the work zone can be estimated by establishing a relationship between speed reduction and the primary factors impacting the work zone capacity. The proposed methodology can be helpful in evaluating the variability of work zone capacity and selecting better the work zone traffic control strategies to improve the capacity and construction staging.

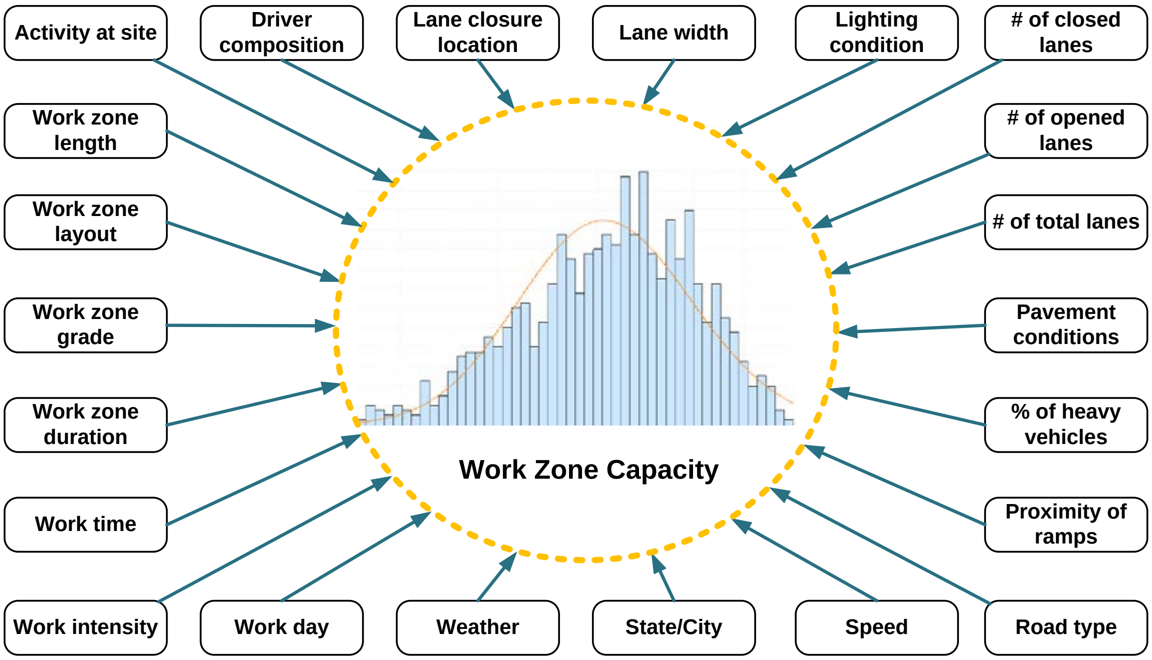


Figure 24 Twenty-two factors affecting work zone capacity

There are some general analytical methods from simple deterministic queuing theory using a spreadsheet to microscopic modeling through SimTraffic or CORSIM, but each method is only able to focus on an estimation of what will happen around the local work zone, and each provides a basis for evaluation of lane closure times, as well as the variation of this analytical extensiveness between different agencies.

Both parametric approaches and non-parametric approaches require a large number of data and the specific factors of the distance of warning signs, lane traffic distributions and lane merge strategies on field sites is not taken into account for these two case studies in California and Delaware. In that case, simulation approaches can be considered as the better alternative method in evaluating those factors on work zone capacity. Future study will focus on a hybrid method that will be comprehensively integrated in the study of increasing the work zone capacity. Notably, a probability distribution rather than a constant value should be developed in the work zone distribution models because of variations in the zone capacity with a fluctuant confidence.

Analyzing transportation impacts can improve the overall understanding of the relationships between mobility, financial, environmental, safety, and user costs, which can further affect work zone decision making. Work zone analysis should never be directly used to make key decisions, but instead developed as a trusted resource for understanding the potential mobility impacts and using this information to inform key decisions. The informative value used by decision-makers will directly relate to how well the analyst has an understanding for both the context for analysis on either decision to be supported or relevant performance to be measured and the context for validation of data and staff resources. However, the job of the work zone analyst extends not only beyond merely conducting an analysis and reporting results, but also to provide decision-makers with a broader understanding relevant to the findings of the analysis within the decision-making context. A well-summarized level of understanding placed in the context can be provided in front of the decision-makers and other staff working on the project, even if decision-makers do not have first-hand experience with the analytical approach.

4.2 Recommendation

This study provides the following recommendations: 1) since the present definition of capacity in HCM 2000 is subjective, then it varies from one study to another, and capacity values obtained by different methods should be compared together carefully. Also it is of importance to distinguish between rates of breakdown flow and mean queue discharge flow and between the applications of each definition. Incorrect definition and use of inappropriate capacity values may lead to significant error. 2) To capture the breakdown probability distribution that is of interest in traffic management and control, multiple breakdown events should involve into the analysis of traffic data. And to provide the generic estimation model, the sufficient data with various conditions should be collected. Such a model would help traffic engineers analyze the risk of traffic breakdown under various conditions.3) Also, the work zone capacity can be reported in passenger car equivalent units. Usually, the capacity values in vehicles per hour underestimates the significant effect of heavy vehicles on traffic flow, especially under the condition with only a single open lane that prevents passenger vehicles from passing the slow-moving heavy vehicles. 4) Work zone specific equivalency factors should be considered for improving the accuracy of work zone capacity estimation.

Although the field capacities were not measured uniformly, they were measured at different specific locations such as the beginning of the taper, the activity area, or the end of the taper area. The variability of capacity values as a character of the methodology was exemplified by using the field studies in Delaware. How to define the applicable capacity is problem considered by each agency. The queue discharge flow (QDF) might be the best methodology due to closer to the true value of work zones capacity, but it is harder to derive than either 85th percentile or the 15-min sustained flow. The 15-min sustained flow might be better to the 85th percentile flow, because the latter is up to the traffic demand.

4.3 Directions for Future Work

The following recommendations are made for future studies:

This study is based on data for one lane closure (2→1, 3→2) on multilane signalized roadways in Delaware. For work zones with different number of lane closures and configuration (e.g., lane shifting, merging and crossover), the results may not be applicable and cannot necessarily be transferred to other locations directly. It is recommended to do further study for those conditions.

Intelligent Transportation Systems (ITS) technology can be applied in work zones to enhance safety and mobility of work zones A detailed analysis of using ITS in work zones is needed.

The flow-occupancy curve developed in the second case study for multilane signalized corridors in Delaware did not have enough data to quantify the reduced capacity during flow breakdown. Further field data is needed to quantify the reduced capacity for different work zone conditions.

The future research will dedicate to comparing the three methods by using data obtained from long-term work zones. Regarding the threshold values, A more sensitive analysis between the pre-queue flow (PQF) and QDF values used in the re-scaled method should also be conducted.

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APPENDICES

Appendix A: Work zone capacity studies by the state DOTs

Table 16: Work zone capacity estimates established by various states

State DOTs	Capacity (vphpl)	Title of Documents	Year	Link
ALDOT	1,500	1. Work Zone Lane Closure Analysis Model; 2. Characterizing Work Zone Configurations and Effects	2009	http://ntl.bts.gov/lib/31000/31600/31609/07404-Work_Zone_Lane_Closure_Analysis_Model.pdf
ADOT&PF	N/A	1. Alaska Highway Preconstruction Manual, Chapter 14. Highway Work Zone Safety and Traffic Control Plans;	2008	http://www.dot.alaska.gov/stwddes/dcsprecon/assets/pdf/preconhwy/chapters/chapter14.pdf
ADOT		Implementation Guidelines for Work Zone Safety & Mobility	2009	
AHTD	N/A	KDOT Traffic Control Review Policy	2014	https://www.arkansashighways.com/human_resources_division/SafetyManual50.pdf
Caltrans	1,100-16,00	1. web-based Lane Closure System (LCS); 2. California Department of Transportation Construction Manual; 3. California Department of Transportation (2006) Traffic Manual	2006	http://www.dot.ca.gov/trafficops/tcd/workzones.html
CDOT	1,800 - 2,300	1. Lane Closure Schedules and Technical Report 2. FY2013 Work Zone Safety and Mobility Process Review	2015	https://www.codot.gov/library/traffic/lane-close-work-zone-safety/work-zone-safety-mobility-program/CDOT-Process-Review-Report-070511.pdf/at_download/file

State DOTs	Capacity (vphpl)	Title of Documents	Year	Link
CONNDOT	1,500–1,800	1. Connecticut Work Zone Improvement Plan; 2. Evaluation of Interstate Highway Capacity for Short-Term Work Zone Lane Closures; 3. 2010 Work Zone Safety and Mobility Process Review; 4. Delay and User Cost Estimation for Work Zones on Urban Arterials	2004	http://www.ct.gov/dot/lib/dot/documents/dconstruction/workzone/2011_work_zone_process_review_report_(final)_signed.pdf http://www.ct.gov/dot/lib/dot/documents/dconstruction/workzone/wzip_action_plan_signed_copy_conndot_052213__fhwa_052913.pdf
DELDOT	1,170 - 1,520	Work Zone Safety and Mobility	2007	https://www.deldot.gov/information/pubs_forms/.../de.../final_rule_9_10_2007.pdf
FDOT	1,800	Freeway Work Zone Capacity - Florida Department of Transportation	2007	www.fdot.gov/research/Completed_Proj/Summary_PL/FDOT_BD545_51_b_rpt.pdf
GDOT	N/A	Traffic Control	2012	www.dot.ga.gov/PartnerSmart/Business/Source/special_provisions/shelf/sp150.pdf
HDOT	1,450 - 1,600	Safety & Temporary Traffic Control in the Landscape Maintenance Zone	2013	https://hidot.hawaii.gov/highways/files/2013/02/Landscape-ch4_SAFETY.pdf
ITD	1,800-2,000	Work zone safety and mobility program	2012	itd.idaho.gov/wp-content/uploads/.../Work-Zone-Safety-and-Mobility-Program.pdf
IDOT	1,500 - 1,600	1. Work Zone Transportation Management Plans; 2. Evaluation of Construction Work Zone Operational Issues: Capacity, Queue, and Delay	2013	http://www.idot.illinois.gov/assets/uploads/files/doing-business/manuals-split/design-and-environment/bde-manual/chapter%2013%20work%20zone%20transportation%20management%20plans.pdf
INDOT	1250	1. INDOT's Work Zone Traffic Control Guidelines; 2. INDOT Work Zone Safety Mobility Policy; 3. Construction work zone safety.	2013	www.in.gov/indot/files/WorkZoneTCH.pdf
Iowa DOT	1,400–1,600	Capacity of Freeway Work Zone Lane Closures	2000	www.ctre.iastate.edu/pubs/midcon/maze.pdf
KDOT	1500	1. Kansas Work Zone Safety and Mobility Processes and Procedures; 2. Highway Work	2008	lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1121&context=intrans_reports

State DOTs	Capacity (vphpl)	Title of Documents	Year	Link
		Zone Capacity Estimation Using Field Data from Kansa		
KYTC	900-1,200	Policy and Procedure for the Safety and Mobility of Traffic Through Work Zones	2008	transportation.ky.gov/Construction/Documents/workzonepolicy.pdf
DOTD	1,400-1,600	Design of Lane Merges at Rural Freeway Construction Work Zones	2012	http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.269.2617&rep=rep1&type=pdf
MaineDOT	N/A	MaineDOT Survey Safety Manual	2007	https://www.workzonesafety.org/files/documents/database_documents/Maine_survey_safety_manual2007.pdf
MDOT	1,170 - 1,600	Maryland State Highway Administration Work Zone Lane Closure Analysis Guidelines.	2006	https://www.roads.maryland.gov/OOTS/WorkZoneAnalysisGuide_Sept08.pdf
MassDOT	1,170-1,520	Work Zone Management - MassDOT	2006	http://www.massdot.state.ma.us/Portals/8/docs/designGuide/CH_17_a.pdf
MDOT	1,400-1,700	1. MDOT Work Zone Safety & Mobility Manual; 2. Work Zone Safety & Mobility Process Review	2010	https://www.michigan.gov/documents/mdot/MDOT_MobilityProcessRevReportFinal_414393_7.pdf
Mn/DOT	1,800	1. Development of a Guideline for Work Zone Diversion Rate and Capacity Reduction; 2. 2012 CMS Manual of Practice	2016	www.dot.state.mn.us/research/TS/2016/201612.pdf
MDOT	1,200-1,400	Missouri Work Zone Capacity	2011	digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1058&context=matcreports
MoDOT	1,240 - 1,430	MoDOT Work-Zone Guidelines - Missouri Department of Transportation Missouri Work Zone Capacity		www.modot.org/business/documents/MoDOTWorkZonesGuidelines2.pdf https://pdfs.semanticscholar.org/718d/a9dddea81c7429bfb9e7d4f4aa52237d3440.pdf
MDT	N/A	1. Work Zone Safety and Mobility; 2. MDT Work Zone Traffic Control Manual http://www.mdt.mt.gov/publications/manuals.shtml	2015	https://www.mdt.mt.gov/other/webdata/external/cadd/wzsm/WZSM_GUIDANCE.pdf

State DOTs	Capacity (vphpl)	Title of Documents	Year	Link
NDOR	1,730	Alternative Information to Alleviate Work Zone-Related Delays	1999	http://ntl.bts.gov/lib/16000/16000/16076/PB2000102426.pdf
NDOT	1,375–1,400	Evaluation of Interstate Highway Capacity for Short-Term Work Zone Lane Closures	2004	http://trrjournalonline.trb.org/doi/abs/10.3141/1877-10
NHDOT	N/A	Guidelines for Implementation of the Work Zone Safety and Mobility Policy	2007	https://www.nh.gov/dot/org/projectdevelopment/highwaydesign/documents/WorkZoneSafetyPolicy.pdf
NJDOT	HCM	Manual for Traffic Control in Work Zones	2011	http://www.state.nj.us/turnpike/traffic-manual.html
NMDOT	1,200-1,860	Work Zone Safety	2003	http://dot.state.nm.us/content/dam/nmdot/Research/NM00SAF01_I-40WORKZONE2003.pdf
NYSDOT	1,600-1800	1. Surface Transportation Control Statewide Guidelines; 2. Two-Lane, Two-Way Operations in Construction Work Zones	2013	https://www.dot.ny.gov/main/business-center/designbuildproject6/repository/Surface_Transportation_Control_Statewide_Guidelines-20140924.pdf
NCDOT	1,640	Capacity for North Carolina Freeway Work Zones	1996	trrjournalonline.trb.org/doi/pdf/10.3141/1529-04
NDDOT	1,300	Work Zone Safety & Mobility	2007	http://www.dot.nd.gov/manuals/manuals-publications.htm#contractors
ODOT	HCM 2010	Permitted Lane Closure, FAQ & Definitions	2016	http://www.dot.state.oh.us/districts/D01/PlanningPrograms/trafficstudies/WorkZones/Pages/default.aspx
ODOT	N/A	1. Guidelines for Temporary Traffic Control ; 2. Construction Work Plan	2014	http://www.okladot.state.ok.us/traffic/pdfs/trafficcontrol.pdf
ODOT	1,400–1,600	1. Work Zone Traffic Analysis Manual - Oregon.gov; 2. Web-Based Work Zone Traffic Analysis Tool Users' Guide; 3. Evaluation of Interstate Highway Capacity for Short-Term Work Zone Lane Closures	2010	https://www.oregon.gov/ODOT/HWY/TRAFFIC-ROADWAY/docs/pdf/wzta_manual.pdf

State DOTs	Capacity (vphpl)	Title of Documents	Year	Link
PennDOT	1500	1. Temporary Traffic Control Guidelines; 2. Pennsylvania Work Zone Pocket Guide for Municipalities & Utilities	2014	http://www.dot.state.pa.us/Portal%20Information/Traffic%20Signal%20Portal/TTCPUBS.html
RIDOT	HCM 1997, NCHRP Report 475	1. Work Zone Safety Policy; 2. Traffic Design Manual	2008	http://www.dot.ri.gov/documents/doingbusiness/RIDOT_Work_Zone_Safety_and_Mobility_Policy.pdf
SCDOT	800	1. Work Zone Safety Guidelines for the South Carolina Department of Transportation, Municipalities, Counties, Utilities, and Contractors; 2. Evaluation of Interstate Highway Capacity for Short-Term Work Zone Lane Closures	2013	http://trrjournalonline.trb.org/doi/abs/10.3141/1877-10
SDDOT	N/A	Applications of ITS in South Dakota Work Zones	2004	http://www.sddot.com/business/research/projects/docs/SD2003_16_Final_Report.pdf
TDOT	N/A	Work Zone Safety and Mobility Manual	2007	https://www.tn.gov/tdot/article/roadway-design-work-zone-safety-and-mobility-manual
TxDOT	1,170 - 1,340	Traffic Capacity Through Urban Freeway Work Zones in Texas	1999	https://trid.trb.org/view.aspx?id=187787
UDOT	N/A	1. Development of a Statewide User Cost Manual for Rural Work Zones in Utah; 2. Evaluation of Utah Work Zone Practices	2010	http://www.mountain-plains.org/pubs/pdf/MPC10-228B.pdf
VTrans	N/A	Work Zone Safety Mobility Appendix A - Temp. Traffic Control Devices 9-12	2011	http://vtrans.vermont.gov/sites/aot/files/highway/documents/publications/WorkZoneSafetyMobility%20Appendix%20A%20-%20Temp.%20Traffic%20Control%20Devices%209-12.pdf
VDOT	1,300	Online data from the Virginia Department of Transportation	2004	www.virginiadot.org/vtrc/main/online_reports/pdf/05-r6.pdf
WSDOT	1,300	Work Zone Safety and Mobility	2015	http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-

State DOTs	Capacity (vphpl)	Title of Documents	Year	Link
				01/1010.pdf
WVDOT	N/A	Temporary Traffic Control Manual	2006	http://www.transportation.wv.gov/highways/traffic/Documents/TemporaryTrafficControlManual2006.pdf
WisDOT	1,600 - 2,000	Freeway Work Zone Lane Capacity	2007	http://www.eng.mu.edu/drakopoa/web_documents/Work%20Zone%20capacity/Freeway%20Work%20Zone%20Lane%20Capacity.pdf
WYDOT	HCM and Synchro	Traffic Control for Roadway Work Operations	2011	http://www.dot.state.wy.us/files/live/sites/wydot/files/shared/Highway_Development/Utilities/Traffic%20Control%20for%20Roadway%20Work%20Operations%202011.pdf

Appendix B: Time Series Plots for Speed and Flow

Time-series plots of flow and speed measurements are presented in this section. In reviewing the figures, the following observations were made:

1) The data illustrate typical temporal and spatial characteristics of traffic. The volume measured at six sites showed similar patterns of recurring congestion or fluctuations in general.
2) Recurring congestions occur regularly as traffic demand overwhelms and lasts until traffic is restored to normal conditions around 9:30 a.m. for morning peak and 8:00 p.m. for evening peak, respectively.
3) The speed reduction at station 6 is greater than those at other stations. A possible reason could be lane reductions occur near ramps, which may results in operation below capacity between 8 a.m. and 6 p.m.

B_1: Time series plots for speed and flow, sensor location 1, Los Angeles Area

B_2: Time series plots for speed and flow, sensor location 2, Los Angeles Area

B_3: Time series plots for speed and flow, sensor location 3, Los Angeles Area

B_4: Time series plots for speed and flow, sensor location 4, Los Angeles Area

B_5: Time series plots for speed and flow, sensor location 5, Los Angeles Area

B_6: Time series plots for speed and flow, sensor location 6, Los Angeles Area

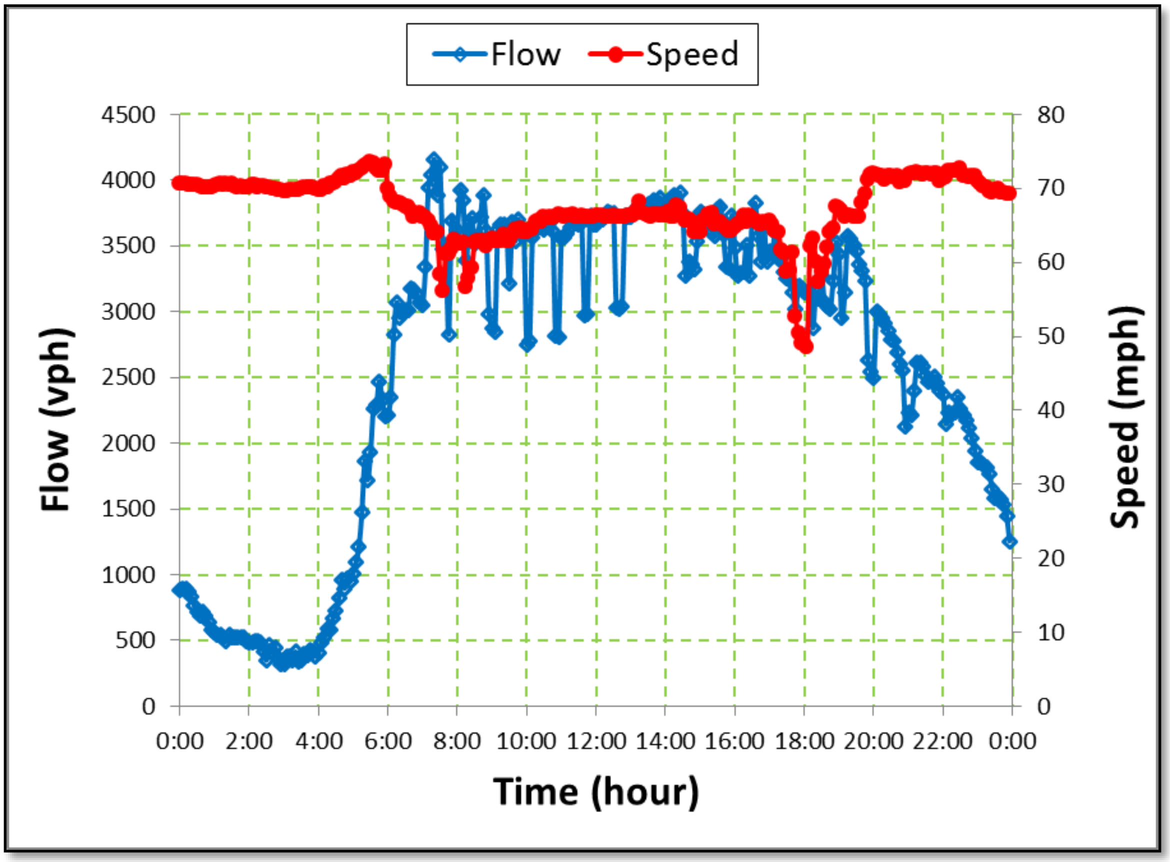


Figure 25: Time series plots for speed and flow, sensor location 1, Los Angeles Area

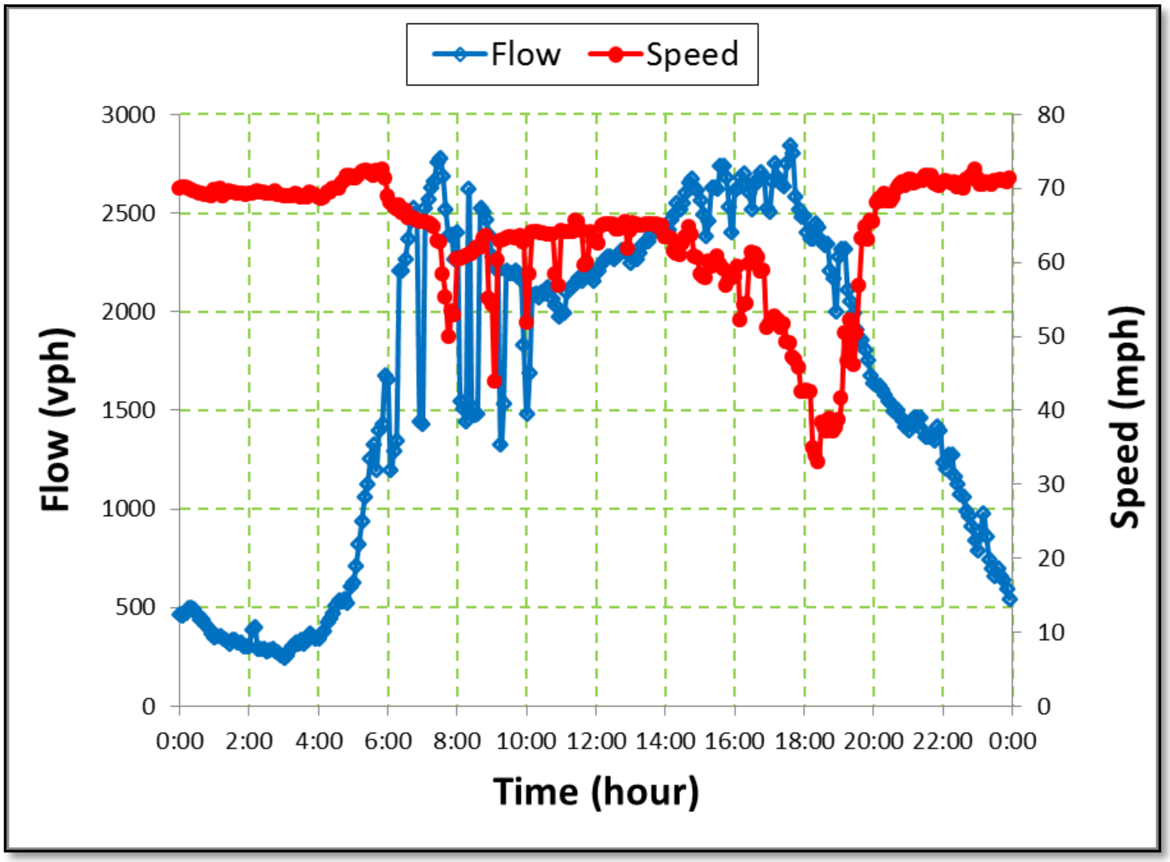


Figure 26: Time series plots for speed and flow, sensor location 2, Los Angeles Area

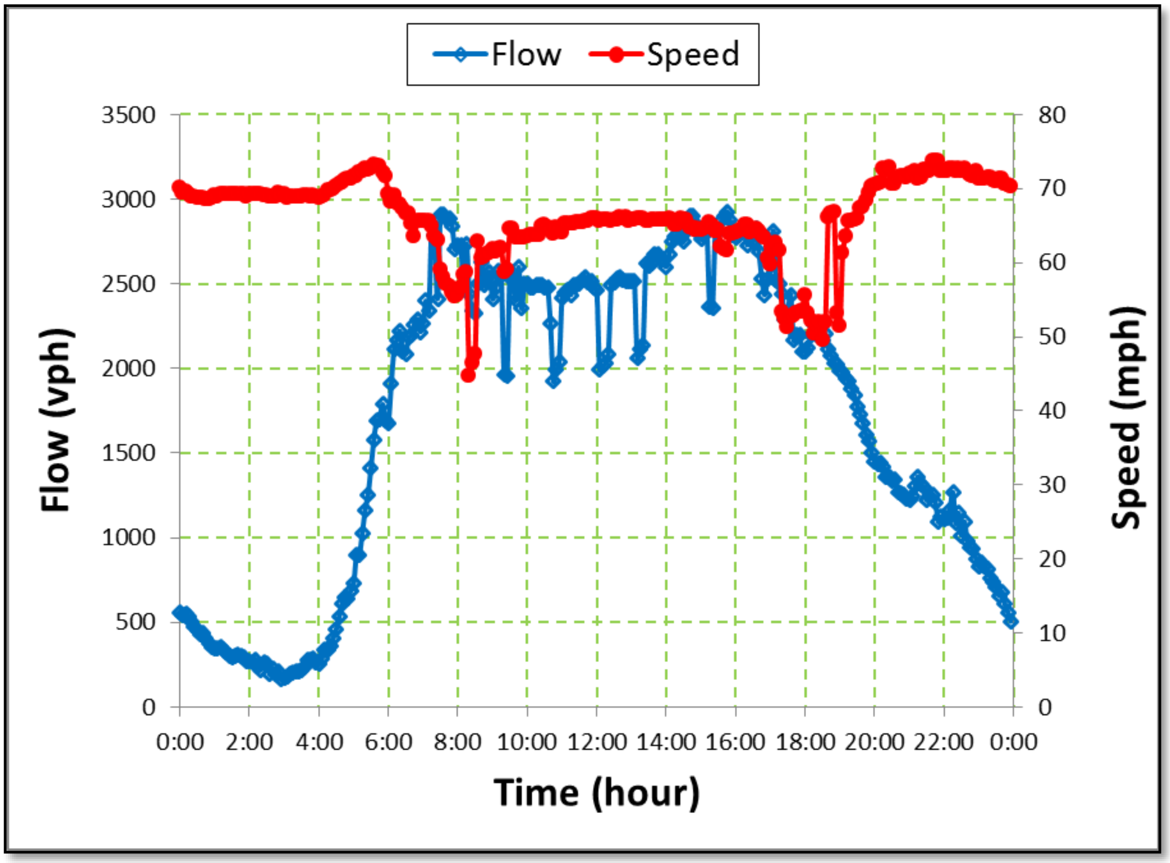


Figure 27: Time series plots for speed and flow, sensor location 3, Los Angeles Area

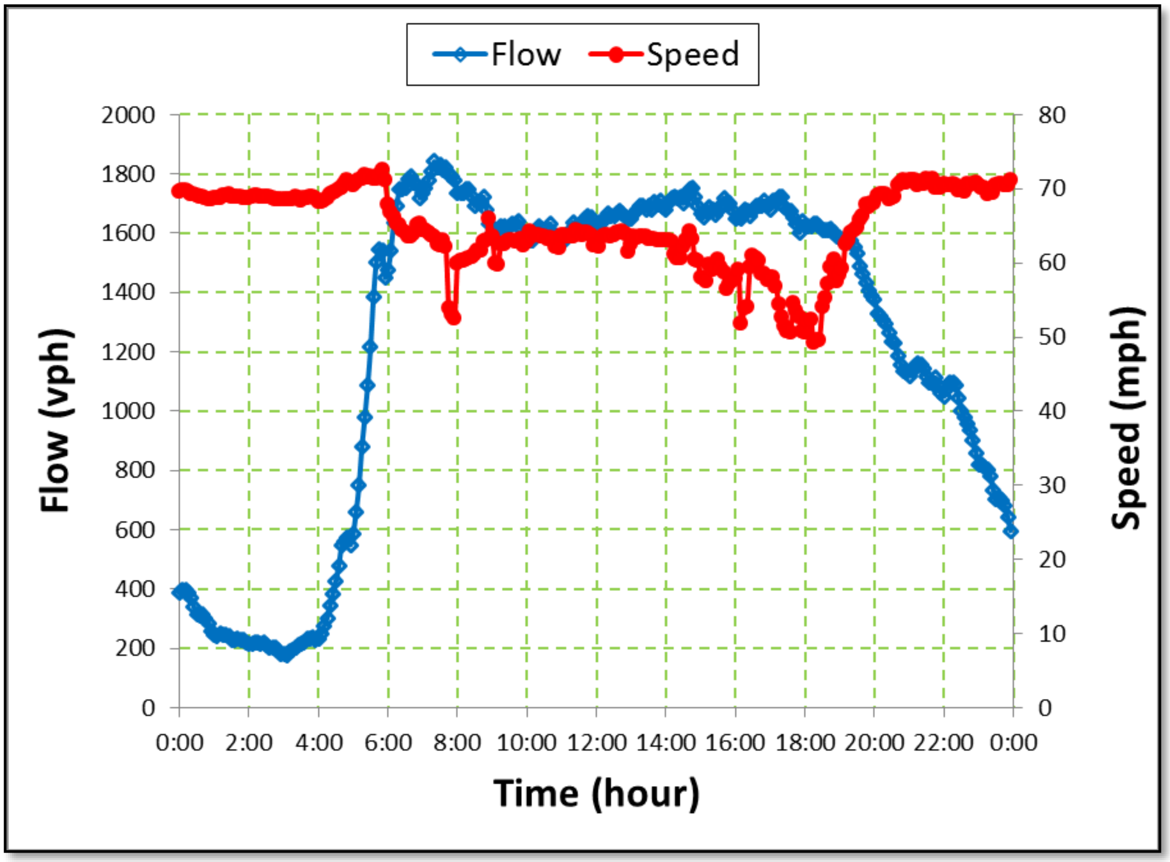


Figure 28: Time series plots for speed and flow, sensor location 4, Los Angeles Area

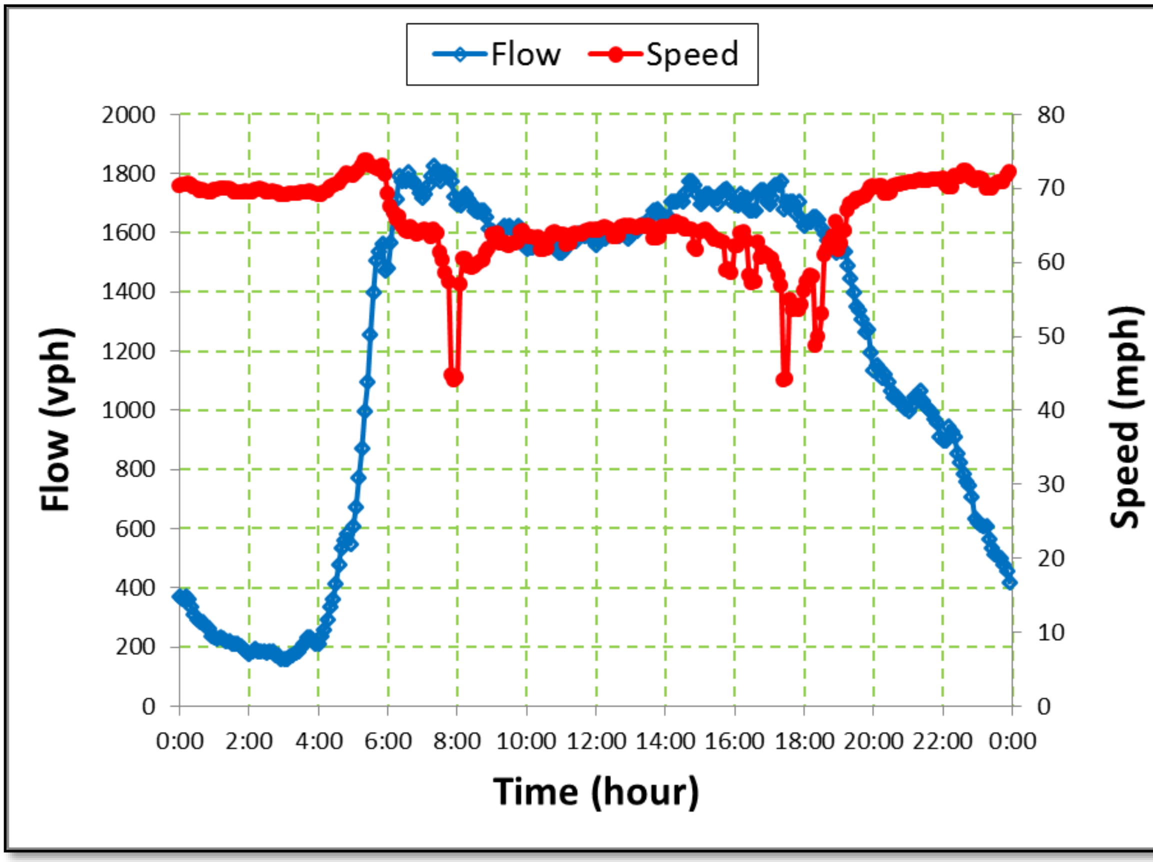


Figure 29: Time series plots for speed and flow, sensor location 5, Los Angeles Area

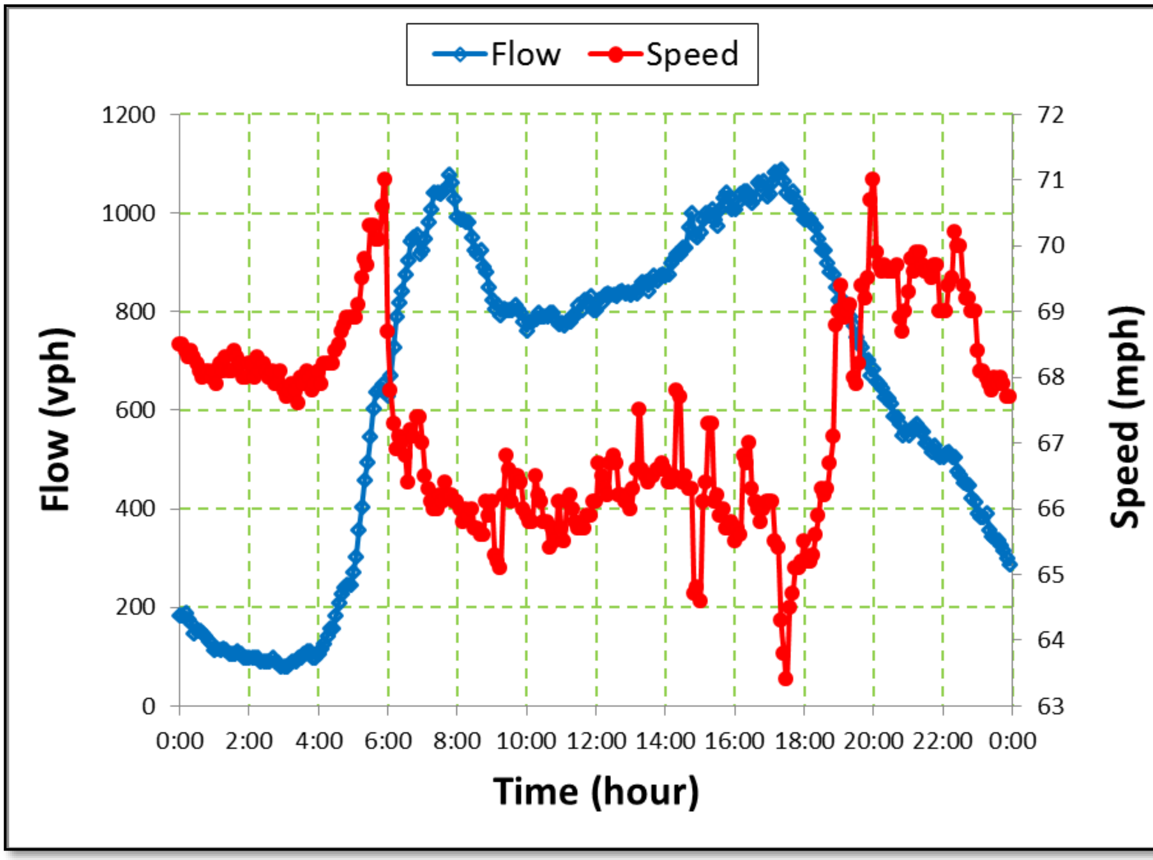


Figure 30: Time series plots for speed and flow, sensor location 6, Los Angeles Area

Appendix C: List of multilane signalized corridors in Delaware

Table 17: Multilane signalized corridors in New Castle County

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
SR 92	Naamans Rd.	US 202 to Foulk Rd.	EB	2.4	2	40,45
	Naamans Rd.	Foulk Rd. to US 202	WB	2.4	2	45,40
	Naamans Rd.	Foulk Rd. to I-95	EB	2.6	2	45,50
	Naamans Rd.	I-95 to Foulk Rd.	WB	2.6	2	40,50,45
	Naamans Rd.	I-95 to US 13	EB	0.8	2	50,35
	Naamans Rd.	US 13 to I-95	WB	0.8	2	40
SR 92	**Naamans Rd.**	**US 202 to US 13**	**EB**	**5.8**		
Total	**Naamans Rd.**	**US 13 to US 202**	**WB**	**5.8**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
US 202	Concord Pike	Market St. to I-95	NB	1.0	1,2	25
	Concord Pike	I-95 to Market St.	SB	1.0	2,1	45,25
	Concord Pike	I-95 to Foulke Rd	NB	0.7	2,3	25,35
	Concord Pike	Foulke Rd. to I-95	SB	0.7	3,4,2	35,45
	Concord Pike	SR 261 to 141 JCT	NB	0.6	3	35
	Concord Pike	141 JCT. To Sr. 261	SB	0.6	3	40,35
	Concord Pike	141 JCT to Silverside Rd.	NB	1.6	3	35,40
	Concord Pike	Silverside Rd. to 141 JCT	SB	1.7	3	45,40
	Concord Pike	Silverside Rd. to SR. 92	NB	1.4	3	40,50
	Concord Pike	SR. 92 to Silverside Rd.	SB	1.4	3	50,45
	Concord Pike	SR. 92 - PA Line	NB	0.8	3,2	50
	Concord Pike	PA Line - SR. 92	SB	0.8	2,3	50
US 202	**Concord Pike**	**Market St. to 491 JCT**	**NB**	**6.1**		
Total	**Concord Pike**	**491 JCT to Market St.**	**SB**	**6.2**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
SR 7	Limestone Rd.	Little Balt. to PA Line	NB	1.7	1	50
	Limestone Rd.	PA Line to Little Balt.	SB	1.7	1,2	50
	Limestone Rd.	72 to Little Balt.	NB	1.1	2	50
	Limestone Rd.	Little Balt. to 72	SB	1.1	2	50

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
	Limestone Rd.	New Linden Hill to 72	NB	1.1	2	50
	Limestone Rd.	72 to New Linden Hill	SB	1.1	2	50
	Limestone Rd.	2 to New Linden Hill	NB	2.1	2	40,50
	Limestone Rd.	New Linden Hill to 2	SB	2.1	2	50,40
	Limestone Rd.	SR 4 to Route 2	NB	0.9	2	50,45
	Limestone Rd.	Route 2 to SR 4	SB	0.9	2	40,45
	Limestone Rd.	SR 4 (Stanton) to SR 4 (Newport)	NB	1.2	3	50
	Limestone Rd.	SR 4 (Newport) to SR 4 (Stanton)	SB	1.2	3	45,50
	Limestone Rd.	I-95 to SR 4 (Stanton)	NB	0.9	2	55
	Limestone Rd.	SR 4 (Stanton) to I-95	SB	0.9	2	50,45
SR 7	**Limestone Rd.**	**SR 4 to PA Line**	**NB**	**9.1**		
Total	**Limestone Rd.**	**PA Line to SR 4**	**SB**	**9.1**		

SR 141	Centre Rd.	Brandywine to US 202	NB	2.0	1,2	35,40,45,50,35
	Centre Rd.	US 202 to Brandywine	SB	2.0	2	35,45,35
	Centre Rd.	SR 52 to Brandywine	NB	0.8	2,1	35
	Centre Rd.	Brandywine to SR 52	SB	0.8	2,1	35
	Centre Rd.	SR 48 to SR 52	NB	1.2	2	45,50,45,35
	Centre Rd.	SR 52 to SR 48	SB	1.2	2	35,50
	Centre Rd.	SR 2 to SR 48	NB	1.8	2	50,35,45
	Centre Rd.	SR 48 to SR 2	SB	1.8	2	50,45,35,50
	Centre Rd.	SR 4 to SR 2	NB	1.8	2,3	50
	Centre Rd.	SR 2 to SR 4	SB	1.8	3,2	50
	Centre Rd.	I-95 to SR 4	NB	0.9	2	50
	Centre Rd.	SR 4 to I-95	SB	0.9	2	50
SR 141	Centre Rd.	US 13 to I-95	NB	1.6	2	45,50
Cont'd	Centre Rd.	I-95 to US 13	SB	1.6	2	50,40
	Centre Rd.	SR 273 to US 13	NB	1.3	2	45
	Centre Rd.	US 13 to SR 273	SB	1.3	2	40,45
SR 141	**Centre Rd.**	**SR 273 to US 202**	**NB**	**11.3**		
Total	**Centre Rd.**	**US 202 to SR 273**	**SB**	**11.3**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
SR 52	PA Avenue	Rd 82 to PA Line	NB	3.3	2	50,35
	PA Avenue	PA Line to Rd 82	SB	3.3	2	35,50
	PA Avenue	SR 141 to Rd 82	NB	1.3	2	35,50
	PA Avenue	Rd 82 to SR 141	SB	1.3	2	50,35
	PA Avenue	Overpass to SR 141	NB	1.0	2	35
	PA Avenue	SR 141 to Overpass	SB	1.0	2	35
	PA Avenue	RR Xing to Overpass	NB	0.7	2	25,35
	PA Avenue	Overpass to RR Xing	SB	0.7	2	35,25
	PA Avenue	I-95 to RR Xing	NB	0.8	2,3	25
	PA Avenue	RR Xing to I-95	SB	0.8	4,2	25
	PA Avenue	Market St. to I-95	NB	0.6	4,3	25
	PA Avenue	I-95 to Market St.	SB	0.6	4	25
SR 52	**PA Avenue**	**Market St. to PA Line**	**NB**	**7.6**		
Total	**PA Avenue**	**PA Line to Market St.**	**SB**	**7.6**		
SR 2	Kirkwood Hwy	72 to Main St.	WB	1.2	2	40,35
	Kirkwood Hwy	Main St. to 72	EB	1.2	2	35
	Kirkwood Hwy	PollyD. Hill to SR 72	WB	0.6	2	45,40
	Kirkwood Hwy	SR 72 to PollyD. Hill	EB	0.6	2	35,40
	Kirkwood Hwy	Overpass to PollyD. Hill	WB	1.5	2	45
	Kirkwood Hwy	PollyD. Hill to Overpass	EB	1.5	2	40,45
	Kirkwood Hwy	SR7 to Overpass	WB	1.8	3,2	45
	Kirkwood Hwy	Overpass to SR 7	EB	1.8	2,3	45
	Kirkwood Hwy	Best Buy to SR7	WB	0.6	3	45
	Kirkwood Hwy	SR 7 to Best Buy	EB	0.6	3	45
	Kirkwood Hwy	SR 141 to Best Buy	WB	1.6	3,2,3	40,45
	Kirkwood Hwy	Best Buy to SR 141	EB	1.6	3	45,40
	Kirkwood Hwy	SR 100 to SR 141	WB	1.7	2	35,40
	Kirkwood Hwy	SR 141 to SR 100	EB	1.7	2	40,35
	Kirkwood Hwy	Rt. 48 to SR 100	WB	1.0	2	25,35
	Kirkwood Hwy	SR 100 to Rt. 48	EB	1.0	2	35,25

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
	Kirkwood Hwy	PA Ave to Rt. 48	WB	0.7	3	25
	Kirkwood Hwy	Rt. 48 to PA Ave.	EB	0.7	2	25
SR2	**Kirkwood Hwy**	**PA Ave. to Main St.**	**WB**	**10.7**		
Total	**Kirkwood Hwy**	**Main St. to PA Ave.**	**EB**	**10.7**		
SR 4	Christiana Pkwy	SR 896 to Elkton	WB	1.4	2,1	50
	Christiana Pkwy	Elkton to SR 896	EB	1.4	2	50,35
	Chestnut Hill Rd.	SR 72 to SR 896	WB	0.9	2	50
	Chestnut Hill Rd.	SR 896 to SR 72	EB	0.9	2	50
	Chestnut Hill Rd.	SR 273 to SR 72	WB	2.5	2	50
	Chestnut Hill Rd.	SR 72 to SR 273	EB	2.5	2	50
	Chestnut Hill Rd.	Rt. 58 to SR 273	WB	1.8	2	50
	Chestnut Hill Rd.	SR 273 to Rt. 58	EB	1.8	2	50
	Chestnut Hill Rd.	SR 7 to Rt. 58	WB	1.0	2	50
	Chestnut Hill Rd.	Rt. 58 to SR 7	EB	1.0	2	50
SR 4	**Chestnut Hill Rd.**	**SR 7 to Elkton Rd.**	**WB**	**7.6**		
Total	**Chestnut Hill Rd.**	**Elkton Rd. to SR 7**	**EB**	**7.6**		
SR 4	Maryland Ave.	1st State to SR7	WB	1.0	2	40
	Maryland Ave.	SR7 to 1st State	EB	1.0	2	40,45
	Maryland Ave.	SR 141 to 1st State	WB	1.2	2	30,35,45
	Maryland Ave.	1st State to SR 141	EB	1.2	2	35,30
	Maryland Ave.	SR 100 to SR 141	WB	1.8	2	30,40,30
	Maryland Ave.	SR 141 to SR 100	EB	1.8	2	30,40,30
	Maryland Ave.	SR 48 to SR 100	WB	1.4	2	25,35
	Maryland Ave.	SR 100 to SR 48	EB	1.4	2	35,25
SR 4	**Maryland Ave.**	**SR 48 to SR 7**	**WB**	**5.4**		
Total	**Maryland Ave.**	**SR 7 to SR 48**	**EB**	**5.4**		
SR 273	SR 273	SR 141 to US 13	WB	1.4	1	35,50,35
	SR 273	US 13 to SR 141	EB	1.4	1	45,50,35
	SR 273	US 13 to SR 58	WB	0.4	2	45

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
	SR 273	SR 58 to US 13	EB	0.4	2	45
	SR 273	SR 58 to SR 37	WB	1.5	2	45
	SR 273	SR 37 to SR 58	EB	1.5	2	45
	SR 273	SR 37 to SR 1	WB	0.7	2	45
	SR 273	SR 1 to SR 37	EB	0.7	2	45
	SR 273	SR 1 to I-95	WB	1.7	2	50
	SR 273	I-95 to SR 1	EB	1.7	2	50
	SR 273	I-95 to Rt. 4	WB	1.2	2	45
	SR 273	Rt. 4 to I-95	EB	1.2	2	45
	SR 273	Rt 4 to Library Ave.	WB	2.5	2	35
	SR 273	Library Ave. to R4	EB	2.5	2	45
	Main St.	Library Ave. to Deer Pk.	WB	1.1	2	35
	Main St.	Deer Pk. to Library Ave.	EB	1.5	2	45
	SR 273	Deer Park to MD Line	WB	1.9	1	25,35
	SR 273	MD Line to Deer Park	EB	1.9	1	40,35,25
SR 273	**SR 273**	**SR 141 to MD Line**	**WB**	**12.4**		
Total	**SR 273**	**MD Line to SR 141**	**EB**	**12.8**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
US 13	DuPont Hwy	I-495 to Delaware Ave.	NB	2.2	2	35,25
	DuPont Hwy	Delaware Ave. to I-495	SB	2.3	2	25,35,50
	DuPont Hwy	I-295 to I-495	NB	1.8	2	50
	DuPont Hwy	I-495 to I-295	SB	1.8	2	50
	DuPont Hwy	141 to I-295	NB	1.3	2	35,25
	DuPont Hwy	I-295 to 141	SB	1.3	2	25,35,50
	DuPont Hwy	SR 273 to 141	NB	1.3	2	35,25
	DuPont Hwy	141 to SR 273	SB	1.3	2	25,35,50
	DuPont Hwy	US 40 to SR 273	NB	1.0	2	35,25
	DuPont Hwy	SR 273 to US40	SB	1.0	2	25,35,50
	DuPont Hwy	SR1/US13 Split to US 40	NB	3.6	2	55,50
	DuPont Hwy	US 40 to SR1/US13 Merge	SB	3.2	2,3	55
	DuPont Hwy	US13/SR1 Merge to US13/SR1 Split	NB	2.1	2,3	55

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
	DuPont Hwy	US13/SR1 Merge to US13/SR1 Split	SB	2.6	2,3	55
	DuPont Hwy	SR 896 to SR1/US13 Merge	NB	5.7	2	55
	DuPont Hwy	SR1/US13 Split to SR 896	SB	5.8	2	55
	DuPont Hwy	SR 299 to SR 896	NB	3.1	2	35,55,45
	DuPont Hwy	SR 896 to SR 299	SB	3.1	2	55,45,35
	DuPont Hwy	SR 71 to SR 299	NB	5.4	2	55,45,35
	DuPont Hwy	SR 299 to SR 71	SB	5.4	2	35,45,55
	DuPont Hwy	County Ln to SR 71	NB	5.8	2	55,45,35
	DuPont Hwy	SR 71 to County Ln	SB	5.8	2	35,45,55
US 13	**DuPont Hwy**	**County Ln to Del. Ave.**	**NB**	**33.3**		
Total	**DuPont Hwy**	**Del. Ave. to County Ln**	**SB**	**33.6**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
US 40	Pulaski Hwy	US 13 to SR 1	WB	2.3	2	50
	Pulaski Hwy	SR 1 to US 13	EB	2.3	2	55,35
US 40	Pulaski Hwy	SR 1 to SR 7	WB	0.4	3	35,50
Cont'd	Pulaski Hwy	SR 7 to SR 1	EB	0.4	3	50,55
	Pulaski Hwy	SR 7 to Porter Rd.	WB	2.1	3,2	50
	Pulaski Hwy	Porter Rd. to SR 7	EB	2.1	2	55,50
	Pulaski Hwy	Porter Rd. to SR 72	WB	1.4	2	55
	Pulaski Hwy	SR 72 to Porter Rd.	EB	1.4	2	55, 50
	Pulaski Hwy	SR 72 to SR 896	WB	1.4	2	55
	Pulaski Hwy	SR 896 to SR 72	EB	1.4	2	55
	Pulaski Hwy	SR 896 to MD Line	WB	2.4	2	55
	Pulaski Hwy	MD Line to SR 896	EB	2.4	2	55
US 40	**Pulaski Hwy**	**US 13 to MD Line**	**WB**	**10.0**		
Total	**Pulaski Hwy**	**MD Line to US 13**	**EB**	**10.0**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
SR 896	SR 896	US 13 to US 301	NB	3.5	1	50,35,25
	SR 896	US 301 to US 13	SB	3.5	1	25,35,50
	SR 896	US 301 to SR 15	NB	2.2	2	50,55
	SR 896	SR 15 to US 301	SB	2.2	2	55
	SR 896	SR 15 to SR 71	NB	2.0	2	55

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
	SR 896	SR 71 to SR 15	SB	2.0	2	55
	SR 896	SR 71 to Porter Rd.	NB	2.0	2	55
	SR 896	Porter Rd. to SR 71	SB	2.0	2	55
	SR 896	Porter Rd. to US 40	NB	1.4	2,3	55
	SR 896	US 40 to Porter Rd.	SB	1.4	3,2	55
SR 896	**SR 896**	**US 13 to US 40**	**NB**	**11.1**		
SubTotal	**SR 896**	**US 40 to US 13**	**SB**	**11.1**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
SR 896	SR 896	US 40 to Old Baltimore	NB	2.2	3,2	50
	SR 896	Old Baltimore to US 40	SB	2.2	2	50
	SR 896	Old Baltimore to I-95	NB	0.8	2	50,40
	SR 896	I-95 to Old Baltimore	SB	0.8	2	50
	SR 896	I-95 to SR 4	NB	0.9	2	40,35
	SR 896	SR 4 to I-95	SB	0.9	2	35,50
	SR 896	SR 4 to Chrysler	NB	0.6	2	50
	SR 896	Chrysler to SR 4	SB	0.6	2	35
	SR 896	Chrysler to Park Place	NB	0.5	2,1	50,45
	SR 896	Park Place to Chrysler	SB	0.5	2	45,50
	SR 896	Park Place to Del. Ave @ South Coll.	NB	0.5	2	35
	SR 896	Del. Ave @ South Coll. To Park Place	SB	0.5	2	35
	SR 896	Del. Ave @ South Coll. To Deer Park	NB	0.2	2	35,25
	SR 896	Deer Park to Del. Ave @ South Coll	SB	0.2	2	25,35
	SR 896	Deer Park to PA Line	NB	3.1	1	25,35,45
	SR 896	PA Line to Deer Park	SB	3.1	1	50,45,35,25
SR 896	**SR 896**	**US 40 to PA Line**	**NB**	**8.7**		
SubTotal	**SR 896**	**PA Line to US 40**	**SB**	**8.7**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
SR 896	**SR 896**	**US 13 to PA Line**	**NB**	**19.8**		
Total	**SR 896**	**PA Line to US 13**	**SB**	**19.8**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
48/41	Lancaster Pk.	PA Line to SR 41	EB	2.7	2,1	45,35
	Lancaster Pk.	SR 41 to PA Line	WB	2.7	2,1	45,35

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
	Lancaster Pk.	SR 41 to Hercules CC	EB	1.9	1	50
	Lancaster Pk.	Hercules CC to SR 41	WB	1.9	2,1	50
	Lancaster Pk.	Hercules CC to SR 141	EB	1.9	1,2	45
	Lancaster Pk.	SR 141 to Hercules CC	WB	1.9	2,1	45,50
	Lancaster Pk.	SR 141 to SR 100	EB	0.9	2	40
	Lancaster Pk.	SR 100 to SR 141	WB	0.9	2	40
	Lancaster Pk.	SR 100 to SR 2	EB	0.8	2,1	25
	Lancaster Pk.	SR 2 to SR 100	WB	0.8	1,2	25
	Lancaster Pk.	SR 2 to I-95	EB	0.8	2,1	25
	Lancaster Pk.	I-95 to SR 2	WB	0.8	1,2	25
	Lancaster Pk.	I-95 to Market St.	EB	0.5	2,1	25
	Lancaster Pk.	Market St. to I-95	WB	0.5	1,2	25
48/41	**Lancaster Pk.**	**PA Line to Market St.**	**EB**	**9.5**		
Total	**Lancaster Pk.**	**Market St. to PA Line**	**WB**	**9.5**		

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
SR 261	Foulk Road	PA line to Naamans	SB	0.6	1,2	35,45
	Foulk Road	Naamans to PA line	NB	0.6	2,1	45,35
	Foulk Road	Naamans Rd. to Silverside	SB	1.4	1,2	35,45
	Foulk Road	Silverside to Naamans Rd	NB	1.4	2,1	45,35
	Foulk Road	Silverside to Shipley	SB	1.2	2	45
	Foulk Road	Shipley to Silverside	NB	1.2	2	45
	Foulk Road	Shipley to US 202	SB	1.4	2	45
	Foulk Road	US 202 to Shipley	NB	1.4	2	45
SR 261	**Foulk Road**	**PA line to US 202**	**SB**	**4.6**		
Total	**Foulk Road**	**US 202 to PA line**	**NB**	**4.6**		
SR 2	Cleveland Ave	SR 896 to Paper Mill	EB	0.6	1	25
	Cleveland Ave	Paper Mill to SR 896	WB	0.6	1	25
	Cleveland Ave	Paper Mill to SR 72	EB	0.6	2	35
	Cleveland Ave	SR 72 to Paper Mill	WB	0.6	2	35
	Cleveland Ave	SR 72 to SR 273	EB	0.1	2	35
	Cleveland Ave	SR 273 to SR 72	WB	0.1	1	35

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
	Cleveland Ave	SR 273 to Marrows Rd	EB	0.2	2	35
	Cleveland Ave	Marrows Rd to SR 273	WB	0.2	1	35
SR 2	**Cleveland Ave**	**SR 896 to Marrows Rd**	**EB**	**1.5**		
Total	**Cleveland Ave**	**Marrows Rd to SR 896**	**WB**	**1.5**		

SR 2	Elkton Road	Deer Park to Park Place	WB	0.8	2	25,35
	Elkton Road	Park Place to Deer Park	EB	0.8	2	35,25
	Elkton Road	Park Place to SR 4	WB	0.9	2	35,45
	Elkton Road	SR 4 to Park Place	EB	0.9	2	50,45,35
	Elkton Road	SR 4 to MD Line	WB	1.0	2	50
	Elkton Road	MD Line to SR 4	EB	1.0	2	50
SR 2	**Elkton Road**	**Deer Park to MD Line**	**WB**	**2.6**		
Total	**Elkton Road**	**MD Line to Deer Park**	**EB**	**2.6**		

Table 18: Multilane signalized corridors in Kent County

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
US 13	US 13	Sussex Ln to Rt 14	NB	6.2	2	55,45
	US 13	Rt 14 to Sussex Ln	SB	6.2	2	45,55
	US 13	Rt 14 to Rt 12	NB	5.8	2	45,55,45
	US 13	Rt 12 to Rt 14	SB	5.8	2	45,55,45,35
	US 13	Rt 12 to Rt 10a	NB	4.5	2	45,55
	US 13	Rt 10a to Rt 12	SB	4.5	2	55,45
	US 13	Rt 10a to Rt 10	NB	3.0	2	55,50
	US 13	Rt 10 to Rt 10a	SB	3.0	2	50,55
	US 13	Rt 10 to Rt 8	NB	3.8	2	50,35
	US 13	Rt 8 to Rt 10	SB	3.8	2	35,50
	US 13	Rt 8 to Scarborough Rd.	NB	3.4	3,2	35,40,45,55
	US 13	Scarborough Rd. to Rt 8	SB	3.4	2,3	55,45,40,35
	US 13	Scarborough Rd. to Rt 42	NB	2.0	2	55
	US 13	Rt 42 to Scarborough Rd.	SB	2.0	2	55
	US 13	SR 42 to Exit 114	NB	4.2	2	55,45,35
	US 13	Exit 114 to SR 42	SB	4.2	2	35,45,55
	US 13	Exit 114 to NCC Line	NB	2.1	2	35,45
	US 13	NCC Line to Exit 114	SB	2.1	2	35,45,55
US 113	US 113	US 13 to SR 10	SB	2.2	2	45
	US 113	SR 10 to US 13	NB	2.2	2	45
	US 113	10 to Exit 93	SB	1.0	2	55
	US 113	Exit 93 to 10	NB	1.0	2	50,55
	US 113	Exit 93 to SR 9	SB	1.7	2	55
	US 113	SR 9 to Exit 93	NB	1.7	2	55
	US 113	SR 9 to Rd 18 (Bowers)	SB	4.5	2	55
	US 113	Rd 18 (Bowers) to SR 9	NB	4.5	2	55
	US 113	Bowers to SR 12	SB	3.4	2	55
	US 113	SR 12 to Bowers	NB	3.4	2	55
	US 113	SR 12 to SR 1	SB	4.1	2	55
	US 113	SR 1 to SR 12	NB	4.1	2	55
	US 113	SR 1 to Sussex Line	SB	2.0	1,2	45,40
	US 113	Sussex Line to SR 1	NB	2.1	2,1	40,45

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
SR 10	E Lebanon Rd	SR 1 to SR 10A	WB	1.6	2	50
	E Lebanon Rd	SR 10A to SR 1	EB	1.6	2	50
	W Lebanon Rd	SR 10A to US 13	WB	1.2	2	40,50
	W Lebanon Rd	US 13 to SR 10A	EB	1.2	2	40,50

Table 19: Multilane signalized corridors in Sussex County

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
US 13	US 13	County Line to SR 16	SB	2.0	2	55,45
	US 13	SR 16 to County Line	NB	2.0	2	45,55
	US 13	SR 16 to SR 404 West	SB	3.3	2	35,55
	US 13	SR 404 West to SR 16	NB	3.3	2	55,35
	US 13	SR 404 West to SR 404 East	SB	2.5	2	55
	US 13	SR 404 East to SR 404 West	NB	2.5	2	55
	US 13	SR 404 East to SR 20 West	SB	4.9	2	55,45
	US 13	SR 20 West to SR 404 East	NB	4.9	2	45,55
	US 13	SR 20 West to US 9	SB	6.0	2	55
	US 13	US 9 to SR 20 West	NB	6.0	2	55
	US 13	US 9 to SR 24	SB	1.1	2	55
	US 13	SR 24 to US 9	NB	1.1	2	55
	US 13	SR 24 to SR 30	SB	3.7	2	55
	US 13	SR 30 to SR 24	NB	3.7	2	55
	US 13	SR 30 to MD Line (SR 54)	SB	3.2	2	55
	US 13	MD Line (SR 54) to SR 30	NB	3.2	2	55
US 13	**US 13**	**County Line to MD Line (SR 54)**	**SB**	**26.7**		
Total	**US 13**	**MD Line (SR 54) to County Line**	**NB**	**26.7**		

US 113	US 113	County Line to SR 16	SB	7.4	2	50,55
	US 113	SR 16 to County Line	NB	7.4	2	55,50,40
	US 113	SR 16 to SR 404/18	SB	8.0	2	55
	US 113	SR 404/18 to SR 16	NB	8.0	2	55
	US 113	SR 404/18 to US 9	SB	1.2	2	50
	US 113	US 9 to SR 404/18	NB	1.2	2	50
	US 113	US 9 to SR 20 West	SB	7.1	2	55
	US 113	SR 20 West to US 9	NB	7.1	2	55,50
	US 113	SR 20 West to SR 24	SB	1.5	2	50
	US 113	SR 24 to SR 20 West	NB	1.5	2	50
	US 113	SR 24 to SR 20 East	SB	1.6	2	50,55

Route	Route Name	Segment	Dir.	Dist. (miles)	# of Lanes	Posted Speed (mph)
	US 113	SR 20 East to SR 24	NB	1.6	2	55,50
	US 113	SR 20 East to SR 26	SB	2.0	2	55
	US 113	SR 26 to SR 20 East	NB	2.0	2	55
	US 113	SR 26 to MD Line	SB	6.6	2,1	55,50
	US 113	MD Line to SR 26	NB	6.6	2	50,55
US 113	**US 113**	**County Line to MD Line**	**SB**	**35.4**		
Total	**US 113**	**MD Line to County Line**	**NB**	**35.4**		

Appendix D: Data Collection Locations

1. New Castle County

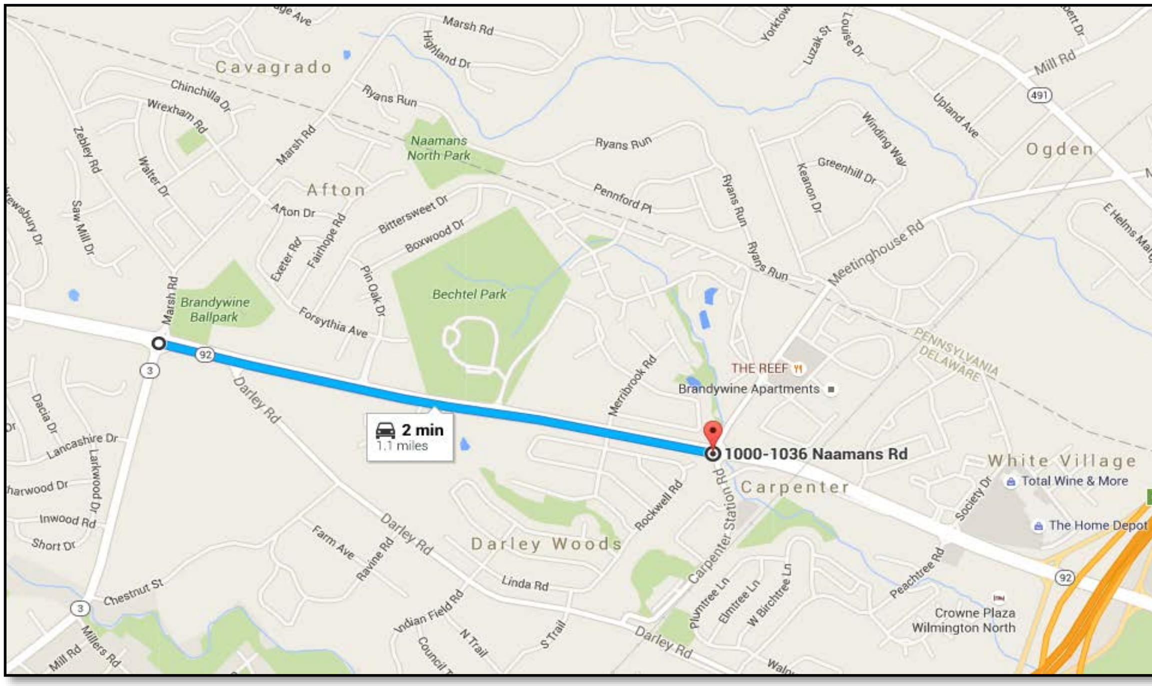


Figure 31: Naamans Rd., Foulk Rd. to I-95, EB/WB; 6/13/2014 -7/25/2014, 9am-4pm

(Imagery © 2016 Google, map data © 2016 Google)

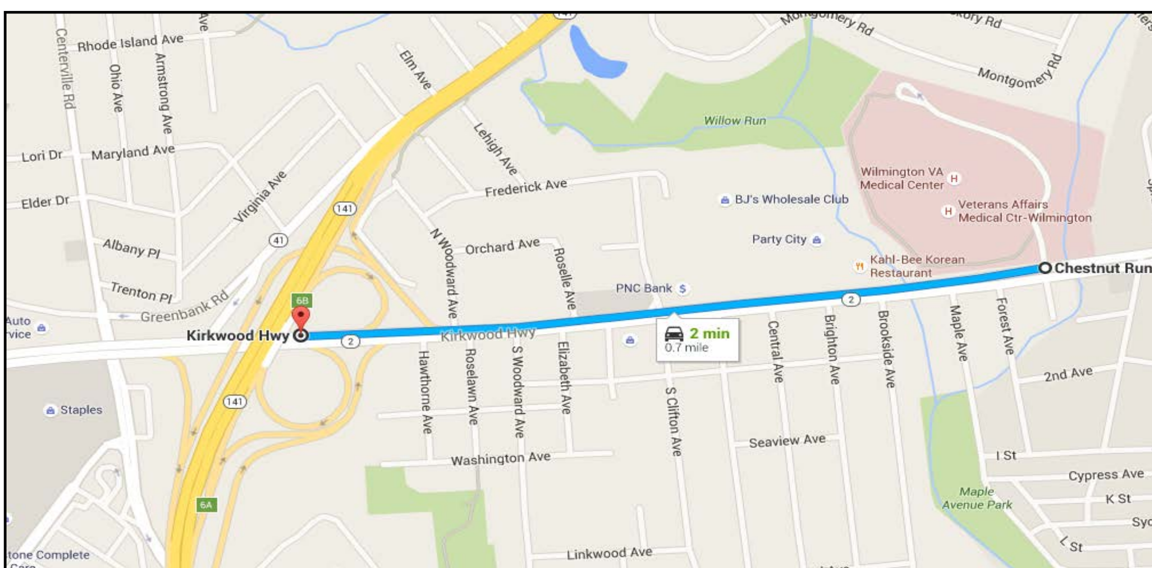


Figure 32: Kirkwood Hwy, SR 100 to SR 141, WB/EB, 4/20/2015 - 5/8/2015, 24/7

(Imagery © 2016 Google, map data © 2016 Google)

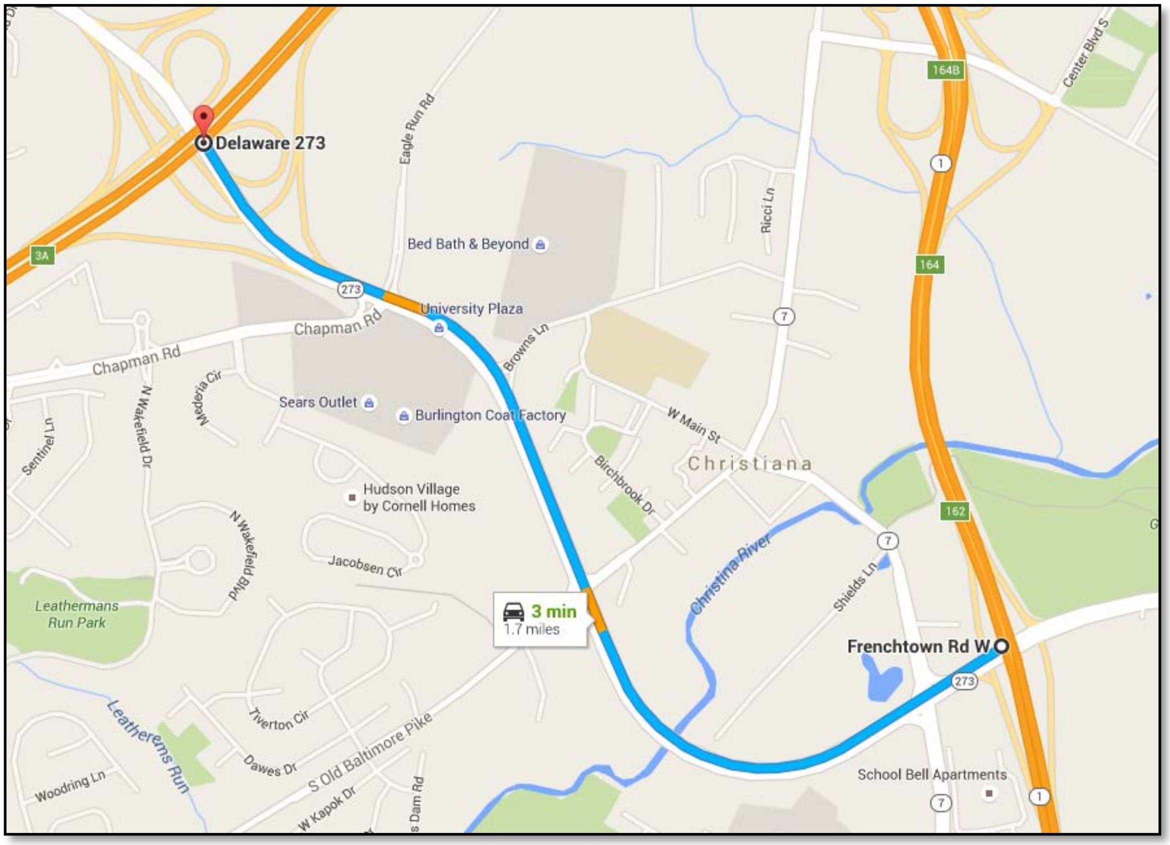


Figure 33: SR 273, SR 1 to I-95, WB/EB, 1/16/2015 - 2/27/2015 8am- 3pm
(Imagery © 2016 Google, map data © 2016 Google)

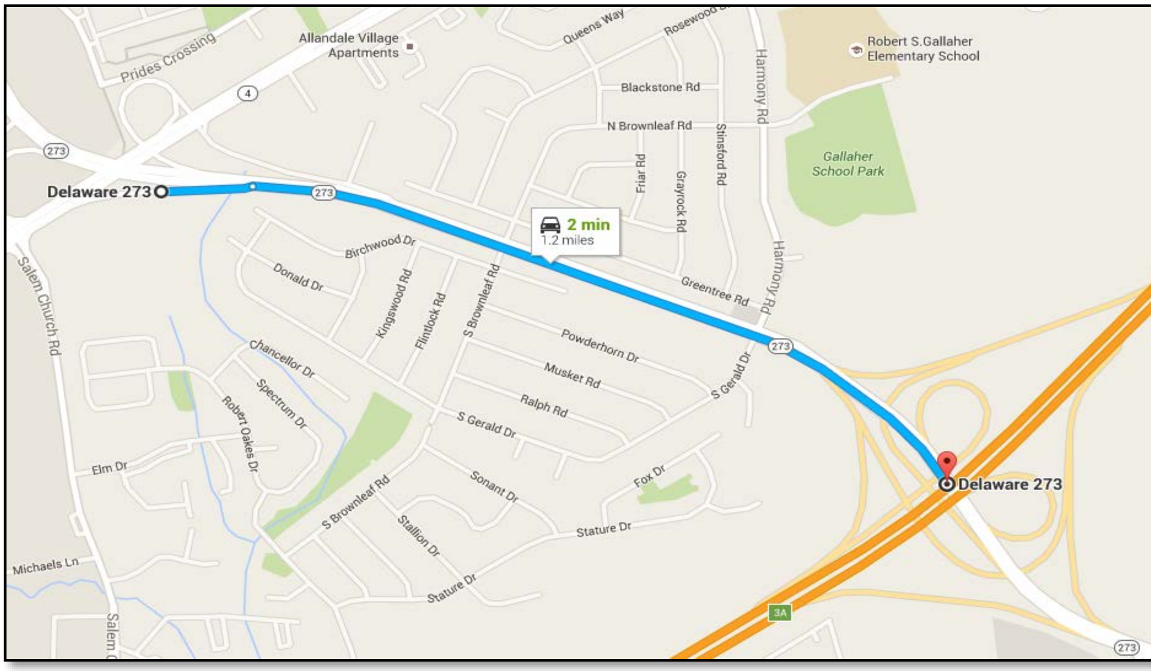


Figure 34: SR 273, Rt. 4 to I-95, EB only, 9/15/2014 - 9/19/2014, 9am-3pm
(Imagery © 2016 Google, map data © 2016 Google)

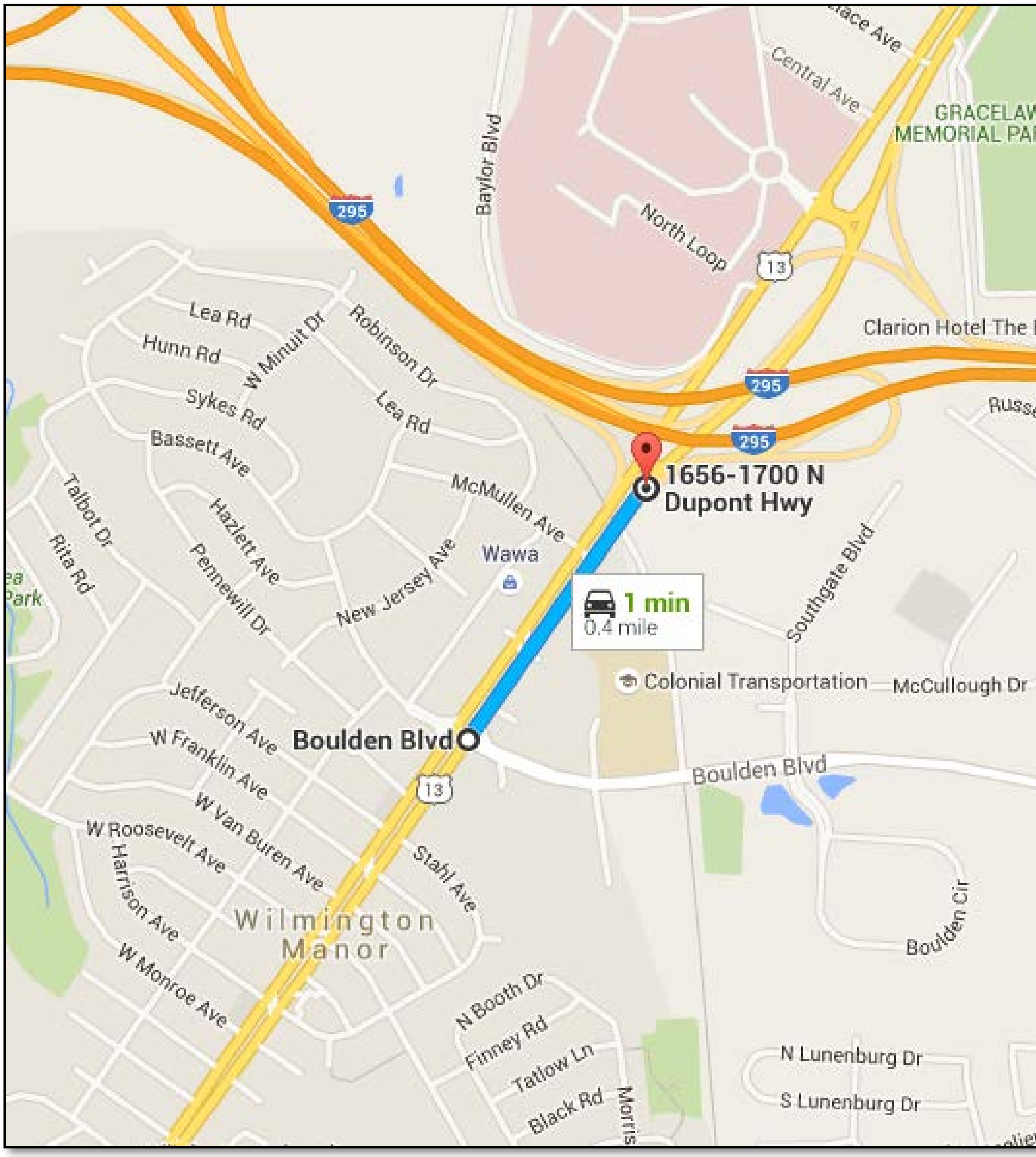


Figure 35: DuPont Hwy, 141 to I-295, NB only, 1/6/2014 - 7/6/2015 24/7

(Imagery © 2016 Google, map data © 2016 Google)

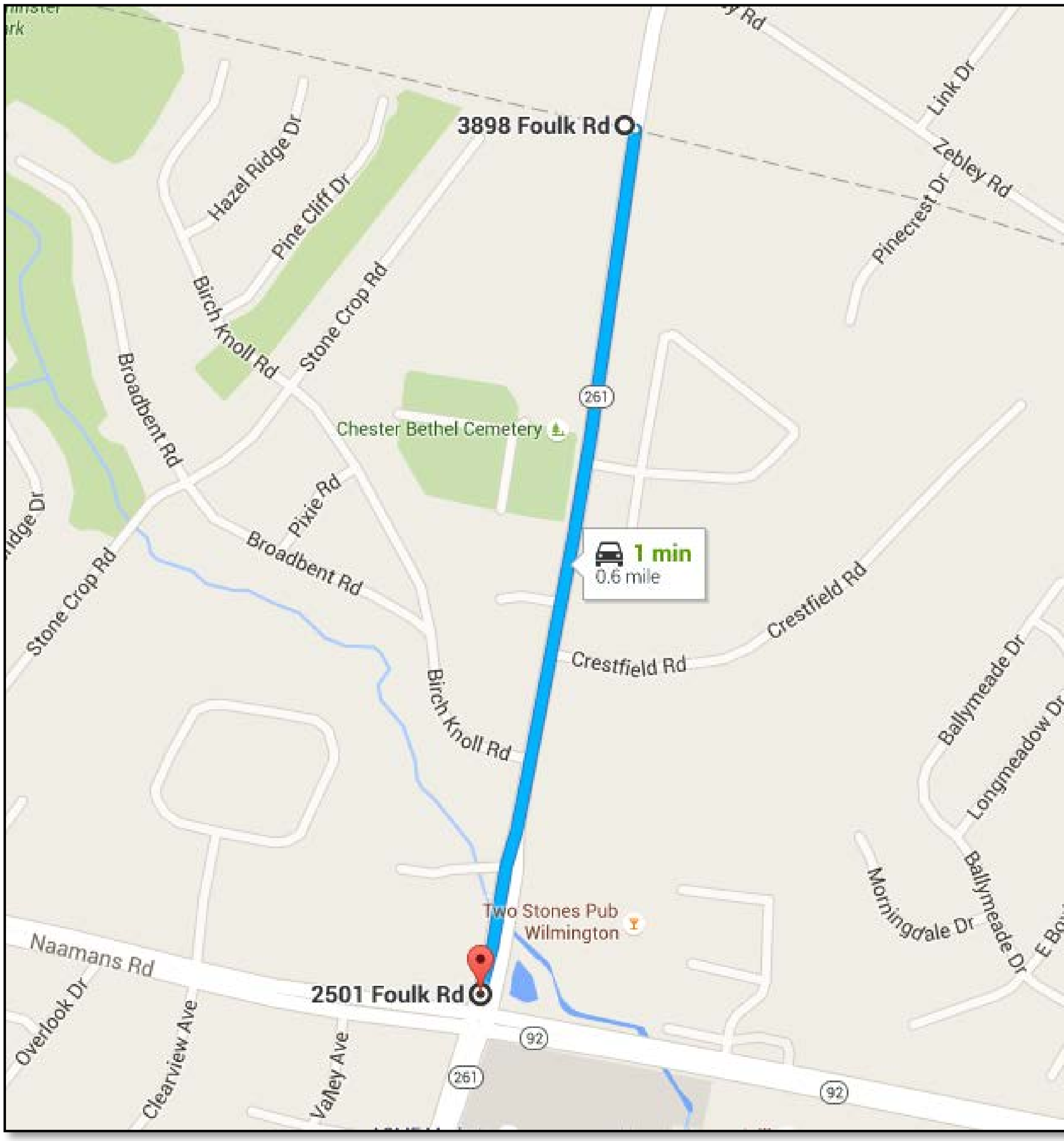


Figure 36: Foulk Road, PA line to Naamans, SB/NB, 5/20/2013 - 6/28/2013, 7am - 5pm

(Imagery © 2016 Google, map data © 2016 Google)

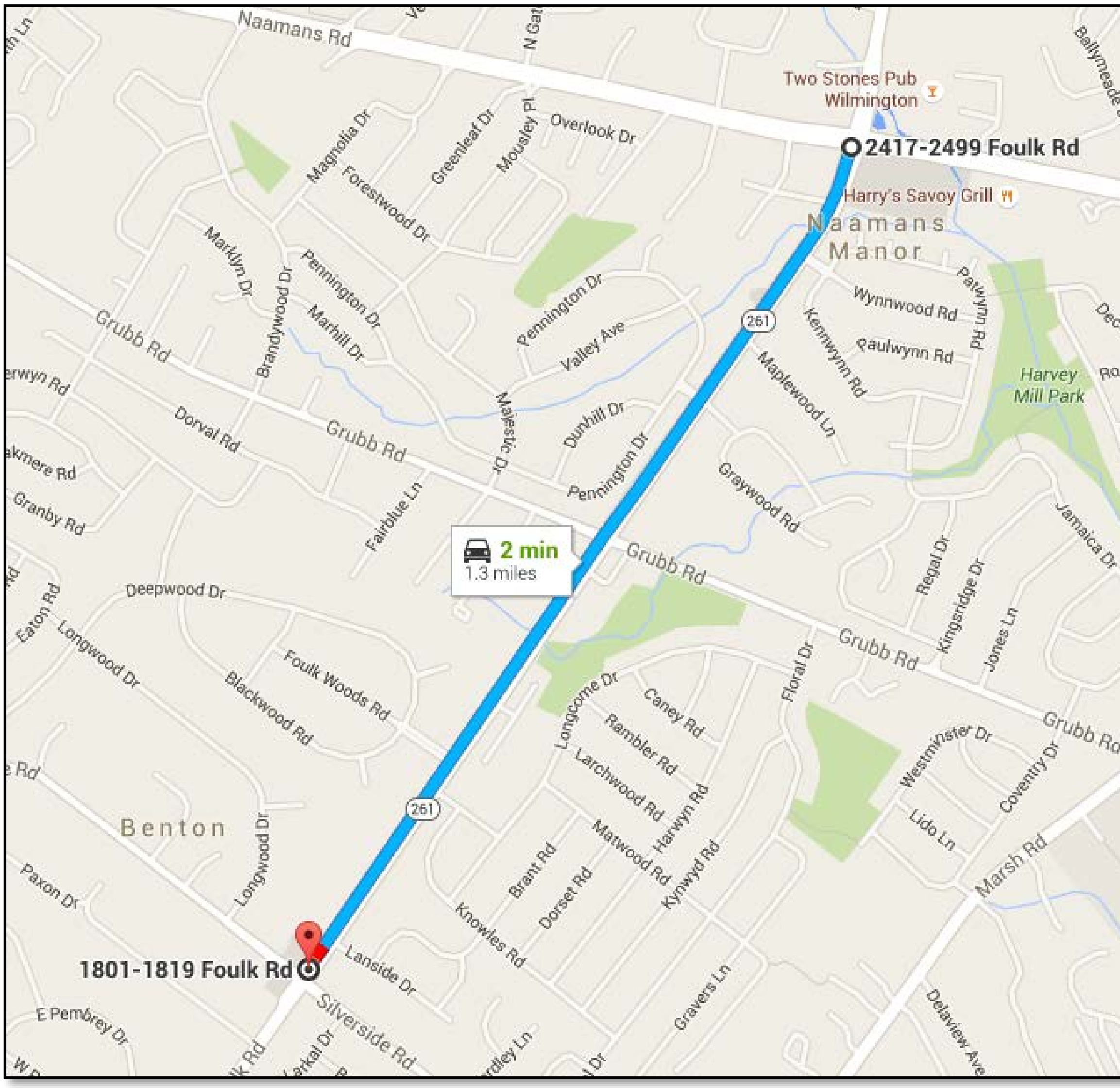


Figure 37: Foulk Rd, Naamans Rd. to Silverside, SB/NB, 6/25/2012 -11/15/2012, 7am - 5pm

(Imagery © 2016 Google, map data © 2016 Google)

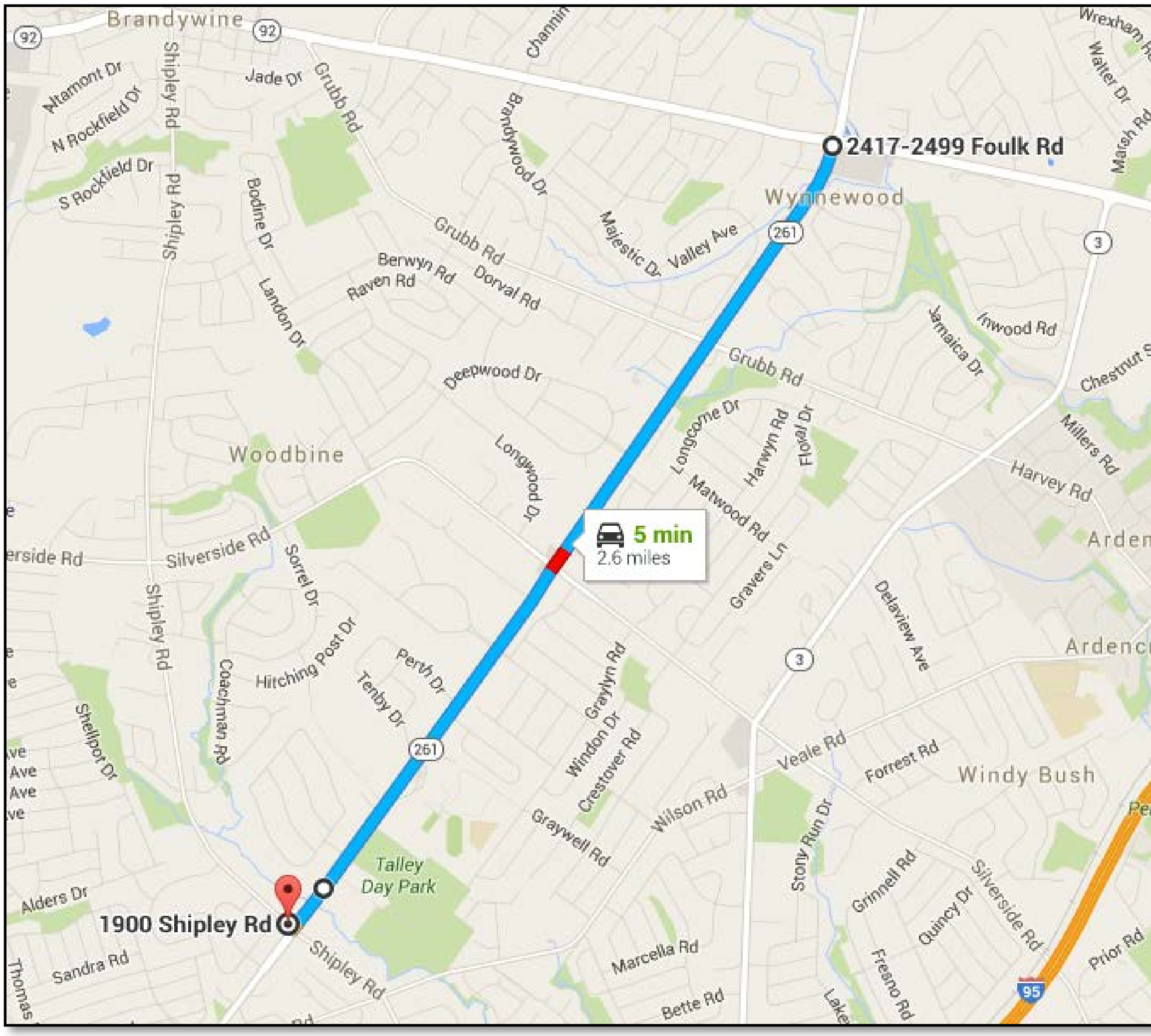


Figure 38: Foulk Road, Silverside to Shipley, SB/NB, 6/25/2012 - 11/15/2012, 7am - 5pm

(Imagery © 2016 Google, map data © 2016 Google)

2. Kent County

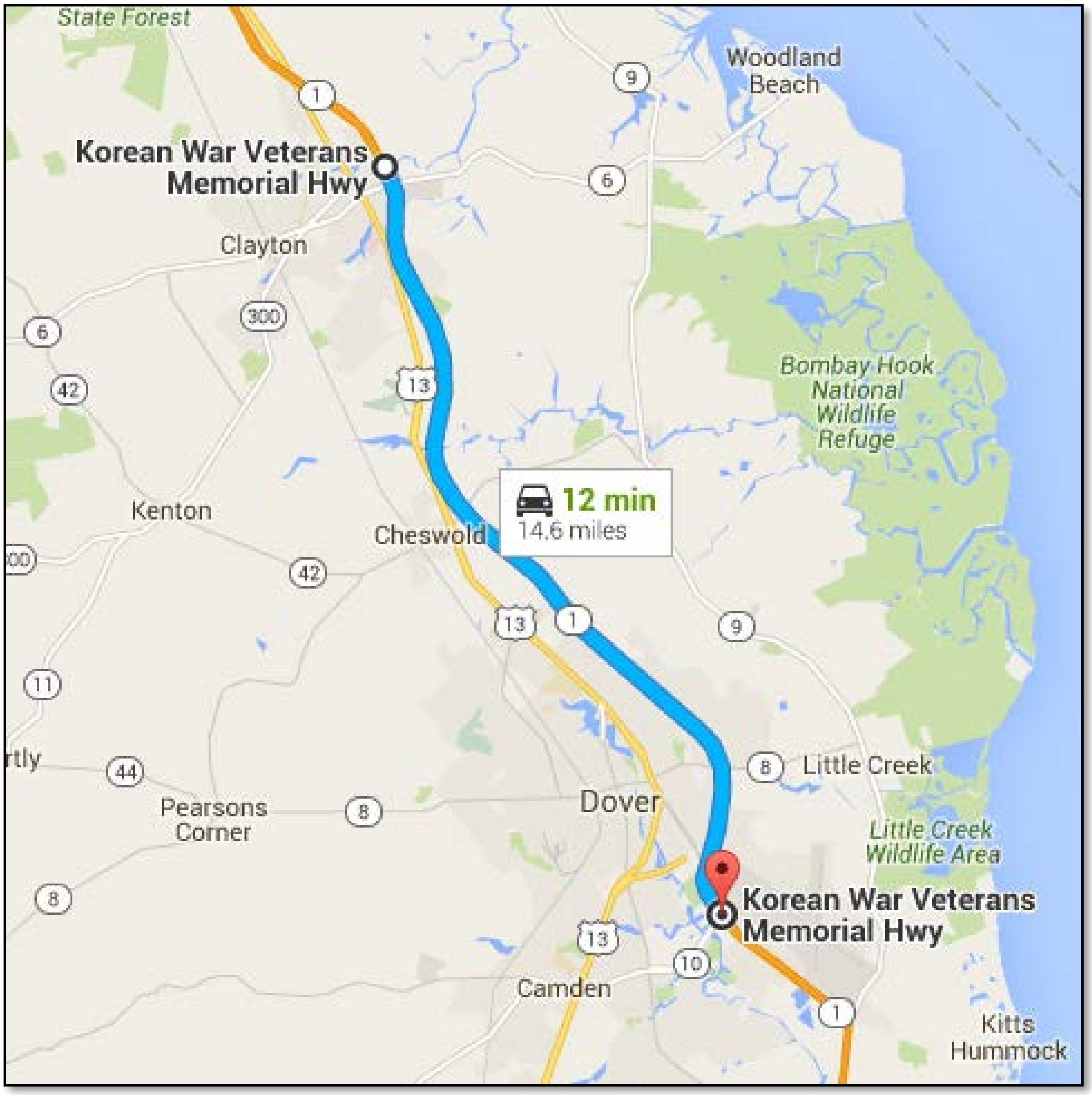


Figure 39: Relief Route, NB only, 12/14/2012 -12/31/2014, 8am -2pm

(Imagery © 2016 Google, map data © 2016 Google)

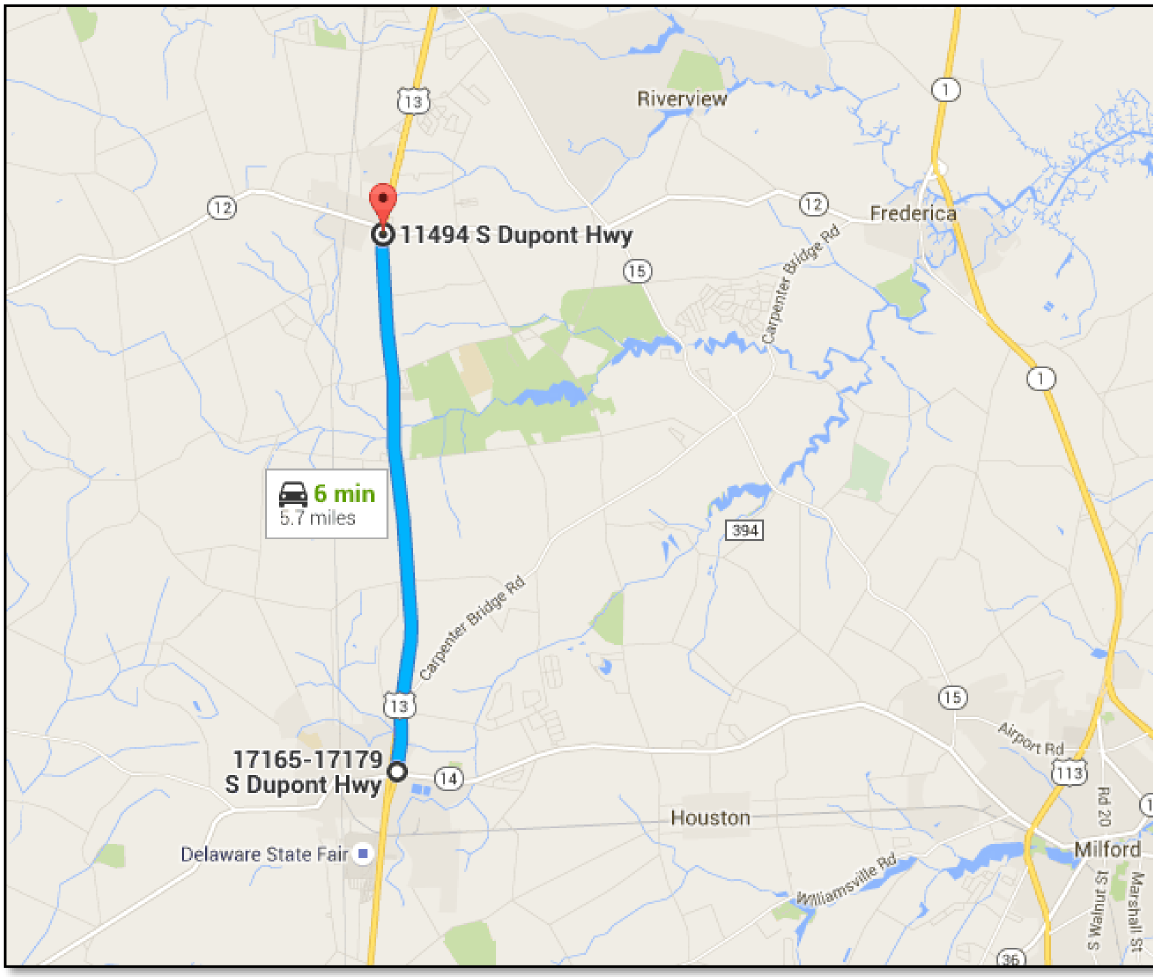


Figure 40: US 13, Rt 14 to Rt 12, NB, 5/5/2014 -5/30/2014, 9am -2pm
(Imagery © 2016 Google, map data © 2016 Google)

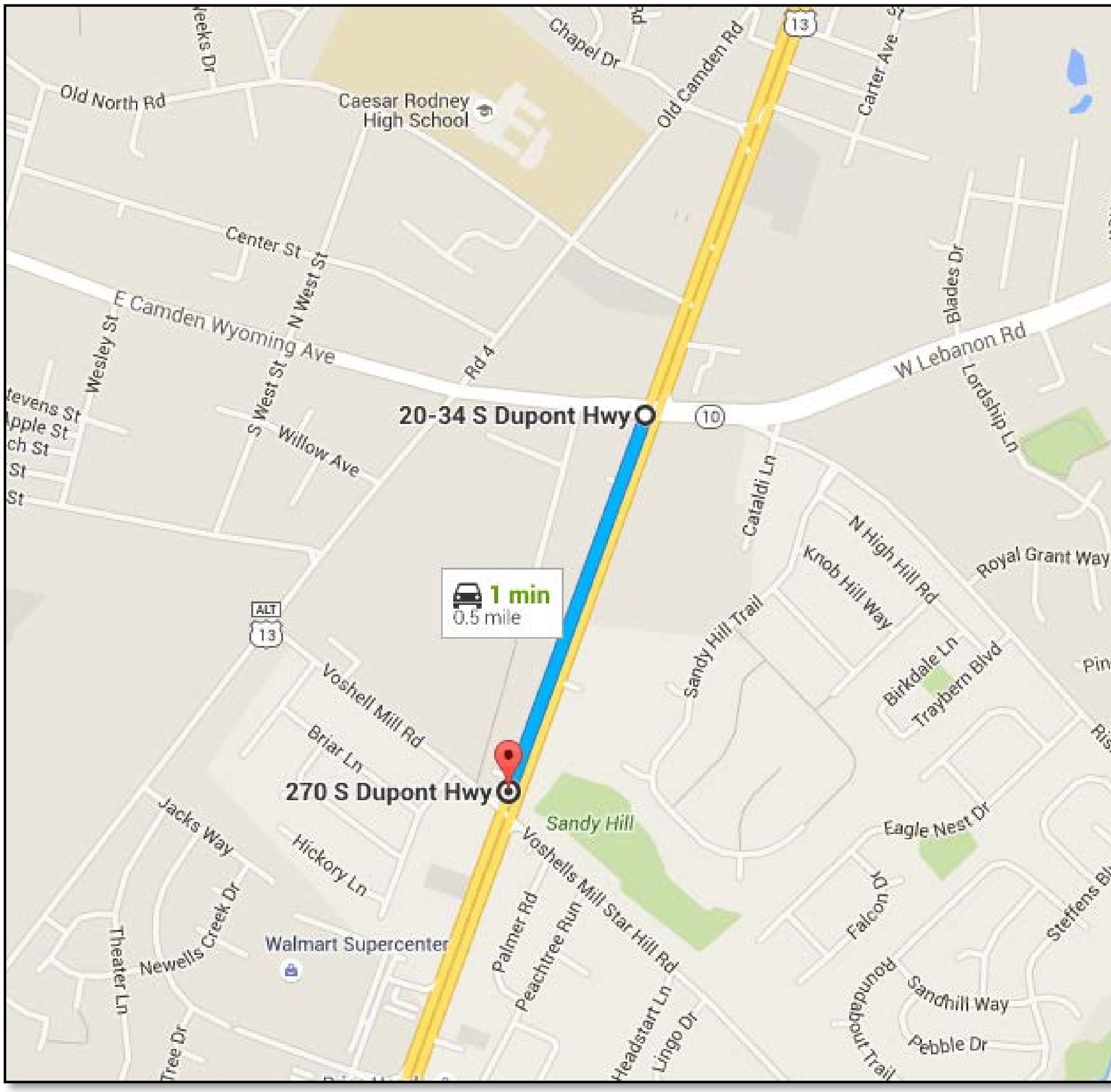


Figure 41: US 13, Rt 10a to Rt 10, NB/SB, 11/28/2013 -11/29/2013, 8am - 3pm

(Imagery © 2016 Google, map data © 2016 Google)

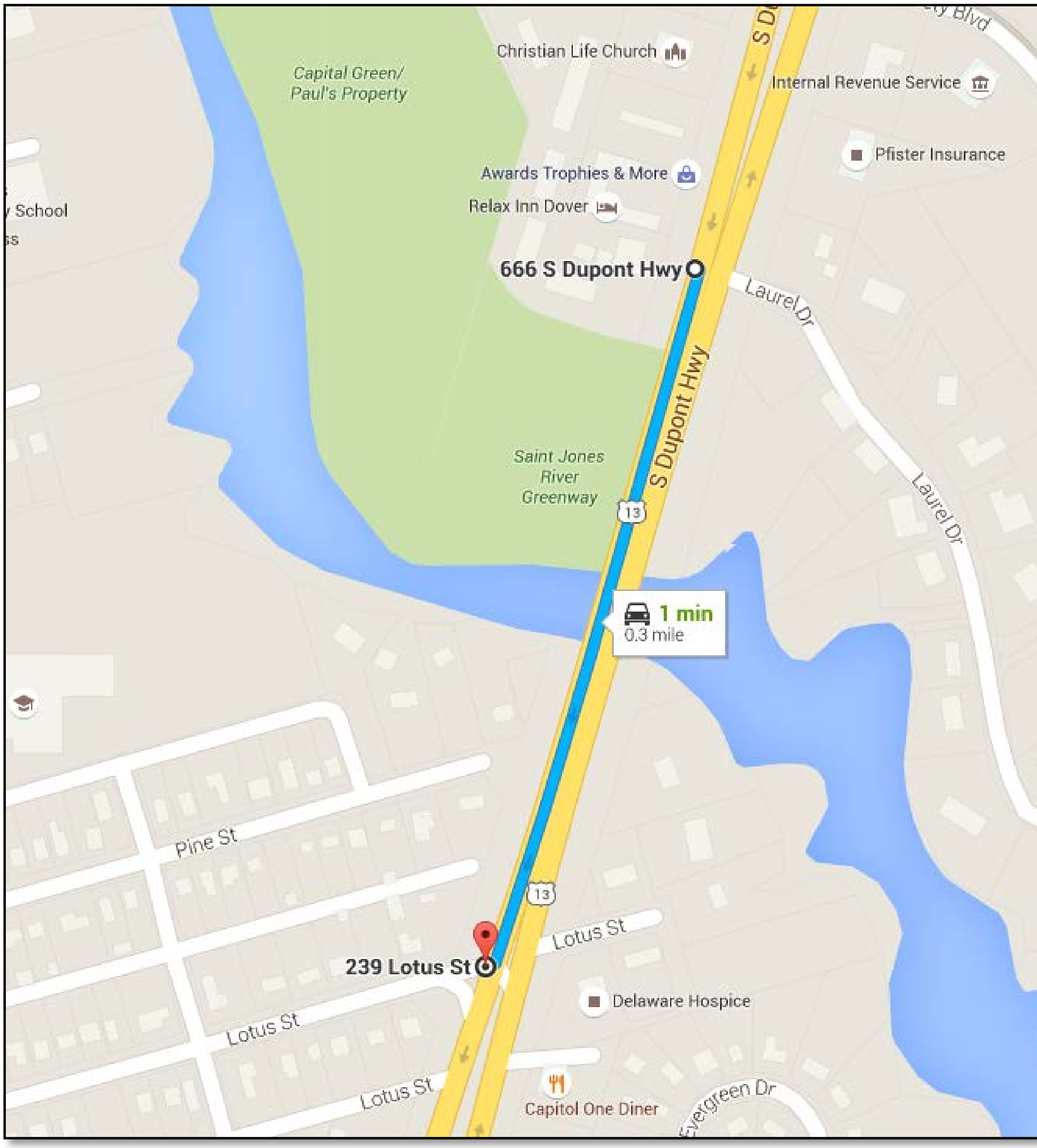


Figure 42: US 13, Rt 10 to Rt 8, NB/SB,12/2/2013-3/14/2014,8am -3pm
(Imagery © 2016 Google, map data © 2016 Google)

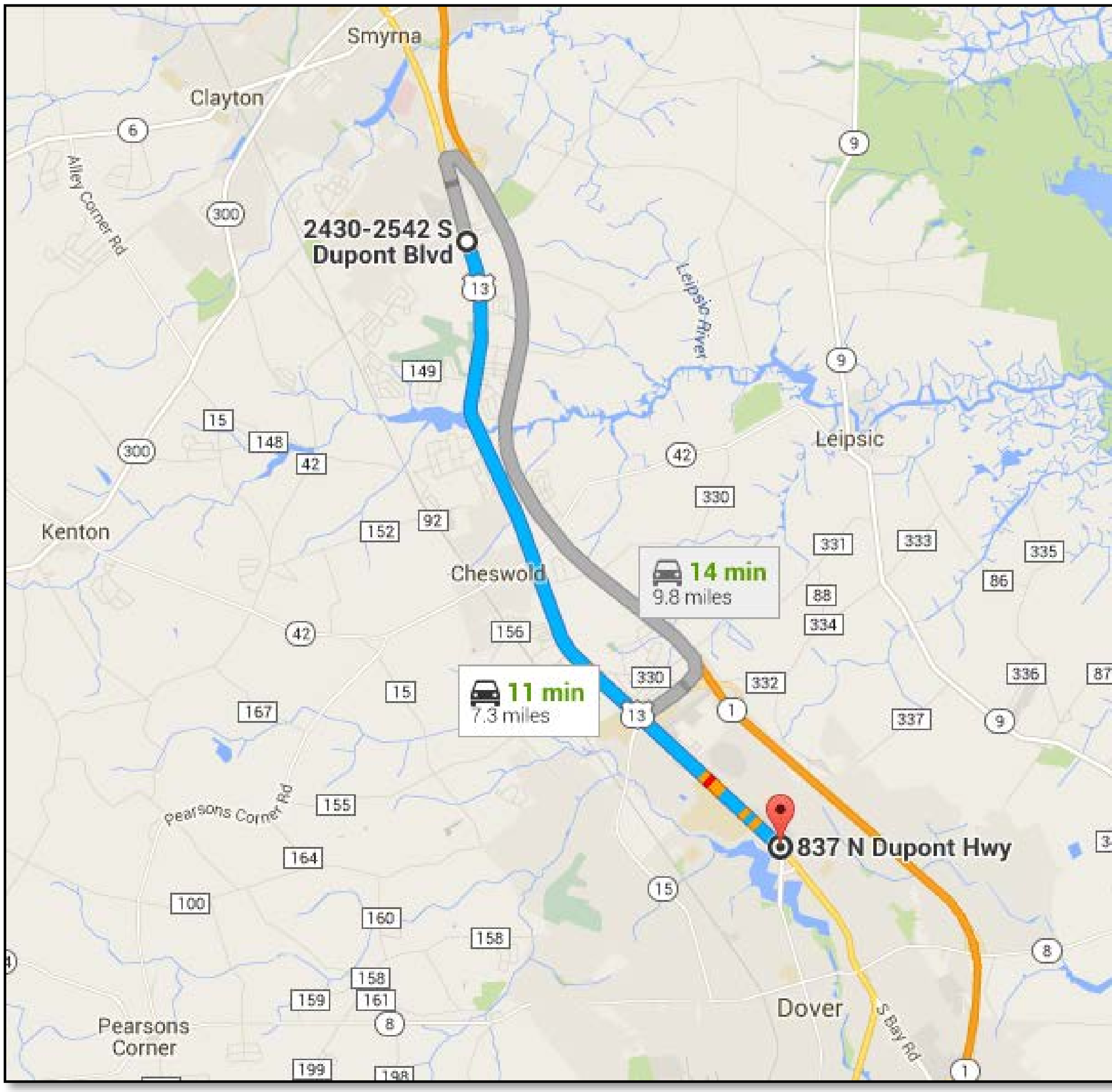


Figure 43: US 13, Rt 8 to Scarborough Rd., NB/SB,1/20/2014 -3/14/2014, 9am-3pm
(Imagery © 2016 Google, map data © 2016 Google)

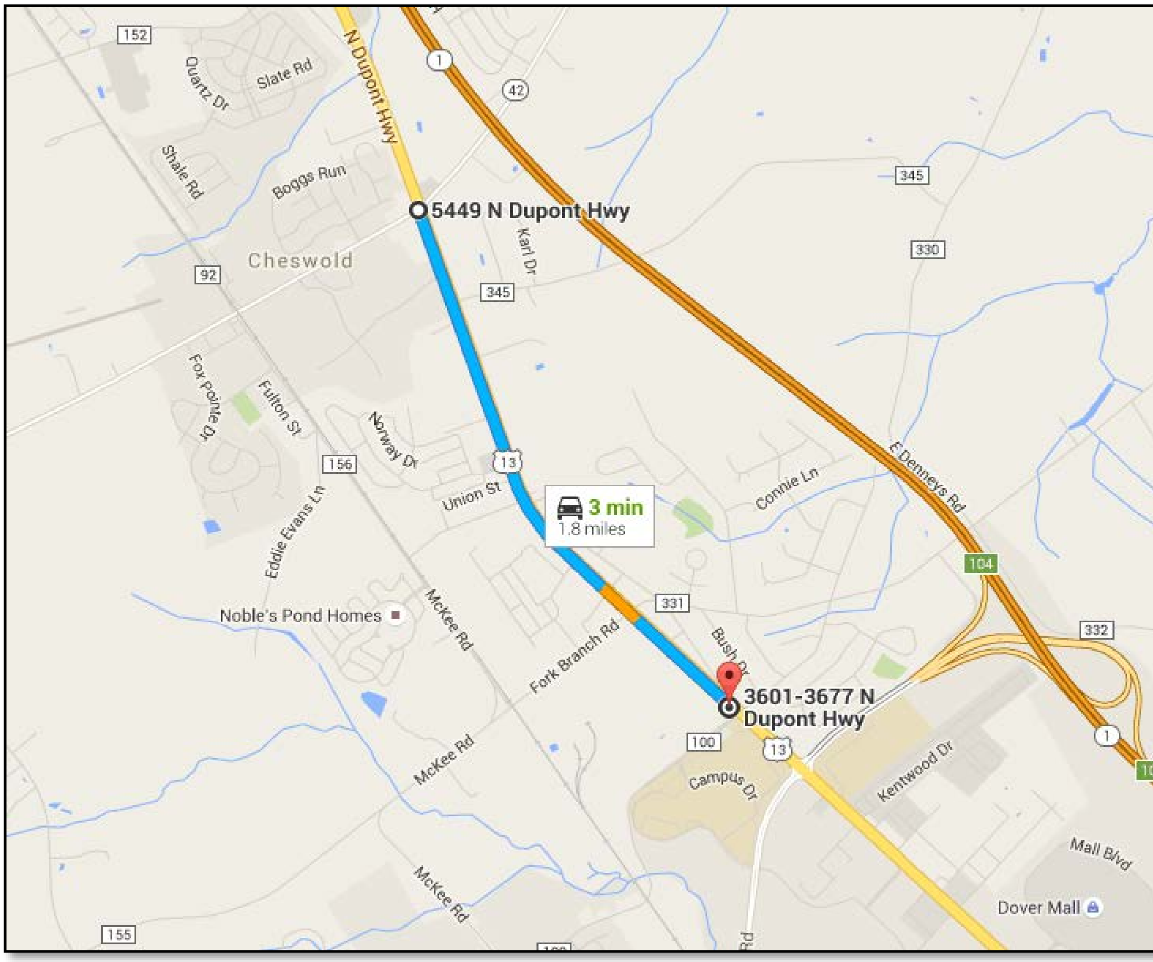


Figure 44: US 13,Scarborough Rd. to Rt 42,NB/SB, 1/4/2013 - 2/8/2013, 9am -3pm

(Imagery © 2016 Google, map data © 2016 Google)

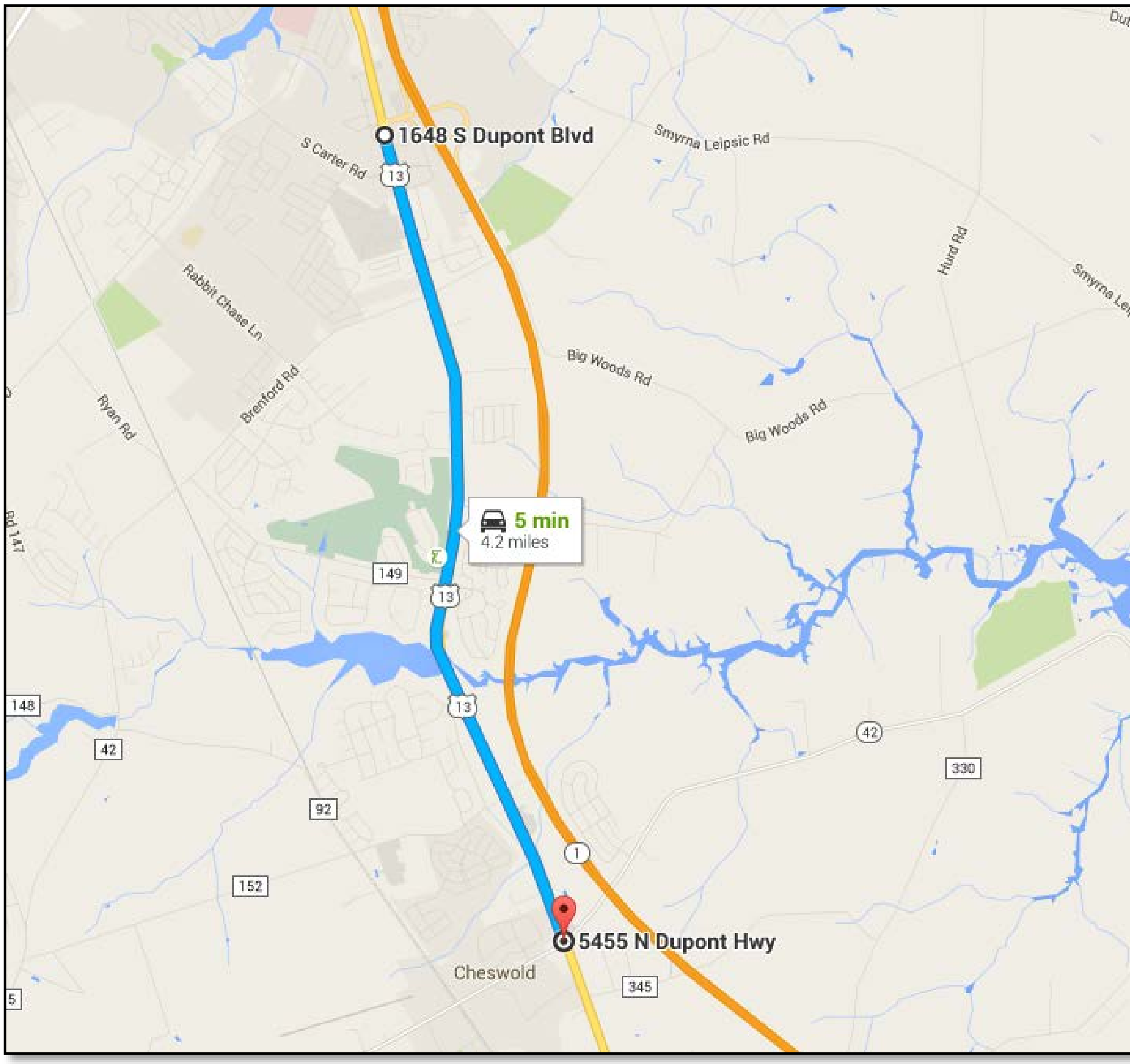


Figure 45: US 13,SR 42 to Exit 114,NB only,1/20/2014 -3/14/2014, 9am-3pm
(Imagery © 2016 Google, map data © 2016 Google)

3. Sussex County

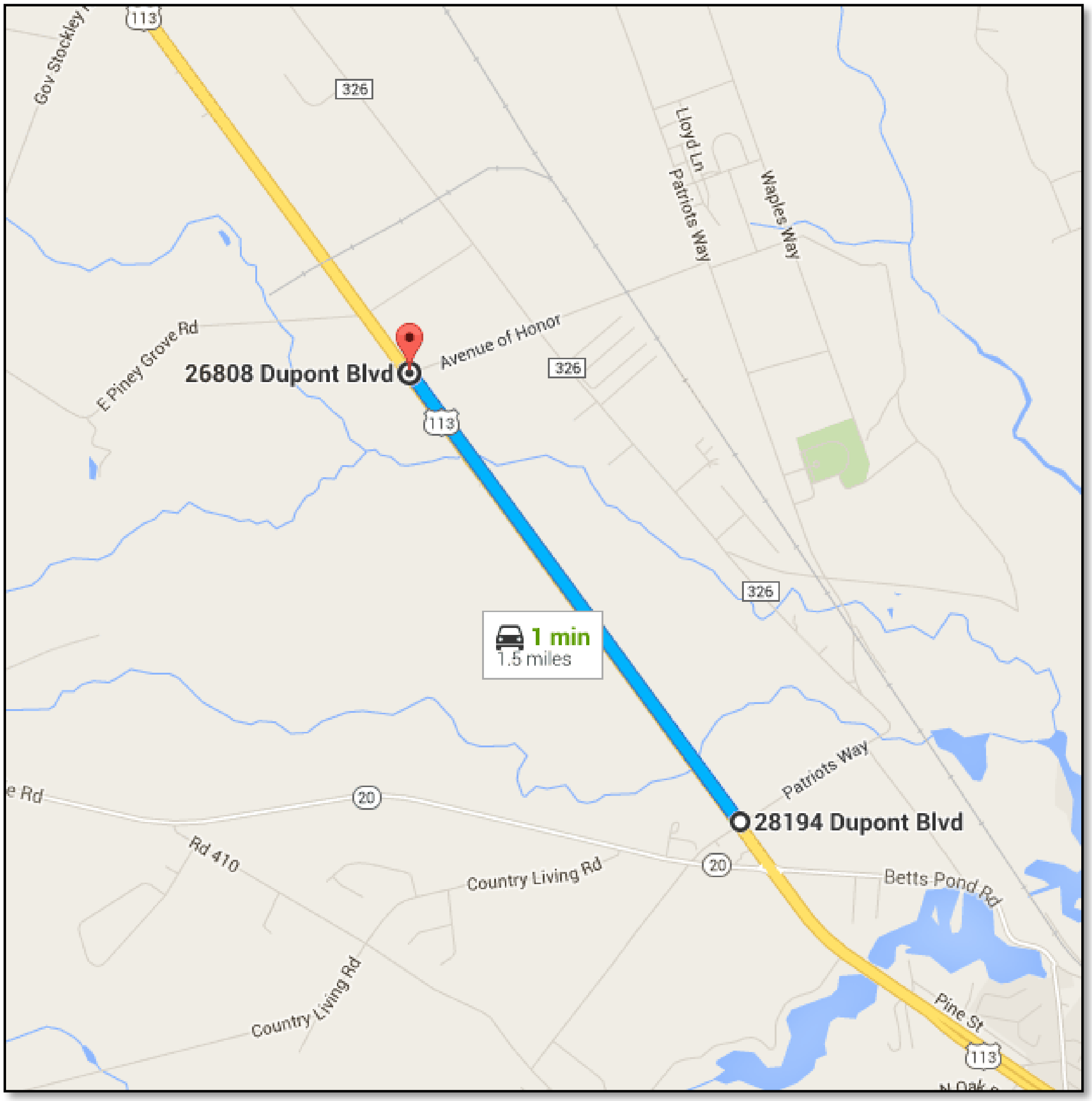


Figure 46: US 113, US 9 to SR 20 West, SB/NB, 12/4/2014 -2/20/2015, 7 am -5pm
(Imagery © 2016 Google, map data © 2016 Google)

Appendix E: Flow-occupancy scatter plots

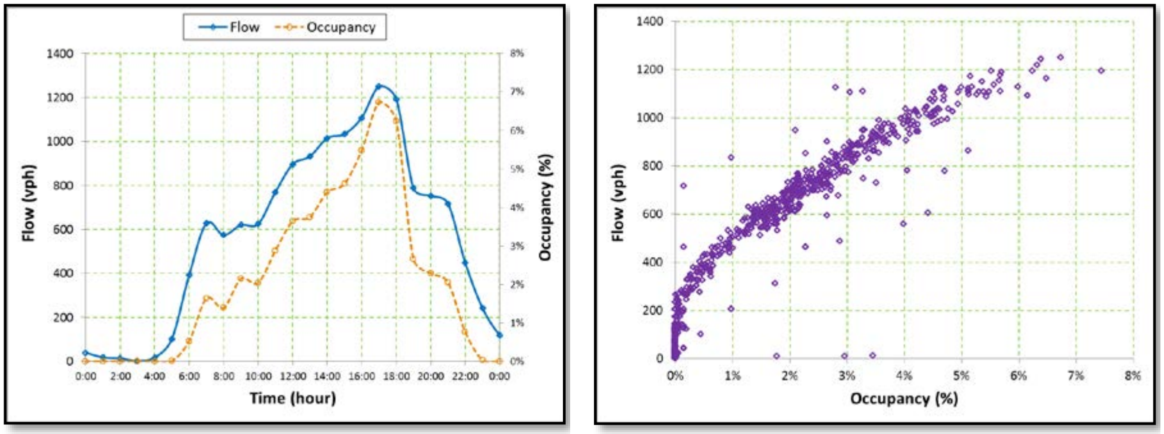


Figure 47: Flow-occupancy scatter plots for Naamans Rd., Foulk Rd. to I-95,EB

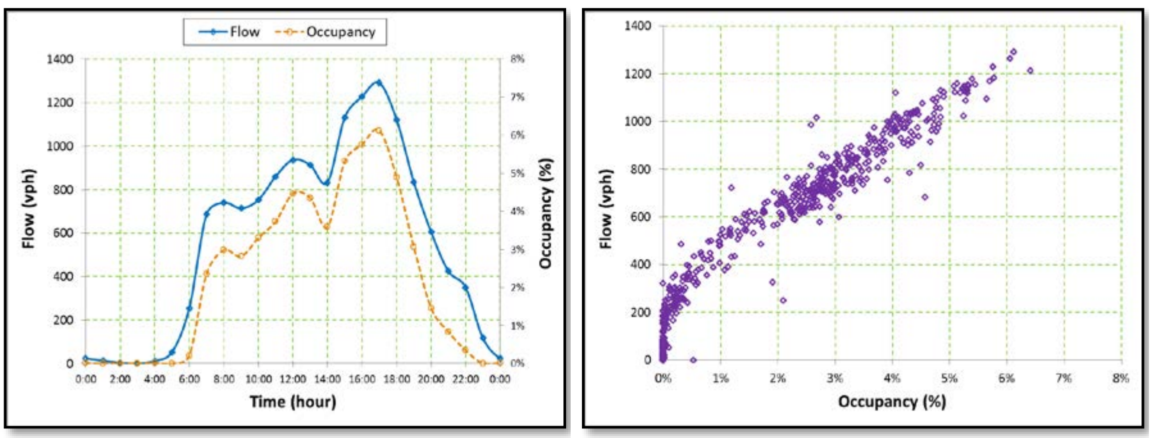


Figure 48: Flow-occupancy scatter plots for Naamans Rd., Foulk Rd. to I-95,WB

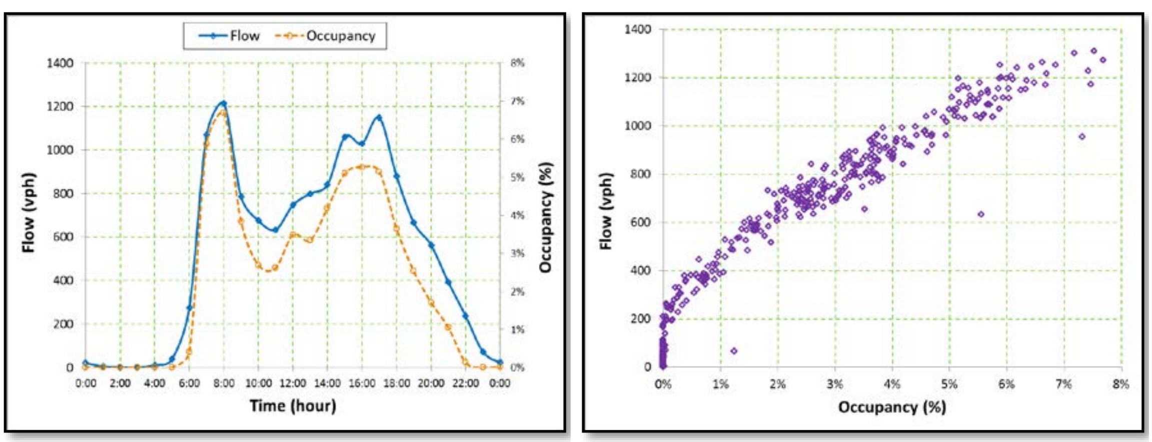


Figure 49: Flow-occupancy scatter plots for Kirkwood Hwy, SR 100 to SR 141,EB

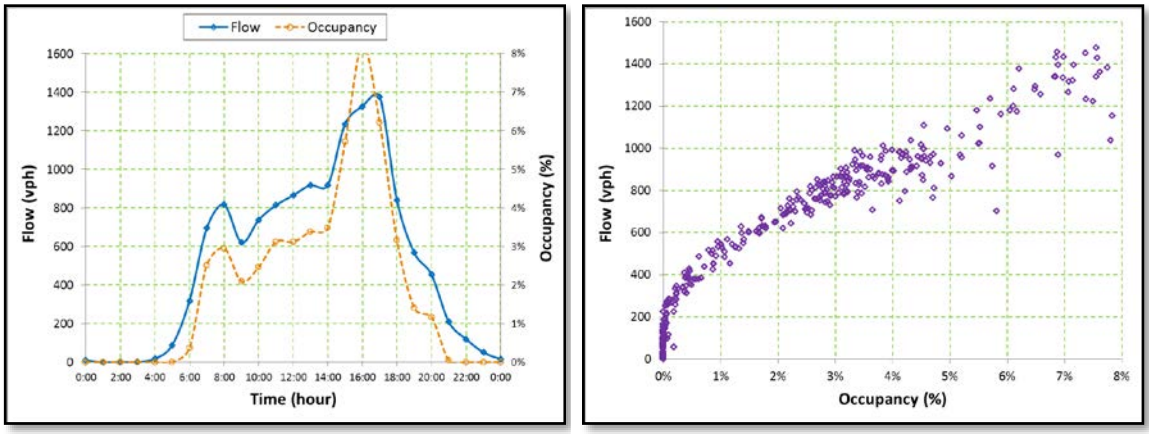


Figure 50: Flow-occupancy scatter plots for Kirkwood Hwy, SR 100 to SR 141,WB

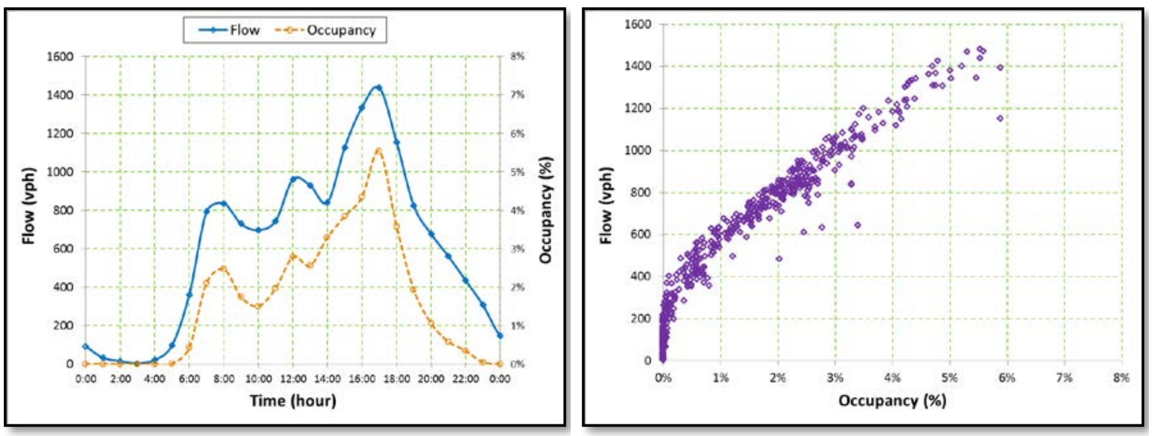


Figure 51: Flow-occupancy scatter plots for SR 273, SR 1 to I-95,EB

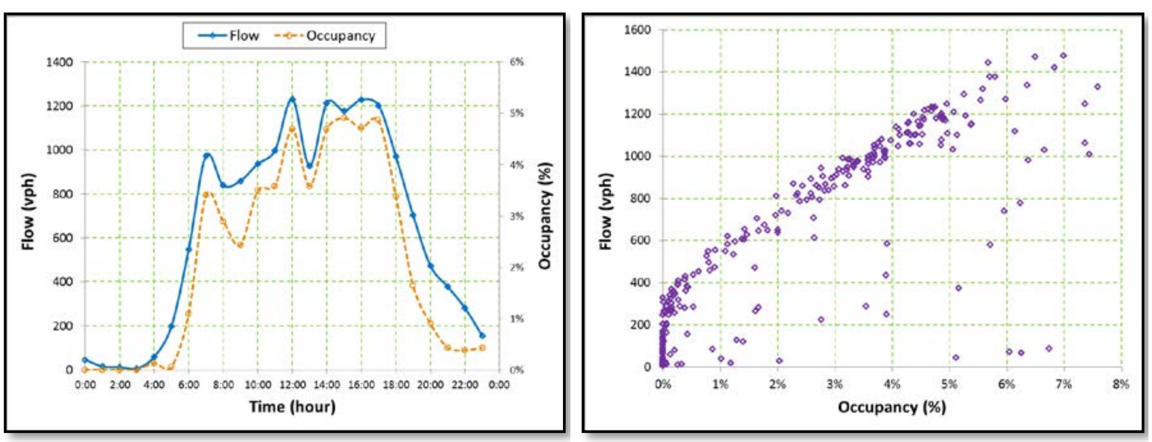


Figure 52: Flow-occupancy scatter plots for SR 273, SR 1 to I-95,WB

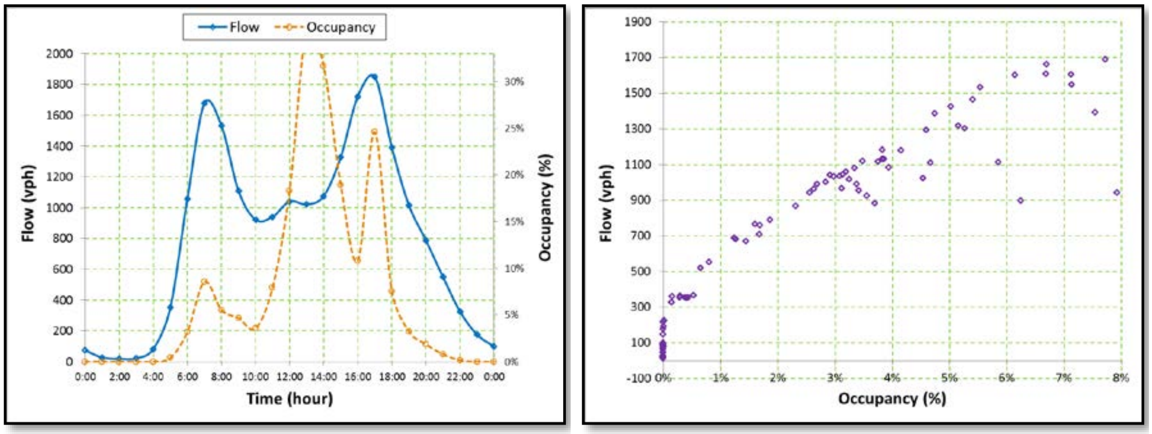


Figure 53: Flow-occupancy scatter plots for SR 273, Rt. 4 to I-95, EB

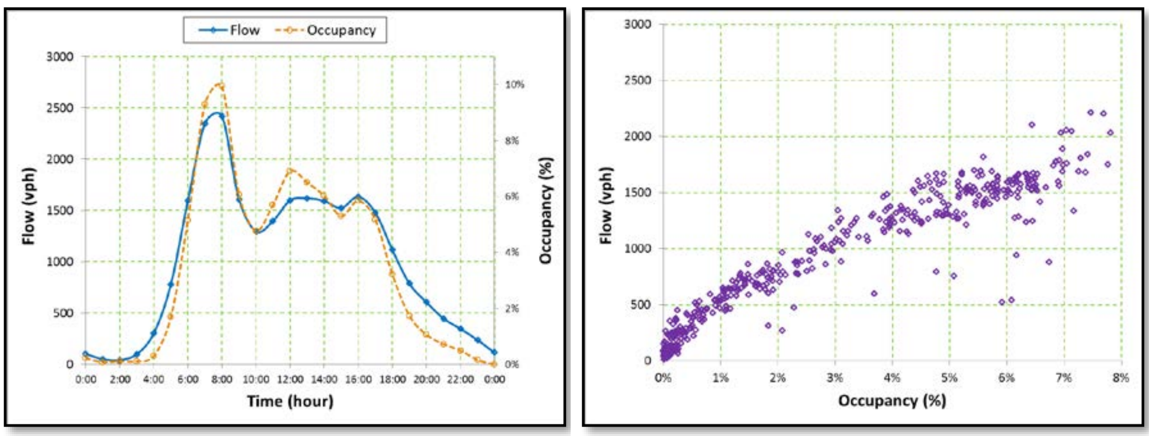


Figure 54: Flow-occupancy scatter plots for DuPont Hwy, 141 to I-295,NB

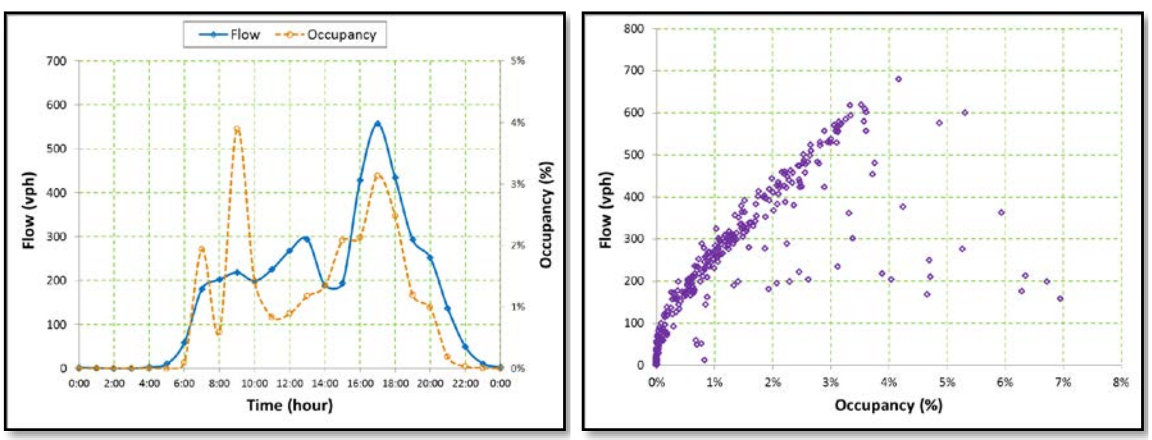


Figure 55: Flow-occupancy scatter plots for Foulk Road, PA line to Naamans, NB

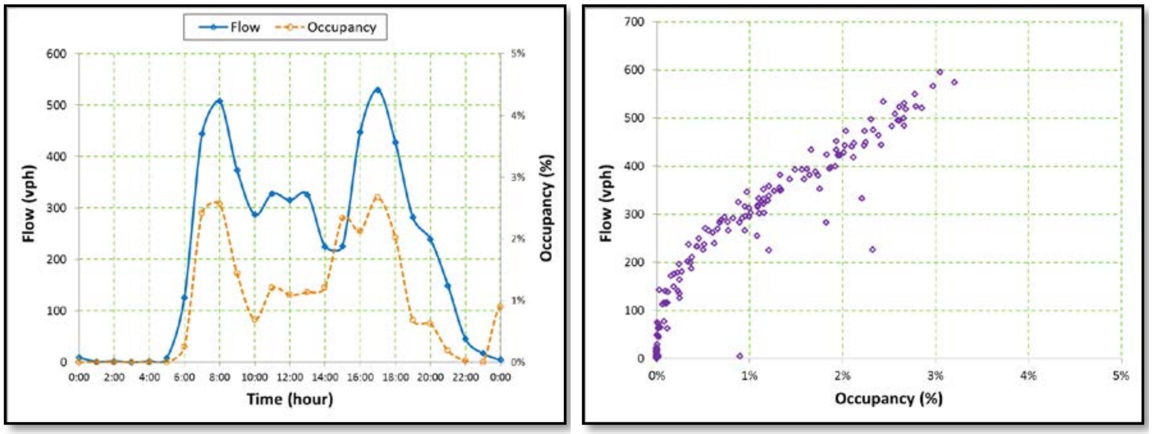


Figure 56: Flow-occupancy scatter plots for Foulk Road, PA line to Naamans, SB

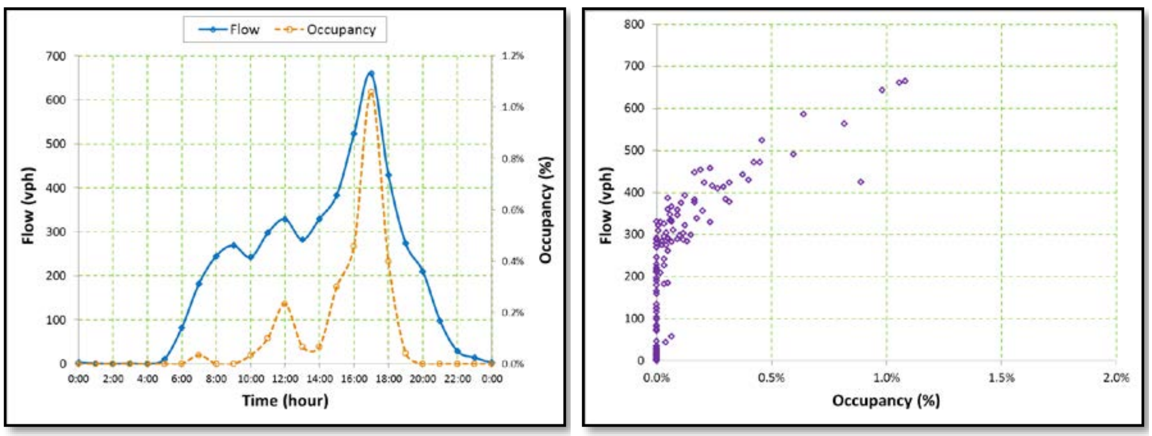


Figure 57: Flow-occupancy scatter plots for Foulk Road, Naamans Rd. to Silverside, NB

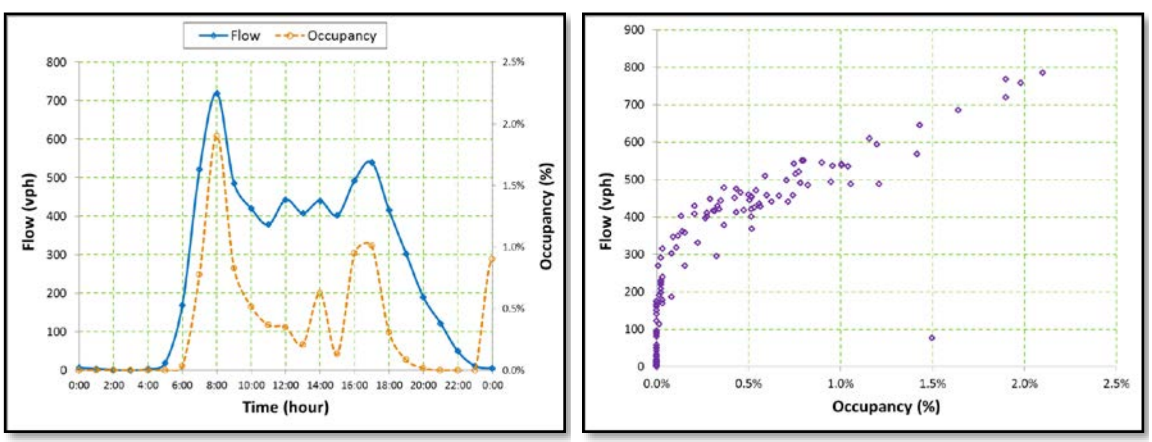


Figure 58: Flow-occupancy scatter plots for Foulk Road, Naamans Rd. to Silverside, SB

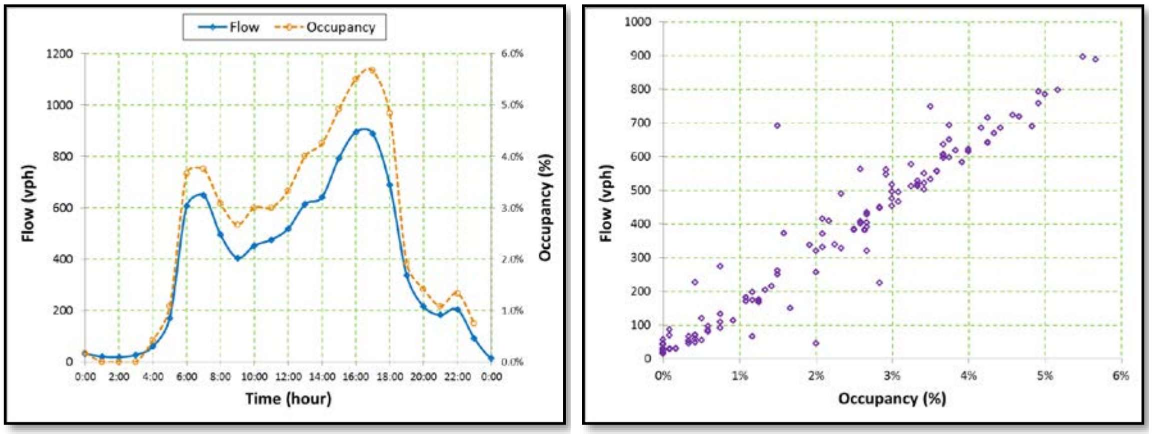


Figure 59: Flow-occupancy scatter plots for Relief Route, Exit 95 to NCC County Line, NB

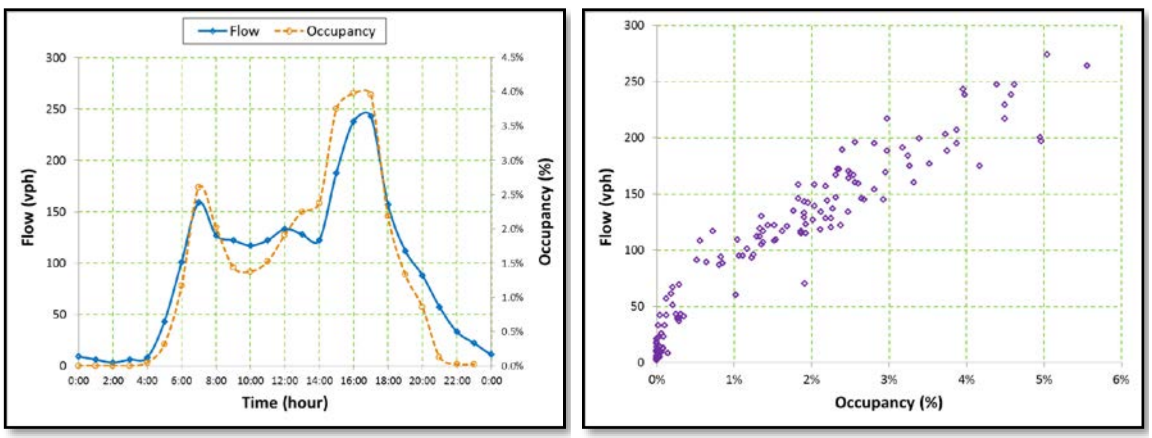


Figure 60: Flow-occupancy scatter plots for US 13, Rt 14 to Rt 12, NB

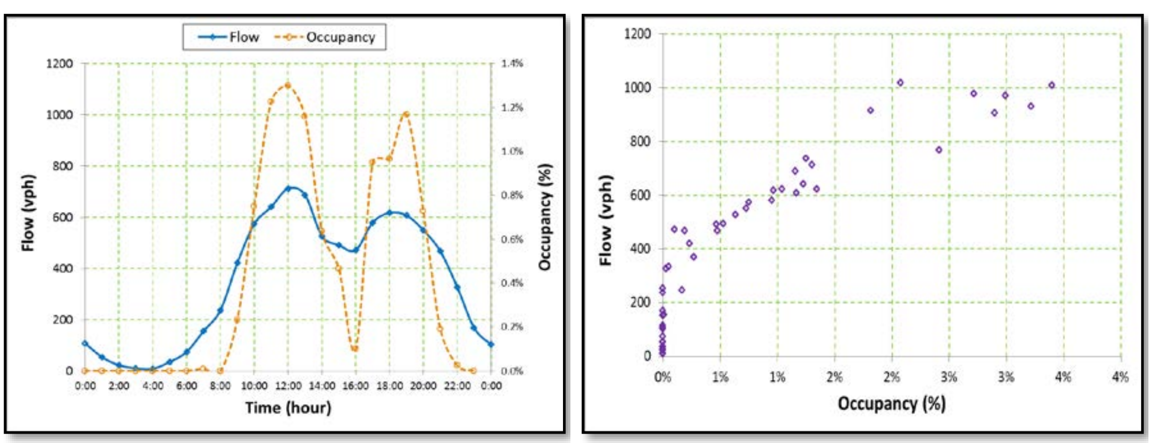


Figure 61: Flow-occupancy scatter plots for US 13, Rt 10a to Rt 10, NB

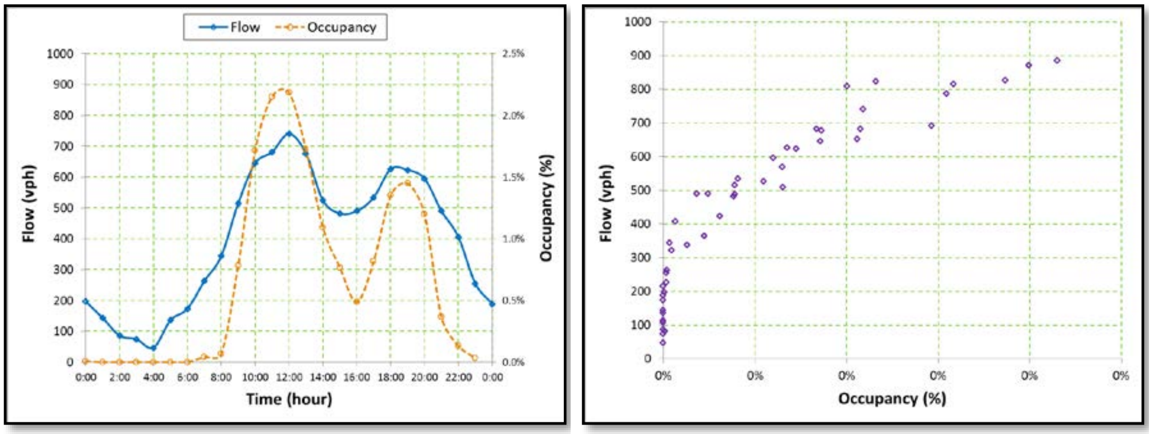


Figure 62: Flow-occupancy scatter plots for US 13, Rt 10a to Rt 10, SB

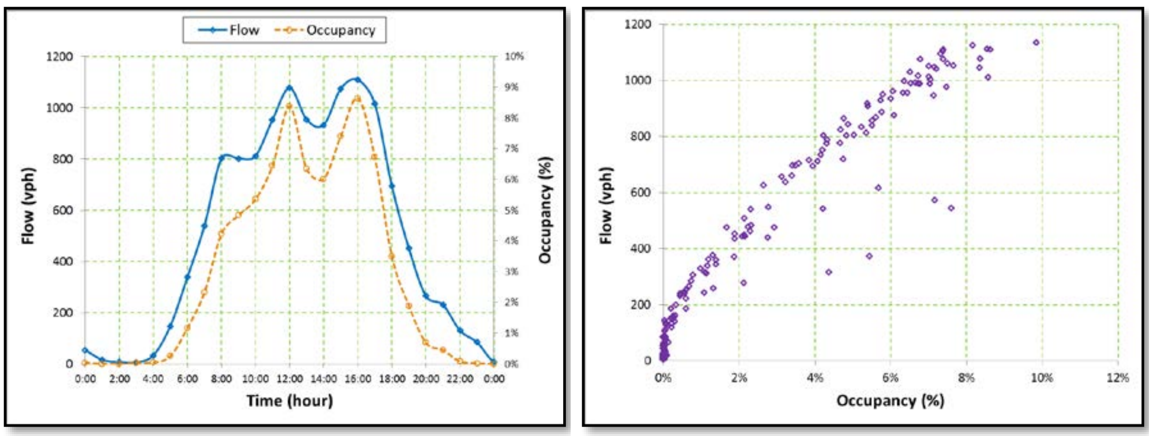


Figure 63: Flow-occupancy scatter plots for US 13,Rt 10 to Rt 8, NB

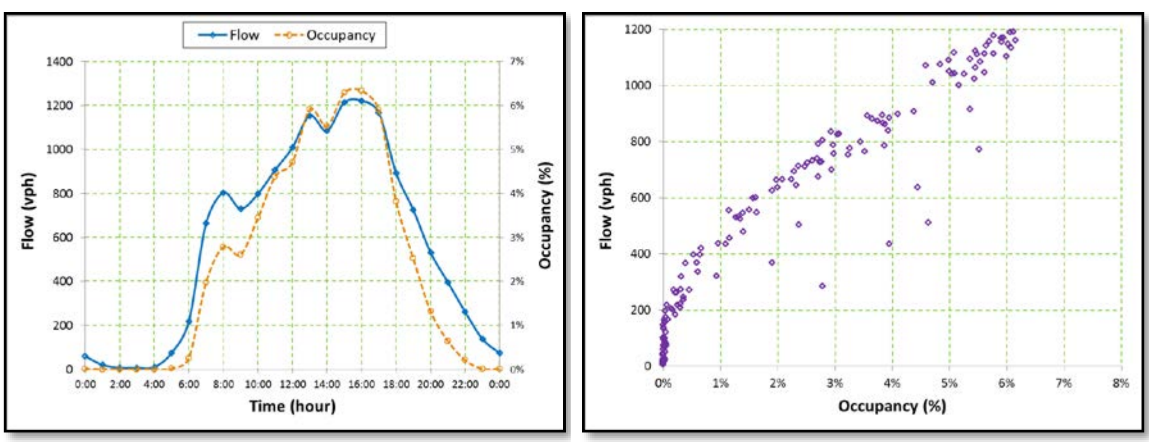


Figure 64: Flow-occupancy scatter plots for US 13,Rt 10 to Rt 8, SB

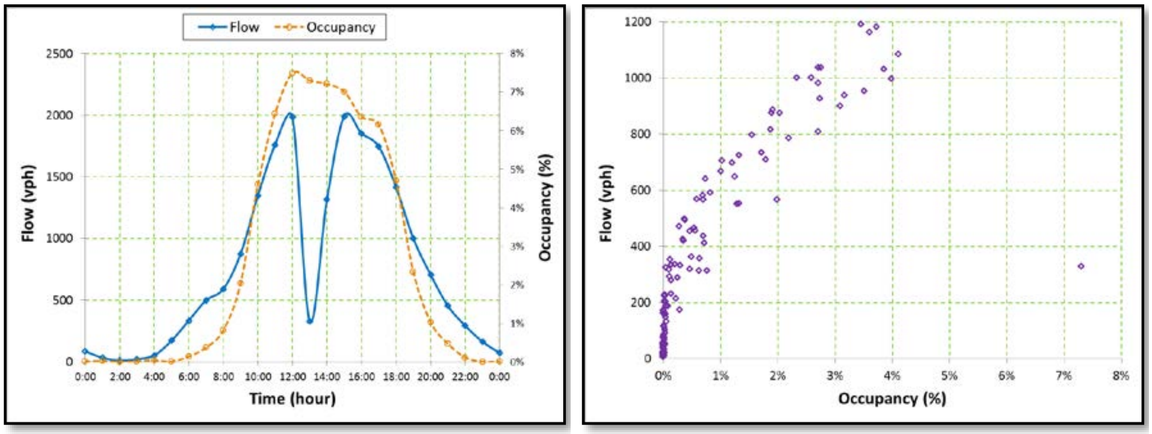


Figure 65: Flow-occupancy scatter plots for US 13,Rt 8 to Scarborough Rd, NB

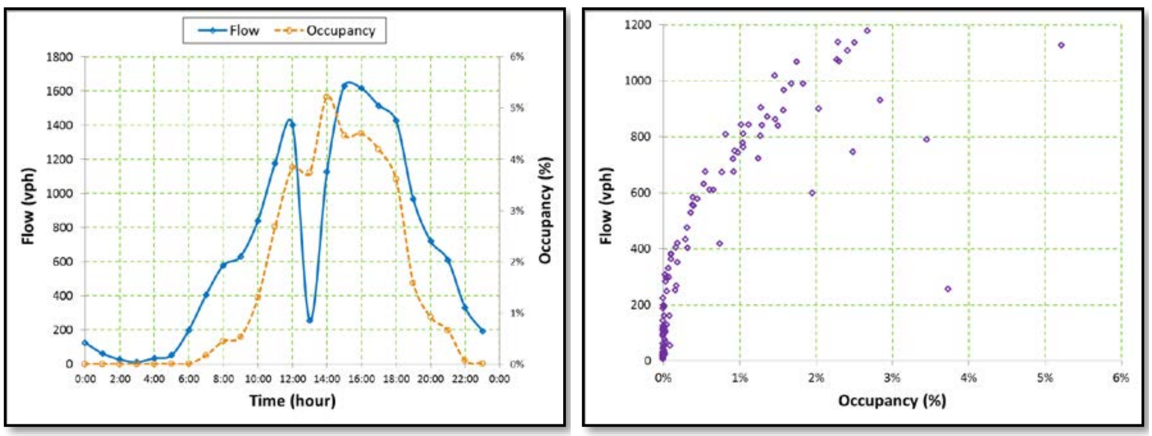


Figure 66: Flow-occupancy scatter plots for US 13,Rt 8 to Scarborough Rd, SB

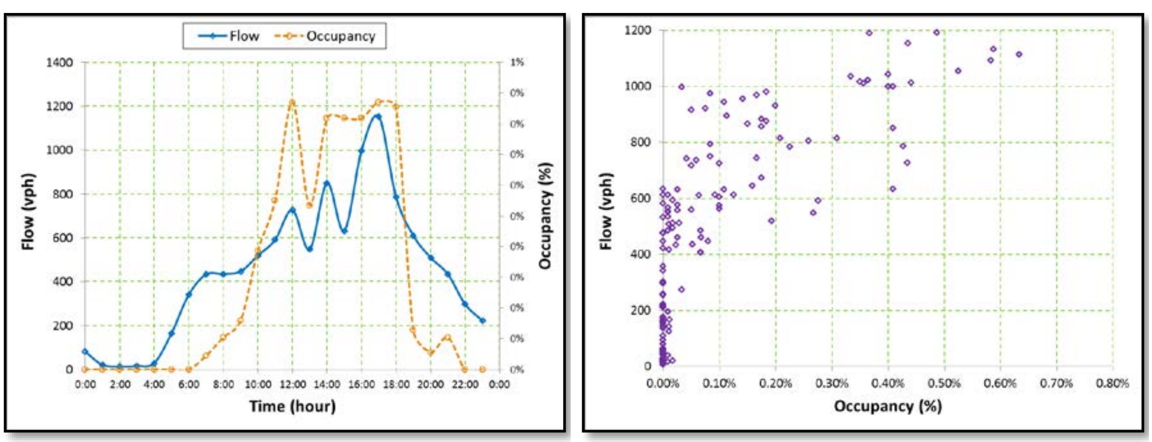
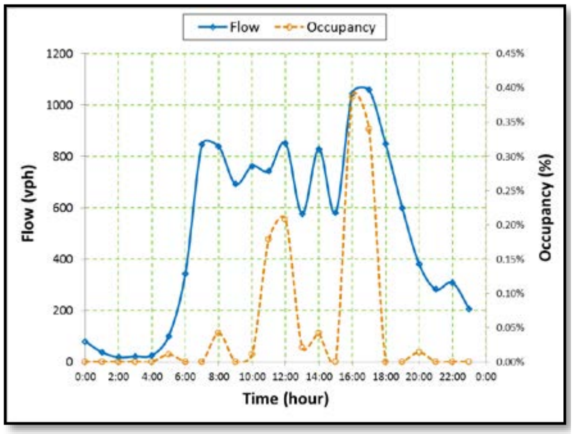


Figure 67: Flow-occupancy scatter plots for US 13,Scarborough Rd. to Rt 42, NB



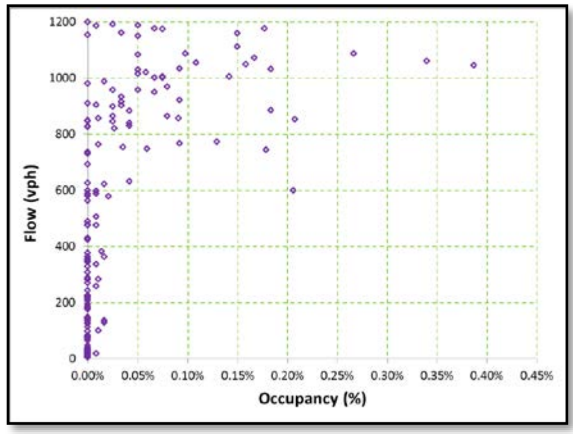


Figure 68: Flow-occupancy scatter plots for US 13,Scarborough Rd. to Rt 42,SB

Appendix F: List of Acronyms

AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
ADOT	Arizona Department of Transportation
AF	Adjustment Factor
AHTD	Arkansas State Highway and Transportation Department
ADOT&PF	Alaska Department of Transportation and Public Facilities
ALDOT	Alabama State Department of Transportation
ATIS	Advanced Traveler Information System
ATR	Automatic Traffic Recorder
BPR	Bureau of Public Road
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CLV	Critical Lane Volume
CMP	Corridor Management Plan
CONNDOT	Connecticut Department of Transportation
CPM	Critical Path Method
DE	Delaware
DELDOT	Delaware Department of Transportation
DE-MUTCD	Delaware Manual on Uniform Traffic Control Devices
Dir.	Direction
Dist.	Distance
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation and Development
EB	Eastbound
FD	Fundamental Diagrams
FDOT	Florida Department of Transportation
FFT	Free Flow Thresholds
FFTT	Free Flow Travel Time

FHWA	Federal Highway Administration
FRESIM	**Fre**eway **Sim**ulation
GDOT	Georgia Department of Transportation
HCM	Highway Capacity Manual
HCS	Highway Capacity Software
HDOT	Hawaii Department of Transportation
HOV	High Occupancy Vehicles
HV	heavy vehicle
I	Interstate (route)
IDOT	Illinois Department of Transportation
INDOT	Indiana Department of Transportation
Iowa DOT	Iowa Department of Transportation
ITD	Idaho Transportation Department
ITS	Intelligent Transportation Systems
KDOT	Kansas Department of Transportation
KYTC	Kentucky Transportation Cabinet
LCS	Lane Closure System
LOS	Level of Service
LR	Lane Rental
MaineDOT	Maine Department of Transportation
MassDOT	Massachusetts Department of Transportation
MDOT	Maryland Department of Transportation
MDOT	Michigan Department of Transportation
MDOT	Mississippi Department of Transportation
MDT	Montana Department of Transportation
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
MOE	Measure of Effectiveness
MQL	Maximum Queue Length
MPH	Mile per hour
MUTCD	Manual on Uniform Traffic Control Devices

NB	Northbound
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NDDOT	North Dakota Department of Transportation
NDOR	Nebraska Department of Roads
NDOT	Nevada Department of Transportation
NHDOT	New Hampshire Department of Transportation
NJDOT	New Jersey Department of Transportation
NMDOT	New Mexico Department of Transportation
NYSDOT	New York State Department of Transportation
ODOT	Ohio Department of Transportation
ODOT	Oklahoma Department of Transportation
ODOT	Oregon Department of Transportation
PCE	Passenger Car Equivalents
Pcphpl	Passenger cars per hour per lane
PeMS	Performance Measurement System
PennDOT	Pennsylvania Department of Transportation
PQF	Pre-Queue Flow
QDF	Queue Discharge Flow
QUEWZ	Queue and User Cost Evaluation of Work Zones
Rd	Road
RIDOT	Rhode Island Department of Transportation
RUC	Road User Cost
SB	Southbound
SCDOT	South Carolina Department of Transportation
SDDOT	South Dakota Department of Transportation
SR	State Route
STA	State Transportation Agencies
TCP	Traffic Control Plan
TDM	Travel Demand Model/ Transportation Demand Management
TDOT	Tennessee Department of Transportation

TMC	Transportation Management Center
TMP	Transportation Management Plan
TTI	Travel Time Index
TxDOT	Texas Department of Transportation
TWLTL	Two-way left-turn lane
UDOT	Utah Department of Transportation
US	United States (route)
USDOT	United States Department of Transportation
VDOT	Virginia Department of Transportation
VMT	Vehicle Miles Traveled
VPH	Vehicles Per Hour
VPHPL	Vehicles Per Hour Per Lane
VTrans	Vermont Agency of Transportation
WB	Westbound
WisDOT	Wisconsin Department of Transportation
WSDOT	Washington State Department of Transportation
WVDOT	West Virginia Department of Transportation
WYDOT	Wyoming Department of Transportation
WZ	Work Zone
WZTA	Work Zone Traffic Analysis

Appendix G: List of Symbols

% OCC	Percent occupancy
μ	The mean of the variable's natural logarithm, and
a	Shape parameter
a_{WZ}	Percentage drop in prebreakdown capacity at the work zone due to queuing conditions
b	Scale parameter
c_a	Adjusted capacity (vph);
c_{WZ}	work zone capacity (pc/h/ln)
E_R	Passenger-car equivalent for RVs.
E_T	Passenger-car equivalent for trucks and buses, and
F(x)	Cumulative probability of freeway breakdown at flow rate x
f_{AT}	Indicator factor for area type. 0 for urban areas, and 1 for rural areas
f_{BT}	Indicator variable for barrier type. 0 for concrete and hard barrier separation, and 1 for cone, plastic drum, or other soft barrier separation;
f_{DN}	Indicator variable for daylight or night. 0 for daylight, and 1 for night
f_{HV}	Heavy-vehicle adjustment factor,
f_{HV}	Heavy-vehicle adjustment factor;
f_{LAT}	Lateral distance from the edge of travel lane adjacent to the work zone to the barrier, barricades, or cones
k	Density (pc/mile)
I	Adjustment factor for type, intensity, and proximity of work activity;
LCSI	lane closure severity index
L_d	Detection zone length (feet)
L_v	Average vehicle length (feet)
N	Number of lanes open through the work zone;
N_o	Number of open lanes in the work zone
OR	Open ratio, the ratio of the number of open lanes during road work to the total (or normal) number of lanes
P_R	Proportion of rvs in the traffic stream,
P_T	Proportion of trucks and buses in the traffic stream,
QDR_{WZ}	Average 15-min queue discharge rate (pc/h/ln)
R	Manual adjustment for on-ramps (vph).
x	Random variable

x	Flow rate (veh/h)
γ	Shift parameter
σ	Standard deviation of the variable's natural logarithm

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