REPLICATION OF FREEWAY WORK ZONE CAPACITY VALUES IN A MICROSCOPIC SIMULATION MODEL

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The undersigned appointed by the dean of the Graduate School, have examined the thesis entitled

REPLICATION OF FREEWAY WORK ZONE CAPACITY VALUES IN A MICROSCOPIC SIMULATION MODEL

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UNIT CONVERSION CHART

Metric (SI) Units to U.S Units

Symbol	Units	Multiply by	Convert to	Symbol
km	Kilometer	0.621	Miles	mi
m	Meters	3.28	Feet	ft
KW	Kilowatt	1.34	Horse Power	HP
Kg	Kilogram	2.20	Pound	lb

U.S Units to Metric (SI) Units

Symbol	Units	Multiply by	Convert to	Symbol
mi	Miles	1.609	Kilometer	km
ft	Feet	0.305	Meters	m
HP	Horse Power	0.746	Kilowatt	KW
lb	Pound	0.454	Kilogram	Kg

ABSTRACT

Evaluating the traffic impacts of work zones is vital for any transportation agency for planning and scheduling work activity. Traffic impacts can be accurately estimated using microscopic simulation models due to their ability to simulate individual vehicles and their interactions that can have a strong impact on various performance measures such as capacity, queue length, and travel delays. One challenge in using these simulation models is obtaining the desired work zone capacity values which tend to vary from one state to another. Thus, the default parameter values in the model which are suitable for normal traffic conditions are unsuitable for work zone conditions let alone for conditions specific to particular states. A few studies have been conducted on parameter selection to obtain the desired capacity values. However, none of these studies have provided a convenient look-up table (or a chart) for the parameter values that will replicate the field observed capacities. Without such provision it has not been possible for state agencies to utilize many of the research recommendations. This research provides the practitioner a simple method for choosing appropriate values of driving behavior parameters in the VISSIM micro-simulation model to match the desired field capacity for work zones operating in a typical early merge system. Besides the car-following and lane changing driver behavior parameters this research also recommends the appropriate truck characteristics for use while modeling freeways in U.S. The default truck characteristics that are commonly used in VISSIM do not reflect the typical U.S. truck fleet characteristics. For example, the default length of trucks in VISSIM is 33.51 feet. In U.S, truck lengths vary from 30 feet to as long as 80 feet. This distinction is especially critical given the significant impact that trucks have on work zone capacity and queue lengths.

The two most significant car-following parameters and one lane changing parameter were selected and varied to obtain different work zone capacity values. *CC1* is the desired time headway, *CC2* is the longitudinal following threshold during a following process, and *SRF* is the safety distance reduction factor representative of lane changing aggressiveness. Additionally, for each recommended set of driving behavior parameters, lane distribution of the closed lane at different points upstream of the taper was collected. It was verified that the recommended parameter values not only produce the desired capacities but also create traffic conditions consistent with traffic flow theory. To apply this method, a transportation agency with the knowledge of lane distribution at specific points upstream from the work zone chooses a unique set of driving behavior parameters from the table to match the observed field capacity. Finally, multivariate regression models were developed to analyze relationship between the selected driver behavior parameters with work zone capacity, truck percentage, and lane distribution.

CHAPTER 1

INTRODUCTION AND MOTIVATION

1.1 Introduction

Departments of transportation (DOTs) in the United States face the challenge of scheduling road construction and maintenance activities with as little traffic impact as possible. Traffic impacts mainly include increased travel times, travel delays and queuing. Typically, construction and maintenance activities involve single or multiple lane closures for a certain duration of time. The scheduling of lane closures and work activity is done primarily based on the expected length of queues at the work zone. Traffic engineers determine the expected queue lengths based on a combination of their past experience and analysis tools. Analysis tools such as QUEWZ, Quick Zone, CA4PRS, custom spreadsheet models, Highway Capacity Software (HCS), and simulation tools (e.g., SYNCHRO and CORSIM) are used to model work zone flow conditions and to compute corresponding queue lengths and travel delays. Simulation tools are being increasingly used in state agencies at different levels of a project including planning, impact assessment, design, and construction due to their ability to model simple to complex networks with high accuracy and also allow users to model individual drivers and their maneuvers that can have an impact on various measures of effectiveness (MOEs). Past studies such as Brist et al. (*1*) compared micro simulation models VISSIM, CORSIM, and SIMTRAFFIC with HCM 2000 under various traffic scenarios and suggested that if simulation model parameters are well calibrated they can produce results that are identical to the results produced by the well accepted HCM methodology. On the contrary, few studies (*2)* contended that the simulation models can not replicate oversaturated travel conditions that exist in work zones with considerable queue formation. This is mainly due to the lack of proper guidelines to calibrate such models.

Unlike all the macroscopic and analytical tools which use a deterministic queuing model to compute the queue lengths (procedure documented in the HCM 2000) (*3*), microscopic simulation models such as VISSIM derive queue lengths based on car-following and lane changing models which is a more accurate representation of reality. In most of the analytical tools, capacity, which is deemed as the maximum number of vehicles that can pass through a section for a given period, usually an hour, is used as an input along with the travel demand, truck composition and road way geometrics to compute MOEs such as travel delays, and queue lengths. However, in microscopic simulation models capacity is not a direct input to the model, rather it is an output variable that is a function of driver behavior parameters. In order to accurately use the simulation models for traffic analysis of work zones, it is necessary to calibrate the models to match the field conditions (such as lane capacity, queue lengths and lane utilization) by adjusting the driver behavior parameters. The default parameters in a simulation model including driving behavior parameters, truck characteristics and performance, are usually suggested for use while modeling normal traffic conditions. They may not, and in most cases will not, be able to model the traffic conditions at work zones. Unfortunately, there is very little guidance on choosing the driving behavior parameters in simulation models that will replicate the actual field conditions in work zones. Roadway capacities at work zones are lower than the capacities under normal operating conditions. Furthermore, empirical studies have shown that these reduced capacity values are not uniform across all states (see Table 1 below and also state agency survey results in the literature review section). This disparity means that a unique driving behavior parameter set cannot be used by all states to obtain state-specific capacity values.

1.2 Layout of the Research

Chapter 2 starts with the specific objectives accomplished in this research and a brief description of the simulation tool used. Chapter 3 reviews documented research related to this study. Chapter 4 narrates the methodology adopted to accomplish the study objectives. Chapter 5 presents the results and analysis, while, Chapter 6 presents study conclusions and recommendations for future research. Figure 1 shows the step by step procedure adopted in this thesis.

TABLE 1 Variation of Roadway Capacities across States

State	2 to 1 Lane Configuration	3 to 1 Lane Configuration	Units	Source
Texas	1340	1170	vphpl	HCM 2000 (*3*), Dudek and Richards (*4*)
North Carolina	1690	1640	vphpl	Dixon and Hummer (*5*)
Connecticut	1500 to 1800	1500 to 1800	vphpl	Sarasua et al (*6*)
Missouri	1240	960	vphpl	Missouri DOT (7)
Nevada	1375 to 1400	1375 to 1400	vphpl	Sarasua et al (*6*)
Oregon	1400 to 1600	1400 to 1600	pcphpl	Sarasua et al (*6*)
South Carolina	950	950	vphpl	Sarasua et al (*6*)
Washington	1350	1350	vphpl	Sarasua et al (*6*)
Wisconsin	1600 to 2000	1600 to 2000	pcphpl	Sarasua et al (*6*)
Florida	1800	1800	vphpl	Elefteriadou et al (*8*)
Iowa	1400 to 1600		pcphpl	Maze et al (*9*)

Where, vphpl means vehicles per hour per lane,

pcphpl means passenger car per hour per lane,

vph means vehicle per hour,

“ **3 to 2** “ means out of 3 lanes only 2 lanes are open, “**3 to 1**” means out of 3 lanes only 1 lane is open.

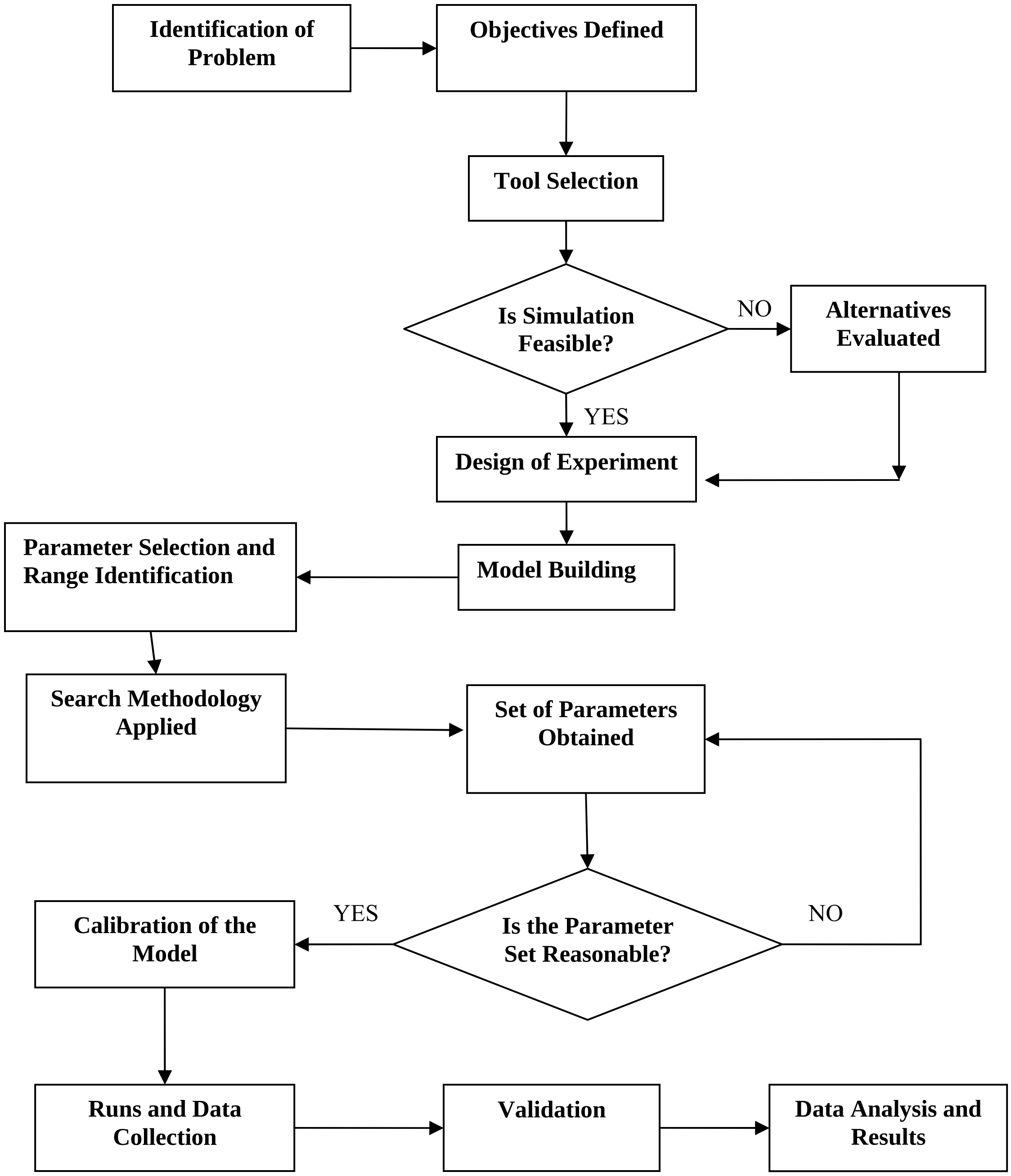

FIGURE 1 Flow chart showing the general procedure adopted in this study.

1.3 Objectives

The main goal of this study is to determine a set of driver behavior parameters for a simulation model that would yield work zone capacity values used by state DOTs. To do this, the following objectives had to be addressed:

1) Identify the set of driver behavior parameters that impact capacity. This objective was accomplished through literature review (in Chapter 3) and simulation testing.

2) Recommend appropriate vehicular characteristics, particularly for trucks while modeling freeway work zones in U.S.

3) Establish the upper and lower bounds (or threshold values) for each of the selected driver behavior parameters and conduct simulations for feasible combinations of parameter values.

4) Determine the parameter values that can produce state-specific capacities. The state-specific capacities are obtained from the literature and a state of practice survey for various lane configurations and truck compositions.

5) Generate look-up tables to assist practitioners to select a set of parameter values that would yield desired capacity for a given work zone configuration.

6) Develop multivariate regression models to express the relationship between the selected parameters, lane configuration, truck percentages, and work zone capacity.

CHAPTER 2

TRAFFIC SIMULATION MODELS

2.1 Classification of Simulation Models

Traffic simulation tools are being increasingly used for different traffic operations studies due to their ability to address traffic issues in a more efficient way compared to other analytical tools that provide limited insights. Many studies (*10, 11, 12*) suggest that the results obtained from simulation tools are accurate and practitioners should look beyond traditional tools like HCM. Based on the level of detail of the traffic stream represented, traffic simulation models can be broadly classified into three categories (*13*).

1) Macroscopic Models: These models simulate traffic flows in a network based on the well established relationships (such as shock wave theory, conservation of flow) among the aggregated traffic flow variables - speed, flow and density. Although these models can be used to assess both the temporal and spatial extent of traffic phenomena such as congestion and delay, their inability to model individual vehicle interaction, which can strongly influence network performance measures such as capacity, queue length, often forces practitioners to search for models with higher resolution.

2) Mesoscopic Models: These models have the ability to simulate individual vehicles but their individual reactions are based on aggregated traffic flow characteristics including average speed, flow and density. These models can be used, for example, in evaluating individual travel time of the vehicles based on average speed conditions prevailing in the network.

3) Microscopic Models: These models are more advanced from the above two models mainly due to their ability to simulate individual vehicles and their interactions. These models generate exact trajectories of individual vehicles based on certain car-following and lane changing algorithms. These models provide users the flexibility to change many parameters such as minimum headways, desired following distance, lane changing maneuvers to replicate field conditions Capacity flows essentially result from these fundamental elements of individual driver behavior. On the contrary, both macroscopic and mesoscopic simulation models do no have any such car following and lane changing parameters.

Given the importance of individual vehicle behavior in a congested network (*14,15*), microscopic simulation tool was deemed to be more appropriate in comparison to other models mentioned above. There are many micro simulation tools such as CORSIM, PARAMICS, VISSIM, AIMSUN, which are being widely used by researchers and transportation practitioners. In this study VISSIM 5.0 version was used for simulation. VISSIM developed by Planning Transport Verkehr (PTV) has an advantage over other micro simulation models as it is based on "psycho-physical" driver behavior model where the current speed of the vehicle depends upon its driver's perception of the speed of the preceding vehicle, particularly during following condition. Moreover, it provides significant control over individual driver behavior classified by different vehicle categories in terms of both car following and lane changing phenomenon.

2.2 Brief Description of VISSIM Simulation Program

VISSIM is a microscopic, stochastic, discrete time-step based simulation where individual vehicles represent the most basic elements of the simulation. It is based on the Wiedemann "psycho-physical" car-following model and lane changing model (*16*). The characteristics and behavior of individual vehicles (and drivers) affect performance measures such as speed, throughput, and queue length. VISSIM has two basic car following models: Wiedemann 74 and Wiedemann 99 and a lane changing model. The car-following model that represents freeway conditions, Wiedemann 99 car following model (W-99), has 10 user defined driving behavior parameters: *CC0, CC1, CC2…, CC8, CC9* (*16*) which classify drivers into one of the four driving modes (*17*):

1) Free driving: Under this driving condition the driver always want to maintain its desired speed and there is no influence of the preceding vehicle. In other words this driving scenario is similar to free flow driving condition.
2) Approaching: This driving condition is applied whenever a vehicle approaches another vehicle where the driver continues to decelerate to adapt its own speed with the lower speed of the preceding vehicle.
3) Following: Under this driving condition the driver would follow the preceding vehicle almost without accelerating or decelerating and thus maintaining approximately constant safety distance to the preceding vehicle.
4) Braking: Whenever the distance to the preceding vehicle tends to fall below the desired safety distance the driver would decelerate.

In W-99 a driver either accelerates or decelerates to change from one driving mode to other as soon as some threshold value expressed in terms of relative speed and distance is reached (*17*). Thus the whole car following process is based on repetitive acceleration or deceleration of individual vehicles with drivers having different perceptions of speed difference, desired speed, and the safety distance between two successive vehicles. Here is a brief description of the 10 driving behavior parameters used in W-99 car following model.

CC0 is the standstill distance which defines the desired distance between two consecutive vehicles at stopped condition. The default value is 4.94 ft.

CC1 is the desired time headway for the following vehicle. Based on these values the safety distance can be computed as $dx_{safe} = CC0+CC1* v$, where v is the speed of the vehicle (*16*). The default value is 0.90 seconds (secs). Higher *CC1* values characterize less aggressive drivers.

CC2 defines the threshold that restricts longitudinal oscillation beyond safety distance in a following process. The default value is approximately 13 ft.

CC3 characterizes the entry to the “following” mode of driving. It initiates the driver to decelerate when he recognizes a slower leading vehicle. It defines the time at which the driver starts to decelerate before reaching the safety distance.

CC4 and *CC5* control the speed oscillations after the vehicle enters the “following” mode of driving. Smaller values represent a more sensitive reaction of the driver to the acceleration or deceleration of the leading vehicle. *CC4* is used for negative speed difference and *CC5* is used for positive speed difference. The default value of *CC4*/*CC5* is -0.35/0.35.

CC6 represents dependency of speed oscillation on distance in the "following" state. Increased value of *CC6* results in an increase of speed oscillation as the distance to the preceding vehicle increases. But when the distance to the preceding vehicle exceeds the "following" threshold value, the driver tends to behave independently of the preceding vehicle. *CC7, CC8, and CC9* parameters control the acceleration process.

The lane changing model in VISSIM is based on the driver response to the perception of the surrounding traffic. It uses gap acceptance criteria where a driver changes lanes provided the available gap is greater than the critical gap. The decision to change lanes depends on the following hierarchical set of conditions: the desire to change lanes, favorable driving conditions in the neighboring lanes, and the possibility to change lanes (gap availability). Based on these conditions the lane changing phenomena is broadly classified into two types: 1) discretionary lane change which includes drivers who want to change from slow moving lanes to fast moving lanes and, 2) necessary lane change in case of any lane closure due to work zones, incidents and route selection. A detailed description of the lane changing algorithm is presented in Wiedemann and Reiter (*17*). Necessary lane changes depend on the aggressiveness of drivers in accepting/rejecting gaps in the adjacent lanes that is represented by parameters such as acceptable and maximum deceleration values of lane changing and trailing vehicles, and safety distance reduction factor (*SRF*). The safety reduction factor (*SRF*) refers to the reduction in safety distance (dx_{safe}) to the trailing and leading vehicle on the desired lane and the safety distance to the leading vehicle in the current lane. The default value of *SRF* is 0.6 which means the safety distance during lane changing is reduced by 40%. A lower

SRF value (say 0.4) would mean that the safety distance for lane changing is reduced by 60% which suggests that drivers are more aggressive in accepting shorter gaps. Apart from the above mentioned parameters influencing lane changing behavior, there is another important parameter in VISSIM called "lane change distance" which is defined as the distance upstream of the merge area such as ramp, taper in case of work zone where vehicle will start attempting to change lane defining the point vehicles for the first time start reacting to an work zone, any incident or route selection downstream in the network. This parameter has a very strong influence on the overall lane changing phenomenon and thus affecting various traffic measures including capacity (*18*).

CHAPTER 3

LITERATURE REVIEW

The literature review done for this research can be divided into two sections: 1) Work Zone Field Capacity Studies and 2) Work Zone Simulation Studies. The first section of the literature mainly focuses on the definition of work zone capacity, the location where capacity should be observed within a work zone and analyzing the relationship between observed capacity and other work zone traffic characteristics. The second section reviews the simulation studies conducted to estimate work zone capacity and identifying the most influential model parameters that affect capacity. In addition to the review of prior studies, a summary of the survey results of work zone capacity estimation policies of state DOTs across the nation is documented in this chapter.

3.1 Work Zone Field Capacity Studies

Dudek and Richards (*4*) calculated work zone capacity values based on traffic volumes collected while queues were formed upstream from the closure and thus essentially governed by queue discharge flow rate.

Persaud and Hurdle (*19*) investigated the four prevailing definitions of capacity: “maximum flow”, “specified percentile flow”, “mean queue discharge flow” and “expected maximum flow”. For each definition they assumed capacity to be a single number, rather than a distribution with certain mean and variance. Their results suggested that the value of capacity based on expected maximum flow is dependent on the averaging interval and length of the total observation period. However, as the average interval's size increases the expected maximum flow rate gets closer to the average queue discharge flow rate. But mean queue discharge flow rate is independent of both the size of the interval and the total observation length. Other definitions of capacity, percentile flow and maximum flow, like the expected maximum flow, fail to provide a quantitative estimate of the extent of congestion unlike the mean queue discharge rate which seems to be the most appropriate definition for capacity.

Hurdle and Dutta (*20*) looked upon capacity as a service rate of a queuing system which is the mean flow through bottleneck, provided an upstream queue is present. The notion of capacity drop after queue formation yielded another definition of capacity known as the pre-queue mean flow rate. Capacity can be looked upon as the maximum average or the expected maximum pre-queue flow or queue discharge flow rate observed over a period of time for many days. Their analysis suggested that the mean queue discharge rate is the best estimate of capacity for freeways.

Benekohal and Chitturi (*21*) described a methodology to estimate work zone capacity based on data collected at 11 work zone sites in Illinois. A speed flow relationship was developed which described the congestion part of the speed flow graph as, $q=145.68 * U^{0.6857}$, where q is in pcphpl and U, speed is in mph. Their model was based upon the reduction of "operating speed" caused by factors such as work zone intensity, lane width, and lateral clearance. The capacity at these reduced "operating speeds" was further adjusted for traffic composition and pattern as,

$Cadj = C_{uo} * f_{HV} * PF$, where f_{HV} is the heavy vehicle factor

and PF defines the platooning factor.

Alkaisy and Hall (*22*) developed two site specific capacity estimation models and a generic model based on data collected at 6 long term work zones in Ontario, Canada. The authors defined freeway work zone capacity as the mean queue discharge flow as it was deemed to reasonably represent the maximum sustainable flow observed in the work zone. The factors considered to affect the base capacity were heavy vehicles, driver population, light conditions, inclement weather, work activity on sites, lane closure configuration and rain. The generic capacity estimation model was of multiplicative form and their estimation on capacity ranged from 1853 to 2225 pcphpl with a mean estimate of 2000 pcphpl. The generic model they came up with is more applicable for long term work zones which typically induce higher capacity values compared to short term work zones.

Alkaisy and Hall (*23*) further examined the impact of driver population on work zone capacity. They considered the familiarity of driver population and the value of time perceived by them to examine their impact on capacity. They came up with a driver population factor of 0.93 for afternoon peak period and 0.84 for weekends suggesting more capacity reduction expected on weekends compared to weekdays.

Dixon et al. (*5)* measured speed flow collapse at the end of the transition area as well as near the actual activity area inside the work zone to estimate work zone capacity. Their study indicated that the bottleneck was initiated at the end of the transition area but a second bottleneck can be observed near the activity area due to lower queue discharge volume in the presence of heavy work near the activity area. Their report suggested that for a high intensity work zone in a 2 to 1 lane configuration the capacity value at the activity area is around 1200 vphpl and 1500 vphpl for rural and urban areas, respectively.

They used 95th percentile flow value as the capacity because they justified that these percentile values eliminated outliers and conformed to the general speed flow graphs. They concluded in their study that for less intense work zones the end of the transition area is the ideal location to measure capacity but for high intensity work zones actual activity area determines the work zone capacity value.

Tarko (*24*) in his paper on estimating work zone capacity introduced a high order continuum model of freeway traffic that incorporated lane change decisions based on the rate of lane changing, desirable speed of the driver and time for such maneuvers.

Maze et al. (*9*) estimated capacities for freeway work zones in rural Iowa and concluded that capacity values ranged from 1400 pcph to 1600 pcph. They define capacity as the average highest volume immediately before and after queue conditions over 15 minute interval periods. They justify their definition of capacity, since the onset of congestion can be predicted from this and potential traffic management strategies can be implemented before queue formation to mitigate congestion.

Kim et al. (*25*) used a multiple regression technique to come up with an estimate on work zone capacity for work zones in Maryland. They considered various factors ranging from number and location of closed lanes, percentage of heavy vehicles, and lateral distance to the open travel lanes, work zone length, intensity and a combinational factor of work zone grade and proportion of heavy vehicles.. However, the use of some of these variables is questionable given the high amount of correlations between the variables.

Adeli and Jiang (*26*) developed a model based on neuro-fuzzy logic to estimate work zone capacity. They considered as many as 17 factors to come up with their model and found that the neuro-fuzzy model yields more accurate results than other existing models.

Highway Capacity Manual (HCM) (*3*) defines capacity as the "maximum sustained 15-min, expressed in passenger cars per hour per lane, that can be accommodated by a uniform freeway segment under prevailing traffic and roadway conditions in one direction of flow." Based on the above definition of capacity HCM 2000 recommends a base capacity value of 1600 passenger car per hour per lane (pcphpl) for short term work zones (i.e. work zones that exist for few days with closed lanes separated from open lanes by temporary delineators or cones). HCM 2000 also states that this base value of the capacity should be modified by applying certain adjustment factors based on work zone intensity (defined by the number of workers present, type of machineries used and proximity of work activity to the travel lanes), effect of heavy vehicles and presence of ramps near work zone. If a ramp is located within 1500 ft upstream of the closure the base capacity should be reduced by the ramp volume up to a maximum of half of the capacity value. The following equation governs the work zone capacity value in HCM 2000:

$$C_a = (1600 + I - R) \times f_{HV} \times N$$

where, I= adjustment factor work zone intensity (ranges from -160 pcphpl to 160 pcphpl)

R= adjustment factor for ramp presence as mentioned above.

f_{HV}= heavy vehicle factor as define in HCM 2000.

N= number of open lanes in the work zone.

For long term work zones HCM 2000 suggests that the capacity value can be approximately 1550 vehicle per hour (vphpl) for 2 to 1 lane closure (which means out of 2 lanes 1 lane is open within the work zone) when a crossover is present and 1750 vph in the absence of a crossover. For 3 to 2 lane configuration work zone capacity value can range from 1750 to 2060 vehicle per hour pr lane (vphpl). Although lane width reduction factor is not accounted in the capacity estimation equation, HCM does suggest that reduction in lane width can decrease capacity significantly.

The base value of work zone capacity recommended by HCM 2000 is higher compared to the values suggested in other literature (*6, 7*). The work zone intensity is not clearly defined in HCM which makes it difficult to apply the appropriate adjustment factor for work zone intensity. There are few other factors mentioned in recent studies such as location of closed lane, lane closure configuration, lane width and lateral clearance that are not accounted for in the HCM work zone capacity estimation model. Moreover, the passenger car equivalent value (PCE) used in the model to account for the heavy vehicles is derived from the normal freeway operation rather than any work zone condition or oversaturated freeway condition while some studies (*27*) observed that the reduction in work zone free flow speeds of heavy vehicles is significantly greater than the reduction in passenger cars compared to a basic freeway section. This greater reduction in free flow speeds of the trucks should be accounted to calculate PCE values for trucks in work zone operations as it directly affects the performance of traffic stream and should be accounted to calculate PCE value for trucks in work zones (*28*). Thus, the HCM 2000 work zone capacity estimation model is not robust enough to accurately estimate work zone capacities.

Sarasua et al. (*6*) conducted studies on 22 work zone sites in South Carolina and estimated the base capacities for short term work zone capacity was 1460 pcphpl. The base capacity was estimated by collecting speed- flow- density data and using Greenshield's linear relationship between speed and density. They proposed a work zone capacity estimation model similar to HCM 2000 (*3*):

$$\text{Capacity (in vph)} = (1460 + \text{I}) \times \text{N} \times \text{f}_{\text{HV}},$$

where, I is the work zone intensity adjustment factor that ranges from -146 vph to +146 vph, and N is the number of open lanes and f_{HV} is the heavy vehicle adjustment factor.

Chitturi et al. (*27*) suggested speed reduction of 10, 7, 4.4 and 2.1 mph for lane widths of 10, 10.5, 11 and 11.5 ft respectively from their studies of eleven Interstate highway work zones with 2 to 1 lane configuration. Their results showed a significant difference in speed reduction for passenger car compared to heavy vehicles and also concluded that drivers tend to reduce speeds more in a work zone than in a basic freeway section for a given lane width.

Jiang (*29*) in his study of traffic flow characteristics of freeway work zones in Indiana suggested the definition of work zone capacity as the flow rate just before a sharp drop in speed, followed by a sustained period of low speed condition and varying traffic flow rate. The study also suggested that except for some time the queue discharge flow was found to be lower than their definition of work zone capacity. They also recommended that queue discharge rate is more suitable to estimate delays and queue lengths at work zones. Traffic data including volume, speed, vehicle classification were collected at 5 minute and 1 hour intervals for high and low traffic volume hours respectively.

Kittelson and Roess (*30*) critically analyzed the current definition of freeway capacity given in HCM 2000 which neglected the stochastic concept of capacity in spite of enough research conducted in recent years corroborating the fact that capacity can vary at a given location over time. But there is no general consensus about what statistics should be used to define this stochastic element. Another important issue of comparing maximum sustained flow rate before breakdown with queue discharge rate was also raised and mentioned that many arguments have been placed in the past in the favor of using queue discharge value as the capacity of a facility.

Lorenz and Elefteriadou (*31*) suggested a revised definition of freeway capacity. HCM 2000 (*3*) defines capacity as the maximum sustained 15-min flow rate observed in a uniform freeway segment under prevailing traffic and road conditions. But their study refuted the concept of a single value capacity definition. A probabilistic definition of capacity was proposed where corresponding to a value of capacity for a freeway segment there is an associated probability that the freeway will breakdown at that value. Also, this probability of breakdown was dependent on the time interval used to collect flows. But this definition of capacity is quite subjective since the "probability of breakdown" could vary depending upon the operating agency's perspective on acceptable risk of breakdown.

Elefteriadou and Heaslip (*32*) collected data from a 3 to 2 freeway work zone along I-95, Jacksonville, Florida for 15 days and calculated four different measures of capacity: maximum breakdown flow (the maximum flow before the breakdown indicated by a sudden drop of speed that sustained for certain period of time), the breakdown flow (the flow at the onset of congestion), maximum and average queue discharge flow (flow between the start and the end of the congestion). Their study suggested out of these four measures average discharge flow had the lowest variance and deemed more suitable in defining the capacity of the work zone. Their study also concluded that there was no significant difference in the capacity between left lane and right lane closures

The literature review so far suggests multiple definitions of work zone capacity mainly based on pre-queue conditions and congested conditions (i.e. queue discharge flow). Each definition has its own justification. Past studies such as Jiang (*29*) showed that usually pre-queue flows (i.e. the breakdown flows) are higher than mean queue discharge flows. The choice of a capacity definition depends on the purpose and application. If the main purpose is to identify the onset of congestion then the pre-queue flow rate definition is appropriate. But if the intent is to determine the queue lengths, traffic delays and analyzing user costs, the use of mean queue discharge rate is more appropriate (*4, 19, 33, 34, 35, 36)*.

3.2 Summary of Survey Results on Work Zone Capacity Estimation

One of the objectives of this research was to document the work zone capacity estimation policies of state DOTs across the nation. A survey questionnaire was prepared and sent to 50 DOTs in the country via email. 24 DOTs responded to the survey. The complete survey questionnaire is shown in Appendix A. The survey consisted of two sections. The first section (questions 2 to 5, question 1 being the name of the state DOT) inquired about the definition of work zone capacity and the location where it is measured in the work zone. The second section (questions 6 to 9) were related to factors affecting work zone capacity, tools used by DOTs to estimate capacity, and capacity values for different lane configurations. The different work zone capacity values adopted by DOTs were directly related to the main goal of this research. Summaries of the responses to each question follow.

Work Zone Capacity Definition

Majority of the state DOTs define work zone capacity as the maximum observed hourly flow during pre-queue conditions. Only four state DOTs, Texas, Washington DC, Maine and Washington consider mean queue discharge flow as the work zone capacity. Few states such as Oregon, Colorado define work zone capacity as the maximum observed 15 minute flow rate irrespective of the presence or absence of queue.

Work Zone Capacity Measurement in Field

54% of the respondents indicated that they collect field data to estimate work zone capacity. Majority of these states collect volume, queue lengths and speed of the vehicles in the work zone to estimate capacity. Few states such as Minnesota, Washington DC, Montana and Oregon also measure average headways of the vehicles in the work zone. Results also suggest that majority of these states measure a work zone capacity well in to the work zone area (i.e. near activity area). Few states such as Iowa, Oregon and Wisconsin measure capacity at the beginning of the taper and only Massachusetts prefers measuring it at the end of the taper area. Remaining DOTs seem to use pre-defined work zone capacity values from the past experience and simulation studies.

Tools to Estimate Work Zone Capacity

Majority of the respondents follow HCM procedure to estimate work zone capacity. Only few states such as West Virginia, Texas and Washington use analytical tools such as Quewz to estimate capacity values, while New York and Rhode Island use micro-simulation tools such as VISSIM and CORSIM for work zone capacity estimation. Florida DOT has developed their own work lane closure policy document based on some past empirical studies.

Factors Influencing Work Zone Capacity

The majority of the states responding to the survey indicated that they consider all factors documented in HCM 2000, i.e., proportion of heavy vehicles, presence of ramp, work zone intensity and number of open lanes while estimating capacity. In addition many DOTs also consider length of work zone, location of closed lane, posted speed limit, short term versus long term and night time versus day time as factors affecting work zone capacity. All the DOTs were asked to specify the adjustment values for each selected factor. Only Wisconsin DOT gave their estimate of the adjustment factors which are as follows:

- Capacity values for urban work zones are typically more than rural areas by 200 pcphpl.
- If the shoulder width is less than 6 ft the base capacity value should be reduced by a factor of 0.97.

- Presence of ramp within 1500 ft of the work zone reduces the base capacity value by hourly ramp volume or maximum of 600 vph.
- One truck is equivalent to 2 passenger cars.
- Long term work zones may have capacities as much as 150 pcphpl higher than short term work zones.
- Lane width adjustments: Multiply base capacity by 0.97 if lane width is 11 ft. and by 0.95 if lane width is 10.5 ft.
- Work zone capacity with crossover may have 200 pcphpl less than without crossover, especially in rural areas.

Work Zone Capacity Values Adopted by State DOTs.

Table 2 indicates the work zone capacity values adopted by the state DOTs that responded to the survey.

TABLE 2 Survey Results of Work Zone Capacity Values Adopted by State DOTs

State	2 to 1	3 to 1	3 to 2	2 way 1 lane	Median Crossover
Florida	1800 vph		3600 vph	1400 vph	
Wisconsin	1500 pcphpl	1500 pcphpl	1500 pcphpl		1400 pcphpl
Nevada	1500-1600 pcphpl	1500-1600 pcphpl	1500-1600 pcphpl	1500-1600 pcphpl	1500-1600 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		1800 pcphpl
New Jersey	1300-1400 vphpl	1200-1300 vphpl	3000-3200 vphpl	600-750 vphpl	1200-1500 vphpl

Where, vph means Vehicles Per Hour , pcphpl means Passenger Car Per Hour and

vphpl means Vehicles Per Hour Per Lane

Work Zone Lane Closure Policy

Most of the states indicated that they have a policy of closing lanes either during night time or off-peak hours depending on the type of roadway (i.e. highway or a secondary roadway)

3.3 Work Zone Simulation Studies

Gomes et al. (*15*) in their simulation study in VISSIM used three car-following parameters, namely CC0, *CC1* and CC4/CC5 pair to replicate the value of field capacity. They created three basic link types namely, Freeway, "Soft curve" and "Hard curve" and for each link type a unique set of driver behavior parameters was calculated. CC0 value was changed globally from 1.5 to 1.7 secs and this parameter was used specifically to calibrate queue length as it has more significance at low speed conditions. The CC4/ CC5 parameter was also globally increased from its default value of -0.35/0.35 to -2.0/2.0. It showed that the default value of CC4/CC5 produced no congestion. The overall selection of parameter values was done manually and based on visual interpretation of results. The most "parsimonious" parameter set that met all the calibration goals (location of bottlenecks, extent of queue and its initial and final time, utilization of HOV lanes, on-ramp performance) was selected for each link type.

Hadi et al. (*37*) studied the reduction in highway capacity due to incidents. Three micro-simulation models – CORSIM, VISSIM and AIMSUN were used to simulate a basic freeway segment and for each model selected calibration parameters were tuned to achieve the target link capacity for normal and incident conditions. They defined link capacity as the vehicle throughput per hour that can traverse the link, provided there is enough demand to reach capacity. For VISSIM, they identified *CC1* as the strongest parameter influencing the freeway capacity. Their study suggested that the default value of *CC1* gives a capacity value of 2360 vphpl for freeway which is in conjunction with HCM 2000 (*3*). Their study also concluded that changing speed is analogous to changing the car following parameters in terms of altering capacity values. Since incident conditions are similar to work zones where flow is constrained by the formation of bottleneck, conclusions from this study are applicable for simulating work zone conditions in VISSIM.

Lownes et al. (*18*) did an analysis of the quantitative impact of VISSIM driving behavior parameters in estimating capacity. They considered each parameter at a time and varied it to investigate its impact on capacity, keeping all other parameters at their calibrated values. They investigated the impact of 11 parameters which included 10 Weidman 99 driving behavior parameter and Look-back distance (now called lane changing distance). Each of the 10 behavior parameters was tested at four levels, namely, “low”, “medium”, “calibrated” and “high” depending upon the values selected for each parameter. The calibrated values were obtained using the FHWA calibration methodology guidelines (*13*) and do not represent the optimal values for each parameter. Statistical t-test was performed for each level to examine the significance of their impact on capacity. The results suggested that only high *CC0* values produced significant differences but *CC1* values at all four levels resulted in significant difference in the simulated capacity. Similarly for *CC2*, as its value increased, a drop in the mean value of capacity was observed. Other driving behavior parameters, except for high values of *CC4/CC5* pair, did not show any significant impact on road capacity. Apart from these three *CC* parameters the impact of look-back distance on capacity was examined and was found to be significant at alpha=0.01 level of significance.

Chitturi et al. (*38*) examined the relationship between capacity and the two most important driving behavior parameters in VISSIM, namely, *CC0* and *CC1*. They suggested that for low speed conditions the impact of CC0 on capacity is significant but as the speed increases its effect diminishes while the impact of *CC1* increases. Variation on capacity was examined for each set of *CC1* and *CC0* values. They did 30 simulation runs for each set to account for the stochastic nature of the micro-simulation model. Their results showed that for higher values of *CC1* the contribution of *CC0* towards capacity is negligible and also for lower *CC1* values the variation of capacity was higher and hence such low values of *CC1* should be used with lot of caution. They recommended that *CC1* values lower than 0.8 should not be used to eliminate such variation in capacity.

Fellendorf (*39*) discusses the scope and requirements of validating a micro-simulation model in VISSIM. The paper focuses on validating lane changing behavior of the model by plotting lane volume distribution for each lane.

Elefteriadou et al. (*8)* developed a procedure to estimate work zone capacity for freeway based on simulation. CORSIM micro-simulation tool was used to model 2 to 1, 3 to 1 and 3 to 2 work zone lane configurations. They recommended that their methodology should be validated with field data before using it. The maximum throughput measured at the actual lane closure link was defined as the capacity. In the simulation model vehicle distribution for each lane was an input variable. Three warning sign configurations were modeled based on their location upstream of the work zone to evaluate their impact on the capacity. Three truck percentages, 0%, 10% and 20%, were used in the models. Three values for rubbernecking factor (0%, 15% and 25%) were introduced to identify their effect on capacity. A total of 243 scenarios were created and each scenario was simulated for 15 runs. Their results identified three most important factors affecting capacity, which were rubbernecking factor, lane distribution immediately upstream and downstream of the work zone warning signs and truck percentages. Based on simulation study, they created two models for estimating capacity – one for planning purposes which can be applied before work zone is in place to estimate capacity, and another for operational analysis which is useful after the work zone is in place as speed measurements, lane distribution are available to be used as input. In the planning model initially unadjusted capacity is estimated which is a function of truck percentages, grade and rubbernecking factor. Then these unadjusted capacity values are used to derive the actual capacity by applying adjustment factors for factors such as day time or night time conditions, driver population characteristics, presence of ramps, and rain. As mentioned before, the values for these adjustment factors were borrowed from previous research.

Ping and Zhu (*40*) in their simulation study of work zones considered the location of warning signs and location of closed lanes as additional factors apart from other pre-established parameters contributing towards the capacity of work zones. Their simulated capacity value ranged from 1320 vphpl to 1920 vphpl. Based on the simulation runs authors developed two regression models analyzing the relationship between capacity and other work zone parameters including the number of open lanes, free flow speed in normal freeway segment (*ffs*) and in work zone (*wffs*), grade, percentage of trucks, location of warning signs and closed lane. The two regression models are as follows:

$$i)\ Capacity = 1617 + lane + V_{ffs} \times W_{ffs} - 11.43 \times grade - 13.41 \times \%truck$$
$$+ 0.008 \times warning.$$

where, *lane* = -4.9 for 2 to 1, 147.4 for 3 to 2 and 0.0 for 3 to 1 work zones

V_{ffs} = 0.48 for 55 mph ffs, 0.50 for 60 mph and 0.56 for 70 mph ffs.

The R^2 of the model was reported to be 0.762.

$$ii)\ Capacity = 1619 + lane + V_{ffs} \times W_{ffs} - 10.2 \times grade - 12.00 \times \%truck$$
$$+ (truck * lane) + (grade * lane) - 1.97 \times (truck * grade)$$

where, *lane* = -3.6 for 2 to 1, 177.0 for 3 to 2 and 0.0 for 3 to 1 work zones

*truck*lane* = -0.17 for 2 to 1, -3.95 for 3 to 2 and 0.0 for 3 to 1 work zones

*grade*lane* = -0.93 for 2 to 1, -19.7 for 3 to 2 and 0.0 for 3 to 1 work zones

The V_{ffs} values were same as the other model. The R^2 of the model was reported to be 0.94.

When the two models were compared with other models such as Kim et al. (*25*) they showed better performance.

Beacher et al. (*41*) examined the impact of the late merge strategy for 2 to 1 lane and 3 to 2 lane configurations and found the increase in throughput and decrease in time in queue is not statistically significant. However the results obtained may be biased due to site specific characteristics including geometric and driver population characteristics.

Apart from field data analysis they also conducted a simulation study in VISSIM which suggested that the late merge strategy significantly improved capacity only for 3 to 1 lane configuration with more than 20% heavy vehicles.

CHAPTER 4

DESIGN OF EXPERIMENTS

4.1 Capacity Definition

In this study, capacity is defined as the mean queue discharge flow rate measured immediately downstream of the taper area. This definition has been recommended by several empirical studies on roadway capacity (*4, 19, 22, 33, 34, 35, 36*). The work zone capacity in this simulation model was estimated as the average hourly through put collected at the end of the transition area (i.e. the taper) in the presence of queue upstream of the work zone.

4.2 Parameter Selection

Based on the above literature it can be concluded that *CC0, CC1, CC2, CC4/CC5* have an impact on the lane capacities under bottleneck conditions. Parameters *CC0* and *CC1* determine the safety distance $dx_{safe} = CC0 + CC1 * v$, where v is the speed of the vehicle, that in turn determines capacity. The sensitivity of dx_{safe} with respect to *CC0* is much lower as compared to its sensitivity with respect to *CC1*. For example, at operating speeds of 30 mph under normal traffic conditions, varying the *CC0* value from 4.9 ft to 10 ft and *CC1* constant at 1.0 results in a meager capacity drop from 2100 vphpl to 2000 vphpl. However, varying the *CC1* value from 1.0 to 1.8 secs and *CC0* fixed at 4.9 ft resulted in a significant capacity drop from 2300 vphpl to 1500 vphpl. Since the objective of this research is to cover a wide range of capacity values, *CC1* was varied and *CC0* was set to its default value. The average following distance during a following process lies within the interval [dx_{safe}, dx_{safe} + *CC2*] during capacity conditions. Thus, *CC2* parameter is also varied in the study. For *CC4*/ *CC5* car following parameter visual interpretation suggested that values higher than -3/3 resulted in an unstable car following process. And, values lower than -3/3 did not produce any significant variation of capacity, also suggested in the study conducted by Lownes et al. (*18*). Therefore *CC4*/*CC5* pair was dropped from further consideration and set to default values.

All VISSIM based studies reviewed earlier have considered only the car following parameters while calibrating models for work zone conditions. None of those studies have considered the lane changing parameters, which can be very crucial in work zone lane reduction situations. The lane changing distance (previously known as look-back distance in earlier versions of VISSIM) is not a driving behavior parameter in the Wiedemann's lane changing algorithm. Although it can initiate the lane changing process by describing the position at which vehicles start to look for gaps in the adjacent lanes; it does not however, affect any other aspect of the lane changing algorithm. As described earlier, the safety distance reduction factor (*SRF*) is a critical parameter that reflects the aggressiveness of the drivers when changing lanes. In this study, the lane changing parameter, *SRF*, in addition to the car following parameters *CC1* and *CC2* are varied to achieve different work zone capacity values recommended by different states.

4.2 Study of Truck Characteristics in VISSIM

In this simulation study two categories of vehicles were included, passenger cars and trucks or heavy gross vehicles (HGVs). The default truck characteristics (HGVs) such as length, weight and power used in VISSIM do not represent the actual truck characteristics in U.S. For example the default length of trucks in VISSIM is only 33.51 feet. In U.S truck lengths vary from 30 feet to as long as 80 feet. Therefore, it is not appropriate to use the default truck characteristics while modeling work zones on roadways in U.S. In this study, U.S. specific truck characteristics are identified and used in the simulation models. Figure 2 shows the different classes of trucks seen on U.S. freeways.

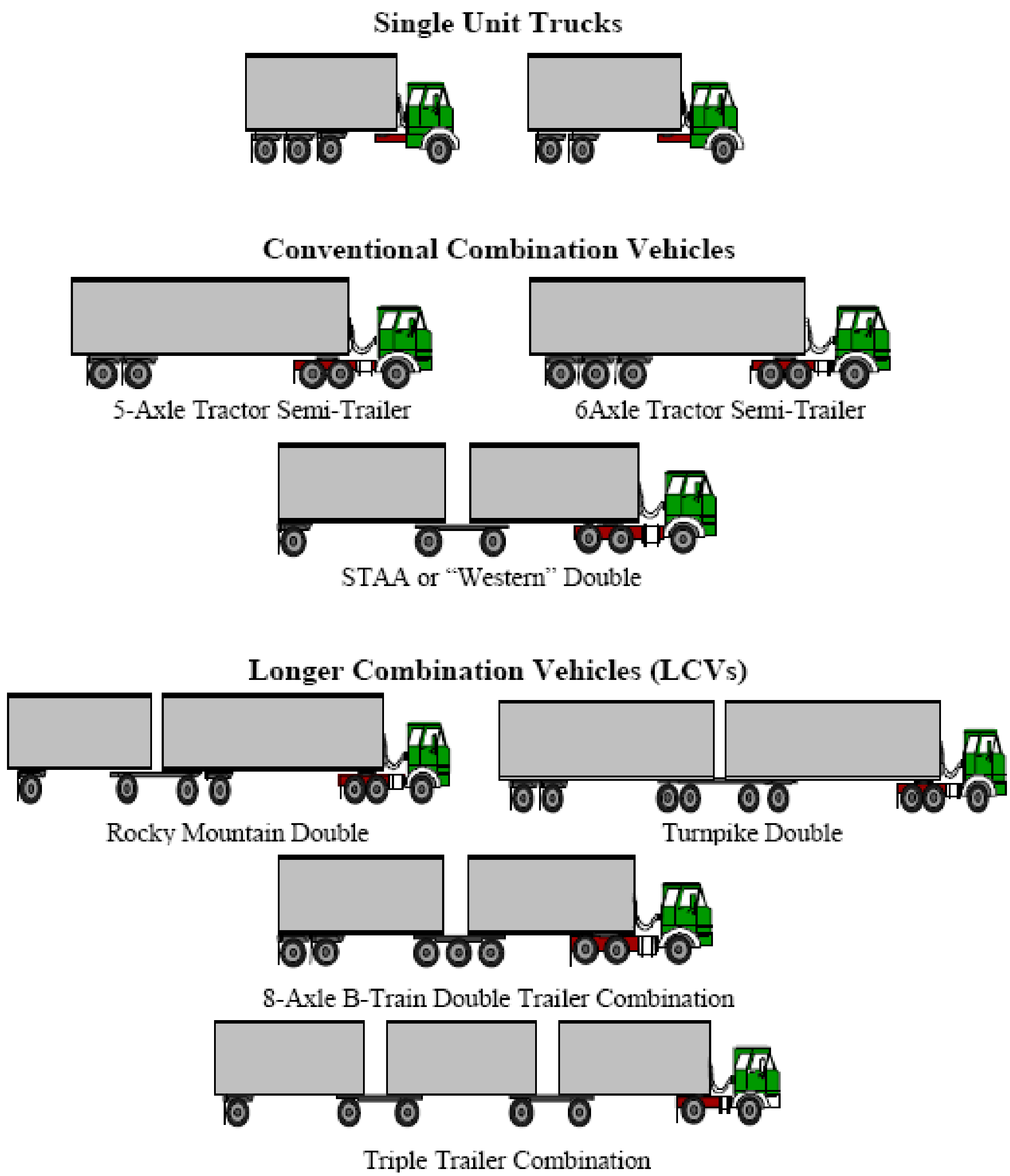

FIGURE 2 Truck configurations used in U.S

(Figure from NCHRP 505 report (*42*))

Out of these different classes of trucks the two most frequently observed classes are Single Unit trucks and Conventional Combinational trucks. Table 3 adapted from NCHRP 505 report (*42*) shows the composition of U.S truck fleet for the year 2000.

TABLE 3 U.S Truck fleet Characteristics

(From NCHRP report (*42*))

Vehicle class	Number of vehicles 1994	Number of vehicles 2000	Number of vehicles Percent share of truck fleet	Vehicle miles traveled (in millions) 1994	Vehicle miles traveled (in millions) 2000	Vehicle miles traveled (in millions) Percent share of truck fleet
2-axle single-unit truck	3,213,020	3,747,984	57.3	46,035	53,700	29.5
3-axle single-unit truck	594,197	693,130	10.6	8,322	9,707	5.3
4-axle or more single-unit truck	106,162	123,838	1.9	2,480	2,893	1.6
3-axle tractor-semitrailer	101,217	118,069	1.8	2,733	3,188	1.8
4-axle tractor-semitrailer	227,306	265,152	4.1	9,311	10,861	6.0
5-axle tractor-semitrailer	1,027,760	1,198,880	18.3	71,920	83,895	46.1
6-axle tractor-semitrailer	95,740	111,681	1.7	5,186	6,049	3.3
7-axle tractor-semitrailer	8,972	10,466	0.2	468	546	0.3
3- or 4-axle truck-trailer	87,384	101,934	1.6	1,098	1,280	0.7
5-axle truck-trailer	51,933	60,579	0.9	1,590	1,855	1.0
6-axle or more truck-trailer	11,635	13,572	0.2	432	503	0.3
5-axle double	51,710	60,319	0.9	4,512	5,263	2.9
6-axle double	7,609	8,876	0.1	627	731	0.4
7-axle double	7,887	9,201	0.1	542	632	0.4
8-axle or more double	9,319	10,871	0.2	650	759	0.4
Triples	1,203	1,404	0.0	108	126	0.1
Total	5,603,054	6,535,956		156,014	181,988	

2nd Highest Percentage

Highest Percentage

Based on the percentage shares shown in the last column of Table 3, it is clear that 5-axle tractor-semitrailers (46.1%) and 2-axle single unit truck (29.5%) have the two major shares. In this study, we will focus on only these two truck classes. Figures 3 and 4 below show the typical dimension of a 2-axle single unit truck and 5-axle tractor-semi trailer (*42*). However, the distribution of single unit trucks and tractor trailer trucks can vary significantly from one state to another state and even from one region to another within a state. So it is very hard to come up with a single distribution of trucks which can replicate all the truck scenarios everywhere in the country. For example in the state of Virginia 2-axle single unit trucks comprise in an average 35% of the total truck composition (*43*) whereas in Missouri it is as high as 54% (*44*). So the difference is quite significant from one state to another. In this simulation study based on the most recent study on vehicles miles of travel and related data on highways conducted by FHWA (*46*) only two categories of trucks were considered; 35% of the total truck composition was assumed to consist of 2-axle single unit truck of 30 ft length, with the remainder consisting of 5-axle tractor-semi trailer of 73.5 ft length.

Another important truck characteristic is the power to weight ratio which determines a truck's ability to accelerate and maintain speeds on an upgrade. VISSIM does not have any input for power-to-weight ratio but it has separate weight and power distributions for HGVs. The power-to-weight ratio is calculated in Kilowatt per Tonne (KW/T) within the model by randomly choosing a weight value from the weight distribution and a power value from the power distribution for each truck in the traffic mix. The power-to-weight ratio is constrained, in VISSIM, between 7 to 30 KW/T so as to avoid any extreme ratios. In other words, whenever the computed ratio falls below 7KW/T it is set to 7KW/T and if the ratio is higher than 30, it is set to 30 KW/T. NCHRP 505 report (*42*) and the FHWA truck size study (*46*) suggest that the weight of a 2-axle single unit truck ranges from 9.08 T (i.e. 20,000 lb) to 27.24 T (i.e. 60,000 lb) while most of the combinational trucks have gross weight more than 27.24 T and only 3 % single trailer combinational trucks weigh more than 36.32 T (i.e. 80,000 lb). Figure 5 shows the weight distribution of the trucks assumed in this simulation study. The weight ranges from 9.080 T (i.e. 9080 kg) to 36.32 T (i.e. 36320 kg) with an 85th percentile weight of 27.24 T (i.e. 27264 kg). In recent years the power-to-weight ratios of trucks have been increasing quite steadily. One of the few studies on the current prevailing power-to-weight ratio of trucks was conducted on freeways and two lane highways in California, Colorado and Pennsylvania (*42*). Table 4 shows the study results. The average 5th and 95th percentile power-to-weight ratios in the three states were 7.3 KW/T and 18.88 KW/T respectively. As mentioned before, VISSIM has a limitation of randomly selecting a weight value and a power value from their respective distributions and then compute the power-to-weight ratio for each truck. The maximum and minimum values for power used in the simulation model are calculated based on the 5th and 95th percentile weight to power ratio values from the above mentioned study (*42)* and for each case, weight of the truck is kept constant at 27.24 T (i.e. 60,000 lb) which is the 85th percentile value of the weight distribution. This assumption seems reasonable and all the possible values of power-to-weight ratios fall between 7 KW/T and 30 KW/T, the VISSIM thresholds. Figure 6 shows the power distribution for trucks used in the VISSIM model.

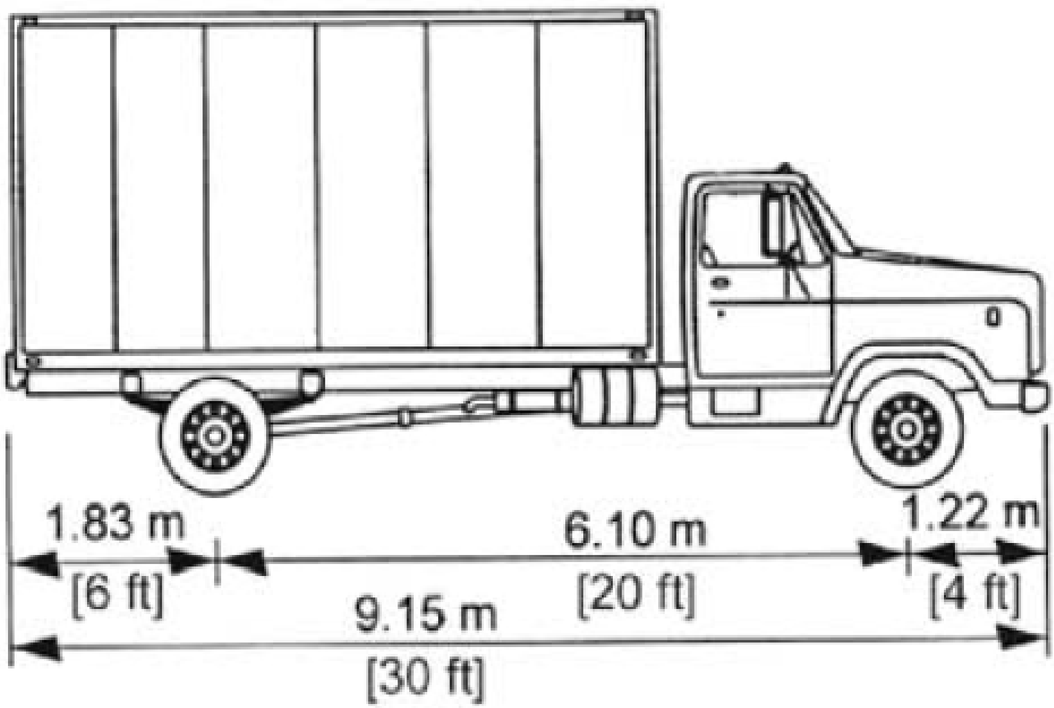

FIGURE 3 Dimension of single unit truck

(Figure from NCHRP 505 (*42*))

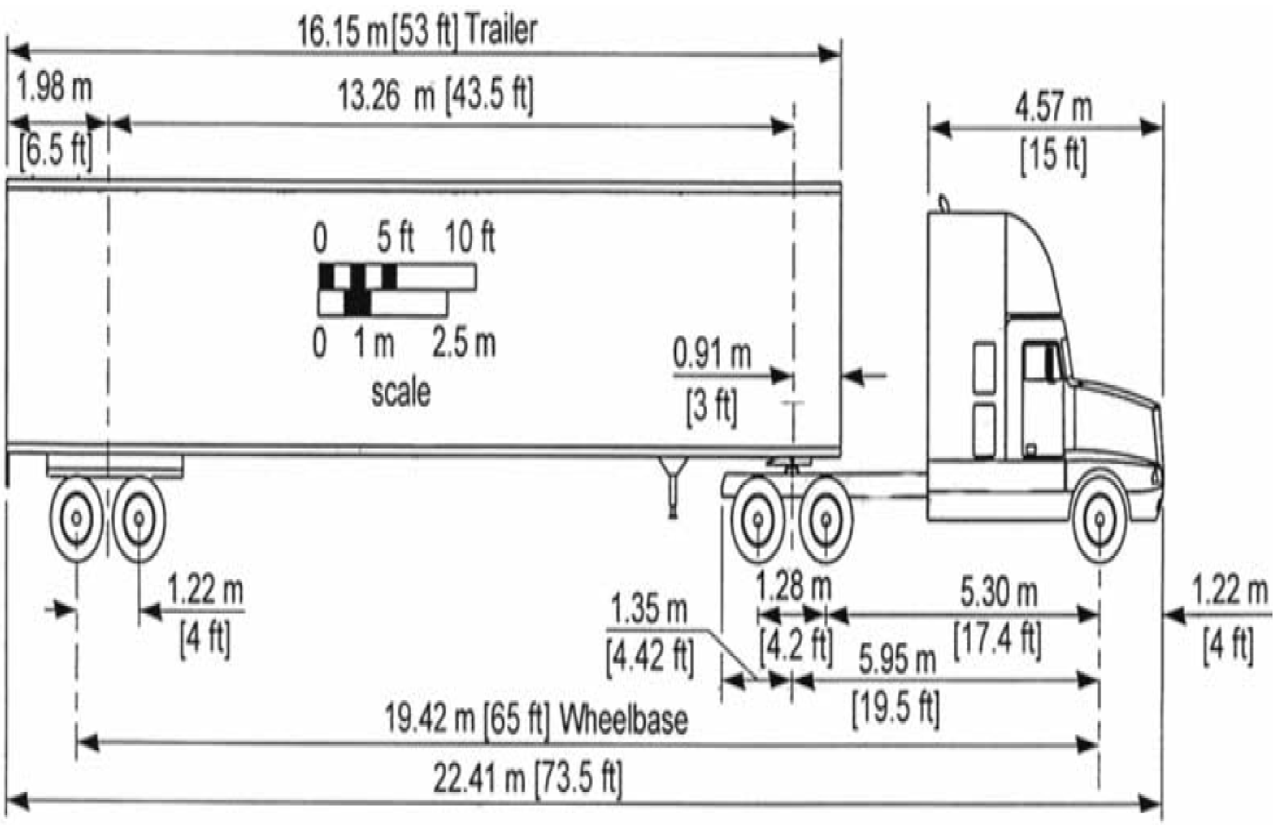

FIGURE 4 Dimension of 5-axle tractor semi trailer

(Figure from NCHRP 505 (*42*))

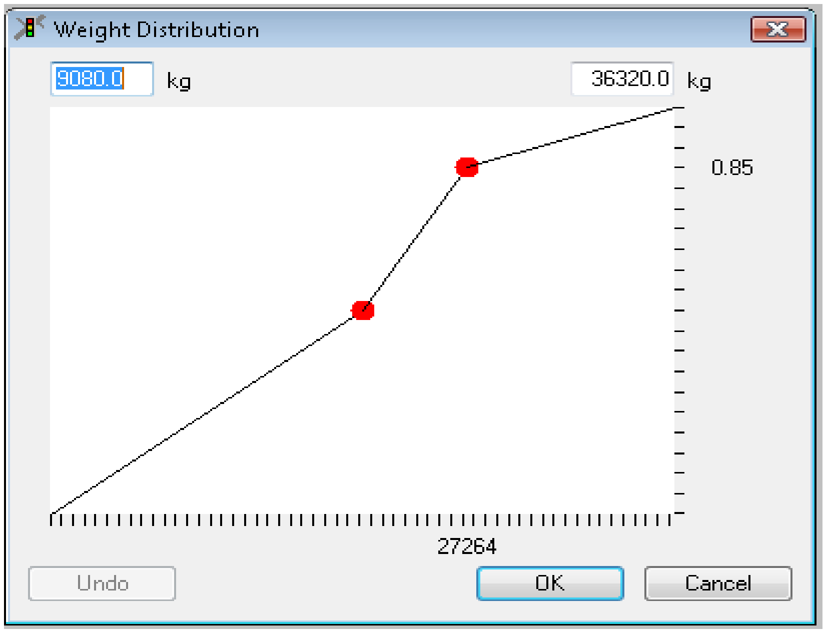

FIGURE 5 Weight distribution for trucks used in the model

TABLE 4 Power-to-Weight Ratio for Trucks from the 1997 Study

(Adapted from NCHRP 505 (*42*))

	Power-to-Weight Ratio (KW/T)		
Percentile	CALIFORNIA	COLORADO	PENNSYLVANIA
5th	7.33	8.26	6.5
25th	10.02	10.81	8.47
50th	11.65	14.29	9.78
75th	14.67	18.89	11.57
95th	19.6	23.7	14.7

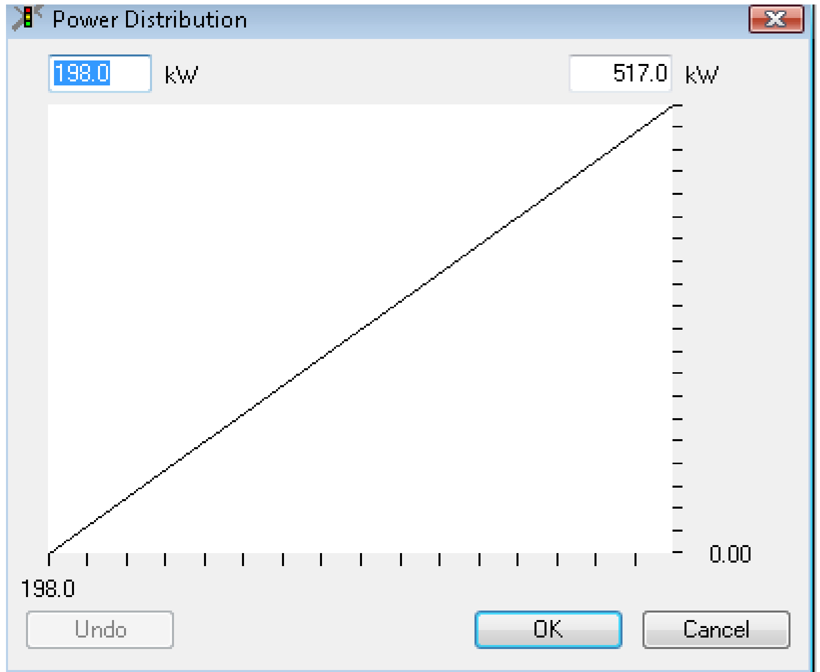

FIGURE 6 Power distribution for trucks used in the VISSIM model

To illustrate the impact of truck characteristics on capacity estimates in work zone simulation models, two scenarios were simulated. In scenario 1, the default truck characteristics in VISSIM were used and in scenario 2 the previously developed U.S. specific truck characteristics were used. The driver behavior parameters were set to default values for both scenarios. Results for 10% and 20% trucks are shown in Table 5.

TABLE 5 Capacity Values for Default Parameters and U.S Truck Configuration

	Default Truck Configuration			U.S Truck Configuration		
Lane Configuration	2 to 1	3 to 2	3 to 1	2 to 1	3 to 2	3 to 1
Truck Percentage	(vph)	(vphpl)	(vphpl)	(vph)	(vphpl)	(vphpl)
10%	2179	2120	1898	2067	2096	1841
20%	2074	2045	1530	1874	1909	1509

Figure 7 below further illustrates the difference in capacity values for a 2 to 1 work zone configuration between the two scenarios. Capacity values for 3 to 1 and 3 to 2 work zone lane configuration, particularly for high truck configuration may not be appropriate for comparison as in those scenarios too many vehicles tend to back up in the closed lanes as they do not get enough gap to change lanes for the given set of driver behavior parameter used (in this case default values). Also due to such huge queuing of vehicles in the closed lanes a phenomenon termed as "cooperative lane changing" happened from time to time, where after the queue in the closed lane reaches a certain point the vehicles in the open lane come to a complete stop and wait until all the preceding vehicles in the closed lane merged into the open lanes. Such phenomenon is unrealistic and can yield inaccurate capacity values. This also demanded a better set of driving behavior parameters instead of default values to replicate oversaturated work zone conditions, particularly for high truck percentage scenarios. However, it is quite evident from the results obtained for 2 to1 work zone configuration that truck characteristics can have a strong impact on capacity values, particularly for higher truck compositions. So in this study the U.S. specific truck characteristics were used instead of the default values for all work zone models (see Table 6).

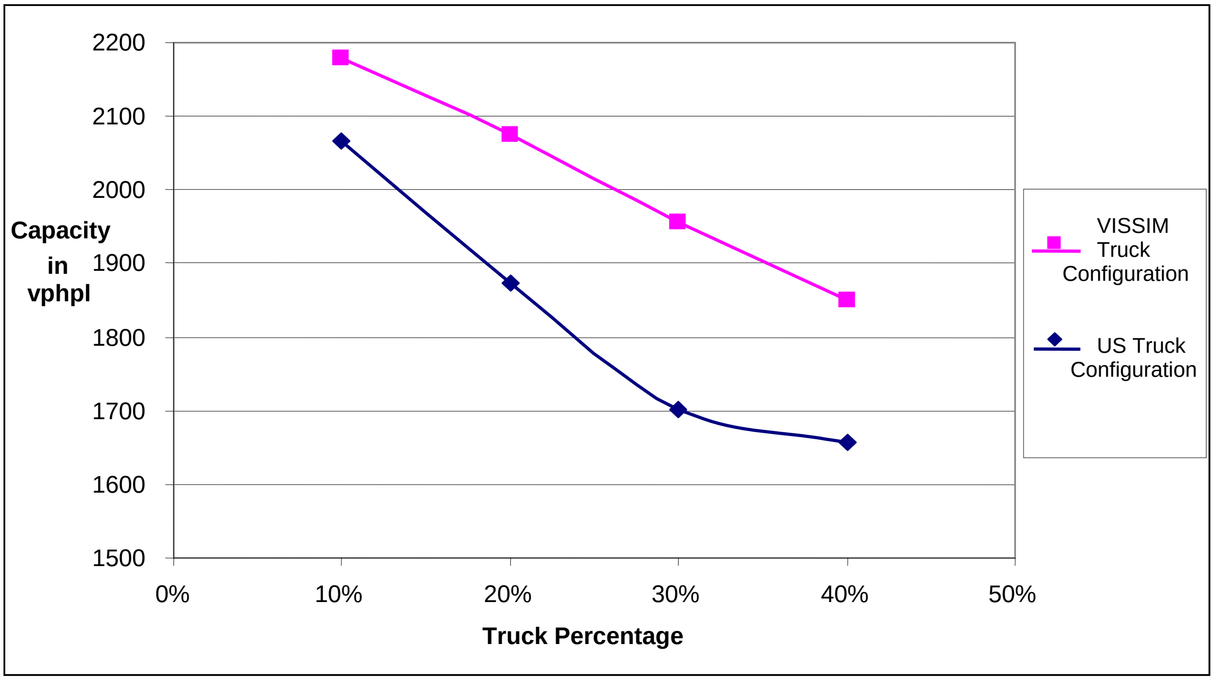

TABLE 6 Comparison of Truck Configuration Modeled with Vissim Default Values

	Default Values		Used Values	
	Min	Max	Min	Max
Weight(in kg)	2800	40,000	9080	36320
Power(in KW)	150	400	198	517
Truck Lengths	33.51 ft		65% with 73.5 ft	35% with 30 ft

4.3 Work Zone Lane Configurations

In this thesis, the following three most common work zone configurations on freeways and multilane highways were studied.

- 2 to 1 work zone configuration
- 3 to 2 work zone configuration

- 3 to 1 work zone configuration

where, configuration “X” to “Y” implies that out of “X” lanes only “Y” lanes are open (in one direction).

Figures 8 to 10 describe the layout of each work zone configuration with data collection points in the simulation model.

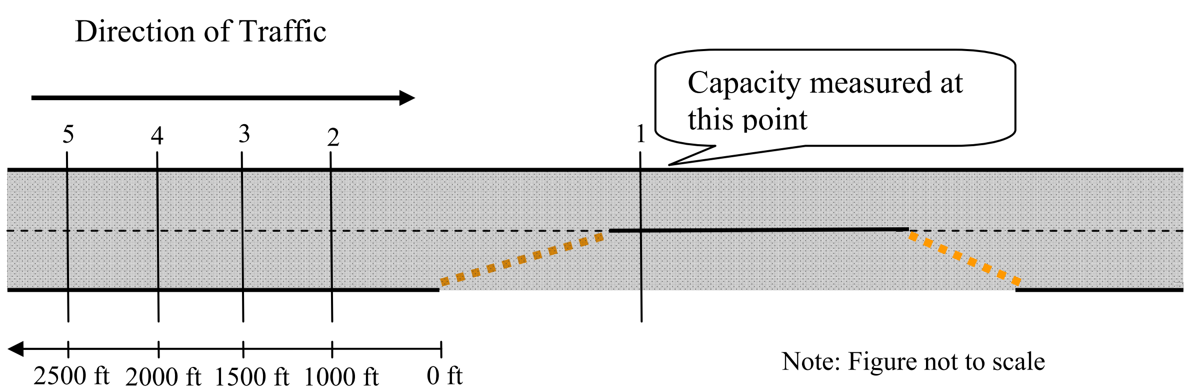

FIGURE 8 Layout of data collection points for 2 to 1 lane

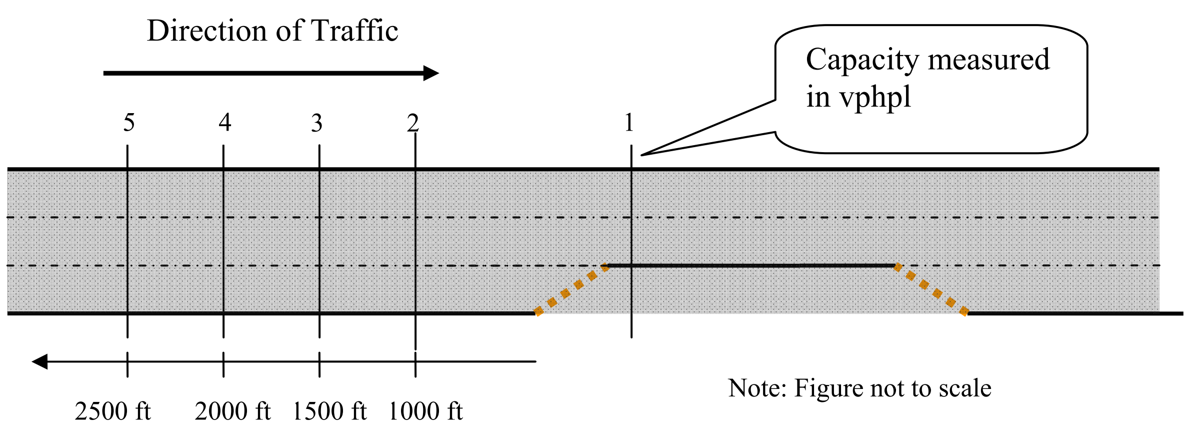

FIGURE 9 Layout of data collection points for 3 to 2 lane

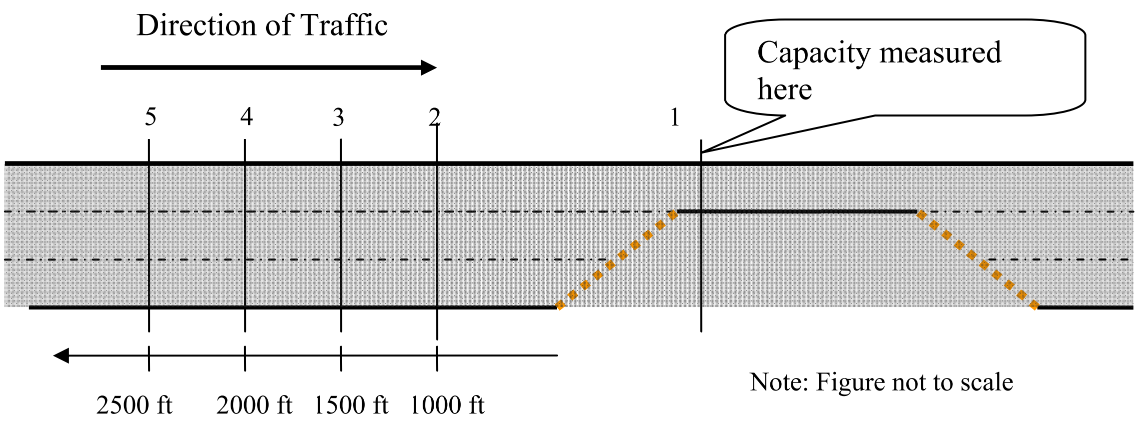

FIGURE 10 Layout of data collection points for 3 to 1 lane

Various past studies (*3, 22, 25, 40*) have considered percentage of trucks as a significant variable influencing the capacity of a work zone. Our goal of this study is to come up with a set of parameters that can replicate most prevailing work zone conditions in U.S. Therefore it is important to have a good range of truck percentages that are representative of traffic compositions at work zones thorough out the country. The different truck percentages studied in this thesis are shown in Table 7.

TABLE 7 Truck Percentages Used for Different Work Zone Configurations

Work Zone Lane Configurations		
2 to 1	**3 to 2**	**3 to 1**
10%	5%	5%
20%	10%	10%
30%	20%	20%
40%		

Truck percentages for 2 to 1 work zone lane configuration were selected on the assumption that majority of this category of work zones are found in rural areas where the truck percentages can be as high as 40%. For example in Missouri the average truck percentage in rural areas on I-70 is more than 40%. Similarly, other two configurations i.e. 3 to 2 and 3 to 1 typically represent work zones near urban areas where truck percentages can be as low as 5 %.

4.4 Selection of Parameter Values

The range of values for the identified driving behavior parameters in VISSIM was obtained by visually inspecting the simulation runs for different parameter values. Threshold values, both lower bound and upper bound, kept unrealistic and unsafe driving behavior conditions from occurring. Table 8 shows the range of values for each parameter used in this study.

TABLE 8 Ranges of Driving Behavior Parameters

Parameters	Minimum	Maximum
CC1	0.9 secs	1.8 secs
CC2	10 ft	55 ft
SRF	0.15	0.6

One of the goals of this study was to create different combinations of parameter values that correspond to different capacities. Two methods for creating parameter combinations, the exhaustive search (ES) method and the Latin Hypercube Sampling (LHS) were used in this study. LHS has been widely used in the areas of simulation modeling and probabilistic risk assessment (*47*). LHS method begins by selecting n different values for each of the p variables. Suppose, we have X_1, X_2, $X_3 \ldots X_p$ variables. Then, for each of those p variables n values are selected by dividing the range of each variable into n non-overlapping intervals and then one value from each interval is selected using a probability distribution defined for that interval. The n values obtained for X_1 are paired in random with n values obtained for X_2. Then these n pairs of X_1 and X_2 values are randomly combined with n values of X_3. This process is continued until n randomly selected combinations of all the p variables are obtained. The end result is a matrix of (n × p) input variables. One of the major advantages of LHS is its ability to sample at least one value of the parameter from each interval. So the sample's values should have a good representation of the overall population. For more details on LHS, see Mckay (*47*) and Wyss and Jorgensen (*48*).

In this study the number of variables was 3 (*CC1*, *CC2* and *SRF*). The ranges for all three parameters were previously defined in Table 8. When LHS was used to generate combinations of these three parameter values it could only produce as many observations as the number of intervals into which the parameters were divided. Given this limitation, it was not possible to generate a sufficiently large sample. When the interval size was further reduced in order to increase the number of intervals it resulted in parameter combinations with very small variations which was not desirable for replicating a wide range of capacity values. Therefore, LHS method was deemed not appropriate in this study. Instead, the ES method was used to generate a sufficiently large sample. *CC1* value was increased from 0.9 secs to 1.8 secs with an increment of 0.1 secs. *CC2* value was varied from 15 ft to 60 ft at an increment of 5 ft. Similarly, *SRF* factor was reduced from its default value of 0.6 to 0.15 at an interval of 0.05. The increments were chosen in order to produce a wide range of values that were not redundant. A total of 900 (i.e. 9 for *CC1*, 10 for *CC2* and 10 for *SRF*) unique combinations of *CC1*, *CC2* and *SRF* factor were created. These combinations were then simulated and traffic conditions were visualized. Those parameter sets that resulted in unrealistic traffic flow conditions such as "cooperative lane changing behavior" (explained previously) and vehicles traveling at high speeds (more than 40 mph) on the open lane while a large number of vehicles were waiting in the closed lane to merge, were identified visually and eliminated from further analysis. It was not possible to visually interpret each of the 900 simulation files, so a general pattern for the occurrence of such extreme scenarios was identified based on the occupancy rate of the vehicles 500 ft or 1000 ft upstream of the taper obtained from the data collection points in the simulation model (occupancy rate is defined as the percentage of time a detector is occupied by vehicles).

Figures 11 and 12 describe simulation snapshots of a scenario that was eliminated based on high occupancy rate at 500 ft upstream of the taper.

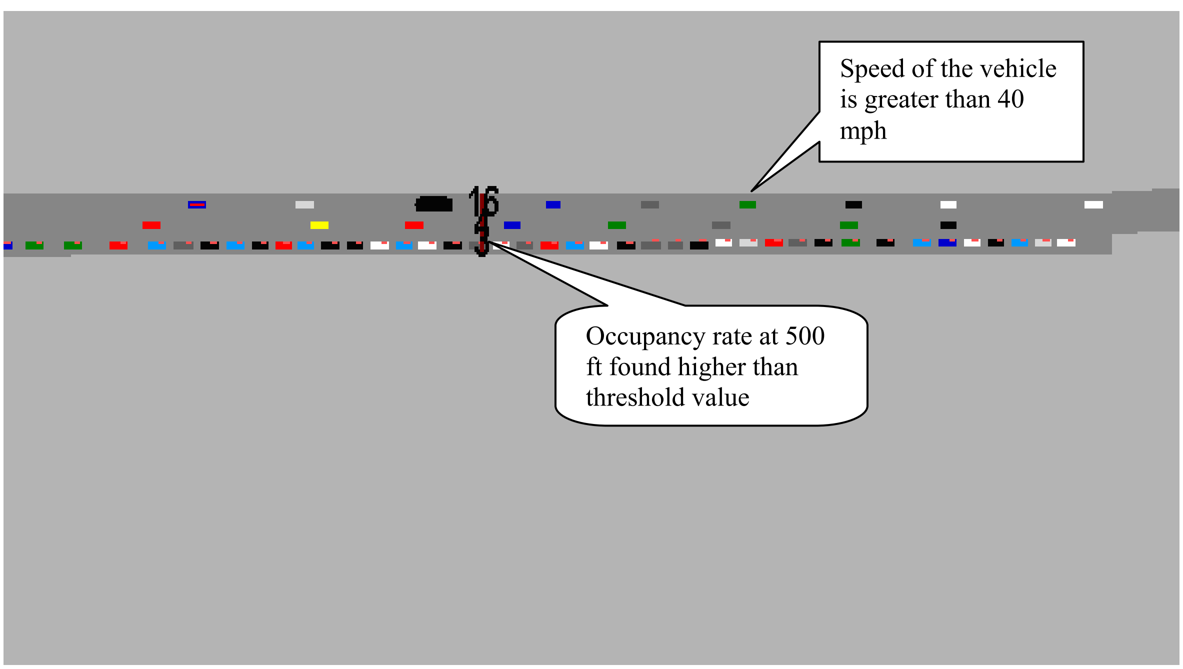

FIGURE 11 Large queue backing up on closed lane u/s of the taper

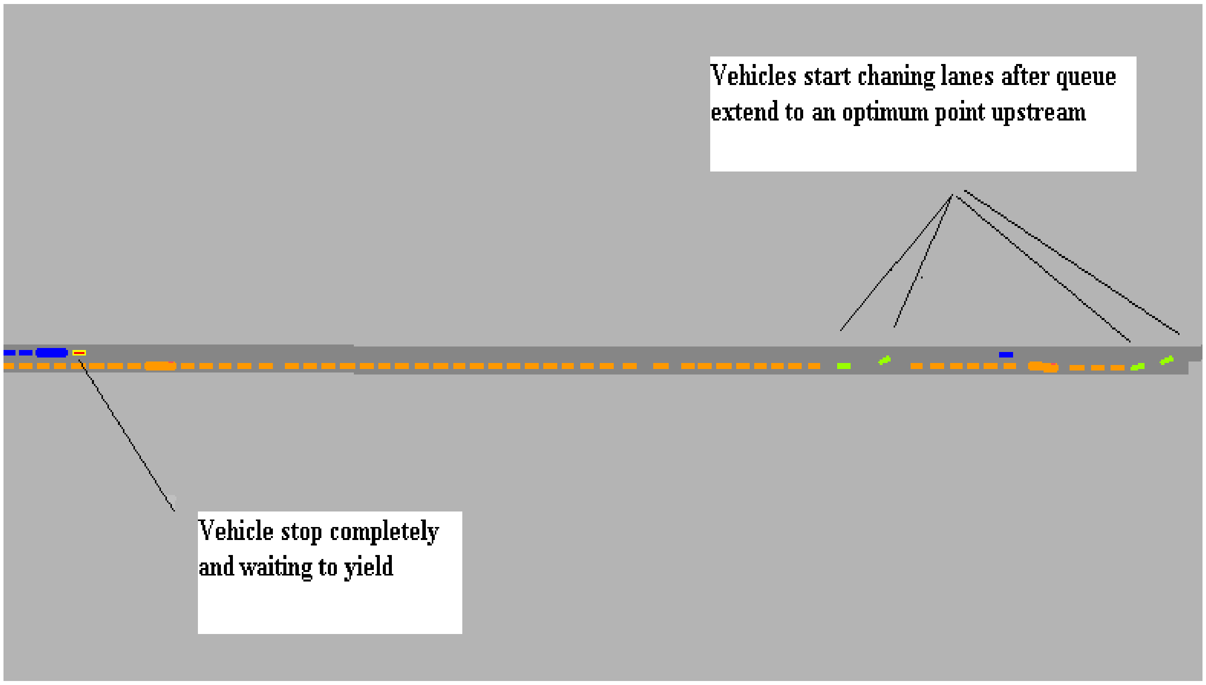

FIGURE 12 Cooperative lane changing phenomenon observed in VISSIM

Occupancy rate thresholds were determined by visually distinguishing the scenarios where the above phenomenon occurred from the expected normal conditions. The threshold values ranged from 3% to 15% depending on the work zone lane configuration and truck percentage.

After the threshold occupancy rate was established scenarios with occupancies exceeding threshold values were discarded. Thus out of 900 combinations of parameter values only those sets which produced acceptable traffic flow conditions in the work zone were considered for further analysis. Then each scenario was simulated 5 times with different random seeds to account for the variability introduced by the stochastic nature of the micro-simulation model. Driver behavior model of W-99 was selected to replicate all freeway work zone conditions. The desired speed distribution (a VISSIM input) through the work zone was assumed to be between 45 mph and 55 mph with 85th percentile speed of 50 mph. This assumption was made based on a typical 20 mph speed limit reduction in work zones (e.g. Missouri freeways). Although other states may use different speed limit reductions in work zones, the methodology and results obtained in this research are still valid as speed limits do not influence the results obtained for oversaturated conditions where only low speed conditions prevail.

The lane changing distance for passenger cars was set to 2500 ft upstream of the taper. This value was determined based on the distance at which the 'right lane closed' sign is visible to the drivers.

However the lane changing distance for trucks were assumed to be much higher as commercial vehicle operators are believed to have prior information about the work zone schedule. Trucks were assumed to change lanes way ahead of the installed 'work ahead' sign. So the lane changing distance for trucks was set to approximately 2 miles upstream of the actual closure. This large lane changing distance for trucks also eliminated scenarios where too many trucks backed up in the closed lane waiting for gaps to merge, while vehicles in the open lanes were traveling at high speeds without yielding to the waiting trucks.

Another parameter included in the lane changing behavior of VISSIM is "waiting time before diffusion" which defines the maximum amount of time a vehicle waits to merge at the emergency stop before it disappears from the network (*16*). The default value of the parameter is only one minute, however, in this study its value was set to 5 minutes in order to reduce the number of vehicles disappearing from the network.

4.5 VISSIM Models for Different Work Zone Lane Configurations

4.5.1 *2 to 1 lane configuration*

Initially a freeway section with 2 lanes was created in VISSIM with one lane dropped for more than a mile to model a work zone with 2 to 1 lane configuration (see Figure 8). In this study the right lane was closed. A few work zone capacity estimation models (*49*) considered the location of closed lane as an explanatory variable and found that it is very difficult to clearly identify if it has any significant impact on capacity. A study conducted by Elefteriadou and Heaslip (*32*) showed that there is no significant difference in work zone capacity values between left lane and right lane closure. Therefore, the choice of closed lane in this study should not have any impact on the resulting capacity values. The typical spacing of traffic signs in a work zone in Missouri (*50*) is shown in Figure 13. Vehicle demand of 3000 vph was entered into the model to provide adequate demand to reach capacity conditions. Truck percentages for this configuration included 10%, 20%, 30% and 40%.

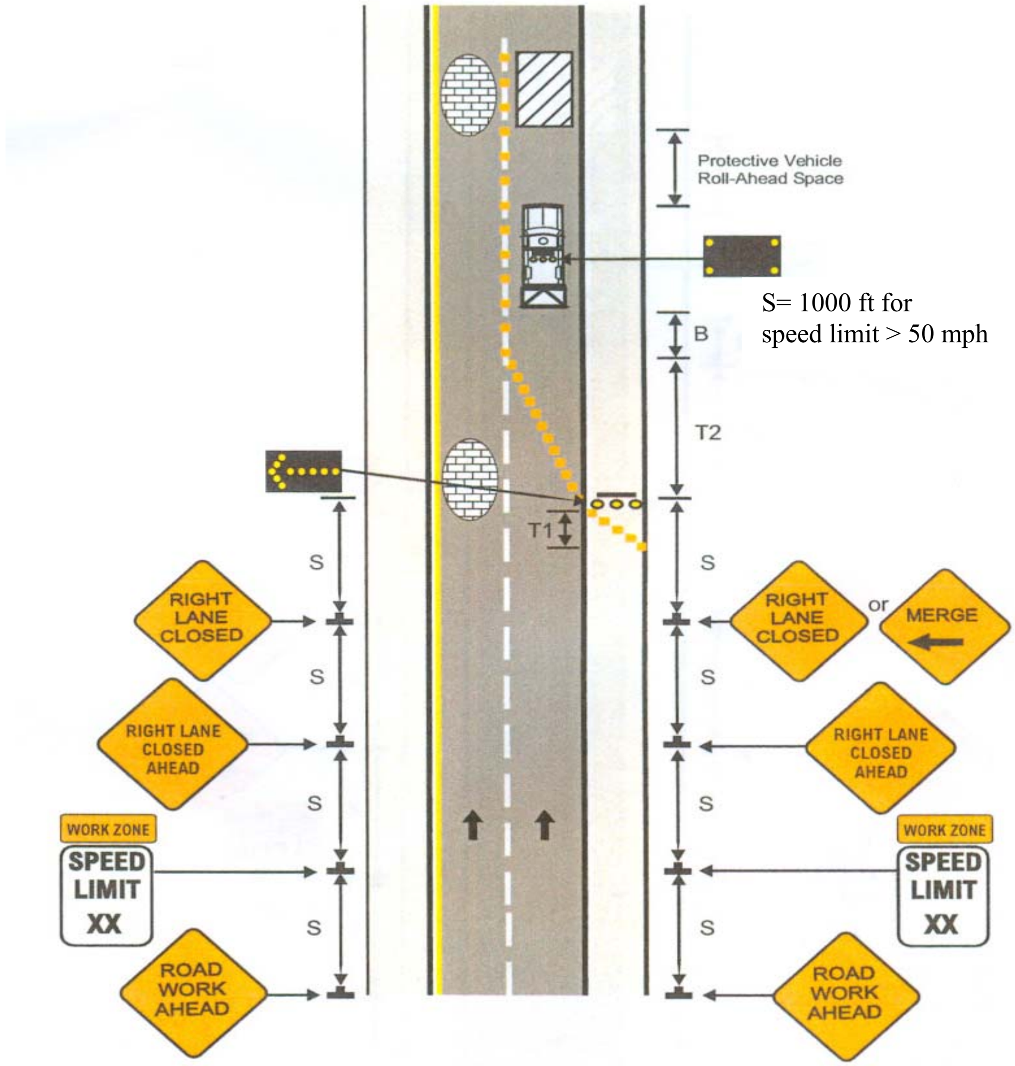

FIGURE 13 Typical layout of a 2 to 1 work zone in Missouri

4.5.2 *3 to 2 lane configuration*

A 3 lane freeway section with 2 lanes open and one lane closed (right most lane) for work activity was simulated (see Figure 9). The driver behavior models, speed distributions, and other settings were same as 2 to 1 lane configuration. Vehicle demand of 5000 vph was entered into the model to provide adequate demand to reach capacity conditions. The same procedure of scenario generation was repeated for different truck compositions. Three different truck percentages, 5%, 10% and 20% were modeled.

4.5.3 *3 to 1 lane configuration*

A 3 to 1 lane configuration is similar to the 3 to 2 lane work zone set up with an additional lane closure resulting in only one open lane - the left most lane (see Figure 10). Vehicle demand and truck compositions were also identical to the 3 to 2 lane work zone configuration. Each scenario was run for five different random seeds.

All the simulations were carried out on Pentium 4, 1.80 GHz processors. The number of scenarios (i.e. unique combinations of the selected three parameters) obtained after applying the occupancy filter are shown in Table 9.

TABLE 9 Number of Scenarios Retained for Various Lane Configurations and Truck%

	Work Zone Lane Configuration		
Truck %	2 to 1	3 to 2	3 to 1
5%		678	401
10%	648	667	375
20%	572	621	67
30%	536		
40%	121		

Figure 14 below suggests that as the truck percentage increases, the number of scenarios below the occupancy threshold decreases. The decrease is even more significant in the case of 3 to 1 configuration due to the numerous lane changing maneuvers.

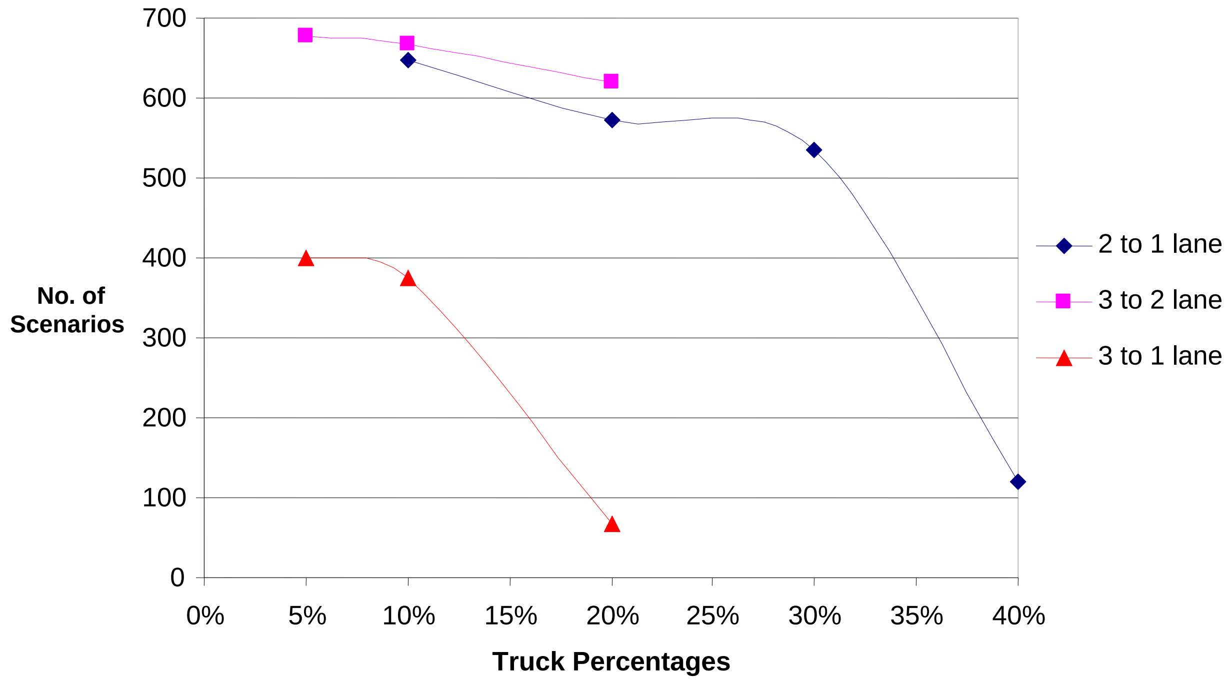

FIGURE 14 Number of scenarios simulated for different lane configurations

It was not possible to manually create 900 VISSIM files by changing the driving behavior parameters each time. So a script modifying language PERL (*51*) was used to create all VISSIM input files (*.inp format) for different parameter sets. The next step was to generate evaluation files to collect traffic data for multiple simulation runs in VISSIM. For that purpose Microsoft Visual Basic which supports the VISSIM COM (*52*) server was used. Finally a Matlab (*53*) code was generated to process the volume data and calculate the hourly throughput and lane distribution for each scenario.

4.6 Type of Data Collected from the Simulation Model

- Traffic volume
- Occupancy rate

- Vehicle speed
- Queue length

Using data collection points, volume, mean speed, and occupancy rate were collected for a period of 1 hour at the following four different locations (see Figure 15 below): 1) immediately downstream of the taper to get the capacity value, 2) 500 ft upstream of the taper, 3) 1000 ft upstream of the taper , 4) 1500 ft upstream of the taper. Capacity was calculated as hourly throughput measured at data collection point 1. For all other data collection points the proportion of hourly volume in the closed lane to the total hourly volume across the point (sum of open and closed lane volumes) was calculated. So we had percentage of lane distribution at 1000 ft, 1500 ft and 2000 ft upstream of the actual closure. These data can be used to replicate any work zone condition where lane distribution data in addition to capacity value is available for calibration (*39*). For all the scenarios data were collected from 400 seconds to 4000 seconds for a one hour time interval. The start up time which is the time required to fill the network with adequate traffic was set to 400 seconds for all scenarios in this study. The mean values for all the performance measures from the five simulation runs with different random seeds were computed for each scenario. In addition to the volume data collected for capacity estimation, occupancy rate at 500 ft upstream of the taper was collected initially to eliminate those unacceptable traffic scenarios as mentioned before.

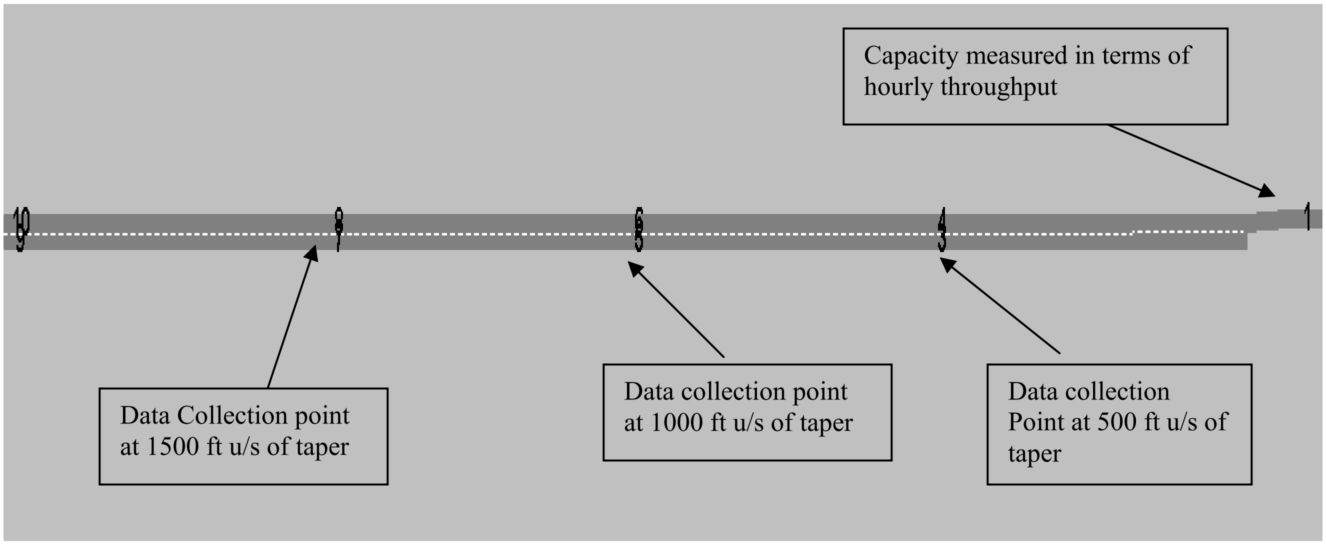

FIGURE 15 Layout of data collection point for 2 to 1 work zone in VISSIM

CHAPTER 5

RESULTS AND ANALYSIS

5.1 Results from Simulation

As mentioned in the previous chapter, the proportion of right lane traffic to the total through traffic, also called lane distribution, was obtained for all the data collection points. The capacity value for each scenario was plotted against the proportion of right lane traffic at different locations upstream of the taper. Plots of capacity versus lane distribution at 1000 ft upstream of the taper are shown in this section while similar plots at 1500 ft upstream of the taper can be found in Appendix B.

For the 2 to 1 lane configuration, these plots are shown in Figures 16, 17, 18 and 19. The data labels in the figures correspond to unique parameter scenario for each truck composition as listed in Tables 10, 11, 12 and 13, respectively. Out of the acceptable scenarios (i.e. parameter sets) there were few scenarios that produced same capacity with identical lane distribution values. After comparing them it was found that those redundant scenarios had very similar parameter values, and hence were not displayed in the corresponding plots and tables. However, all those scenarios were later considered while building the regression model.

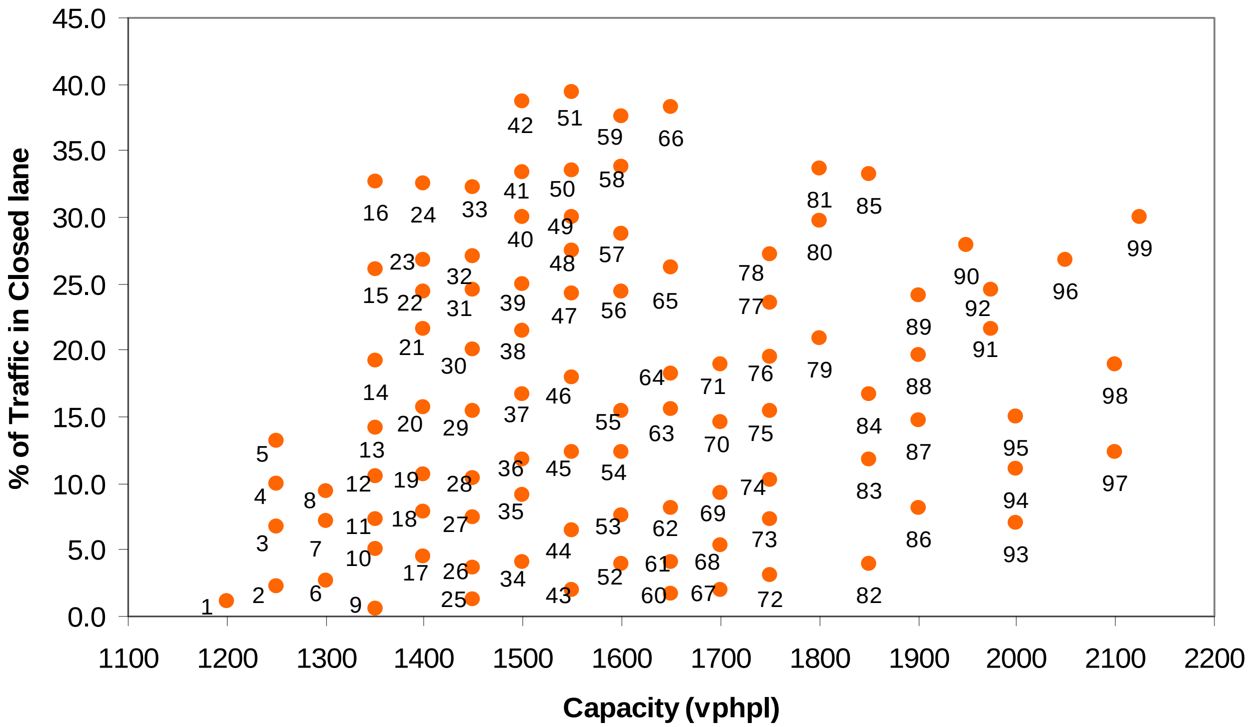

FIGURE 16 Lane distribution at 1000 ft u/s of taper for 10% trucks in a 2 to 1 lane

TABLE 10 Parameter Combinations for 10% Trucks for 2 to 1 Lane

INDEX	***CC1*** **(in secs)**	***CC2*** **(in ft)**	***SRF***	INDEX	***CC1*** **(in secs)**	***CC2*** **(in ft)**	***SRF***	INDEX	***CC1*** **(in secs)**	***CC2*** **(in ft)**	***SRF***
1	1.8	55.0	0.40	34	1.2	55.0	0.45	67	1.0	45.0	0.25
2	1.7	55.0	0.45	35	1.2	55.0	0.55	68	1.1	40.0	0.30
3	1.7	55.0	0.55	36	1.2	55.0	0.60	69	1.0	45.0	0.40
4	1.7	55.0	0.60	37	1.5	35.0	0.45	70	1.1	40.0	0.45
5	1.8	50.0	0.60	38	1.5	35.0	0.50	71	1.1	40.0	0.50
6	1.6	55.0	0.45	39	1.4	40.0	0.60	72	1.3	25.0	0.15
7	1.6	55.0	0.55	40	1.6	30.0	0.50	73	1.2	30.0	0.25
8	1.6	55.0	0.60	41	1.5	35.0	0.60	74	1.3	25.0	0.25
9	1.6	45.0	0.25	42	1.8	15.0	0.25	75	1.3	25.0	0.30
10	1.5	55.0	0.50	43	1.1	55.0	0.35	76	1.0	40.0	0.50
11	1.5	55.0	0.55	44	1.2	50.0	0.45	77	1.0	40.0	0.55
12	1.5	55.0	0.60	45	1.5	30.0	0.35	78	1.0	40.0	0.60
13	1.8	35.0	0.45	46	1.5	30.0	0.40	79	1.3	20.0	0.25
14	1.7	40.0	0.55	47	1.5	30.0	0.45	80	1.0	35.0	0.55
15	1.8	35.0	0.55	48	1.4	35.0	0.55	81	1.1	30.0	0.50
16	1.8	35.0	0.60	49	1.5	30.0	0.50	82	1.0	35.0	0.20
17	1.6	40.0	0.35	50	1.4	35.0	0.60	83	1.1	30.0	0.30
18	1.4	55.0	0.55	51	1.7	15.0	0.25	84	1.1	30.0	0.35
19	1.6	40.0	0.45	52	1.0	55.0	0.40	85	1.2	20.0	0.30
20	1.7	35.0	0.45	53	1.1	50.0	0.45	86	1.2	20.0	0.15
21	1.7	35.0	0.50	54	1.7	15.0	0.15	87	1.2	20.0	0.20
22	1.6	40.0	0.60	55	1.6	20.0	0.25	88	1.0	30.0	0.35
23	1.7	35.0	0.55	56	1.6	20.0	0.30	89	1.0	30.0	0.40
24	1.7	35.0	0.60	57	1.5	25.0	0.40	90	1.0	25.0	0.35
25	1.3	55.0	0.35	58	1.3	35.0	0.60	91	1.0	25.0	0.30
26	1.3	55.0	0.45	59	1.4	30.0	0.55	92	1.1	20.0	0.25
27	1.6	35.0	0.35	60	1.1	45.0	0.25	93	1.0	25.0	0.15
28	1.6	35.0	0.40	61	1.0	50.0	0.35	94	1.0	25.0	0.20
29	1.4	45.0	0.55	62	1.0	50.0	0.45	95	1.0	25.0	0.25
30	1.5	40.0	0.55	63	1.1	45.0	0.50	96	1.1	15.0	0.15
31	1.5	40.0	0.60	64	1.5	20.0	0.25	97	1.0	20.0	0.15
32	1.6	35.0	0.55	65	1.5	20.0	0.30	98	1.0	20.0	0.20
33	1.6	35.0	0.60	66	1.3	30.0	0.55	99	1.0	15.0	0.15

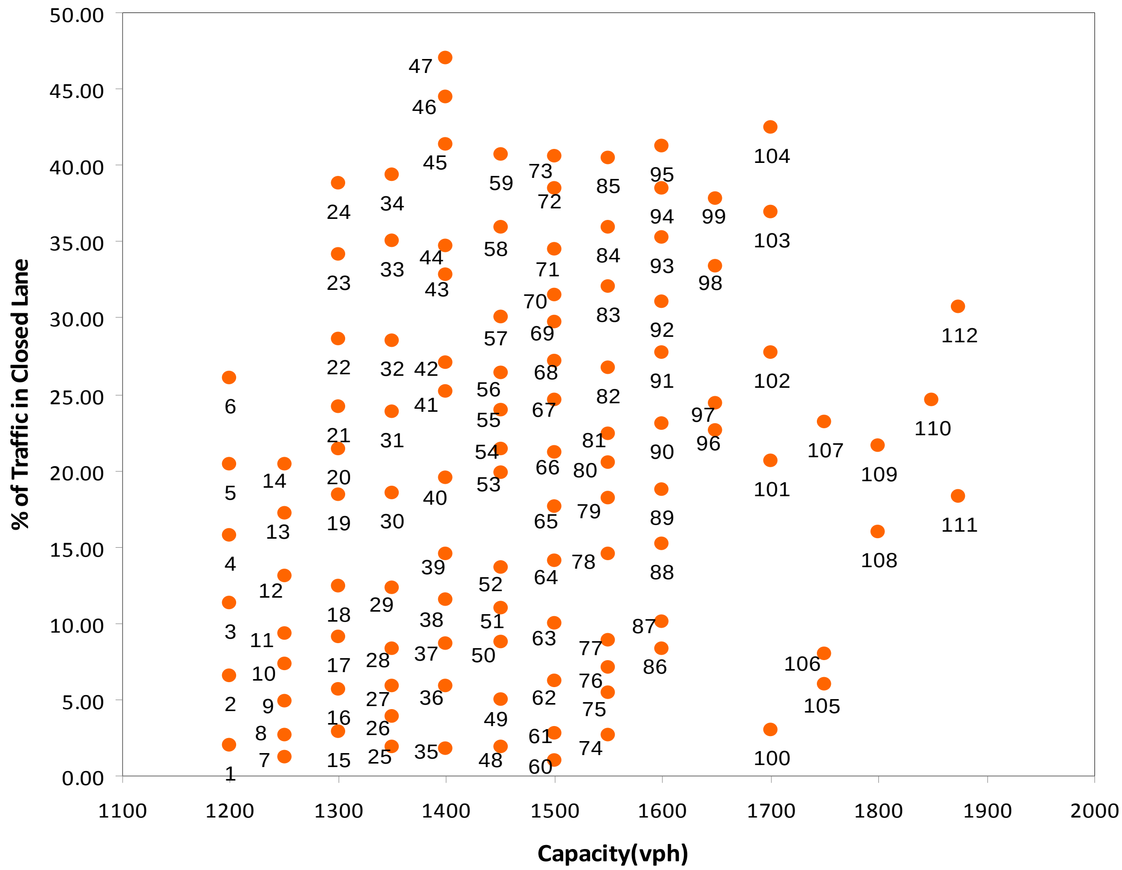

FIGURE 17 Lane distribution at 1000 ft u/s of taper for 20% trucks in a 2 to 1 lane

TABLE 11 Parameter Combinations for 20% Trucks for 2 to 1 Lane

Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*	Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*	Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*
1	1.7	55.0	0.35	38	1.7	30.0	0.25	75	1.3	35.0	0.20
2	1.8	50.0	0.40	39	1.4	45.0	0.40	76	1.5	25.0	0.15
3	1.8	50.0	0.45	40	1.5	40.0	0.40	77	1.4	30.0	0.20
4	1.8	50.0	0.50	41	1.5	40.0	0.45	78	1.0	50.0	0.40
5	1.8	50.0	0.55	42	1.3	50.0	0.60	79	1.0	50.0	0.45
6	1.8	50.0	0.60	43	1.4	45.0	0.60	80	1.3	35.0	0.35
7	1.6	55.0	0.30	44	1.5	40.0	0.55	81	1.0	50.0	0.50
8	1.6	55.0	0.35	45	1.7	25.0	0.40	82	1.0	50.0	0.55
9	1.6	55.0	0.40	46	1.6	30.0	0.50	83	1.4	25.0	0.30
10	1.7	50.0	0.40	47	1.5	35.0	0.60	84	1.3	30.0	0.40
11	1.6	55.0	0.45	48	1.4	40.0	0.20	85	1.1	40.0	0.60
12	1.6	55.0	0.50	49	1.4	40.0	0.25	86	1.4	25.0	0.15
13	1.7	50.0	0.50	50	1.4	40.0	0.30	87	1.3	30.0	0.20
14	1.6	55.0	0.60	51	1.3	45.0	0.35	88	1.3	30.0	0.25
15	1.5	55.0	0.35	52	1.5	35.0	0.30	89	1.0	45.0	0.40
16	1.5	55.0	0.40	53	1.5	35.0	0.35	90	1.0	45.0	0.45
17	1.5	55.0	0.45	54	1.3	45.0	0.45	91	1.0	45.0	0.50
18	1.5	55.0	0.50	55	1.1	55.0	0.60	92	1.0	45.0	0.55
19	1.8	35.0	0.35	56	1.3	45.0	0.50	93	1.1	35.0	0.45
20	1.5	55.0	0.60	57	1.3	45.0	0.55	94	1.2	30.0	0.40
21	1.8	35.0	0.40	58	1.6	25.0	0.35	95	1.0	40.0	0.60
22	1.7	40.0	0.50	59	1.3	40.0	0.60	96	1.2	30.0	0.30
23	1.7	40.0	0.55	60	1.3	40.0	0.15	97	1.0	40.0	0.40
24	1.7	40.0	0.60	61	1.3	40.0	0.20	98	1.1	30.0	0.35
25	1.6	40.0	0.20	62	1.3	40.0	0.25	99	1.2	25.0	0.30
26	1.6	40.0	0.25	63	1.0	55.0	0.40	100	1.0	40.0	0.15
27	1.4	55.0	0.40	64	1.0	55.0	0.45	101	1.3	20.0	0.15
28	1.6	40.0	0.30	65	1.0	55.0	0.50	102	1.2	25.0	0.25
29	1.6	40.0	0.35	66	1.0	55.0	0.55	103	1.1	25.0	0.30
30	1.6	40.0	0.40	67	1.0	55.0	0.60	104	1.0	25.0	0.30
31	1.5	45.0	0.50	68	1.2	45.0	0.50	105	1.0	35.0	0.15
32	1.5	45.0	0.55	69	1.1	50.0	0.60	106	1.1	30.0	0.15
33	1.6	40.0	0.55	70	1.2	45.0	0.55	107	1.2	20.0	0.15
34	1.6	40.0	0.60	71	1.2	45.0	0.60	108	1.0	30.0	0.20
35	1.5	40.0	0.20	72	1.3	35.0	0.50	109	1.0	30.0	0.25
36	1.4	45.0	0.30	73	1.2	40.0	0.60	110	1.0	25.0	0.20
37	1.5	40.0	0.30	74	1.3	35.0	0.15	111	1.0	25.0	0.15
								112	1.0	20.0	0.15

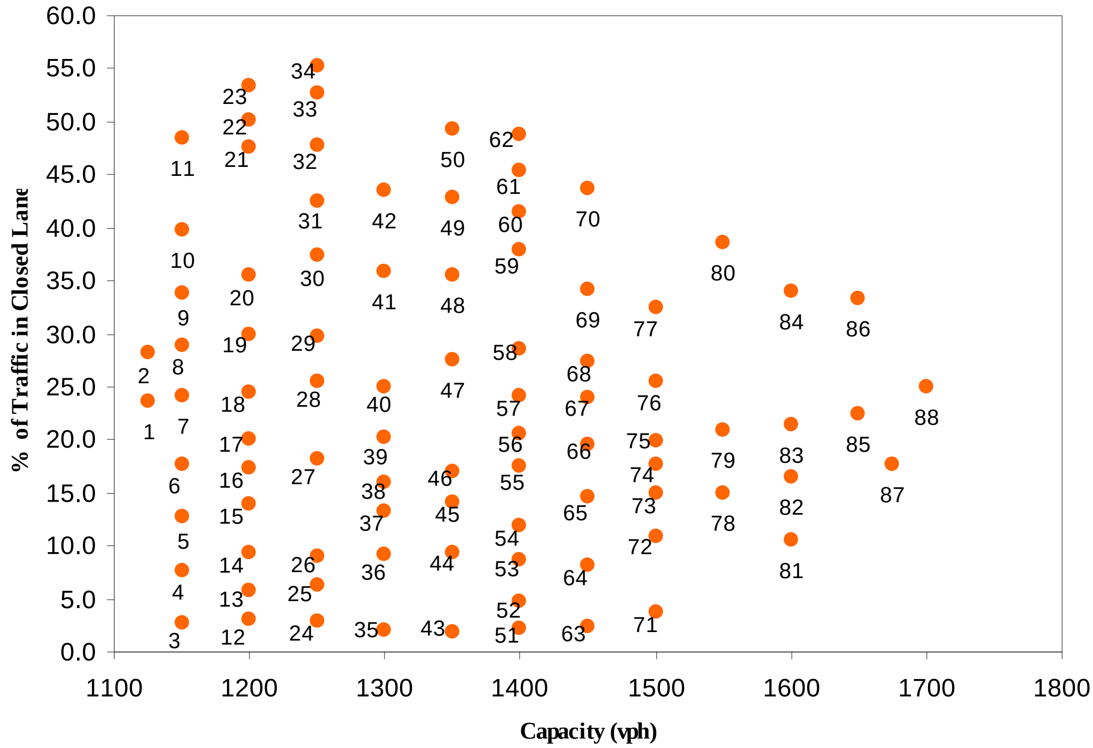

FIGURE 18 Lane distribution at 1000 ft u/s of taper for 30% trucks in a 2 to 1 lane

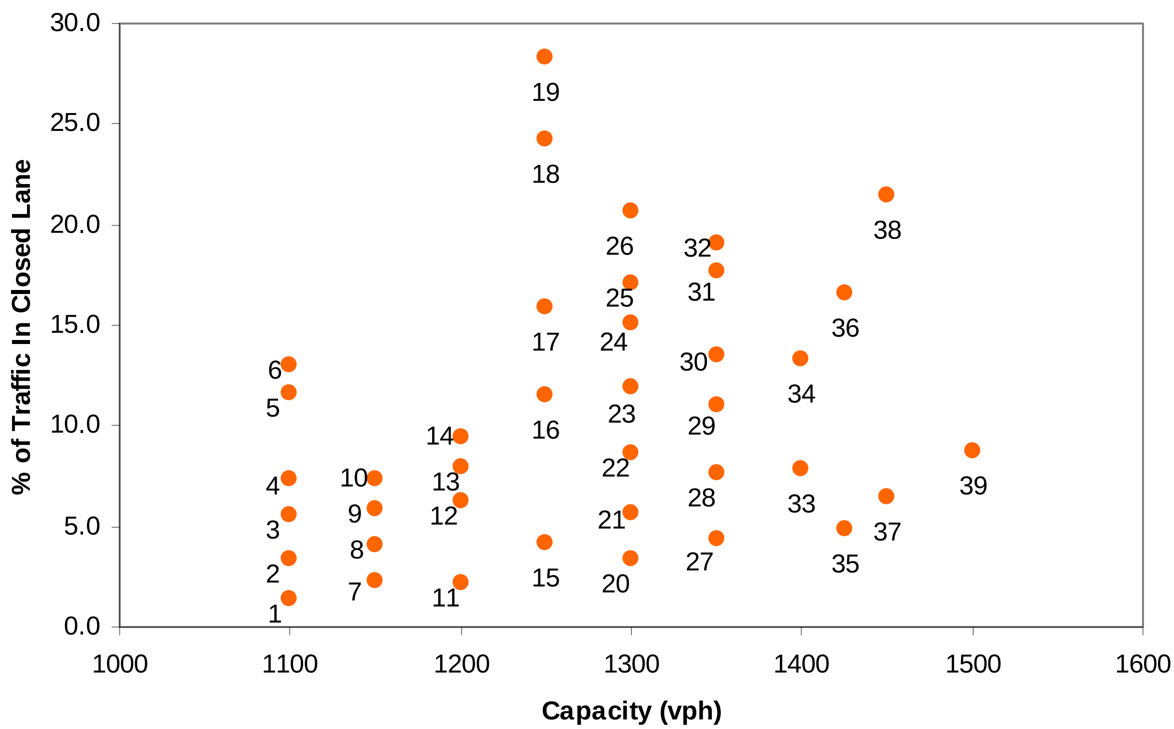

FIGURE 19 Lane distribution at 1000 ft u/s of taper for 40% trucks in a 2 to 1 lane

TABLE 12 Parameter Combinations for 30% Trucks for 2 to 1 Lane

Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*	Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*
1	1.8	55.0	0.55	45	1.5	45.0	0.35
2	1.8	55.0	0.60	46	1.4	55.0	0.45
3	1.8	55.0	0.30	47	1.5	35.0	0.35
4	1.8	55.0	0.40	48	1.2	50.0	0.60
5	1.8	55.0	0.45	49	1.7	45.0	0.60
6	1.7	55.0	0.50	50	1.6	40.0	0.60
7	1.8	55.0	0.55	51	1.3	45.0	0.15
8	1.7	55.0	0.60	52	1.3	50.0	0.25
9	1.8	50.0	0.60	53	1.1	50.0	0.30
10	1.8	45.0	0.60	54	1.2	50.0	0.35
11	1.7	40.0	0.60	55	1.4	55.0	0.45
12	1.6	55.0	0.30	56	1.3	35.0	0.30
13	1.8	55.0	0.35	57	1.1	45.0	0.40
14	1.8	55.0	0.40	58	1.4	55.0	0.60
15	1.6	55.0	0.45	59	1.1	40.0	0.45
16	1.7	50.0	0.45	60	1.2	30.0	0.35
17	1.7	55.0	0.50	61	1.0	20.0	0.25
18	1.7	55.0	0.55	62	1.1	35.0	0.50
19	1.8	45.0	0.50	63	1.1	55.0	0.15
20	1.7	50.0	0.60	64	1.2	55.0	0.30
21	1.7	40.0	0.60	65	1.4	30.0	0.20
22	1.7	35.0	0.55	66	1.1	50.0	0.40
23	1.6	35.0	0.60	67	1.5	50.0	0.45
24	1.5	55.0	0.25	68	1.0	50.0	0.50
25	1.6	55.0	0.35	69	1.2	45.0	0.50
26	1.6	55.0	0.40	70	1.4	40.0	0.55
27	1.5	45.0	0.40	71	1.0	45.0	0.15
28	1.6	45.0	0.45	72	1.1	30.0	0.15
29	1.5	55.0	0.60	73	1.1	45.0	0.30
30	1.7	40.0	0.50	74	1.3	30.0	0.20
31	1.4	40.0	0.55	75	1.3	45.0	0.35
32	1.6	40.0	0.60	76	1.3	20.0	0.15
33	1.8	25.0	0.40	77	1.1	40.0	0.40
34	1.8	35.0	0.60	78	1.1	40.0	0.25
35	1.6	40.0	0.15	79	1.1	40.0	0.30
36	1.7	45.0	0.30	80	1.2	30.0	0.30
37	1.8	45.0	0.35	81	1.2	35.0	0.15
38	1.3	55.0	0.45	82	1.1	35.0	0.20
39	1.7	55.0	0.50	83	1.0	35.0	0.25
40	1.5	55.0	0.55	84	1.0	20.0	0.15
41	1.3	50.0	0.60	85	1.0	30.0	0.20
42	1.5	45.0	0.60	86	1.0	25.0	0.20
43	1.3	45.0	0.15	87	1.0	30.0	0.15
44	1.3	55.0	0.35	88	1.0	25.0	0.15

TABLE 13 Parameter Combinations for 40% Trucks for 2 to 1 Lane

Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*
1	1.8	55.0	0.15
2	1.8	55.0	0.25
3	1.8	55.0	0.30
4	1.8	55.0	0.35
5	1.8	55.0	0.40
6	1.8	55.0	0.45
7	1.8	45.0	0.15
8	1.7	55.0	0.25
9	1.8	45.0	0.25
10	1.7	50.0	0.30
11	1.6	50.0	0.15
12	1.5	55.0	0.30
13	1.5	50.0	0.30
14	1.5	55.0	0.35
15	1.4	55.0	0.20
16	1.3	55.0	0.35
17	1.3	55.0	0.40
18	1.2	55.0	0.50
19	1.2	55.0	0.55
20	1.3	50.0	0.15
21	1.2	55.0	0.25
22	1.2	55.0	0.30
23	1.2	50.0	0.30
24	1.2	50.0	0.35
25	1.1	55.0	0.40
26	1.1	55.0	0.45
27	1.1	55.0	0.15
28	1.1	55.0	0.25
29	1.0	55.0	0.30
30	1.0	55.0	0.35
31	1.0	55.0	0.40
32	1.0	55.0	0.45
33	1.0	50.0	0.20
34	1.0	50.0	0.30
35	1.0	50.0	0.15
36	1.0	45.0	0.30
37	1.0	45.0	0.15
38	1.0	40.0	0.30
39	1.0	40.0	0.15

An illustrative example of how to use these charts follows. Let us consider a 2 to 1 work zone site for which the lane distribution for the closed lane is 10% at 1000 ft from the taper and a capacity of 1200 vphpl were observed in the field. The truck percentage was found to be approximately 40%. In Figure 19 the parameter set that corresponds to the data in this example is number 14. From Table 13, the parameter values can be read for this set number 14 as 1.5 secs, 55 ft, and 0.35 for *CC1*, *CC2*, *SRF* parameters respectively.

The respective plots for the 3 to 2 lane configuration are shown in Figures 20, 21, 22, and Table 14, 15, 16 list the corresponding parameter sets.

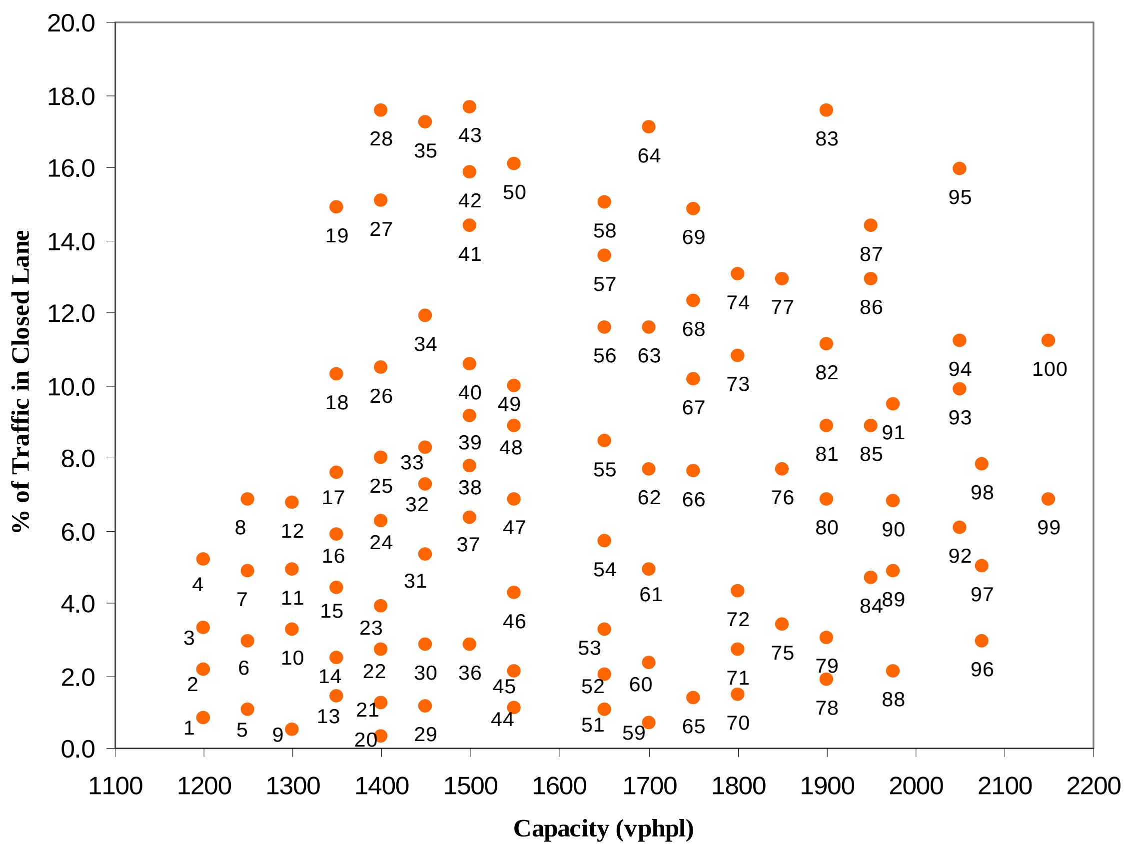

FIGURE 20 Lane distribution at 1000 ft u/s of taper for 5 % trucks in a 3 to 2 lane

TABLE 14 Parameter Combinations for 5 % Trucks for 3 to 2 Lane

Index	***CC1* (in secs)**	***CC2* (in ft)**	***SRF***	Index	***CC1* (in secs)**	***CC2* (in ft)**	***SRF***	Index	***CC1* (in secs)**	***CC2* (in ft)**	***SRF***
1	1.8	55.0	0.40	35	1.7	25.0	0.50	69	1.5	10.0	0.15
2	1.8	55.0	0.50	36	1.0	55.0	0.45	70	1.2	25.0	0.20
3	1.8	55.0	0.55	37	1.3	45.0	0.55	71	1.2	25.0	0.25
4	1.8	55.0	0.60	38	1.4	40.0	0.55	72	1.2	25.0	0.30
5	1.8	45.0	0.40	39	1.3	45.0	0.60	73	1.1	30.0	0.45
6	1.8	45.0	0.50	40	1.4	40.0	0.60	74	1.0	35.0	0.55
7	1.8	45.0	0.55	41	1.3	35.0	0.60	75	1.0	35.0	0.30
8	1.8	45.0	0.60	42	1.7	20.0	0.40	76	1.3	15.0	0.20
9	1.7	45.0	0.35	43	1.6	25.0	0.50	77	1.3	15.0	0.25
10	1.7	45.0	0.50	44	1.3	40.0	0.30	78	1.0	30.0	0.20
11	1.7	45.0	0.55	45	1.4	35.0	0.35	79	1.0	30.0	0.25
12	1.7	45.0	0.60	46	1.3	40.0	0.45	80	1.0	30.0	0.35
13	1.7	40.0	0.40	47	1.0	55.0	0.60	81	1.0	30.0	0.40
14	1.7	40.0	0.45	48	1.7	15.0	0.25	82	1.0	30.0	0.45
15	1.5	50.0	0.55	49	1.3	40.0	0.60	83	1.3	10.0	0.15
16	1.5	50.0	0.60	50	1.7	15.0	0.30	84	1.2	15.0	0.15
17	1.6	45.0	0.60	51	1.1	45.0	0.30	85	1.2	15.0	0.20
18	1.8	30.0	0.50	52	1.0	50.0	0.35	86	1.0	25.0	0.40
19	1.8	30.0	0.55	53	1.4	25.0	0.30	87	1.1	20.0	0.35
20	1.5	45.0	0.30	54	1.4	25.0	0.35	88	1.1	20.0	0.15
21	1.5	45.0	0.40	55	1.0	50.0	0.60	89	1.0	25.0	0.25
22	1.6	40.0	0.45	56	1.3	30.0	0.50	90	1.0	25.0	0.30
23	1.5	45.0	0.50	57	1.4	25.0	0.45	91	1.0	25.0	0.35
24	1.4	50.0	0.60	58	1.3	30.0	0.55	92	1.1	15.0	0.15
25	1.5	45.0	0.60	59	1.0	45.0	0.25	93	1.1	15.0	0.20
26	1.7	30.0	0.50	60	1.0	45.0	0.35	94	1.0	20.0	0.30
27	1.7	30.0	0.55	61	1.0	45.0	0.45	95	1.0	15.0	0.25
28	1.8	25.0	0.50	62	1.1	40.0	0.50	96	1.0	20.0	0.15
29	1.5	40.0	0.35	63	1.4	20.0	0.35	97	1.0	20.0	0.20
30	1.4	45.0	0.45	64	1.4	20.0	0.40	98	1.0	20.0	0.25
31	1.3	50.0	0.55	65	1.1	35.0	0.25	99	1.0	15.0	0.15
32	1.3	50.0	0.60	66	1.1	35.0	0.45	100	1.0	15.0	0.20
33	1.4	45.0	0.60	67	1.0	40.0	0.55				
34	1.7	25.0	0.45	68	1.0	40.0	0.60				

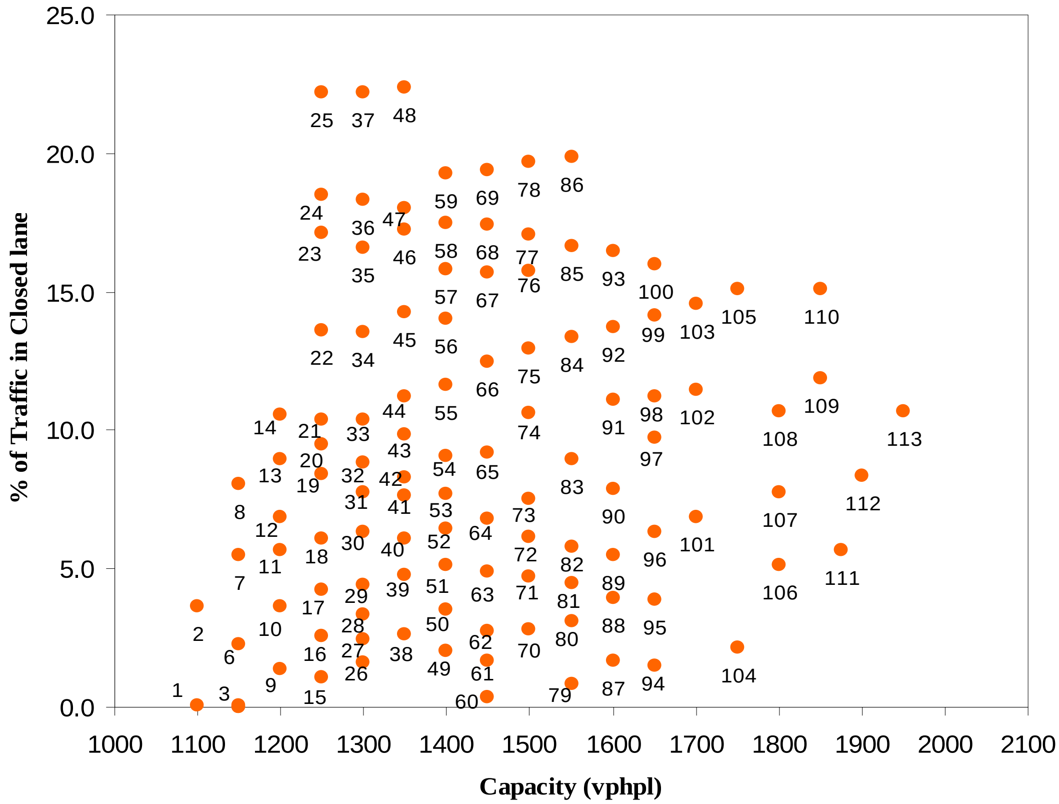

FIGURE 21 Lane distribution at 1000 ft u/s of taper for 10% trucks in a 3 to 2 lane

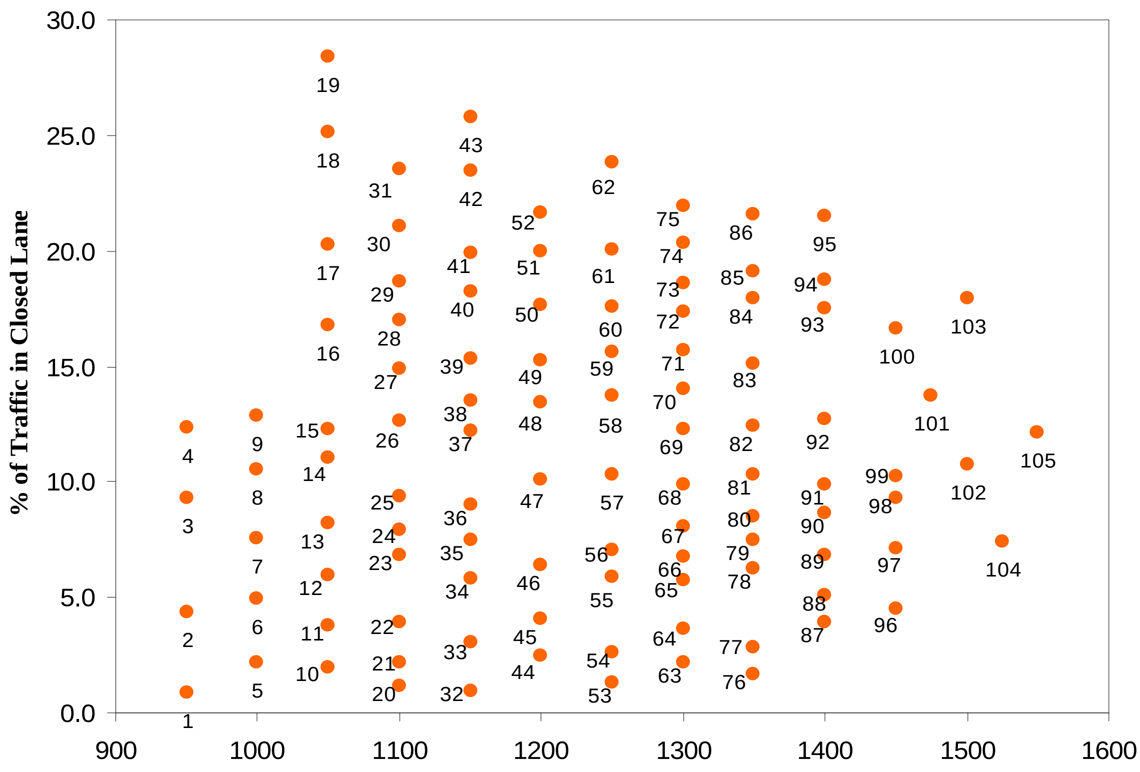

FIGURE 22 Lane distribution at 1000 ft u/s of taper for 20% trucks in a 3 to 2 lane

TABLE 15 Parameter Combinations for 10% Trucks for 3 to 2 Lane

Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*	Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*	Index	*CC1* (in secs	*CC2* (in ft)	*SRF*
1	1.8	55.0	0.20	39	1.3	50.0	0.45	77	1.4	25.0	0.45
2	1.8	55.0	0.50	40	1.3	50.0	0.50	78	1.3	30.0	0.55
3	1.7	55.0	0.15	41	1.2	55.0	0.55	79	1.0	45.0	0.20
4	1.8	45.0	0.15	42	1.3	50.0	0.55	80	1.1	40.0	0.30
5	1.8	45.0	0.20	43	1.3	50.0	0.60	81	1.0	45.0	0.35
6	1.7	55.0	0.45	44	1.6	30.0	0.45	82	1.0	45.0	0.40
7	1.7	55.0	0.55	45	1.5	35.0	0.55	83	1.1	40.0	0.45
8	1.8	45.0	0.55	46	1.5	35.0	0.60	84	1.0	45.0	0.60
9	1.8	40.0	0.35	47	1.6	30.0	0.55	85	1.4	20.0	0.35
10	1.7	45.0	0.45	48	1.6	30.0	0.60	86	1.2	30.0	0.55
11	1.7	45.0	0.50	49	1.1	55.0	0.35	87	1.1	35.0	0.20
12	1.6	50.0	0.55	50	1.2	50.0	0.40	88	1.0	40.0	0.30
13	1.6	50.0	0.60	51	1.2	50.0	0.45	89	1.0	40.0	0.35
14	1.7	45.0	0.60	52	1.1	55.0	0.50	90	1.0	40.0	0.40
15	1.5	50.0	0.35	53	1.1	55.0	0.55	91	1.0	40.0	0.50
16	1.6	45.0	0.40	54	1.1	55.0	0.60	92	1.0	40.0	0.55
17	1.6	45.0	0.45	55	1.5	30.0	0.45	93	1.4	15.0	0.25
18	1.4	55.0	0.55	56	1.4	35.0	0.55	94	1.1	30.0	0.15
19	1.4	55.0	0.60	57	1.5	30.0	0.50	95	1.0	35.0	0.25
20	1.5	50.0	0.60	58	1.4	35.0	0.60	96	1.1	30.0	0.30
21	1.6	45.0	0.60	59	1.7	15.0	0.30	97	1.0	35.0	0.40
22	1.8	30.0	0.50	60	1.1	50.0	0.20	98	1.1	30.0	0.40
23	1.7	35.0	0.60	61	1.1	50.0	0.30	99	1.0	35.0	0.50
24	1.8	30.0	0.55	62	1.2	45.0	0.35	100	1.0	35.0	0.55
25	1.8	30.0	0.60	63	1.0	55.0	0.45	101	1.3	15.0	0.15
26	1.4	50.0	0.35	64	1.1	50.0	0.50	102	1.3	15.0	0.20
27	1.4	50.0	0.40	65	1.1	50.0	0.55	103	1.0	30.0	0.45
28	1.5	45.0	0.40	66	1.5	25.0	0.40	104	1.0	30.0	0.15
29	1.5	45.0	0.45	67	1.4	30.0	0.50	105	1.1	20.0	0.30
30	1.3	55.0	0.55	68	1.3	35.0	0.60	106	1.0	25.0	0.20
31	1.4	50.0	0.55	69	1.4	30.0	0.55	107	1.0	25.0	0.25
32	1.3	55.0	0.60	70	1.0	50.0	0.35	108	1.0	25.0	0.30
33	1.7	30.0	0.45	71	1.0	50.0	0.40	109	1.0	20.0	0.25
34	1.6	35.0	0.55	72	1.0	50.0	0.45	110	1.0	20.0	0.30
35	1.6	35.0	0.60	73	1.6	15.0	0.20	111	1.0	20.0	0.15
36	1.7	30.0	0.55	74	1.5	20.0	0.30	112	1.0	20.0	0.20
37	1.7	30.0	0.60	75	1.1	45.0	0.60	113	1.0	15.0	0.15
38	1.2	55.0	0.40	76	1.5	20.0	0.35				

TABLE 16 Parameter Combinations For 20% Trucks for 3 to 2 Lane

Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*	Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*	Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*
1	1.8	55.0	0.30	36	1.2	55.0	0.50	71	1.0	45.0	0.55
2	1.8	55.0	0.45	37	1.2	55.0	0.55	72	1.0	45.0	0.60
3	1.8	55.0	0.55	38	1.2	55.0	0.60	73	1.3	25.0	0.35
4	1.8	55.0	0.60	39	1.5	35.0	0.45	74	1.2	30.0	0.45
5	1.7	50.0	0.35	40	1.5	35.0	0.50	75	1.1	35.0	0.55
6	1.7	55.0	0.45	41	1.4	40.0	0.60	76	1.0	40.0	0.15
7	1.8	45.0	0.45	42	1.5	35.0	0.60	77	1.2	30.0	0.15
8	1.8	45.0	0.50	43	1.5	30.0	0.55	78	1.1	35.0	0.25
9	1.6	55.0	0.60	44	1.2	50.0	0.30	79	1.3	25.0	0.20
10	1.5	55.0	0.35	45	1.1	55.0	0.35	80	1.1	35.0	0.30
11	1.5	55.0	0.40	46	1.1	55.0	0.40	81	1.0	40.0	0.35
12	1.5	55.0	0.45	47	1.1	55.0	0.50	82	1.0	40.0	0.40
13	1.5	55.0	0.50	48	1.0	55.0	0.60	83	1.0	40.0	0.45
14	1.5	55.0	0.55	49	1.1	50.0	0.60	84	1.3	20.0	0.25
15	1.5	55.0	0.60	50	1.2	45.0	0.60	85	1.0	35.0	0.50
16	1.6	45.0	0.60	51	1.3	40.0	0.60	86	1.1	30.0	0.45
17	1.7	40.0	0.60	52	1.4	35.0	0.55	87	1.1	30.0	0.15
18	1.8	30.0	0.55	53	1.0	50.0	0.20	88	1.0	35.0	0.20
19	1.8	30.0	0.60	54	1.0	55.0	0.30	89	1.0	35.0	0.25
20	1.4	55.0	0.30	55	1.2	40.0	0.30	90	1.2	25.0	0.20
21	1.5	45.0	0.30	56	1.3	35.0	0.30	91	1.0	35.0	0.30
22	1.5	45.0	0.35	57	1.0	50.0	0.45	92	1.0	35.0	0.35
23	1.5	45.0	0.40	58	1.0	50.0	0.55	93	1.1	25.0	0.30
24	1.4	50.0	0.45	59	1.0	50.0	0.60	94	1.0	30.0	0.40
25	1.5	45.0	0.45	60	1.1	45.0	0.60	95	1.0	30.0	0.45
26	1.4	50.0	0.55	61	1.2	40.0	0.60	96	1.0	30.0	0.15
27	1.4	50.0	0.60	62	1.2	35.0	0.60	97	1.0	30.0	0.20
28	1.5	45.0	0.60	63	1.3	30.0	0.15	98	1.1	25.0	0.20
29	1.7	30.0	0.45	64	1.2	35.0	0.20	99	1.0	30.0	0.25
30	1.6	35.0	0.55	65	1.2	35.0	0.25	100	1.1	20.0	0.20
31	1.6	35.0	0.60	66	1.1	40.0	0.30	101	1.0	25.0	0.25
32	1.3	50.0	0.25	67	1.2	35.0	0.30	102	1.0	25.0	0.20
33	1.2	55.0	0.35	68	1.0	45.0	0.40	103	1.0	20.0	0.20
34	1.2	55.0	0.40	69	1.0	45.0	0.45	104	1.0	25.0	0.15
35	1.2	55.0	0.45	70	1.1	40.0	0.45	105	1.0	20.0	0.15

When the parameter sets were compared across charts the trends were in agreement with traffic flow theory. For example, the parameter sets corresponding to a certain lane distribution and capacity value for 20% trucks (see Figure 22) reflects greater driver aggressiveness as compared to the parameter sets resulting in same capacity for 5% trucks (see Figure 20). It was also evident from the charts that for lower capacity values there were very few parameter sets for high lane distribution values since drivers tend to merge sooner when longer gaps are available in the adjacent lane (typical for work zones with low capacity).

The respective plots for the 3 to 1 lane configuration are shown in Figures 23, 24, 25 and Table 17, 18 and 19 list the corresponding parameter sets.

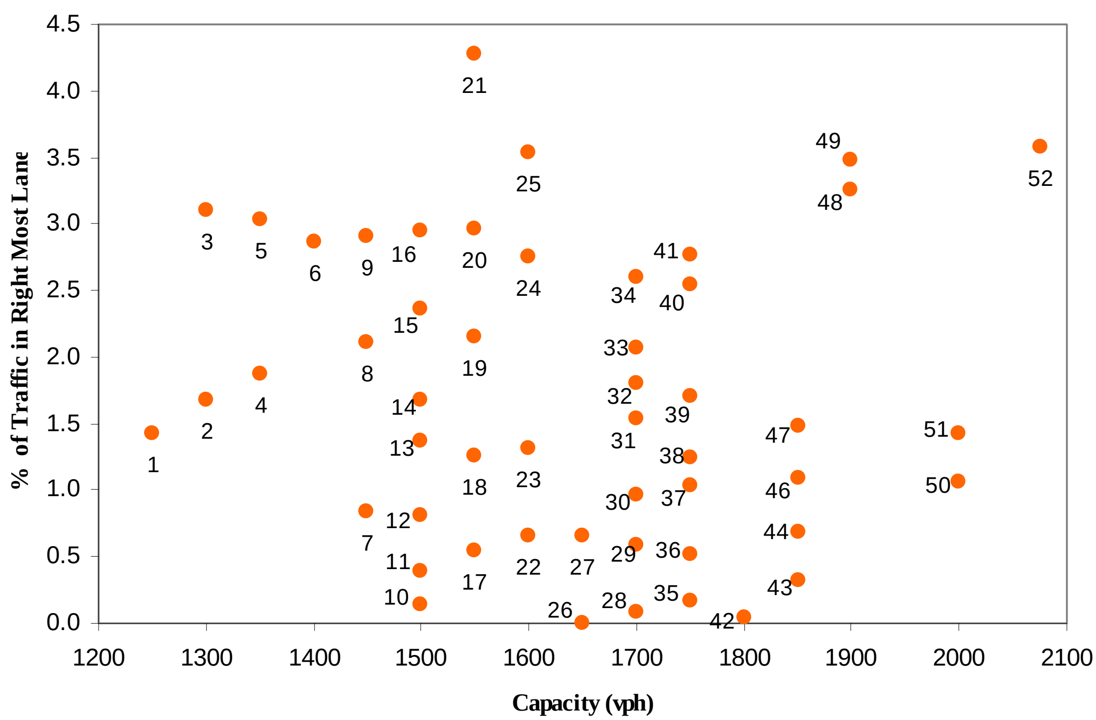

FIGURE 23 Lane distribution at 1000 ft u/s of taper for 5% trucks in a 3 to 1 lane

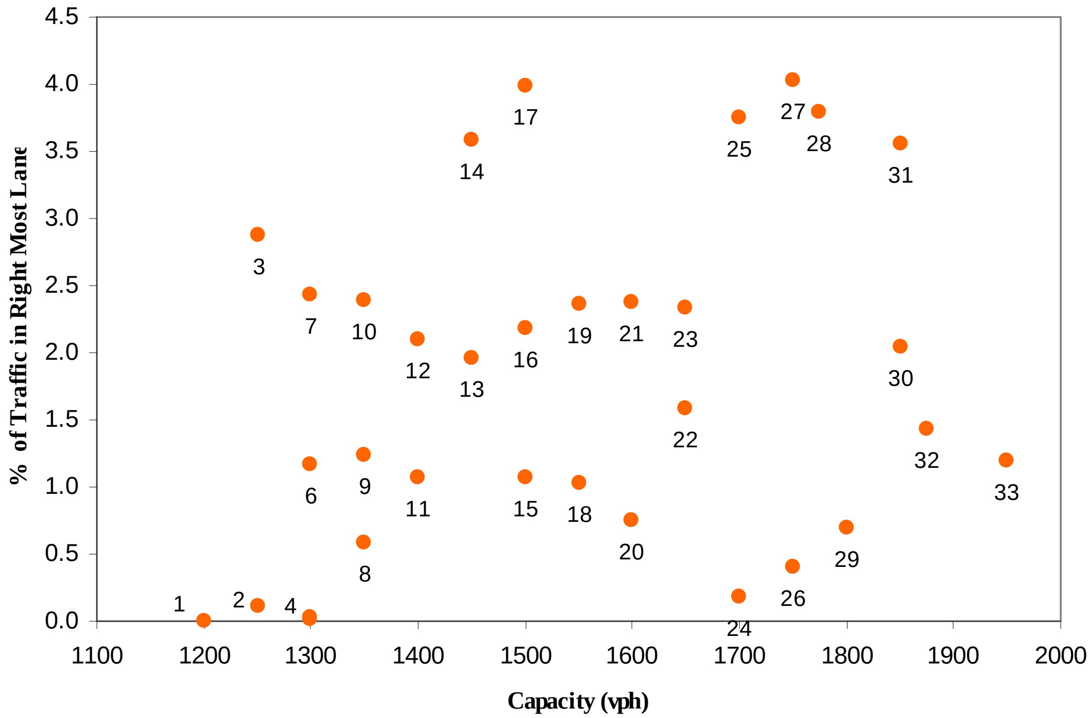

FIGURE 24 Lane distribution at 1000 ft u/s of taper for 10% trucks in a 3 to 1 lane

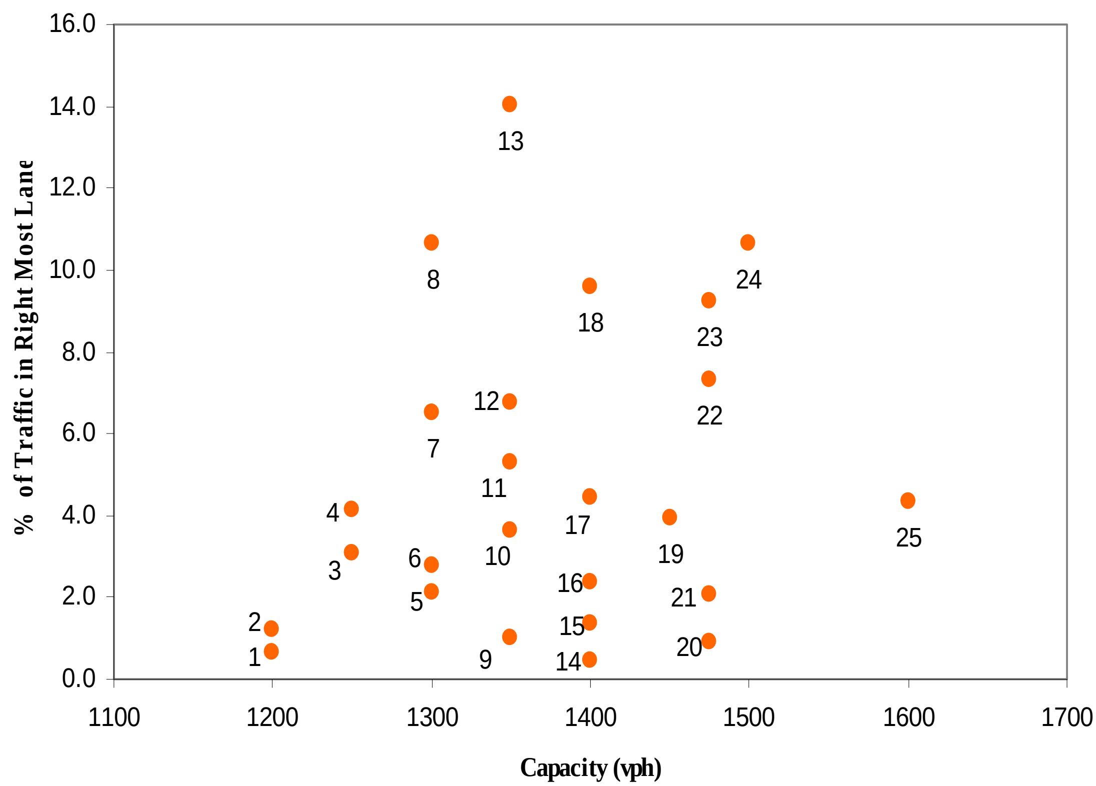

FIGURE 25 Lane distribution at 1000 ft u/s of taper for 20% trucks in a 3 to 1 lane

TABLE 17 Parameter Combinations for 5% Trucks for 3 to 1 Lane

Index	***CC1* (in secs)**	***CC2* (in ft)**	***SRF***	**Index**	***CC1* (in secs)**	***CC2* (in ft)**	***SRF***
1	1.8	55.0	0.60	27	1.0	55.0	0.55
2	1.8	45.0	0.50	28	1.0	50.0	0.25
3	1.8	45.0	0.55	29	1.0	50.0	0.50
4	1.6	50.0	0.60	30	1.0	50.0	0.55
5	1.7	45.0	0.55	31	1.2	40.0	0.40
6	1.6	45.0	0.55	32	1.1	45.0	0.50
7	1.5	45.0	0.45	33	1.0	50.0	0.60
8	1.4	50.0	0.60	34	1.2	40.0	0.45
9	1.5	45.0	0.55	35	1.2	35.0	0.15
10	1.4	45.0	0.30	36	1.3	30.0	0.15
11	1.4	45.0	0.40	37	1.0	45.0	0.45
12	1.5	40.0	0.35	38	1.3	30.0	0.20
13	1.4	45.0	0.50	39	1.0	45.0	0.50
14	1.5	40.0	0.40	40	1.0	45.0	0.55
15	1.5	40.0	0.45	41	1.2	35.0	0.35
16	1.4	45.0	0.55	42	1.0	45.0	0.30
17	1.5	35.0	0.25	43	1.0	40.0	0.25
18	1.4	40.0	0.40	44	1.0	40.0	0.30
19	1.4	40.0	0.45	45	1.1	35.0	0.25
20	1.6	30.0	0.25	46	1.0	40.0	0.35
21	1.4	40.0	0.50	47	1.1	35.0	0.30
22	1.1	55.0	0.55	48	1.1	30.0	0.25
23	1.5	30.0	0.20	49	1.2	25.0	0.15
24	1.5	30.0	0.25	50	1.0	30.0	0.15
25	1.6	25.0	0.15	51	1.0	30.0	0.20
26	1.1	50.0	0.20	52	1.0	25.0	0.15

TABLE 18 Parameter Combinations for 10% Trucks for 3 to 1 Lane

Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*	Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*
1	1.8	55.0	0.15	18	1.1	55.0	0.60
2	1.8	50.0	0.35	19	1.3	45.0	0.50
3	1.8	50.0	0.60	20	1.0	55.0	0.55
4	1.6	55.0	0.25	21	1.1	50.0	0.60
5	1.7	50.0	0.30	22	1.0	50.0	0.55
6	1.6	55.0	0.60	23	1.1	45.0	0.50
7	1.7	50.0	0.60	24	1.0	50.0	0.30
8	1.5	55.0	0.55	25	1.4	25.0	0.15
9	1.5	55.0	0.60	26	1.0	45.0	0.35
10	1.6	50.0	0.60	27	1.3	25.0	0.15
11	1.4	55.0	0.60	28	1.2	30.0	0.25
12	1.5	50.0	0.60	29	1.0	40.0	0.30
13	1.4	50.0	0.60	30	1.0	35.0	0.30
14	1.7	30.0	0.25	31	1.2	25.0	0.15
15	1.2	55.0	0.60	32	1.0	35.0	0.25
16	1.3	50.0	0.60	33	1.0	30.0	0.15
17	1.7	25.0	0.15				

TABLE 19 Parameter Combinations for 20% Trucks for 3 to 1 Lane

Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*	Index	*CC1* (in secs)	*CC2* (in ft)	*SRF*
1	1.8	55.0	0.30	14	1.3	55.0	0.25
2	1.8	55.0	0.25	15	1.3	55.0	0.20
3	1.7	50.0	0.40	16	1.5	40.0	0.25
4	1.6	55.0	0.60	17	1.5	40.0	0.30
5	1.5	55.0	0.45	18	1.4	40.0	0.40
6	1.6	50.0	0.20	19	1.6	30.0	0.15
7	1.6	45.0	0.45	20	1.3	45.0	0.15
8	1.8	35.0	0.35	21	1.1	55.0	0.25
9	1.4	55.0	0.15	22	1.5	30.0	0.20
10	1.8	30.0	0.15	23	1.6	25.0	0.15
11	1.4	50.0	0.50	24	1.5	25.0	0.15
12	1.4	50.0	0.55	25	1.2	35.0	0.20
13	1.8	25.0	0.20				

For 3 to 1 lane configuration the number of parameter combinations shown in the charts is considerably lower compared to 2 to 1 and 3 to 2 work zone lane configuration as many parameter combinations that produced identical lane distribution were removed while preparing these charts.

As we move from left to right in all the figures the index values increase with capacity. A review of the parameter values corresponding to these indexes reveals a trend that is common for all scenarios – high *CC1*, *CC2*, and *SRF* values resulted in low capacity values and low *CC1*, *CC2*, and *SRF* values resulted in high capacity values. The trend implies that when drivers maintain longer headways and look for longer gaps to merge, the capacities will be low and vice versa. Also, typically lower *SRF* values are associated with high capacity values and vice versa, which implies that the capacity tends to increase as more vehicles accepting shorter gaps to merge upstream of the taper.

5.2 Validation of the Results

The results obtained from these simulation runs were validated against some actual data observed in the field. Actual data was obtained from two studies conducted by Ohio Department of Transportation (*54*). Data from two specific work zone sites, one at Sandusky and other at Cambridge, in Ohio were used for validation. Both were 2 to 1 work zone lane configurations on freeways. Table 20 describes the traffic characteristics observed in these two work zones.

TABLE 20 Characteristics of Two Work Zones Observed in Ohio

Work Zone Sites	Capacity (vph)	Maximum Queue length (in miles)	Percentage of Heavy Vehicles
Cambridge (with 12 feet lane width)	1098	6.2	28
Sandusky	1250	2.3	19

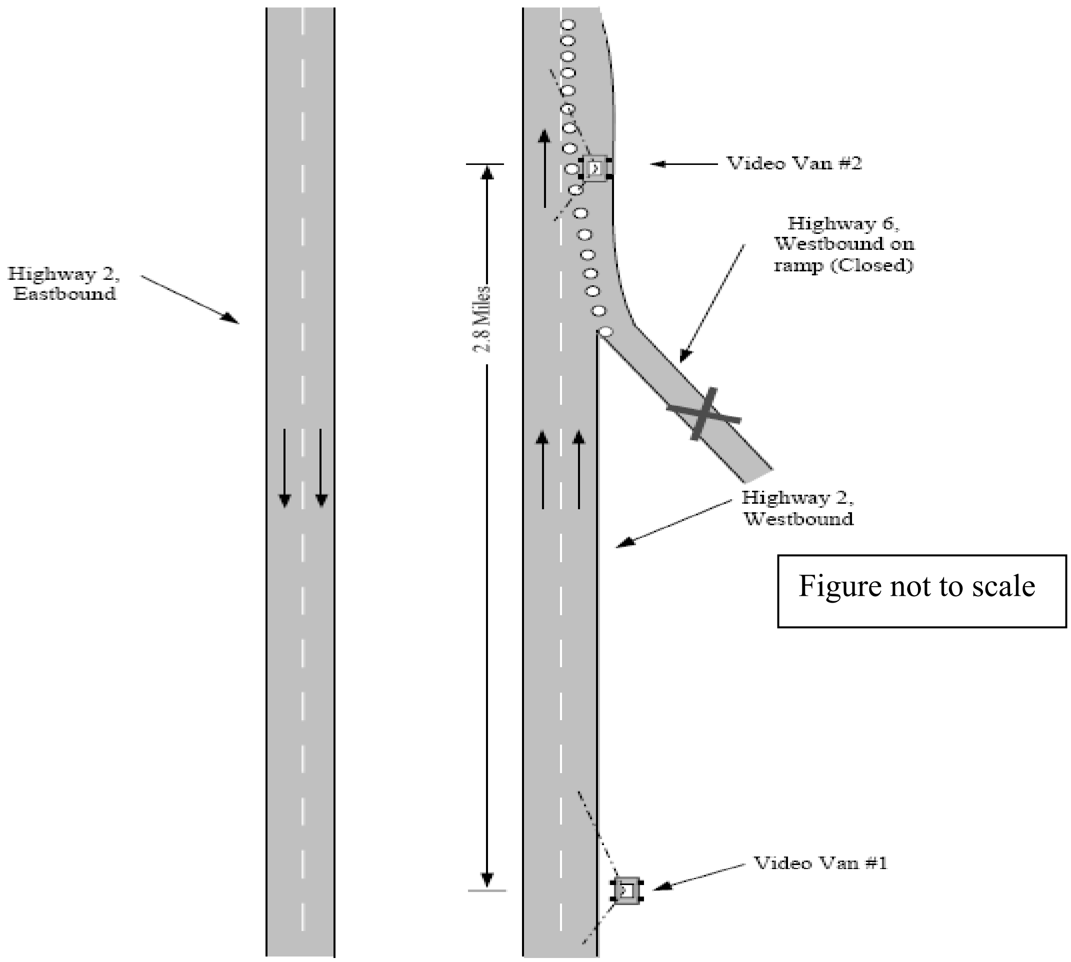

FIGURE 26 Work zone layout of Sandusky site in Ohio

(Figure from ODOT Report (*54*))

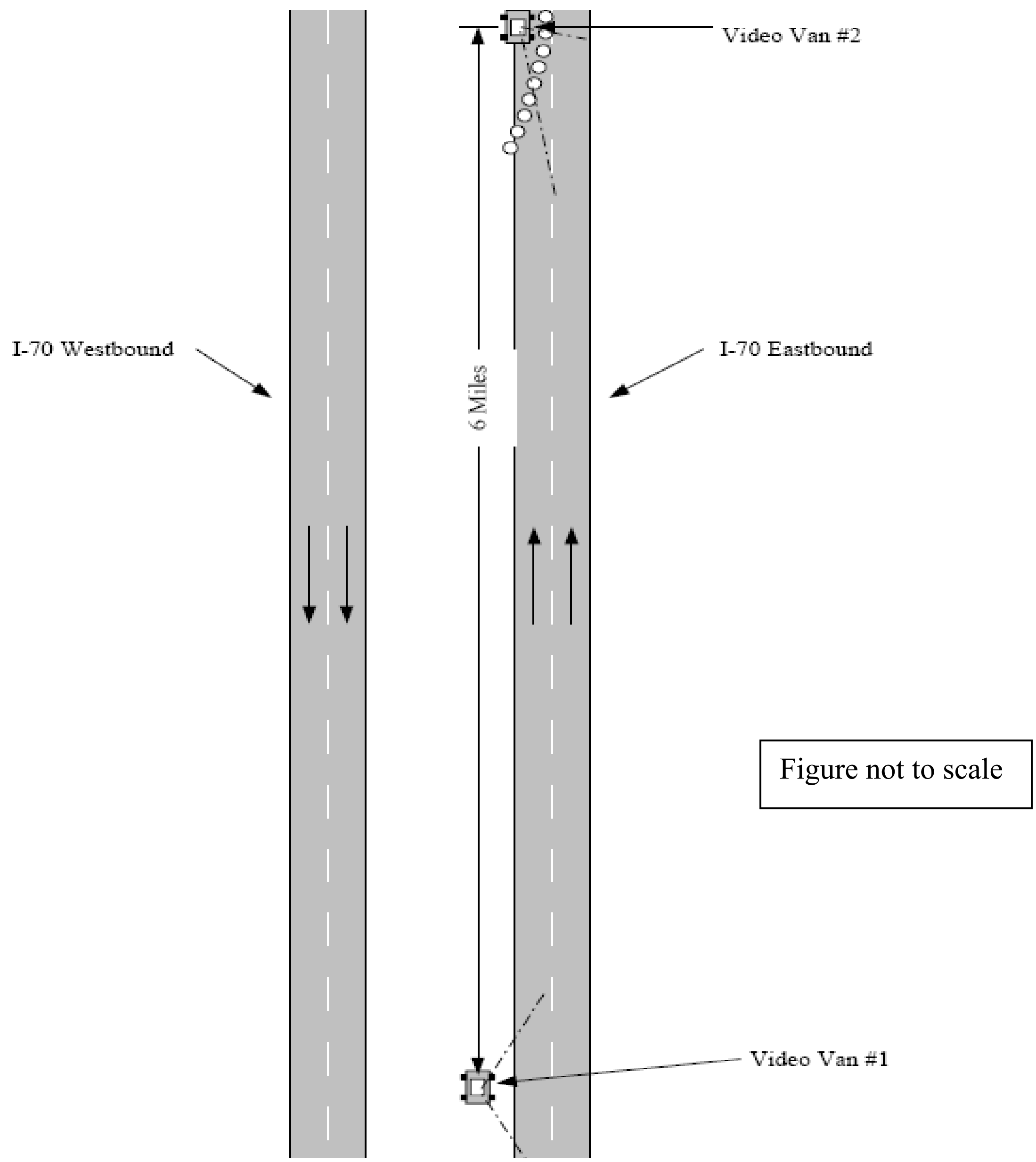

FIGURE 27 Work zone layout of Cambridge site in Ohio

(Figure from ODOT Report (*54*))

For Sandusky site parameter sets from Table 11 corresponding to a capacity of 1250 vph and 20% heavy vehicle traffic were obtained. There were 8 unique parameter sets that produced the capacity of 1250 vph. Each of the 8 scenarios was coded in

VISSIM with truck percentage as 19% and hourly volume data was obtained from the ODOT Report (*53*). Capacity and queue lengths were collected. Table 21 below shows capacity values obtained from each of those scenarios.

TABLE 21 Results of the Parameter Sets Selected for Sandusky Site

Index	*CC1* (secs)	*CC2* (ft)	*SRF*	Capacity (vph)	% Error
1	1.6	55.0	0.60	1276	2.08
2	1.7	50.0	0.50	1232	1.44
3	1.6	55.0	0.50	1256	0.48
4	1.7	50.0	0.45	1244	0.48
5	1.6	55.0	0.45	1260	0.8
6	1.6	55.0	0.35	1252	0.16
7	1.6	55.0	0.40	1236	1.12
8	1.7	50.0	0.40	1204	3.68

The highlighted parameter sets produced best results where error percentage in estimated capacity was less than 1% and the maximum queue length observed in each of these selected set was approximately 2.38 miles compared to actual observed maximum queue length of 2.3 miles.

For Cambridge site which had a capacity of 1098 vph with heavy vehicle composition of 28%, parameters were obtained from Table 12 (rounding off to 30% heavy vehicles). Two sets of parameters were found to produce capacity of 1125 vph which was the closest to the observed field capacity. Table 22 shows the selected parameter sets used to replicate this Cambridge site.

TABLE 22 Parameter Sets Used to Validate Cambridge Site

Index	***CC1* (secs)**	***CC2* (ft)**	***SRF***
1	1.8	55.0	0.55
2	1.8	55.0	0.60

Similar to the method used for Sandusky study each of these two scenarios was run in VISSIM with truck composition set to 28 % and the input demand volume data was obtained from the ODOT Report (*54*). Since the two sets of parameters were very similar they produced identical results. The capacity obtained from the simulation was 1096 vph which was very close to the actual observed capacity of 1098 vph. However the maximum queue obtained was 2.35 miles which was way below the actual observed maximum queue length, 6.2 miles. However as mentioned in the ODOT Report (*54*) and the study conducted by Schnell et al. (*2*), such discrepancy in queue length estimation could be attributed to the fact that drivers were found to merge very far upstream of the actual merge area resulting in minimum use of the closed lane and thus resulting in longer queues than expected . In order to account for such a phenomenon the “lane changing distance” (*16*) in VISSIM which was fixed at 2500 ft upstream of the taper for passenger cars was increased gradually and corresponding capacity and queue lengths were collected. It was found that by varying the “lane changing distance” the maximum queue lengths observed in the field could be obtained from simulation without any significant impact on capacity.

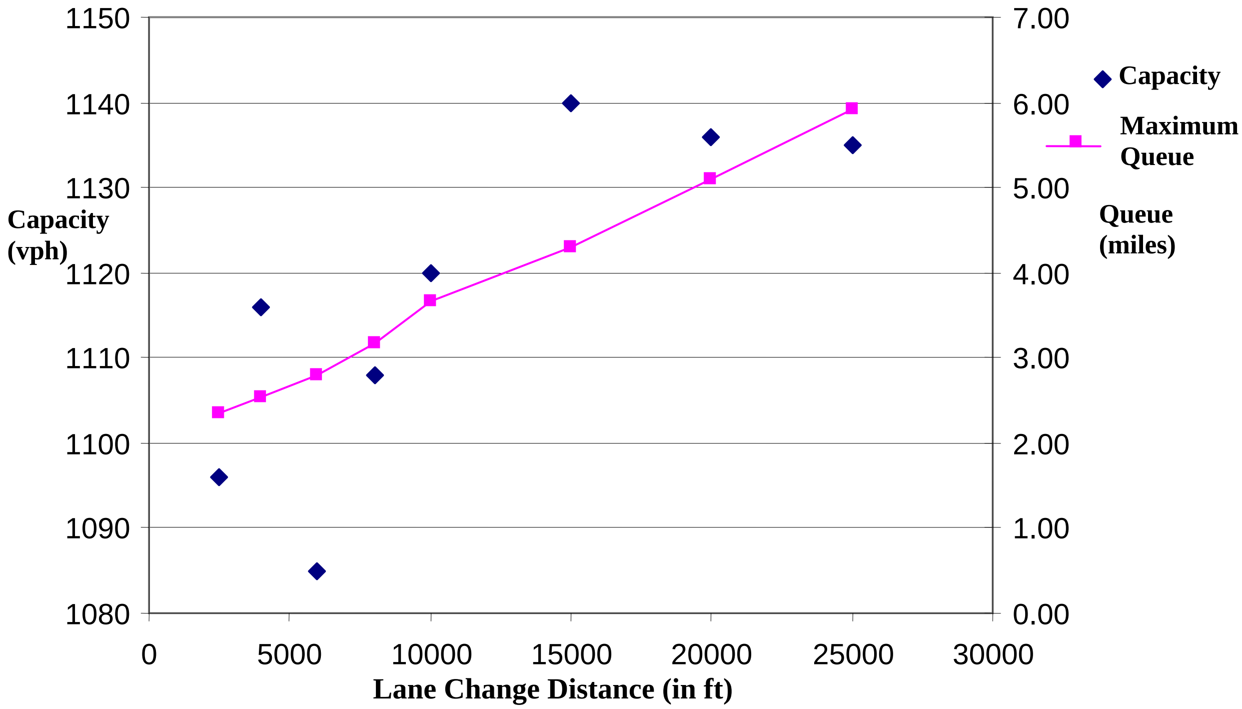

FIGURE 28 Capacity and max. queue length variation with lane changing distance

Figure 28 shows the variation of capacity and queue lengths as the "lane changing distance" was increased. It was found that the variation of lane changing distance from 2500 ft to 25,000 ft resulted in capacity values only within 20 vph standard deviation, whereas the actual observed maximum queue length of 6.2 miles was achieved at 25,000 ft "lane changing distance".

Thus, if the point upstream of the merge area where the vehicles begin to change lane is approximately known, that value could be used to accurately predict the observed queue lengths in addition to the use of recommended set of driving parameters corresponding to a given a work zone capacity and truck composition.

5.3 Multivariate Linear Regression Model

The next step in this study was to build regression models for estimating *CC1, CC2* and *SRF* for a given capacity, truck percentage and lane distribution of the closed lane at 1000 feet upstream of the taper. Results from the simulation runs were used to build multivariate regression models for *CC1, CC2* and *SRF.*

Multivariate regression model is an extension of multiple regression models where relationships between p responses with a set of k explanatory variables are modeled. For example suppose we have (Y_1, Y_2, $Y_3 \ldots Y_p$) p possibly correlated responses and (X_1, $X_2, \ldots X_k$) k predictors, then each of the responses can be modeled separately by p univariate linear models as:

$$
\begin{array}{l}
Y_1 = B_{01} + B_{11}X_1 + B_{21}X_2 + \ldots\ldots + B_{k1}X_k + \epsilon_1 \\
Y_2 = B_{02} + B_{12}X_1 + B_{22}X_2 + \ldots\ldots + B_{k2}X_k + \epsilon_2 \\
Y_3 = B_{03} + B_{13}X_1 + B_{23}X_2 + \ldots\ldots + B_{k3}X_k + \epsilon_3 \\
\vdots \quad\quad \vdots \quad\quad \vdots \quad\quad\quad \vdots \quad\quad \ldots\ldots \quad\quad \vdots \quad\quad \vdots \\
Y_p = B_{0p} + B_{1p}X_1 + B_{2p}X_2 + \ldots\ldots + B_{kp}X_k + \epsilon p
\end{array}
$$

The above set of equations can be together written in a multivariate regression form as:

$$Y = XB + \epsilon$$

where, Y represents n×p matrix with n denotes the sample size.

X represents n × (k+1) matrix = $[1 : X_1 : X_2 : X_3 : \ldots\ldots X_k]$

Є (error term) is n×p matrix = $[\epsilon_1 : \epsilon_2 : \epsilon_3 : \ldots\ldots \epsilon_p]$

and

$$B = \begin{vmatrix} B_{01} & B_{02} & \cdots\cdots & B_{0p} \\ B_{11} & B_{12} & \cdots\cdots & B_{1p} \\ \vdots & \vdots & \cdots\cdots & \vdots \\ B_{k1} & B_{k2} & \cdots\cdots & B_{kp} \end{vmatrix}$$

The basic assumptions of the model are $E[\epsilon_i] = 0$ and Covariance $(\epsilon_i, \epsilon_j) = \sigma_{ij}I$, for i, j = 1, 2,…m, which defines the dependence between the response variables.

In this research *CC1*, *CC2* and *SRF* are the three responses and capacity, truck percentage and lane distribution of closed lane at 1000 ft upstream of the taper are the three independent variables. Three separate multivariate models are developed for each work zone lane configuration, i.e. each for 2 to 1, 3 to 2 and 3 to1 work zones. Proc GLM procedure from SAS9.1 (*55*) was used to model the multivariate regression. The results from the SAS output are shown below:

5.3.1 Multivariate Analysis for 2 to 1 Work Zone Configuration

All four multivariate test statistics (*56*) and exact F-test values from SAS output (see Table 23, 24, 25) indicate that with very small *p* values, all three independent variables capacity, truck percentage and lane distribution at 1000 ft upstream of the taper indeed have a significant effect on *CC1, CC2* and *SRF.*

TABLE 23 MANOVA Test and Exact F Statistics for No Overall Capacity Effect

Statistic **	**Value**	**F Value**	**Num DF**	**Den DF**	***p* (Pr > F)** *
Wilks' Lambda	0.205	2405.36	3	1870	<.0001
Pillai's Trace	0.794	2405.36	3	1870	<.0001
Hotelling-Lawley Trace	3.859	2405.36	3	1870	<.0001
Roy's Greatest Root	3.859	2405.36	3	1870	<.0001

* very small *p* values; hence null hypothesis rejected.

** Four Multivariate test statistics.

TABLE 24 MANOVA Test and Exact F Statistics for No Overall Truck% Effect

Statistic	**Value**	**F Value**	**Num DF**	**Den DF**	***p* (Pr > F)** *
Wilks' Lambda	0.738	221.76	3	1870	<.0001
Pillai's Trace	0.262	221.76	3	1870	<.0001
Hotelling-Lawley Trace	0.356	221.76	3	1870	<.0001
Roy's Greatest Root	0.356	221.76	3	1870	<.0001

* very small *p* values; hence null hypothesis rejected.

TABLE 25 MANOVA Test and Exact F Statistics for No Lane Distribution Effect

Statistic	**Value**	**F Value**	**Num DF**	**Den DF**	***p* (Pr > F)** *
Wilks' Lambda	0.134	4029.46	3	1870	<.0001
Pillai's Trace	0.866	4029.46	3	1870	<.0001
Hotelling-Lawley Trace	6.464	4029.46	3	1870	<.0001
Roy's Greatest Root	6.464	4029.46	3	1870	<.0001

* very small *p* values; hence null hypothesis rejected.

Table 26 below shows the relationship between three responses (*CC1*, *CC2* and *SRF*). It was found that that there is a negative correlation between *CC1* and *CC2*, which means for a fixed capacity, truck percentage and lane distribution if *CC1* was increased, *CC2* would tend to decrease. On the contrary, for a given capacity and truck percentage if *CC2,* i.e. the longitudinal oscillation of the vehicles in the following process increases, *SRF* would also increase, i.e. the drivers become less aggressive in changing lanes. This positive correlation between *CC2* and *SRF* was also observed in other work zone lane configurations (see Table 34, 42).

TABLE 26 Partial Correlation Coefficients for 2 to1 Lane

DF = 1872	CC1	CC2	SRF
CC1	1.00	-0.934	-0.67
CC2	-0.934	1.00	0.768
SRF	-0.67	0.768	1.00

where DF means degrees of freedom.

TABLE 27 Regression Model for 2 to 1 Configuration

$CC1 = 2.974 - 0.0009 \times CAP + 0.0267 \times TC + 0.0022 \times LD - 0.000029 \times CAP \times TC$
$CC2 = 82.39 - 0.0266 \times CAP + 0.208 \times TC + 0.302 \times LD - 0.00009 \times CAP \times TC$
$SRF = 0.656 - 0.0002 \times CAP + 0.0057 \times TC + 0.0078 \times LD - 0.000009 \times CAP \times TC$

where *CC1* is in seconds , *CC2* is in feet, *CAP* stands for capacity in vehicles per hour, *TC* is the truck percentage, *LD* means lane distribution of the closed lane at 1000 ft upstream of the taper.

TABLE 28 Test of Coefficient Significance for *CC1* Model for 2 to 1 lane

Parameter	**Estimate**	**Standard Error**	**t Value**	***p* (Pr > |t|)**
Intercept	2.974	0.068	43.31	<.0001
CAP	-0.0009	0.00004	-19.31	<.0001
TC	0.0267	0.0033	8.04	<.0001
LD	0.0022	0.0003	7.95	<.0001
CAP*TC	-0.000029	0.000002	-12.46	<.0001

Results from Table 28 indicate that the coefficients of all the explanatory variables (i.e. capacity, truck percentage, their combination and lane distribution) and intercept for *CC1* model are significant as the *p* values were found very low.

TABLE 29 Test of Coefficient Significance for *CC2* Model for 2 to 1 Lane

Parameter	Estimate	Standard Error	t Value	*p* (Pr > |t|)
Intercept	82.390	3.667	22.47	<.0001
CAP	-0.027	0.002	-10.73	<.0001
TC	0.208	0.177	1.18	0.2397
LD	-0.302	0.0148	-20.41	<.0001
CAP*TC	-0.00009	0.00013	-0.71	0.4790

Table 29 shows that only the intercept, the coefficient of capacity and lane distribution are significant at α level of 0.05. In other words it means that only capacity and lane distribution contributed significantly towards *CC2*. However, to maintain a consistency for all 2 to 1 lane configuration models other independent variables were also retained in the model.

TABLE 30 Test of Coefficient Significance for *SRF* Model for 2 to 1 Lane

Parameter	Estimate	Standard Error	t Value	*p* (Pr > |t|)
Intercept	0.6562	0.042	15.44	<.0001
CAP	- .0002	0.00002	-7.01	<.0001
TC	0.0057	0.002	2.80	0.0052
LD	0.0078	0.0002	45.74	<.0001
CAP*TC	-.000009	0.000001	-6.14	<.0001

Table 30 indicates that all the explanatory variables including the intercept were significant at α level of 0.05 for the *SRF* model

5.3.2 Multivariate Analysis for 3 to 2 Work Zone Configuration

Similar to 2 to 1 lane configuration, all the four multivariate tests and exact F-test values from SAS output (see Table 31, 32, 33) indicate that all the three independent variables capacity, truck percentage and lane distribution at 1000 ft upstream of the taper have a significant effect on *CC1, CC2* and *SRF.*

TABLE 31 MANOVA Test and Exact F Statistics for No Overall Capacity Effect

Statistic	Value	F Value	Num DF	Den DF	*p* (Pr > F) *
Wilks' Lambda	0.11	5244.63	3	1957	<.0001
Pillai's Trace	0.89	5244.63	3	1957	<.0001
Hotelling-Lawley Trace	8.04	5244.63	3	1957	<.0001
Roy's Greatest Root	8.04	5244.63	3	1957	<.0001

* very small *p* values; hence null hypothesis rejected.

TABLE 32 MANOVA Test and Exact F Statistics for No Overall Truck% Effect

Statistic	Value	F Value	Num DF	Den DF	*p* (Pr > F) *
Wilks' Lambda	0.88	84.14	3	1957	<.0001
Pillai's Trace	0.11	84.14	3	1957	<.0001
Hotelling-Lawley Trace	0.13	84.14	3	1957	<.0001
Roy's Greatest Root	0.13	84.14	3	1957	<.0001

* very small *p* values; hence null hypothesis rejected.

TABLE 33 MANOVA Test and Exact F Statistics for No Lane Distribution Effect

Statistic	Value	F Value	Num DF	Den DF	*p* (Pr > F) *
Wilks' Lambda	0.74	222.71	3	1957	<.0001
Pillai's Trace	0.25	222.71	3	1957	<.0001
Hotelling-Lawley Trace	0.34	222.71	3	1957	<.0001
Roy's Greatest Root	0.34	222.71	3	1957	<.0001

* very small *p* values; hence null hypothesis rejected.

TABLE 34 Partial Correlation Coefficients for 3 to 2 Lane

DF = 1959	CC1	CC2	SRF
CC1	1.00	-0.96	-0.67
CC2	-0.96	1.00	0.70
SRF	-0.67	0.70	1.00

TABLE 35 Regression Model for 3 to 2 Configuration

$CC1 = 3.106 - 0.001 \times CAP + 0.02 \times TC + 0.0006 \times LD - 0.00004 \times CAP \times TC + 0.000008 \times CAP \times LD - 0.00033 \times TC \times LD$
$CC2 = 89.05 - 0.029 \times CAP + 0.078 \times TC + 1.373 \times LD - 0.0005 \times CAP \times TC + 0.00033 \times CAP \times LD + 0.024 \times TC \times LD$
$SRF = 0.579 - 0.0001 \times CAP - 0.001 \times TC + 0.062 \times LD - 0.000006 \times CAP \times TC - 0.00002 \times CAP \times LD - 0.0009 \times TC \times LD$

where *CC1* is in seconds , *CC2* is in feet, *CAP* stands for capacity in vehicles per hour, *TC* is the truck percentage, *LD* means lane distribution of the closed lane at 1000 ft upstream of the taper.

Table 36 below suggests that for *CC1* model in 3 to 2 work zone configuration except lane distribution the coefficient of all the explanatory variables and intercept are significant.

TABLE 36 Test of Coefficient Significance for *CC1* Model for 3 to 2 Lane

Parameter	Estimate	Standard Error	t Value	*p* (Pr > |t|)
Intercept	3.106	0.062	50.05	<.0001
CAP	-0.001	0.0004	-24.08	<.0001
TC	0.02	0.004	4.19	<.0001
LD	0.0006	0.007	0.08	0.9327
CAP*TC	-0.00004	0.00003	-11.08	<.0001
CAP*LD	0.000008	0.000004	1.91	0.0564
TC*LD	-0.0003	0.00014	-2.37	0.0179

For *CC2* model, Table 37, 38 (see below) show that the truck percentage did not contribute significantly towards *CC2* and *SRF* respectively. The result was similar to 2 to 1 work zone configuration.

TABLE 37 Test of Coefficient Significance for *CC2* Model for 3 to 2 Lane

Parameter	Estimate	Standard Error	t Value	*p* (Pr > |t|)
Intercept	89.05	3.69	24.10	<.0001
CAP	-0.029	0.002	-11.76	<.0001
TC	0.078	0.250	0.31	0.7601
LD	-1.373	0.429	-3.20	0.0014
CAP*TC	-0.0005	0.0002	-2.50	0.0124
CAP*LD	0.00033	0.0002	1.34	0.1807
TC*LD	0.0240	0.0084	2.88	0.0040

TABLE 38 Test of Coefficient Significance for *SRF* Model for 3 to 2 Lane

Parameter	Estimate	Standard Error	t Value	*p* (Pr > |t|)
Intercept	0.579	0.037	15.59	<.0001
CAP	-.0001	0.00002	-6.83	<.0001
TC	-.001	0.002	-0.42	0.6727
LD	0.062	0.004	14.27	<.0001
CAP*TC	-.000006	0.00002	-3.08	0.0021
CAP*LD	-.00002	0.00002	-9.19	<.0001
TC*LD	-.0009	0.00008	-10.72	<.0001

5.3.3 Multivariate Analysis for 3 to 1 Work Zone Configuration

Table 39, 40, 41 indicate that all the three explanatory variables have significant impact on CC1, CC2 and SRF.

TABLE 39 MANOVA Test and Exact F Statistics for No Overall Capacity Effect

Statistic	Value	F Value	Num DF	Den DF	*p* (Pr > F) *
Wilks' Lambda	0.086	2964.27	3	834	<.0001
Pillai's Trace	0.914	2964.27	3	834	<.0001
Hotelling-Lawley Trace	10.66	2964.27	3	834	<.0001
Roy's Greatest Root	10.66	2964.27	3	834	<.0001

* very small *p* values; hence null hypothesis rejected.

TABLE 40 MANOVA Test and Exact F Statistics for No Overall Truck% Effect

Statistic	Value	F Value	Num DF	Den DF	*p* (Pr > F) *
Wilks' Lambda	0.806	66.76	3	834	<.0001
Pillai's Trace	0.193	66.76	3	834	<.0001
Hotelling-Lawley Trace	0.240	66.76	3	834	<.0001
Roy's Greatest Root	0.240	66.76	3	834	<.0001

* very small *p* values; hence null hypothesis rejected.

TABLE 41 MANOVA Test and Exact F Statistics for No Lane Distribution Effect

Statistic	Value	F Value	Num DF	Den DF	*p* (Pr > F)*
Wilks' Lambda	0.822	60.10	3	834	<.0001
Pillai's Trace	0.177	60.10	3	834	<.0001
Hotelling-Lawley Trace	0.216	60.10	3	834	<.0001
Roy's Greatest Root	0.216	60.10	3	834	<.0001

* very small *p* values; hence null hypothesis rejected.

TABLE 42 Partial Correlation Coefficients for 3 to 1 Lane

DF = 836	CC1	CC2	SRF
CC1	1.00	-0.95	-0.61
CC2	-0.95	1.00	0.66
SRF	-0.61	0.66	1.00

TABLE 43 Regression Model for 3 to 1 Configuration

$CC1 = 3.48 - 0.0014 \times CAP + 0.018 \times TC - 0.079 \times LD - 0.00002 \times CAP \times TC + 0.0001 \times CAP \times LD - 0.003 \times TC \times LD$
$CC2 = 62.35 - 0.0089 \times CAP + 0.955 \times TC + 2.095 \times LD - 0.0007 \times CAP \times TC - 0.0043 \times CAP \times LD + 0.112 \times TC \times LD$
$SRF = 0.555 - 0.0002 \times CAP - 0.0199 \times TC + 0.361 \times LD + 0.00001 \times CAP \times TC - 0.0002 \times CAP \times LD - 0.0053 \times TC \times LD$

where *CC1* is in seconds , *CC2* is in feet, *CAP* stands for capacity in vehicles per hour, *TC* is the truck percentage, *LD* means lane distribution of the closed lane at 1000 ft upstream of the taper.

Table 44 indicates that for *CC1* model all the independent variables included in the model are significant. But for *CC2* model (see Table 45) truck percentage and its combined impact with capacity did not contribute significantly. However these non significant variables were retained in the *CC2* model as they were found to have strong impact on both or either *CC1* and *SRF* variables.

TABLE 44 Test of Coefficient Significance for *CC1* Model for 3 to 1 Lane

Parameter	**Estimate**	**Standard Error**	**t Value**	***p* (Pr > |t|)**
Intercept	3.48	0.083	42.19	<.0001
CAP	-0.0014	0.00005	-24.34	<.0001
TC	0.018	0.009	1.93	0.0536
LD	-0.079	0.034	-2.32	0.0208
CAP*TC	-0.00002	0.000006	-2.52	0.0119
CAP*LD	0.0001	0.00002	5.09	<.0001
TC*LD	-0.003	0.0005	-5.43	<.0001

TABLE 45 Test of Coefficient Significance for *CC2* Model for 3 to 1 Lane

Parameter	Estimate	Standard Error	t Value	*p* (Pr > |t|)
Intercept	62.35	4.67	13.35	<.0001
CAP	-0.0089	0.003	-2.81	0.0051
TC	0.955	0.528	1.81	0.0710
LD	2.095	1.950	1.07	0.2829
CAP*TC	-0.0007	0.0003	-1.89	0.0589
CAP*LD	-0.0043	0.001	-3.69	0.0002
TC*LD	0.112	0.027	4.05	<.0001

TABLE 46 Test of Coefficient Significance for *SRF* Model for 3 to 1 Lane

Parameter	Estimate	Standard Error	t Value	*p* (Pr > |t|)
Intercept	0.555	0.089	6.18	<.0001
CAP	-.0002	0.00006	-2.72	0.0066
TC	-.0199	0.010	-1.96	0.050
LD	0.361	0.037	9.63	<.0001
CAP*TC	0.00001	0.000007	1.71	0.0869
CAP*LD	-.0002	0.00002	-7.95	<.0001
TC*LD	-.0053	0.0005	-9.94	<.0001

CHAPTER 6

CONCLUSIONS

Replication of freeway work zone capacity values adopted by different state agencies was accomplished by modifying driver behavior parameters in the simulation model for the most prevailing work zone conditions such as lane configurations and truck percentages. This study also recommends the set of driver behavior parameters that would yield the desired work zone capacity values. The following conclusions can be made from this study:

- Micro-simulation tools such as VISSIM can be effectively used to model oversaturated work zone conditions, however it is necessary to adjust driver behavior parameters which control individual vehicle interactions in order to replicate exact field conditions in terms of observed capacity, queue lengths and other performance measures.

- Besides driver behavior parameters including both car-following and lane changing, the default truck characteristics in VISSIM are significantly different from U.S. truck fleet that is observed on freeways. Hence, the truck characteristics such as length, weight, power should be adjusted in accordance with the prevailing truck characteristics in U.S.

- This thesis provides practitioners a simple method for choosing appropriate values of driving behavior parameters in the VISSIM micro-simulation model to match the desired field capacity for work zones operating in a typical early merge system. To apply this method, a transportation agency with the knowledge of lane distribution at a specific point (1000ft) upstream of the work zone chooses a unique set of driving behavior parameters from the table to match the observed field capacity.

- In addition to the car-following driver behavior parameters, a lane changing parameter called safety reduction factor (*SRF*), which reflects the aggressiveness of the drivers changing lanes, that has a strong impact on the work zone capacity was considered as a part of calibration process.

- Both the car-following and lane changing parameters (i.e. *CC1, CC2* and *SRF*) should be carefully selected while modeling any oversaturated work zone in order to avoid any erroneous driver behavior patterns leading to unrealistic traffic conditions. The parameter values recommended in this thesis will produce traffic conditions consistent with traffic flow theory.

- With the knowledge of average lane changing distance upstream of the taper and the recommended set of driving behavior parameters, it is possible to accurately estimate the queue lengths that will be observed in a work zone.

This hypothesis was verified for one of the case studies in Ohio analyzed in this thesis.

- Capacity values resulting from the chosen driving behavior parameter ranges were found to be approximately between 1200 vphpl and 2100 vphpl for 2 to 1, 3 to 2 and 3 to 1 lane configurations depending on truck percentages. In order to obtain capacities outside this interval (<1200 or >2100) either the parameter ranges have to be extended or additional parameters, such as *CC0* and lane changing deceleration thresholds, should be explored.

- In this study, although the input demand was fixed at 3000 vph and 5000 vph for the 2 to 1, 3 to 1 and 3 to 2 configurations, respectively, the resulting capacity is not a function of this demand as long as the demand is sufficiently high to generate queues. However, the queue lengths will depend on the demand and they can be recorded from the simulation model with the use of parameters recommended in the charts.

- By selecting the appropriate driver behavior parameters from the developed charts the impact of variables such as work zone intensity and lane width reduction on work zone capacity can also be modeled. For example, if the impact of lane width reduction on capacity has been quantified based on empirical studies, the corresponding set of parameters for the reduced capacity can be obtained from the charts developed in this thesis.

- Multivariate analysis of *CC1, CC2* and *SRF* indicated that capacity, truck percentage and lane distribution at a specified point (here, 1000 feet upstream of the taper) contributed significantly towards *CC1, CC2* and *SRF* for all the three work zone lane configurations. The results also suggested that for a given capacity, truck percentage and lane distribution CC1 and *CC2* have a strong negative correlation, however *CC2* and *SRF* are positively correlated which implies that for a given work zone traffic characteristics such as capacity if the longitudinal oscillation of the vehicles in the following process increases the drivers become less aggressive in changing lanes.

- Future research will focus on applying these recommended set of driving behavior parameters for the late merge strategy in work zones given its increased use by DOTs across the country.

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APPENDIX A

Survey Questionnaire

Section I

1. Name of the organization or agency you belong to?

2. Please choose your agency's definition of work zone capacity?

   - Based on maximum hourly flow rate before queue formation
   - Based on maximum 15 minute flow rate
   - Based on mean queue discharge flow
   - Based on 95th percentile of mean queue discharge flow

3. Does your agency collect field data to measure work zone capacity?

   - Yes
   - No

4. If you answered yes to the above question, please state the type of traffic data collected to calculate capacity (please check all that apply)

   - Speed of the vehicles in the work zone
   - Volume of traffic
   - Queue length
   - Headways
   - Other, please specify

5. At what location is the capacity value measured?

- Beginning of the taper area
- End of the taper area
- Well into lane closure
- Other, please specify

Section II

6. In addition to the field data collected, does your agency use any of the following methods to estimate the work zone capacity values? (Please check all that apply)

- HCM procedure
- Work zone software (If yes, please specify below the name of the software)
- Simulation Tool (If yes, please specify below which ones)
- Regression Tool (If yes, please specify below which ones)

7. Which of the following factors are considered while estimating work zone capacities? Also, please state what adjustment factors your agency uses for the selected factors.

- work zone configuration (number of total lanes before work zone to number of lanes open during work zone)
- location of closed lane(left or middle or right)
- presence of ramps near the work zone
- length of work zone

- work zone grade
- driver familiarity
- intensity of the work zone
- proportion of heavy vehicles
- work duration factor
- lane width
- posted speed reduction
- partial lane closure versus crossover
- horizontal alignment
- day time versus night time
- short term versus long term
- type of lane delineation (whether cones or concrete barriers used to separate closed lanes from open ones)
- if any other , please mention here

Please specify the adjustment factors here.

8. What is the average value(s) of work zone capacity in your state for each of the following lane configurations (i.e. actual number of lanes before work zone to the number of lane open during work zone)

For 2 to 1 lane (specify units) …………………………

For 3 to 2 lane (specify units) …………………………

For 3 to 1 lane (specify units) …………………………

For 2 way 1 lane (specify units) …………………………

For work zones with median crossover …………………..

(Head to head traffic control)

9. Does your agency have a policy on when lane closures can/cannot occur?

- Yes, Off-peak hours only
- Yes, Nighttime only
- No
- Others, Please specify

10. Please provide your contact information if you would you like to receive a copy of the survey results. Thank you for your participation in the survey.

Name ……………………………..

Company…………………………

Email ……………………………

Phone ……………………………

APPENDIX B

In addition to 1000 ft upstream of the taper lane utilization was also collected at 1500 ft upstream of the taper. Figures 30 to 40 show the plots of percentage of traffic in the closed lane at 1500 ft upstream of the merge area versus capacity measured for the three lane configurations and varying truck percentages.

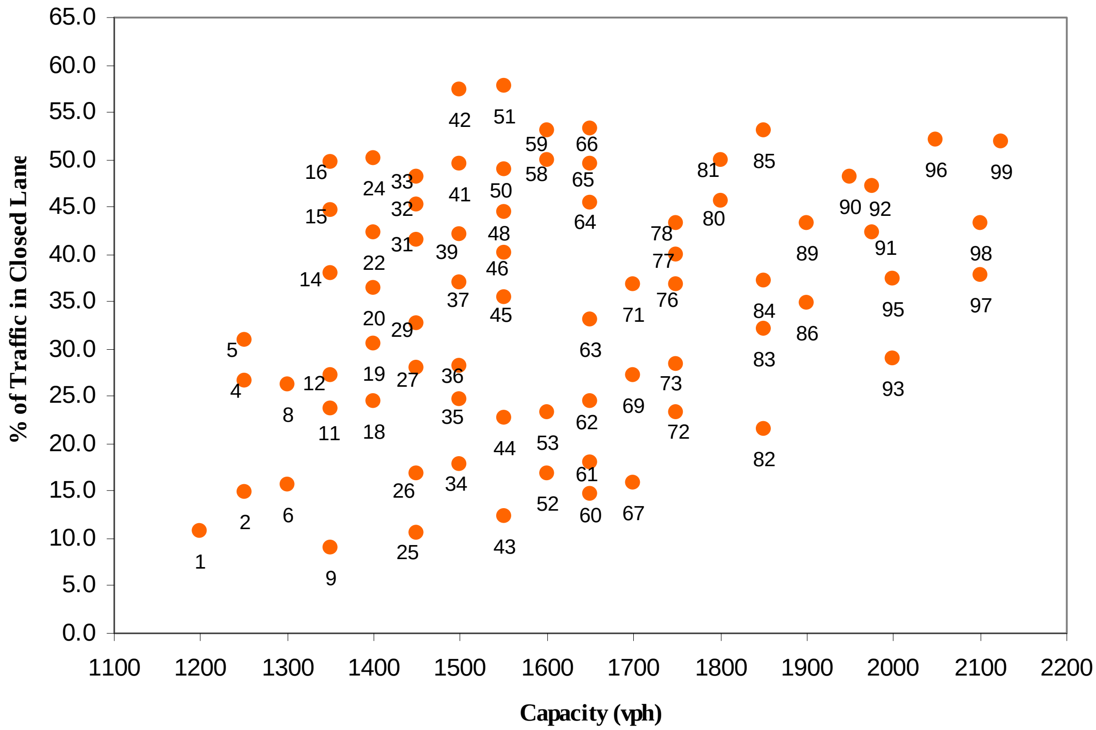

FIGURE 29 Lane distribution at 1500 ft u/s of taper for 10% trucks in a 2 to 1 lane

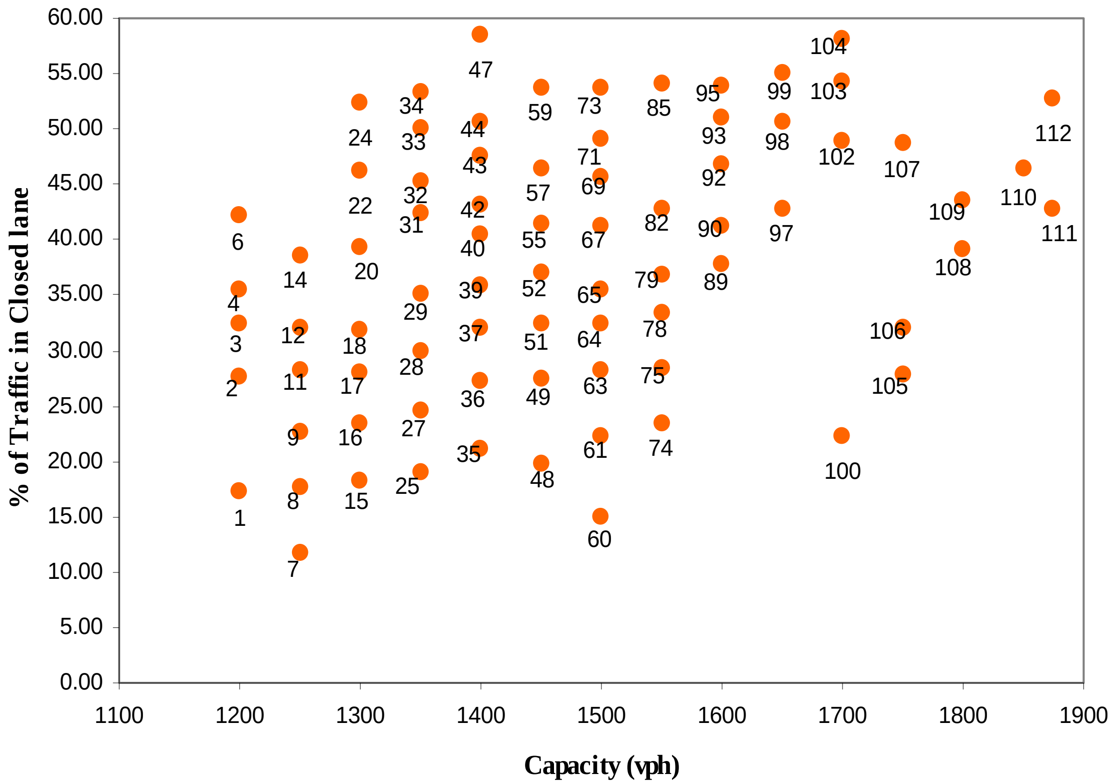

FIGURE 30 Lane distribution at 1500 ft u/s of taper for 20% trucks in a 2 to 1 lane

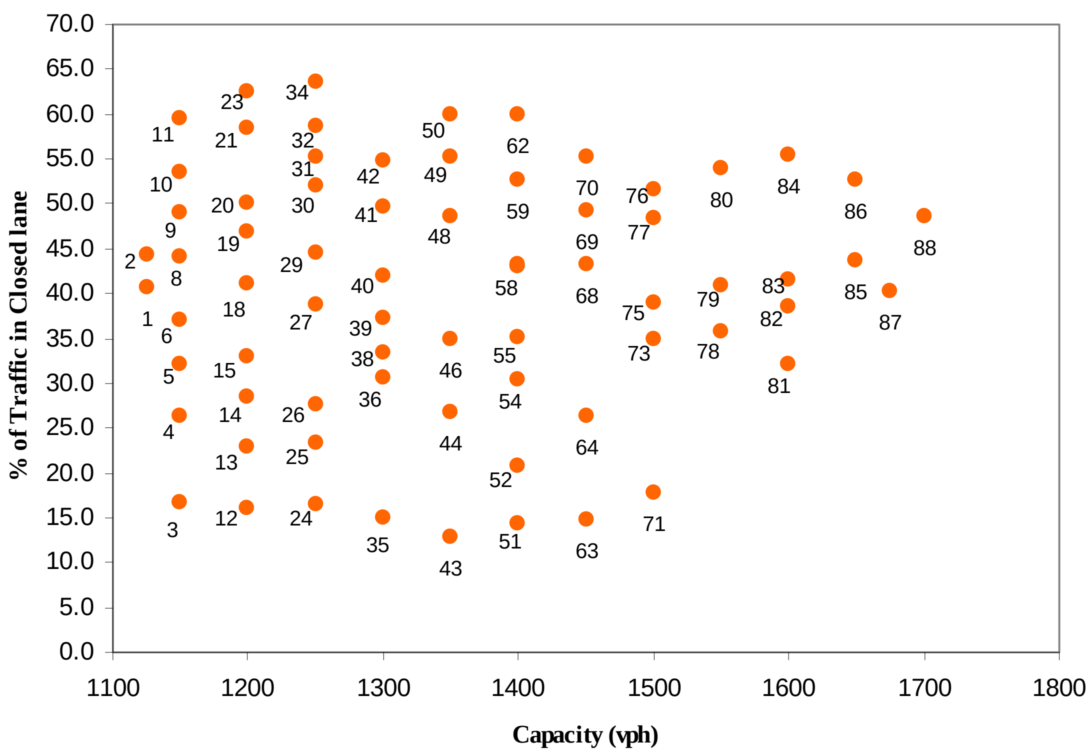

FIGURE 31 Lane distribution at 1500 ft u/s of taper for 30% trucks in a 2 to 1 lane

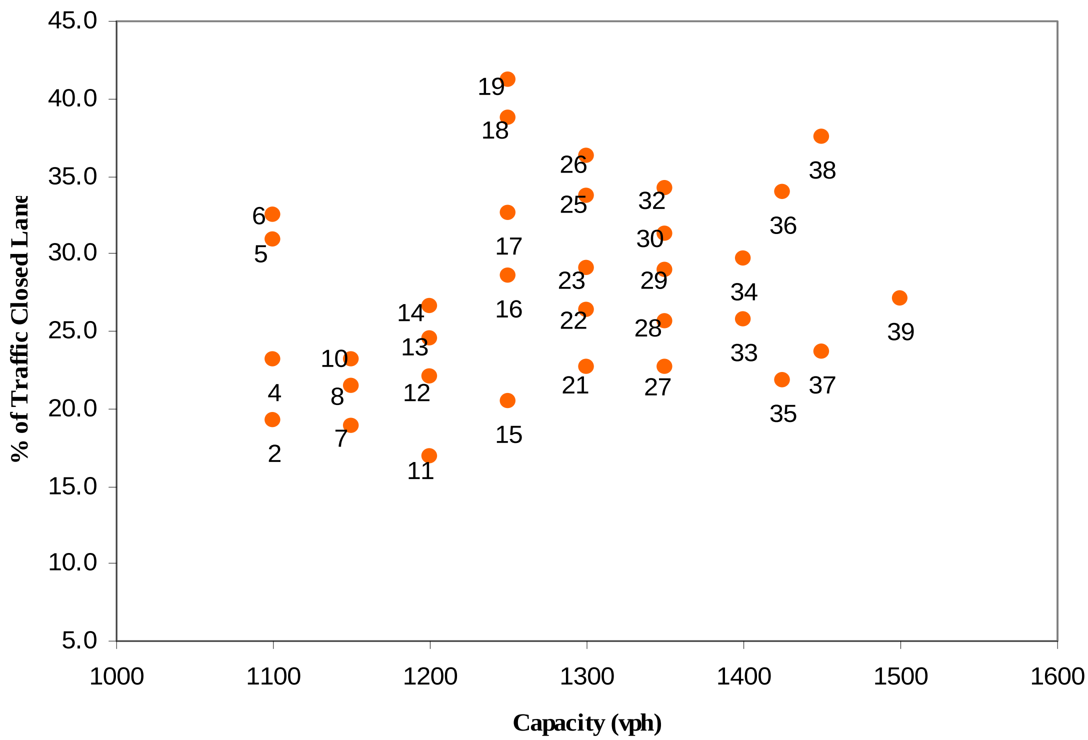

FIGURE 32 Lane distribution at 1500 ft u/s of taper for 40% trucks in a 2 to 1 lane

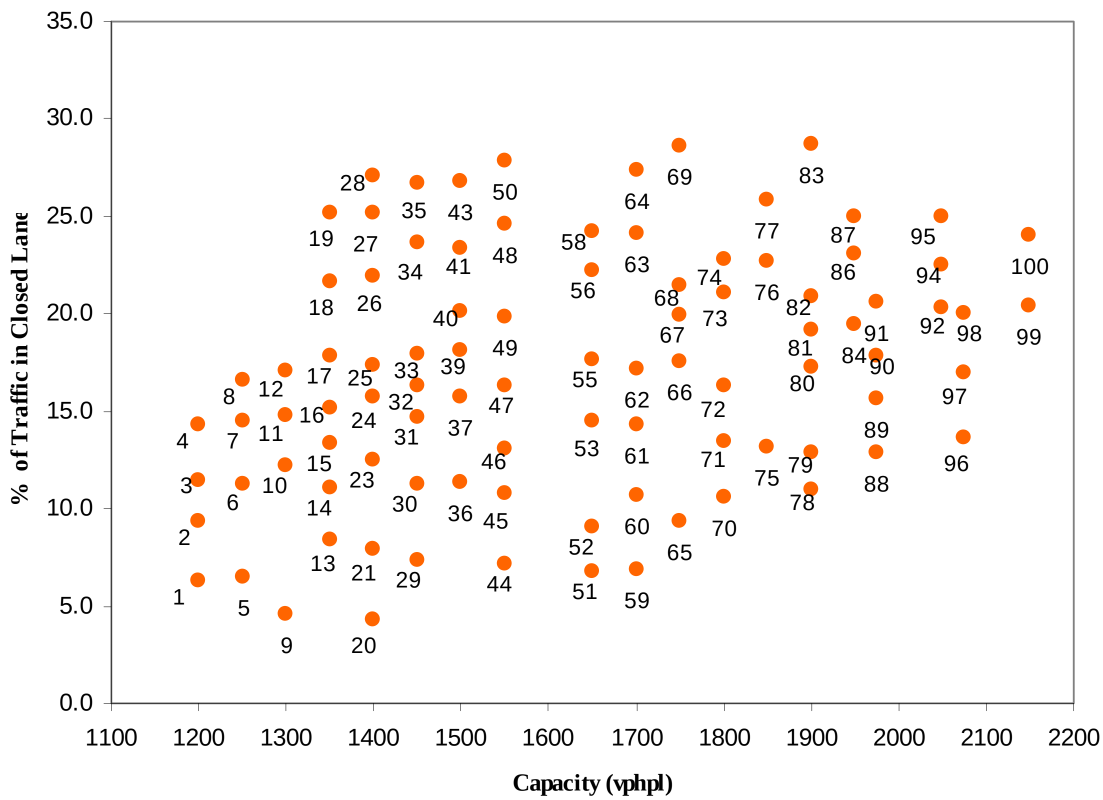

FIGURE 33 Lane distribution at 1500 ft u/s of taper for 5% trucks in a 3 to 2 lane

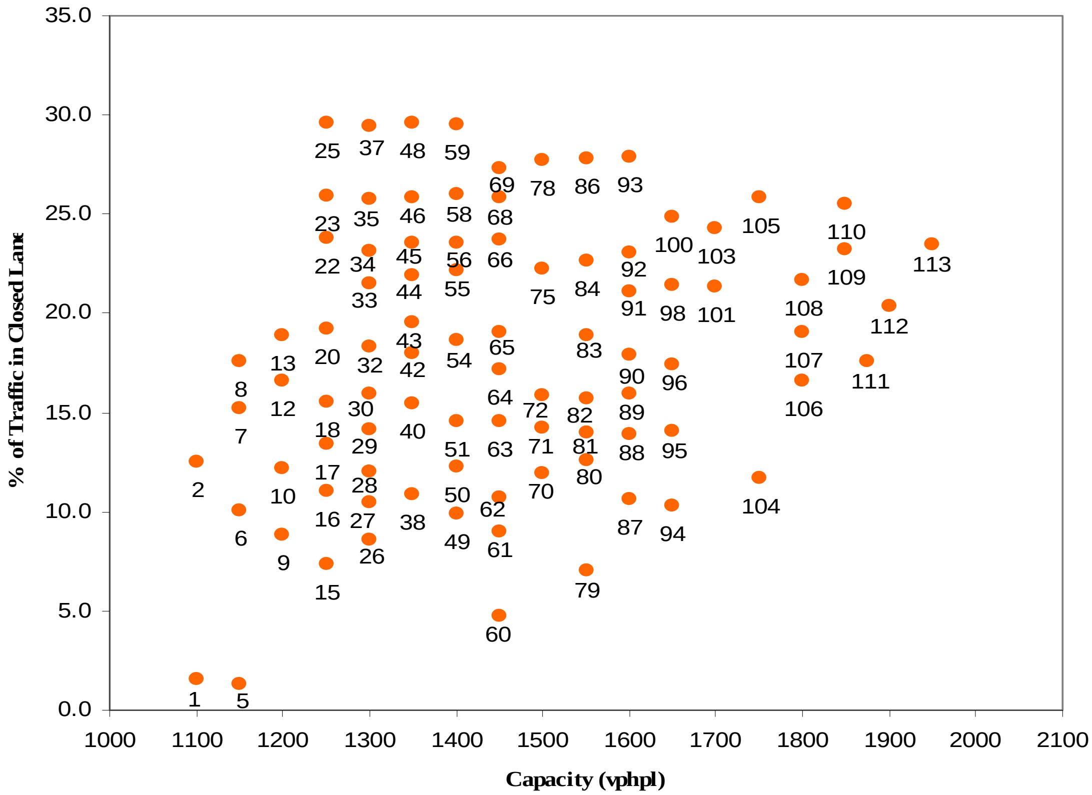

FIGURE 34 Lane distribution at 1500 ft u/s of taper for 10% trucks in a 3 to 2 lane

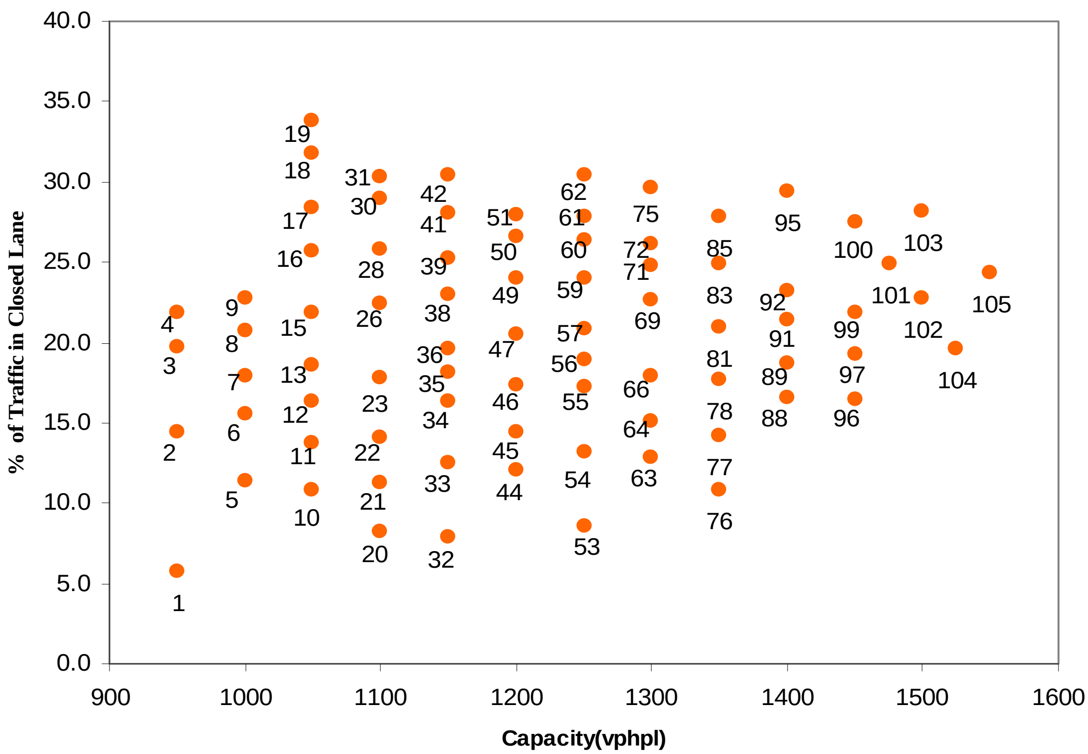

FIGURE 35 Lane distribution at 1500 ft u/s of taper for 20% trucks in a 3 to 2 lane

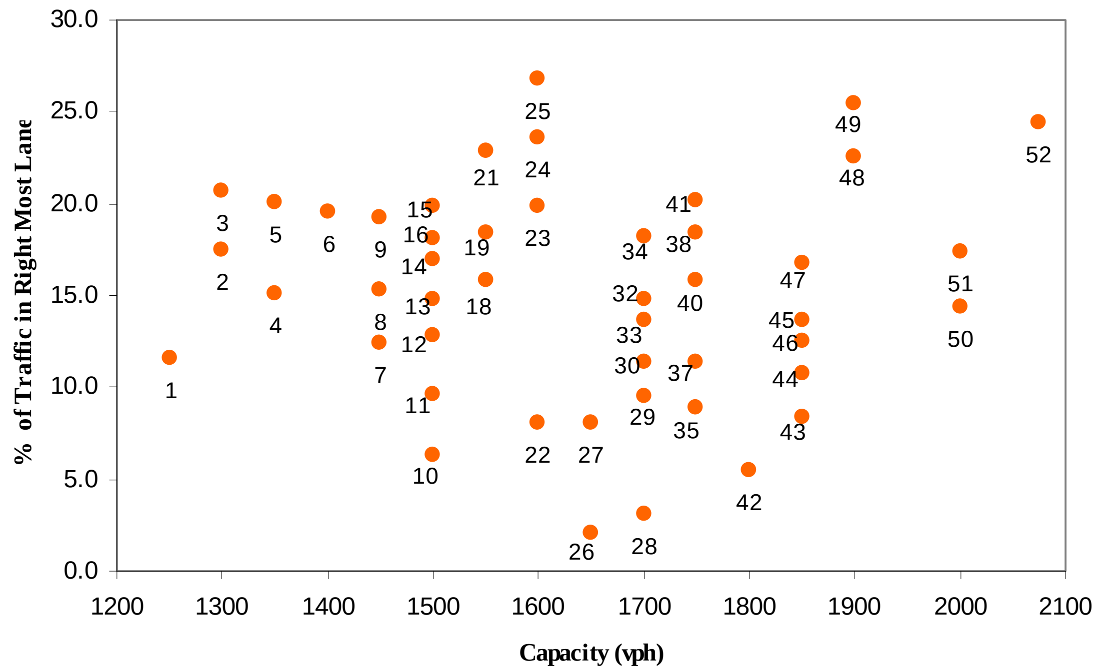

FIGURE 36 Lane distribution at 1500 ft u/s of taper for 5% trucks in a 3 to 1 lane

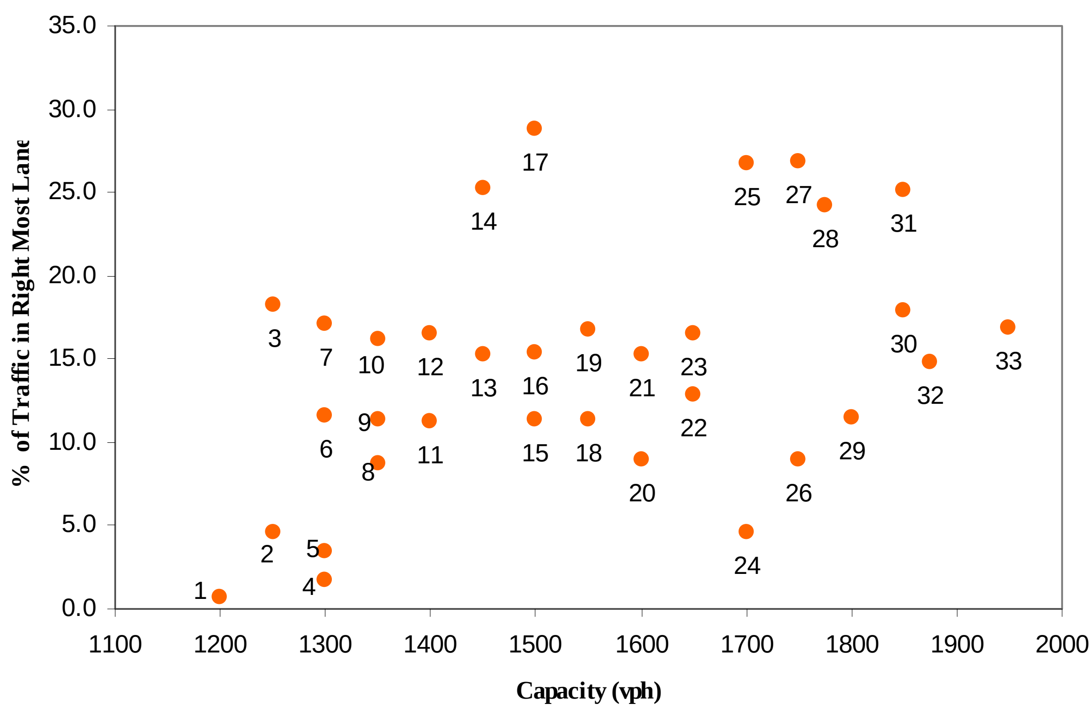

FIGURE 37 Lane distribution at 1500 ft u/s of taper for 10% trucks in a 3 to 1 lane

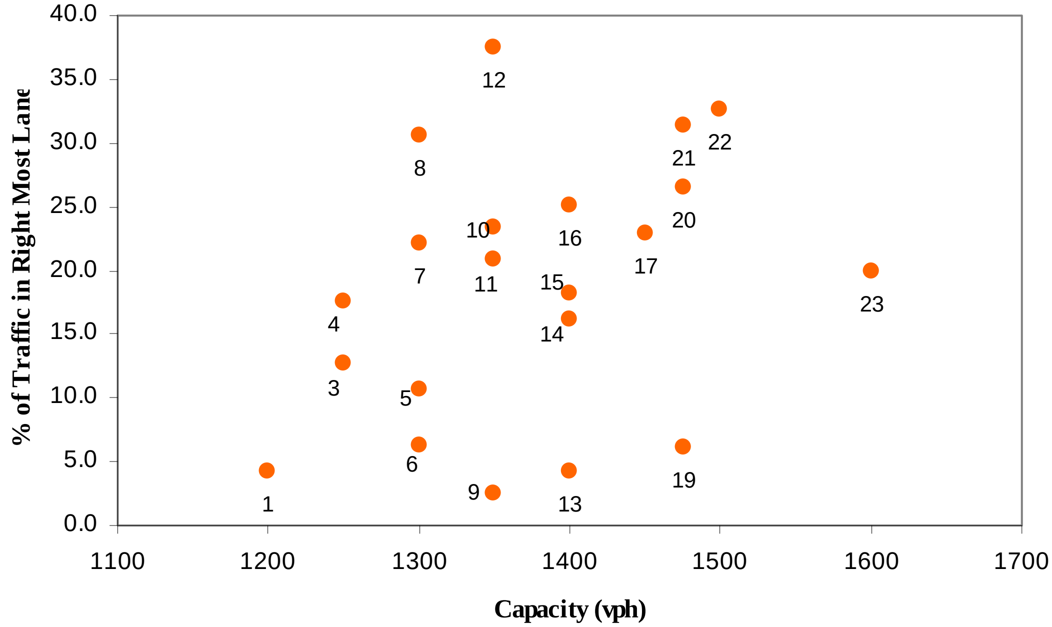

FIGURE 38 Lane distribution at 1500 ft u/s of taper for 20% trucks in a 3 to 1 lane