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THE FLORIDA DEPARTMENT OF TRANSPORTATION

SYSTEM PLANNING OFFICE

on Project

"Impact of Trucks on Arterial LOS and Freeway Work Zone Capacity"

FDOT Contract BD-545-51 (UF Project 00054954)

Part B : Freeway Work Zone Capacity

July 2007

University of Florida
Transportation Research Center
Department of Civil and Coastal Engineering

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METRIC CONVERSION CHART

U.S. UNITS TO METRIC (SI) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

METRIC (SI) UNITS TO U.S. UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

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16. Abstract

The existing FDOT lane closure analysis method was developed several years ago, and it is the desire of the Department to evaluate and update it. The objective of this research was to develop analytical models and procedures for estimating the capacity of a freeway work zone considering various parameters. Due to unavailability of real-world work zone data, the study was based on simulation. CORSIM (version 5.1) was used to develop a comprehensive database which was used in the analytical model development. Models were developed for three types of work zone configurations (2-to-1, 3-to-2, and 3-to-1 lane closures). Two different types of models were developed for each configuration; a planning model and an operational model. The planning model is the simplest one and it can be applied when the work zone is not in place. The operational model requires more data as input, and should be used for estimating the capacity of an existing work zone. Since this research was entirely based on simulation, the results and conclusions should be viewed with caution. It is likely that field observations would result in different capacity values, and that additional factors (such as time of day, etc.) would affect the results.

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EXECUTIVE SUMMARY

The existing FDOT lane closure analysis method was developed several years ago, and it is the desire of the Department to evaluate and update it accordingly. The objective of this research was to develop analytical models and procedures for estimating the capacity of a freeway work zone considering various geometric and traffic parameters. Due to unavailability of real-world work zone data, the study was based on simulation. CORSIM (version 5.1) was used to develop a comprehensive database which was used in the analytical model development. Models were developed for three types of work zone configurations (2-to-1, 3-to-2, and 3-to-1 lane closures). Two different types of models were developed for each lane closure configuration; a planning model and an operational model. The planning model is the simplest one and it applies when a capacity estimate is required, but the work zone is not in place. The operational model requires more data as input, and it may be used for estimating the capacity of an existing work zone.

The following were concluded from the research:

- The capacity estimates obtained from the HCM 2000 and the current FDOT procedure are based on different input variables and therefore are difficult to compare.
- The proposed methodology (both the planning and operational analysis applications) considers a larger combination of geometric, traffic, and work zone characteristics to estimate capacity.
- The capacity values obtained by the proposed methodology fall somewhere between the HCM 2000 and the FDOT procedure estimates (for both the planning and operational analysis applications). Generally the HCM 2000 values are lower, while the FDOT values are higher than those obtained by the proposed method.

Since this research was entirely based on simulation, the results and conclusions should be viewed with caution. It is likely that field observations would result in different capacity values, and that additional factors (such as day of week, time of day,

etc.) would affect the results. The general trends however observed with simulation should generally be valid in the field as well.

The following are the recommendations from this research:

- The methods presented here should be applied on a trial basis to existing and upcoming work zone projects, so that they can be tested and validated for actual projects before widely applied.
- Field data should be collected at various sites and with various work zone configurations, so that the procedures developed here can be thoroughly evaluated, and the simulated capacity estimates compared to field estimates.

In addition, the following recommendations are provided regarding possible improvements to the CORSIM simulator for improving its capability to simulate work zones:

- The software should consider specific algorithms for accommodating work zones (rather than using the incident or lane closure function). These algorithms should consider the taper section provided upstream of the work zone, and should provide a specific relationship between the rubbernecking factor and work intensity in the work zone.
- CORSIM results are currently not sensitive to the effects of closing the right vs. the left lane. Its algorithms should be modified to allow for relatively slower traffic in the rightmost lanes (this should not be restricted to trucks only).
- CORSIM results are currently not sensitive to the length of the work zone. Previous research has shown that this might actually affect capacity, therefore additional research is warranted to evaluate whether this is the case, and if yes, to modify CORSIM accordingly.
- Various geometric elements (such as lane width and shoulder width) are currently not considered within CORSIM. Its algorithms should be modified to consider such factors more generally and also with respect to work zones.

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1. INTRODUCTION

Chapter 10 of the FDOT Plans Preparation Manual (PPM) titled "Work Zone Traffic Control" contains a lane closure analysis procedure (pp. 10-30 – 10-43) that calculates the restricted capacity for roadway segments with a lane closure. Based on the hourly traffic demand, restrictions may then be placed on the time of day/night that the lane can be closed. This procedure applies capacity reduction and other factors to the capacity flow rate to determine the restricted capacity. This procedure was developed approximately 10 years ago, and it is the desire of the Department to evaluate and update this procedure against more current publications including the HCM2000 and other available pertinent research.

1.1. Research Objectives and Scope

The primary objective of this research was to develop analytical models and procedures for estimating the capacity of a freeway work zone considering various geometric and traffic parameters. These can be used to update the FDOT lane closure analysis procedure for freeway work zones. Due to unavailability of real-world work zone data, the study is based on simulation. CORSIM (version 5.1) was used to develop a comprehensive database which was used in the analytical model development. Models were developed for three types of work zone configurations (2-to-1, 3-to-2, and 3-to-1 lane closures). Two different types of models were developed for each lane closure configuration; a planning model and an operational model. The planning model is the simplest one and it applies when a capacity estimate is required, but the work zone is not in place. The operational model requires more data as input, and it may be used for estimating the capacity of an existing work zone.

1.2. Organization of the Report

Chapter 2 of this report summarizes the literature review conducted for this project, while Chapter 3 presents the research methodology. Chapter 4 discusses the simulation process and results. Chapters 5, 6, and 7 describe the analytical model development and

present the capacity estimation models. Chapter 8 provides conclusions and recommendations.

2. LITERATURE REVIEW

An extensive literature review was conducted to identify and evaluate existing research involving freeway work zone lane closures. The first section discusses the treatment of work zone capacity in the Highway Capacity Manual (HCM 2000), while the second section reviews the current FDOT lane closure analysis procedure. Next, a review of the literature on capacity estimation for work zones is provided. The fourth section reviews the software available for work zone analysis, since many computer models have used capacity as a key input parameter to help quantify queue length and delay and to calculate delay costs. Next, literature on early vs. late merging strategies at work zones is discussed. The sixth section reviews briefly other aspects pertinent to work zones and work zone operations which are more indirectly related to work zone capacity. The last section summarizes the literature review findings and provides conclusions and recommendations.

2.1. Work Zone Capacity in the Highway Capacity Manual (HCM 2000)

The HCM 2000 defines capacity as "the maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions; usually expressed as vehicles per hour, passenger cars per hour, or persons per hour." The HCM 2000 (Chapter 22, Freeway Facilities) distinguishes between short-term and long-term work zones and recommends that a value of 1600 pc/h/ln be used as the base capacity value for short-term freeway work zones, regardless of the lane closure configuration. It is stated that this base value may be higher or lower when adjustments are applied in accordance to the specific work zone's prevailing conditions. The intensity of work activity—characterized by the number of workers, types of machinery, and proximity of travel lanes to work under way—can have an effect on the capacity, increasing or reducing the base value by up to ten percent. Also,

the HCM 2000 states that the effect of heavy vehicles should be considered, as truck presence leads to reduction of capacity. Another element reducing the base capacity value is the presence of ramps. The HCM 2000 recommends that to minimize the impact of ramp presence on capacity, ramps should be located at least 1,500 ft. upstream from the beginning of the full closure. If that cannot be done, and the ramp is within the taper or the work zone itself, then either the ramp volume should be added to the mainline volume to be served, or the capacity of the work zone should be decreased by the ramp volume (up to a maximum of half of the capacity of one lane). The HCM 2000 provides the following equation (Equation 22-2, HCM 2000) for estimating capacity at work zones, which considers reductions due to the three elements discussed above:

$$c_a = (1{,}600 + I - R) * f_{HV} * N \qquad (2\text{-}1)$$

where:

c_a = adjusted mainline capacity (veh/h)

f_{HV} = adjustment for heavy vehicles; defined in HCM Equation 22-1

I = adjustment factor for type, intensity, and location of the work activity (ranges from -10% to +10% of base capacity, or -160 to +160 pc/h/ln)

R = adjustment for ramps, as described in the preceding paragraph

N = number of lanes open through the short-term work zone

The HCM 2000 also provides capacity values for long-term construction zones. For a two-to-one lane closure the average capacity is close to 1,550 veh/h/ln if a crossover is present and the manual suggests that this capacity may be as high as 1,750 veh/h/ln if there is no crossover but only a merge to a single lane. In the case of a three-to-two lane closure the capacity ranges between 1,780 and 2,060 veh/h/ln (Exhibit 22-4, HCM 2000).

An additional factor discussed in the HCM 2000, which would decrease capacity and can be considered for both short-term and long-term work zones, is the lane width. It is stated that capacity may decrease by 9-14% for lane widths of 10-11 ft. Note that this factor is not included in the capacity estimation equation, nor does the HCM discuss potential interactions between the various factors affecting capacity.

2.2. Current FDOT Lane Closure Analysis Procedure

The FDOT lane closure analysis procedure was developed in 1995 and does not consider operating characteristics of the traffic stream in its reduction estimate. Rather, geometric conditions form the basis of the method. The procedure considers the following lane reduction configurations:

- 2-lane, 2-way facility converted to 2-way, 1-lane
- 4-lane, 2-way facility converted to 1-way, 1-lane
- 6-lane, 2-way facility converted to 1-way, 2-lane

The base capacities for the three configurations listed above are 1400, 1800, and 3600 vehicles per hour, respectively. Capacity reduction factors are applied to these base values so that an estimate of restricted capacity may be obtained. The obstruction factor is based on the width of the travel lane and the lateral clearance to the travel lane. A lateral clearance of 6 feet and a lane width of 12 feet results in a reduction factor of 1.00, or no reduction. A lateral clearance of 0 feet and a lane width of 9 feet results in a maximum reduction factor of 0.65. The other reduction factor used is the work zone factor, which is based on the length of the work zone and ranges from 0.98 to 0.50 for work zone lengths of 200 feet through 6000 feet, respectively.

2.3. Work Zone Capacity Determination in the Literature

There have been several articles in the literature reporting on capacity estimation for freeway work zones. Krammes and Lopez (1994) presented recommendations on estimating the capacities of short-term freeway work zone lane closures which served as the basis for the HCM 2000 methodology. The study consisted of analyzing lane closures in Texas between 1987 and 1991. The data collected represent over 45 hours of capacity counts at 33 different freeway work zones with short-term lane closures. Five different lane closure configurations were analyzed, and data were only used from time periods during which traffic was queued in all lanes upstream of the work zone area. Capacity counts were taken only at the upstream end of the activity area (i.e., the beginning of the bottleneck). The results of their study showed an average short-term work-zone lane

closure capacity value of 1600 pcphpl, and it was recommended that this value be used as the starting base value when analyzing these freeway segments. It was also recommended that this value be adjusted for the effects of heavy vehicle presence, intensity of the work zone, and the presence of entrance or exit ramps near the beginning of the lane closure. The following equation estimates capacity in a lane closure, taking into consideration the effects of work zone activity intensity, number of open lanes, and the presence of ramps and heavy vehicle in the traffic stream.

$$C = (1600 + I - R) * H * N \qquad (2\text{-}2)$$

where:

C = estimated work zone capacity (vph)

I = adjustment for type and intensity of work activity (pcphpl) suggested in the research

R = adjustment for presence of ramps (pcphpl) suggested in the research

H = heavy vehicle adjustment factor given in the HCM

N= number of lanes open through the work zone

Dixon et al. (1996) defined and determined work zone capacity values for rural and urban freeways without continuous frontage roads. Variables studied are as follows:

- Night versus day construction
- Intensity of work activity (heavy, moderate, or light)
- Proximity of work to active lanes
- Proximity of interchanges to the work zone
- Work zone configuration

The research included analysis of speed-flow relationships to compute capacity. The collapse from uninterrupted flow (queue initiation) is defined as work zone capacity for the end of the transition area (beginning of the bottleneck). Smaller capacity at the activity-area leads to the conclusion that the transition region functions as an initial bottleneck, whereas the activity area represents a second, more constricted bottleneck. Therefore, capacity estimation adjacent to an active work zone area was also computed

where lower queue-discharge volume takes place. For heavy work in a two-lane to one-lane work zone configuration, the capacity values proposed at the active work area are approximately 1,200 vehicles per hour per lane for rural sites and 1,500 vehicles per hour per lane for urban sites.

Tarko (1997) described extensions to the higher order continuum model of freeway traffic to incorporate lane drops. The model can handle a lane change maneuver in the vicinity of lane drops. It includes the lane change component that incorporates drivers' responses to the geometry and traffic factors as an extension to the fundamental relationship obtained from the definitions of q, k, and v, the continuity equation which expresses the law of conservation of traffic stream and the momentum equation which accounts for the acceleration/deceleration and inertia characteristics of the traffic mass. The lane change components are based on the lane change rate, proportion of drivers changing lanes, time for lane change maneuver and desirable speed. The desirable speed is the speed drivers consider safe and convenient under given traffic and geometry conditions. The presented model considers two factors of the desirable speed: (1) Traffic density (traffic conditions), and (2) Lane change decision (effect of lane change).

Enberg and Mannan (1998) proposed three models to estimate capacity of a work zone on one of the main freeways in southern Finland. Capacities were determined using the van Aerde model, a polynomial model and a binomial model. The van Aerde model uses an analogy of back propagation neural networks in the following manner:

$$V = \frac{V_f}{2} - \frac{C_1}{2C_3} + \frac{1}{2C_3 d}(1 - \sqrt{d^2\left[(C_3V_f + C_1)^2 + 4C_2C_3\right] - 2d(C_3V_f + C_1) + 1}) \qquad (2\text{-}3)$$

Where:

V_f = Free flow speed (km/h)

V = Speed (km/h)

C_1 = Fixed distance headway constant (km)

C_2 = First variable distance headway constant (km^2/h)

C_3 =Second variable distance headway constant (h)

D = Density (veh/km)

In the polynomial model, to estimate the capacity of the work zone for each lane and both directions, a set of regression equations were developed. The regression models were polynomials of the second degree based on traffic flow (Q, veh/h) as a function of density (d, veh/km).

The third model is based on a binomial approach considering the influence of the vehicle types and their combination on the capacity which follows a binomial distribution. The maximum capacity for each lane is calculated as follows:

$$Q_{(\max,lanetype)} = 3600\sum_{i=1}^{m} a^2 \frac{1}{\bar{t}_{aa}} + b^2 \frac{1}{\bar{t}_{bb}} + a(1-a)\frac{1}{\bar{t}_{ab}} + (1-a)a\frac{1}{\bar{t}_{ba}} \qquad (2\text{-}4)$$

Where:

a = Proportion of light vehicles

b = Proportion of heavy vehicles

t = Mean time headway

The results were comparable to oversees findings for lane reductions (closures) from 3 to 2. The estimated capacity based on the binomial model was about 1-3% higher than the observed capacity based on the empirical data. The capacity values given by the polynomial model were quite close to the field observations. The best results were obtained with the van Aerde model.

Research by Maze *et al.* (1999) evaluated traffic flow behavior at rural interstate highway work zones, and estimated the traffic carrying capacity of work zone lane closures. Traffic performance data were collected at an Iowa interstate highway work zone using data collection trailers, constructed exclusively for this project. The trailers use a pneumatic mast to hoist video cameras 30 feet above the pavement's surface where the cameras collected video of traffic operations. Traffic performance data were collected at one work zone on Interstate Highway 80 where two lanes are reduced to one lane. Through analysis of these data, a work zone lane closure capacity from 1,374 to 1,630 passenger cars per hour was estimated.

Additional research was completed by Maze *et al.* (2000) considering the capacities of work zones in rural Iowa. The paper discusses the procedure for developing an estimate for vehicular capacity through rural interstate work zones in Iowa. The

following field data were collected during the summer of 1998 on Interstate Highway 80 between U.S. 61 and Interstate Highway 74:

- Traffic flow characteristics—speed, density, and volume—at the end of the lane closure taper
- Traffic flow characteristics upstream from the lane closure (500 feet)
- The length of the queues throughout congested conditions. This is a measure of storage and the difference in queue length from one time interval to the next is the speed that the queue grows or is discharged.

One aspect of particular interest to the research was the observation of the rate at which the queue increases or decreases. Field observation found that backward moving queues were forming at speeds as high as 40 mi/h. With oncoming, unsuspecting traffic arriving at 65 to 70 mi/h, this creates unsafe relative speeds of 100 mi/h, a problem for rural Iowa's interstate traffic. It was concluded in the report that the capacities in rural Iowa for work zone lane closures varied from 1,400 to 1,600 passenger cars. This capacity estimation assumed a passenger car equivalency (PCE) value of 1.5 for heavy vehicles.

Al-Kaisy et al. (2000) used field data to investigate freeway capacity at long-term lane closures due to rehabilitation work. Data from two lane closures at the same construction site (eastbound and westbound) were examined. The site is located on the Gardiner Expressway in the southern part of downtown Toronto. Data were collected during 4 days, totaling around 53 hours of congested traffic operations. Results showed significant variation in freeway capacity in the work zones. Four intervening variables were investigated; and all exhibited significant but different effects on freeway work-zone capacity. These variables included temporal variation (which is thought to relate to driver characteristics), grade, day of week, and weather conditions. The results confirmed the pressing need for more extensive field data that will allow better identification of the effect of various control variables on work-zone capacity.

The objectives of a study by Kim *et al.* (2001) were to investigate various factors that contribute to capacity reduction in work zones and to suggest a new methodology to

estimate the work zone capacity. The new capacity estimation model is based on traffic and geometric data collected at 12 freeway work zone sites with four lanes in one direction. Traffic data were collected mainly after the peak hour during daylight and night (Maryland State Highway Administration (SHA) has a policy that lanes cannot be closed during the peak-hour.) Multiple-regression analysis was used to develop a model to predict work zone capacity as a function of several key independent factors such as the number of closed lanes, the proportion of heavy vehicles, grade, and the intensity of work activity. The proposed model was compared with other existing capacity models, including the Krammes and Lopez model discussed above, and showed improved performance for all of the validation data. The following equation estimates capacity through a lane closure, and considers additional factors such as lateral distance to the open travel lanes, work zone length, and the location of the closed lanes (left or right or even middle):

$$\begin{aligned} Capacity &= 1857 - 168.1 * NUMCL - 37.0 * LOCCL - 9.0 * HV \\ &+ 92.7 * LD - 34.3 * WL - 106.1 * WIH - 2.3 * WG * HV \end{aligned} \tag{2-5}$$

Where:

NUMCL = Number of closed lanes

LOCCL = Location of closed lanes (which lanes are closed)

HV = Proportion of heavy vehicles

LD = Lateral distance to the open travel lanes

WL = Work zone length

WIH = Intensity of heavy work zone activity

WG * HV = Work zone grade * Proportion of heavy vehicles

According to the above model, Kim *et al.* (2001) suggest that work zone length has an effect on capacity in the following manner: a long work zone length will likely have more intense work activity, thus reducing capacity. However, there is already a term in the model, WIH, that considers work zone intensity. It is unclear then why there is an individual term for work zone length, and not an interaction term with intensity.

A work zone capacity model was developed by Adeli and Jiang (2003) using neuro-fuzzy logic. The model developed includes several factors for estimating the work

zone capacity such as: the percentage of trucks (x_1), pavement grade (x_2), number of lanes (x_3), number of lane closures (x_4), lane width (x_5), work zone layout (merging, lane shifting and crossover) (x_6), work intensity (work zone type – 6 categories) (x_7), length of closure (x_8), work zone speed (x_9), proximity of interchanges (x_{10}), work zone location (x_{11}), work zone duration (x_{12}), work time (daytime or night) (x_{13}), work day (x_{14}), weather condition (x_{15}), pavement condition (x_{16}), driver composition (x_{17}). These data were available for seven work zone locations. Since some of these variables have linguistic values and some have numerical values, all variables were normalized using non-linear spline-based functions. Furthermore, the capacity was normalized to the range of zero to one using the equation:

$$C_n = (C - C_{\min}) / (C_{\max} - C_{\min}) \qquad (2\text{-}6)$$

Where:

C_n = normalized work zone capacity

C_{min}, C_{max} = minimum and maximum work zone capacity value from the data

A fuzzy logic inference mechanism was employed to estimate the work zone capacity. This mechanism uses a set of *N* IF-THEN fuzzy implication rules which correspond to the number of clusters for the available data set. The estimated work zone capacity was obtained as the summation of the outputs of the *N* implication rules. The developed neuro-fuzzy model was generalized to estimate new data and it was further evaluated through testing data sets.

The accuracy of the estimated work zone capacity of the proposed model was tested through a comparison with the empirical models developed by Krammes and Lopez (1994) and Kim et al. (2001) with the data sets of the seven work zone locations. The authors concluded that the neuro-fuzzy model in general provides more accurate estimations of work zone capacity.

Sarasua *et al.* (2004) conducted a study in South Carolina to determine the number of vehicles per lane per hour that can pass through short-term, interstate work zone lane closures, with minimum acceptable levels of delay. After review of other states' policies, the methodology was developed based on a 12-month data collection period during 2001-2002 from 22 work zone sites along South Carolina's interstate system. Heavy vehicles

were considered in the analysis, implementing the software Satflo2 to develop PCEs based on recorded time headways. Sarasua's paper presents a summary of the data collection procedures and data analysis methods, as well as the final form of the work zone capacity model. The research recommended a base capacity value of 1460 pcphpl.

A report by Benekohal and Chitturi (2004) describes a methodology for estimating both operating speeds and capacity at interstate work zones. Data were collected at 11 work zones in Illinois with time-coded video recording equipment. Headways, speeds, and travel times were among the performance measures recorded. The following speed-flow relationship was developed from the data to establish the lower part (congested part) of the speed-flow curve:

$$q = 145.68 * U^{0.6857} \quad (2\text{-}7)$$

Where:

q = Flow in passenger cars per hour per lane (pcphpl)

U = Speed in mi/h (input speed must be lower than the speed at capacity)

The free flow part of the curve is based on information from the HCM 2000 and on field data collected in work zones. The authors state that the capacity model is based on the principle that work zone operating factors (such as work intensity, lane width, lateral clearance, etc.) cause reductions in the "operating speed". Operating speed in a work zone is defined as the speed at which the vehicles would travel through the work activity area after reducing their speed due to work intensity, lane width, lateral clearance, and other factors. The adjusted capacity is estimated as follows:

$$C_{adj} = C_{U0} * f_{HV} * PF \quad (2\text{-}8)$$

Where:

C_{adj} = adjusted capacity (vphpl)

C_{U0} = capacity at operating speed U0

f_{HV} = heavy vehicle factor

PF = platooning factor (which accounts for the underutilization of available capacity, and is a function of drivers' aggressiveness, traffic volume, and work zone operations)

The model was validated for a two-to-one lane closure, but the authors recommended additional data collection from work zones with different lane closure configurations to further verify the validity of their methodology.

Al-Kaisy and Hall (2003) examined freeway capacity of long-term reconstruction zones and developed site specific work zone capacity models. Based on data collected at six reconstruction sites in Ontario, Canada, with different types of closure, the authors concluded that the capacity ranges between 1,853 and 2,252 pcphpl, with a mean estimate of capacity at 2,000 pcphpl. Initially, two types of site-specific capacity models were developed, and finally a generic capacity model was proposed. These capacity models depend on the base capacity which is modified by several factors. These factors that were identified to affect capacity are the heavy vehicles, the driver population, the light conditions, the inclement weather, the work activity on site, the configuration of the lane closure, and the rain. The first model which is multiplicative is as follows:

$$C = C_b \times f_{HV} \times f_{d1} \times f_{d2} \times f_w \times f_s \times f_r \qquad (2\text{-}9)$$

Where:

C= Work zone capacity (vphpl),

C_b = Base work zone capacity (pcphpl),

f_{HV} = Adjustment factor for heavy vehicles (from HCM2000),

f_{d1} = Adjustment factor for off-peak weekday driver population (off-peak = f_{d1}, else=1),

f_{d2} = Adjustment factor for weekend driver population (weekend = f_{d2}, else=1),

f_w = Adjustment factor for work activity (work activity=f_w, no work activity=1),

f_s = Adjustment factor for side of lane closure (left lanes closed=f_s, right lanes closed=1),

f_r = Adjustment factor for rain (rain= f_r, no rain=1).

Optimization was used to derive the parameters of the model and the base capacity. The optimization procedure resulted in the following parameter values: C_b = 2,050, E_{HV}= 2.778, f_{d1}= 0.961, f_{d2}= 0.825, f_w= 0.966, f_s= 0.943, f_r= 0.976 and the coefficient of determination was 0.63.

The second model was derived through regression and is given by the following equation:

$$C = 1964 - 20.9P_{HV} - 82D_1 - 352D_2 - 172W - 121S - 71R + 55SD_1 + 185WD_2 + 58SD_2 + 107RD_2 \quad \text{(2-10)}$$

Where:

C = Work zone capacity (vphpl),

P_{HV} = Percentage of heavy vehicles in the traffic stream,

D_1 = Off-peak weekday driver population (off-peak=1, else=0),

D_2 = Weekend driver population (weekend=1, else=0),

W = Work activity at site (work activity =1, no work activity=0),

S = Side of lane closure (left lanes closed=1, right lanes closed=0),

R = Rain (rain=1, else=0), and

SD_1, WD_2, SD_2, and RD_2 = Interaction terms.

The coefficient of determination for the above equation is 0.68 and the model suggests that the base capacity is 1964 pcphpl.

The generic capacity model has a multiplicative format, given by the equation below, and it also includes interactions between the variables.

$$C = C_b \times f_{HV} \times f_d \times f_w \times f_s \times f_r \times f_l \times f_i \quad \text{(Eq. 2-11)}$$

Where:

C = Work zone capacity (vphpl),

C_b = Base work zone capacity (pcphpl),

f_{HV} = Adjustment factor for heavy vehicles,

f_d = Adjustment factor for driver population,

f_w = Adjustment factor for work activity,

f_s = Adjustment factor for side of lane closure,

f_r = Adjustment factor for rain,

f_l = Adjustment factor for light condition, and

f_i = Adjustment factor for non-additive interactive effects.

The recommended values of the proposed capacity model can be found in Al-Kaisy and Hall (2003). Although the model includes several geometric, traffic and environmental conditions it does not address the impact of lane width and it is recommended that for non-ideal lane widths the capacity should be adjusted in the same proportions as given in the HCM procedures for normal freeway sections. Furthermore, this model was developed from data taken from long-term work zones which typically induce higher capacities than short-term work zones as the commuters become familiar with the work zone configuration.

The same authors examined the effect of driver population at freeway reconstruction zones (Al-Kaisy and Hall, 2001). Driver population refers to the mix of driver types in a traffic stream by trip purpose. Two aspects of driver characteristics are viewed as being related to the trip purpose. The first is the familiarity of drivers with the facility and its environs, which is thought to affect the efficiency of facility use by drivers. The second and less evident aspect is the value of time perceived by drivers for a specific trip purpose and its potential effect on driver behavior and, consequently, on the efficiency of use of a highway facility. On the basis of a factor of 1.0 for commuter traffic, a driver population factor of 0.93 was estimated for the afternoon peak period and a driver population factor of 0.84 was estimated for weekends. Also, the driver population factor is likely responsible for a capacity reduction on weekends compared with the capacity on weekdays. This capacity reduction was 12 percent in one direction of travel and 17 percent in the other direction.

Ping and Zhu (2006) used CORSIM to derive work zone capacities under various network configurations. The parameters tested for their experimental design consisted of the number of open lanes, the free-flow speed in the normal freeway segment and in the work zone, grade, trucks percentage, location of warning sign and location of closed lane. The derived capacity was found to range between 1,320 vphpln and 1,920 vphpln depending on the level of each parameter. The authors developed the following two capacity regression models:

$$Capacity = 1617 + lane + value(ffs) * wffs - 11.43 * grade$$
$$- 13.41 * truck + 0.008 * warning \qquad (2\text{-}12)$$
$$R^2 = 0.762$$

Where:

lane = -4.9 when lane configuration is 2, 1, 147.4 when lane configuration is 3, 2, 0.0 when lane configuration is 3, 1

value(ffs) = 0.48 when *ff s*= 55 mi/h, 0.50 when *ff s*= 60 mi/h, 0.56 when *ff s*= 70 mi/h

$$Capacity = 1619 + lane + value(ffs) * wffs - 10.2 * grade - 12.0 * truck$$
$$+ truck * lane + grade * lane - 1.97 * truck * grade \qquad (2\text{-}13)$$
$$R^2 = 0.944$$

Where:

lane = -3.6 when lane configuration is 2, 1, 177 when lane configuration is 3, 2, 0.0 when lane configuration is 3, 1

value(ffs) =0.48 when *ff s*= 55 mi/h, 0.50 when *ff s*= 60 mi/h, 0.55 when *ff s*= 70 mi/h

*truck*lane* =-0.17 when lane configuration is 2, 1, *truck*lane* = -3.95 when lane, configuration is 3, 2

*truck*lane* =0.0 when lane configuration is 3, 1, *grade*lane* =-0.93 when lane, configuration is 2, 1

*grade*lane* =-19.7 when lane configuration is 3, 2, *grade*lane* = 0.0 when lane, configuration is 3, 1.

The two models were compared with Kim's capacity estimation model (2001) and some field data, after making some assumptions necessary for the comparison. The results show that this model performs better than Kim's model.

2.4. Work Zone Analysis Software

Most computer models, such as *Queue and User Cost Evaluation of Work Zones* (QUEWZ), have used capacity as a key input parameter to help quantify queue length and delay, and to calculate delay costs. Memmott and Dudek (1984) developed QUEWZ to estimate user costs incurred due to lane closures. The software is designed to evaluate work zones on freeways, but is also adaptable to different types of highways (Associated

Press, 1989). The model analyzes traffic flow through lane closures, and helps plan and schedule freeway work-zone operations by estimating queue lengths and the additional road user costs. The costs are calculated as a function of the capacity through work zones, average speeds, delay through the lane closure section, queue delay, changes in vehicle running costs, and total user costs. Since its development, QUEWZ has undergone two major modifications. One of these is the ability to determine acceptable schedules for alternative lane closure configurations—crossover or partial lane closure—based on motorist-specified maximum acceptable queue or delay. The second of these improvements is the development of the algorithm that can consider natural road user diversion away from the freeway work zone to a more desirable, unspecified, alternate route (Associated Press, 1989).

Another popular software package is QuickZone (Federal Highway Administration, 2000), which was released in February 2005 in its full version. QuickZone 2.0 is an enhanced version of QuickZone, an Excel-based software tool for estimating queues and delays in work zones. The maximum allowable queues and delays are calculated as part of the procedure in optimizing a staging/phasing plan and developing a traffic mitigation strategy. As a result, lane closure schedules are recommended to minimize user costs. This is a quick and easy method, with a user-friendly, concise spreadsheet setup. Within the software, however, the PCE factor is fixed at 2.3 for all heavy vehicles, and the capacity of the work zone is fixed at 1200 pcphpl. This PCE value—2.3—is higher than the value reported in the HCM for basic freeway segments (Chapter 23) for level terrain, which is 1.5. This 1.5 value is the same one that is applied to the heavy vehicle adjustment factor for short-term freeway work zones in Chapter 22. The capacity value, fixed at 1200 pcphpl, is also quite conservative. As a result, delays estimated using this software would typically be higher than those estimated using the HCM 2000 analysis.

2.5. Early and Late-Merge Maneuvers Upstream of a Work Zone

This section discusses types of merge strategies that have been developed to improve work zone operations. Examples of such strategies include “early merge” and “late merge”. These can be implemented in the field using physical barriers or double-lane markings, or even with the presence of a law enforcement vehicle. Variations of

these include the dynamic early merge (used in Indiana, known as the Indiana Lane Merge) and dynamic late merge. The dynamic early merge is intended to provide warning and merge signs at variable distances upstream of the back of the queue. This upstream distance depends upon the queue length, which is sensed by sonic detectors and enforced with flashing *do not pass* signs. The dynamic late merge uses the late merge strategy only when congestion is present, otherwise conventional merging is used. The Nebraska Department of Roads (NDOR) refers to conventional merging as NDOR Merging. Another merging strategy, called Zip merging, is primarily used in Europe and was developed in the Netherlands. With this strategy, each driver does not change lanes until a fixed distance from the lane closure, alternating between those in the through lane and the closed lane. Technology has further allowed for improvements in merging and work zone safety with the creation of "Smart" Work Zones. These are capable of detecting congestion and providing real-time advisory information to travelers encouraging them to divert to an alternate route. The remainder of this section discusses literature related to the relationship between these strategies and capacity of the work zone.

McCoy *et al.* (1999) identified twelve alternative strategies to control traffic speeds and merging operations in advance of lane closures. Field evaluations of the NDOR Merge and two alternatives, the Indiana Lane Merge and Late Merge, were conducted. Based on the data collected, a benefit-cost analysis showed the cost-effectiveness of four alternative traffic control strategies relative to the NDOR Merge. The four alternatives evaluated were: (1) the Indiana Lane Merge, (2) Late Merge, (3) Enhanced Late Merge, and (4) “Smart” Work Zone. The NDOR Merge was found to be the most cost-effective merge control strategy for directional average daily traffic values below 16,000 to 20,500 vehicles, depending on the percentage of trucks. The Late Merge, Enhanced Late Merge, and “Smart” Work Zone were the most cost-effective alternatives at higher traffic volumes.

An attempt to evaluate the effects that late mergers have on work zones is reported by Maze and Kamyab (1999) in their *Work Zone Simulation Model*. During the summer of 1998, traffic flow data were collected at merge areas of work zone lane closures on freeways in rural Iowa. Using video image processing technology, the merge areas were observed from the point of the flashing merge arrow board to the point where the

bottleneck begins—the site of construction. Virtual detectors were used to collect traffic flow rates, speeds, and headways at the two ends of the merge area. Travel times were also obtained by the noted vehicles' arrival and departure times. These data were used to develop a microscopic simulation model specifically designed to examine the effects that slow-moving vehicles and late mergers have on delay and average speed. The model was developed for a work zone with a two-to-one configuration—two lanes reduced to a single lane (Maze and Kamyab, 1999). The model can estimate delay, as well as the length and dissipation time of the queue. The authors report that the length of the queue is overestimated, because the model places 97 percent of vehicles in the through lane, rather than distributing them more evenly over both through and merge lanes. For that reason, queue length estimates are not included in the model and further data collection and model enhancements are recommended before accurate queue length estimates can be obtained.

In a study by Walters and Cooner (2001), it is reported that stress levels are reduced in 50% of drivers when bottleneck and work zone improvements are made. Researchers tested the late merge concept, originally developed in Pennsylvania, at a work zone on Interstate 30 in Dallas, Texas. The report indicates that the Late Merge concept is feasible on an urban freeway where three lanes are reduced to two (Walters and Cooner, 2001). Further testing of this concept and other innovative merge strategies such as Early and Zip Merging is recommended to determine the most efficient, safe, and least stressful method of encouraging merging at lane closures.

The late merge strategy was also assessed by Beacher *et al.* (2005) in a field test conducted over several months. Conducted on a primary route in Tappahannock, Virginia, a 2-to-1 lane closure was analyzed and the results compared with those of traditional work zone lane closure strategies. Although an increase in throughput was observed, the increase was not statistically significant. Similarly, time in queue decreased, but the decrease was not statistically significant (Beacher *et al.*, 2005). The report concludes that despite the lack of statistical significance, more drivers were present in the closed lane, indicating a positive response to the late merge signs. The authors indicate potential statistical biases (such as driver population and site-specific characteristics) may have had error-inducing effects on the analysis. In conjunction with

the above field evaluation, the late merge concept was evaluated by comparing it to traditional traffic control using a full factorial analysis. Results of the computer simulations showed that the late merge produced a statistically significant increase in throughput volume versus the traditional merge for the 3-to-1 lane closure configuration across all combinations of analysis factors. Although the 2-to-1 and 3-to-2 configurations did not show significant improvement in throughput overall, it was found that as the percentage of heavy vehicles increased, the late merge did foster higher throughput volumes than traditional traffic control. The simulation results indicated that the late merge may not provide as much of a benefit as previous studies had indicated, and that application of the late merge may be more appropriate in situations where heavy vehicles comprise more than 20 percent of the traffic stream (Beacher *et al.*, 2005).

2.6. Other Research Related to Freeway Work Zones

This section summarizes literature review findings related to other aspects of work zone analysis, including safety, traffic diversion, and delay and queuing estimation.

2.6.1. Safety

Generally, crash rates are higher in work zones than on stretches of highway under normal operation, and there are several articles in the literature assessing safety around work zones. For example, Pal and Sinha (1996) developed a model that systematically selects appropriate lane closure strategies based on predicted crash rates. Each lane closure strategy was evaluated through consideration of the additional travel time, additional vehicle operating cost, safety, traffic control cost, and contractors' needs. Opinion surveys of the subcontractors at each of the project sites were conducted which identify four subcomponents involved in their perceived need: worker safety, equipment safety, work productivity, and work quality. The data used were collected from 17 Interstate 4R projects in Indiana. Information obtained from the INDOT included type of lane closure strategy used, duration of closure, length of section closed, and traffic data: average daily traffic, hourly variation in volume, directional splits, vehicle mix, and project costs. Also, the number of crashes was obtained for several years during the

construction activities at each site as well as for normal operating conditions at the same sites. Pal and Sinha implemented the analytic hierarchy approach to synthesize the study results. Computer software was developed that can be used to select an appropriate lane closure strategy based upon the described parameters. The user-required inputs are work zone length, traffic volume, duration of the project, crash rate under normal conditions, and total project cost. The software applies regression models to estimate the user-travel time and vehicle operating cost, traffic control cost, and expected number of crashes. This procedure is recommended for selecting between a partial or crossover lane closure with statistically sufficient accuracy (Pal and Sinha, 1996).

2.6.2. Traffic Diversion

Ullman (1996) explored how natural diversion affects traffic volumes at the exit and entrance ramps upstream of temporary work zone lane closures on high volume, urban Texas freeways. Data collection was scheduled to begin before the start time of the lane closure and continued through the time when the lane closure was removed and the queues on the freeway were completely dissipated. These field studies were limited to urban freeways with frontage roads, and of primary interest was observation of traffic operations at the two facilities before, during, and after the work activity. Data were collected and studies constrained to within the midday off-peak period (9:00am to 4:00pm), as lane closures are prohibited by law during peak traffic periods in Texas. The following performance measures were obtained from the data collection activities:

- Changes in volumes on the freeway, frontage road, and ramp volumes hour by hour during lane closure
- Freeway and frontage road travel times
- Propagation of queuing on the freeway upstream of the lane closure over time

Ullman (1996) discusses further the concept of natural diversion as well as the requirements for a motorist to make a conscious decision in avoiding the congestion. The results of the study show that queue stabilization can occur because flow conditions within the queue are not uniform and tend to change as a function of the distance from

the beginning of the lane closure bottleneck. The author indicates that these changes can be explained by shock wave theory within a traffic stream, and that the stabilization results are consistent with this theory. Thus significant amounts of diversion at temporary closures can have extensive effects upstream of the bottleneck. This queue stabilization results in lower user delay values. Then, additional costs of usage can be estimated using regular input-output or shock-wave analysis based on historical traffic volumes. Another important result is that these temporary lane closures do not only affect the entrance and exit ramps immediately upstream of the closure, but can extend significantly further than previous models have predicted. Ullman (1996) recommends that the potential effects of diversion on alternative routes should be considered a significant distance upstream of the temporary work zone.

2.6.3. Delay and Queuing

A large part of selecting an appropriate traffic management strategy is work-zone related traffic delay. Martinelli (1996) provided a comprehensive and detailed estimation of traffic delay due to a freeway work zone, where the roadway in one direction is closed and the traffic is diverted to share the roadway in the opposite direction. The total delay was dissected into speed reduction delay and congestion delay. Various methods were developed to predict speed reduction delay for several roadway conditions. A mathematical model was developed to determine the length of the queue upstream of a work zone and a technique was created to predict daily congestion delay under any given condition. Alternative roadway closure patterns along the length of a given project were assessed in terms of traffic control cost and additional road user costs. The optimal work zone length for a given project was examined. Procedures were developed to determine the optimal work zone length.

A study conducted by Chien and Chowdhury (2002) indicates that delays are always underestimated when using deterministic queuing theory. Therefore, despite the costs associated with many simulation runs, the report recommends simulation as a viable alternative, when combined with queuing theory. The authors developed a methodology that approximates delays by combining CORSIM simulation data and deterministic queuing while considering various geometric conditions and time-varying traffic

distribution. The traffic flow distribution over time and the work zone capacity are the two major inputs to the model. The queuing delay is then calculated from the estimated queue lengths of the previous time period. Delay values from work zone traffic operations on a segment of I-80 in New Jersey were predicted using deterministic queuing, CORSIM simulations, and the proposed model. Because the model is dependent on the accuracy of the CORSIM delay curve, extensive calibration and validation of CORSIM may be required.

Schnell et al. (2002) studied whether commercially available traffic simulation models could be calibrated to yield accurate queue length and delay time predictions for planning purposes in freeway work zones. Four work zones on multilane freeways were selected by ODOT for collection of the calibration data. Traffic flow video records were obtained at the four selected work zones by two ODOT video recording vans equipped with 15-m masts. Traffic flow parameters were extracted from the video records with the Mobilizer-PC software package. The traffic simulation and prediction tools investigated included the Highway Capacity Software (HCS), Synchro, CORSIM (under ITRAF and TRAFVU), NetSim, and a macroscopic model called QueWZ92. Simulation models were constructed with all models for the selected work zones, and the simulated queue lengths and delay times were compared with the data extracted from the field data with Mobilizer-PC. The results of this study indicated that the microscopic simulation packages could not be calibrated to the oversaturated conditions that existed at the work zones. The calibrated microscopic simulation packages underestimated the length of the queues that formed in the real world. The macroscopic QueWZ92 produced more accurate estimates than did the microscopic packages.

Ullman and Dudek (2003) described a new theoretical method developed to predict more accurately queue lengths upstream of a temporary work zone lane closure. The authors state that the queues and delays that develop upstream of closures in urban areas are much shorter than those estimated using historical traffic volume data. Rather than propagating, these queues often stabilize upstream over the duration of the lane closure (Ullman and Dudek, 2003). The new formulation is based on a traditional macroscopic perspective of traffic flow on a section in which flow, speed, and density are known. A

new, permeable pipe analogy is presented to represent the work zone's creation of a stimulus for diversion. The mathematical components of the model include:

- A shock wave theory to model the propagation of the traffic queue
- An energy model of traffic flow that illustrates the reduction in speed and its effect on natural diversion tendencies
- A mathematical analogy of urban roadway section as fluid flow through a section of permeable pipe

This macroscopic model predicts queue stabilization at some point, so overestimation of queue lengths does not occur. The authors recommend that more work is required to further comprehend the stimuli that affect permeability of a corridor, and to develop a model that can estimate what this level of permeability may be for a given set of conditions.

Chitturi and Benekohal (2005) performed a study on the effects of narrowing lanes and reduced lateral clearances on the free-flow speeds (FFS) of cars and heavy vehicles in work zone areas. The findings report that the reductions in FFS in work zones due to narrow lanes are higher than the reductions given in the HCM for normal freeway sections, although the reduction due to narrow lateral clearance was comparable. Because of the wider dimensions of heavy vehicles, the reduction in FFS of heavy vehicles is greater than that of passenger cars. As a result, heavy vehicles are affected more adversely than passenger cars, and it is recommended that the speed reductions due to narrow lanes should take into account the percentage of heavy vehicles in the traffic stream. The reductions for passenger cars and heavy vehicles have not been quantified separately because of the limited data for heavy vehicles. Until such data become available, it is recommended that 10, 7, 4.4 and 2.1 mi/h be used for speed reduction in work zones for lane widths of 10, 10.5, 11 and 11.5 ft respectively (Chitturi and Benekohal, 2005).

2.7. Summary and Conclusions

The literature review showed that there have been several models developed to estimate freeway work zone capacity. Different approaches have focused on different aspects of work zone capacity. Some methods focus on the geometric aspects of the work zone, such as lane width, presence of interchanges, etc., while others focus on traffic stream parameters, such as driver population, and presence of trucks in the traffic stream.

Work zone capacity base values obtained around the country have varied since the introduction of Krammes and Lopez's Texas-based recommendation of 1600 pcphpl (which is also used in the HCM 2000). The Iowa-based study by Maze produced a model that recommended base values ranging from 1374 to 1630 pcphpl, depending on the location within the state. Sarasua's model estimates a value of 1460 pcphpl for South Carolina, while the QuickZone 2.0 software implements a conservative 1200 pcphpl in its analyses. A greater capacity in the range of 1,853 – 2,252 pcphpl is suggested by Al-Kaisy and Hall (2003) for long-term work zones.

The remainder of this section summarizes the conclusions of the literature review with respect to a) the accuracy and comprehensiveness of the HCM 2000 freeway work zone analysis, and b) all geometric, traffic, and environmental factors considered in various capacity analysis methodologies.

2.7.1. Assessment of the HCM 2000

The work zone methodology of the HCM 2000 is based primarily on the study performed by Krammes and Lopez (1994). The methodology uses a base capacity of 1,600 pcphpln however other research and analysis software have recommended lower capacity values (Maze et al., 2000; Sarasua et al., 2004; FHWA, 2000). The HCM 2000 methodology incorporates the effect of heavy vehicles on capacity, however research performed by Al-Kaisy and Hall (2003) suggests that the passenger car equivalency factors are larger at long-term work zones.

Work zone capacity may decrease with increasing work zone intensity, and the HCM 2000 includes a modification of the base capacity value to account for the intensity of the work zone activity. No guidelines are provided however with respect to the

numerical value of that factor, and it is recommended that the engineer apply their professional judgment to evaluate the effect of work intensity on work zone capacity.

Lastly, the methodology states that if there is an entrance ramp within 500 ft downstream of the beginning of the full lane closure the ramp will affect the capacity of the work zone. However, no modification factors are provided for the ramp proximity adjustment, and again it is recommended that the engineer use their judgment in applying this factor.

2.7.2. Factors Considered in Estimating Work Zone Capacity

Previous work zone capacity models have incorporated various geometric, traffic, and environmental factors. These are:

- Presence of ramps along the work zone
- Number of closed lanes
- Lane width
- Lateral clearance
- Grade of roadway segment
- Passenger-car equivalency factor and heavy vehicle presence
- Driver population along work zones (Al-Kaisy and Hall, 2003)
- Merge strategies (late vs. early merge)
- Light conditions (Al-Kaisy and Hall, 2003)
- Effect of rain (Al-Kaisy and Hall, 2003)
- Intensity of work activity

The current FDOT procedure only considers geometric factors in its capacity reduction model. It does not consider traffic and environmental factors such as the driver population, and intensity of work activity.

3. METHODOLOGY OVERVIEW AND SIMULATED CAPACITY ESTIMATES

The research approach followed in this research is based on simulation. The initial intent of the study was to use a combination of field data and simulation to obtain the capacity of various work zone configurations, and based on these develop capacity estimation models. No appropriate locations were identified in Florida however to collect field data, primarily because recently FDOT has minimized the work zone activity during the day; the traffic during the night hours is much lighter, and therefore capacity conditions are not regularly reached. Simulation modeling cannot replace field data collection; it can, however, offer insights into the relative capacities under different geometric configurations and traffic stream scenarios.

CORSIM (version 5.1) was used to develop a comprehensive database which was used in the analytical model development. Models were developed for three types of work zone configurations (2-to-1, 3-to-2, and 3-to-1 lane closures). Two different types of models were developed for each lane closure configuration; a planning model and an operational model. The planning model is the simplest one and it applies when a capacity estimate is required, but the work zone is not in place. The operational model requires more data as input, and it may be used for estimating the capacity of an existing work zone.

This section describes the simulation model development for determining the capacity of freeway work zones under various traffic, geometric, and control conditions. A large matrix of scenarios was created considering many of the factors identified in the literature as having an impact on freeway work zone capacity. Data such as speeds, vehicle lane distributions, time headways, and maximum throughput (i.e., capacity) were obtained from the simulation output files to assess the relationships between input parameters and the capacity through the work zone lane closure. The remainder of this chapter discusses the simulation package selected, presents the freeway work zone scenarios simulated, and finally provides capacity estimates for these scenarios.

3.1. Simulator Selection

The software package *CORSIM* was selected for use in the study. The software, originally developed by FHWA, has been widely used and validated in the past twenty years, and it is available to the University of Florida through McTrans, allowing for a high level of software support in understanding the software's algorithms. *CORSIM* has the ability to simulate freeway sections with its integrated model *FRESIM 5.1,* which has been updated with an improved *FRESIM* engine (Owen *et al.,* 2000). *FRESIM* allows for the analysis of incidents on freeways as either lane closures, lane drops, or a shoulder incident, which can be simulated by applying the "rubbernecking factor" to the length of the segment affected. The literature reports that older versions of *FRESIM* were unreliable when simulating lane closures, as it did not account for slow-moving vehicles that severely impacted the queue lengths in the field (Dixon et al., 1995). According to the conclusions of that research, the large queues observed in the field were due to the existence of one or two vehicles in a data set that traveled inexplicably slowly through the work zone—much slower than the distribution of speeds in a simulation—and thus caused a queue buildup that did not appear in the simulator. As a result, *FRESIM* underestimated the delay because these vehicles did not exist in the simulation runs. Therefore, the behavior of vehicles at the lane closure was not replicating actual conditions (Dixon *et al.*, 1995). The 1995 report used *FRESIM* 4.5, and since then, various improvements have been implemented which have led to the *CORSIM* version 5.1. Therefore the research team evaluated this new version of the software to assess its capabilities and limitations in simulating freeway work zones. In the process of developing these scenarios the research team identified several improvements that can be implemented in CORSIM to improve its algorithms for simulating freeway work zones. These are identified and discussed later in this chapter.

There is no explicit simulation of a work zone in *FRESIM* (the freeway simulation component of CORSIM); instead, there are two techniques that allow *FRESIM* to approximate a work zone lane closure. The first of these is identified as a *lane drop.* The software allows up to three lane additions or drops to occur within the same link. To simulate a right-lane closure, the rightmost lane would be *dropped* at a point specified at a distance from the upstream node, and then it would be added at another specified point

designated by providing the distance from the upstream node. The second technique that can be used to simulate a lane closure is identified as an *incident.* The user can create multiple incidents during different times of the simulation on the same link. Such incidents include capacity reduction due to a shoulder incident (requires a rubbernecking factor) and/or blockage at the point of the incident. Each of these can occur simultaneously and on several lanes if desired. Both techniques require as input the distance to the warning sign upstream indicating that a lane closure is approaching. Neither technique takes into consideration the taper section prior to the lane closure.

To evaluate which of the two techniques would be used in this study, a test network was created to compare the results from each technique. The test network was also used to evaluate whether closing the right lane produced the same results as closing the left lane of the freeway. It was concluded that the performance of the freeway segment when the left or right lane were closed, and when the incident or lane drop techniques were used, were very similar. This might not be the case in the field, however, and it is recommended that future research should evaluate this assumption. With respect to the simulation scenarios being created, it was concluded that there was no need to consider separately left and right lane closures. Also, since the two techniques of simulating a lane closure produce almost identical values, the technique which offers more options in the simulation, incident analysis, was selected to be used in all simulation runs. Most importantly, the incident technique allows for the effects of "rubbernecking" to be implemented along the lane closure, which can replicate the intensity of work zone activity.

Lane distribution is an input into CORSIM 5.1, and it determines the rate at which vehicles are generated at each lane; however vehicles eventually choose their lanes based on traffic conditions, and the initial lane distributions do not necessarily remain for long after the vehicles' entrance into the simulated network. The degree to which vehicles make these lane changes can be controlled by modification of the driver behavior parameters within the software. When vehicles pass the simulated work zone warning sign, they react and merge based on existing queues, gaps, travel speeds, and driver aggression level.

3.2. Freeway Work Zone Simulated Scenarios

This section presents the simulated test network, the input variables and scenarios studied, input modeling assumptions, and the outputs obtained from the simulation.

3.2.1. Simulated Test Network

Figure 1 presents the simulated test segment to be studied. The configuration was designed so that appropriate output data may be obtained by the simulator, but it can also be considered in the future if field data are to be collected in the vicinity of a work zone.

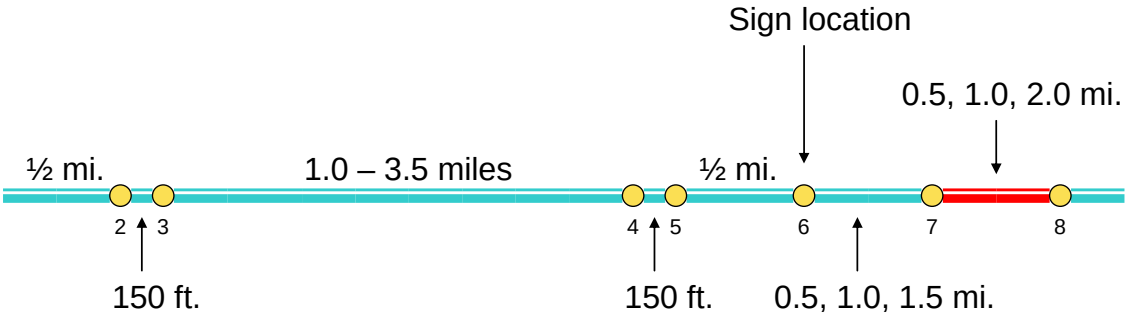


Figure 1. Sketch of the Simulated Freeway Network

There are a total of nine nodes (2-8 displayed in yellow). The feeder node is located 0.5 miles upstream of node 2. CORSIM provides output information by link, therefore several links were created to obtain statistics at selected locations along the freeway test section. The characteristics and function of each link are as follows:

- Link (2,3) – 150 feet in length; used to verify headway values being collected by the data station (located halfway between nodes 2 and 3)

- Link (3,4) – Length is variable from 1 to 3.5 miles; created to give vehicles adequate time for discretionary lane changes an adequate distance upstream of the work zone; variable distance is due to variability in link (6,7) so that the length of the entire network can be kept constant (see discussion regarding link (6,7) below)

- Link (4,5) – 150 feet in length; created to verify headway values being collected by the data station (located halfway between nodes 4 and 5)

- Link (5,6) – Always 0.5 miles in length; created to observe the driver behavior immediately upstream of the work zone warning sign

- Link (6,7) – Length varies between 0.5 and 1.5 miles; this is the distance from the work zone to the upstream warning sign. The variability of this distance is one reason for the variability in the length of Link (3,4). The overall network length is kept constant, so Link (3,4) is either lengthened or shortened when Link (6,7) is either shortened or lengthened, respectively

- Link (7,8) – Length varies between 0.5 and 2.0 miles; this is the lane closure link. There is a data collection station placed halfway between nodes 7 and 8, in order to verify headway data on that link.

3.2.2. Input Variables and Simulation Scenarios

The variables selected to be tested as inputs in the simulation scenarios are:

- Lane configurations – 2/1, 3/2, 3/1 (approaching number of lanes/open number of lanes though the work zone)

- Volume distributions (percentages) are as follows:

  (2/1 closure) – 50/50, 40/60, 30/70 (left/right)

  (3/2 and 3/1 closure) – 20/40/40, 30/30/40, 30/40/30 (left/middle/right)

These input volume distributions were selected by considering reasonable operating conditions for a free-flowing freeway network. For example, a 20/80 input distribution was not used because it is unlikely that such a distribution would be observed in the field.

- Distance of Sign Upstream of Work Zone – 0.5 mi, 1.0 mi, 1.5 mi

The warning sign placement upstream of the work zone is to be at a distance no less than 0.5 miles for facilities where the posted speed limit is 45 mi/h or more (Design Standards, Index 600, Sheet 4 of 10). Two additional configurations (1.0

mi and 1.5 mi) are investigated, to evaluate the effects of the distance of the warning sign upstream from the work zone.

- Presence of trucks (percentage) – 0%, 10%, 20%

The presence of trucks ranges from zero to twenty percent, again limited by the consideration of reasonable, or likely, operating conditions.

- Rubbernecking factor (percentage) – 0%, 15%, 25%

The rubbernecking factor ranges from zero to twenty-five percent, and is used to model any type of incident on the shoulder or the presence of law-enforcement vehicles or general road work equipment. Because there is no literature on the effect of the rubbernecking factor, several simulation runs were made to identify and understand the way this factor affects the capacity of the roadway.

Another factor originally considered as an input variable was the length of the work zone. The maximum length of the work zones is limited by the FDOT Design Standards for 2006. These state that for any facility where the speed limit is greater than 55 mi/h, the length of the work zone shall not exceed a length of 2 miles (Design Standards, Index 600, Sheet 2 of 10). Preliminary simulation experiments showed that there is no relationship between the length of a work zone and the capacity throughput. As the length of the work zone increases, no significant variation in vehicular flow was observed through the lane closure. This variable was therefore not considered in the simulation experiments.

Table 1 summarizes the simulation scenarios studied. A total of 243 scenarios were created, and each was been simulated for 15 runs, giving a total of 3,645 output files, or data points for further analysis. It was calculated that 10 simulation runs per scenario are required for a 15% error tolerance in the sample mean, and thus to further increase final model precision, 15 runs per scenario were simulated.

Table 1. Input Parameters for Freeway Work Zone Simulations

Variable	Level 1	Level 2	Level 3	Description
Lane configuration	2-to-1	3-to-2	3-to1	total-to-open lanes in work zone
Lane distributions	50 / 50	40 / 60	30 / 70	left % / right %
	20 / 40 / 40	30 / 30 / 40	30 / 40 / 30	left % / middle % / right %
Upstream sign distance	0.5	1	1.5	Miles
Truck %	0	10	20	percentage
Rubber %	0	15	25	percentage

In addition to the work zone scenarios described above, non-work zone segments were simulated, to be able to compare the relative capacity drop when a particular work zone configuration is installed. The non-work zone scenarios tested have the same input values as the corresponding work zone segments, with the differences being that the lane closure and the upstream sign are removed and the rubbernecking factor has zero value. Additionally, the free-flow speed along the link with the work zone was changed back to 65 mi/h (it was reduced to 55 mi/h in the work zone scenarios). Table 2 provides the input parameter values used for the simulation of the non-work segments.

Table 2. Variation of Input Parameters for Non-Work Zones

Variable	Level 1	Level 2	Level 3	Units
Lane configuration	2	3		total number of lanes in non-work zone
Lane distributions	50 / 50	40 / 60	30 / 70	left % / right %
	20 / 40 / 40	30 / 30 / 40	30 / 40 / 30	left % / middle % / right %
Upstream sign distance	0.5	1	1.5	miles
Truck %	0	10	20	percentage

To derive the capacity values for the non-work zone segments the input demand for all scenarios was 9,999 veh/h, similarly to the work zone scenarios.

3.2.3. Modeling Assumptions—Input Fixed Values

This subsection summarizes the modeling assumptions and inputs used in the simulated scenarios, including free-flow speed, demand, and other considerations. The free-flow speed used throughout all analyses was 55 mi/h through the work zone; this value cannot be lower than 10 mi/h less than the mainline free-flow travel speed (Design Standards, Index 600, Sheet 3 of 10). Because the facility being modeled can be a state highway or freeway facility, a free flow speed of 65 mi/h is used for segments upstream and downstream of the work zone.

The upstream demand was set at 9,999 veh/h; this was the value recommended by CORSIM developers to ensure that breakdown will indeed occur similarly in all scenarios. Regarding truck traffic *CORSIM* provides three choices: not biased or restricted to any lanes, biased to a set of lanes, and restricted to a set of lanes. The lanes to which a truck is biased can be specified. For the purposes of this project trucks are modeled as biased to traveling on the rightmost lane of the freeway, which is more prevalent in the State of Florida.

3.2.4. Simulation Output

Various output data were collected from the simulations to model the effects of geometric, traffic, and work zone characteristics on work zone capacity. The following outputs were collected from the simulation experiments:

- Volumes by lane through link (7,8); the maximum volumes represent capacity
- Vehicle lane distributions through all links
- Speeds by lane through all links
- Number of lane changes through all links

3.3. Capacity Estimates Using Simulation

This section summarizes the capacity obtained by the simulator for both work zone and non-work zone freeway segments. For each lane closure configuration the corresponding capacity values are provided as a function of the percentage of trucks and the lane distribution. A range of capacity values is given for all work zone segments, based on the various combinations of the remaining factors, such as the rubbernecking factor and the upstream sign distance. The capacity ranges for each lane closure configuration along with average capacity values (in vehicles per hour per lane) are provided in Table 3. As expected, the presence of trucks has a significant impact on the capacity of the work zone. The lane distribution upstream of the work zone does not appear to affect the capacity significantly. The same can be concluded with respect to the type of lane closure (e.g., 2-1, vs. 3-1). The effect of the rubbernecking factor however appears to be more significant, as evidenced by the relatively wide range between the minimum and maximum values shown in Table 3.

Table 3. Capacity Values (vphpl) for Various Freeway Work Zone Configurations

Lane Closure	Lane Distribution	Truck %								
		0%			10%			20%		
		Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.
2-to-1	50/50	1378	1964	1568	1336	1939	1562	1299	1720	1458
	40/60	1376	1979	1564	1346	1977	1563	1292	1756	1461
	30/70	1379	1968	1569	1340	1982	1566	1288	1726	1456
3-to-2	20/40/40	1374	2093	1605	1336	1894	1539	1299	1719	1453
	30/30/40	1372	2091	1604	1335	1894	1540	1291	1722	1450
	30/40/30	1380	2097	1610	1331	1892	1536	1298	1732	1454
3-to-1	20/40/40	1380	1776	1562	1354	1844	1545	1311	1728	1467
	30/30/40	1363	1771	1557	1350	1849	1546	1311	1719	1464
	30/40/30	1373	1755	1557	1351	1845	1548	1299	1718	1460

The capacity values for the non-work zone segments are presented in Table 4. The trends in those capacity values are similar to those reported for the work zone scenarios.

Table 4. Capacity Values (vphpl) for 2-Lane and 3-Lane Non-Work Zone Segments

Number of Lanes	Lane Distribution	Truck %		
		0%	10%	20%
2 lanes (veh/h/ln)	50/50	2154	1869	1685
	40/60	2164	1859	1660
	30/70	2171	1869	1683
3 lanes (veh/h/ln)	20/40/40	2151	1885	1646
	30/30/40	2149	1879	1638
	30/40/30	2164	1888	1637

Based on the capacities for the work zones and the non-work zones from the simulation models it is possible to estimate the capacity reduction that is due to the presence of a work zone for the three lane closure configurations studied. Table 5 presents these capacity reduction ratios. It can be concluded that in the simulator, the capacity is more sharply reduced when there are no trucks through the work zone. The capacity reduction factors when no trucks are present are 0.63 to 0.97, while they range from 0.79 to 1.06 when trucks are 20%. The values above 1.0 indicate that the capacity with the work zone is higher than that without the work zone, which is due to random variation in the simulated observations, and is not statistically significant.

Table 5. Capacity Reduction Ratios for 2-Lane and 3-Lane Freeways

	Lane Distribution	Capacity Reduction Ratios								
		0% Trucks			10% Trucks			20% Trucks		
		Min	Max	Avg.	Min	Max	Avg.	Min	Max	Avg.
2-Lane	**50/50**	0.64	0.91	0.73	0.71	1.04	0.84	0.77	1.02	0.87
vs.	**40/60**	0.64	0.91	0.72	0.72	1.06	0.84	0.78	1.06	0.88
2-to-1	**30/70**	0.64	0.91	0.72	0.72	1.06	0.84	0.77	1.03	0.86
3-Lane	**20/40/40**	0.64	0.97	0.75	0.71	1.00	0.82	0.79	1.04	0.88
vs.	**30/30/40**	0.64	0.97	0.75	0.71	1.01	0.82	0.79	1.05	0.89
3-to-2	**30/40/30**	0.64	0.97	0.74	0.70	1.00	0.81	0.79	1.06	0.89
3-Lane	**20/40/40**	0.64	0.83	0.73	0.72	0.98	0.82	0.80	1.05	0.89
vs.	**30/30/40**	0.63	0.82	0.72	0.72	0.98	0.82	0.80	1.05	0.89
3-to-1	**30/40/30**	0.63	0.81	0.72	0.72	0.98	0.82	0.79	1.05	0.89

4. RELATIONSHIPS BETWEEN INPUTS AND CAPACITY IN THE SIMULATION

This section presents the investigation of relationships between the simulation input and work zone capacity and other performance measures. This investigation was conducted to identify the important factors that would be suitable for consideration into the capacity estimation models. Relationships between selected input and output variables are presented in this section for each work zone configuration.

4.1. 2-to-1 Lane Closure

For this test configuration, a two-lane freeway segment is reduced to one lane with the rightmost lane closed. The following input variables and performance measures were plotted against the value of capacity through the lane closure and are displayed in the following order in this section:

Input Variables:

- Upstream sign distance
- Truck percentage
- Rubbernecking factor

Performance Measures (from simulated data):

- Capacity through lane closure (shown plotted against all other data)
- Lane changes per link
- Average speed
- Lane distributions upstream of the work zone warning sign

Figure 2 shows the relationship between the work zone capacity and the location of the upstream warning sign. As the distance to the upstream warning sing increases, there is a small increase in capacity. This relationship becomes more significant when viewed in combination with the lane distributions of link (6,7) as an interaction variable.

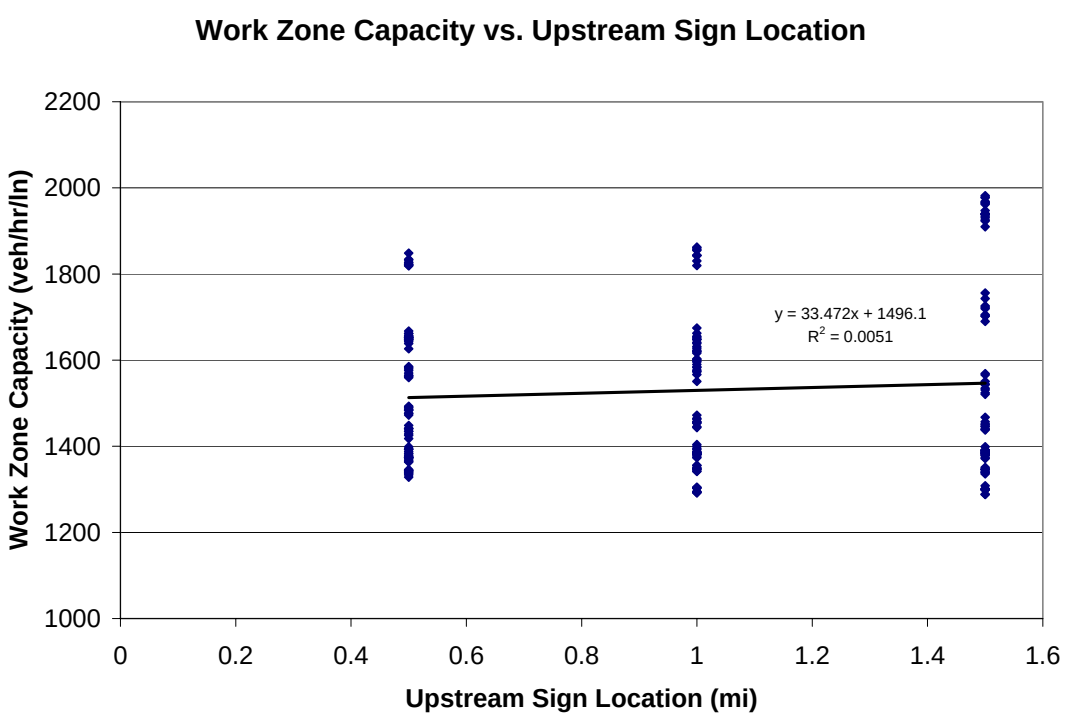


Figure 2. Relationship between Work Zone Capacity and Upstream Warning Sign Distance

Figure 3 and Figure 4 show the effects of increases in the truck percentage and the rubbernecking factor respectively, on the work zone capacity. Figure 3 shows that an increasing percentage of trucks in the traffic stream leads to a decrease in capacity. Similarly, increasing the rubbernecking factor results in a capacity decrease. In CORSIM an increase in the rubbernecking yields lower speeds through the work zone, which then results in lower capacity. This variable can be used as a surrogate to work zone intensity or other factors that may directly affect the speed through the work zone.

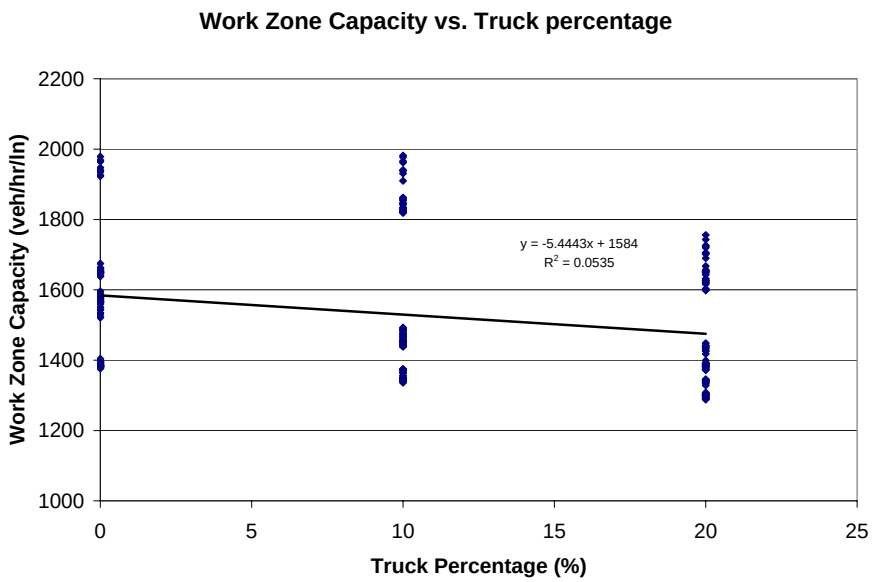


Figure 3. Relationship between Work Zone Capacity and Truck Presence in Traffic Stream

The speeds in the link immediately downstream of the lane closure warning sign were also considered, and their relationship to the throughput capacity is shown in Figure 5. An increase in the speed of lane 1 (closed lane) does not increase capacity as much as a higher speed in lane 2 (through lane). This is because a higher speed in lane 1 implies less congestion and thus smoother merging into the through lane. In the case of less congestion, there is a steady flow of vehicles traveling in lane 2 which increases the capacity more significantly with an increase in traffic stream speed.

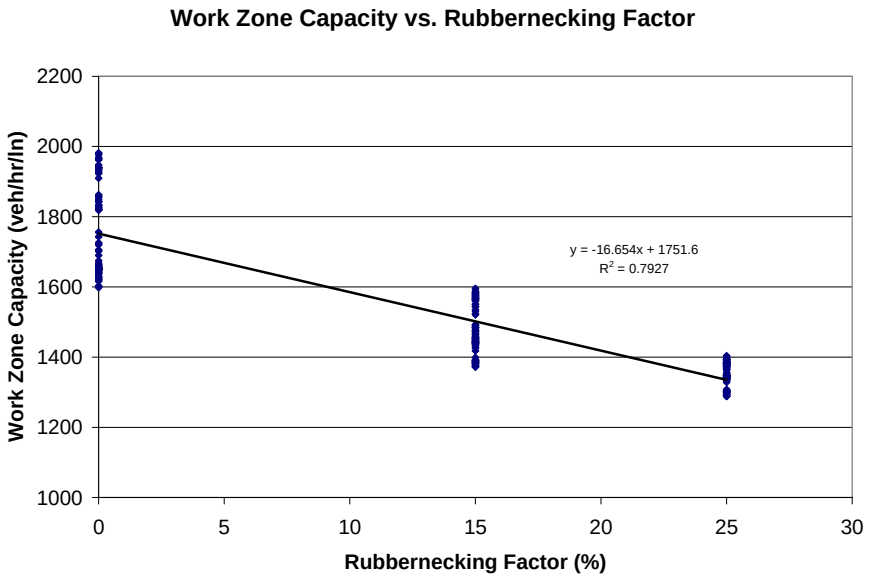


Figure 4. Relationship between Work Zone Capacity and Percent Rubbernecking Factor

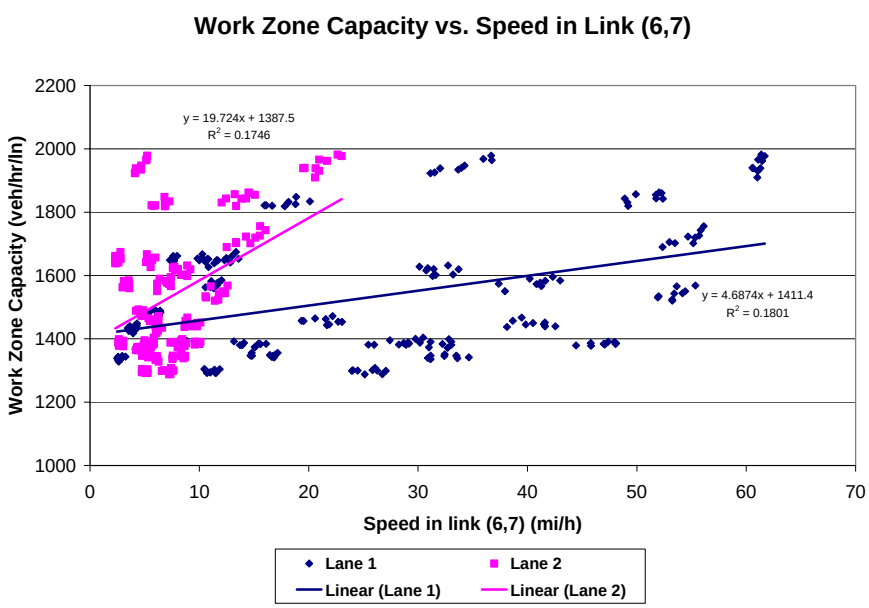


Figure 5. Relationship between Work Zone Capacity and the Average Speed per Vehicle in Lanes 1 and 2 of Link (6,7)

Another important relationship that was identified is the distribution of vehicles in links upstream and immediately downstream of the work zone warning sign. These relationships are important if an agency wants to implement a particular traffic management strategy. If higher capacities are a result of lower percentages of merging vehicles, for example, then an early merge strategy is an effective option. Figure 6 shows the relationship between vehicular lane distributions at various locations upstream of the work zone and work zone capacity. The relationship is similar for links (4,5) and (5,6), which are further upstream of the work zone warning sign. In CORSIM vehicles tend to become equally distributed between freeway lanes, despite the initial lane distribution entered into the software. This occurs because of the lane-changing logic inherent into CORSIM. Therefore the lane distributions at those two links were not significant input variables and were not incorporated in the capacity estimation models. However, the lane distributions immediately upstream and downstream of the work zone warning sign (links (6,7) and (7,8)) were significant, and considered in the model development.

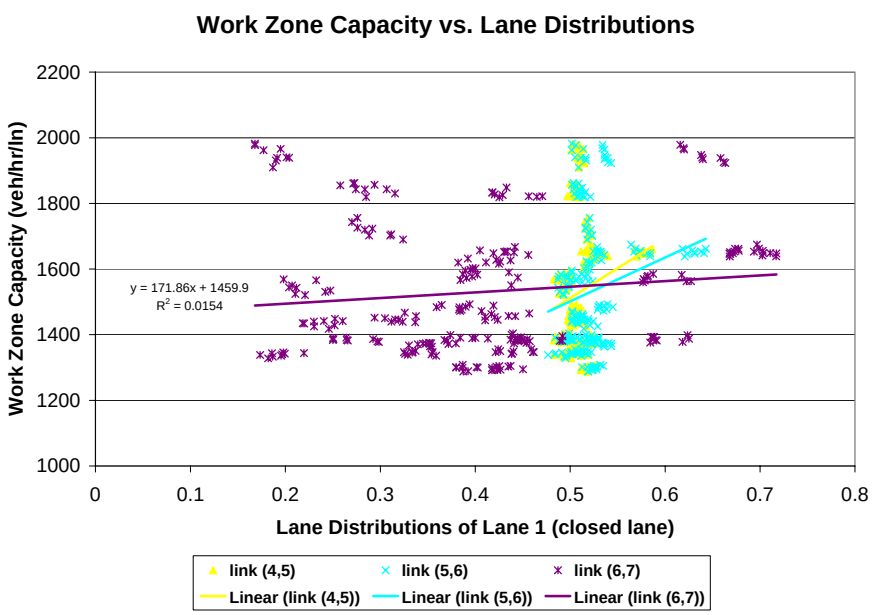


Figure 6. Relationship between Work Zone Capacity and the Vehicular Distributions on Lane 1of All Links

There was some interaction observed between the distribution of vehicles in link (6,7) and the sign distance (this is also the length of link (6.7)). With an increasing sign distance, a higher fraction of the traffic stream is present in the through lane (lane 1) while a lower fraction is in the closed lane. Longer warning distances upstream of a lane closure allow vehicles more time and space to merge into the through lane. The interaction of these two terms—lane distributions of link (6,7) and upstream sign distance—were plotted against capacity to verify that a relationship existed. These results are illustrated in Figure 7. As shown, the net effect of increasing sign distance and lane distribution is positive for lane one.

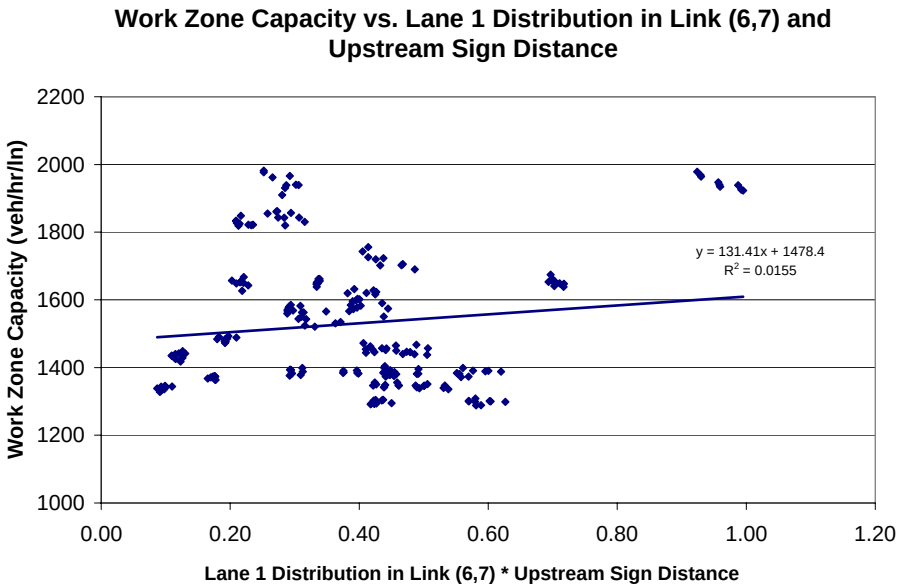


Figure 7. Relationship between Work Zone Capacity and the Interaction of Lane Distributions in Link (6,7) and Upstream Sign Distance

Another interaction was observed between the location of the upstream warning sign and the average speeds of vehicles in link (6,7). Their combined effect on capacity is shown in Figure 8. The results indicate that there is a relationship between these variables and the interaction of speeds and sign distance was considered in the capacity estimation models.

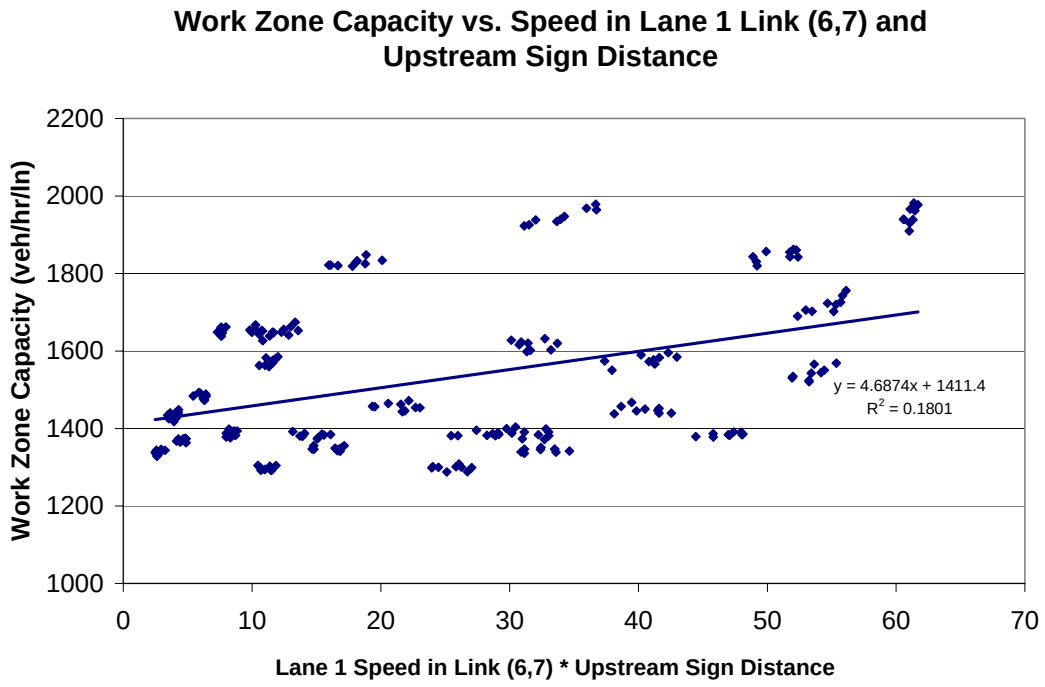


Figure 8. Relationship between the Work Zone Capacity and the Interaction of the Speeds in Lane 1 of Link (6,7) and the Location of the Upstream Warning Sign

Even though all of these variables were initially considered for inclusion in the capacity estimation models, some of them were not statistically significant while a few others did not show a significant trend. Table 6 lists the variables discussed above, and indicates which of these variables are eventually used in developing the capacity estimation models (discussed in Chapters 5 through 7 of this report).

Table 6. List of independent variables for 2-to-1 lane closures and their relationship to work zone capacity

Independent Variable	Used in final model? (Y/N)	Why?
Upstream sign distance (SignDist)	Y	Affects positively the capacity
Truck percentage	Y	Strong lineal relationship to capacity
%Rubbernecking	Y	Strong lineal relationship to capacity
Speed Lane1(6,7)	N	Not statistically significant
Speed Lane2(6,7)	N	Not statistically significant
DistLane1(4,5)	N	Not apparent relationship with capacity
DistLane1(5,6)	N	Not apparent relationship with capacity
DistLane1(6,7)	Y	Affects positively the capacity
DistLane1(6,7)*SignDist	Y	Affects positively the capacity
Speed Lane1(6,7)*SignDist	Y	Strong lineal relationship with capacity

4.2. 3-to-2 Lane Closure

For this test segment, a three-lane freeway segment is reduced to two lanes with the rightmost lane closed. The input variables and performance measures discussed in the 2-to-1 model development were plotted against the value of capacity through the lane closure.

Figure 9 figure presents the relationship between the work zone capacity and the distance of the warning sign upstream of the work zone. Similarly to the 2-to-1 lane closure, increasing the sign distance has a positive effect on the capacity of the work zone. When the sign is placed further upstream, merging is smoother, resulting in a capacity increase. This relationship becomes more significant when viewed in combination with the lane distributions of link (6,7) and the speed of the closed lane of link (6,7) as an interaction variable.

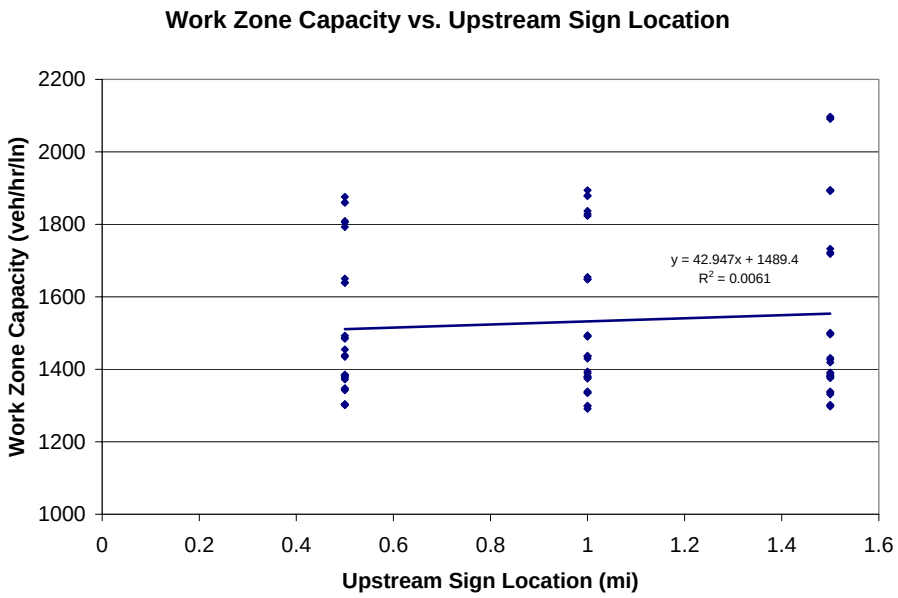


Figure 9. Relationship between Work Zone Capacity and Upstream Warning Sign Distance

Figure 10 shows the relationship between capacity and truck percentage, while Figure 11 shows the relationship between capacity and the rubbernecking factor. The effect of trucks on capacity is similar for all lane closure configurations: increasing the percentage of trucks yields a decrease in capacity. The truck percentage is expected to be an important variable for these models as well.

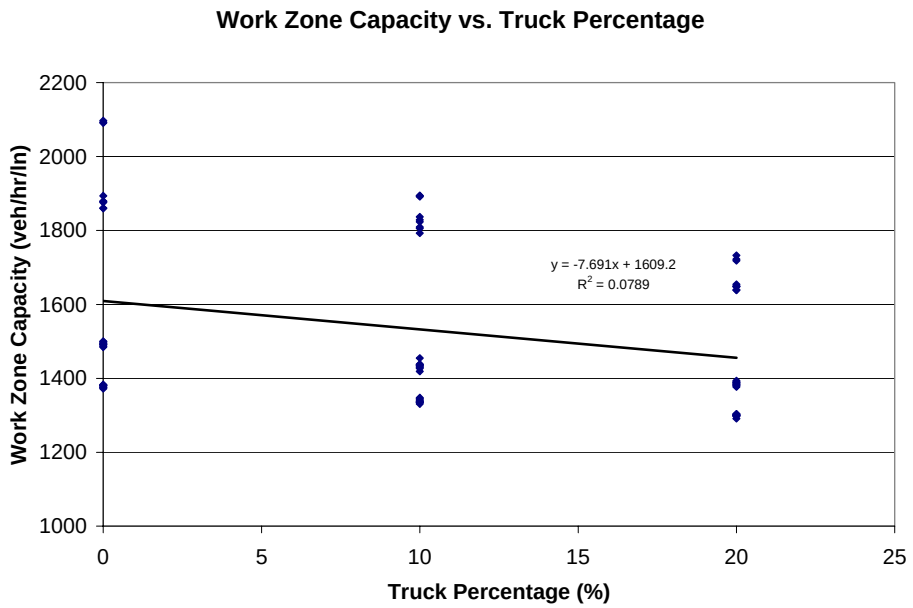


Figure 10. Relationship between Work Zone Capacity and Presence of Trucks in Traffic Stream

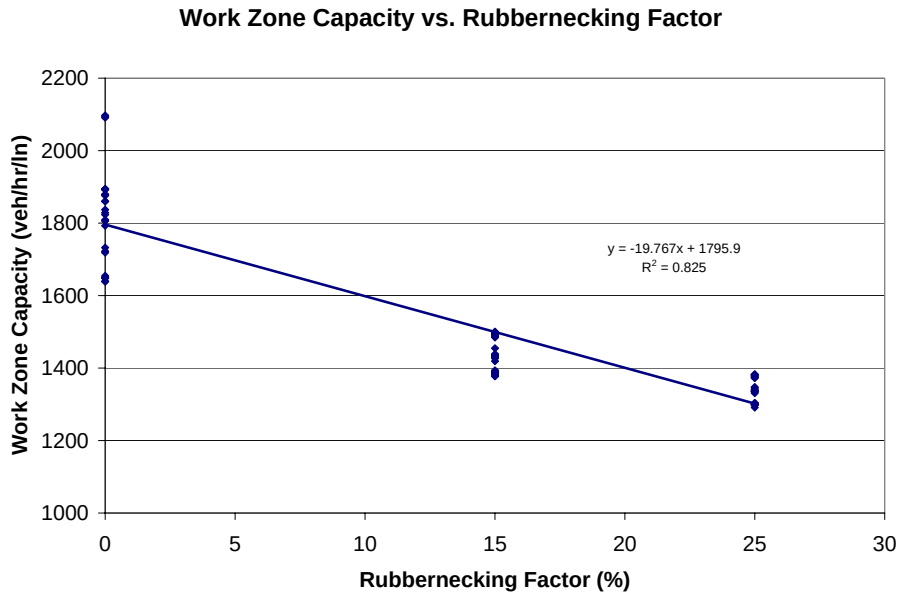


Figure 11. Relationship between Work Zone Capacity and Rubbernecking Factor

Similarly, increasing the rubbernecking factor yields lower speeds through the work zone, thus a decrease in capacity through the lane closure. This variable is expected to be a significant factor in the capacity estimation models.

The speeds in the link upstream of the warning sign location were also considered, and their relationship to the throughput capacity is shown in Figure 12. The speed in Link (5,6) was considered in the capacity estimation model development, however, this variable was included taking into consideration the interaction of speed with the location of the warning sign. The direct relationship between the work zone capacity and this interaction term is illustrated in Figure 133. Increased speed on the right-most lane results in increasing capacity, especially if the sign is located further upstream, as the vehicles have more opportunities for smooth merging.

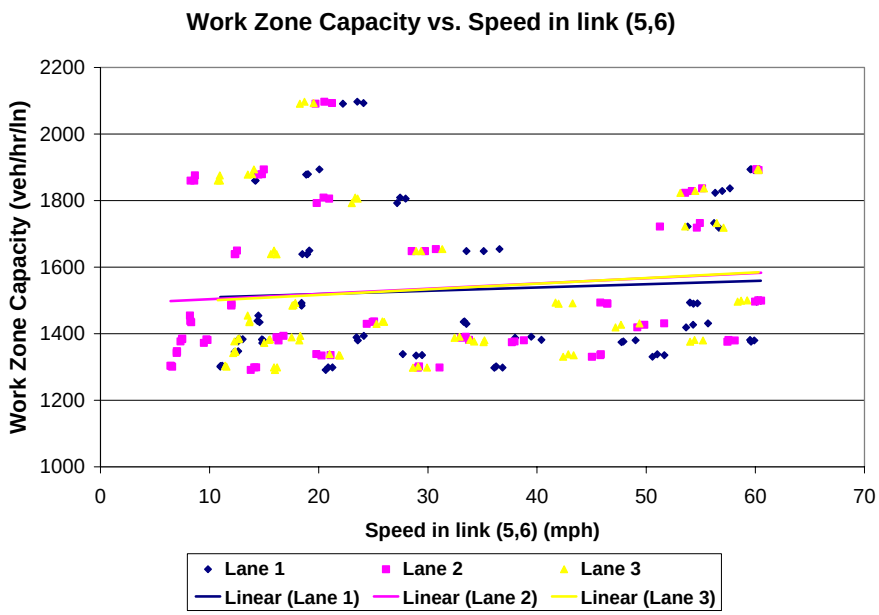


Figure 12. Relationship between Work Zone Capacity and the Average Speed per Vehicle in Lanes 1, 2, and 3 of Link (5,6)

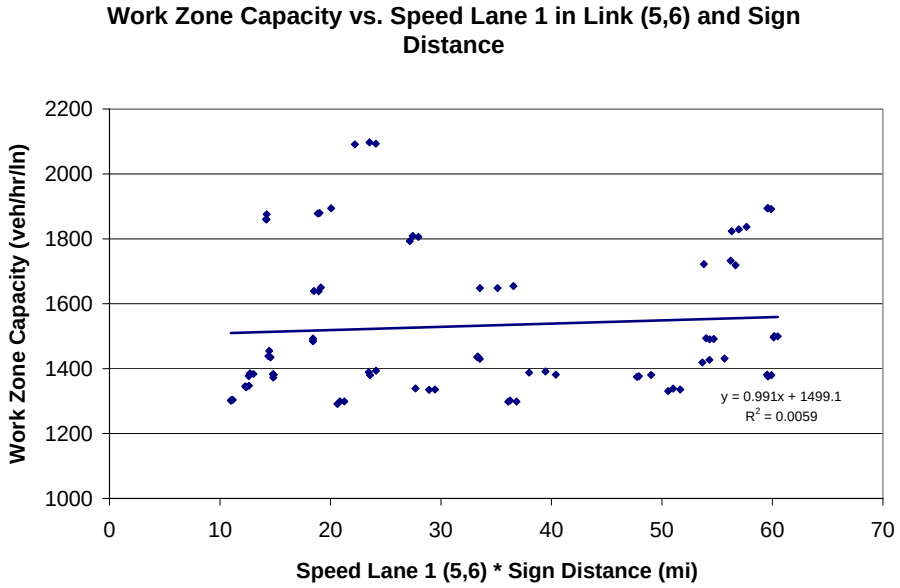


Figure 13. Relationship between Work Zone Capacity and the Interaction of the Speeds in Lane 1 of Link (5,6) and the Location of the Upstream Warning Sign

Another important relationship that was identified is that of the distribution of vehicles in links upstream and immediately downstream of the work zone warning sign. Figure 144 shows the effect that the vehicular lane distributions have on work zone capacity. The effects of the vehicular lane distributions on link (6,7) will be considered in the final model of the operational procedure, considering its interaction with the sign distance. The interaction of these two terms—lane distributions of link (6,7) and upstream sign distance—were plotted against capacity in Figure 15. The net effect of increasing sign distance and lane distribution is positive for lane one. This means that the impact of the lane distribution on capacity depends also on the location of the sign. This factor is included in the capacity estimation model.

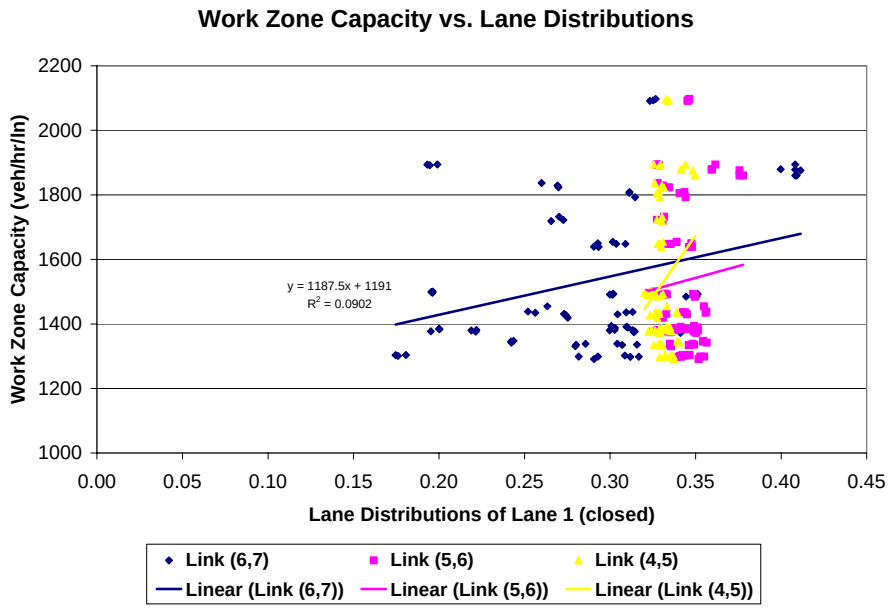


Figure 14. Relationship between Work Zone Capacity and the Vehicular Distributions on Lane 1 of All Links

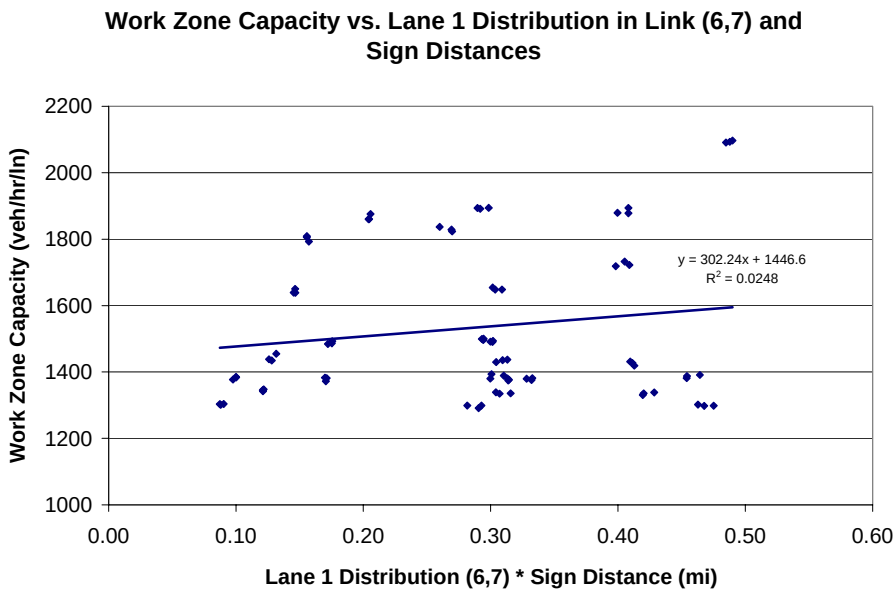


Figure 15. Relationship between Work Zone Capacity and the Interaction of Lane Distributions in Link (6,7) and Upstream Sign Distance

Table 7 summarizes the variables that were initially considered for the model development, and indicates which ones are included in the final models based on whether they were found to be statistically significant. The models developed for 3-to-2 lane closures are discussed further in Chapters 5 through 7 of this report.

Table 7. List of independent variables for 3-to-2 lane closures and their relationship to work zone capacity

Independent Variable	Used in final model? (Y/N)	Why?
Upstream sign distance (SignDist)	Y	Affects positively the capacity
Truck percentage	Y	Strong lineal relationship to capacity
%Rubbernecking	Y	Strong lineal relationship to capacity
Speed Lane1(5,6)	N	Not statistically significant
Speed Lane2(5,6)	N	Not statistically significant
Speed Lane3(5,6)	N	Not statistically significant
DistLane1(4,5)	N	Not apparent relationship with capacity
DistLane1(5,6)	N	Not apparent relationship with capacity
DistLane1(6,7)	N	Not statistically significant
DistLane1(6,7)*SignDist	Y	Affects positively the capacity
Speed Lane1(5,6)*SignDist	Y	Statistically significant interaction

4.3. 3-to-1 Lane Closure

For this test segment, a three-lane freeway segment is reduced to one lane with the two rightmost lanes closed. The graphical representations of these relationships are shown in the following sections. The same input variables and performance measures as the other two lane closure types are considered for the 3-to-1 lane closure.

The relationship between work zone capacity and the location of the warning sign is illustrated in Figure 16. As shown, there is no apparent trend between the sign distance and the capacity. Additionally, the sign distance variable interacts with the speed and the lane distribution similarly to the previous configurations. However, no significant trend was found between the interaction of these terms and capacity. It is likely that for the 3-to-1 lane closure, the location of the warning sign does not have any significant effect on merging operations, and thus on the capacity of the open lane. Therefore, the location of the warning sign was not included in the capacity estimation model for this configuration.

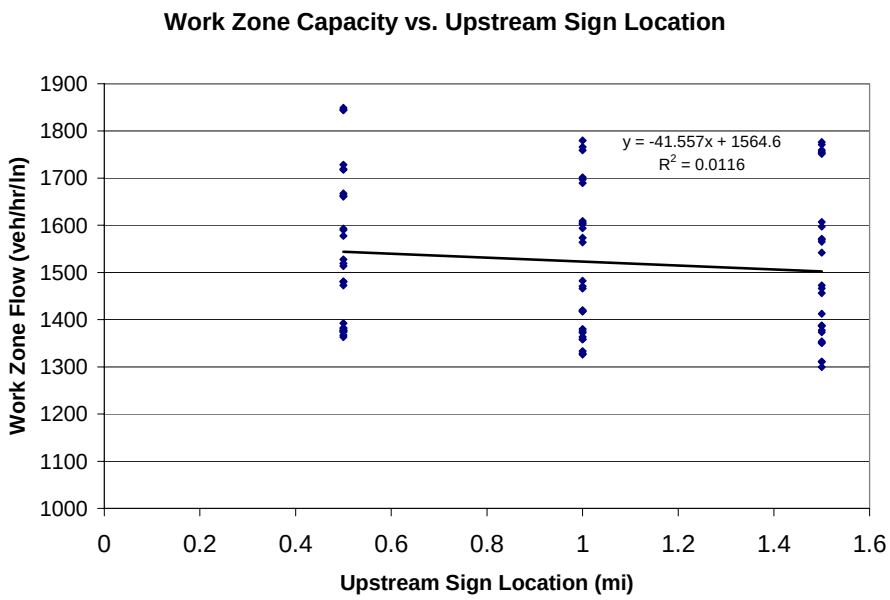


Figure 16. Relationship between Work Zone Capacity and Upstream Warning Sign Distance

Figure 17 and Figure 18 present the effect of truck presence and the rubbernecking factor on the work zone capacity. As expected, an increase in the percentage of trucks or percent of rubbernecking factor has a negative impact on the work zone capacity. Both of these variables were included in the final capacity models.

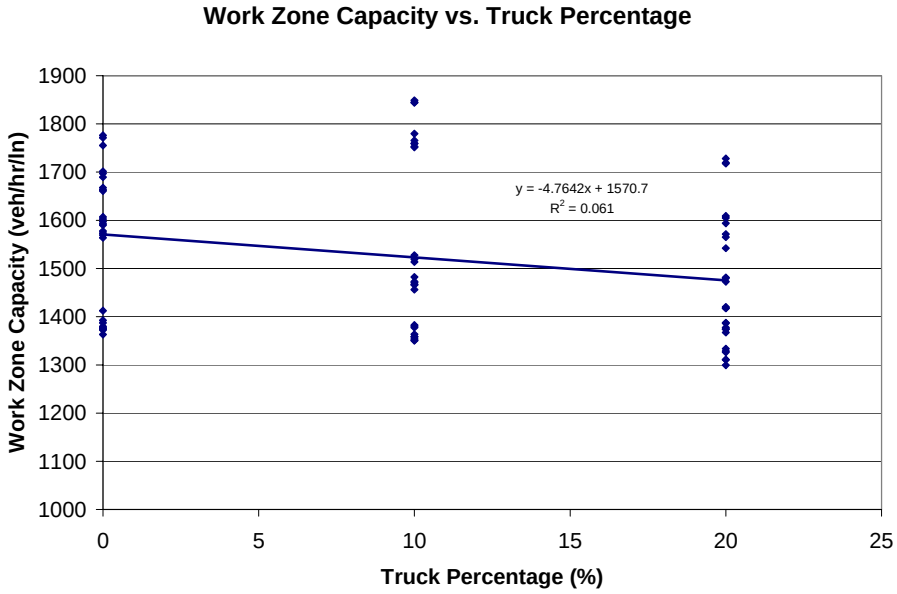


Figure 17. Relationship between Work Zone Capacity and Truck Presence in Traffic Stream

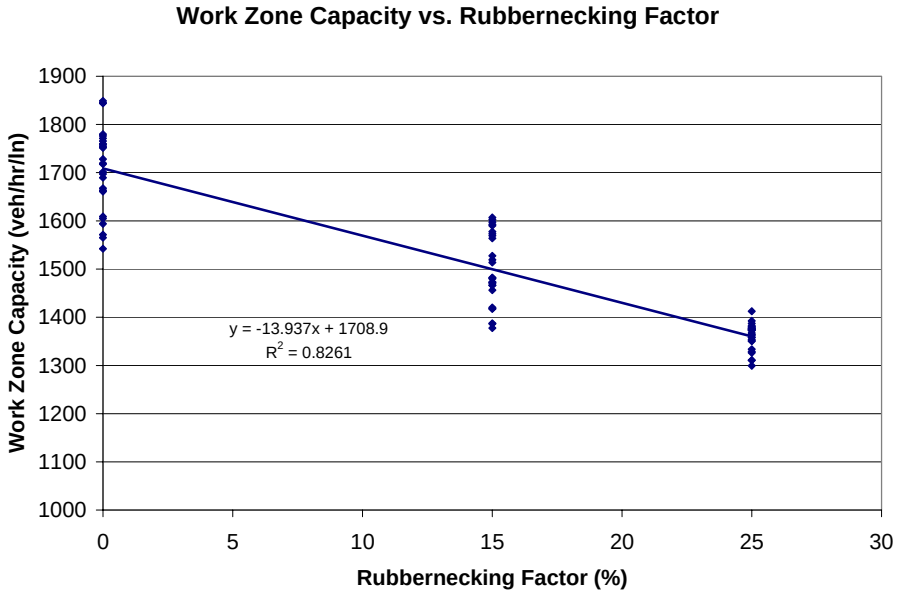


Figure 18. Relationship between Work Zone Capacity and Rubbernecking Factor

The relationship between speeds in all lanes immediately downstream of the work zone is illustrated in Figure 19. An increase of the speed in lane 2 (inner closed lane) results in greater increase in capacity that the speed of lane 1 (outer closed lane). The

speeds in lane 3 (open lane) are generally very low which reflects the adverse operations from reducing a three lane freeway to only one open lane.

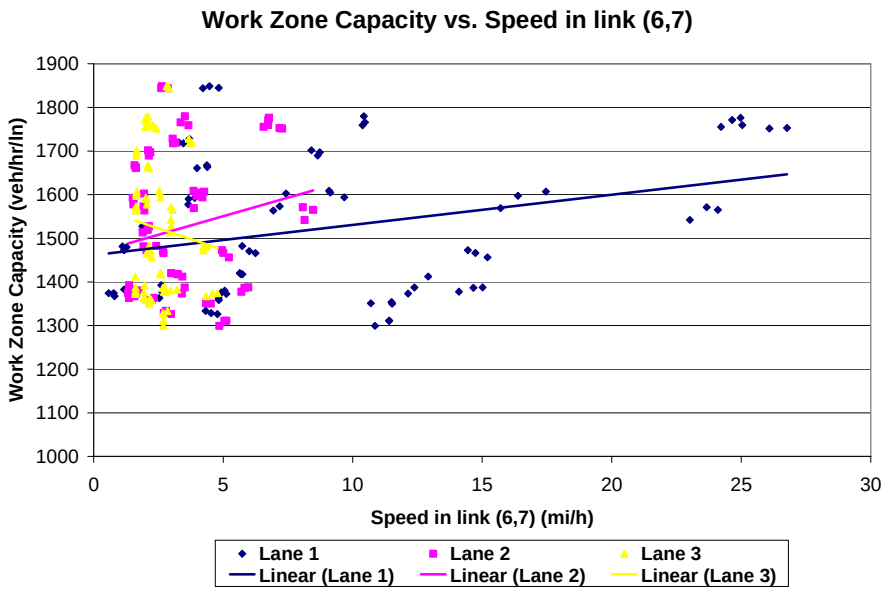


Figure 19. Relationship between Work Zone Capacity and the Average Speed per Vehicle in Lanes1, 2 and 3 of Link (6,7)

The distribution of vehicles was examined for this type of lane closure as well. Figure 20 shows the effect of the vehicular lane distributions on the work zone capacity. As shown the percent of traffic in the open lane has a significant effect on capacity, therefore this variable will be considered for inclusion in the capacity estimation models.

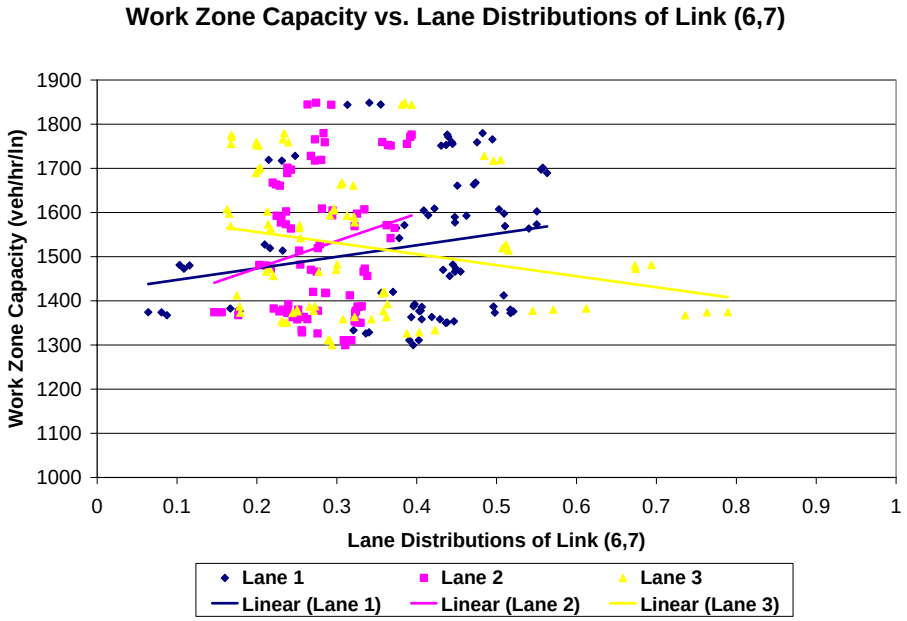


Figure 20. Relationship between Work Zone Capacity and the Vehicular Distributions on Lanes 1, 2 and 3 of Link (6,7)

There was some interaction between the distribution of vehicles in link (6,7) and the sign distance (this is also the length of link (6,7)). The interaction of these two terms—lane distributions of link (6,7) and upstream sign distance—were plotted against capacity to verify that a relationship existed. These results are presented in Figure 21. As shown, there is no effect of the interaction of lane distribution and sign distance on the work zone capacity. Therefore, this interaction term was not included in the final models.

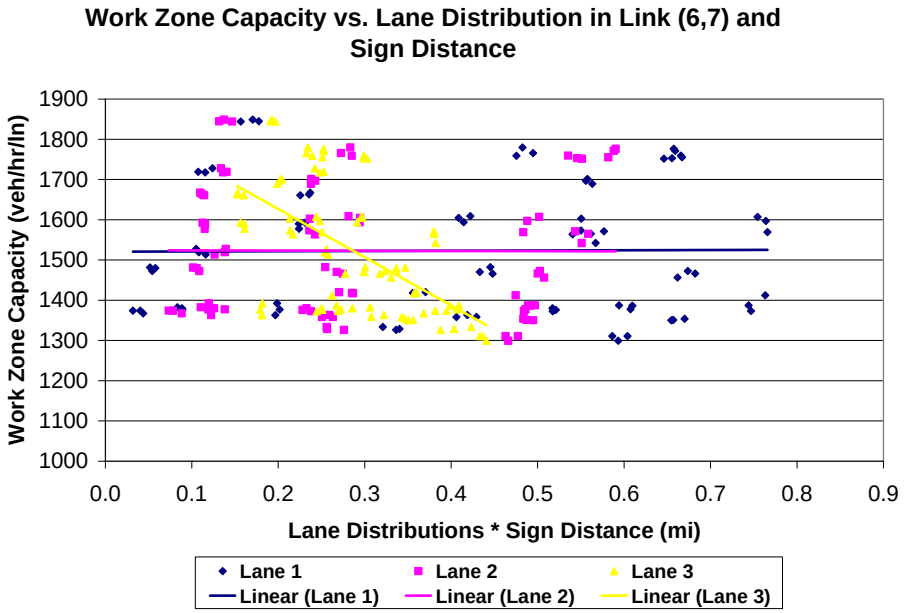


Figure 21. Relationship between Work Zone Capacity and the Interaction of Lane Distributions in Link (6,7) and Upstream Sign Distance

Another interaction was observed between the location of the upstream warning sign and the speeds of vehicles in the middle lane of link (6,7). Their combined effect on capacity is shown below in Figure 22. The results do not show a clear trend between these variables, and the interaction of speeds and sign distance will not be considered in the final models.

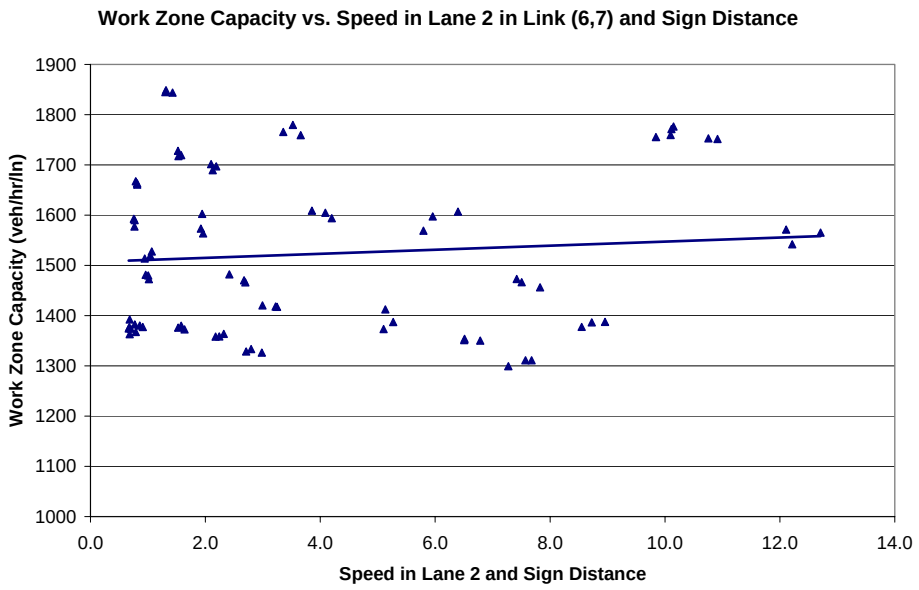


Figure 22. Relationship between Work Zone Capacity and the Interaction of the Speeds in Lane 2 of Link (6,7) and the Location of the Upstream Warning Sign

A summary of the variables to be considered for inclusion in the model development is given in Table 8. This table also shows which variables were eventually included in the final models and which were not statistically significant or did not affect capacity. The models for 3-to-1 lane closures are further discussed in Chapters 5 through 7 of this report.

Table 8. List of independent variables for 3-to-1 lane closures and their relationship to work zone capacity

Independent Variable	Used in final model? (Y/N)	Why?
Upstream sign distance (SignDist)	N	Not statistically significant
Truck percentage	Y	Strong lineal relationship to capacity
%Rubbernecking	Y	Strong lineal relationship to capacity
Speed Lane1(6,7)	N	Not statistically significant
Speed Lane2(6,7)	N	Not statistically significant
Speed Lane3(6,7)	N	Not apparent relationship with capacity
DistLane1(6,7)	N	Not statistically significant
DistLane2(6,7)	N	Not statistically significant
DistLane3(6,7)	Y	Strong relationship with capacity
DistLane1(6,7)*SignDist	N	Not apparent relationship with capacity
DistLane2(6,7)*SignDist	N	Not apparent relationship with capacity
DistLane3(6,7)*SignDist	N	Not apparent relationship with capacity
Speed Lane2(6,7)*SignDist	N	Not statistically significant

5. CAPACITY MODEL DEVELOPMENT

Based on the relationships depicted in the previous chapter, capacity estimation models for each lane closure type were developed using general linear regression techniques using the statistical software MINITAB®. The independent variables for each of the three lane closure configurations were selected based on a 0.05 level of significance.

This section first describes and defines the dependent variable and the selected independent variables used in the capacity estimation models. The second part presents the planning applications models, while the last part describes the operational applications models.

5.1 Description and Definition of Independent Variables

This subsection describes the variables used in the capacity estimation models. These variables were selected because a) they could be represented in the simulator to evaluate their impact on capacity, and b) simulation modeling showed that they were statistically significant in determining capacity. These variables are associated with traffic operations (for example, speeds and lane distributions) or with work zone configuration (for example, distance to the first upstream work zone warning sign). Variables related to highway geometry (such as lane widths and lateral clearance) are not typically taken into consideration in simulation models, therefore the procedure developed in this project relies on previous research findings to account for such factors.

The following variables were used in the development of the proposed planning and operational models:

C_{unadj} - *Unadjusted Capacity:* This is the dependent variable of the regression models and represents the maximum number of vehicles that travel through the work zone lane closure given specific input values for the simulation model parameters. In the simulation model it was assumed that capacity conditions were reached when there was a speed drop of at least 30% from the free flow speed on the link immediately upstream of the work zone. Unadjusted capacity is given in units of veh/hr/lane; for the 3-to-2 lane closure configuration, this value is the average of both open lanes through the work zone.

C_{adj} - Adjusted Capacity: This is the capacity estimate adjusted for effects which the simulation cannot consider, but which have been documented elsewhere in the literature using field data (for example the effects of lighting and weather).

SignDist – Sign Distance. This variable represents the distance from the first upstream work zone warning sign to the beginning of the work zone. This variable is always the same length as link (6,7), and is reported in miles.

$f_{HV\text{-}F}$. - Heavy Vehicle Adjustment Factor: This variable represents the heavy vehicle adjustment factor for the traffic traveling on the freeway. Its value depends on the proportion of heavy vehicles in the traffic stream as well as the freeway terrain (level or upgrade). The proportion of heavy vehicles ($P_{HV\text{-}F}$) is input as a decimal number (e.g. 0.2 for 20%) and the terrain of the freeway is input in terms of the passenger-car equivalents for heavy vehicles ($E_{HV\text{-}F}$). The passenger-car equivalents used are 2.4 for level terrain and 3.0 for 3% upgrade over a 1-km long freeway segment (Al-Kaisy and Hall, 2003).

Rubber% - Rubbernecking Factor: This variable represents the degree to which capacity is reduced due to the presence of workers and as a function of the work zone intensity within the lane closure. A higher rubbernecking factor leads to a decrease in capacity throughput. Field data were not available to calibrate this factor, however this methodology uses previous research findings (Al-Kaisy and Hall, 2003), based on which a capacity drop of 7% was observed when there was activity at the work zone. The corresponding rubbernecking factor that results in a 7% capacity reduction (averaged for all three lane closure configurations) was estimated to be 5.6%. Thus, work zone activity was simulated using a rubbernecking factor of 5.6%; a value of 0% was entered if there was no work activity. A higher value may be chosen as input if there is evidence that the work activity contributes to more than 7% capacity reduction, i.e. due to presence of law enforcement or heavy construction equipment and workers.

$SpdLan1(6,7)_{adj}$ – Adjusted Speed in Lane 1 Upstream of the Work Zone: This variable, reported in mi/h, represents the adjusted speed in the rightmost lane (lane 1) of link (6,7). This speed is adjusted to account for the effects of the lane width and the lateral clearance on the freeway. If the speed on link (6,7) is measured directly in the field, then the value obtained represents the adjusted speed.

$SpdLan1(5,6)_{adj}$ – Adjusted Speed in Lane 1 Upstream of the Warning Sign: This variable, reported in mi/h, represents the adjusted speed in the rightmost lane (lane 1) of link (5,6). This speed is adjusted to account for the effects of the lane width and the lateral clearance on the freeway. If the speed on link (5,6) is measured directly at the field then the value obtained represents the adjusted speed.

$SpdLan1(6,7)_{adj}$ × SignDist. This variable is an interaction term between the adjusted speed of vehicles in lane 1 of link (6,7) and the distance to the first upstream work zone warning sign. This variable is used because when the distance to the sign is shorter, there is a higher probability that the queue would extend upstream of the warning sign and into the upstream link (6,7), which would in turn have lower speeds.

SpdLan1(5,6) × SignDist. This variable is an interaction term between the speed of vehicles in lane 1 of link (5,6) and the upstream distance of the work zone warning sign. This interaction is used for the same reason reported above: when the distance to the sign is shorter, there is a higher probability that the queue would extend further upstream of the warning sign and into link (5,6), which would in turn have lower speeds.

DistrLan1(6,7), DistrLan3(6,7) – Percent of Traffic in Lane 1, Lane 3, Upstream of the Work Zone: These variables represent the fraction (percent divided by 100) of vehicles present in the rightmost (lane 1) and leftmost (lane 3) lanes of link (6,7). For example, if 10% of vehicles are traveling in lane 1, the input value would be 0.10.

DistLan1(6,7) × SignDist. This variable is an interaction term between the distribution of vehicles in lane 1 of link (6,7) and the distance to the first upstream work zone warning sign. The interaction results because longer sign distances create more opportunities to merge into the open lane, increasing thus the percent of traffic in the open lane (lane 1).

5.2. Capacity Estimation Model for Planning Applications

The planning model can be applied before the work zone is in place to obtain a capacity estimate, or compare alternative lane closure configurations to maximize capacity. Inputs to this model include truck percentage, grade, and rubbernecking factor. In addition, adjustments are made to the capacity estimates to account for factors such as lighting conditions (daytime or nighttime with illumination), driver population (peak

hours-weekdays, off-peak weekdays or weekends), rain (light to moderate, heavy or no rain), and the presence of ramps. These adjustment factors were developed based on literature review findings (presented in Chapter 2).

This section presents the final models for planning applications for each lane closure configuration, followed by a sensitivity analysis evaluating the effect of changes in the independent variables on capacity estimates. Then these capacity estimates are compared to those obtained from the HCM 2000 and the current FDOT methodology. Finally a step-by-step procedure for implementing the current methodology is presented, along with several examples.

5.2.1. Unadjusted Capacity Models

This section presents the regression models of capacity for all three lane closure configurations. These represent the unadjusted capacity estimates, which are subsequently adjusted to account for the effects of additional factors (see Section 5.2.2 Step-by-Step Procedure).

2-to-1 Lane Closure Configuration

The dependent variable, C_{unadj}^{2-to-1}, represents the number of vehicles per hour per lane that travel through the open lane given a set of input values. The regression model developed is shown below:

$$C_{unadj}^{2-to-1} = 1330.31 + 475.52 \times f_{HV\text{-}F} + (-16.65) \times Rubber\% \qquad (5\text{-}1)$$

The adjusted R^2 value for the relationship in Equation 5-1 is 0.841. The intercept (1330.31) in this and all subsequent models is not an estimate of base capacity, because the input variables cannot all assume zero values. For example, in the above equation, the heavy vehicle factor cannot be zero.

3-to-2 Lane Closure Configuration

The dependent variable, C_{unadj}^{3-to-2}, represents the average number of vehicles per hour per lane that travel through the work zone, given a set of input values. To calculate the total number of vehicles per hour through the work zone, the C_{unadj}^{3-to-2} value should be multiplied by two. The model is shown below:

$$C_{unadj}^{3-to-2} = 1179.66 + 695.5 \times f_{HV\text{-}F} + (-19.77) \times Rubber\% \quad (5\text{-}2)$$

The adjusted R^2 value for the relationship in Equation 5-2 is 0.90.

3-to-1 Lane Closure Configuration

The dependent variable, C_{unadj}^{3-to-1}, represents the number of vehicles per hour per lane that travel through the open lane given a set of input values. The model is shown below:

$$C_{unadj}^{3-to-1} = 1336.98 + 419.74 \times f_{HV\text{-}F} + (-13.94) \times Rubber\% \quad (5\text{-}3)$$

The adjusted R^2 value for the relationship in Equation 5-3 is 0.88.

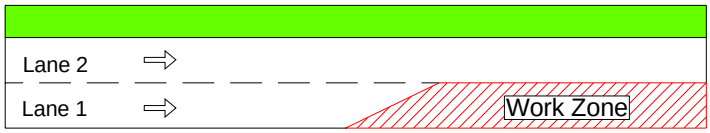
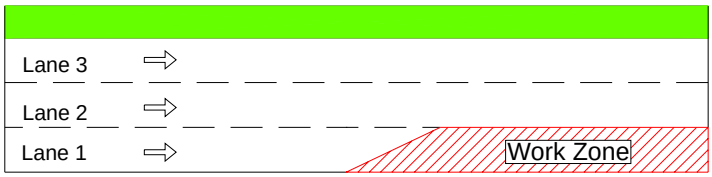
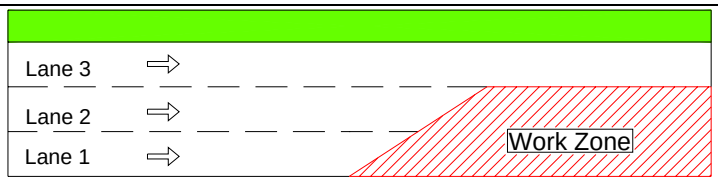
5.2.2. Step-by Step Procedure

This section presents the step-by step procedure for applying the planning applications procedure to estimate the capacity of freeway work zones. Table 9 provides a list of all input data required for applying this procedure, along with the notation used in this report. Table 10 provides the equations for obtaining unadjusted capacity for each of the three configurations, and the equation for obtaining the final, adjusted capacity estimate, which applies to all three configurations.

Table 9. Required Input Data for Estimating Capacity in Planning Applications

Geometric Input Data	Notation
Terrain (level, rolling, mountainous)	N/A
Number of lanes on the on-ramp (if one is present along the work zone)	N
Traffic Characteristics Data	
Driver population (peak hours-weekdays, off-peak weekdays or weekends)	f_d
Driver population for traffic on the on-ramp (commuter of recreational)	f_p
Passenger car equivalencies (based on terrain and vehicle type percentage) for the freeway and the ramp (if present)	$E_{HV\text{-}F}$ $E_{HV\text{-}R}$ $E_{R\text{-}R}$
Percent rubbernecking (%)	Rubber%
Demand Data	
Ramp volume (veh/h)	v_R
Percent trucks on freeway and ramp (%)	$P_{HV\text{-}F}$, $P_{HV\text{-}R}$
Percent recreational vehicles for traffic on the on-ramp (%)	$P_{R\text{-}R}$
Lighting and Weather Data	
Light conditions (daytime or nighttime with illumination)	f_l
Rain (no rain, light to moderate rain or heavy rain)	f_r

Table 10. Capacity Models for Planning Procedure by Type of Lane Closure

Lane Closure Type	CAPACITY MODEL FOR PLANNING PROCEDURE
2 TO 1	 $C_{unadj}^{2-to-1} = 1330 + 476 * f_{HV-F} - 16.7 * \%Rubbernecking$ (1)
3 TO 2	 $C_{unadj}^{3-to-2} = 1180 + 695 * f_{HV-F} - 19.8 * \%Rubbernecking$ (2)
3 TO 1	 $C_{unadj}^{3-to-1} = 1337 + 420 * f_{HV-F} - 13.9 * \%Rubbernecking$ (3)
ALL	$C_{adj} = f_l * f_d * f_r * (C_{unadj} - v_R)$ (4)

The step-by step procedure for estimating capacity is presented in Table 11.

Table 11. Computational Steps for Determining Work Zone Capacity in Planning Applications

STEPS

1. Adjust for the presence of heavy vehicles on the freeway	$f_{HV-F} = \dfrac{1}{1 + P_{HV-F}(E_{HV-F} - 1)}$ Where: E_{HV-F} = 2.4, for level terrain E_{HV-F} = 3.0, 3% 1-km upgrade P_{HV-F} = proportion of heavy vehicles on the freeway
2. Obtain % rubbernecking	Rubber% = 0% for no-work activity Rubber% = 5.6% for presence of work activity
3. Calculate unadjusted capacity	Use the appropriate capacity model from Table 10 - equations (1) through (3)
4. Adjust for lighting conditions	f_l = 1.00 for daytime f_l = 0.96 nighttime with illumination
5. Adjust for driver population	f_d = 1.00 peak hours-weekdays f_d = 0.93 off-peak weekdays f_d = 0.84 weekends
6. Adjust for rain	f_r = 1.00 no rain f_r = 0.95 light to moderate rain f_r = 0.90 heavy rain
7. Adjust for presence of an on-ramp through the work zone	Use when an on-ramp is located within 500 ft of the work zone. The capacity of the work zone is decreased by the ramp volume (up to a maximum of half of the capacity of one lane). Obtain equivalent passenger-car flow rate for the ramp volume $v_R = \dfrac{V_R}{PHF * N * f_{HV-R} * f_P}$, where: V_R = the ramp volume (veh/h) N = ramp number of lanes f_P = driver population factor for ramp volume f_{HV-R} = Heavy vehicle adjustment factor for the ramp volume as defined in HCM 2000 Equation 23-3. $f_{HV-R} = \dfrac{1}{1 + P_{HV-R}(E_{HV-R} - 1) + P_{R-R}(E_{R-R} - 1)}$
8. Calculate adjusted capacity	$C_{adj} = f_l * f_d * f_r * (C_{unadj} - v_R)$

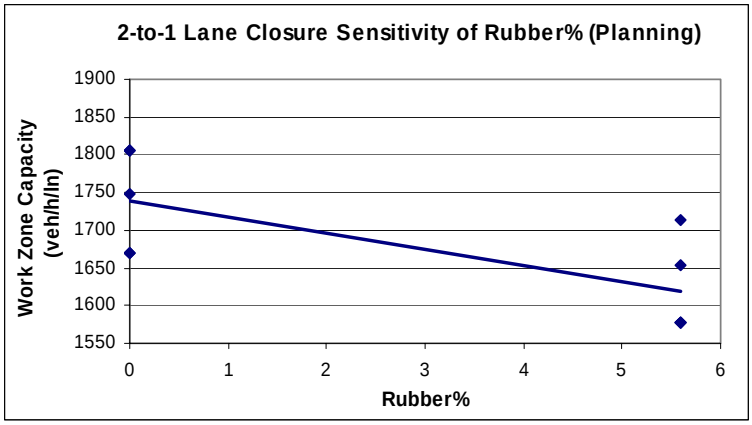
5.2.3. Sensitivity Analysis

Sensitivity analysis was performed to evaluate the impact of changes to specific input variables to the capacity estimate, and confirm that the trends in the models reflect the trends in the simulated data. The sensitivity analysis pertains only to the models estimating unadjusted capacity. Ten different input scenarios, shown in Table 12, were developed and tested. These scenarios were developed based on reasonable ranges of values for each input variable. The unadjusted capacity values were calculated using equations 1 through 3 in Table 10.

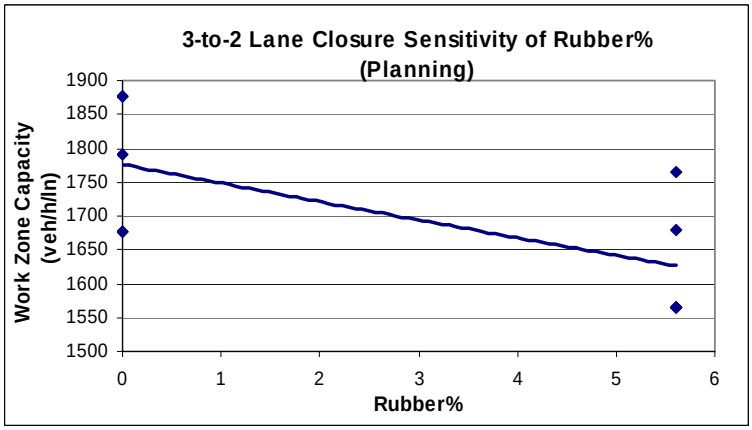
Table 12. Sensitivity Analysis Inputs and Capacity Estimates for Planning Models

Scenario #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Rubber%	5.6	0.0	0.0	0.0	0.0	0.0	5.6	5.6	5.6	5.6
$\mathbf{P_{HV\text{-}F}}$	0.2	0.0	0.2	0.2	0.1	0.0	0.0	0.2	0.2	0.1
$\mathbf{E_{HV\text{-}F}}$	3.0	2.4	3.0	3.0	2.4	2.4	2.4	3.0	3.0	2.4
$\mathbf{f_{HV\text{-}F}}$	0.714	1.0	0.714	0.714	0.877	1.0	1.0	0.714	0.714	0.877
C_{unadj}^{2-to-1}	1577	1806	1670	1670	1747	1806	1713	1577	1577	1654
C_{unadj}^{3-to-2}	1565	1875	1676	1676	1790	1875	1765	1565	1565	1679
C_{unadj}^{3-to-1}	1561	1760	1644	1644	1710	1760	1677	1561	1561	1627

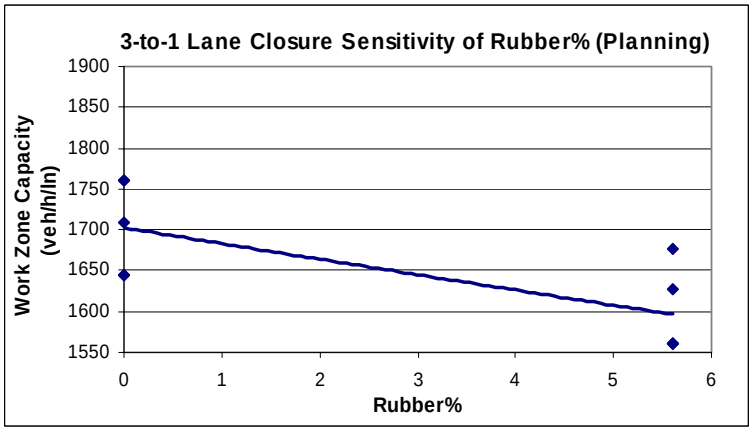
Figure 23 presents graphically the sensitivity analysis results for the rubbernecking factor. The two input values correspond to the "no-work activity" scenario (Rubber% = 0%) and the "presence of work activity" scenario (Rubber% = 5.6%). Introducing the rubbernecking factor results in an average capacity reduction of approximately 7%. Figure 24 presents the results of the sensitivity analysis for the heavy vehicle adjustment factor. As shown, increasing the percentage of trucks leads to a decrease in capacity. An increase of 30% in the heavy vehicle factor results in a decrease of approximately 12% in capacity.



(A)

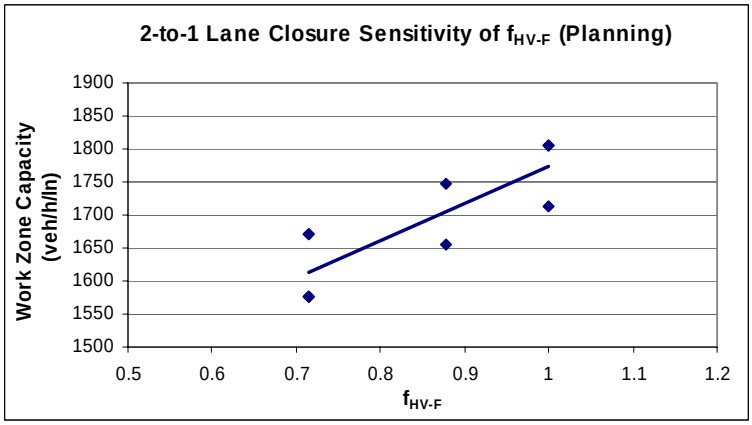


(B)

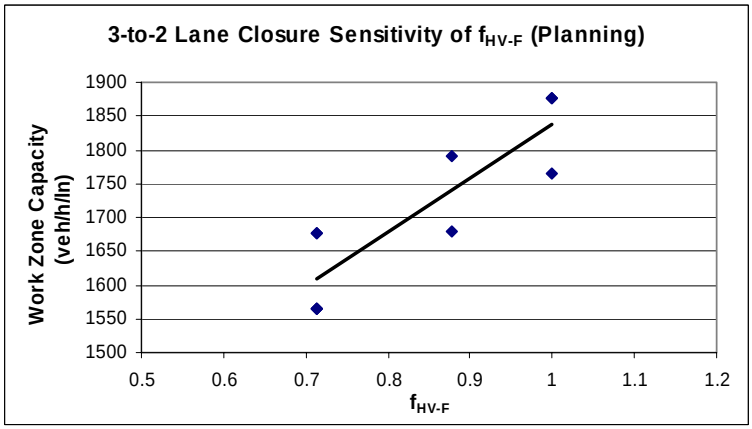


(C)

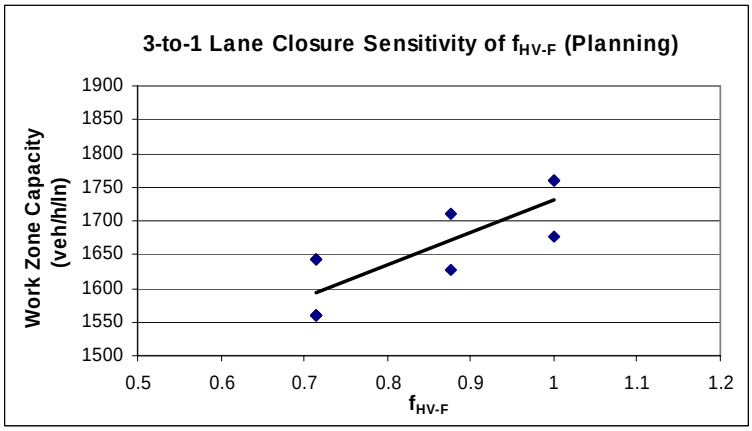
Figure 23. Sensitivity of Rubbernecking % on (A) 2-to-1, (B) 3-to-2, and (C) 3-to-1 Work Zone Capacity Models for Planning Applications



(A)



(B)



(C)

Figure 24. Sensitivity of Heavy Vehicle Adjustment Factor f_{HV-F} on (A) 2-to-1, (B) 3-to-2, and (C) 3-to-1 Work Zone Capacity Models for Planning Applications

5.2.4. Comparisons to the HCM 2000 and FDOT Lane Closure Analysis

The proposed models for capacity estimation were compared to the HCM 2000 and the current FDOT guidelines. An overview of the HCM 2000 and FDOT models is provided in Table 13. As shown, the variables used in each of these two methods are quite different, which makes the comparison between these two methods very difficult.

Table 13. The HCM 2000 and FDOT Lane Closure Analysis Methods

HCM 2000	FDOT
$C = (1600 + I - R) * f_{HV} * N$	**1800 * OF * WZF**
C = estimated work zone capacity (veh/h)	OF = Obstruction factor based on lateral clearance and lane width
I = adjustment for type and intensity of work activity (pc/h/ln). Ranges from -160 to +160 pc/h/ln	
R = adjustment for presence of ramps (pc/h/ln)	WZF = Work zone factor based on the work zone length (N/A here)
f_{HV} = heavy vehicle adjustment factor given in the HCM 2000	
N= number of open lanes	

To perform the comparison, a specific work zone configuration (labeled the default case) was developed and used to test each model. Then each of the input variables were varied and the respective capacity estimates were obtained from each of the three models. Since each of these models uses different input parameters, an effort was made to choose input values that are compatible and comparable. The default case has the following characteristics:

- Lane width, LW = 11 ft
- Lateral clearance, LC = 6 ft
- Medium to intense work zone activity: Rubbernecking factor = 5.6% (for proposed models), -160 pc/h/ln (for HCM 2000)
- Level terrain
- Heavy vehicles % = 10%: PCE factor = 2.4 (for proposed models), 1.5 (for HCM 2000 model)

- No rain, commuter traffic only, no ramps in the vicinity of the work zone, good lighting conditions.

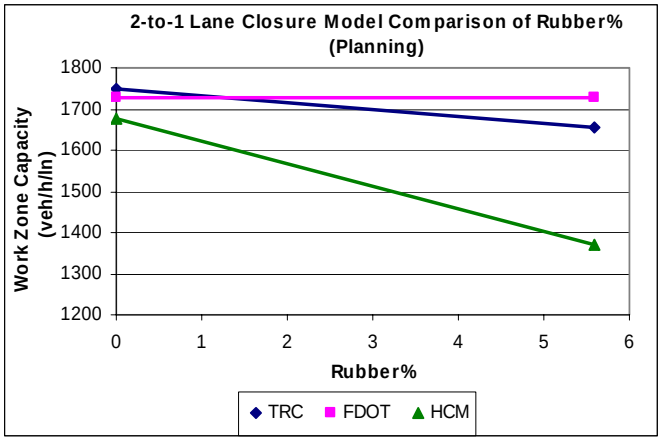
Table 14 presents the resulting capacity estimates for the default case as well as for the range of input values tested. The FDOT method does not provide any capacity estimates for the 3-to-1 lane closures. Also, the capacity estimates from the FDOT procedure depend only on the Obstruction Factor (a function of lateral clearance and lane width), and the Work Zone Factor (based on the work zone length). The models developed in this project however do not depend on the lane width/lateral clearance (at least for the planning applications), nor on the work zone factor (because work zone length was not found to be a significant variable in the simulations). As shown, the current FDOT method provides a single capacity value (1,728 vphpl) for all these configurations. The HCM 2000 method estimates range from 1,309 to 1,676 vphpl. while the proposed method estimates provide a wider range, from 1,588 to 1,790 vphpl, and provide different values for each of the three work zone configurations.

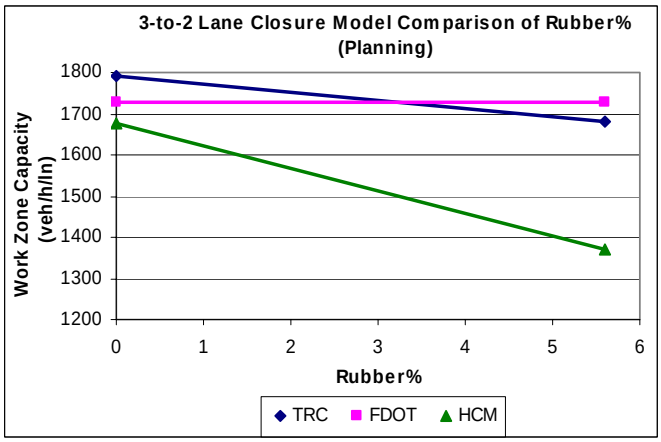
Figures 25 and 26 present graphically the relationships of the rubbernecking factor and the percent heavy vehicles to capacity for each of the three methods. As shown, the capacity estimates from the proposed planning models (labeled as TRC models) fall between the two other models. Compared to the proposed models, the HCM 2000 method underestimates capacity, while the FDOT method overestimates it. The presence of workers in the vicinity of the work zone has a more pronounced effect in the HCM 2000 method than in the proposed new set of models. Note that the case tested here was assumed to have good lighting and other such conditions. Given unfavorable conditions of lighting, rain, driver population and presence of on-ramps, the predicted capacity from the proposed models will be lower; the other two methods however do not consider these conditions, and thus their estimates would remain unchanged.

Table 14. Parameter Values for Model Comparisons – Planning Application

Parameter	Default Case Values	Range in Values	C_{unadj}^{2-to-1} (vphpl)	C_{unadj}^{3-to-1} (vphpl)	C_{unadj}^{3-to-2} (vphpl)
Proposed Models					
%Rubber	5.6	0	1748	1710	1790
		5.6	1654	1627	1679
$f_{HV\text{-}F}$	0.877	1.000	1713	1677	1765
		0.877	1654	1627	1679
		0.781	1609	1588	1612
HCM 2000 Model					
%Rubber	-160	160	1676	1676	1676
		-160	1371	1371	1371
$f_{HV\text{-}F}$	0.952	1.000	1440	1440	1440
		0.952	1371	1371	1371
		0.909	1309	1309	1309
FDOT					
Obstruction Factor	0.96*	*N/A*	1728	*N/A*	1728

*****: For lane width 11 ft and lateral clearance 6 ft, the obstruction factor is 0.96.





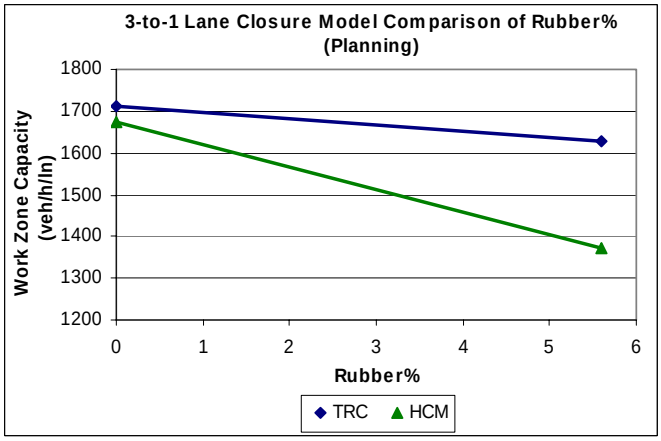
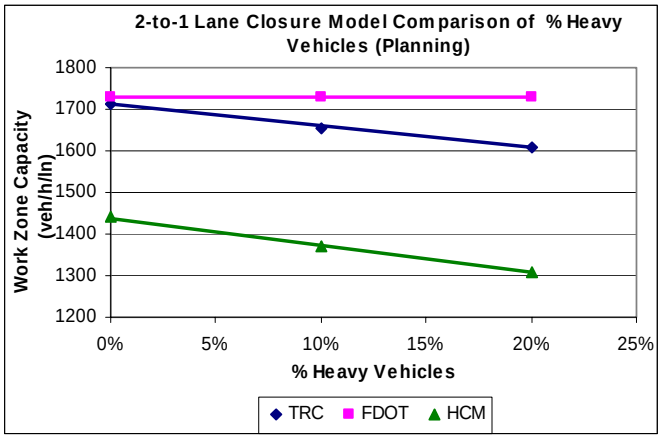
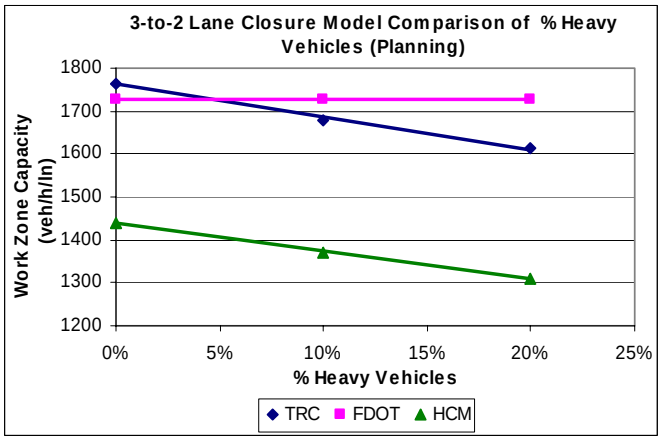


Figure 25. Comparison of Capacity Estimates Between Proposed Model, HCM 2000 and FDOT Models, for All Three Lane Closure Configurations and for Varying Rubbernecking Factor (Planning Applications)





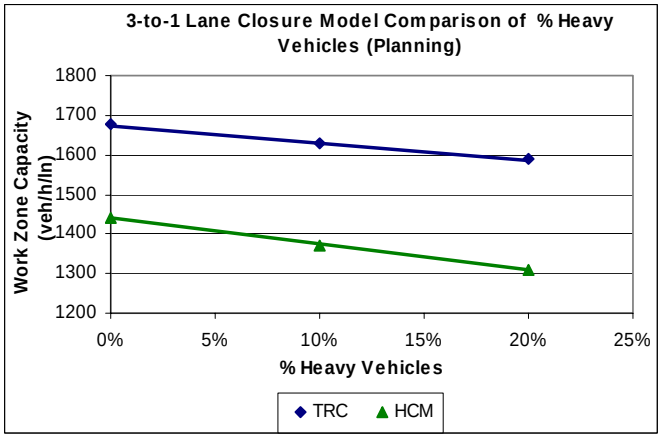


Figure 26. Comparison of Capacity Estimates Between Proposed Model, HCM 2000 and FDOT Models, for All Three Lane Closure Configurations and for Varying Percent of Heavy Vehicles (Planning Applications)

5.2.5. Example Problems

This section presents three example problems of work zone capacity estimation for planning purposes. Each example corresponds to a different lane closure configuration.

Example Problem 1

Calculate the capacity of a 2-to-1 lane closure, with the following characteristics:

- Level terrain
- 5% trucks
- Work activity present at the work zone
- Lighting conditions: daytime
- Driver population: off-peak weekdays
- Weather/Rain: light to moderate rain
- Presence of ramp within 500 ft downstream of the beginning of the work zone.
- Ramp volume R= 100 veh/h
- For Ramp: PHF = 0.90, f_{HV}, f_P = 1.0

STEPS

1. Adjust for heavy vehicle presence	$f_{HV-F} = \frac{1}{1+P_{HV}(E_{HV}-1)} = \frac{1}{1+0.05*(2.4-1)}$ $f_{HV-F} = 0.9346$
2. Obtain % rubbernecking	There is working activity present at the work zone therefore Rubber% = 5.6 %
3. Calculate unadjusted capacity	From Equation (1) of Table 10: $C_{unadj}^{2-to-1} = 1330 + 476 * f_{HV-F} - 16.7 * Rubber\% =$ $1330 + 476 * 0.9346 - 16.7 * 5.6 \Rightarrow$ $C_{unadj}^{2-to-1} = 1681 pc/h/\ln$
4. Adjust for lighting conditions	For daytime $f_l = 1.00$
5. Adjust for driver population	For off-peak weekdays $f_d = 0.93$
6. Adjust for rain	For light to moderate rain $f_r = 0.95$
7. Adjust for presence of ramps	$v_R = \frac{V_R}{PHF * N * f_{HV-R} * f_P} = \frac{100}{0.90*1*1*1} \Rightarrow$ $v_R = 111.11 pc/h/\ln$
8. Calculate adjusted capacity	$C_{adj}^{2-to-1} = f_l * f_d * f_r * \left(C_{unadj}^{2-to-1} - v_R\right) =$ $1.00*0.93*0.95*(1681-111) \Rightarrow$ $C_{adj}^{2-to-1} = 1387 pc/h/\ln$

Example Problem 2

Calculate the capacity of a 3-to-2 lane closure with the following characteristics:

- Level terrain
- 10% trucks
- Work activity present at the work zone
- Lighting conditions: daytime
- Driver population: off-peak weekdays
- Weather/Rain: light to moderate rain
- Presence of ramp within 500 ft downstream of the beginning of the work zone.
- Ramp volume R= 100 veh/h
- For Ramp: PHF = 0.90, f_{HV}, f_P = 1.0

STEPS

1. Adjust for heavy vehicle presence	$f_{HV-F} = \frac{1}{1+P_{HV}(E_{HV}-1)} = \frac{1}{1+0.10*(2.4-1)}$ $f_{HV-F} = 0.877$
2. Obtain % rubbernecking	There is working activity present at the work zone therefore Rubber% = 5.6%
3. Calculate unadjusted capacity	From Equation (2) of Table 10: $C_{unadj}^{3-to-2} = 1180 + 695 * f_{HV-F} - 19.8 * Rubber\% =$ $= 1180 + 695 * 0.877 - 19.8 * 5.6 \Rightarrow$ $C_{unadj}^{3-to-2} = 1679\, pc/h/\ln$
4. Adjust for lighting conditions	For daytime $f_l = 1.00$
5. Adjust for driver population	For off-peak weekdays $f_d = 0.93$
6. Adjust for rain	For light to moderate rain $f_r = 0.95$
7. Adjust for presence of ramps	$v_R = \frac{V_R}{PHF * N * f_{HV-R} * f_P} = \frac{100}{0.90*1*1*1} \Rightarrow$ $v_R = 111.11\, pc/h/\ln$
8. Calculate adjusted capacity	$C_{adj}^{3-to-2} = f_l * f_d * f_r * \left(C_{unadj}^{3-to-2} - v_R\right) =$ $1.00*0.93*0.95*(1679-111) \Rightarrow$ $C_{adj}^{3-to-2} = 1385\, pc/h/\ln$

Example Problem 3

Calculate the capacity of a 3-to-1 lane closure with the following characteristics:

- Level terrain
- 10% trucks
- Work activity present at the work zone
- Lighting conditions: daytime
- Driver population: peak hours - weekdays
- Weather/Rain: light to moderate rain
- Presence of ramp within 500 ft downstream of the beginning of the work zone.
- Ramp volume R= 100 veh/h
- For Ramp: PHF = 0.90, f_{HV}, f_P = 1.0

STEPS

1. Adjust for heavy vehicle presence	$f_{HV-F} = \frac{1}{1+P_{HV}(E_{HV}-1)} = \frac{1}{1+0.10*(2.4-1)}$ $f_{HV-F} = 0.877$
2. Obtain % rubbernecking	There is working activity present at the work zone therefore Rubber% = 5.6 %
3. Calculate unadjusted capacity	From Equation (3) of Table 10: $C_{unadj}^{3-to-1} = 1337 + 420 * f_{HV-F} - 13.9 * Rubber\% =$ $= 1337 + 420 * 0.877 - 13.9 * 5.6 \Rightarrow$ $C_{unadj}^{3-to-1} = 1627\, pc/h/\ln$
4. Adjust for lighting conditions	For daytime $f_l = 1.00$
5. Adjust for driver population	For peak hours - weekdays $f_d = 1.00$
6. Adjust for rain	For light to moderate rain $f_r = 0.95$
7. Adjust for presence of ramps	$v_R = \frac{V_R}{PHF * N * f_{HV-R} * f_P} = \frac{100}{0.90*1*1*1} \Rightarrow$ $v_R = 111.11\, pc/h/\ln$
8. Calculate adjusted capacity	$C_{adj}^{3-to-1} = f_l * f_d * f_r * \left(C_{unadj}^{3-to-1} - v_R\right) =$ $1.00*1.00*0.95*(1627-111) \Rightarrow$ $C_{adj}^{3-to-1} = 1440\, pc/h/\ln$

5.3. Capacity Estimation Model for Operational Analysis Applications

The operational analysis model can be applied when the work zone is already in place and measurements of speed, lane distributions and other work zone related inputs are available. It can also be applied to evaluate the capacity of various work zone configurations as a function of anticipated prevailing conditions. The values of vehicle speeds and distributions upstream of the work zone are the primary inputs into the models. The distance to the first upstream work zone warning sign, truck percentage, and work zone intensity are also required inputs. Speeds and lane distributions are performance measures that can be manipulated to a certain extent through warning signs, physical barriers, or enforcement. Therefore the operational analysis models proposed

here can also be used to assess the impacts of various types of work zone management strategies on capacity.

This section presents the final models developed for operational analysis applications for each lane closure configuration, followed by a sensitivity analysis evaluating the effect of changes in the independent variables on capacity estimates. Then these capacity estimates are compared to those obtained from the HCM 2000 and the current FDOT methodology. Finally a step-by-step procedure for implementing the current methodology is presented, along with several examples.

5.3.1. Unadjusted Capacity Models

This section presents the regression models of capacity for all three lane closure configurations. These represent the unadjusted capacity estimates, which are subsequently adjusted to account for the effects of additional factors (see Section 5.3.2 Step-by-Step Procedure).

2-to 1 Lane Closure Configuration

The dependent variable, C_{unadj}^{2-to-1}, represents the number of vehicles per hour per lane that travel through the open lane given a set of input values. The model is shown below:

$$
\begin{aligned}
C_{unadj}^{2-to-1} &= 1854.79 \\
&+ (-692.73) \times SignDist \\
&+ 190.76 \times f_{HV\text{-}F} \\
&+ (-12.35) \times Rubber\% \\
&+ (-467.35) \times DistrLan1(6,7) \\
&+ 829.24 \times DistrLan1(6,7) \times SignDist \\
&+ 7.43 \times SpeedLan1(6,7)adj \times SignDist \qquad (5\text{-}4)
\end{aligned}
$$

The adjusted R^2 value for the relationship in Equation 5-4 is 0.915.

3-to -2 Lane Closure Configuration

The dependent variable, C_{unadj}^{3-to-2}, represents the average number of vehicles per hour per lane that travel through the work zone, given a set of input values. To calculate the total number of vehicles per hour through the work zone, the C_{unadj}^{3-to-2} value should be multiplied by two. The model is shown below:

$$
\begin{aligned}
C_{unadj}^{3-to-2} \quad &= 917.41 \\
&+ 460.9 \times SignDist \\
&+ 853.59 \times f_{HV\text{-}F} \\
&+ (-20.38) \times Rubber\% \\
&+ -611.3 \times DistrLan1(6,7) \times SignDist \\
&+ -4.03 \times SpeedLan1(5,6)adj \times SignDist \qquad (5\text{-}5)
\end{aligned}
$$

The adjusted R^2 value for the relationship in Equation 5-5 is 0.932.

3-to -1 Lane Closure Configuration

The dependent variable, C_{unadj}^{3-to-1}, represents the number of vehicles per hour per lane that travel through the open lane given a set of input values. The model is shown below:

$$
\begin{aligned}
C_{unadj}^{3-to-1} \quad &= 1177.50 \\
&+ 549.81 \times f_{HV\text{-}F} \\
&+ (-14.52) \times Rubber\% \\
&+ 156.70 \times DistrLan3(6,7) \qquad (5\text{-}6)
\end{aligned}
$$

The adjusted R^2 value for the relationship in Equation 5-6 is 0.895. Compared to the previous models of capacity, this model is simpler, as several of the variables tested (speeds, location of upstream sign, interaction effects) were not proven to be statistically significant for a 95% confidence level. This may be because the work zone has two open lanes, which may result in a smoother transition of traffic into the work zone, with less lane changes and turbulence at the beginning of the bottleneck.

5.3.2. Step by step Procedure

This section presents the step-by step procedure for applying the operational analysis procedure to estimate the capacity of freeway work zones. Table 15 provides a list of all input data required for applying this procedure, along with the notation used in this report. To facilitate application of this procedure and estimate the capacity of the work zone before it is implemented, Table 16 (reproduced from the HCM 2000) provides estimates of speed reductions that can be applied to the speeds before the installation of the work zone to estimate the impact of various types of closures. If the work zone is installed and the speeds are directly measured in the field, Table 16 should not be used; the analyst should consider these field measurements as the adjusted values of speed.

Table 16 provides the equations for obtaining unadjusted capacity for each of the three configurations, and the equation for obtaining the final, adjusted capacity estimate, which applies to all three configurations.

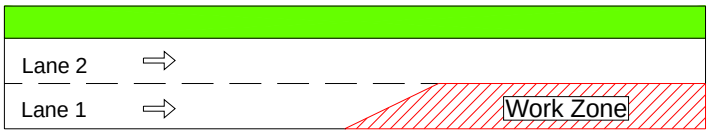
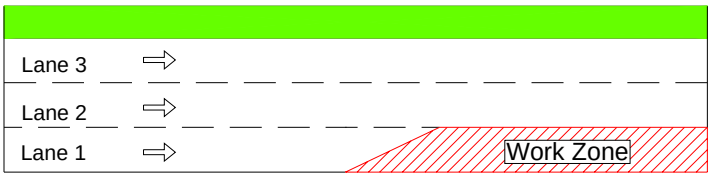
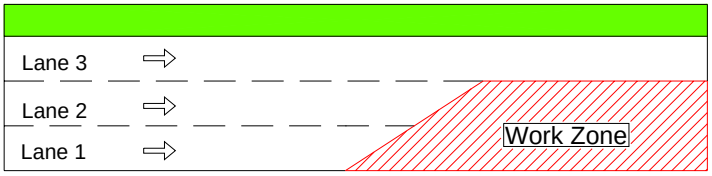
Table 15. Required Input Data for Estimating Capacity in Operational Analysis Applications

Geometric Input Data	Notation
Terrain (level, rolling, mountainous)	N/A
Sign distance (mi)	SignDist
Mainline average lane width (ft)	f_{LW}
Mainline average lateral clearance (ft)	f_{LC}
Number of lanes on the on-ramp (if one is present along the work zone)	N
Traffic Characteristics Data	
Average mainline speed on the shoulder lane upstream of the work zone (link 6,7) and upstream of the warning sign (link (5,6) (mi/h)	SpeedLan1(6,7) SpeedLan1(5,6)
Lane distribution on shoulder and median lanes (%)	DistrLan1(6,7) DistrLan3(6,7)
Driver population (peak hours-weekdays, off-peak weekdays or weekends)	f_d
Driver population for ramp (commuter of recreational)	f_p
Passenger car equivalencies (based on terrain and vehicle type percentage) for the freeway and the ramp (if present)	$E_{HV\text{-}F}$ $E_{HV\text{-}R}$ $E_{R\text{-}R}$
Percent rubbernecking (%)	Rubber%
Demand Data	
Ramp volume (veh/h)	v_R
Percent trucks on freeway and ramp (%)	$P_{HV\text{-}F}$, $P_{HV\text{-}R}$
Percent recreational vehicles on ramp (%)	$P_{R\text{-}R}$
Lighting and Weather Data	
Light conditions (daytime or nighttime with illumination)	f_l
Rain (no rain, light to moderate rain or heavy rain)	f_r

Table 16. Speed Estimation Procedure

Speed Adjustments			
Lane Width Adjustment (f_{LW})	Lane Width (ft)	Reduction in Speed (mi/h)	
	12	0.0	
	11	1.9	
	10	6.6	
Lateral Clearance Adjustment (f_{LC})	Right-Shoulder Lateral Clearance (ft)	Reduction in Speed (mi/h)	
		Lanes in One Direction	
		1	2
	≥6	0.0	0.0
	5	0.8	0.6
	4	1.6	1.2
	3	2.4	1.8
	2	3.2	2.4
	1	4.0	3.0
	0	4.8	3.6

Table 17. Capacity Models for Operational Procedure by Type of Lane Closure

Lane Closure Type	CAPACITY MODEL FOR OPERATIONAL PROCEDURE
2 TO 1	 $C_{unadj}^{2-to-1} = 1855 - 693 * SignDist + 191 * f_{HV-F} - 12.3 * Rubber\%$ $- 467 * DistrLan1(6,7) + 829 * DistrLan1(6,7) * SignDist$ (5) $+ 7.43 * SpeedLan1(6,7)_{adj} * SignDist$
3 TO 2	 $C_{unadj}^{3-to-2} = 917 + 461 * SignDist + 854 * f_{HV-F} - 20.4 * Rubber\%$ $- 611 * DistrLan1(6,7) * SignDist - 4.03 * SpeedLan1(5,6)_{adj} * SignDist$ (6)
3 TO 1	 $C_{unadj}^{3-to-1} = 1177 + 550 * f_{HV-F} - 14.5 * Rubber\% + 157 * DistrLan3(6,7)$ (7)
ALL	$C_{adj} = f_l * f_d * f_r * (C_{unadj} - v_R)$ (8)

The step-by-step procedure for estimating capacity for operational analysis applications is presented in Table 18.

Table 18. Computational Steps for Determining Work Zone Capacity in Operational Applications

STEPS

1. Adjust for heavy vehicle presence	$f_{HV-F} = \dfrac{1}{1 + P_{HV-F}(E_{HV-F} - 1)}$ Where: $E_{HV\text{-}F}$ = 2.4, for level terrain $E_{HV\text{-}F}$ = 3.0, 3% 1-km upgrade $P_{HV\text{-}F}$ = proportion of heavy vehicles
2. Obtain % rubbernecking	Rubber% = 0% for no work activity Rubber% = 5.6 % for presence of work activity
3. Obtain the Sign Distance	This is the distance from the first upstream work zone warning sign to the beginning of the work zone (mi).
4. Obtain the vehicular lane distributions upstream of the work zone	*DistrLan1(6,7)*: Percentage of traffic on the shoulder (closed) lane downstream from warning sign and upstream of the work zone(applicable to the 2-to-1 and 3-to-2 capacity models). *DistrLan3(6,7)*: Percentage of traffic on the median (open) lane downstream from warning sign and upstream of the work zone (applicable to the 3-to-1 capacity model).
5. Obtain the speeds of each lane upstream of the work zone	$SpeedLan1(6,7)_{unadj}$: Average speed on the shoulder lane downstream of the warning sign and upstream of the work zone (applicable to the 2-to-1 capacity model) $SpeedLan1(5,6)_{unadj}$: Estimated average speed on the shoulder lane ½ mi upstream of the warning sign (applicable to the 3-to-2 capacity model)

6. (OPTIONAL – USE ONLY IF FIELD MEASURED SPEEDS ARE NOT AVAILABLE) Adjust speeds for lane width and for lateral clearance	If speeds are estimated from speed data: Subtract the lane width and lateral clearance adjustment factors from the measured speeds (Table 17). $SpeedLan1(6,7)_{adj} = SpeedLan1(6,7)_{unadj} - f_{LW} - f_{LC}$ $SpeedLan1(5,6)_{adj} = SpeedLan1(5,6)_{unadj} - f_{LW} - f_{LC}$
7. Calculate unadjusted capacity	Use capacity models from equations (6) through (8) depending on the lane closure type
8. Adjust for lighting conditions	f_l = 1.00 for daytime f_l = 0.96 nighttime with illumination
9. Adjust for driver population	f_d = 1.00 peak hours-weekdays f_d = 0.93 off-peak weekdays f_d = 0.84 weekends
10. Adjust for rain	f_r = 1.00 no rain f_r = 0.95 light to moderate rain f_r = 0.90 heavy rain
11. Adjust for presence of ramps	Use when on ramp is located within 500 ft of work zone. The capacity of the work zone is decreased by the ramp volume (up to a maximum of half of the capacity of one lane). Obtain equivalent passenger-car flow rate for the ramp volume $v_R = \frac{V_R}{PHF * N * f_{HV-R} * f_P}$, where: V_R = the ramp volume (veh/h) N = ramp number of lanes f_P = driver population factor for ramp volume f_{HV-R} = Heavy vehicle adjustment factor for the ramp volume as defined in HCM 2000 Equation 23-3. $f_{HV-R} = \frac{1}{1 + P_{HV-R}(E_{HV-R} - 1) + P_{R-R}(E_{R-R} - 1)}$
12. Calculate adjusted capacity	$C_{adj} = f_l * f_d * f_r * (C_{unadj} - v_R)$

5.3.3. *Sensitivity Analysis*

As for the planning applications models, sensitivity analysis was performed to evaluate the impact of changes to specific input variables to the capacity estimate, and confirm that the trends in the models reflect the trends in the simulated data. The sensitivity analysis pertains only to the models estimating unadjusted capacity. Ten different input scenarios, shown in Table 19, were developed and tested. These scenarios were developed based on reasonable ranges of values for each input variable. The unadjusted capacity values were calculated using equations 5 through 7 in Table 17.

Table 19. Sensitivity Analysis Inputs and Capacity Estimates for Operational Models

Scenario#	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Rubber%	5.6	0	0	0	0	0	5.6	5.6	5.6	5.6
$\mathbf{P_{HV\text{-}F}}$	0.2	0.0	0.2	0.2	0.1	0.0	0.0	0.2	0.2	0.1
$\mathbf{E_{HV\text{-}F}}$	3.0	2.4	3.0	3.0	2.4	2.4	2.4	3.0	3.0	2.4
$\mathbf{f_{HV\text{-}F}}$	0.714	1.0	0.714	0.714	0.877	1.0	1.0	0.714	0.714	0.877
SpeedLan1(6,7)$_{adj}$ **SpeedLan1(5,6)$_{adj}$**	20	50	35	50	20	35	20	50	35	35
DistrLan1(6,7)	0.3	0.7	0.5	0.5	0.3	0.7	0.7	0.5	0.3	0.7
SignDist	0.5	1.5	1	1.5	0.5	0.5	1.5	1	1	1.5
DistrLan3(6,7)	0.4	0.3	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.3
C_{unadj}^{2-to-1}	1635	2107	1739	1897	1735	1793	1704	1782	1598	1848
C_{unadj}^{3-to-2}	1511	1519	1541	1458	1765	1717	1586	1367	1549	1390
C_{unadj}^{3-to-1}	1551	1774	1633	1617	1722	1790	1693	1551	1551	1625

Figure 27 presents the sensitivity analysis results for the 2-to-1 lane configuration. The results indicate that the three parameters (sign distance, speed upstream of the work zone, and percent of traffic in) have an overall positive effect on capacity, with speed having the greatest impact. This likely happens because higher speeds on the lane to be closed result in higher throughput for the work zone. The sensitivity analysis results for

the rubbernecking factor and the presence of heavy vehicles are similar to those presented for the planning models, thus, they are not shown here.

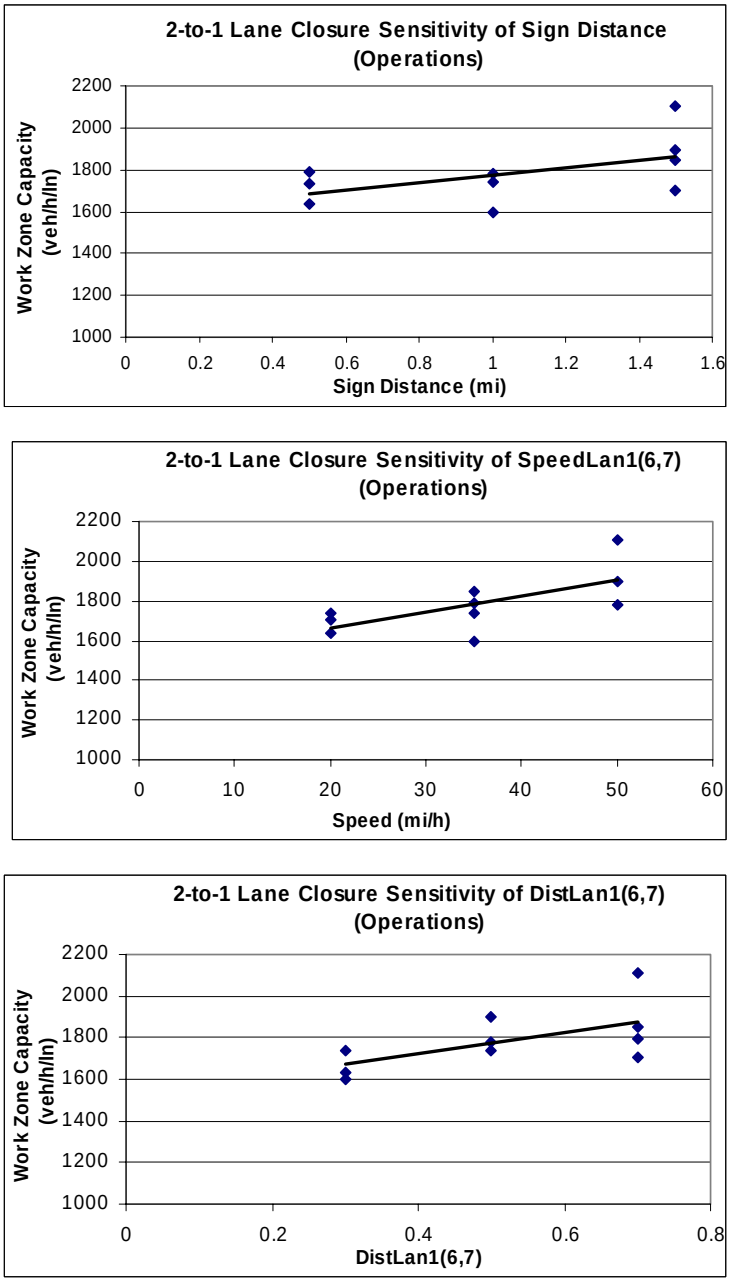


Figure 27. Sensitivity Analysis of (A) Sign Distance, (B) SpeedLan1(6,7) and (C) DistLan1(6,7) for the 2-to-1 Lane Closure Capacity Model (Operational Applications)

Figure 28 presents the sensitivity analysis results for the 3-2 lane configuration. As shown, the sign distance, the speed and the distribution of traffic all have a negative effect on capacity for the scenarios tested here. The speed found to be significant for this

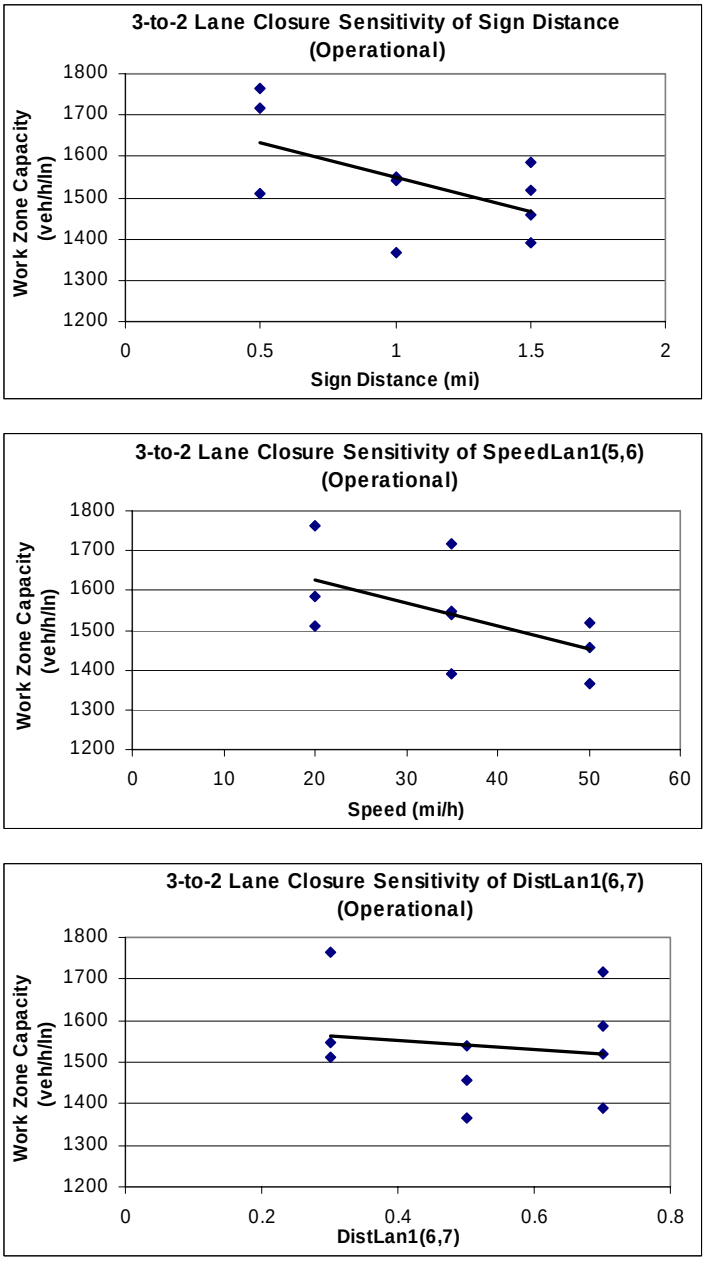


Figure 28. Sensitivity Analysis of (A) Sign Distance, (B) SpeedLan1(5,6) and (C) DistLan1(6,7) for the 3-to-2 Lane Closure Capacity Model (Operational Applications)

configuration is that upstream of the warning sign (not upstream of the work zone as in the 2-to-1 configuration). This speed measurement is shown to have the greatest impact on capacity, compared to the other two parameters. Higher speeds upstream of the warning sign on the lane to be closed might create greater turbulence for the through vehicles on the open lanes, thus reducing the capacity of the work zone.

The capacity model for the 3-to-1 lane closure is simpler than the previous models. Statistical analysis showed that the work zone capacity for this type of lane closure is not related to the location of the warning sign or the speed upstream of the lane drop. This occurs probably due to the fact that traffic operations are quite congested from the merging of 3 lanes into only 1. As a result, the speed of the vehicles even upstream of the sign distance is reduced due to the long queues that are forming at the bottleneck. Thus, only the distribution of traffic on the open lane was found to be statistically significant, as it gives an indication of the amount of friction between the vehicles that are traveling along the open lane and the vehicles that try to merge. Figure 29 shows the relationship between the percent of traffic in the open lane and capacity, for the ten scenarios tested.

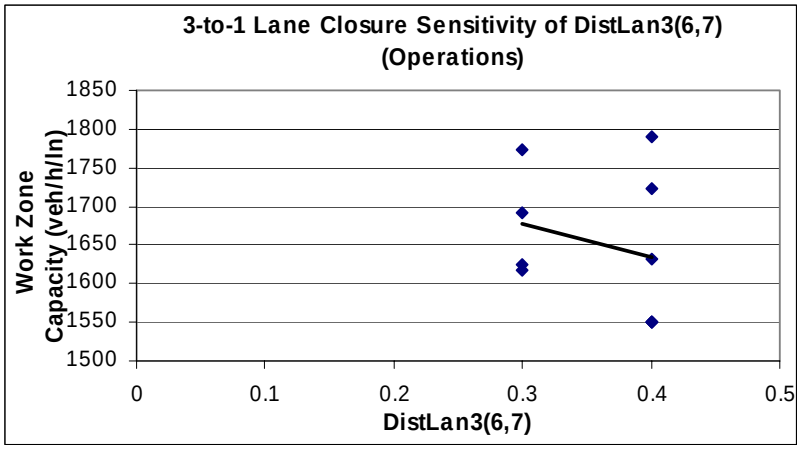


Figure 29. Sensitivity Analysis of DistLan3(6,7) for the 3-to-1 Lane Closure Capacity Model (Operational Applications)

5.3.4. Comparisons to the HCM 2000 and FDOT Lane Closure Analysis

The proposed models of capacity were compared to the HCM 2000 and the current FDOT guidelines, and the results are presented in Table 1320. To perform the comparison, a specific work zone configuration (labeled the default case) was developed

and used to test each model. Then each of the model parameters were varied and the respective capacity estimates were obtained from each of the three methods. Since each of these methods includes different input parameters, an effort was made to choose input values that are compatible and comparable. The default case has the following characteristics:

- Lane Width, LW = 11 ft
- Lateral Clearance, LC = 6 ft
- Medium to intense work zone activity: Rubbernecking factor = 5.6% (for proposed models), -160 pc/h/ln (for HCM 2000 model)
- Level terrain
- Heavy Vehicles % = 10%: PCE factor = 2.4 (for proposed models), 1.5 (for HCM 2000 model)
- Sign Distance = 1.0 mi
- Speed in Lane 1 (unadjusted) = 20 mi/h
- Lane Distribution in to-be-closed lane = 0.4
- Lane Distribution in open lane = 0.4
- No rain, commuter traffic only, no ramps in the vicinity of the work zone, good lighting conditions.

Table 20. Parameter Values for Model Comparisons – Operational Application

Proposed Models					
Parameter	Default Values	Range Values	C_{unadj}^{2-to-1}	C_{unadj}^{3-to-1}	C_{unadj}^{3-to-2}
%Rubber	5.6	0	1609	1722	1810
		5.6	1540	1641	1696
f_{HV-F}	0.877	1.000	1563	1709	1800
		0.877	1540	1641	1696
		0.781	1522	1588	1614
SignDist	1.0	0.5	1653	—	1624
		1.0	1540	—	1696
		1.5	1426		1767
$Speed_{unadj}$	20	15	1503	—	1716
		20	1540	—	1696
		25	1577	—	1675
Lane Width	11	10	1505	—	1714
		11	1540	—	1696
		12	1554	—	1688
Lateral Clearance	6	6	1510	—	1708
		5	1516	—	1705
		4	1522	—	1703
		3	1528	—	1700
		2	1534	—	1698
		1	1540	—	1696
Lane Distribution	0.4	0.3	1504	1625	1757
		0.4	1540	1641	1696
		0.5 (not for 3-to-1 model)	1576	—	1634

Table 20. Parameters Values for Model Comparisons – Operational Application (cont'd)

HCM 2000 Model					
%Rubber	-160	160 -160	1676 1371	1676 1371	1676 1371
$f_{HV\text{-}F}$	0.952	1.000 0.952 0.909	1440 1371 1309	1440 1371 1309	1440 1371 1309
SignDist	1.0	*N/A*	1371	—	1371
$Speed_{unadj}$	20	*N/A*	1371	—	1371
Lane Width	11	*N/A*	1371	—	1371
Lateral Clearance	6	*N/A*	1371	—	1371
Lane Distribution	0.4	*N/A*	1371	1371	1371
FDOT					
Lane Width	11	10 11 12	1620 1728 1800	— — —	1620 1728 1800
Lateral Clearance	6	6 5 4 3 2 1	1548 1620 1656 1692 1710 1728	— — — — — —	1548 1620 1656 1692 1710 1728
Obstruction Factor	0.96	*N/A*	1728	—	1728

Figures 30 though 32 present the effect of rubbernecking factor, percent of trucks, location of warning sign, unadjusted speed, lane width and lateral clearance, and lane distributions on capacity for all three models. These show that the capacity estimates from the proposed operational models fall somewhere between the HCM 2000 and the FDOT models. Similarly to the planning models and compared to the operational

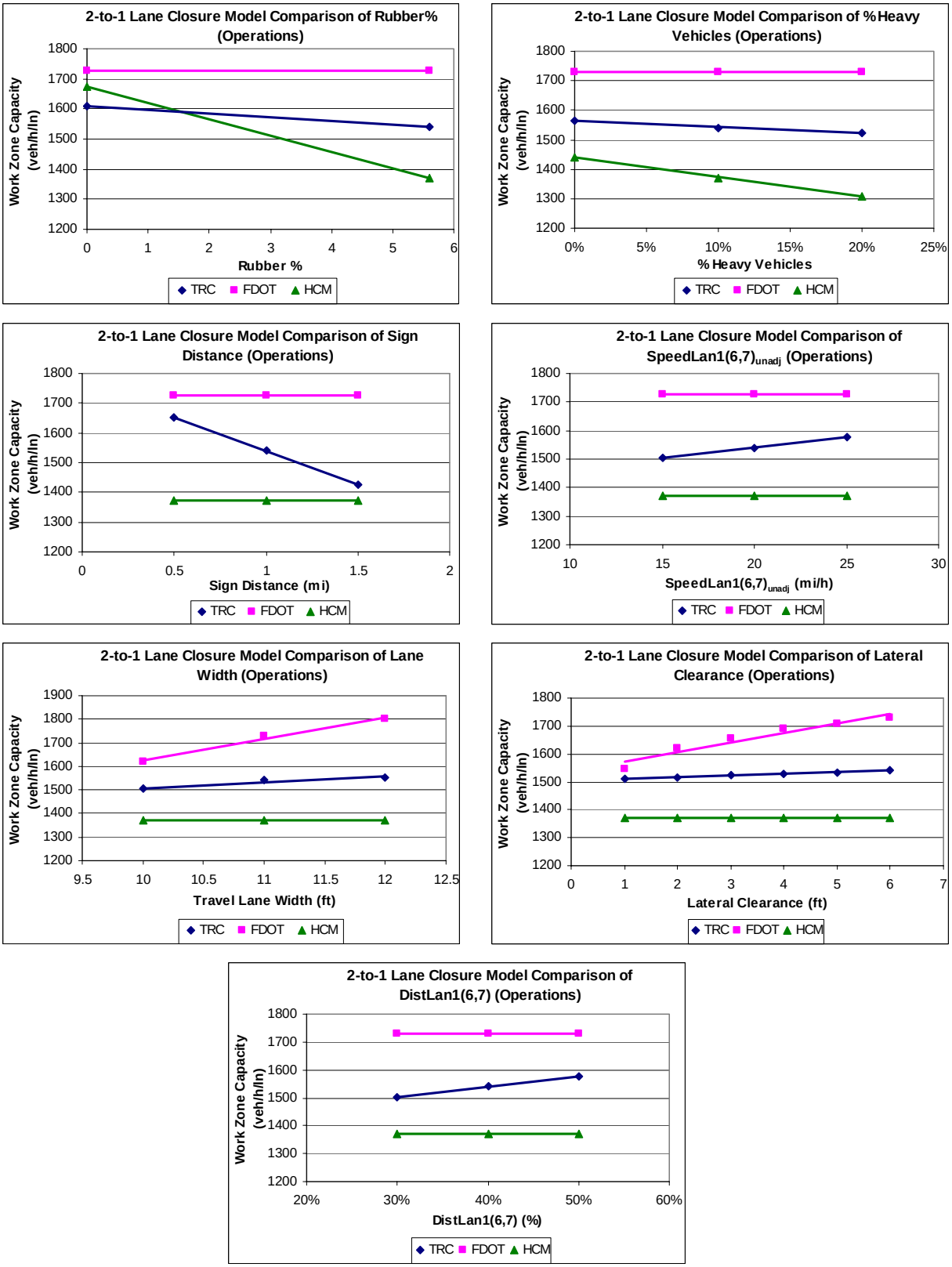


Figure 30. Comparison of Capacity Estimates Between Proposed Model, HCM 2000 and FDOT Models, for 2-to-1 Lane Closure Configurations and for All Model Parameters (Operational Applications)

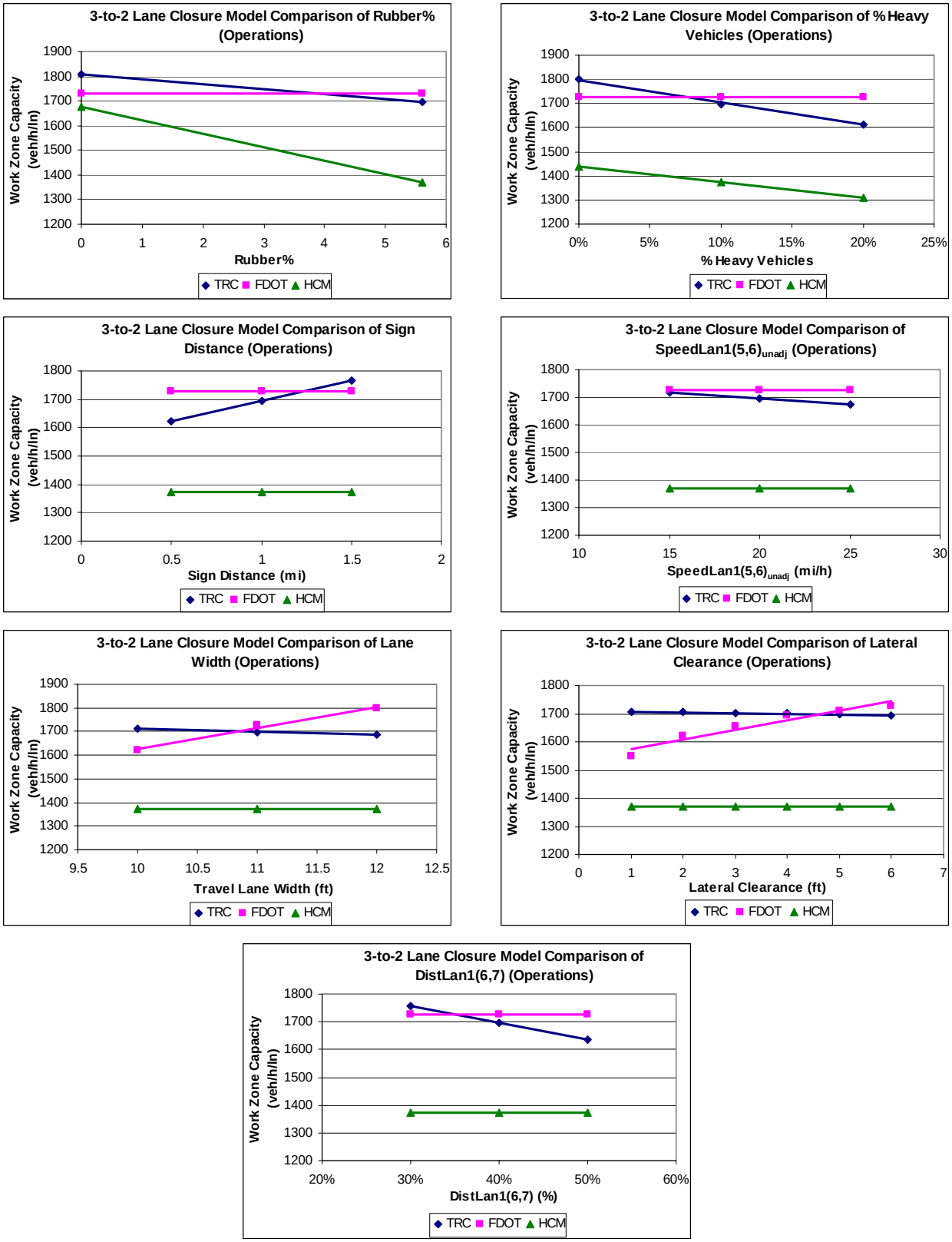


Figure 31. Comparison of Capacity Estimates Between Proposed Model, HCM 2000 and FDOT Models, for 3-to-2 Lane Closure Configurations and for All Model Parameters (Operational Applications)

analysis method the HCM 2000 method underestimates capacity and the FDOT method overestimates it. Also, as was the case for the planning models, this comparison assumed favorable lighting and other environmental conditions. Given unfavorable conditions such as inadequate lighting, rain, driver population unfamiliar with the site, the predicted capacity from the operational analysis models will be lower.

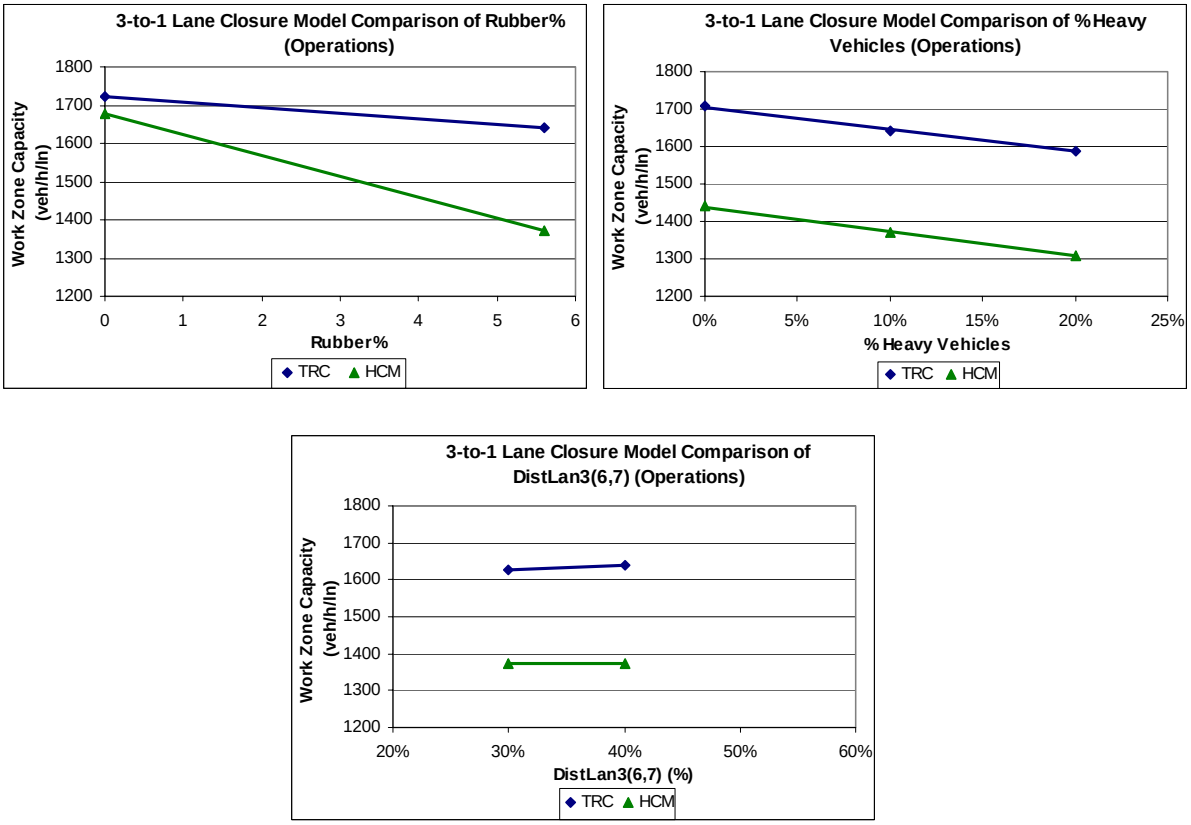


Figure 32. Comparison of Capacity Estimates Between Proposed Model and HCM 2000, for 3-to-1 Lane Closure Configurations and for All Model Parameters (Operational Applications)

5.3.5. Example Problems

This section presents three example problems of work zone capacity estimation for operational analysis. Each example analyzes a different lane closure configuration.

Example Problem 1

Calculate the capacity of a 2-to-1 lane closure with the following characteristics:

- Sign Distance = 0.5 mi
- Level terrain
- 5% trucks
- Work activity present at the work zone
- 40% traffic on lane 1 (shoulder lane)
- Lane width = 12 ft
- Lateral clearance = 4 ft
- Estimated average speed on shoulder lane between the sign and the beginning of the work zone = 45 mi/h
- Lighting conditions: daytime
- Driver population: off-peak weekdays
- Weather/Rain: light to moderate rain
- Presence of ramp within 500 ft downstream of the beginning of the work zone.
- Ramp volume R= 100 veh/h
- For Ramp: PHF = 0.90, f_{HV}, f_P = 1.0

STEPS

1. Adjust for heavy vehicle presence	$f_{HV-F} = \frac{1}{1+P_{HV}(E_{HV}-1)} = \frac{1}{1+0.05*(2.4-1)}$ $f_{HV-F} = 0.9345$
2. Obtain % rubbernecking	There is working activity present at the work zone therefore Rubber% = 5.6%
3. Determine the Sign Distance	SignDist = 0.5 mi
4. Determine the distribution of the right-most lane	0.40 of traffic on the shoulder lane
5. Determine the speed of the right-most lane	Estimated average speed between the sign and the beginning of the work zone is $SpeedLan1(6,7)_{unadj}$ = 45 mi
6. Adjust speeds for lane width and for lateral clearance	$SpeedLan1(6,7)_{adj} = SpeedLan1(6,7)_{unadj} - f_{LW} - f_{LC} =$ 45 – 0.0 – 1.6 = 43.4
7. Calculate unadjusted capacity	From Equation (6): $C_{unadj}^{2-to-1} = 1855 - 693*SignDist + 191*f_{HV-F}$ $-12.3*Rubber\% - 467*DistrLan1(6,7)$ $+829*DistrLan1(6,7)*SignDist$ $+7.43*SpeedLan1(6,7)_{adj}*SignDist =$ $=1855-693*0.5+191*0.9345-12.3*5.6-467*0.4$ $+829*0.4*0.5+7.43*43.4*0.5 \Rightarrow$ $C_{unadj} = 1758\,pc/h/\ln$
8. Adjust for lighting conditions	For daytime f_l = 1.00
9. Adjust for driver population	For off-peak weekdays f_d = 0.93
10. Adjust for rain	For light to moderate rain f_r = 0.95
11. Adjust for presence of ramps	$v_R = \frac{V_R}{PHF*N*f_{HV-R}*f_P} = \frac{100}{0.90*1*1*1} \Rightarrow$ $v_R = 111.11\,pc/h/\ln$
12. Calculate adjusted capacity	$C_{adj}^{2-to-1} = f_l*f_d*f_r*\left(C_{unadj}^{2-to-1} - v_R\right) =$ $1.00*0.93*0.95*(1758-111) \Rightarrow$ $C_{adj}^{2-to-1} = 1455\,pc/h/\ln$

Example Problem 2

Calculate the capacity of a 3-to-2 lane closure with the following characteristics:

- Sign Distance = 0.5 mi
- Level terrain
- 10% trucks
- Work activity present at the work zone
- 40% traffic on lane 1 (shoulder lane)
- Lane width = 12 ft
- Lateral clearance = 4 ft
- Estimated average speed on shoulder lane upstream of the warning sign = 45 mi/h
- Lighting conditions: daytime
- Driver population: off-peak weekdays
- Weather/Rain: light to moderate rain
- Presence of ramp within 500 ft downstream of the beginning of the work zone.
- Ramp volume R= 100 veh/h
- For Ramp: PHF = 0.90, f_{HV}, f_P = 1.0

STEPS

1. Adjust for heavy vehicle presence	$f_{HV-F} = \frac{1}{1+P_{HV}(E_{HV}-1)} = \frac{1}{1+0.10*(2.4-1)}$ $f_{HV-F} = 0.877$
2. Obtain % rubbernecking	There is working activity present at the work zone therefore Rubber% = 5.6%
3. Determine the Sign Distance	SignDist = 0.5 mi
4. Determine the distribution of the right-most lane	0.40 of traffic on the shoulder lane
5. Determine the speed of the right-most lane	Estimated average speed upstream of the sign is $SpeedLan1(5,6)_{unadj}$ = 45 mi
6. Adjust speeds for lane width and for lateral clearance	$SpeedLan1(5,6)_{adj} = SpeedLan1(5,6)_{unadj} - f_{LW} - f_{LC} =$ 45 – 0.0 – 1.6 = 43.4
7. Calculate unadjusted capacity	From Equation (7): $C_{unadj}^{3-to-2} = 917 + 461*SignDist + 854*f_{HV-F}$ $-20.4*Rubber\% - 611*DistrLan1(6,7)*SignDist$ $-4.03*SpeedLan1(5,6)_{adj}*SignDist =$ $917+461*0.5+854*0.877-20.4*5.6$ $-611*0.4*0.5-4.03*43.4*0.5 \Rightarrow$ $C_{unadj}^{3-to-2} = 1573\,pc/h/\ln$
8. Adjust for lighting conditions	For daytime f_l = 1.00
9. Adjust for driver population	For off-peak weekdays f_d = 0.93
10. Adjust for rain	For light to moderate rain f_r = 0.95
11. Adjust for presence of ramps	$v_R = \frac{V_R}{PHF*N*f_{HV-R}*f_P} = \frac{100}{0.90*1*1*1} \Rightarrow$ $v_R = 111.11\,pc/h/\ln$
12. Calculate adjusted capacity	$C_{adj}^{3-to-2} = f_l*f_d*f_r*\left(C_{unadj}^{3-to-2} - v_R\right) =$ $1.00*0.93*0.95*(1573-111) \Rightarrow$ $C_{adj}^{3-to-2} = 1291\,pc/h/\ln$

Example Problem 3

Calculate the capacity of a 3-to-1 lane closure with the following characteristics:

- Level terrain
- 10% trucks
- Work activity present at the work zone
- 40% traffic on median lane (open lane)
- Lane width = 12 ft
- Lateral clearance = 4 ft
- Lighting conditions: daytime
- Driver population: peak hours - weekdays
- Weather/Rain: light to moderate rain
- Presence of ramp within 500 ft downstream of the beginning of the work zone.
- Ramp volume R= 100 veh/h
- For Ramp: PHF = 0.90, f_{HV}, f_P = 1.0

STEPS

1. Adjust for heavy vehicles	$f_{HV-F} = \frac{1}{1+P_{HV}(E_{HV}-1)} = \frac{1}{1+0.10*(2.4-1)}$ $f_{HV-F} = 0.877$
2. Obtain % rubbernecking	There is working activity present at the work zone therefore Rubber% = 5.6%
3. Determine the distribution of the right-most lane(s)	Distribution of traffic on median lane: *DistrLan3(6,7)* = 0.40
4. Calculate unadjusted capacity	From Equation (8): $C_{unadj}^{3-to-1} = 1177 + 550 * f_{HV-F}$ $-14.5 * Rubber\% + 157 * DistrLan3(6,7) =$ $= 1177 + 550 * 0.877 - 14.5 * 5.6 + 157 * 0.4 \Rightarrow$ $C_{unadj}^{3-to-1} = 1641 pc/h/\ln$
5. Adjust for lighting conditions	For daytime $f_l = 1.00$
6. Adjust for driver population	For peak hours - weekdays $f_d = 1.00$
7. Adjust for rain	For light to moderate rain $f_r = 0.95$
8. Adjust for presence of ramps	$v_R = \frac{V_R}{PHF * N * f_{HV-R} * f_P} = \frac{100}{0.90*1*1*1} \Rightarrow$ $v_R = 111.11 pc/h/\ln$
9. Calculate adjusted capacity	$C_{adj}^{3-to-1} = f_l * f_d * f_r * \left(C_{unadj}^{3-to-1} - v_R\right) =$ $1.00*1.00*0.95*(1641-111) \Rightarrow$ $C_{adj}^{3-to-1} = 1454 pc/h/\ln$

6. CONCLUSIONS AND RECOMMENDATIONS

The existing FDOT lane closure analysis method was developed several years ago, and it is the desire of the Department to evaluate and update it accordingly. The objective of this research was to develop analytical models and procedures for estimating the capacity of a freeway work zone considering various geometric and traffic parameters. Due to unavailability of real-world work zone data, the study was based on simulation. CORSIM (version 5.1) was used to develop a comprehensive database which was used in the analytical model development. Models were developed for three types of work zone configurations (2-to-1, 3-to-2, and 3-to-1 lane closures). Two different types of models were developed for each lane closure configuration; a planning model and an operational model. The planning model is the simplest one and it applies when a capacity estimate is required, but the work zone is not in place. The operational model requires more data as input, and it may be used for estimating the capacity of an existing work zone.

The following were concluded from the research:

- The capacity estimates obtained from the HCM 2000 and the current FDOT procedure are based on different input variables and therefore are difficult to compare.
- The proposed methodology (both the planning and operational analysis applications) considers a larger combination of geometric, traffic, and work zone characteristics to estimate capacity.
- The capacity values obtained by the proposed methodology fall somewhere between the HCM 2000 and the FDOT procedure estimates (for both the planning and operational analysis applications). Generally the HCM 2000 values are lower, while the FDOT values are higher than those obtained by the proposed method.

Since this research was entirely based on simulation, the results and conclusions should be viewed with caution. It is likely that field observations would result in different capacity values, and that additional factors (such as day of week, time of day,

etc.) would affect the results. The general trends however observed with simulation should generally be valid in the field as well.

The following are the recommendations from this research:

- The methods presented here should be applied on a trial basis to existing and upcoming work zone projects, so that they can be tested and validated for actual projects before widely applied.
- Field data should be collected at various sites and with various work zone configurations, so that the procedures developed here can be thoroughly evaluated, and the simulated capacity estimates compared to field estimates.

In addition, the following recommendations are provided regarding possible improvements to the CORSIM simulator for improving its capability to simulate work zones:

- The software should consider specific algorithms for accommodating work zones (rather than using the incident or lane closure function). These algorithms should consider the taper section provided upstream of the work zone, and should provide a specific relationship between the rubbernecking factor and work intensity in the work zone.
- CORSIM results are currently not sensitive to the effects of closing the right vs. the left lane. Its algorithms should be modified to allow for relatively slower traffic in the rightmost lanes (this should not be restricted to trucks only).
- CORSIM results are currently not sensitive to the length of the work zone. Previous research has shown that this might actually affect capacity, therefore additional research is warranted to evaluate whether this is the case, and if yes, to modify CORSIM accordingly.
- Various geometric elements (such as lane width and shoulder width) are currently not considered within CORSIM. Its algorithms should be modified to consider such factors more generally and also with respect to work zones.

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