SIMULATION-BASED APPROACH TO ESTIMATE THE CAPACITY OF A TEMPORARY FREEWAY WORK ZONE LANE CLOSURE

By

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This document is dedicated to my parents and sister
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The Florida Department of Transportation (FDOT) is interested in updating its methodologies for estimating capacities on freeway work zones in Florida. The current methods have not been modified since 1995, and the FDOT is particularly interested in new ways to facilitate the scheduling and managing of lane closures. This thesis proposes new simulation-based models for estimating the capacity of a temporary freeway work zone lane closure. Some of the factors considered in model development include the location of the upstream warning sign, the presence of trucks, the presence of law enforcement and/or heavy equipment, and the length of the work zone. In addition to these inputs, the average speeds per vehicle and the vehicular lane distributions for specific network links were considered in model development. A large matrix of scenarios was created so that the effects of all combinations of factors could be observed. Data were collected from simulation of these scenarios using the software package CORSIM 5.1. Three lane closure configurations—2-to-1, 3-to-2, and 3-to-1—were
simulated and one model for estimating capacity was developed for each. All models for each lane closure configuration consider the input factors named previously as well as average speeds per vehicle and lane distributions of vehicles upstream of the work zone lane closure. The final models show the effects of each of these factors on the throughput capacity of a freeway lane closure. A higher fraction of vehicles in the to-be closed lane(s) prior to the work zone leads to a significant decrease in capacity. Likewise, higher speeds in the to-be closed lane(s) also lead to a capacity decrease. The result of this simulation modeling offers valuable insights into the relative capacities under different geometric configurations and traffic stream scenarios. Future research is recommended to calibrate the models to actual field conditions.
CHAPTER 1
INTRODUCTION

This section presents a brief description of existing problems and current issues facing transportation agencies. A background is given on specific problem areas and the efforts attempted to increase efficient traffic stream flow through a work zone lane closure. The problem statement is then provided, followed by a concise statement of objectives for this research.

Background

Many state transportation agencies are experiencing growing congestion and traffic delays in work zones on rural interstate highways. This congestion results in unproductive and wasteful delays for both motorists and commercial vehicles. It also creates hazardous conditions in which vehicles stopped in the queues are being approached by vehicles upstream at very high speeds. The delays also result in driver frustration, making some drivers willing to take unsafe risks in an effort to bypass delays.

The Florida Department of Transportation (FDOT) is currently interested in updating its existing methodologies for estimating capacity values through a lane closure. These capacity values through work zones are important so that queues and thus delays can be accurately estimated as well. The level of operation of a facility can be assessed from these queue lengths and delay values. The current methods have not been updated since 1995, and the FDOT is particularly interested in an updated method that will facilitate the scheduling and managing of short-term work zone lane closures on freeways. The development of this updated capacity estimation procedure will form a
part of a decision matrix that the FDOT is developing to assist engineers and contractors in selecting the proper tools to evaluate lane closures.

The need to maintain adequate traffic flow through short-term interstate work zones is vital on today’s heavily-traveled freeways. Numerous states have policies that provide guidance for when short-term lane closures can be instituted. These policies are related to maximum allowable traffic flows, vehicle delays, and queue lengths. Generally, these threshold limits are defined on a state by state basis as a function of traffic stream characteristics, highway geometry, work zone location, type of construction activities, and work zone configuration (Sarasua, 2004).

Limited research by State Departments of Transportation—Nebraska and Indiana, for example—has been conducted involving the identification and evaluation of alternative strategies designed to control traffic speeds and merging operations in advance of lane closures (McCoy et al., 1999). In addition, work has been done in the fields of early merging and late merging strategies: models have been developed to predict delays, queue lengths, and lane capacities using many rural interstate areas of the United States as observation sites for data gathering (Beacher et al., 2005). The early merge encourages vehicles to merge into the through lane at locations far upstream of the lane closure. This can be achieved by signs or physical barriers. The late merge concept is designed to encourage drivers to use all lanes approaching a lane closure and then alternate their entry into the through lane, guided by static signs in addition to normal work zone traffic control. Although some states have put these into practice, only a handful of short-term field studies have formally evaluated their effectiveness. There is
little information available on when the early or late merge should be used, however, and a limited understanding of the factors that influence their performance.

The FDOT requires an updated method that will facilitate the scheduling and managing of the lane closures and considers additional operational factors. Some of the same factors used in the current methodology will be considered as well as new factors that may also have an effect on capacity reduction.

**Problem Statement**

The existing procedure used by the FDOT applies an obstruction factor based on lateral clearance and travel lane width, and a work zone factor based on work zone length to the base capacity to estimate a restricted capacity. The procedure was developed in 1995 and does not account for operating characteristics of the facility. It is also limited in that the restricted capacities are estimated for 2, 4, and 6-lane two-way facilities that are converted into one-way facilities. The updated capacity model will consider several additional operating factors in addition to those considered in the current methodology. Furthermore, the updated model will estimate restricted capacities for one-way freeway facilities with lane reductions.

**Research Objective**

The objective of this research is to develop an analytical model to estimate the capacity of a temporary freeway work zone based on various geometric and traffic factors. One factor of particular interest is the vehicular lane distributions at different distances upstream of the lane closure. The effect of lane distributions of vehicles upstream of a temporary freeway work zone on the capacity of the work zone has not been previously investigated. This relationship is important for selecting an optimal traffic management strategy to implement in order to maximize traffic flow and
passenger safety through the work zone. Another new factor that will be considered is the average travel speed of vehicles by lane, also upstream of the work zone. This factor will serve to compare capacity values at different speeds, potentially leading to speed-control strategies to maximize throughput. The lane distributions’ and upstream speeds’ relationship to the work zone environment and early merge and late merge implementation can begin to answer questions regarding which strategy may be preferred for a given set of environmental and geometric conditions.

The model(s) developed will be based on the work zone environment and geometry, the percentage of large trucks present in the traffic stream, and the presence of other conditions that may affect capacity through the lane closure. The relationships between the lane distributions and performance measures through the lane closure will also be developed to enhance the traffic management strategy selection process.
CHAPTER 2
LITERATURE REVIEW

An extensive literature review was conducted to identify and evaluate existing research involving freeway work zone lane closures. Specific focus was given to capacity models developed for estimating vehicular flow through said lane closures. This chapter presents several angles of work zone capacity research ranging from existing capacity models to their implementation as part of different types of traffic management strategies. The first section discusses the treatment of work zone capacity in the Highway Capacity Manual (HCM 2000). The next section presents a review of the current FDOT methodology and its limitations, followed by a review of the literature on capacity and its definition for work zones. 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 freeway merging and general traffic management strategies is reviewed. Then, a section is presented outlining previous research on queuing and delay estimation; both being important in identifying additional factors that may affect capacity. The last section includes a brief summary of the findings and recommendations from the literature.

Work Zone Capacity in the Highway Capacity Manual (HCM2000)

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) 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:

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

(Eq. 2-1)

where

\[ c_a = \text{adjusted mainline capacity (veh/h)} \]

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

An additional factor discussed in the HCM 2000, which would decrease capacity and can be considered, 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.

Current FDOT Methodology

The Florida Department of Transportation is interested in updating its methodology for estimating restricted capacity through a temporary work zone lane closure. Their 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 is limited to 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, respectively, for the three configurations listed above, are 1400, 1800, and 3600 vehicles per hour. Capacity reduction factors are then applied to these base values so that an estimate of restricted capacity may be obtained. The obstruction factor is obtained from a table and 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 considered in the method is a work zone factor that is also obtained from a table. This reduction factor 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.

**Work Zone Capacity in the Literature**

There are several articles in the literature on lane-closures in freeway work zones. Krammes and Lopez (1994) presented recommendations on estimating the capacities of short-term freeway work zone lane closures. Their research 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, Equation 2-2, 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.
\[ C = (1600 + I - R) \times H \times N \]  

(Eq. 2-2)

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

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 mph. With oncoming, unsuspecting traffic arriving at 65 to 70 mph, this creates unsafe relative speeds of 100 mph, 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.

Kim et al. (2001) conducted further research on the capacity of work zones. The study objectives 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).

\[
\text{Capacity} = 1857 - 168.1 \times \text{NUMCL} - 37.0 \times \text{LOCCL} - 9.0 \times \text{HV} \\
+ 92.7 \times \text{LD} - 34.3 \times \text{WL} - 106.1 \times \text{WIH} - 2.3 \times \text{WG} \times \text{HV} \quad \text{(Eq. 2-3)}
\]

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 \times HV = Work zone grade \times Proportion of heavy vehicles

According to the above model, Kim et al. suggests 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.

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:

\[ q = 145.68 \times U^{0.6857} \]  
\[ \text{(Eq. 2-4)} \]

where:

- \( q \) = flow in passenger cars per hour per lane (pcphpl)
- \( U \) = speed in mph (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:

\[ C_{adj} = C_{U0} \times f_{HV} \times PF \]  
\[ \text{(Eq. 2-5)} \]

where

- \( C_{adj} \) = adjusted capacity (vphpl)
\[ C_{U0} = \text{capacity at operating speed U0} \]

\[ f_{HV} = \text{heavy vehicle factor} \]

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.

**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 2.0, which was released in February 2005 in its full version (Federal Highway Administration, 2000). This software 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.

**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. The distance is dependent 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).

**Other Freeway Work Zone Literature**

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

**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).

**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 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. Ullman indicates that these changes can be explained by shock wave theory within a traffic stream, and shows 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 “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 recommends that the potential effects of diversion on alternative routes should be considered a significant distance upstream of the temporary work zone (Ullman, 1996).

**Delay and Queuing**

A large part of selecting an appropriate traffic management strategy is work-zone related traffic delay. A study conducted by Chien and Chowdhurry (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.

Ullman and Dudek (2003) describe a new theoretical method that more accurately predicts the lengths of queues that develop under 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 the following in its algorithm:

- 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. However, Ullman and Dudek 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 of vehicles 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 mph 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).

**Summary and Conclusions**

A review of the literature illustrates many ways of developing a model that estimates capacity through a temporary work zone. No two procedures are alike, differing in the ways that data are collected and analyzed as well as in the selection of factors that affect capacity reduction. The following is a summary of those work-zone capacity-reducing factors that have been included in existing models:

- number of closed lanes
- heavy vehicle presence
- grade of roadway segment
- intensity of work activity
- merge strategies such as late merge and early merge
- lane widths
- presence and location of ramps
- proximity of travel lanes to work zone activity
Work zone capacity base values obtained around the country have varied since the introduction of Krammes and Lopez’s Texas-based recommendation of 1600 pcp/hpl (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 pcp/hpl, depending on the location within the state. Sarasua’s model estimates a value of 1460 pcp/hpl for South Carolina, and the QuickZone 2.0 software implements a conservative 1200 pcp/hpl in its analyses. The current FDOT procedure only considers geometric factors in its capacity reduction model and should be updated with factors that consider operational characteristics of the traffic stream.
CHAPTER 3
METHODOLOGY

At the onset of this research, the goal was to locate 4 different freeway segments with temporary lane closures. Two of these were to be lane closures on two-lane segments reduced to one lane and the remaining two were to be three-lane segments reduced to two lanes (from this point on, these will be referred to as a 2-to-1 and 3-to-2 lane closures, respectively). The data were to be collected during daylight hours via video recording devices installed at key locations throughout and upstream of the work zone. Several sites were located, but complications quickly arose. The status of the different projects (percent completed) were not known exactly, so coordinating with the project managers to set up data-collection equipment was not possible. In addition, contractors have been urged to move toward night construction on the incentive of higher pay if freeway delays are minimized. Nighttime lane closures do not experience the same volumes of traffic as during the peak hours of the day, so breakdown, a required condition for capacity estimation, is typically not observed.

As a result of these obstacles to field data collection, computer simulation of the lane closure incidents was selected as the next best tool for collecting the data. Simulation modeling cannot replace field data collection; it can, however, offer insights into the relative capacities under different geometric configurations and traffic stream scenarios. A large matrix of scenarios was thus created that considered many of the factors identified from previous research. Each scenario was input into the simulator and run 15 times to ensure that the mean error was within the tolerance limit. Data such as
speeds, vehicle lane distributions, headways, and volumes were gathered from the output files and combined with the input factors to develop significant relationships between these variables and the capacity through the work zone lane closure.

Simulator Selection

The software package CORSIM was selected for use in the study for several reasons. This software is available to the University of Florida through McTrans, allowing for a high level of software support in understanding the algorithms. In addition, CORSIM has the ability to simulate freeway sections with its integrated package FRESIM, and the 5.1 edition has been updated with an improved FRESIM engine (Owen et al., 2000). The following are the principal improvements that were made over past versions of CORSIM:

- Errors in FRESIM collision avoidance were corrected
- Destination assignment and leader determination were eliminated
- Changes were made to the logic that deals with vehicles crossing interface nodes to improve the car following between networks
- Errors in processing truck restriction lanes were corrected
- An error in the way vehicle counts on Record Type 53 were converted into entry volumes was corrected.

In addition to these improvements, FRESIM allows for the analysis of incidents on freeways as either lane closures, lane drops, or even a shoulder incident, which can be simulated by the addition of a rubbernecking factor to the length of the segment affected. Calibration of a FRESIM network is possible using techniques such as rubbernecking and car-following sensitivity factors, allowing for a realistic representation of real-world conditions.
Challenges with Previous Versions of CORSIM/FRESIM

Despite the obvious advantages, several problems arose when considering CORSIM as the software package of choice. Literature from 1995 explains that FRESIM was unreliable when simulating lane closures, as it did not account for slow-moving vehicles that severely impacted the queue lengths in the field. According to Dixon et al. (1995), the large queues observed in the field were due to the existence of one or two vehicles in a data set that traveled inexplicably slow 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 the software FRESIM version 4.5, and since then, improvements such as those named previously have led to the version 5.1 release (McTrans).

Resolved Challenges with Current Versions of CORSIM/FRESIM

After several initial simulation trials, it was determined that even CORSIM 5.1 has several processing problems with the FRESIM outputs. These problems with FRESIM were forwarded to the software development team, and the developers ran the same *.trf files so that the same outputs could be obtained and evaluated. It was concluded that these are indeed problems with CORSIM 5.1 and that the newest version, CORSIM 6.0, corrects all of these issues. Although not currently commercially available, the University has obtained a Beta copy of the newest software for testing purposes only. CORSIM 5.1 will be used for all analyses in this report.
The first problem is an inconsistency in the volumes of vehicles when reported *by link* and *by lane*. The software developers quickly corrected this issue, identifying that the correct outputs from 5.1 were those *by lane*. Therefore, only values of vehicles by lane will be extracted from version 5.1. A second issue with CORSIM 5.1 involves the output from the data stations. A data station is placed on several of the links of a freeway and headway and speed data are collected at a specified point from the upstream node (Note: this is not a detector, but a data station. Its only function is to collect speed and headway statistics at a point of interest). The output files, however, report what seems to be an incorrect distribution of headway values. There are too many values in the 0.4 to 1.2 second-range, which is not realistic for freeway operating conditions. This second issue with vehicle headways and distributions, is a result of model input driver-type parameters. Because no field data were available for calibration, these parameters are set to the default values for all simulation runs. According to the software developers, the default values for the car-following parameters are set up to maximize throughput in any scenario; as a result, the distribution may seem unrealistically skewed (McTrans). This will effectively lead to higher flow rates and thus higher capacity values through the work zone, and this issue is discussed in model development results. The third issue is related to the headway values reported by the data stations. The mean headways reported for each link should be specific and different by lane. However, for each data station, the headways are equal by lane. This issue was also resolved quickly. There is an error in output processing in version 5.1 and the headways by lane per link should be calculated from the average volume given *by lane* per link. Thus, the data collected for headways by lane was calculated and not taken directly from the incorrect output.
CORSIM 5.1—with the described corrections—will therefore be used for all analyses. Data were collected accurately from the 5.1 output based upon the corrections from the software developers.

**Modeling of Work Zones with CORSIM 5.1**

This section presents the preliminary analyses needed to create appropriate scenarios. The first section defines the operating conditions of the network simulated. The way in which CORSIM can simulate a work zone is described second, followed by a detailed justification of closing only the rightmost lanes. The last sub-section summarizes the results, including the number of runs required per scenario, and the way in which the work zone will be simulated.

**Operating Conditions**

A test network was created in order to evaluate whether a *lane drop* or *incident* approach should be used for the study. With 15% trucks present on the freeway, the breakdown volume for a 2-to-1 lane closure was found to be 1900 veh/hr. The breakdown volume, as defined for this study, is the minimum volume that will cause free-flow speeds to be reduced by 30% or more at the link immediately upstream of the lane closure. Furthermore, this decrease in speed leads to queue formation upstream of the lane closure location (for the remainder of the document, the location of the lane closure will be referred to as the bottleneck). As a result, the discharge of this queue into the work zone lane closure is causing the facility to operate at capacity. This flow, 1900 veh/hr, is used throughout the following experiments. Another consideration in operating conditions relates to the driving behavior of trucks. Throughout all experiments and simulation runs, trucks will be biased to traveling on the rightmost lane of the freeway segment. *FRESIM* provides three choices for truck behavior: 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 on the on-screen interface within *FRESIM*. For all 2-to-1, 3-to-2 and 3-to-1 lane closures, trucks will be biased to traveling in the rightmost lane or lanes.

**Simulation of a Work Zone**

There is no explicit simulation of a work zone in *FRESIM*; instead, there are two techniques that allow *FRESIM* to approximate a work zone lane closure, and both are built-in to the user-friendly interface. The first of these is identified as a *lane add/drop*. The options allow up to three lane additions or drops to occur within the same link. So, 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 again by a 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 a point of incident. Each of these can occur simultaneously and on several lanes if desired. Both techniques require an upstream distance for a warning sign, signaling that a lane closure is approaching. It should also be noted that neither technique has an input for a taper prior to the lane closure. The *incident* technique was used in all analyses for this study and the justification is given in the Results of Preliminary Analyses section.

**Lane Closure Location**

The next step was to evaluate whether closing the right lane produced the same results as closing the left lane. The value that was selected as a performance measure
was network-wide average delay. The results of the first experiment comparing the delay values between lane closure techniques as well as left and right closures are presented in the following table, Table 3 - 1.

Table 3 - 1. Delay Values for Combinations of Lane Closures and Lane Distributions (Ten Simulation Runs)

Trucks biased to rightmost lane
Results based on 10 simulation runs
All flows 1900 veh/hr

<table>
<thead>
<tr>
<th>Lane distribution L% / R%</th>
<th>Trucks %</th>
<th>Incident Delay (veh-hr)</th>
<th>Lane Drop Delay (veh-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Lane Closure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60/40</td>
<td>0</td>
<td>6.066</td>
<td>5.991</td>
</tr>
<tr>
<td>40/60</td>
<td>0</td>
<td>6.092</td>
<td>6.118</td>
</tr>
<tr>
<td>60/40</td>
<td>15</td>
<td>68.703</td>
<td>75.899</td>
</tr>
<tr>
<td>40/60</td>
<td>15</td>
<td>61.552</td>
<td>65.217</td>
</tr>
<tr>
<td>Left Lane Closure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40/60</td>
<td>0</td>
<td>6.028</td>
<td>5.967</td>
</tr>
<tr>
<td>60/40</td>
<td>0</td>
<td>6.216</td>
<td>6.288</td>
</tr>
<tr>
<td>40/60</td>
<td>15</td>
<td>56.306</td>
<td>47.353</td>
</tr>
<tr>
<td>60/40</td>
<td>15</td>
<td>60.312</td>
<td>42.463</td>
</tr>
</tbody>
</table>

As can be seen from Table 3 - 1 above, the experiment was run for both the lane drop and incident techniques. In order to accept that closing the left lane produces the same results as closing the right lane, the first value of delay in the incident column for Right Lane Closure should match the first value of delay in the incident column for Left Lane Closure, and so on. The values are similar between right and left lane closures for 0% truck presence, but differ greatly when truck presence is increased to 15%. Also, the
values between the incident technique and lane drop technique show no consistency and no intuitive reasoning can explain the differences between the numbers. Because of these discrepancies, it is not possible to determine whether closing the right lane will produce the same results as closing the left lane by using network-wide average delay as a performance measure. This value does not describe what is happening per vehicle, which causes an inconsistent result that is based upon how many vehicles enter the system, which is dependent upon flow and breakdown conditions. Therefore, a different performance measure was considered that does look at the value per vehicle. Average speed per vehicle was considered and it was found that 9.71 runs are required for an error tolerance of 15% (see below for calculation):

<table>
<thead>
<tr>
<th>Run #</th>
<th>Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36.62</td>
</tr>
<tr>
<td>2</td>
<td>29.80</td>
</tr>
<tr>
<td>3</td>
<td>32.02</td>
</tr>
<tr>
<td>4</td>
<td>54.82</td>
</tr>
<tr>
<td>5</td>
<td>54.48</td>
</tr>
<tr>
<td>6</td>
<td>51.10</td>
</tr>
<tr>
<td>7</td>
<td>48.14</td>
</tr>
<tr>
<td>8</td>
<td>42.30</td>
</tr>
<tr>
<td>9</td>
<td>32.24</td>
</tr>
<tr>
<td>10</td>
<td>33.58</td>
</tr>
</tbody>
</table>

Calculation of required number of simulation runs:

Sample Size, \( n = 10 \)

Sample Mean, \( M_N = 41.51 \)

Sample Std. Dev., \( S_N = 9.899 \)

Error (15%), \( E = 0.15 \times M_N = 6.227 \)

95% Confidence Interval: \( +/- \left(1.96 \times \frac{S_N}{\sqrt{n}}\right) = +/- (6.135) \)
Required number of runs for 15% error tolerance:

\[ N = 1.96^2 \times S_n^2 / E^2 = 9.709 \]

Thus 10 runs are used to compare the values of speed. The results are displayed below in Table 3 - 3.

Table 3 - 3. Average Speed Values for Different Combinations of Lane Closures and Lane Distributions
Trucks biased to rightmost lane
Results of Ten Simulation Runs
All flows 1900 veh/hr

<table>
<thead>
<tr>
<th>Lane distribution L% / R%</th>
<th>Trucks %</th>
<th>Incident Speed (mph)</th>
<th>Lane Drop Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60/40</td>
<td>0</td>
<td>61.483</td>
<td>61.490</td>
</tr>
<tr>
<td>40/60</td>
<td>0</td>
<td>61.481</td>
<td>61.478</td>
</tr>
<tr>
<td>60/40</td>
<td>15</td>
<td>41.289</td>
<td>40.015</td>
</tr>
<tr>
<td>40/60</td>
<td>15</td>
<td>42.773</td>
<td>42.503</td>
</tr>
<tr>
<td>40/60</td>
<td>0</td>
<td>61.536</td>
<td>61.520</td>
</tr>
<tr>
<td>60/40</td>
<td>0</td>
<td>61.410</td>
<td>61.403</td>
</tr>
<tr>
<td>40/60</td>
<td>15</td>
<td>45.397</td>
<td>46.725</td>
</tr>
<tr>
<td>60/40</td>
<td>15</td>
<td>44.195</td>
<td>49.084</td>
</tr>
</tbody>
</table>

As seen in Table 3 - 3 above, the values of average speed per vehicle between left and right lane closures as well as between incident and lane drop techniques are very close and within the 15% tolerance error.
Results of Preliminary Analyses

From these results (10 runs based upon 15% error tolerance), it is concluded that any simulation scenario analysis need not be performed on both a left and right lane closure, but only on one, as the other will produce the same result. In addition, because the two techniques of simulating a lane closure produce almost identical values within 15% error, the technique which offers more options in the simulation is selected. Therefore, the use of an incident will be used in all simulation runs throughout the report, and the lane drop technique will not be used. This decision is based on the versatility of the incident technique, allowing for the effects of a rubberneck to be simultaneously implemented with a lane closure.

Simulation Scenarios

This section will outline the network schematic, the input variables and fixed values, the number of required simulation runs, and the simulated data that will be collected.

Simulated Test Section

Figure 3 - 1 below shows the simulated test segment that is analyzed.

Figure 3 - 1. Sketch of the freeway network used in data collection
There are a total of nine nodes (2-8 displayed). The feeder node is located 0.5 miles upstream of node 2. The following is a discussion of the function and characteristics of each link:

- **Link (2,3)** – 150 feet in length; created to verify headways 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 a far distance upstream of the work zone; variable distance is due to variability in links (6,7) and (7,8) (see 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 prior to the work zone warning sign.
- **Link (6,7)** – Length is variable from 0.5 to 1.5 miles; this is the distance from the work zone to the upstream warning sign. The changing of this distance is one reason for the variability in the length of Link (3,4). The overall network length is constant, so Link (3,4) is either lengthened or shortened when Link (6,7) is either shortened or lengthened, respectively.
- **Link (7,8)** – Length is variable from 0.5 to 2.0 miles; this is the link in which the lane closure is in place. The changing of this distance is the other reason for the variability in the length of Link (3,4). The overall network length is constant, so Link (3,4) is either lengthened or shortened when Link (7,8) is either shortened or lengthened, respectively. There is also a data station placed halfway between nodes 7 and 8, in order to verify headway data on that link.

**Input Variables**

The variables selected for the model development are listed below and their values and limitations are described in detail following the list:

- **Lane Configurations** – 2/1, 3/2, 3/1
- **Volume Distributions (percentages)**
  - (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)
- **Length of Work Zone** – 0.5 mi, 1.0 mi, 2.0 mi
- **Distance of Sign Upstream of Work Zone** – 0.5 mi, 1.0 mi, 1.5 mi
- **Presence of trucks (percentage)** – 0%, 10%, 20%
- **Rubbernecking factor (percentage)** – 0%, 15%, 25%
The input volume distributions were determined 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. 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 mph, the length of the work zone shall not exceed a length of 2 miles (Design Standards, Index 600, Sheet 2 of 10). Also, 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 mph or more (Design Standards, Index 600, Sheet 4 of 10).

The analysis of the effect of the work zone length on the work zone capacity showed no significant relationship between the two variables. Figure 3 - 2 below illustrates the relationship between the work zone capacity and the length of the work zone lane closure from the simulated data.

![Work Zone Capacity vs. Work Zone Length](image)

Figure 3 - 2. Relationship between work zone flow and work zone length
From Figure 3 - 2 above, there exists 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 exists through the lane closure. This variable will therefore not be included in any of simulation runs for all lane closure configurations.

The presence of trucks ranges from zero to twenty percent, again limited by the consideration of reasonable operating conditions. Similarly, the rubbernecking factor ranges from zero to twenty-five percent, and will be 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.

To view the effect of the rubberneck factor on a freeway work zone lane closure segment, the capacity of that segment is compared to the rubberneck factor used. The scenario tested is a 2-to-1 lane closure with a flow rate of 2200 veh/hr distributed 40% in the through (left) lane and 60% in the closed (right) lane. The length of the work zone is 0.5 miles, truck presence is at 20%, and the advance warning sign is located at 0.5 miles upstream of the bottleneck. Table 3 - 4 below illustrates the effects of the rubbernecking factor on the capacity through a work zone lane closure:
Table 3 - 4. Effects of Rubbernecking Factor on Capacity through Work Zone Lane Closure

Trucks biased to rightmost lane
Results of Five Simulation Runs
All flows 2200 veh/hr

<table>
<thead>
<tr>
<th>Rubberneck Factor (%)</th>
<th>Average Headways through Work Zone (5 simulation runs)</th>
<th>Average of headways</th>
<th>Capacity (veh/hr/ln)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.65, 1.64, 1.64, 1.64</td>
<td>1.64</td>
<td>2192.5</td>
</tr>
<tr>
<td>5</td>
<td>2.01, 1.98, 2.09, 2.02, 2.11</td>
<td>2.04</td>
<td>1763.0</td>
</tr>
<tr>
<td>15</td>
<td>2.24, 2.20, 2.25, 2.25, 2.26</td>
<td>2.24</td>
<td>1607.1</td>
</tr>
<tr>
<td>25</td>
<td>2.61, 2.51, 2.47, 2.61, 2.47</td>
<td>2.53</td>
<td>1420.7</td>
</tr>
<tr>
<td>35</td>
<td>2.79, 2.76, 2.78, 2.78, 2.79</td>
<td>2.78</td>
<td>1295.0</td>
</tr>
<tr>
<td>45</td>
<td>2.98, 2.99, 2.98, 2.97, 2.96</td>
<td>2.98</td>
<td>1210.0</td>
</tr>
</tbody>
</table>

The results indicate that an increase in the rubbernecking factor leads to a decrease in capacity. The capacity through the work zone is calculated by dividing 3600 (seconds/hour) by the headway value (seconds/vehicle) in the previous column. This relationship is not linear with values greater than 25%. In addition, the percentage of rubbernecking does not reduce the capacity by the same percent. For example, the 5% rubbernecking factor reduces capacity by nearly 20%, whereas a 25% rubbernecking factor has only a slightly increased effect on capacity reduction. After this point, increasing the rubbernecking factor does not have as large an effect and it is for these reasons that 25% will be the maximum rubbernecking factor applied in this study.

**Simulated Test Section Setup—Input Fixed Values**

As limited by the FDOT Design Standards, the free-flow speed that will be used throughout all analyses will be 55 mph through the work zone; this value cannot be lower than 10 mph less than the mainline free-flow travel speed (Design Standards, Index 600,
Because the facility being modeled can be a state highway or freeway facility, a free flow speed for mainline traffic of 65 mph will be used throughout the analysis.

A value of 2400 vehicles per hour per non-closed lane will be implemented as the fixed flow rate. This is the flow rate at which breakdown occurs—speed reduction of at least 30% immediately upstream to the lane closure—with nothing other than passenger cars present in the traffic stream. This base case did not include any trucks and had a rubbernecking factor of zero percent. The traffic entering the system was distributed equally between lanes—50/50—and the upstream sign was placed at 1.5 miles upstream of the beginning of the bottleneck. This flow rate of 2400 vehicles per hour per non-closed lane will cause a queue to form and the discharge causes the downstream link to operate at capacity. Therefore, for 2-to-1 and 3-to-1 lane closure configurations, the flow rate will be fixed at 2400 veh/hr. For the 3-to-2 lane closure, the flow rate will be 4800 veh/hr.

The relationships that are shown in CHAPTER 4: MODEL DEVELOPMENT do not appear to have any values of capacity between 2000 and 2200 veh/hr/ln. Each point plotted is the average of 15 simulation runs. Therefore, the average of the runs do not have values of capacity between 2000 and 2200, but the full dataset does include values between these numbers. This apparent absence of data is a result of the type of breakdown that is occurring based on the characteristics of the traffic stream for specific scenarios. All values of capacity above 2200 veh/hr/ln have only passenger cars in the traffic stream and both the rubbernecking factor and truck percentage is at zero. The type of breakdown that occurs in this case is different than if any other factor is present. With
only passenger cars in the traffic stream, queues are building and recovering throughout the simulation time period. There is a shockwave present that travels upstream, causing breakdown conditions to occur and dissipate throughout the traffic stream. Therefore, because free-flow speed is reduced by at least 30%, capacity is being observed downstream through the work zone. Once a rubbernecking factor or a presence of trucks is introduced into the traffic stream, however, capacity through the work zone is reduced due to a breakdown in speeds that is greater than 50%, causing a permanent queue o form that does not recover within the simulation time period. As a result, there is a constant discharge of vehicles into the work zone, and capacity conditions are also observed, but the values are lower than the passenger-car only traffic stream.

**Required Number of Simulation Runs**

As calculated previously, 10 simulation runs per scenario are required for a 15% error tolerance in the sample mean. In order to obtain a higher number of data points from the data collection (from simulation) and thus further increase final model precision, 15 runs per scenario will be simulated.

**Total Number of Simulation Scenarios**

There will be four variable input values per lane closure configuration, each with three levels of variation. For thoroughness, every effect that each variable has on the other will be analyzed, and thus a total of 243 different scenarios will be analyzed, each simulated 15 times:

\[ 4 \text{ input values, 3 levels} \quad N_{\text{scen}} = 3^4 = 81 \] (per lane closure configuration)

Table 3 - 5 below illustrates the three levels of variation for each variable for all lane closure configurations. Because there are two other configurations—3/2 and 3/1—the total number of scenarios is 243.
Table 3 - 5. Variation of Input Parameters

<table>
<thead>
<tr>
<th>Variable</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>lane configuration</td>
<td>2-to-1</td>
<td>3-to-2</td>
<td>3-to-1</td>
<td>total-to-open lanes in work zone</td>
</tr>
<tr>
<td>lane distributions</td>
<td>50 / 50</td>
<td>40 / 60</td>
<td>30 / 70</td>
<td>left % / right %</td>
</tr>
<tr>
<td></td>
<td>20 / 40 / 40</td>
<td>30 / 30 / 40</td>
<td>30 / 40 / 30</td>
<td>left % / middle % / right %</td>
</tr>
<tr>
<td>upstream sign distance</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>miles</td>
</tr>
<tr>
<td>truck %</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>percentage</td>
</tr>
<tr>
<td>rubber %</td>
<td>0</td>
<td>15</td>
<td>25</td>
<td>percentage</td>
</tr>
</tbody>
</table>

As a result, the 243 files created will each be simulated for 15 runs, giving a total of 3,645 output files, or data points for model development.

**Output Values**

In addition to the variables described in the previous section, data from the simulations will be collected to model the lane distributions and their effect on work zone capacity. The following values will be taken from the output files and used for model development:

- Volumes by lane through link (7,8)
- Vehicle lane distributions through all links
- Speeds by lane through all links
- Number of lane changes through all links

TRAFVU screen shots for each of the 3 different lane closure configurations are provided in APPENDIX F.
CHAPTER 4
MODEL DEVELOPMENT

The software package STATISTICA (Release 7) was used in developing the relationships between selected performance measures and the vehicular capacity through the temporary lane closure. This section summarizes the process of data analysis and model development for each of the three lane closure configurations. First, the relationships between collected data and capacity will be outlined and identified. This leads into the development of the models, using General Linear Regression techniques as provided by the software. The final models consist of a combination of highly-correlated, statistically significant parameters that are obtainable from field data collection. As a result, the models are practical and easy to use. Finally, an example outlining the steps in using each of the models will be provided for each respective lane closure configuration.

Data Analysis

The network created for simulation has been designed so that field data may be input into the appropriate location on the freeway segment. For this reason, many links were created upstream of the lane closure in order to collect lane distribution data significant distances upstream of the first lane closure warning sign. For the development of the models, however, only those lane distributions from links (4,5), (5,6), and (6,7) are considered. In CORSIM 5.1, lane distributions upstream of the warning sign are not affected by the work zone. Therefore, the simulated behavior of vehicles just upstream of the location of the warning sign is the same as that of vehicles three to four miles
upstream in *CORSIM 5.1* (this is not expected in the field, which is the reason for the existence of more upstream links not used in modeling). When simulated vehicles pass the sign, they react and merge based on existing queues, gaps, travel speeds, and driver aggression level. Because the warning sign is located at Node 6 for all simulation scenarios, the parameters for lane distributions, speeds, and lane changes will only be estimated for the aforementioned links in the model development.

In addition, the lane distributions that were input into the simulation are not used in model development. Rather, the actual lane distribution data collected from links (4,5), (5,6), and (6,7) were used. The program distributes the vehicles into lanes as designated by the input percentages. However, immediately upon entry into the system, vehicles begin to make discretionary lane changes that alter the input lane distribution percentages. The degree to which vehicles make these lane changes can be controlled by modification of the driver behavior parameters within the software. The lack of field data made any modifications irrelevant and thus the default values for driver types were used. These numeric default values range from not aggressive to very aggressive for ten driver types, and 10% of each type comprise the traffic stream (the user cannot modify this). For that reason, observed lane distributions are used in model development.

**2-to-1 Lane Closure Model Development**

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
- Speeds per vehicle
- Actual lane distributions

Figure 4 - 1 below shows the relationship between the work zone capacity and the location of the upstream warning sign.

![Graph showing relationship between work zone capacity and upstream sign location](image-url)

\[ y = 9.4476x + 1581.5 \]

\[ R^2 = 0.0002 \]

Figure 4 - 1. Relationship between work zone capacity and upstream warning sign distance

As the distance of upstream warning increases, there is a small increase in capacity. This relationship, though immediately not apparent, becomes more significant when
viewed in combination with the lane distributions of link (6,7) as an interaction variable. This is discussed later in this section with Figure 4 - 9.

The following two figures (4 - 2, 4 - 3) show the effects of an increase in the truck percentage and an increase in the rubbernecking factor on the throughput capacity.

**Work Zone Capacity vs. Truck percentage**

\[ y = -14.651x + 1737.5 \]
\[ R^2 = 0.1552 \]

![Figure 4 - 2. Relationship between work zone capacity and truck presence in traffic stream](image)

**Work Zone Capacity vs. Rubbernecking Factor**

\[ y = -24.407x + 1916.4 \]
\[ R^2 = 0.6821 \]

![Figure 4 - 3. Relationship between work zone capacity and truck presence in traffic stream](image)
Both figures above show that an increasing percentage of trucks in the traffic stream or an increasing rubbernecking factor leads directly to a decrease in capacity through the lane closure. These variables are expected to be significant factors in the final models.

The relationship between the number of lane changes in link (6,7) and the throughput capacity is shown below in Figure 4 - 4.

*Work Zone Capacity vs. Lane Changes in (6,7)*

Figure 4 - 4. Relationship between work zone capacity and lane changes in link (6,7)

There is a positive correlation indicating that an increasing number of lane changes leads to a higher value of capacity. Although considered in model development, this variable was ultimately not included in the final models. This variable cannot be collected easily in the field. In addition, the effect of this variable is captured by other included model parameters that are more important and could not be excluded. For
example, as shown below in Figure 4 - 5, the number of lane changes is correlated to the length of link (6,7).

![Lane Changes in Link (6,7) vs. Length of Link (6,7)](image)

\[ y = 22.861x + 241.31 \]
\[ R^2 = 0.0809 \]

Figure 4 - 5. Relationship between the number of lane changes in link (6,7) and the length of link (6,7)

The number of lane changes did not show significance when included in the model with other parameters that were more important (the effect of the number of lane changes is captured by the percentage of vehicles traveling on lane 1 and lane 2, represented as vehicle lane distributions in the final models). The distance of the link (6,7)—which also captures the effect of the lane changes—however, is included in the final models represented by the variable upstream sign distance.

Figure 4 - 6 illustrates the relationship between the speeds of vehicles in all lanes in the link upstream of the placement of the warning sign. At this point, the vehicles have not seen and thus have not reacted to any type of warning or work zone ahead.
Figure 4 - 6. Relationship between work zone capacity and the average speed per vehicle in lanes one and two of link (5,6)

Both lanes show an increase in capacity with increasing link speeds. This variable will thus be considered in model development.

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 below in Figure 4 - 7.
There is a strong relationship between these variables, which were also considered in the final model development. An increase in speed in 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 this 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.

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. 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 4 - 8 below shows the effect that the vehicular lane distributions have on work zone capacity.

\[ y = -1412.8x + 2073.4 \]

\[ R^2 = 0.3943 \]

Figure 4 - 8. Relationship between work zone capacity and the vehicular distributions on lane one of all links

The relationship is similar for links (4,5) and (5,6), and therefore only link (5,6) will be considered in the model development. The effects of the vehicular lane distributions immediately before and after a work zone sign will thus be considered in the final models.

In model development, 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)). 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. This relationship is illustrated below.

![Lane Distributions of Link (6,7) vs. Upstream Sign Location](image)

Figure 4 - 9. Relationship between vehicular lane distributions in lanes one and two of link (6,7) and the location of the upstream warning sign

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 below.
Figure 4 - 10. Relationship between work zone capacity and the interaction of lane distributions in link (6,7) and upstream sign distance

As a result, the net effect of increasing sign distance and lane distribution is negative for lane one. This factor is included in the final model.

Another interaction was observed between the location of upstream warning sign and the average speeds of vehicles in link (6,7). Their combined effect on capacity is shown below in Figure 4 – 11.
Figure 4 - 11. 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.

The results indicate that there is a relationship between these variables, and the interaction of speeds and sign distance is considered in the final model.

Another important interaction between variables was observed between the average speeds in lane 1 and lane 2 of both links (5,6) and (6,7). As shown in the following figures, the two lanes’ speeds are highly dependent on each other; as a result, both lanes’ speeds cannot be used together in the model. Therefore, a polynomial regression—of order 2—was performed on each link. The resulting equations predict the speeds of lane 2 for each link from the lane 1 speed data. These relationships are shown in the following figures, Figure 4 – 12 and .4 – 13.
Speeds in Link (5,6)

\[ y = 0.0188x^2 - 0.3209x + 10.532 \]
\[ R^2 = 0.9893 \]
\[ R = 0.9946 \]

Figure 4 - 12. Relationship between the speeds in lane 1 and lane 2 of link (5,6)

Speeds in Link (6,7)

\[ y = 0.0143x^2 - 0.5816x + 9.2131 \]
\[ R^2 = 0.8541 \]
\[ R = 0.9242 \]

Figure 4 - 13. Relationship between the speeds in lane 1 and lane 2 of link (6,7)
From the results above, the polynomial expressions were used to calculate the predicted values of the speeds in lane 2, and those predicted values were used in model development when both lanes were considered.

**3-to-2 Lane Closure Model Development**

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. The graphical representations of these relationships are shown in APPENDIX A: *Model Development Relationships for a 3-to-2 Lane Closure Configuration*. The progression of relationships follows that of the 2-to-1 lane closure configuration and the same variables will be considered in the final model development.

**3-to-1 Lane Closure Model Development**

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 APPENDIX B: *Model Development Relationships for a 3-to-1 Lane Closure Configuration*.

**Final Models**

This section presents the final models for each of the three lane closure configurations, with all variables within a 0.05 level of significance. The models are based upon the relationships described in previous sections, with work zone capacity through each lane closure as the dependent variable. One model that can be used to predict capacity was developed for each of the three lane closure configurations studied. The values of vehicle speeds and distributions in the closed lanes are the primary inputs into the models. Sign distance, truck percentage, and rubbernecking factor also
contribute to the final value of work zone capacity. Speeds and lane distributions are performance measures that can be controlled in a work zone. Signs or physical barriers can encourage or require lane merges, maintaining traffic stream speeds and/or vehicle travel lanes. Therefore, having both of these factors present in the models provides a view of the effect of different types of management strategies to be imposed through the work zone.

**Variable Explanations and Example of Model Usage**

The variables used in the developed models are defined in detail below. Their limitations in range, based on collected data, and an example of capacity calculations for each of the lane closure configurations are reported in APPENDIX E.

*Capacity.* This is the dependent variable and represents the maximum number of vehicles that travel through the work zone lane closure given specific input values for the model parameters. This traffic stream condition is a result of a drop in free-flow speed of at least 30% in the link immediately upstream of the work zone. This value is given in units of veh/hr/lane, and for the 3-to-2 lane closure configuration, this value is the average of both open lanes.

*Intercept.* This is the value that is being adjusted by other parameters in each of the models. By itself, it is not an estimate of the base capacity of any of the lane configurations because inputting zeros for all other parameters is not reasonable. The unit of this variable is veh/hr/lane.

*SignDist.* This variable represents the upstream distance of the work zone warning sign. Because this variable is always the same length as link (6,7), some interactions have been noted and accounted for in the model development. This variable is input into the model as miles.
Truck%. This variable represents the percentage of heavy vehicles in the traffic stream. It is input into the model as a whole number (e.g. 20 for 20%).

Rubber%. This variable represents the degree to which capacity is reduced due to any additional factors within the lane closure. A higher rubbernecking factor leads to a decrease in capacity throughput, and it is input into the model as a whole number (e.g. 20 for 20%). The value of this variable should be chosen carefully, since field data has not yet been acquired to properly calibrate its effect. With a zero percent rubbernecking factor, no additional events are causing capacity reduction other than the geometry of the work zone and factors discussed previously. However, it may be possible that there is a presence of law enforcement or heavy construction equipment and workers, which would lead to additional decrease in capacity as drivers react to the more hazardous driving conditions. Hence a rubbernecking factor ranging from 5 to 25 percent may be used to simulate this additional reduction in capacity.

SpdLan1(5,6). This variable represents the speed of vehicles in lanes 1 of link (5,6) (lane 1 being the rightmost lane). The units of this variable are in mph and should be input into the model as such.

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 a result of the following logic: scenarios that have shorter sign distances have higher likelihoods of producing queues extending beyond the warning sign into link (5,6). If queues in a particular lane extend into link (5,6) then the average speeds per vehicle are thus affected (reduced) at this link.
CalcSpdLan2(5,6). There is a strong correlation between the actual speeds of lane 1 and lane 2 for link (5,6). This variable is a polynomial regression of order 2 that estimates the speeds in lane 2 of link (5,6) using the speeds in lane 1 of link (5,6) as an input.

SpdLan1(6,7), SpdLan2(6,7). These variables represent the speeds in lanes 1 and 2 of link (6,7) (lane 1 being the rightmost lane). The units of these variables are in mph and should be input into the models as such.

SpdLan1(6,7) × SignDist, SpdLan2(6,7) × Sign Dist. These variables are interaction terms between the speed of vehicles in lanes 1 and 2 of link (6,7) and the upstream distance of the work zone warning sign. This interaction is a result of scenarios that have shorter sign distances have higher likelihoods of producing queues extending beyond the warning sign into the upstream link (5,6). If queues in a particular lane extend into link (5,6) then the average speeds per vehicle are thus affected (reduced) at this link.

CalcSpdLan2(6,7). There is a strong correlation between the actual speeds of lane 1 and lane 2 for link (6,7). This variable is a polynomial regression of order 2 that estimates the speeds in lane 2 of link (6,7) using the speeds in lane 1 of link (6,7) as an input.

CalcSpdLan3(6,7). There is a strong correlation between the actual speeds of lane 2 and lane 3 for link (6,7). This variable is a polynomial regression of order 2 that estimates the speeds in lane 3 of link (6,7) using the speeds in lane 2 of link (6,7) as an input.
**DistrLan1(6,7), DistrLan2(6,7).** These variables represent the fraction (percent divided by 100) of vehicles present in lane 1 of link (6,7). For example, if 10% of vehicles are traveling in lane 1, the input value would be 0.10 into the model for this variable.

**DistLan1(6,7) \times SignDist, DistLan2(6,7) \times SignDist.** These variables are interaction terms between the distribution of vehicles in lanes 1 and 2, respectively, of link (6,7) and the upstream distance of the work zone warning sign. The interaction is a result of the relative ease for vehicles to merge into the non-closed lane, given specific link lengths. A larger sign distance creates more space for vehicles to merge into the through lane(s). The sign distance is input in units of miles, and the lane distributions as a decimal (*e.g.* 0.1, 0.5, *etc.*).

**Capacity Estimation Models for each Lane Closure Configuration**

The following sections present the final models for each lane closure configuration. For actual STATISTICA output screen shots (including *p-stats* and *t-stats*), please see APPENDIX D.

**2-to-1 lane closure configuration**

The following model estimates the capacity for a 2-to-1 lane closure configuration (Equation 4-1). The dependent variable, *Capacity2to1*, 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:
\[ \text{Capacity}_{2to1} = 1623.02 \]

\[ + (740.88) \times \text{SignDist} \]

\[ + (-14.23) \times \text{Truck}\% \]

\[ + (-22.83) \times \text{Rubber}\% \]

\[ + (-409.76) \times \text{DistrLan1(6,7)} \times \text{SignDist} \]

\[ + (-13.513) \times \text{SpdLan1(6,7)} \times \text{SignDist} \]

\[ + (26.69) \times \text{CalcSpdLan2(6,7)} \]

(Eq. 4-1)

The adjusted \( R^2 \) value for the relationship in Equation 4-1 is 0.971.

The variable \( \text{CalcSpdLan2(6,7)} \) is calculated from the input variable \( \text{SpdLan1(6,7)} \):

\[ \text{CalcSpdLan2(6,7)} = 0.0143 \times (\text{SpdLan1(6,7)})^2 \]

\[ - 0.5816 \times \text{SpdLan1(6,7)} \]

\[ + 9.213 \]

(Eq. 4-2)

The \( R \) value for the relationship in Equation 4-2 is 0.9242.

**3-to-2 lane closure configuration**

The following model estimates the capacity for a 3-to-2 lane closure configuration (Equation 4-3). The dependent variable, \( \text{Capacity}_{3to2Avg} \), 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 \( \text{Capacity}_{3to2Avg} \) value should be multiplied by two. The model is shown below:
\[ \text{Capacity}_{3to2\text{Avg}} = 1595.84 \\
+ (711.49 \times \text{SignDist}) \\
+ (-5.87 \times \text{Truck\%}) \\
+ (-17.88 \times \text{Rubber\%}) \\
+ (-1211.94 \times \text{DistrLan1}(6,7) \times \text{SignDist}) \\
+ (-10.58 \times \text{SpdLan1}(5,6) \times \text{SignDist}) \\
+ (9.30 \times \text{CalcSpdLan2}(5,6)) \]  
(Eq. 4-3)

The adjusted R\(^2\) value for the relationship in Equation 4-3 is 0.954.

The variable \text{CalcSpdLan2}(5,6) is calculated from the input variable \text{SpdLan1}(5,6):

\[ \text{CalcSpdLan2}(6,7) = 0.0188 \times (\text{SpdLan1}(5,6))^2 \\
- 0.3209 \times \text{SpdLan1}(5,6) \\
+ 10.532 \]  
(Eq. 4-4)

The R value for the relationship in Equation 4-4 is 0.9946.

### 3-to-1 lane closure configuration

The following model estimates the capacity for a 3-to-1 lane closure configuration (Equation 4-5). The dependent variable, \text{Capacity}_{3to1}, represents the average number of vehicles per hour per lane that travel through Lane 3, given a set of input values. The model is shown below.
\[ \text{Capacity}_{3to1} = 1665.42 \\
+ (763.56) \times \text{SignDist} \\
+ (-10.12) \times \text{Truck}\% \\
+ (-20.07) \times \text{Rubber}\% \\
+ (-1698.76) \times \text{DistrLan1}(6,7) \times \text{SignDist} \\
+ (-626.50) \times \text{DistrLan2}(6,7) \times \text{SignDist} \\
+ (-13.513) \times \text{SpdLan2}(6,7) \times \text{SignDist} \\
+ (26.84) \times \text{CalcSpdLan3}(6,7) \]  
\text{(Eq. 4-5)}

The adjusted R² value for the relationship in Equation 4-5 is 0.976

The variable \( \text{CalcSpdLan3}(6,7) \) is calculated from the input variable \( \text{SpdLan2}(6,7) \):

\[ \text{CalcSpdLan3}(6,7) = 0.0136 \times (\text{SpdLan2}(5,6))^2 \\
- 0.5144 \times \text{SpdLan2}(5,6) \\
+ 8.108 \]  
\text{(Eq. 4-6)}

**Discussion of Results**

Three models were developed for each of the three lane closure configurations on a temporary freeway work zone. The parameters selected are easily visualized and can be efficiently collected from the field. The first section below discusses the effect of the three models’ variables on the capacity throughput of the work zone lane closure. The second section describes the way in which the models can be applied by the FDOT and the assumptions that must be made in using the capacity estimates.
Effects of Model Variables on Capacity

The relationship of the link (5,6) speeds to capacity is important because the vehicles in the traffic stream at this point have not yet seen the work zone warning sign, which is located at node 6. The speeds in lane 1 (actual) and 2 (predicted) of link (5,6) was modeled for the 3-to-2 lane closure configuration. Lane 2 is the first open through lane (merging from right to left) of the work zone and lane 1 is the lane immediately to the right of that (the lane from which vehicles are merging). The model parameters show that for link (5,6), higher speeds in the to-be through lane lead to an increase in capacity and thus lower speeds lead to lower values of capacity. Higher speeds imply that the queue created at the lane closure does not extend upstream of the warning sign and vehicles are merging and passing through the work zone smoothly. Higher speeds on the to-be closed lane, however, lead directly to a decrease in capacity. This relationship is also a function of queue length growth on the through lane. Depending on the level of congestion (defined by the other user inputs), a queue may also form on the merging lane. Because vehicles are merging into the through lane once they pass the warning sign, the queue will grow much faster on the through lane than on the merging lane. This may cause vehicles upstream in the to-be through lane to slow down (lower speeds lead to a lower capacity) while vehicles in the to-be closed lane are maintaining free flow speed. Thus, high speeds in the to-be closed lane lead to quick queue buildup in the through lane and the congestion leads to a lower capacity value. Lower speeds in the to-be closed lane imply that the queue has extended beyond the warning sign and all lanes are congested, thus also leading to a reduction in capacity by both speed parameters. The 3-to-2 lane closure configuration was the only one that was modeled using the speeds in link (5,6). This is because the work zone has two open through lanes, and the vehicular behavior
was more correlated to that of vehicles before they first encounter the work zone warning sign. Vehicles can make discretionary lane changes in this work zone configuration, as they can in the upstream link (5,6). The other two lane closure configurations, 2-to-1 and 3-to-1, are modeled using the speeds in link (6,7). This is the link after the vehicles have seen the warning sign and are required to make a merging maneuver as soon as possible. The speeds in link (6,7) were more closely correlated to the behavior of vehicles in the work zones where only one through lane was open. The parameter estimates suggest that the same trend exists that was observed in the upstream link (5,6). Higher speeds in the to-be closed lanes lead to a decrease in capacity, while higher speeds in the to-be open lanes lead to an increase in work zone capacity. The speeds in the lanes considered are correlated (see Figure 4 – 13), and speeds as high as 50 mph on the to-be closed lane show speeds of less than 20 mph on the to-be open lane. Therefore, high speeds of the vehicles in the to-be closed lane are merging into a congested to-be through lane in which the speeds are not high, thus overall reducing capacity through the work zone. Capacity is lower because of the creation of a shockwave on the through lane every time a rapidly moving vehicle slows down after merging into the through. This does not lead to a constant queue discharge on the through lane. When vehicle speeds are higher than 50 mph on the to-be closed lane, however, vehicle speeds on the through lane are also higher, indicating a much smoother merging pattern and thus overall increasing capacity (with the increasing speeds in the to-be closed lane).

The second relationship developed is between work zone capacity and the vehicular lane distributions upstream of the work zone. For all lane closure configurations, the model parameters show that for link (6,7), a larger fraction of vehicles in the to-be closed
lane(s) leads to a decrease in capacity. This effect is a result of the quantity of merging maneuvers occurring after the warning sign. A higher fraction of vehicles in the to-be closed lane(s) leads to a higher required number of merging maneuvers. A lower number of merging maneuvers is a result of a higher fraction of vehicles in the to-be through lane(s)—and thus a lower fraction in the to-be closed lane(s)—which leads directly to a steady traffic stream moving more efficiently through the work zone. A higher number of merging maneuvers leads to an increase in the amount of shockwaves present in the to-be through lane; these shockwaves disrupt the steady discharge of the queue into the work zone and reduce the work zone capacity.

In addition to the speed and lane distribution relationships, the distance of the warning sign, the presence of trucks, and a rubbernecking factor also contribute an effect to capacity. The distance of the upstream warning sign increases the work zone capacity with an increasing distance. This variable has some interaction with the lane distributions and speed values, and is thus implemented in the models as an interaction term. The increasing effect that warning sign distance has on capacity, however, is not greater than the decreasing effect of the lane distribution factor or of the speed factor. Thus the interaction of the two terms leads to a net decreasing effect on capacity, as seen in the models’ negative interaction term coefficients. As the models’ parameters illustrate, a higher percentage of trucks present in the traffic stream leads to a decrease in capacity. The greatest decrease in capacity due to truck presence occurs for the 2-to-1 lane configuration; this is a result of the simulation scenarios having been set up with trucks biased to travel in the rightmost lane. Because there are only two travel lanes in this configuration, the truck presence has a strong effect. The smallest decrease in capacity is
observed with the 3-to-2 lane closure configuration. Again, because trucks are biased to
the rightmost lane, all trucks entering link (6,7) will be present in lane 1. However,
because there are three travel lanes and two of them are open, the effect of truck presence
is not as pronounced as with the 2-to-1 or even 3-to-1 configurations. A rubbernecking
factor ranging from 0 to 25% also reduces the capacity through the work zone in all three
lane closure configurations. The reduction is achieved by the software by increasing time
headways between vehicles traveling through the work zone, and the factor is included to
simulate any additional reason for a capacity reduction.

Model Application by the FDOT

The current method employed by the FDOT considers only the geometric
characteristics of a potential work zone in order to estimate the capacity. The new
models developed consider some geometric characteristics as well as traffic operating
conditions. These models are intended to be used as tools to estimate the capacity of a
work zone lane closure, given a set of geometric and traffic operating inputs with the
work zone already in place. To use the models effectively, the geometric and operational
conditions specified in capacity estimation should be implemented and regulated in the
field. The models developed for the new methodology require the input of some
distance of the upstream warning sign
- Truck percentage – this value can be obtained for different times of day
- Rubbernecking factor – this value is a result of the quantity of workers and/or
heavy equipment present throughout the work zone
The new models estimate a capacity value based on a combination of the above factors and additional factors that are not obtainable before the work is built. These are listed below:

- Vehicle lane distributions upstream of the work zone lane closure
- Average speed per vehicle upstream of the work zone lane closure

Because the current FDOT methodology uses only geometric factors, these can be specified and a value for capacity is estimated before the work zone is built. With the new models, the engineers should obtain the data for truck percentages and decide on the location of the upstream warning sign and rubbernecking factors. When inputting the values for the lane distributions and speeds, however, the user should be aware of several issues. First, the speeds and lane distributions are the values for the work zone once it is already in place. These are not the values for the regular operating conditions observed with no work zones in place. Second, the models were developed based on simulated data that ensured breakdown and the creation of a bottleneck at the location of the lane closure. Therefore, the capacity estimates resulting from the models are for operating conditions where a queue is formed at the start of the lane closure on the through lane(s). Finally, the lane distributions and speed values input into the models for capacity estimation must be maintained when constructing the work zone. Otherwise, the capacity values estimated by the models will not be observed in the field operations. For example, if a Lane 1 average speed of 30 mph is used when estimating capacity, the speed for that link of actual roadway should be enforced at 30 mph for the capacity estimate to replicated in the field. Speed limit signs and law enforcement can help to encourage the desired traffic stream behavior. The same holds true for the lane distributions inputs. If
the models are applied with a Lane 1 vehicular distribution of 10%, for example, then that value should be enforced in the field as well. Signs encouraging early merging or even the use of additional barriers can help achieve the desired distribution of vehicles.
CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

This section identifies the primary results and conclusions from the analyses presented in this thesis. The effects of the model factors on work zone capacity are summarized and discussed. In addition, the reasons for the differences in capacity estimation between models and between lane closure configurations are outlined. The models developed are only one step toward a full understanding of the effects of specific factors on work zone capacity. For this reason, recommendations for further investigation are also presented following the conclusions.

Conclusions

There are several factors that were identified to have significant effects on the capacity of a temporary freeway work zone lane closure. The percentage of trucks present in the traffic stream and the rubbernecking factor both decrease the capacity of the lane closure. The rubbernecking factor has a greater effect on capacity reduction than the presence of trucks—represented by the larger (more negative) coefficients for this factor. Therefore, when considering lane closure schedules during peak hour traffic (high volumes of vehicles), times of day (or night) should be avoided when high percentages of trucks in the traffic stream are present. In addition, consideration should be given to the quantity of workers and presence of heavy equipment and/or law enforcement vehicles in the work zone. A large presence of a combination of these factors will contribute to a high rubbernecking factor, thus reducing capacity further. To be able to correlate a
specific rubbernecking factor with a level of worker/equipment presence, field data for this variable should be collected and analyzed.

The average of speeds of vehicles directly upstream of the work zone warning sign had varying effects by lane. As noted in CHAPTER 4: MODEL DEVELOPMENT, the speeds of lane 2 are correlated to those in lane 1, and the speeds in lane 3 are correlated to those in lane 2 for congested conditions. A higher capacity is observed with higher speeds in the to-be through lanes, and a lower capacity with higher speeds in the to-be closed lanes. As a result, in order to increase the efficiency of a work zone lane closure, higher speeds—in the range of 25 to 45 mph—should be maintained (upstream and downstream of the warning sign) through the lanes that are not closed.

The model results also show the effect of vehicle lane distributions downstream of the location of the warning sign. There is a strong reduction in capacity if a high fraction of vehicles are present in the to-be closed lane(s). This is an important conclusion when considering traffic management upstream of a lane closure on a freeway. A work zone will operate much more smoothly—and thus have a greater capacity—if vehicles are encouraged (or required) to merge into the through lane at a greater distance upstream from the location of the warning sign.

The location of the upstream warning sign increases capacity throughput with an increasing warning distance for all lane closure configurations. In all models, this variable is included both as a stand-alone variable and as an interaction term. As an interaction term, however, it’s positive effect is not greater than the negative effect of the variable with which it’s interacting, so the net effect of the variables together is a decrease in capacity. These interaction variables included the speeds of vehicles in link
(5,6) (upstream of the warning sign), the speeds of vehicles in link (6,7), and the lane distributions of vehicles in link (6,7). As a result, a lane closure configuration will have greater capacity throughput if advance warning is given to the vehicles in the traffic stream.

**Recommendations**

Strong relationships between work zone capacity and upstream speeds and upstream lane distributions were identified and presented in model form in this report. The relative differences in capacity provided by different input traffic stream scenarios are valuable but do not represent actual field capacities. Presented in this section are recommendations to calibrate the existing models and to conduct further research in the direction of early merge traffic management strategies.

**Calibration**

Between lane closure configurations, there are expected differences in capacity results for the same input values into the models (see APPENDIX E). The variables have the same effect on capacity (increase or decrease), but the relative effect (value of coefficient) of each factor is different. This relative difference is valuable information and can be used for capacity comparisons for different inputs. Even more valuable is the ability to estimate actual capacity values for the different lane closure configurations. In order to achieve actual capacity estimates, however, field data for each scenario must be collected to accurately calibrate the models so that it replicates actual traffic stream conditions.

The way in which vehicles behave on a freeway and with a lane closure present is likely not the same as the default values of a simulator for this behavior. As a result, field data for vehicular lane changing behavior and driving speeds is fundamental to model
calibration. Car-following parameters can also be adjusted within the software, so this
data will also have some impact on the actual capacity values.

In addition to driver behavior, the rubbernecking factor requires calibration. For
each field data collection scenario, information should be collected regarding the
presence of additional obstructions or congestion within the work zone (degree of
presence of law enforcement, heavy equipment, and workers). The data can be modeled
and a table can be developed that correlates a definite rubbernecking factor with a
specified scenario of field conditions. If there are many variables that affect the
rubbernecking factor, then a full model can be used in which the user specifies the inputs
and a rubbernecking factor is estimated. These factors will contribute to a reduction in
capacity represented by the rubbernecking factor in the models. Thus, the field data will
lead to a rubbernecking range defined to specific field conditions.

Without calibration, the output values reported by the models will be
approximately 10 to 20 percent too high, as typical work zone base capacities range from
1400 to 1700 passenger cars per hour per lane. The default driver behavior values are the
primary cause for this overestimate. These default values applied by the software
CORSIM .1 are chosen to maximize the flow through any facility, and any modification
will lead to a decrease in the output values (Schnell and Aktan, 2001).

**Future Research and Applications**

The effects of traffic stream speeds and vehicle lane distributions on capacity can
be considered in the selection of work zone traffic management strategies for lane
closures. With these results, further research is recommended with each of the scenarios
in order to determine their effectiveness as recommendations for management strategies.
The models give relative capacity estimates for different inputs, so it is a simple task to
identify the optimal flow conditions that maximize the capacity throughput. However, it is a more difficult task to implement these optimized conditions in the field. An important work zone consideration that is ignored by the models is safety, for example. High speeds may be ideal but not feasible. A high fraction of vehicles in the through lane will increase capacity, but this also leads to more lane changes far distances upstream of the work zone and thus more of a possibility of accidents due to the higher operating speeds at that location. In addition to safety concerns, there also exist implementation difficulties with enforcement of specific conditions. If a predicted capacity is estimated based on a desired traffic stream speed of 30 mph, for example, then some kind of enforcement is required to ensure that this is the speed occurring in the field. The same difficulty exists with the enforcement of a desired lane distribution, when estimating a capacity value for a lane configuration.

The results of the lane distribution effects on capacity imply that an early merge strategy is effective in increasing the flow of the traffic stream through a work zone. However, this may only be effective (or possible) when there are few trucks, a low rubbernecking factor, and a sign location greater than 0.5 miles, for example. The effectiveness of an early merge has been investigated in some states, and future research will allow a clearer understanding of when to use this strategy.

The goal of using an early merge strategy is to place as many vehicles as possible into the through lane far distances upstream of the work zone. The possibility to model this scenario with CORSIM 5.1 is limited; the work zone sign leads vehicles to merge, but the bottleneck is still created at the point of the lane closure, as would be expected in actual conditions. With CORSIM 6.0 (not released in its full version until the end of
April 2006), at the point of an incident, vehicles begin merging very aggressively at the location of the incident warning sign. This way, the bottleneck forms around the sign location, not at the location of the lane closure. The aggressive merging movements and the creation of the bottleneck around the warning sign is intended to maximize the throughput capacity in the work zone (see APPENDIX C for CORSIM 5.1 and 6.0 output comparisons for the same input file). Therefore, even though this behavior is not expected in field conditions, CORSIM 6.0 can be used to vary the locations of the bottleneck formations upstream of the work zone, effectively simulating an early merge scenario. CORSIM 6.0 places over 95% of the vehicles in the through lane just before the lane closure location, whereas CORSIM 5.1, depending on the flow rate and truck percentage, places anywhere from 50% to 90% in the through lane (see APPENDIX C for output data from each version). Because the goal of the research, in part, is to verify the relationship between the upstream distance of the warning sign and the work-zone throughput capacity, the algorithm used in CORSIM 6.0 would skew these results. For future early merge research, however, this may prove to be a valuable tool.

As stated previously in this thesis, simulation modeling cannot provide as much information as field data collection. The relative capacities provided by the models, however, provide valuable information to a user interested in optimizing the efficiency of a lane closure operation. The speeds and lane distributions upstream of a warning sign have an effect on capacity throughput and this information can be used in scheduling and managing a temporary freeway lane closure.
APPENDIX A
MODEL DEVELOPMENT RELATIONSHIPS FOR A 3-to-2 LANE CLOSURE CONFIGURATION

Work Zone Capacity vs. Upstream Sign Location

\[ y = 27.64x + 1523 \]

\[ R^2 = 0.0019 \]
Work Zone Capacity vs. Truck Percentage

\[ y = -10.44x + 1655 \]
\[ R^2 = 0.1085 \]

Work Zone Capacity vs. Rubbernecking Factor

\[ y = -22.082x + 1845.1 \]
\[ R^2 = 0.7689 \]
Work Zone Capacity vs. Lane Changes in (6,7)

\[ y = 0.6724x + 1115.5 \]
\[ R^2 = 0.5246 \]

Lane Changes in Link (6,7) vs. Length of Link (6,7)

\[ y = 436.49x + 210.61 \]
\[ R^2 = 0.4089 \]
Work Zone Capacity vs. Speed in link (5,6)

Work Zone Capacity vs. Speed in link (6,7)
Work Zone Capacity vs. Lane Distributions

\[ y = -2189.4x + 2121.2 \]

\[ R^2 = 0.3092 \]

Lane Distributions of Lane 1 (closed lane)

Lane Distributions of Link (6,7) vs. Upstream Sign Location

Lane Distributions of Link (6,7) vs. Upstream Sign Location

Lane 1

Lane 2

Lane 3

Linear (Lane 3)

Linear (Lane 2)

Linear (Lane 1)
Work Zone Capacity vs. Lane 1 Distribution (6,7) and Sign Distance

\[ y = -971.7x + 1711.6 \]
\[ R^2 = 0.192 \]

Work Zone Capacity vs. Speed in Lane 1 (6,7) and Sign Distance

\[ y = 5.0755x + 1309.3 \]
\[ R^2 = 0.2835 \]
**Speeds in Link (5,6)**

\[ y = 0.0087x^2 + 0.4493x + 0.6699 \]

\[ R^2 = 0.9937 \]

\[ R = 0.9968 \]

**Speeds in Link (6,7)**

\[ y = 0.0082x^2 - 0.1876x + 5.9044 \]

\[ R^2 = 0.9378 \]

\[ R = 0.9684 \]
APPENDIX B
MODEL DEVELOPMENT RELATIONSHIPS FOR A 3-TO-1 LANE CLOSURE CONFIGURATION

Work Zone Capacity vs. Upstream Sign Location

\[ y = 12.236x + 1579.5 \]

\[ R^2 = 0.0003 \]
Work Zone Capacity vs. Truck Percentage

\[ y = -14.614x + 1737.8 \]

\[ R^2 = 0.1542 \]

Work Zone Capacity vs. Rubberneeking Factor

\[ y = -24.29x + 1915.6 \]

\[ R^2 = 0.6745 \]
Work Zone Capacity vs. Lane Changes in (6,7)

Lane Changes in Link (6,7) vs. Length of Link (6,7)
Work Zone Capacity vs. Lane Distributions

\[ y = -1440.1x + 2142.4 \]

\[ R^2 = 0.494 \]

Lane Distributions of Lanes 1 and 2 (closed lanes)

Lane Distributions of Link (6,7) vs. Upstream Sign Location
Work Zone Capacity vs. Lane 1 Distribution (6,7) and Sign Distance

\[ y = -4618.4x + 1724 \]
\[ R^2 = 0.1779 \]

Work Zone Capacity vs. Lane 2 Distribution (6,7) and Sign Distance

\[ y = -1157.8x + 1964.8 \]
\[ R^2 = 0.3614 \]
Work Zone Capacity vs. Speed in Lane 2 (6,7) and Sign Distance

\[ y = 4.7924x + 1420.5 \]

\[ R^2 = 0.2318 \]

Speeds in Link (5,6)

\[ y = 0.0529x^2 - 3.8355x + 93.881 \]

\[ R^2 = 0.9475 \]

\[ R = 0.9734 \]
Speeds in Link (6,7)

\[ y = 0.0136x^2 - 0.5144x + 8.1082 \]

\[ R^2 = 0.8497 \]

\[ R = 0.9218 \]
APPENDIX C
SAMPLE OUTPUT FILES FROM CORSIM 5.1 AND CORSIM 6.0

The outputs shown below illustrate the differences between two identical input scenarios simulated by two different versions of CORSIM. The two versions being compared are the current one being used in this report, CORSIM 5.1, and a Beta version to be released in April 2006, CORSIM 6.0.

Sample Output from CORSIM 5.1

On the following pages is a sample output for the following scenario (base case):

- 2-to-1 Lane Closure
- Work Zone Length at 0.5 miles
- Input Lane Distributions at 50/50
- Sign Distance at 0.5 miles
- Truck Percentage at 0%
- Rubbernecking Factor at 0%
INPUT FILE NAME: S:\Students\Diego_Arguea\Research\CORSIM\2 to 1 La
RUN DATE       : 01/16/06

VERSION 5.1 (BUILD #301)
RELEASE DATE FEBRUARY 2003

TRAFFIC SIMULATION MODEL
DEVELOPED FOR
U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
FHWA OFFICE OF OPERATIONS RESEARCH, DEVELOPMENT AND TECHNOLOGY

1 CARD FILE LIST
0SEQ.#: 1 2 3 4 5 6 7 8
1 : 10 102005 0 1
2 : 1 0 0 20 7981 0000 0 8 700 7781 7581 2
3 : 900 1 2 3
4 : 60 4
5 : 0 0 0 0 0 0 0 0 0 0 5
6 : 6 7 8 26400 2 1 19
7 : 7 8 9 26400 2 1 19
8 : 8 98002 26400 2 1 19
9 : 8001 1 2 0 2 1 19
10 : 5 6 7 26400 2 1 19
11 : 4 5 6 1500 2 1 19
12 : 1 2 3 26400 2 1 19
13 : 2 3 4 1500 2 1 19
14 : 3 4 5181800 2 1 19
15 : 6 7 0 0 0 11065 1 1 100 20
16 : 7 8 0 0 0 11055 1320 100 20
17 : 8 9 0 0 0 11065 1 1 100 20
18 : 8001 1 0 0 0 11065 1 1 100 20
19 : 5 6 0 0 0 11065 1 1 100 20
20 : 4 5 0 0 0 11065 1 1 75 100 20
21 : 1 2 0 0 0 11065 1 1 100 20
22 : 2 3 0 0 0 11065 1 1 75 100 20
23 : 3 4 0 0 0 11065 1 1 100 20
24 : 6 7 8 10 0
25 : 7 8 9 10 0
26 : 8 98002 100
27 : 8001 1 2 100
28 : 5 6 7 100
29 : 4 5 6 100
30 : 1 2 3 100
31 : 2 3 4 100
32 : 3 4 5 100
33 : 7 8 2 0 2640 099999 0 2640 29
34 : 8001 12400 0 0 100 50 50 50
35 : 0 170
36 : 8002 35000 0 195
37 : 8001 0 0 195
38 : 9 33280 0 195
39 : 7 28000 0 195
TRAF SIMULATION MODEL
DEVELOPED FOR
U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
FHWA OFFICE OF OPERATIONS RESEARCH, DEVELOPMENT AND TECHNOLOGY

DATE = 10/10/2005
USER =
AGENCY =

RUN CONTROL DATA

VALUE RUN PARAMETERS AND OPTIONS

0 RUN IDENTIFICATION NUMBER
1 RUN TYPE CODE = (1, 2, 3) TO RUN (SIMULATION, ASSIGNMENT, BOTH)
(-1, -2, -3) TO CHECK (SIMULATION, ASSIGNMENT, BOTH) ONLY
0 FRESIM OFFLINE INCIDENT DETECTION CODE = (0, 1) IF OFFLINE INCIDENT DETECTION
(IS NOT, IS) BEING PERFORMED
0 FUEL/EMISSION RATE TABLES ARE NOT PRINTED
0 SIMULATION: PERFORMED ENVIRONMENTAL MEASURES: CALCULATED
0 FUEL RATES: EMBEDDED TRAJECTORY FILE: NOT PRINTED

INITIALIZATION CODE (0, 1) = (DO NOT, DO) FORCE FULL INITIALIZATION PERIOD
0 INPUT UNITS CODE = (0, 1) IF INPUT IS IN (ENGLISH, METRIC) UNITS
0 OUTPUT UNITS CODE = (0, 1, 2, 3) IF OUTPUT IS IN (SAME AS INPUT, ENGLISH, METRIC, BOTH)

UNITS
700 CLOCK TIME AT START OF SIMULATION (HHMM)
7581 RANDOM NUMBER SEED
900 DURATION (SEC) OF TIME PERIOD NO. 1
60 LENGTH OF A TIME INTERVAL, SECONDS
10 FRESIM TIME STEP DURATION IN TENTHS-OF-A-SECOND
20 MAXIMUM INITIALIZATION TIME, NUMBER OF TIME INTERVALS
0 NUMBER OF TIME INTERVALS BETWEEN SUCCESSIVE STANDARD OUTPUTS
0 TIME INTERMEDIATE OUTPUT WILL BEGIN AT INTERVALS OF 0 SECS. FOR 0 SECS. FOR

MICROSCOPIC MODELS

1 FRESIM LINK CHARACTERISTICS

--- ONE --- TWO --- THREE ---

--- AUXILIARY LANE ---

TOTAL LINKS: 10

* INDICATES THAT THE DEFAULT VALUE IS USED
LINK TYPE CODE | AUXILIARY LANE TYPE CODE | PAVEMENT CODE | TRUCK RESTRAINT CODE
--- | --- | --- | ---
F FREEWAY LINK UNRESTRICTED | A ACCELERATION LANE | 1 DRY CONCRETE | 0 TRUCKS ARE
R RAMP LINK BIASED TO | D DECELERATION LANE | 2 WET CONCRETE | 1 TRUCKS ARE
REstricted TO | F FULL AUXILIARY LANE | 3 DRY ASPHALT | CERTAIN LANE(S)
| | 4 WET ASPHALT | 2 TRUCKS ARE | CERTAIN LANES(S)

CAR FOLLOWING SENSITIVITY MULTIPLIERS

LINK ID | MULTIPLIER
--- | ---

(NO MODIFIERS WERE PROVIDED - MULTIPLIERS FOR ALL LINKS ARE DEFAULTED TO 1.0)

ANTICIPATORY LANE CHANGE PARAMETERS

FRESIM TURNING MOVEMENTS

----------- MAIN-LINE TRAFFIC -----------
 DOWNSTREAM NODE NO. OF THE MAIN-LINE RECEIVING LINK PERCENTAGE
-------------- --------- ----------- ------
( 6, 7) 8 100.0
( 7, 8) 9 100.0
( 8, 9) 8002 100.0
(8001, 1) 2 100.0
( 5, 6) 7 100.0
( 4, 5) 6 100.0
( 1, 2) 3 100.0
( 2, 3) 4 100.0
( 3, 4) 5 100.0

FRESIM INCIDENT DATA

INCIDENT CODE | DISTANCE FROM | LENGTH | RUBBER NECKING | WARN. SIGN
--- | --- | --- | --- | ---
1 UPSTREAM ROADWAY NODE | 0 | 2640.0 | **** | 0 | 0 | 2640.0

* INCIDENT CODES:
0 - NORMAL SPEED
1 - REDUCED TRAFFIC CAPACITY DUE TO RUBBER NECKING
2 - BLOCKAGE

FRESIM LINK VOLUME

FLOW RATE | TRUCKS | CARPOOL | LANE VIOLATORS
--- | --- | --- | ---
LINK (VEH/HOUR) | PERCENT | PERCENT | PERCENT HOV
-------------- | ----------- | ----------- | --------------
(8001, 1) 2400 0 0 1.00

FRESIM LANE ALIGNMENT TABLE

DISTANCE FROM LINK | UPST. NODE | UPSTREAM FEEDING LANE NUMBER | REASON CODE
--- | --- | --- | ---

TABLE OF FREEWAY WARNING SIGNS

WARNING SIGN OBJECTIVE

--- EXTENT BETWEEN LINK --- DISTANCE BETWEEN TRAFFIC

EXITING THE WARNING SIGN LINK THE WARNING SIGN TRAFFIC

TRAFFIC
**FOR EACH ORIGIN NODE, TABLE PROVIDES LISTING OF PAIRS OF DATA: DESTINATION/ FRACTION OF ENTRY VOLUME TRAVELING TO DESTINATION**

**CURRENT CONTENT/VEHICLES**

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**GRADE CORRECTION FACTORS FOR FUEL CONSUMPTION (USED BY FRESIM ONLY)**

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**INITIALIZATION STATISTICS**

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**ALL EXISTING SUBNETWORKS REACHED EQUILIBRIUM**
CUMULATIVE FRESIM STATISTICS AT TIME 7 15 0

LINK STATISTICS

VEH-MILES

VEHICLES LANE CURR AVG VEH- VEH- TOTAL MOVE DELAY VEH-MILE
MIN TIME TIME M/T TOTAL DELAY VEH/LN/HA VEH/LN-MILE

SPEED LINK IN OUT CHNG CONT CONT MILES MIN TIME TIME M/T TOTAL DELAY VEH/LN/HR VEH/LN-MILE
MILE/HR TYPE

----------- ----- ----- ---- ----- ----- ------- ------- ------ ----- ----- ----- ----- -----  -------   ---------  ---
------- ----

( 6, 7) 597 561 306 62 39.7 291.9 596.1 61.3 28.0 1176.6 39.7
29.38 FRWY

( 7, 8) 561 562 0 22 23.2 280.4 348.5 37.3 28.8 1121.5 23.2
48.28 FRWY

( 8, 9) 562 566 267 12 18.3 281.3 274.6 29.3 27.7 1125.2 18.3
61.48 FRWY

( 5, 6) 603 597 126 20 19.0 299.5 291.1 29.2 27.8 1197.9 19.5
61.74 FRWY

( 4, 5) 604 603 8 2 1.1 17.1 16.6 1.7 1.6 1194.4 19.0
61.89 FRWY

( 1, 2) 599 598 98 20 19.0 301.4 284.3 28.3 27.8 1205.7 19.0
63.60 FRWY

( 2, 3) 598 604 827 129 133.2 2060.6 1997.5 200.3 191.2 1196.9 19.3
61.89 FRWY

NETWORK STATISTICS

VEHICLE-MILES = 3549.1, VEHICLE-MINUTES = 3824.8, MOVING/TOTAL TRIP TIME = 0.872,
AVERAGE CONTENT = 255.0, CURRENT CONTENT = 271.0, SPEED (MPH) = 55.68,
TOTAL DELAY (VEH-MIN) = 491.04, TRAVEL TIME (MIN)/VEH-MILE = 1.08, DELAY TIME (MIN)/ VEH-MILE = 0.14

LINK STATISTICS BY LANE

(SOME STATISTICS APPLY TO HOV LANES ONLY)

SEC./VEHICLE SEC./PERSON

VEHICLE TYPE- IN OUT CONT CONT MILES VOLUME OF VIOLATORS TOTAL MOVE DELAY TIME VEH-LN/TRIP TIME MILES/HR

----------- ----- ----- ---- ----- ------- ------ ------ ---- ---- ---- ---- ----  -------   --------  ---
------- ----

( 6, 7) 1 SOV --- --- 5 322.1 ----- 29.2 28.3 1.0 22.5 21.7 0.7 61.57

( 6, 7) 2 SOV --- --- 57 2012.4 ----- 66.4 27.7 38.7 51.1 21.3 29.8 27.10

( 7, 8) 1 SOV --- --- 0 0.0 ----- 0.0 0.0 0.0 0.0 0.0 0.0 0.00

( 7, 8) 2 SOV --- --- 22 2242.9 ----- 37.3 32.9 4.4 28.7 25.3 3.4 48.28

( 8, 9) 1 SOV --- --- 4 796.8 ----- 27.9 26.7 1.2 21.5 20.5 0.9 64.48

( 8, 9) 2 SOV --- --- 8 1453.7 ----- 30.0 28.5 1.6 23.1 21.9 1.2 59.95

( 5, 6) 1 SOV --- --- 13 1216.5 ----- 29.0 27.7 1.3 22.3 21.3 1.0 62.03

( 5, 6) 2 SOV --- --- 10 1179.4 ----- 29.3 27.9 1.4 22.5 21.4 1.1 61.44

( 4, 5) 1 SOV --- --- 1 1238.5 ----- 1.7 1.6 0.1 1.3 1.2 0.1 61.95

( 4, 5) 2 SOV --- --- 1 1172.9 ----- 1.7 1.6 0.1 1.3 1.2 0.1 61.83

( 1, 2) 1 SOV --- --- 8 1199.1 ----- 28.3 27.8 0.5 21.8 21.4 0.4 63.51

( 1, 2) 2 SOV --- --- 12 1212.4 ----- 28.3 27.7 0.5 21.7 21.3 0.4 63.70

( 2, 3) 1 SOV --- --- 0 1192.6 ----- 1.6 1.6 0.1 1.3 1.2 0.0 62.64

( 2, 3) 2 SOV --- --- 1 1196.2 ----- 1.6 1.6 0.1 1.2 1.2 0.0 63.03

( 3, 4) 1 SOV --- --- 66 1216.1 ----- 200.1 191.1 9.0 153.9 147.0 6.9 61.94

( 3, 4) 2 SOV --- --- 63 1177.5 ----- 200.4 191.2 9.2 154.2 147.1 7.1 61.84

FRESIM CUMULATIVE VALUES OF FUEL CONSUMPTION

VEHICLE TYPE- GALLONS M.P.G.

1 2 3 4 5 6 7 1 2 3 4 5

( 6, 7) FRWY 8.70 16.69 0.00 0.00 0.00 0.00 0.00 7.63 13.53 0.00 0.00 0.00 0.00
### FRESIM CUMULATIVE VALUES OF EMISSION

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### FRESIM INTERMEDIATE LINK STATION DATA AT TIME 7 15 0

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### FRESIM INTERMEDIATE LINK STATION DATA AT TIME 7 15 0

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Sample Output from CORSIM 6.0

On the following pages is a sample output for the following scenario (base case):

- 2-to-1 Lane Closure
- Work Zone Length at 0.5 miles
- Input Lane Distributions at 50/50
- Sign Distance at 0.5 miles
- Truck Percentage at 0%
- Rubbernecking Factor at 0%
INPUT FILE NAME: S:\Projects\Trucks on Arterials, Workzones on Free
RUN DATE : 02/01/06

VERSION 6.0 (BUILD 483)
RELEASE DATE APRIL 2005
TRAF SIMULATION MODEL
DEVELOPED FOR
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
FHWA OFFICE OF OPERATIONS RESEARCH, DEVELOPMENT AND TECHNOLOGY

CARD FILE LIST

0SEQ.# :----+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8

1 : 10 102005 0 1
2 : 1 0 0 20 7981 0000 0 8 700 7781 7581 2
3 : 900 1 0 3 3
4 : 1 60 4
5 : 0 0 0 0 0 0 0 0 0 5
6 : 6 7 8 2640 2 1 19
7 : 7 8 9 2640 2 1 19
8 : 8 98002 2640 2 1 19
9 : 5 6 7 2640 2 1 19
10 : 4 5 6 1500 2 1 19
11 : 1 2 3 2640 2 1 19
12 : 2 3 4 1500 2 1 19
13 : 3 4 5181002 2 1 19
14 : 8001 1 2 0 2 1
15 : 0 0 0 0 11065 1 1 100 20
16 : 7 8 0 0 0 11055 1320 100 20
17 : 8 9 0 0 0 11065 1 1 100 20
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27 : 5 6 7 100 25
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29 : 1 2 3 100 25
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31 : 3 4 5 100 25
32 : 8001 1 2 100 25
33 : 7 8 2 0 2640 2009999 0 2640 25
34 : 8001 12400 0 0 100 50 50 50
35 : 0 170
36 : 8002 35000 0 195
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38 : 1 100 0 195
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FRESIM LINK CHARACTERISTICS

--- AUXILIARY LANE ---

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TOTAL LINKS: 10

* INDICATES THAT THE DEFAULT VALUE IS USED
**Link Type Code**

- **F Freeway Link**: Unrestricted
- **R Ramp Link**: Biased to
- **Restricted To**

**Auxiliary Lane Type Code**

- **A Acceleration Lane**
- **D Deceleration Lane**
- **F Full Auxiliary Lane**

**Pavement Code**

- **1 Dry Concrete**
- **2 Wet Concrete**
- **3 Dry Asphalt**
- **4 Wet Asphalt**

**Truck Restriction**

- **0 Trucks Are Unrestricted**
- **1 Trucks Are Restricted To Certain Lane(s)**
- **2 Trucks Are Restricted To Certain Lanes(s)**

**Car Following Sensitivity Multipliers**

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(No modifiers were provided - multipliers for all links are defaulted to 1.0)

**Anticipatory Lane Change Parameters**

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**Fresim Turning Movements**

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**Fresim Incident Data**

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* INCIDENT CODES:
- 0 - Normal Speed
- 1 - Reduced Traffic Capacity Due to Rubber Necking
- 2 - Blockage

**Fresim Link Volume**

<table>
<thead>
<tr>
<th>FLOW RATE</th>
<th>PERCENT TRUCKS</th>
<th>PERCENT CARPOOLS</th>
<th>PERCENT HOV</th>
</tr>
</thead>
<tbody>
<tr>
<td>LINK</td>
<td>(VEH/HR)</td>
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<tr>
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**Fresim Lane Alignment Table**

<table>
<thead>
<tr>
<th>DISTANCE FROM UPSTREAM FEEDING LANE NUMBER</th>
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</thead>
<tbody>
<tr>
<td>LINK</td>
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<tr>
<td>------</td>
</tr>
<tr>
<td>(6, 7)</td>
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<tr>
<td>(7, 8)</td>
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<tr>
<td>(5, 6)</td>
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<tr>
<td>(4, 5)</td>
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<td>(3, 4)</td>
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</table>

**Table of Freeway Warning Signs**

<table>
<thead>
<tr>
<th>WARNING SIGN OBJECTIVE</th>
<th>DISTANCE BETWEEN</th>
<th>DISTANCE BETWEEN</th>
<th>THE WARNING SIGN</th>
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</thead>
<tbody>
<tr>
<td>EXISTING TRAFFIC</td>
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<td>TRAFFIC</td>
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</tbody>
</table>
FOR EACH ORIGIN NODE, TABLE PROVIDES LISTING OF PAIRS OF DATA: DESTINATION/FRACTION OF ENTRY VOLUME TRAVELING TO DESTINATION

ORIGIN NODE (8001) 9/ 1.000

THE GRAVITY MODEL ACCURACY THRESHOLD IS 5.0E-02

GRAVITY MODEL RESULTS

ENTRY VOL/DEST 9
8001 2400.0 2400.0
SUM VOL 2400.0
DEST VOL 2400.0

FREE FLOW SPEED PERCENTAGES

Driver Type: 1 2 3 4 5 6 7 8 9 10
Percentage: 88 91 94 97 99 101 103 106 109 112

MAXIMUM ACCELERATION TABLE

1 8.00 9.00 6.00 5.00 5.00 5.00 4.00 4.00 2.00 2.00 1.00 1.00
2 6.00 12.00 7.00 4.00 4.00 4.00 2.00 2.00 1.00 1.00 1.00 1.00
3 4.69 5.35 4.94 4.07 4.07 4.07 3.07 3.07 2.07 2.07 1.07 1.07
4 2.81 2.42 1.42 1.12 1.12 1.12 1.12 1.12 1.12 1.12 1.12 1.12
5 2.76 2.37 1.81 1.56 1.56 1.56 1.56 1.56 1.56 1.56 1.56 1.56
6 2.45 2.14 1.42 1.12 0.85 0.85 0.85 0.85 0.85 0.85 0.85 0.85
7 7.47 5.33 3.17 2.66 2.29 2.29 2.29 2.29 2.29 2.29 2.29 2.29

GRADE CORRECTION FACTORS FOR ACCELERATION (USED BY FRESIM ONLY)

1 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31
2 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31
3 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21 0.21
4 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16
5 0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18 0.18
6 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27
7 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27

GRADE CORRECTION FACTORS FOR FUEL CONSUMPTION (USED BY FRESIM ONLY)

1 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31
2 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31
3 0.26 0.26 0.26 0.26 0.26 0.26 0.26 0.26 0.26 0.26 0.26 0.26
4 0.11 0.11 0.11 0.11 0.11 0.11 0.11 0.11 0.11 0.11 0.11 0.11
5 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16 0.16
6 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20 0.20
7 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27 0.27

INITIALIZATION STATISTICS

TIME INTERVAL SUBNETWORK TYPE SUBNETWORK PRIOR CONTENT CURRENT CONTENT PERCENT
NUMBER SUBNETWORK (VEHICLES) (VEHICLES) (VEHICLES)
1 1 FRESIM 0 39 10000
2 2 FRESIM 39 79 102
3 3 FRESIM 79 119 50
4 4 FRESIM 119 159 33
5 5 FRESIM 159 199 25
6 6 FRESIM 199 225 13
7 7 FRESIM 225 234 4
8 8 FRESIM 234 242 3

ALL EXISTING SUBNETWORKS REACHED EQUILIBRIUM
### CUMULATIVE FRESIM STATISTICS AT TIME 7:15:0

#### LINK STATISTICS

<table>
<thead>
<tr>
<th>LINK</th>
<th>VEH-MIN/VEH-MILE</th>
<th>SECONDS/VEHICLE</th>
<th>VEH-MILES</th>
<th>VEH-DELAY</th>
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<td></td>
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<td>MILE/HR</td>
<td>VEHICLES</td>
<td>LANE</td>
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<tr>
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</table>

#### NETWORK STATISTICS

- **Vehicle-Miles**: 3594.3
- **Vehicle-Minutes**: 3698.1
- **Moving/Total Trip Time**: 0.915
- **Average Content**: 246.5
- **Current Content**: 253.0
- **Speed (MPH)**: 58.31
- **Total Delay (VEH-MIN)**: 313.57
- **Travel Time (MIN)/VEH-MILE**: 1.03
- **Delay Time (MIN)/VEH-MILE**: 0.09

#### LINK STATISTICS BY LANE

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<tr>
<th>LINK</th>
<th>TYPE</th>
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#### FRESIM CUMULATIVE VALUES OF FUEL CONSUMPTION

- **Fuel Consumption by Vehicle Type (Gallons)**

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<tr>
<td>SUBNETWORK</td>
<td>FRESIM CUMULATIVE VALUES OF EMISSION</td>
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<tr>
<td>VEHICLE EMISSIONS BY VEHICLE TYPE (GRAMS / MILE)</td>
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<tr>
<td>CARPOOL, VEHICLE TYPES 10 - 16 USER DEFINED</td>
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</tbody>
</table>

**VEHICLE TYPES 1, 2 = AUTO, VEHICLE TYPES 3, 4, 5, 6 = TRUCK, VEHICLE TYPE 7 = TRANSIT BUS, VEHICLE TYPES 8, 9 = CARPOOL, VEHICLE TYPES 10 - 16 USER DEFINED**

**FRESIM CUMULATIVE VALUES OF EMISSION**

<table>
<thead>
<tr>
<th>VEHICLE EMISSIONS BY VEHICLE TYPE (GRAMS / MILE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARPOOL, VEHICLE TYPES 10 - 16 USER DEFINED</td>
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<tbody>
<tr>
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<tr>
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<tbody>
<tr>
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**FRESIM CUMULATIVE VALUES OF EMISSION**

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<tr>
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<tbody>
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<td>CARPOOL, VEHICLE TYPES 10 - 16 USER DEFINED</td>
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### FRESIM Intermediate Link Station Data at Time 7 15 0

**Mean Speed**

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**Mean Headway**

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</tr>
</tbody>
</table>

Vehicle types:
- 1, 2 = Auto
- 3, 4, 5, 6 = Truck
- 7 = Transit Bus
- 8, 9 = Carpool
- 10 - 16 = User Defined
<table>
<thead>
<tr>
<th>LANE</th>
<th>SEC</th>
<th>0.4</th>
<th>0.8</th>
<th>1.6</th>
<th>2.0</th>
<th>2.4</th>
<th>2.8</th>
<th>3.2</th>
<th>3.6</th>
<th>4.0</th>
<th>4.4</th>
<th>4.8</th>
<th>5.2</th>
<th>5.6</th>
<th>6.0</th>
<th>6.4</th>
<th>6.8</th>
<th>7.2</th>
<th>7.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0</td>
<td>1</td>
<td>3.06</td>
<td>7</td>
<td>15</td>
<td>12</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2.93</td>
<td>8</td>
<td>14</td>
<td>12</td>
<td>7</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NETWORK-WIDE AVERAGE STATISTICS**

TOTAL VEHICLE-MILE = 3594.26 VEHICLE-HOURS OF: MOVE TIME = 56.41, DELAY TIME = 5.23, TOTAL TIME = 61.64

AVERAGE SPEED (MPH) = 58.31 MOVE/TOTAL = 0.92 MINUTES/MILE OF: DELAY TIME = 0.09, TOTAL TIME = 1.03

**NETWORK-WIDE STATISTICS FOR SCRIPT PROCESSING**

3594.26, 56.41, 5.23, 61.64, 58.31, 0.92, 0.09, 1.03

TOTAL CPU TIME FOR SIMULATION = 12.67 SECONDS
TOTAL CPU TIME FOR THIS RUN = 12.67 SECONDS

LAST CASE PROCESSED
APPENDIX D
STATISTICA OUTPUT SCREENSHOTS FOR EACH LANE CLOSURE CONFIGURATION

This section presents the output screenshots from the software package STATISTICA used to analyze the data for this report. The models for each lane closure configuration are presented with their corresponding $R^2$ values.

The first column of the output shows the parameter estimates for each of the variables and the third and fourth columns show the t- and p-stats. The red color of the font across the rows is the way in which the software conveys statistical significance of the variables to a pre-specified level. All models are statistically significant within a 95% level of confidence.

2-to-1 Lane Closure Configuration

| Effect               | Parameter Estimates (2 to 1) | One-parameterized model |  |  |  |  |  |  |  |
|----------------------|-------------------------------|-------------------------|---|---|---|---|---|---|
|                      | Param | Std Err | t | p | 95.00% Cl | 95.00% Cl | Beta | St. Err | 95.00% Cl | 95.00% Cl |
| Intercept            | 1923.222 | 21.17982 | 76.5.966 | 0.00000 | 1581.296 | 1664.747 | 0.99622 | 0.079463 | 0.84564 | 1.14695 |
| Sign Dist            | 749.918 | 66.60992 | 11.02523 | 0.00000 | 629.161 | 862.935 | -0.99622 | 0.079463 | 0.84564 | 1.14695 |
| Truck %             | -0.14233 | 0.89644 | -16.42573 | 0.00000 | -15.962 | -12.861 | -0.39279 | 0.018729 | -0.41167 | 0.34938 |
| Percent             | -22.880 | 0.46490 | -35.15698 | 0.00000 | -24.271 | -21.551 | -0.7795 | 0.021975 | -0.81906 | -0.7927 |
| Dei Lan 1(6,7)Sign Dist | -409.799 | 65.74250 | 6.23280 | 0.00000 | -539.275 | -269.241 | -2.09927 | 0.035776 | -0.27542 | 0.14312 |
| Spt Lan 1(6,7)Sign Dist | -13.513 | 0.65227 | -16.37445 | 0.00000 | -15.139 | -11.896 | -1.39621 | 0.081729 | -1.40238 | -1.17726 |
| Sel Spt Lan 1(6,7) | -26.654 | 1.22933 | 21.7444 | 0.00000 | -24.972 | -20.116 | 0.81191 | 0.037357 | 0.73798 | 0.85247 |

| Dependent Variable | Test of SS Whole Model vs. SS Residual (2 to 1) |  |  |  |  |  |  |  |  |  |
|--------------------|------------------------------------------------|---|---|---|---|---|---|---|---|
|                    | Multiple R | Multiple $R^2$ | Adjusted $R^2$ | SS Model | df Model | MS Model | SS Residual | df Residual | MS Residual | F | p |
| Vol Lan 2(7,8) | 0.995786 | 0.971777 | 0.971057 | 21.762325 | 6 | 352.7672 | 63223.36 | 235 | 267.35865 | 1354.211 | 0.00 |
### 3-to-2 Lane Closure Configuration

<table>
<thead>
<tr>
<th>Effect</th>
<th>Parameter Estimates (3 to 2 lane)</th>
<th>Over-parameterized model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VolAv1(7,3)</td>
<td>VolAv2(7,3)</td>
</tr>
<tr>
<td>Intercept</td>
<td>1.995</td>
<td>42.278</td>
</tr>
<tr>
<td>SignDist</td>
<td>71.1</td>
<td>93.666</td>
</tr>
<tr>
<td>Trucks</td>
<td>-6.87</td>
<td>1.259</td>
</tr>
<tr>
<td>Rubble</td>
<td>-17.81</td>
<td>0.928</td>
</tr>
<tr>
<td>LoanDistSignDist</td>
<td>-121.19</td>
<td>112.167</td>
</tr>
<tr>
<td>LoanDistSignDist</td>
<td>-10.61</td>
<td>1.525</td>
</tr>
<tr>
<td>SignDist</td>
<td>3.2</td>
<td>1.322</td>
</tr>
</tbody>
</table>

### 3-to-1 Lane Closure Configuration

<table>
<thead>
<tr>
<th>Effect</th>
<th>Parameter Estimates (3 to 1 lane)</th>
<th>Over-parameterized model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VolAv1(7,3)</td>
<td>VolAv2(7,3)</td>
</tr>
<tr>
<td>Intercept</td>
<td>18.6</td>
<td>4.112</td>
</tr>
<tr>
<td>SignDist</td>
<td>78.3</td>
<td>98.719</td>
</tr>
<tr>
<td>Trucks</td>
<td>-10.1</td>
<td>1.081</td>
</tr>
<tr>
<td>Rubble</td>
<td>-20.9</td>
<td>1.580</td>
</tr>
<tr>
<td>LoanDistSignDist</td>
<td>-18.6</td>
<td>39.657</td>
</tr>
<tr>
<td>LoanDistSignDist</td>
<td>-20.6</td>
<td>1.411</td>
</tr>
<tr>
<td>SignDist</td>
<td>36.6</td>
<td>1.545</td>
</tr>
</tbody>
</table>

### Test of SS Whole Model vs. SS Residual

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Multiple R</th>
<th>Multiple R²</th>
<th>Adjusted R²</th>
<th>SS Model</th>
<th>df Model</th>
<th>MS Model</th>
<th>SS Residual</th>
<th>df Residual</th>
<th>MS Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>VolAv1(7,3)</td>
<td>0.97834</td>
<td>0.95715</td>
<td>0.95758</td>
<td>5190.010</td>
<td>6</td>
<td>865.016</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3229.053</td>
<td>74</td>
<td>3139.260</td>
<td>275.547</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX E
MODEL USAGE EXAMPLE: SAMPLE CAPACITY CALCULATIONS FOR EACH LANE CLOSURE CONFIGURATION

The table on the following page shows a sample calculation of capacity values for all the models given in the text. The Variables are listed to the left, and the trial input values are given in the Trial Values column, each one highlighted in yellow. The highlighted values show the user inputs and the non-highlighted values are calculated from the respective inputs and applied in each respective model. The limitations to the ranges of each of the inputs are listed on the far right side of the table and are discussed following the presentation of the sample calculations table.

The parameter estimates are shown where applicable for each of the models, and the total capacities for each model are displayed across the bottom of the table. These capacities are calculated by summing the Intercept with each of the terms in the same column multiplied by their respective input values in the Trial Values column.

The models and parameters are shown on the following page.
<table>
<thead>
<tr>
<th>Variables</th>
<th>Units</th>
<th>Trial Values</th>
<th>Lane Closure Configuration Parameter Estimates</th>
<th>Range of Input Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2-to-1</td>
<td>3-to-2</td>
</tr>
<tr>
<td>Intercept</td>
<td></td>
<td></td>
<td>1623.022</td>
<td>1595.840</td>
</tr>
<tr>
<td>SignDist</td>
<td>miles</td>
<td></td>
<td>740.878</td>
<td>711.490</td>
</tr>
<tr>
<td>Truck%</td>
<td>%</td>
<td></td>
<td>-14.233</td>
<td>-5.870</td>
</tr>
<tr>
<td>Rubber%</td>
<td>%</td>
<td></td>
<td>-22.830</td>
<td>-17.880</td>
</tr>
<tr>
<td>DistrLan1(6,7)</td>
<td>fraction</td>
<td></td>
<td>0.15</td>
<td>-409.758</td>
</tr>
<tr>
<td>DistrLan2(6,7)</td>
<td>fraction</td>
<td></td>
<td>0.4</td>
<td>-626.500</td>
</tr>
<tr>
<td>SpdLan1(5,6)</td>
<td>mph</td>
<td></td>
<td>35</td>
<td>-10.580</td>
</tr>
<tr>
<td>SpdLan1(6,7)</td>
<td>mph</td>
<td></td>
<td>35</td>
<td>-13.513</td>
</tr>
<tr>
<td>SpdLan2(6,7)</td>
<td>mph</td>
<td></td>
<td>35</td>
<td>-14.370</td>
</tr>
<tr>
<td>DistrLan1(6,7) * SignDist</td>
<td></td>
<td></td>
<td>0.15</td>
<td>-409.758</td>
</tr>
<tr>
<td>DistrLan2(6,7) * SignDist</td>
<td></td>
<td></td>
<td>0.4</td>
<td>-626.500</td>
</tr>
<tr>
<td>SpdLan1(5,6) * SignDist</td>
<td></td>
<td></td>
<td>35</td>
<td>-10.580</td>
</tr>
<tr>
<td>SpdLan1(6,7) * SignDist</td>
<td></td>
<td></td>
<td>35</td>
<td>-13.513</td>
</tr>
<tr>
<td>SpdLan2(6,7) * SignDist</td>
<td></td>
<td></td>
<td>35</td>
<td>-14.370</td>
</tr>
<tr>
<td>CalcSpdLan2(5,6)</td>
<td></td>
<td></td>
<td>22.3305</td>
<td>9.300</td>
</tr>
<tr>
<td>CalcSpdLan2(6,7)</td>
<td></td>
<td></td>
<td>6.3746</td>
<td>26.694</td>
</tr>
<tr>
<td>CalcSpdLan3(6,7)</td>
<td></td>
<td></td>
<td>6.7642</td>
<td>26.840</td>
</tr>
<tr>
<td>Calculated Capacities (veh/hr/ln)</td>
<td></td>
<td></td>
<td>1743.16</td>
<td>1814.81</td>
</tr>
</tbody>
</table>
The usable ranges of values for each of the lane closure configurations are shown below. Following each lane closure model’s range is an explanation of the reasoning behind the numbers.

2-to-1 configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SignDist$</td>
<td>0.5 mi</td>
<td>1.5 mi</td>
</tr>
<tr>
<td>$Truck%$</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>$Rubber%$</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>$DistrLan1(6,7)$</td>
<td>0.043</td>
<td>0.628</td>
</tr>
<tr>
<td>$SpdLan1(6,7)$</td>
<td>2.48</td>
<td>66.28</td>
</tr>
</tbody>
</table>

Notes: The limitations shown for the above configuration are a result of the data ranges that were produced from simulation. For a two-lane facility, the speed of the vehicles in link (6,7) can vary significantly based on the level of congestion present in lane 2. After the work zone sign, there is never a distribution of vehicles higher than 0.63 in lane 1. This implies that the fraction of vehicles in lane 2 must always be greater than 0.37. These implications are practical to keep in mind when inputting values; in doing so, if a capacity estimate appears unreasonable, there may be a traceable input value that is not logical for the traffic stream.
3-to-2 configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SignDist</td>
<td>0.5 mi</td>
<td>1.5 mi</td>
</tr>
<tr>
<td>Truck%</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Rubber%</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>DistrLan1(6,7)</td>
<td>0.076</td>
<td>0.352</td>
</tr>
<tr>
<td>SpdLan1(5,6)</td>
<td>11.0</td>
<td>60.5</td>
</tr>
</tbody>
</table>

Notes: The limitations shown for the above configuration are a result of the data ranges that were produced from simulation. For a three lane facility, the speed of the vehicles in link (5,6) should be assumed to be at approximately free-flow speed unless the queue is backing up beyond the location of the upstream warning sign. If the queue from the lane closure should spill back onto link (5,6), then the value of speeds on lane 1 and lane 2 may be different under specific traffic stream conditions. Because vehicles are merging from lane 1 to lanes 2 and 3 of link (6,7), the queue from lane 2 will spill back onto link (5,6) sooner than the queue in lane 1, causing the speeds in lane 1 to be higher.
### 3-to-1 configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SignDist</td>
<td>0.5 mi</td>
<td>1.5 mi</td>
</tr>
<tr>
<td>Truck%</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Rubber%</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>DistrLan1(6,7)</td>
<td>0.002</td>
<td>0.176</td>
</tr>
<tr>
<td>DistrLan2(6,7)</td>
<td>0.041</td>
<td>0.508</td>
</tr>
<tr>
<td>SpdLan2(6,7)</td>
<td>2.93</td>
<td>66.64</td>
</tr>
</tbody>
</table>

Notes: The limitations shown for the above configuration are a result of the data ranges that were produced from simulation. For this lane configuration, the speeds in lanes 2 will decrease with a growing queue on that lane. If the queue of lane 3 from link (6,7) spills back into link (5,6), then congestion is high, and a queue will likely be forming on lane 2. When inputting lane distribution values, the user should keep in mind that lane 3 of link (6,7) is getting the remaining distribution of vehicles not assigned to lanes 1 or 2. For example, inputting the largest values for both lanes 1 and 2 (0.176 and 0.508, respectively) only leaves 0.316 of the traffic stream in lane 3, the through lane. This is not realistic and the resulting capacity value will not be reasonable.
APPENDIX F
TRAFVU SCREENSHOTS FOR EACH LANE CLOSURE CONFIGURATION

The illustration below shows the TRAFVU screen shots for the following simulation scenarios:

- 0.5 mile upstream warning sign location (not pictured)
- 20% truck presence in the traffic stream
- 15% rubbernecking factor through the work zone (the presence of a rubbernecking factor is depicted by yellow-colored lanes)
The distance shown upstream of lane closure in the illustrations is approximately 0.10 miles. The closed lanes are depicted by red-colored lanes, and the yellow lanes show where the rubbernecking factor is being applied. The 2-to-1, 3-to-2, and 3-to-1 lane closures shown are one minute into the simulation.
LIST OF REFERENCES


Beacher, Andrew G., Fontaine, Michael D., and Garber, Nicholas J. “Guidelines for Using Late Merge Work Zone Traffic Control: Results of a Simulation-Based Study.” Transportation Research Record: Journal of the Transportation Research Board, Issue Number: 1911. 2005.


McTrans (Center for Microcomputers in Transportation). U.S. Department of Transportation, FHWA. Gainesville, FL.


Ullman, Gerald L. “Queuing and Natural Diversion at Short-Term Freeway Work Zone Lane Closures.” *Transportation Research Record: Journal of the Transportation Research Board*, Issue Number: 1529. 1996.


BIOGRAPHICAL SKETCH

Diego Federico Arguea was born in Jerusalem, Israel, in 1981. His parents are from Argentina and he grew there and in California and Florida. He obtained his high school and International Baccalaureate diploma from Pensacola High School, Florida. Mr. Arguea also has had the opportunity to experience one year of overseas education in Madrid, Spain.

Mr. Arguea completed his undergraduate studies in civil engineering at the University of Florida in 2004, also obtaining a minor degree in business and an engineering sales certificate. He was licensed as an E.I.T. in the state of Florida in 2004 and has consulting experience from two internship experiences with civil engineering companies. Mr. Arguea is currently a master’s candidate and research assistant in the Transportation Research Center, also at the University of Florida, Department of Civil and Coastal Engineering, and he will be receiving his Master of Engineering degree in August 2006.

In addition to his studies, Mr. Arguea is active in the University of Florida tennis club and Institute of Transportation Engineers. He was also selected for the annual Eno Transportation Leadership Development Conference in Washington, D.C., and will be attending the conference in May of 2006. Mr. Arguea plans to pursue his interests in transportation engineering and work in the consulting field while maintaining his ties to transportation research.