FINAL REPORT

to

THE FLORIDA DEPARTMENT OF TRANSPORTATION
ROADWAY DESIGN OFFICE

on Project

"Impact of Lane Closures on Roadway Capacity"

FDOT Contract BD-545, RPWO #61 (UF Project 00059056)

PART B: ARTERIAL WORK ZONE CAPACITY

January 31, 2008

The University of Florida

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METRIC CONVERSION CHART

U.S. UNITS TO METRIC (SI) UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
in	Inches	25.4	Millimeters	mm
ft	Feet	0.305	Meters	m
yd	Yards	0.914	Meters	m
mi	Miles	1.61	Kilometers	km

METRIC (SI) UNITS TO U.S. UNITS

LENGTH

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
mm	Millimeters	0.039	Inches	in
m	Meters	3.28	Feet	ft
m	Meters	1.09	Yards	yd
km	Kilometers	0.621	Miles	mi

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16. Abstract

The current Florida Department of Transportation (FDOT) arterial work zone capacity estimation procedure does not account for various operating and work zone characteristics of the facility (i.e. speeds, the position of the closed lanes, etc.). The objectives of this research are to: a) identify the various geometric and traffic factors that might impact the capacity of an arterial work zone, and b) develop analytical model(s) and methods to estimate its capacity. Field data were not available to conduct this research, therefore CORSIM was used to develop several intersection and work zone configurations and obtain relationships between various factors and the capacity of the arterial work zone. A set of appropriate scenarios was developed considering the capabilities of the simulator, the impacts various factors may have on arterial work zone capacity, as well as the sensitivity of those factors with respect to the simulated capacity. Five regression models were developed to predict the capacity of the entire approach, the capacity of the left turning lane group, and the capacity of the through and right turning group for various arterial work zone configurations. In those models, capacity is estimated as a function of various factors including the percent of left turning vehicles, the distance of the work zone to the downstream intersection, the g/C ratios of each lane group, etc.

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EXECUTIVE SUMMARY

The Florida Department of Transportation (FDOT) is interested in updating its existing methodologies for estimating the capacity of arterial lane closures. This estimation is important because capacity is used to forecast queues and delays. The current FDOT arterial work zone capacity estimation procedure is an extension of the one used to estimate freeway work zone capacity, and does not account for various operating and work zone characteristics of the facility (i.e. speeds, the position of the closed lanes, etc.).

A review of the literature showed that little research has been conducted to estimate the capacity of work zones on arterials. State policies use work zone capacity values ranging from 600 to 1520 vphpl, and it is not clear how these values were obtained, or what the relationship is between capacity and various work zone and operational characteristics at the site. There are several software programs that estimate delays due to work zones; however these use capacity as input in their procedures.

Field data were not available to conduct this research, therefore simulation was used to develop several intersection and work zone configurations and obtain relationships between various factors and the capacity of the arterial work zone. CORSIM (version 5.1) was selected to develop a comprehensive database for the model development. A set of appropriate scenarios was developed considering the capabilities of the simulator, the impacts various factors may have on arterial work zone capacity, as well as the sensitivity of those factors with respect to the simulated capacity. Five regression models were developed to predict the capacity of the entire approach, the

capacity of the left turning lane group, and the capacity of the through and right turning group for various arterial work zone configurations. In those models, capacity is estimated as a function of various factors including the percent of left turning vehicles, the distance of the work zone to the downstream intersection, the g/C ratios of each lane group, etc.

The following were concluded from the research:

- There has been very little research on the capacity of arterial work zones, despite the fact that capacity is used as an important input in their evaluation.
- Existing simulators do not specifically model arterial work zones.
- Simulation of arterial work zones showed that the distance of the work zone to the downstream intersection affects the capacity of the entire arterial work zone. Increasing the available storage between the signal and the work zone models results in better utilization of the green at the intersection approach.
- The capacity of the arterial work zone is reduced when one of the movements are blocked by the other. The probability of such blockage increases when the g/C ratios are not optimal or when the channelization at the intersection is not optimal for the respective demands.
- Comparison of the arterial work zone capacity to the respective configurations with no work zones showed that there are selected cases when installing a work zone may increase capacity. Those increases typically occur when the intersection (prior to the work zone installation) is congested. In those cases the work zone funnels traffic through the work zone, and it becomes easier for vehicles to change lanes and reach their destination lane, because there is less blockage. This increase was observed mostly for scenarios with 3-6 lanes at the intersection approach.
- The capacity estimates obtained from the current FDOT procedure are based on an entirely different set of input variables and therefore cannot be directly compared to the capacity estimates obtained by the models developed in this research.
- Since this research was entirely based on simulation, the results and conclusions should be viewed with caution. It is likely that field observations would result in different capacity values and that additional factors would affect the results. The trends observed in the simulation however should generally be valid in the field.

The following are recommendations from this research:

- The models developed in this research should be applied on a trial basis to existing and upcoming arterial work zone projects, so that they can be tested and validated before being incorporated into the FDOT lane closure analysis procedure.

- Field data should be collected at various sites and with various work zone configurations, so that the procedures developed here can be thoroughly evaluated, and the simulated capacity estimates compared to field estimates.
- Specific guidance can be developed on traffic signal control strategies for intersections downstream of a work zone, so that capacity can be maximized.
- Research should be conducted to evaluate the capacity of an arterial work zone and its impact on the upstream intersection. In those cases, spillback would result in a reduction of the effective green for one or more of the upstream intersection approaches. Models can be developed to estimate the lost time and capacity reduction for each of these upstream approaches.

The following recommendations are provided regarding possible improvements to CORSIM with respect to arterial work zone simulation:

- The software should consider replicating the use of taper sections.
- The use of the "rubbernecking" factor in freeway work zone simulation could be applied to arterials as well, provided that there is a specific relationship between the rubbernecking factor and work intensity in the work zone.
- Various geometric elements (such as lane width and shoulder width) are currently not considered within CORSIM. Its algorithms should be modified to consider such factors generally, as well as with respect to work zones.

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1. INTRODUCTION

Many state transportation agencies are experiencing growing congestion and traffic delays in work zones on arterial roads. This congestion results in delays for both motorists and commercial vehicles. The delays also result in driver frustration which causes some drivers to take unsafe risks in an effort to bypass delays. Research has been conducted on the factors that affect the work zone capacity on freeways but little has been done to estimate the capacity of arterial work zones.

The Florida Department of Transportation (FDOT) is currently interested in updating its existing methodologies for estimating the capacity of arterial lane closures. This estimation is important because capacity is used to forecast queues and delays. Excessive queuing and delay on arterials can have major impacts on the network as a whole with the effects spilling over to adjacent intersections and roadways. The current FDOT arterial work zone capacity estimation procedure is an extension of the one used to estimate freeway work zone capacity. The method applies an obstruction factor based on lateral clearance and travel lane width, a work zone factor based on work zone length, and finally the g/C ratio to the base capacity to estimate a restricted capacity. The procedure was developed in 1995 and does not account for various operating and work zone characteristics of the facility (i.e. speeds, the position of the closed lanes, etc.).

Numerous states have policies that provide guidance for the institution of short term lane closures including maximum allowable traffic flows, vehicle delays, and queue lengths (Sarasua, 2004). Those policies are based on capacity estimates, however it is not clear how the existing values were developed, and there are currently no tools to estimate capacity. Generally, capacity values are obtained 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). Also, there have been empirical observations of various factors that affect the operations and capacity of arterial work zones, however capacity estimation models were not found in the literature.

The objectives of this research are to: a) identify the various geometric and traffic factors that might impact the capacity of an arterial work zone, and b) develop analytical model(s) and methods to estimate its capacity.

In the remainder of this report, section two provides a literature review, section three describes the research methodology and provides the capacity estimation models, while section five summarizes the research conclusions and recommendations.

2. LITERATURE REVIEW

An extensive literature search was conducted to identify and review existing research involving arterial work zone lane closures. Little research was found that addressed the issue of capacity in arterial work zones. This section discusses first the design of work zones in the Manual on Uniform Traffic Control Devices (MUTCD 2003). Next, capacity estimates used by other States are presented, followed by a review of the current FDOT methodology and its limitations. The fourth subsection discusses various tools for estimating the capacity or arterial work zones, while the last subsection provides a brief summary of the findings and recommendations from the literature review.

2.1. Work Zone Design in the Manual on Uniform Traffic Control Devices (2003)

The 2003 version of the MUTCD provides guidance to transportation professionals on the design of arterial work zones. This section briefly presents the traffic control and other characteristics of an arterial work zone, as they are specified in the MUTCD.

Figure 1 presents a typical arterial work zone as represented in the FDOT Design Standards (2006). The upstream end of the work zone consists of an area with advance warning signs alerting drivers that a geometric change is imminent. This is followed by the transition zone, where a cone or barrel taper is utilized to guide drivers away from the closed lane and into the open lane. Mathematical formulae have been developed to calculate the length of this taper as a function of the width of the offset (work area width) and the posted speed limit or the 85th percentile speed prior to work starting (Table 1). The end of the work zone is defined as the "termination area" where tapers may be used, if required, to restore normal traffic flow. This area extends until the last road sign is posted designating the end of road work. The lengths of the various segments constituting the work area are based on the activity that is being conducted.

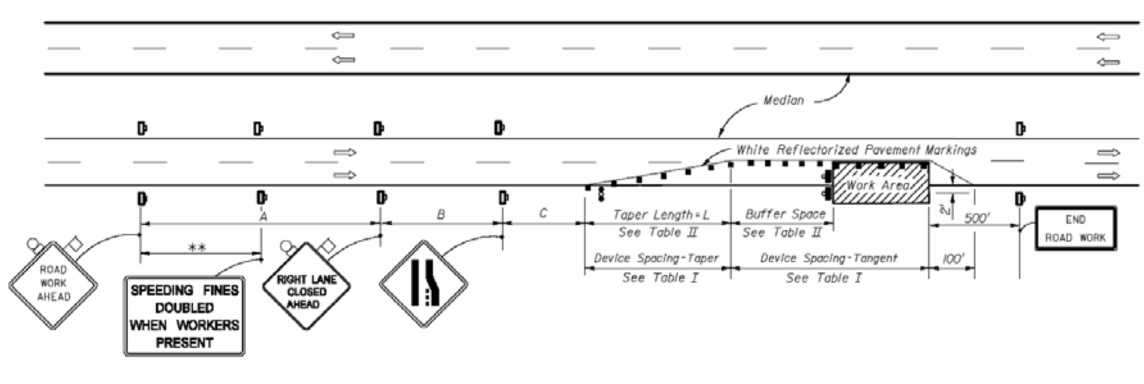


Figure 1: A Common Arterial Work Zone Configuration (FDOT 2006)

Table 1: Work Zone Taper Guidelines (FDOT 2006)

Table II
Buffer Space and Taper Length

Speed (mph)	Buffer Space	Taper Length (12' Lateral Transition)	
	Dist. (ft)	L (ft)	Notes (Merge)
25	155	125	$L = \frac{WS^2}{60}$
30	200	180	
35	250	245	
40	305	320	
45	360	540	$L = WS$
50	425	600	
55	495	660	
60	570	720	
65	645	780	
70	730	840	

When Buffer Space cannot be attained due to geometric constraints, the greatest attainable length shall be used, but not less than 200 ft.

For lateral transitions other than 12', use formula for L shown in the notes column.
Where:
L = Length of taper in feet
W = Width of lateral transition in feet
S = Posted speed limit (mph)

2.2. Arterial Work Zone Capacity Estimates Established by Various States

FHWA's Rule on Work Zone Safety and Mobility (FHWA, 2005) requires states to implement measures that maximize mobility without compromising the safety of highway workers or road users. The rule suggests delay, speed, travel time, and queue lengths as possible performance measures for the assessment of mobility (FHWA, 2005).

There are several tools available for estimating work zone delay and queue length. These are typically estimated based on capacity estimates which are used as input to those tools (Jiang and Adeli, 2004). States provide suggested work zone capacities as follows:

- Massachusetts: 1,170 to 1,520 vphpl; (MassHighway, 2007); It is not clear what is the suggested capacity for arterials and what the number is for freeways.

- Missouri: 1,000 vphpl; (Missouri DOT, 2004); This value is for arterial work zones.

- Washington: 600 vphpl; (Washington DOT, 2006); This value is for multilane urban and suburban roadways.

- South Carolina: 800 vphpl. (Sarasua, et. al., 2004); This value is for all work zones including freeways and arterials.

As shown there is wide variability in the values used, and there is no documentation on how these capacity estimates were obtained. Furthermore, there is little information available on the relative impacts of various work zone related factors on those capacity values.

2.3. FDOT's Existing Methodology

Section 10.14.7 of the FDOT Plans Preparation Manual (PPM) Volume I (1) describes the lane closure analysis, which estimates the restricted capacity for open road and signalized intersections. The analysis determines whether a lane closure should be allowed and whether it should be implemented during the day or night to avoid causing excessive travel delay. The procedure first determines the demand, i.e., the peak hour traffic volume. Next, the user selects the appropriate 'basic" Capacity (C) from Table 2-1.

Table 2: Lane Closure Capacity (FDOT Methodology)

Scenario	Capacity (VPH)
Existing 2-Lane-Converted to 2-Way, 1-Lane	1400
Existing 4-Lane-Converted to 1-Way, 1-Lane	1800
Existing 6-Lane-Converted to 1-Way, 2-Lane	3600

The Restricted Capacity (RC) for open road is then calculated as follows:

$$RC_{\text{open road}} = C \times OF \times WZF \tag{1.1}$$

where:

- C is the base capacity.
- *OF* is obstruction factor, 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.

- *WZF* is Work Zone Factor, based on the length of the work zone, and ranges from 0.98 to 0.50 for work zone lengths of 200 feet through 6,000 feet, respectively. It applies only to closures converted to two-way, one-lane.

RC for arterials differs from that for freeways only if the lane closure is through or within 600 ft. of a signalized intersection. In this case, RC is given as:

$$RC_{\text{arterial road}} = RC_{\text{open road}} \times g / C \qquad (1.2)$$

Where:

- *g/C* is the Ratio of Green to Cycle Time.

If the demand of the facility is below the restricted capacity (i.e., V≤ RC), there is no restriction on the lane closure and no delay is expected. If the demand exceeds the restricted capacity (i.e., V > RC), the analyst next considers the delays throughout the day to determine when the lane closure will be permitted.

In summary, the existing procedure relies on the following assumptions:

- The "basic capacity" of the arterial does not consider geometric characteristics of the site, such as vertical alignment, or other aspects related to the saturation flow rate of the intersection approach.

- Capacity reductions based on lane width and lateral clearance may not be effective measures for capacity reduction. Recent research (HCM 2000) has shown that these may not play a significant role in reducing capacity.

- The capacity reduction due to the signal (g/C ratio – related reduction) applies to 600 ft. upstream of a signalized intersection. The distance effect may vary based on the intersection configuration and one value for distance may not be appropriate.

- The existing procedure does not consider factors such as speeds upstream and through the work zone, nor lane distributions and turning movement types. It also does not consider actuated control and the resulting G/C ratio. These may impact the capacity of an arterial work zone.

2.4. Arterial Work Zone Evaluation Tools

Several research papers focus on the capacity of freeway work zones, however very little research specifically addresses capacity on arterial work zones. No specific procedure was found that calculates the capacity of an arterial work zone or the capacity of a signalized intersection downstream of a work zone. Existing work zone analysis packages focus on the estimation of queue length and delays by using capacity as either input or an intermediate variable. This subsection discusses various tools that have either been developed specifically to analyze arterial lane closures, or that can be used to simulate arterial work zone operations.

In one of the earlier efforts to evaluate arterial work zone operations, Joseph et. al. (1988) developed the Work Zone Analysis Tool for the Arterial (WZATA) to analyze and evaluate lane closures between two signalized intersections. This tool requires as input the saturation flow rate at each of the two intersections. WZATA estimates delay and queuing, but it is not clear if it can estimate the impact of the work zone on the downstream intersection throughput.

Currently, three software products, *QUEWZ*, *QuickZone*, and *CA4PRS,* are used to evaluate arterial work zones. A survey of State DOTs showed that QUEWZ and QuickZone were widely used software packages for the estimation of queue lengths and delays in work zones (Chitturi & Benekohal).

Memmott and Dudek (1984) developed *Queue and User Cost Evaluation of Work Zones* (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. The model uses capacity as input, and analyzes traffic flow through lane closures and helps plan and schedule freeway work-zone operations by estimating queue lengths and 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 an algorithm that can consider natural road user diversion away from the freeway work zone to a more desirable, unspecified, alternate route (Associated Press, 1989).

FHWA's QuickZone is a sketch level tool that "supports assessment of work zone mitigation strategies and estimates the costs, traffic delays, and potential backups associated with these impacts." (McTrans, 2006). QuickZone can be used to evaluate traffic delays associated with work zone schedules in relation to peak and off-peak traffic periods and/or with the employment of diversion routes. The program displays the amount of delay in vehicle hours and the maximum length of the projected traffic queue associated with the work activity. The advantage of QuickZone is that it runs in Microsoft Excel and provides quick estimates for use in planning. QuickZone requires the following input data:

1. *Network data:* Describing the mainline facility under construction as well as adjacent alternatives in the travel corridor.

2. *Project data:* Describing the plan for work zone strategy and phasing, including capacity reductions resulting from work zones.

3. *Travel demand Data:* Describing patterns of pre-construction corridor utilization.

4. *Corridor Management Data:* Describing various congestion mitigation strategies to be implemented in each phase, including estimates of capacity changes from these mitigation strategies. (QuickZone Delay Estimation Program, version 2.0)

As shown, capacity estimation and capacity reductions are inputs in the analysis. The software takes the data presented above and compares expected travel demand against proposed capacity by facility on an hour-by-hour basis for the life of the project to estimate delay and mainline queue growth. This hour-by-hour estimation is conducted using a simple deterministic queuing model for each link in the work zone impact area. Sections of the work zone that are downstream from bottlenecks see lower travel demand because vehicle flow is effectively metered at the upstream bottleneck. Travel time delay is calculated at each bottleneck within the system by tracking the number of queued vehicles. System delay is calculated by summing delay across all bottlenecks. QuickZone first estimates total delay under the assumption that travel behavior will not change in response to capacity reductions associated with the project. This maximum delay profile is used to help characterize the likely behavioral response in the travel corridor. The type and magnitude of change in traveler behavior (as well as the mix of behaviors) will hinge on the severity and duration of delay across project phases. For example, a project generating limited delay on the mainline facility only during off-peak periods is likely to induce small changes in travel behavior, primarily focused on a change of route to some alternative facility. Conversely, a project generating severe peak period delay will drive a broader and more complex traveler response like a wider utilization of adjacent roadways, a shift in travel to non-peak periods, a switch to transit or other modes, or a simple reduction in corridor demand as prospective trips are simply cancelled or directed outside the travel corridor. Queues on detour routes are also monitored.

Depending on the varying demand in the inbound and outbound directions, QuickZone will identify the smallest cycle time for actuated signals that supports the travel demand in each direction. This procedure attempts to limit the amount of delay at the intersection to a minimum. Once directional capacity is calculated, QuickZone tracks delays through the work zones calculating both delay from signals (under-saturated delay) and delay from queuing when demand exceeds effective capacity.

Another package that is used to evaluate the impacts of work zones is CA4PRS (Lee and Ibbs, 2005). CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies), was designed for the California Department of Transportation to provide an integrated analysis of design, construction, and traffic to provide a schedule baseline for highway rehabilitation projects. CA4PRS is a knowledge-based computer simulation model integrated with macroscopic and microscopic traffic simulation tools for estimating road user delay cost due to construction work zone closures for highway rehabilitation and reconstruction, especially under high traffic volume in the urban network. CA4PRS is a production analysis tool designed to estimate the maximum probable length of highway pavement that can be rehabilitated or reconstructed given the various project constraints. The CA4PRS model evaluates "what-if" scenarios with respect to rehabilitation production by comparing various input variables (alternatives). The input variables of CA4PRS are schedule interfaces, pavement design and materials, resource constraints, and lane closure schemes.

Several traffic simulators consider freeway work zones but do not specifically model arterial work zones. They can, however, handle lane closures on specific links. It has been reported that most of the simulators do not have the capabilities to explicitly model work zones (Sterzin et. al, 2005). Sterzin evaluated the following simulators: AIMSUN, ARTEMIS, CORSIM, Cube, Dynasim, DRACULA, INTEGRATION, MITSIM, Paramics, SimTraffic, TransModeler, VISSIM, and WATSim. Ten of the above simulators capture work zone effects by modeling it as a pre-defined incident or lane closure. This approach does not consider work zone specific characteristics such as the presence of workers and enforcement or the effects of work zone warning signs.

2.5. Factors That May Affect Arterial Work Zone Capacity

This subsection summarizes the factors that may influence the capacity of an arterial work zone. First, the freeway work zone capacity literature was examined to determine factors that affect work zone capacity for those facilities. Second, additional factors that affect arterial capacity (without the presence of work zones) were identified. Based on the findings of these two tasks, Table 3 provides a comprehensive list of factors that may affect the capacity of an arterial, along with the corresponding reference source when appropriate.

Table 3: Work Zone Factors Identified from the Literature

Work Zone Factors
Work Zone Length (ft) (Kim et. al., 2001)
Distance of the Work Zone from the Downstream Intersection
Work Zone Sign Distance Upstream of the Work Zone
Work Intensity (Presence of Equipment and Workers) (HCM, 2000)
Police Presence
Lateral Position of the Work Zone (Lane Closed)
Number of Open and Closed Lanes in the Work Zone
Geometric and Control Factors
Terrain or grade (%) (FDOT PPM 2000)
Lane Widths Upstream, Within, and Downstream of the Work Zone (ft) (HCM 2000 FDOT PPM 2000)
Lateral clearance upstream, within, and downstream of the work zone (ft) (HCM, 2000)
Driveway Presence
Posted Speed Limit
Lane Channelization at the Intersection (Including Turn Pockets)
g/C ratios
Traffic Stream Factors
Volumes and Turning Percentages
Presence of Bicycles
Presence of Heavy Vehicles (FDOT PPM 2000)
Pedestrians
Other Environment-Related Factors
Light Conditions (Daytime or Nighttime with Illumination)
Rain (No rain, Light to Moderate Rain or Heavy Rain)

2.6. Literature Summary and Conclusions

In summary, little research has been conducted to estimate the capacity of work zones on arterials. State policies use work zone capacity values ranging from 600 to 1520 vphpl, and it is not clear how these values were obtained, or what the relationship is between capacity and various work zone and operational characteristics at the site. The guidelines in the FDOT PPM do not consider the work zone configuration characteristics, and some important operational attributes, such as channelization at the intersection.

There are several software programs that estimate delays due to work zones; however these use capacity as input in their procedures.

Thus there is a need to assess the impact of various factors on the capacity of an arterial work zone, and to develop methods for estimating this capacity.

3. METHODOLOGY

One of the significant obstacles in the research was that, while the research requires a significant number of sites with various geometric, traffic, and work zone characteristics, large amounts of field data are very seldom available for arterial streets. Collecting data even at a few arterial work zones also proved to be a challenge because identifying appropriate sites for data collection in advance of construction was very difficult. Therefore, simulation was used to develop several intersection and work zone configurations and obtain relationships between various factors and the capacity of the intersection. The advantage of using simulation is that it can be easily used to replicate a variety of field conditions. The disadvantage is that if the simulator is not well calibrated it may not replicate field conditions and the capacity estimates would not be correct. To compensate for this disadvantage specific arterial sections, both with and without work zones, were simulated so that the relative capacity changes for different intersection and work zone configurations could be obtained.

This section discusses the simulator selection and use; it presents the factors found to affect work zone capacity in the simulator, summarizes the scenarios tested and the respective simulation results, and presents the capacity models developed.

3.1. Simulator Selection and Use

The software package CORSIM was selected for use in the study. As discussed in the literature review, none of the existing simulators can explicitly model arterial work zones; however, several can simulate lane closures. CORSIM was selected based on two factors. First, the software, originally developed by FHWA, has been widely used and validated in the past twenty years. Second, its availability to the researchers through McTrans allowed for a high level of software support in understanding the software's algorithms.

The literature reports that older versions of *FRESIM* (the freeway simulation component of CORSIM) were unreliable when simulating lane closures, as the software did not account for slow-moving vehicles that severely impacted the queue lengths in the field (Dixon et al., 1995). According to the conclusions of that research, the large queues observed in the field were due to the existence of one or two vehicles in a data set that traveled inexplicably 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.*, 1996). The 1995 report used *FRESIM* 4.5 and since then improvements have led to the *CORSIM* version 5.1 release (McTrans, 2007).

Initially, a CORSIM network of a work zone along a signalized arterial was created and several runs were performed to assess the reasonableness of the results provided by the software. In those initial runs, several site characteristics such as link distances, number of lanes along each section, and channelization were tested to evaluate their impact on the capacity of the link. Capacity was defined and observed as the discharge flow of the intersection. Flows were obtained by lane and measured at the downstream destination of the lane group and at the virtual stop-bar of the intersection.

Figure 1 shows a CORSIM animation snapshot with a work zone along the eastbound link. The arterial link with the work zone was modeled in CORSIM as three network links. The characteristics and function of each link in the network are as follows:

- Link (2, 10) – 1500 feet in length; vehicles waiting to enter the work zone are queued on this link.
- Link (3, 2) – 300 feet in length; this is the work zone area.
- Link (4, 3) – The length of this link ranges from 100 ft to 1000 ft; this distance also represents the length of the turn pockets.

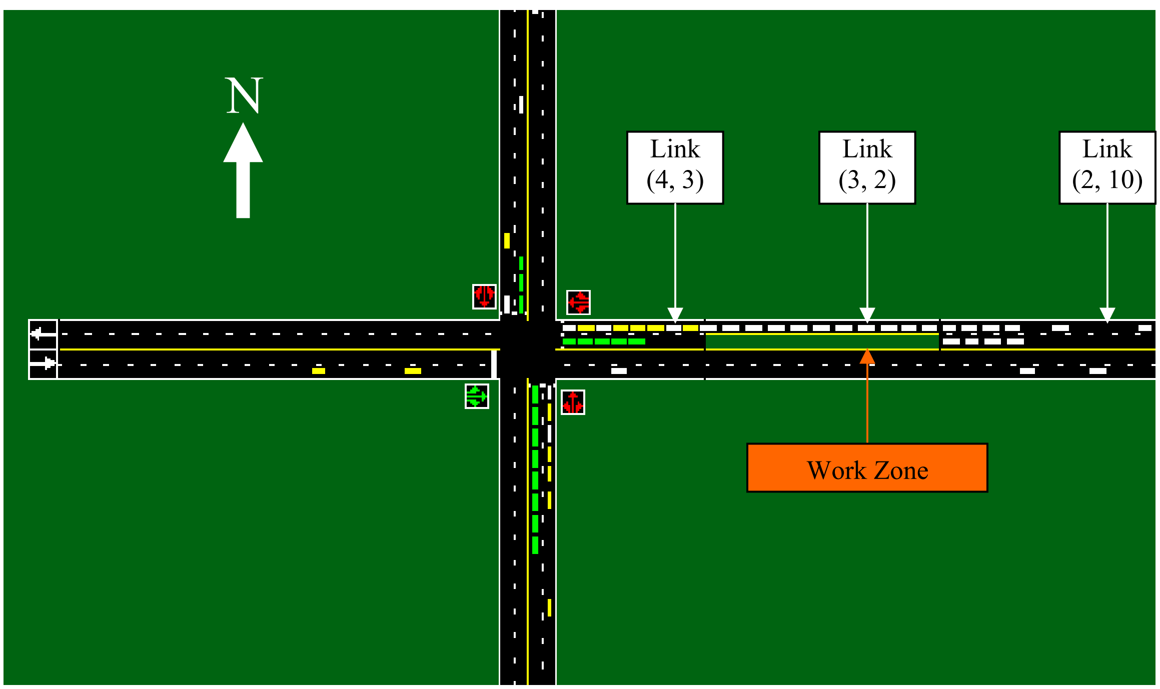


Figure 1: CORSIM Snapshot of an Arterial Work Zone Animation

CORSIM does not replicate the taper portion approaching the work zone, and simulated vehicles merge once they reach the end of the lane as they enter the downstream link. The presence of a taper in the simulator would likely change the operational performance upstream of the work zone; however its effect on capacity should be relatively negligible, as the key parameters in this discharge are the discharge from the work zone and the intersection, and not upstream operations.

Examination of CORSIM results showed unrealistic driver behavior related to lane changing, especially for turning vehicles. It was observed that drivers were not making the maneuvers necessary to execute their desired turn at the downstream intersection. The vehicles were attempting lane changes too close to the intersection which caused the capacity to decrease unrealistically. If the vehicle could not execute the lane change, it would wait for an acceptable gap which blocked drivers trying to proceed through the intersection in adjacent lanes. To allow for appropriate lane changes to occur earlier in the network, the pertinent default values were adjusted. Table 4 summarizes the list of factors modified, and the effect of the respective change.

Table 4: Changes Made to CORSIM Default Values to Simulate Arterial Work Zone Operations

Change	Effect
Percentage of drivers who cooperate with a lane changer was increased from 50% to 100%	This facilitates lane changing and allows vehicles to get to their target lane before reaching the intersection. The problem with the use of the default value was that several vehicles, unable to change lanes, proceeded to the intersection and had to wait there for an unreasonably long time to change lanes, blocking other vehicles.
Time headway from the subject vehicle to the leading vehicle at which all drivers will attempt a lane change was increased from 2 to 3 sec	Increasing this time headway forces drivers to attempt lane changes earlier. This is the headway that is small enough that all drivers would desire a lane change.
Time headway from the subject vehicle to the leading vehicle at which no drivers will attempt a lane change was raised from 5 sec to 10 sec	This parameter, together with the previous one, creates the range within which drivers attempt to make a lane change. Similarly to the previous parameter, increasing this value results in earlier lane changes, because drivers consider a lane change as far back as 10 seconds from the leading vehicle. This significantly increases the probability that drivers would make an early lane change and accounts, to some degree, for information drivers may receive from work zone warning signs.
Drivers will perform lane changes 2000 ft (default is 300 ft) before their desired turn	Increasing this value results in drivers seeking lane changing opportunities earlier, and less likely to have to slow down or stop to reach their "goal" lane.
Safety Factor was changed from .8 to 1.0	This factor is used to compute the lane-changer's estimation of the deceleration that would be acceptable to the follower target vehicle. As this value increases, the acceptable risk increases and the margin of safety decreases. At the same time the lane changes increase.

3.2. Factors Affecting Work Zone Capacity

To create an experimental design that incorporates the most important factors affecting arterial work zone capacity, a list of factors that may affect arterial work zone capacity was first compiled based on literature findings and considering additional factors that may apply specifically to arterial work zones. Next, CORSIM was evaluated for its ability to simulate each of these factors. Finally, a sensitivity analysis was conducted to determine whether each of these factors had an effect on the capacity of the arterial work zone.

3.2.1 Identification of Factors that can be Simulated by CORSIM

Each of the factors that may affect work zone capacity presented in Table 1 was first evaluated to determine whether it can be simulated by CORSIM. Table 5 presents the results of this evaluation. As shown, CORSIM can consider some important traffic operational parameters such as the channelization at the intersection, link lengths and distance of the work zone from the downstream intersection, etc.

CORSIM however cannot take into consideration some work-zone specific factors such as the presence of workers, or the presence of warning signs upstream of the work zone. It also cannot take into consideration some geometric design factors, such as lane width and lateral clearance. Most micro-simulators do not directly simulate these values, however one can approximate their effect by modifying the free-flow speed (or desired speed) of the traffic stream.

One factor that could be simulated in CORSIM but was not selected for further study in this research was the presence of heavy vehicles. Testing this factor in CORSIM would only reflect the assumptions that CORSIM makes regarding heavy vehicles, and would not provide any significant insight on capacity estimation. Also, once capacity estimates are provided in passenger cars per hour, they can be easily converted to vehicles per hour through the use of Passenger Car Equivalency (PCE) values.

Table 5: Factors Potentially Affecting Arterial Work Zone Capacity

Factors	***CORSIM Simulation Possible?***
Work Zone Data	
Work Zone Length (ft)	Yes
Distance of the Work Zone from the Downstream Intersection	Yes
Work Zone Sign Distance Upstream of the Work Zone	No
Work Intensity (Presence of Equipment and Workers)	No
Police Presence	No
Lateral Position of the Work Zone (Lane Closed)	Yes
Number of Open and Closed Lanes in the Work Zone	Yes
Geometric and Control Data	
Terrain or grade (%)	No
Lane Widths Upstream, Within, and Downstream of the Work Zone (ft)	No
Lateral clearance upstream, within, and downstream of the work zone (ft)	No
Driveway Presence	Yes
Posted Speed Limit	Yes
Lane Channelization at the Intersection (Including Turn Pockets)	Yes
g/C ratios	Yes
Traffic Stream Data	
Volumes and Turning Percentages	Yes
Presence of Bicycles	No
Presence of Heavy Vehicles	Yes
Pedestrians	No
Other Environment-Related Data	
Light Conditions (Daytime or Nighttime with Illumination)	No
Rain (No rain, Light to Moderate Rain or Heavy Rain)	No

3.2.2 Sensitivity Analysis

The factors that could be simulated in CORSIM were tested in the simulator to evaluate their impact on the simulated work zone capacity. The value of each factor was modified over a given range of values, keeping all other parameters constant, and the simulated capacity was recorded for each test value. The results of the sensitivity analysis for each factor are discussed below

Work Zone Length: Table 6 presents the results of the sensitivity analysis for the length of the work zone. As shown, the change in this distance does not have any significant effect on capacity, therefore this factor was not included in the final scenarios.

Table 6: Work Zone Length Sensitivity

Work Zone Length (ft)	Capacity (vph)
100	1638
200	1656
300	1672
400	1673
500	1679
600	1665
700	1657
800	1644
900	1642
1000	1646

Distance of the Work Zone to the Downstream Intersection: In general, as the distance from the work zone to the downstream intersection increases; the capacity of the arterial also increases. This happens because more vehicles can come out of the work zone and queue up at the intersection during the red interval. These vehicles can then easily discharge during the green. The capacity of each lane group was found to be related to the amount of storage available between the work zone and the downstream intersection for that lane group. Beyond a distance of 500 ft however, the rate of capacity increase is much lower and it becomes nearly zero beyond 1000 ft.

Lateral Work Zone Position: Work zones may be positioned on any lane on the arterial. A two-lane scenario was examined to determine if CORSIM performed differently when the work zone was on the left lane or the right lane. The results, presented in Table 7, suggest that the position does not significantly affect total approach capacity. In the field this factor may have an effect on capacity, however since it was not found to have an effect in CORSIM, it is not included in the final test scenarios.

Table 7: Work Zone Position Sensitivity

Lateral Position of Work Zone	Capacity (vph)
Right	1667
Left	1697

Number of Lanes Open and Closed in the Work Zone: The number of open and total lanes within the work zone had an effect on the simulated capacity. The capacity increase however was not proportional to the percent of the lane addition (i.e. an increase from one to two lanes did not result in a 100% increase in capacity). Overall, the intersection-related factors had a greater effect on the capacity then the number of lanes within the work zone.

Driveway Presence: The presence of a driveway was examined to determine its effect on arterial work zone capacity. Table 8 presents the capacity as a function of the percent of vehicles turning from the arterial into the driveway. The number of vehicles exiting the driveway was set at 300 vph. The driveway had one lane per direction. As shown, the change in the capacity is not significant. First, vehicles on the mainline do not allow driveway vehicles to enter; driveway vehicles can enter the mainline only when a gap is created by a vehicle exiting the mainline. Second, CORSIM does not model turns accurately because it does not provide for a smooth speed transition between two successive links. Thus this factor is not included in the final test scenarios. However, the impact of the presence of a driveway may be found to have a more significant effect in the field.

Table 8: Driveway Sensitivity Analysis

Driveway Percentage	Capacity (vph)
No Driveway	1476
5%	1534
10%	1440
15%	1548
20%	1491
25%	1590

Posted Speed Limit: Generally an increase in the speed limit resulted in a minor increase in capacity (Table 9). The congestion caused by the work zone and the intersection kept average speeds much below the speed limit, therefore allowing higher speeds did not affect the performance of the network by much.

Table 9: Posted Speed Limit Sensitivity

Posted Speed (mph)	Capacity (vph)
25	1472
30	1476
35	1520
40	1508
45	1528

Lane Channelization at the Intersection (Including Turn Pockets): Figure 2 illustrates the lane channelization scenarios used in the sensitivity analysis. These channelizations are representative of common configurations found in the U.S. Generally, the capacity of an intersection approach is directly impacted by the number of lanes at that approach, however the presence of turn pockets does not always result in significant capacity increases. The capacity increase is typically a function of the demand for the respective turning movements.

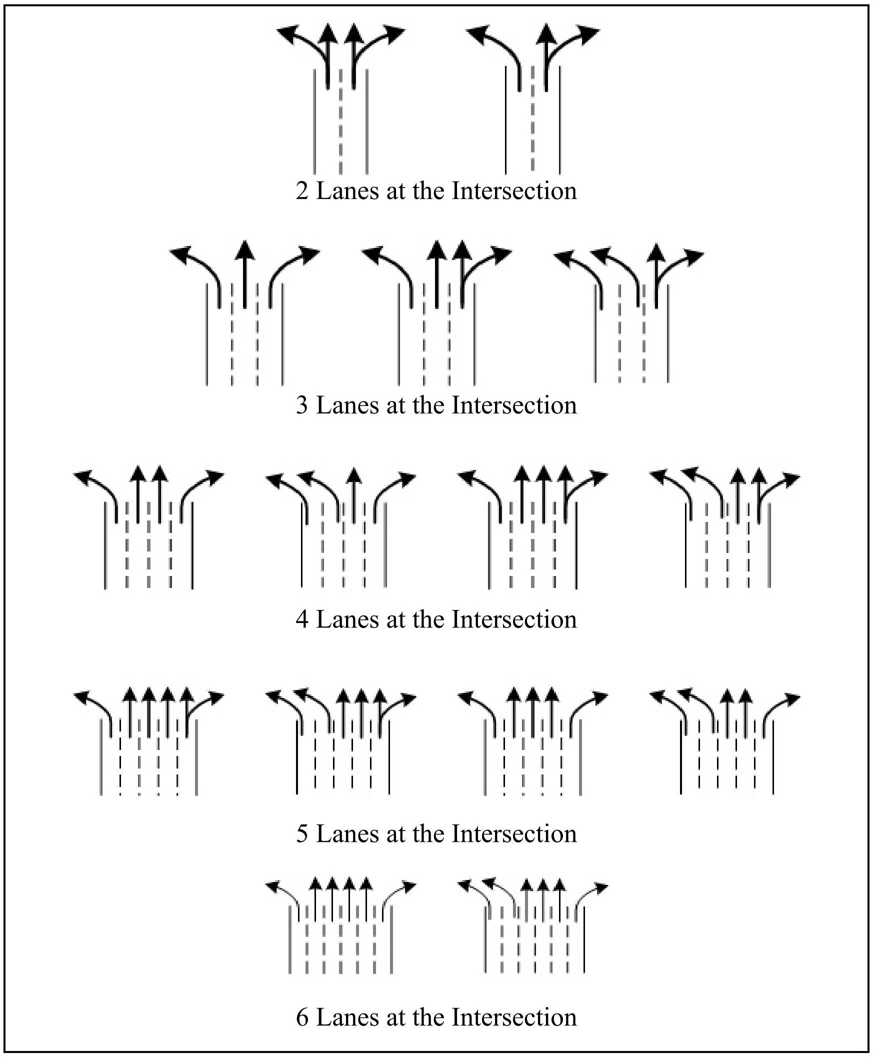


Figure 2: Lane Channelization Configurations Simulated

g/C ratio: The g/C ratio had the greatest overall effect on capacity. An increase of the g/C ratio for the left turn lanes had a negative effect on the approach capacity only when the left turn demand was not high. When the left turn demand was high while the corresponding g/C ratio was low and storage space was inadequate, there was spillover onto through lanes which resulted in overall capacity reduction. Generally the capacity was maximized when the g/C ratio was proportional to the respective demand.

Volumes and Turning Percentages: The turning volumes and percentages for left and right turns had a negative effect on the total capacity of the approach, because an increase in turning movements decreased the capacity of the through lanes. The negative effect of the high left turning percentage was magnified when the left turning g/C was low.

Table 10 summarizes the results of the sensitivity analysis along with the decision whether to include each factor in the development of test scenarios.

Table 10: Results of the Sensitivity Analysis

Factor	Values Tested	Incorporated in the Test Scenarios?
Work Zone Length	100, 200, 300, 400, 500, 600, 700, 800, 900, 1000 ft	No
Distance from Work Zone to Intersection	100, 250, 500, 750, 1000, 1500 ft	Yes
Lateral Position of Work Zone	Left, Right, and Center Lane Closure	No
Driveway Presence	0%, 5%, 10%, 15%, 20%, and 25% of intersection approach volume	No
Posted Speed Limit	25, 30, 35, 40, and 45 MPH	No
Lane Channelization at the Intersection	Configurations shown in Figure 2	Yes
g/C Ratios of Left and Through Phases	.1, .3, .5 (Left) .3, .5, .7 (Through)	Yes
Turn Pockets	Left and Right Turn Pockets	Yes
Right Turning Percentage	0%, 5%, 10%, 15%, 20%, 25%	Yes
Left Turning Percentage	0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%	Yes

3.3. Test scenarios and simulated results

The factors selected to be incorporated in the test scenarios (shown in Table 10) were used to develop a large number of realistic combinations of arterial work zone segments for which capacity was obtained. Table 11 summarizes the scenarios developed. The experimental design was subject to constraints that provided a set of realistic scenarios. These constraints were based on obtaining realistic combinations of turn pocket presence, g/C ratios, and turning percentages.

Table 11: Experimental Design

Factor	Values
Lanes Open and Closed Through Work Zone	1, 2, 3 (Open) & 1, 2 (Closed)
Distance of Work Zone to the Downstream Intersection	100, 250, 500, 750, 1000 ft
Lane Channelization	See Figure 2
Turn Pockets	Up to Two Left Turn Pockets & Up to One Right Turn Pockets
g/C ratio of Left Turning Phase	0.1, 0.3, 0.5
g/C ratio of Through and Right Phase	0.3, 0.5, 0.7
Left Turning Percentage	10%, 25%, 40%
Right Turning Percentage	10%, 25%, 40%

Subject to the Following Constraints

- Through/right phase - 0.7 g/C only with left turning phase - 0.1 g/C
- No dual left turn lanes with 0.1 g/C for left turning phase
- Left turning phase - 0.5 g/C only with through/right phase 0.3 - g/C
- 10% left turning percentage only with 0.1 and 0.3 left turn g/C
- 40% left turning percentage only with 0.3 and 0.5 left turn g/C
- 40% right turning percentage only with 0.5 and 0.7 through/right g/C
- Two-lane arterials - 1 open and 1 closed Lane
- Three-lane arterials - 1 open (and 2 closed) OR 2 open (and 1 closed)
- Four-lane arterials - 2 open (and 2 closed) OR 3 open (and 1 closed)

The work zone link ranged from one to four lanes with one or two lanes closed. The length of the work zone was fixed at 300 ft. The link downstream of the work zone had two to six lanes with up to two exclusive left turn lanes, one right turn lane, and its length varied between 100 and 1000 ft. The intersection signal control was assumed to be pretimed with an exclusive left turning phase when appropriate. Protected left turn phasing only was used. Scenarios with left turn lanes included a g/C ratio for the left turns and another for the through/right movements. Right-turn-on-red was not allowed.

A total of 6640 arterial work zone scenarios were developed, each of which was executed five times to account for stochastic simulator variability. The sample size was estimated using a 95% confidence interval with an acceptable deviation of 100 vehicles per hour in the approach capacity. Simulation outputs consisted primarily of lane-by-lane throughput flows measured at the downstream destination of each lane group and at the virtual stop-bar of the intersection.

3.3.1 Simulation Results for Cases When a Work Zone is Present

The capacity values for the simulated work zone scenarios are presented in Tables 12 through 14 tabulated by the number of lanes at the intersection, number of closed lanes, and the through movement g/C ratio. The g/C ratio and the number of lanes were shown to have the largest effect on the work zone capacity.

Table 12 presents the total capacity of the work zone in vehicles per hour, while Tables 13 and 14 present the through/right turning movement and the left turning movement capacity respectively, in vehicles per hour per lane. The left most column in each of these tables indicates the total number of lanes at the stop-bar (including left and right turn lanes), while the number of open and closed lanes refers to the mainline arterial. The minimum and maximum values in these tables represent the lowest and highest values of capacity measured for the respective set of scenarios (e.g., for varying distances of the work zone to the downstream intersection, varying turning movement percentages, channelization schemes at the intersection, etc.). The first two-lane scenario is for an intersection approach with two through lanes, while the second one is with one left turn lane and one through-and-right lane. The remaining scenarios are for various combinations of lane channelizations for each given number of lanes at the intersection.

Table 12 indicates that, as expected, the capacity of the arterial work zone generally increases with a higher through/right movement g/C ratio, and with the number of lanes at the approach. Note that in some of the scenarios there is a separate left turn phase with its own g/C ratio. In these cases, capacity was found to be affected by both turning percentages and respective g/C ratios. The impact of the number of open and closed lanes was not found to be as significant in terms of the total capacities obtained. The actual throughput depended more on the distance of the work zone to the downstream intersection, as well as various intersection factors. It was observed that if the "storage area" downstream of the work zone could fill up during the red phase, such that the green could be fully utilized, the number of lanes closed upstream did not affect the overall throughput. Capacity was generally found to decrease when one movement blocked the other from reaching the downstream intersection. This blockage was a function of the turning percentages and the distance of the work zone to the downstream intersection.

Table 12: Total Approach Capacity for Arterial Work Zones (in vph)

Number of Lanes at Intersection*	Number of Open Lanes	Number of Closed Lanes	Through/Right Movement g/C Ratio								
			0.3			*0.5*			*0.7*		
			Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*
2 (w/o LT Lane)	1	1	697	1095	976	1162	1718	1558	1574	1695	1650
2 (w LT lane)	1	1	566	1248	755	697	1454	1026	894	1552	1288
3	2	1	578	1707	1019	776	1713	1342	1465	1712	1644
	1	2	577	1734	1022	821	1745	1360	1512	1740	1679
4	3	1	574	1928	1000	855	2388	1407	1265	2698	2071
	2	1	672	1718	1332	1038	1774	1558	1619	1750	1681
	2	2	666	1777	1352	974	1761	1594	1671	1771	1725
	1	2	578	2448	1416	927	2990	1908	2263	3497	2750
	1	1	574	2405	1409	909	2967	1912	2342	3413	2763
5	3	1	694	2470	1405	1011	2996	1890	2214	3595	2764
	2	1	864	1766	1552	1314	1759	1671	1648	1754	1723
	2	2	1115	2898	1872	1450	3811	2382	2687	3663	3270
	1	2	1065	2847	1877	1522	3805	2386	2682	3680	3233
6	2	2	1074	2854	1880	1373	3994	2364	2545	4128	3251
	3	1	1243	3537	2157	1582	3816	2633	2782	3685	3382

*Note: All the open lanes (Column 2) as well as closed lanes (Column 3) are the basic lanes on the arterial. These do not include turn pockets at all. Lanes at intersection (Column 3) may also include turn pockets in some scenarios.

Table 13 tabulates the capacity of the through/right movement per lane, which generally increases as a function of the respective g/C ratio. The per lane throughput is not much affected by the total number of lanes at the approach, but is generally affected by the g/C ratio. In some of the scenarios there is blockage to the through movement by the left turning traffic. This is a function of the percent of traffic turning left, the respective g/C ratio, as well as the distance from the work zone to the downstream intersection. Similarly, the number of open and closed lanes upstream did not always affect the throughput, which was mostly a function of the distance to the downstream intersection and the g/C ratios and turning movements at the intersection.

Table 13: Through/Right Turn Approach Capacity for Arterial Work Zones (in vphpl)

Number of lanes at Intersection	**Number of Open Lanes**	**Number of Closed Lanes**	**Through/Right Movement g/C Ratio**								
			0.3			***0.5***			***0.7***		
			Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*
2 (w/o LT Lane)	1	1	248	579	502	301	958	785	368	857	754
2 (w LT lane)	1	1	210	560	485	474	981	809	743	1394	1140
3	2	1	212	542	419	262	876	611	677	776	748
	1	2	208	548	420	280	864	617	699	788	765
4	3	1	222	547	414	312	928	641	583	1264	959
	2	1	237	543	392	324	768	491	488	555	516
	2	2	240	549	396	326	780	502	512	569	530
	1	2	233	549	409	278	930	600	699	1110	862
	1	1	224	543	408	285	935	601	723	1079	866
5	3	1	248	543	397	308	935	588	693	1138	866
	2	1	209	513	337	266	526	385	382	431	402
	2	2	227	537	399	275	917	552	630	876	780
	1	2	225	543	400	270	916	553	628	882	771
6	2	2	226	543	398	260	917	544	597	992	772
	3	1	206	514	361	257	796	480	522	707	647

Table 14 presents the same information for the left turn movement. The g/C ratio for the left turn generally increases the movement's capacity, provided it is utilized effectively. Generally the throughput of each left turn lane is lower than that of a through or through-and-right lane. The five and six lane scenarios include some configurations with double left turn lanes, and generally those had higher throughput.

Table 14: Left Turn Approach Capacity for Arterial Work Zones (in vphpl)

Number of lanes at Intersection	Number of Open Lanes	Number of Closed Lanes	Left Turn Movement g/C Ratio								
			0.3			*0.5*			*0.7*		
			Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*
2 (w LT lane)	1	1	53	303	142	54	567	225	142	480	269
3	2	1	65	196	150	65	586	271	156	677	342
	1	2	61	196	149	68	584	274	149	729	348
4	3	1	47	199	150	46	585	270	111	868	336
	2	1	52	186	147	31	578	251	86	674	340
	2	2	43	192	148	33	567	257	85	729	355
	1	2	98	192	168	23	578	288	59	960	406
	1	1	109	195	168	23	582	287	56	958	404
5	3	1	80	194	167	52	583	296	118	930	416
	2	1	22	190	136	28	547	250	76	730	361
	2	2	85	194	161	59	586	332	139	850	490
	1	2	86	195	161	57	576	331	125	856	490
6	2	2	132	198	171	44	578	339	114	846	503
	3	1	98	197	162	62	580	348	139	927	553

3.3.2 Simulation Results for Cases without Work Zones (Base Case Scenarios)

The purpose of simulating the same configurations without work zones (base case scenarios) was to obtain a means of comparing the capacities with and without work zones. The comparison is important because of the lack of available field data, since the results can provide insight on capacity changes rather than absolute capacity estimates. These changes are reported as a function of different geometric, traffic control, and work zone configurations.

The base case scenarios consider the same factors and assumptions as those of the work zone scenarios. The total number of base case scenarios was 2800. This number is lower than the total number of scenarios with work zones because the work zone factors are eliminated. The results of the base case simulations are presented in Tables 15 through 17. Table 15 presents the total capacity of the work zone in vehicles per hour, while Tables 16 and 17 present the through/right turning movement and the left turning movement capacities respectively in vehicles per hour per lane. The minimum and maximum values in the tables represent the lowest and highest values for capacity obtained in the scenarios tested. As for the work zone scenarios, the factor that affects capacity the most is the g/C ratios of the left turning and through/right turning movements. Capacity generally increases with increasing g/C ratio, however there are some cases where it decreases. These occur when the demand is held upstream, due to blockage (for example through vehicles blocking access to the left turn lane).

In Table 17, the 4-, 5-, and 6 –lane scenarios include cases with dual left turns, and it mainly because of these that the per lane capacity increases. In these cases the left turning vehicles have greater flexibility in choosing a lane, and there is less blockage to that movement.

Table 15: Base Case Intersection Capacities (in vph)

Number of lanes at Intersection	Number of Lanes on Arterial	Through/Right Movement g/C Ratio								
		0.3			*0.5*			*0.7*		
		Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*
2 (w/o LT Lane)	2	907	1106	1039	1604	2038	1784	2311	2969	2539
2 (w/ LT lane)	2	478	970	707	750	1482	1028	1134	1321	1261
3	2	551	1903	1004	845	2378	1419	1255	2742	2097
	3	598	1932	993	865	2396	1393	1189	2750	1991
4	2	549	2478	1428	937	2995	1921	2334	3540	2762
	3	674	2477	1436	987	3010	1919	2246	3662	2744
	4	746	2500	1392	1037	2918	1875	2138	3786	2790
5	3	1125	2872	1916	1438	3996	2402	2582	4113	3257
	4	1063	2902	1891	1346	3991	2337	2482	4395	3243
6	4	1442	3510	2254	1666	4745	2737	2622	4614	3661

Table 16: Base Case Through/Right Capacities (in vphpl)

Number of lanes at Intersection	Number of Lanes on Arterial	Through/Right Movement g/C Ratio								
		0.3			*0.5*			*0.7*		
		Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*
2 (w/o LT Lane)	2	421	541	491	752	997	849	1090	1475	1208
2 (w/ LT lane)	2	392	554	477	537	925	781	1018	1183	1126
3	2	228	546	415	328	925	645	571	1287	970
	3	228	535	406	319	914	634	548	1289	918
4	2	228	535	406	319	914	634	548	1289	918
	3	229	544	412	285	927	604	722	1123	866
	4	248	526	398	300	903	591	695	1166	860
5	3	248	526	398	300	903	591	695	1166	860
	4	234	522	389	314	891	580	661	1203	875
6	4	234	522	389	314	891	580	661	1203	875

Table 17: Base Case Left Turn Capacities (in vphpl)

Number of lanes at Intersection	Number of Lanes on Arterial	Left Turn Movement g/C Ratio								
		0.3			*0.5*			*0.7*		
		Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*
2 (w/ LT lane)	2	80	196	141	117	572	283	213	433	315
3	2	46	196	149	42	583	274	129	849	339
	3	76	198	152	86	590	277	148	904	355
4	2	76	198	152	86	590	277	148	904	355
	3	108	195	168	20	575	291	64	958	414
	4	83	193	168	72	583	307	148	953	437
5	3	83	193	168	72	583	307	148	953	437
	4	87	200	167	81	569	295	144	949	423
6	4	87	200	167	81	569	295	144	949	423

3.3.3 Comparisons of Base Case and Work Zone Scenarios

The results of the 6640 work zone scenarios were next compared to the respective base case scenarios. Tables 18 through 20 show the percent change in capacity after the work zone is installed (each number is the ratio of the capacity with the work zone over the capacity without the work zone for the same geometric configuration and operational conditions). This analysis was conducted by comparing each scenario within a particular category (number of lanes, etc.) to its respective base case scenario, and identifying the scenario that had the worst decrease in capacity, the scenario that had the lowest decrease in capacity (or highest increase), and calculating the average change in capacity for the entire range of scenarios in the category. As shown there are several scenarios that resulted in a capacity increase when a work zone was installed. The increases in capacity typically occurred when the intersection in the base case (prior to the work zone installation) is congested. In congested conditions, there is often blockage from one movement to another, particularly if the g/C ratios and the channelization are not optimal for the prevailing turning movement demands. In those cases the work zone results in a capacity increase, because it funnels traffic through the work zone, and it becomes easier for vehicles to change lanes and reach their destination lane due to reduced blockage. This increase was observed mostly for scenarios with 3-6 lanes at the intersection approach.

Table 18: **Change in Total Approach Capacity When a Work Zone is Installed**

Number of lanes at Intersection	**Number of Open Lanes**	**Number of Closed Lanes**	**Through/Right Movement g/C Ratio**								
			0.3			***0.5***			***0.7***		
			Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*
2 (w/o LT Lane)	1	1	0.97	1.38	1.08	1.00	1.56	1.16	1.37	1.81	1.54
2 (w LT lane)	1	1	0.46	1.38	0.98	0.78	1.28	1.01	0.80	1.40	1.01
3	1	1	0.70	1.29	0.98	0.75	1.48	1.05	0.78	1.68	1.27
	1	2	0.66	1.50	0.97	0.64	1.40	1.02	0.75	1.60	1.18
4	2	1	0.80	1.35	1.00	0.72	1.37	1.00	0.80	1.02	0.96
	1	1	0.69	1.57	1.06	0.79	1.83	1.22	1.35	2.17	1.65
	1	2	0.77	1.96	1.07	0.75	2.06	1.20	1.28	2.09	1.59
	2	1	0.77	1.50	1.03	0.77	1.33	1.01	0.91	1.19	1.00
	2	2	0.67	1.44	1.01	0.70	1.31	0.99	0.87	1.19	1.01
5	3	1	0.72	1.35	1.00	0.75	1.27	1.00	0.88	1.14	1.01
	1	2	0.77	2.24	1.25	0.91	2.33	1.43	1.51	2.44	1.89
	2	1	0.70	1.50	1.03	0.84	1.30	1.01	0.86	1.14	0.99
	2	2	0.70	1.88	1.02	0.69	1.38	0.98	0.89	1.22	1.00
6	3	1	0.76	1.48	1.01	0.78	1.31	0.99	0.91	1.19	1.00
	2	2	0.84	1.90	1.06	0.79	1.77	1.04	0.90	1.28	1.07

As Table 18 shows, the worst drop in capacity was 46% for two lanes at the intersection, and the maximum increase was 244% for five lanes at the intersection with one open lane and two closed lanes. These extreme values were seen in scenarios that experienced highly congested conditions that caused blockage. Scenarios with a high left turn percentage with a low left turn g/C and little storage resulted in severe blockage for vehicles exiting the work zone which produces higher capacities with the work zone implemented. The two-lane scenario with a left turn lane had a capacity increase because of metering the number of left turns that were queued awaiting the left turn phase.

In Table 19, which shows the capacity change for through and right turns, the worst capacity drop is 39%, and the maximum increase was 376%, both for two lanes at the intersection approach. The capacity increase for the through/right movement only can be extremely high for scenarios when that movement was blocked by another in the base case. In those cases, the installation of a work zone allows for smoother flow of traffic downstream, because it meters the demand to the intersection.

Table 19: Change in the Through/Right Movement Capacity When a Work Zone Is Installed

Number of lanes at Intersection	Number of Open Lanes	Number of Closed Lanes	Through/Right Movement g/C Ratio								
			0.3			*0.5*			*0.7*		
			Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*
2 (w/o LT Lane)	1	1	0.80	1.99	1.03	0.86	2.84	1.19	1.35	3.76	1.68
2 (w LT lane)	1	1	0.39	1.10	0.88	0.69	1.45	0.99	0.79	1.51	1.03
3	1	1	0.75	1.31	0.99	0.79	1.49	1.05	0.79	1.73	1.29
	1	2	0.70	1.43	0.96	0.71	1.46	1.03	0.75	1.65	1.19
4	2	1	0.80	1.23	0.98	0.71	1.41	1.00	0.79	1.02	0.95
	1	1	0.71	1.54	1.06	0.77	1.84	1.23	1.36	2.29	1.69
	1	2	0.73	1.92	1.02	0.73	1.98	1.18	1.26	2.20	1.63
	2	1	0.79	1.27	0.98	0.73	1.27	1.00	0.91	1.20	1.00
	2	2	0.70	1.35	0.97	0.66	1.32	0.98	0.87	1.20	1.01
5	3	1	0.75	1.32	0.99	0.76	1.29	1.00	0.88	1.15	1.01
	1	2	0.80	2.12	1.22	0.86	2.32	1.43	1.49	2.59	1.93
	2	1	0.72	1.42	1.03	0.84	1.30	1.00	0.84	1.15	0.99
	2	2	0.65	1.64	0.98	0.69	1.34	0.96	0.87	1.23	0.99
6	3	1	0.74	1.28	0.99	0.77	1.24	0.98	0.91	1.20	1.00
	2	2	0.78	1.74	1.04	0.73	1.71	1.03	0.89	1.30	1.07

Table 20 presents the capacity change in the left turn movement. The worst capacity drop was 30% for two lanes at the intersection, and the maximum increase was 401% for five lanes at the intersection with two open lanes and one closed lane. Because left turn capacities are much lower than the through, the fluctuation percentage-wise is larger than that of the through/right movement.

Table 20: Change in the Left Turn Movement Capacity When a Work Zone Is Installed

Number of lanes at Intersection	Number of Open Lanes	Number of Closed Lanes	Left Turn Movement g/C Ratio								
			0.3			*0.5*			*0.7*		
			Min	*Max*	*Average*	*Min*	*Max*	*Average*	*Min*	*Max*	*Average*
2 (w LT lane)	1	1	0.30	2.30	1.12	0.49	2.78	1.42	0.48	2.38	1.37
3	1	2	0.63	1.28	0.99	0.60	1.41	1.01	0.61	1.25	0.98
	2	1	0.68	1.44	1.03	0.43	1.78	1.05	0.61	1.73	1.02
4	1	1	0.76	1.63	1.03	0.62	2.53	1.08	0.77	1.81	1.07
	1	2	0.88	2.98	1.24	0.55	2.97	1.18	0.60	1.89	1.15
	2	1	0.75	3.50	1.25	0.63	3.99	1.32	0.69	2.37	1.30
	2	2	0.74	1.26	1.00	0.69	3.56	1.18	0.61	2.60	1.24
	3	1	0.64	1.15	0.99	0.59	4.64	1.18	0.56	3.16	1.19
5	1	2	0.71	1.19	1.00	0.66	2.32	1.04	0.63	1.75	1.03
	2	1	0.87	6.71	1.57	0.64	7.21	1.61	0.64	4.01	1.51
	2	2	0.91	1.75	1.09	0.66	2.29	1.05	0.67	1.67	1.05
	3	1	0.84	1.90	1.09	0.68	2.15	1.09	0.73	2.34	1.16
6	2	2	0.88	1.13	1.00	0.71	1.95	1.06	0.72	1.93	1.11
	3	1	0.87	1.65	1.08	0.79	2.14	1.14	0.94	2.18	1.22

In summary, results of the simulations showed that the work zone had significant drops in capacity when the arterial and downstream intersection in the base case was not congested. However, when the intersection was congested in the base case (i.e., without the work zone), installing a work zone had a metering effect which reduced the demand on the intersection and, in cases where there was blockage caused by inadequate storage, the metering effect improved the efficiency of the intersection.

3.4. Capacity Model Development

Once the simulated data were obtained from CORSIM, they were examined to evaluate trends between the independent factors and throughput by lane group. Data analysis showed that two-lane intersection approaches behaved differently than three- or four-lane approaches. In two-lane approaches, when one of the lanes is for left turns only, there is significant blockage from the through traffic on the left turning vehicles, particularly for low left turn percentages. This occurs because in two-lane approaches there is much less flexibility in lane selection, as well as in the storage availability. Thus two-lane approaches were considered separately, and models were developed specifically for such cases. Furthermore, for the two-lane scenarios, models estimating the capacity of the approach were developed separately for scenarios with one left turn lane and one through and right lane, and for scenarios with two through lanes. This was necessary because the operating characteristics for these two configurations were quite different.

In obtaining the capacity of left turns and through/right lanes separately, it was found that their capacity is affected by the lateral position of the work zone. The lane group that was directly downstream from the lane closure was affected more by the lane closure then the lane that was open through the work zone. This occurred primarily in the two lane scenarios, because with only two lanes on the approach the vehicles were much more likely to experience blockage when attempting to reach their desired lane.

For the three- to six-lane scenarios, a model estimating the capacity of the intersection approach and a model estimating the capacity of each movement (i.e., left turn only, and through/right) were developed. The two sets of models use the same set of factors, and give very comparable results. Capacity is estimated as a function of various factors found to affect capacity, including the percent of left turning vehicles, the distance of the work zone to the downstream intersection, the g/C ratios of each lane group, etc. All models are presented in Table 21, and each of them is discussed in the following sections.

Table 21: Capacity Models for Arterial Work Zones

	2 Lanes - No Left Turns Allowed (R^2 = .782)		
	Variable Name	Coefficients	Standard Error
1	Constant Term	443.364	46.772
2	Distance from Work Zone to Downstream Intersection (ft)	.208	.040
3	g/C Ratio for Intersection Approach	1685.778	79.710
	2 Lanes - One Left Turn Lane and one Through/Right Lane (R^2 = .542)		
	Variable Name	Coefficients	Standard Error
1	Constant Term	58.682	73.550
2	Th/Rt Phase g/C Ratio	1581.307	119.964
3	Distance from Work Zone to Downstream Intersection (ft)	0.124	0.042
4	Left Turn g/C Ratio	521.551	114.665
	Left Turn Capacity for 3 – 6 Lanes at the Intersection (R^2 = .701)		
	Variable Name	Coefficients	Standard Error
1	Constant Term	-337.057	11.092
2	Th, Th/Rt and Rt Lanes	41.907	1.834
3	Left Turning Percentage	803.356	20.912
4	Th/Rt Phase g/C Ratio	207.909	14.492
5	Number of Open Lanes / Total Number of Lanes	145.634	11.052
6	(Left Only Lanes) x (Left turning %) x (Left Phase g/C)	1262.069	27.434
7	Distance from Work Zone to Downstream Intersection (ft)	0.153	0.005
	Through/Right Turn Capacity for 3 – 6 Lanes at the Intersection (R^2 = .724)		
	Variable Name	Coefficients	Standard Error
1	Constant Term	-629.449	27.07
2	Th, Th/Rt and Rt Lanes	359.162	4.476
3	Left Turning Percentage	-2535.577	51.033
4	Th/Rt Phase g/C Ratio	2168.25	35.366
5	Number of Open Lanes / Total Number of Lanes	602.193	26.971
6	(Left Only Lanes) x (Left turning %) x (Left Phase g/C)	1773.573	66.95
7	Distance from Work Zone to Downstream Intersection (ft)	0.282	0.012
	Approach Capacity for 3 - 6 Lanes at the Intersection (R^2 = .64)		
	Variable Name	Coefficients	Standard Error
1	Constant Term	-946.955	32.789
2	Th, Th/Rt and Rt Lanes	422.389	5.562
3	Right Only Lanes	-168.58	9.935
4	Left Turning Percentage	-1751.447	61.788
5	Th/Rt Phase g/C Ratio	2378.501	42.812
6	Number of Open Lanes / Total Number of Lanes	755.362	32.653
7	(Left Only Lanes) x (Left turning %) x (Left Phase g/C)	3078.002	81.083
8	Distance from Work Zone to Downstream Intersection (ft)	0.435	0.015

3.4.1 Capacity for 2 Lanes at the Intersection

The first model presented in Table 21 applies to arterials with one lane open through the work zone and two lanes at the intersection, with no left turns allowed. There is only one phase allocated to the intersection approach. In this model, the capacity increases with the g/C ratio and the distance from the end of the work zone to the downstream intersection. Increased distance from the work zone provides additional storage for queuing, which results in better utilization of the green for the approach.

The second model presented in Table 21 applies to arterials with one lane open through the work zone and two lanes at the intersection, one of which is an exclusive left turn lane. There is a separate, protected, left turn phase. This model estimates the capacity of the entire approach, which, as in the previous model, is a function of the g/C ratios for each of the movements, as well as the storage available for queuing.

3.4.2 Capacity Models for Three to Six Lanes at the Intersection

Left Turning Movements - The third model presented in Table 15 applies to arterials with one or two lanes open through the work zone, three to six lanes at the intersection, and two phases (one for left turns and another for through/right) allocated to the approach. This model predicts the capacity of the left turn movement. The capacity increases with the through/right number of lanes, the through/right g/C ratio, the ratio of open lanes to total lanes, the distance to the downstream intersection, and the left turn percentage. An increase in the through/right lanes provides additional storage and reduces the blockage to the left turning vehicles, which increases the overall capacity. Increasing the g/C ratio for the through/right movement increases the left turn movement capacity because it reduces blockage to the left turning vehicles. The distance from the work zone to the downstream intersection results in increased storage for queued vehicles, which allows for more effective use of the green signal. Increasing the left turning percentage generally resulted in higher throughput for that movement because there is less opportunity for blockage of the left turning vehicles when they are present in the traffic stream in large numbers.

Through and Right Movements - The fourth model presented in Table 15 applies to arterials with one or two lanes open through the work zone, three to six lanes at the intersection, and two phases for the subject approach. This model predicts the capacity of the through and right movements. As shown, the capacity increases with the through/right number of lanes, through/right lane group g/C ratio, distance to the downstream intersection, number of left only lanes, and the left turn g/C ratio. Increasing the number of left turning lanes increases the storage available for that movement, and minimizes blockage to the through traffic, increasing its capacity. The capacity of the through/right movement decreases however when the left turning percentage increases, because there is a higher probability of blockage to the through/right vehicles.

Total Approach Capacity - The fourth model presented in Table 15 estimates the total approach capacity and applies to arterials with one or two lanes open through the work zone, three to six lanes at the intersection, and two phases given to the approach. Capacity increases with the through/right g/C ratio, the ratio of open lanes/total lanes, total number of through/right lanes, left-turn only lanes, left turn g/C ratio, and the distance to the downstream intersection. The number of right-only lanes has a negative impact on capacity because the right turn exclusive lane restricts the through volume to the through only lanes reducing through capacity as well as the overall capacity. The left turn percentage has a negative effect in the total approach capacity, because it generally reduces the through/right throughput due to increased blockage.

3.4.3 Comparison of the total approach and lane group capacity models

A comparison of the total approach capacity model and the combination of the left turn and through/right models indicate that the major difference in the two approaches is in the way that right turn lanes are treated (Table 22). The total approach model includes the effect of the right turn lane on total capacity. In the left turn and through/right models, right turn lanes are not considered separately. Generally the two sets of models yield similar results for the capacity of the arterial work zone. Examples of their application as well as numerical comparisons of results are provided in the next section.

Table 22: Comparison of the Total Approach and Lane Group Capacity Models

	Variable Name	Total Approach Model	Combined Models	Difference
1	Constant Term	-946.955	-966.506	-19.551
2	Th, Th/Rt and Rt Lanes	422.389	401.069	-21.32
3	Right Only Lanes	-168.58	0	168.58
4	Left Turning Percentage	-1751.447	-1732.221	19.226
5	Th/Rt Phase g/C Ratio	2378.501	2376.159	-2.342
6	Number of Open Lanes / Total Number of Lanes	755.362	747.827	-7.535
7	(Left Only Lanes) x (Left turning %) x (Left Phase g/C)	3078.002	3035.642	-42.36
8	Length (ft)	0.435	0.435	0

3.4.4 Comparison of the proposed method to the HCM and the existing FDOT method

This section presents a general comparison of the results produced by the models developed in this project to those obtained by the existing FDOT method. A one-to-one comparison cannot be made, because the two approaches use a different set of variables as inputs. The proposed models are based on variables such as the distance to the downstream intersection and turning percentages, while the existing FDOT method is based mostly on geometric design variables such as lane widths and lateral clearance. Also, the FDOT method uses a "base" capacity, and its relationship to site characteristics is not clear; therefore it is not clear what set of inputs this would correspond to in the new models. The only variable that is common to the two methods is v/c; however the FDOT method does not distinguish between v/c ratios for different movements, and only uses one value for the entire approach. Therefore, the comparison shown here is very general, and only shows the ranges in capacity that could be obtained from each of the two methods. The remainder of the section presents two examples and discusses the differences between the two approaches.

Example 1

Consider a 2 to 1 lane closure with a base capacity of 1800vph. The following two cases are used to obtain the minimum and the maximum possible obtainable capacities using the existing FDOT methodology.

a. Minimum:

   Travel Lane Width: 9 ft with no Lateral Clearance; g/C =0.3. This gives the Obstruction Factor as 0.65.

   Restricted Capacity = (1800)*(0.65)*(0.3) = 351 vph.

b. Maximum:

   Travel Lane Width: 12ft and Lateral Clearance 6ft; g/C = 0.7. This gives the Obstruction Factor as 1.00.

   Restricted capacity = (1800)*(1.00)*(0.7) = 1260 vph.

The range in capacities of a 2-1 lane closure using the new proposed method, assuming a single phase for the entire approach (which means only one v/c is needed) are shown in Table 23.

Table 23: Range in Capacities for a 2-1 Lane Closure

	Variable Name	Coefficients	Min	Max
1	Constant Term	443.364	N/A	N/A
2	Distance to Downstream Intersection (ft)	0.208	100	1000
3	g/C Ratio for the approach (*g/C)*	1685.778	0.3	0.7
	Capacity (vph) =		**970**	**1831**
*The values given here show the possible range in capacities under the assumptions given. Values outside this range may be obtained for other cases.				

Generally, the capacity estimates in this case tend to be higher with the new method. The existing FDOT method predicts a 35% reduction in capacity for 9 ft. lanes and no lateral clearance, which appears to be too steep. The HCM 2000 signalized intersection analysis methodology reduces the saturation flow by only 10% when 9 ft. lanes are present, and there are no reductions applied for lateral clearance. Furthermore, the existing FDOT methodology does not take into consideration the distance from the work zone to the downstream intersection, which significantly affects capacity. Finally, the maximum capacity the FDOT method predicts (1260 vph) is too low, considering that the capacity of a two-lane approach, when there is no work zone present, can reach 2600 vph (for v/c = 0.7).

Example 2

Consider a 3 to 2 lane closure with a 3600 vph base capacity. The following two cases are used to obtain the minimum and the maximum possible obtainable capacities using the existing FDOT methodology.

a. Minimum:

Travel Lane Width: 9 ft with no Lateral Clearance; g/C =0.3. This gives the Obstruction Factor as 0.65.

Restricted Capacity = (3600)*(0.65)*(0.3) = 702 vph

b. Maximum:

Travel Lane Width: 12ft and Lateral Clearance 6ft; g/C = 0.7. This gives the Obstruction Factor as 1.00.

Restricted capacity = (3600)*(1.00)*(0.7) = 2520 vph

The range in capacities for a 3-2 lane closure using the proposed method are shown in Table 24.

Table 24: Range in Capacities for a 3-2 Lane Closure

	Variable Name	**Coefficients**	**Min**	**Max**
1	Constant Term	-946.955	N/A	N/A
2	Number of Th, Th/Rt and Rt Lanes (TTR)	422.389	1	2
3	Number of Right Only Lanes	-168.58	0	1
4	Left Turning Fraction (LTF)	-1751.45	0.4	0.05
5	Th/Rt Phase g/C Ratio ($(g/C)_{TTR}$)	2378.501	0.3	0.7
6	Number of Open Lanes / Total Number of Lanes (N_o/N_t)	755.362	1/3	1/3
7	(Left Only Lanes) x (Left turning %) x (Left Phase g/C) [(LT*LTF*$(g/C)_{LT}$]	3078.002	0.32	0.005
8	Distance to Downstream Intersection (ft)	0.435	100	1000
	Capacity (vph) =		**769**	**2009**
*The values given here show the possible range in capacities under the assumptions given. Values outside this range may be obtained for other cases.				

In this case, the minimum capacity value is comparable for the two methods. The maximum capacity predicted by the existing FDOT method is higher than that predicted by the proposed method by about 500 vph. As indicated above, given that the FDOT method does not take into account the effects of turning movements at the intersection, nor the distance of the work zone to the downstream intersection, it is not possible to compare the results of the two methods on a one-to-one basis.

3.5. Model Applications

This section presents applications of the models. First the models are presented in equation format, and then example problems are provided to illustrate their usage.

Model 1: Total capacity for two lanes at the intersection without an exclusive turn lane

$C_{ALL} = 443.36 + (1685.78 \times g/C) + (0.21 \times D)$

Where:

D =	Distance from the work zone to the intersection
g/C =	g/C Ratio for the approach

Model 2: Total capacity for two lanes at the intersection with an exclusive turn lane

$C_{ALL} = 58.68 + (1581.31 \times (g/C)_{TTR}) + (0.12 \times D) + (521.55 \times (g/C)_{LT})$

Where:

$(g/C)_{TTR}$ =	g/C Ratio for the Through/Right Movement
D =	Distance from the work zone to the intersection
$(g/C)_{LT}$ =	g/C Ratio for the Left Turning Movement

Model 3: *Left turn capacity for three to six lanes at the intersection*

$C_L = -337.1 + (41.9 \times TTR) + (803.3 \times LTP) + (207.9 \times (g/C)_{TTR}) + (145.6 \times N_o/N_t) + (1262.1 \times LT \times LTP \times (g/C)_{LT}) + (0.1 \times D)$

Where:

TTR=	Number of through, through/right, and right turn only lanes
LTP=	Left Turning Percentage
$(g/C)_{TTR}$ =	g/C Ratio for the Through/Right Movement
N_o/N_t=	Number of Open/Number of Total Lanes in the Work Zone
LT=	Left Turning Lanes
$(g/C)_{LT}$ =	g/C Ratio for the Left Turning Movement
D =	Distance from the work zone to the intersection

Model 4: Through/right movement capacity for three to six lanes at the intersection

$$C_{TH} = -629.4 + (359.2 \times TTR) - (2535.6 \times LTP) + (2168.2 \times (g/C)_{TTR}) + (602.2 \times N_o/N_t) + (1773.6 \times LT \times LTP \times (g/C)_{LT}) + (0.3 \times D)$$

Where:

TTR=	Number of through, through/right, and right turn only lanes
LTP=	Left Turning Percentage
$(g/C)_{TTR}$ =	g/C Ratio for the Through/Right Movement
N_o/N_t=	Number of Open/Number of Total Lanes in the Work Zone
LT=	Left Turning Lanes
$(g/C)_{LT}$ =	g/C Ratio for the Left Turning Movement
D =	Distance from the work zone to the intersection

Model 5: Total capacity for three to six lanes at the intersection

$$C_{ALL} = -947 + (422.4 \times TTR) - (1751.45 \times LTP) + (2378.5 \times (g/C)_{TTR}) + (755.4 \times N_o/N_t) + (3078 \times LT \times LTP \times (g/C)_{LT}) + (0.4 \times D) - (168.6 \times RT)$$

Where:

TTR=	Number of through, through/right, and right turn only lanes
LTP=	Left Turning Percentage
$(g/C)_{TTR}$ =	g/C Ratio for the Through/Right Movement
N_o/N_t=	Number of Open/Number of Total Lanes in the Work Zone
LT=	Left Turning Lanes
$(g/C)_{LT}$ =	g/C Ratio for the Left Turning Movement
D =	Distance from the work zone to the intersection
RT =	Right Turn Only Lanes

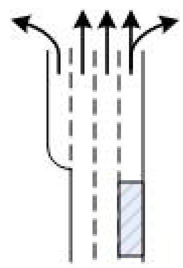
3.5.1 Example Problems

This section presents three example problems for estimating arterial work zone capacity. Each example illustrates the use of the models developed in this research and summarized in the previous section.

Example Problem 1:

Calculate the capacity of a 3-to-2 lane closure (i.e., a total of 3 lanes along the arterial, with 1 lane closed due to the work zone) with the following characteristics:

- Distance from the end of the work zone to the downstream intersection = 500 ft
- Left turn pocket at the downstream intersection = 1
- No right turn only lane
- Schematic of the arterial along with the lane channelization at the downstream intersection as shown below:



- Number of through only lanes = 2
- Number of through and right lanes = 1
- Signal has exclusive left turn phase
- g/C ratio for Th/Rt phase = 0.4
- g/C ratio for left turn phase = 0.1
- Fraction of vehicles in traffic stream that turn left = 0.15

Inputs:

TTR (Through, through/right and right only lanes) = 2+1 = 3

LTP (Left Turning Percentage) = 0.15

$(g/C)_{TTR}$ (g/C Ratio of the Through, Through/Right and Right Turn Lanes) = 0.4

N_o/N_t : Number of open lanes/ Total Number of Lanes = 2/3

LT (Left Only Lanes) = 1

$(g/C)_{LT}$ (Left Phase g/C Ratio) = 0.1

D (Distance between the work zone and the intersection) = 500 ft

Model Application:

(i) The capacity of the left turn lane (C_L) can be estimated using model 3:

C_L = -337.1 + (41.9 x TTR) + (803.3 x LTP) + (207.9 x $(g/C)_{TTR}$) + (145.6 x N_o/N_t) + (1262.1 x LT x LTP x $(g/C)_{LT}$) + (0.1 x D)

Substituting the above input values:

C_L = -337.1 + (41.9 x **3**) + (803.3 x **0.15**) + (207.9 x **0.4**) + (145.6 x **0.67**) + (1262.1 x **1** x **0.15** x **0.1**) + (0.1 x **500**)

C_L = 185 veh/hr.

(ii) The capacity of the through, through/right and right only lanes can be estimated using model 4:

C_{TH} = -629.4 + (359.2 x TTR) - (2535.6 x LTP) + (2168.2 x $(g/C)_{TTR}$) + (602.2 x N_o/N_t) + (1773.6 x LT x LTP x $(g/C)_{LT}$) + (0.3 x D)

Substituting the above input values:
C_{TH} = -629.4 + (359.2 x **3**) - (2535.6 x **0.15**) + (2168.2 x **0.4**) + (602.2 x **0.67**) + (1773.6 x **1** x **0.15** x **0.1**) + (0.3 x **500**)

C_{TH} = 1504 veh/hr.

(iii) The capacity of the entire intersection approach can be calculated using model 5:

C_{ALL} = -947 + (422.4 x TTR) - (1751.45 x LTP) + (2378.5 x $(g/C)_{TTR}$) + (755.4 x N_o/N_t) + (3078 x LT x LTP x $(g/C)_{LT}$) + (0.4 x D) – (168.6 x RT)

Substituting the above input values:

C_{ALL} = -947 + (422.4 x **3**) - (1751.45 x **0.15**) + (2378.5 x 0.4) + (755.4 x **0.67**) + (3078 x **1** x **0.15** x **0.1**) + (0.4 x **500**) – (168.6 x **0**)

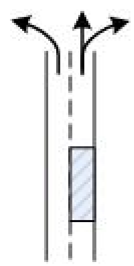
C_{ALL} = 1776 veh/hr.

Estimation of the capacity for each of the two lane groups separately results in a total approach capacity of 185 + 1504 = 1689 veh/hr, while the approach capacity was estimated to be 1776 veh/hr. There is a relatively small difference in the results between the two approaches (less than 100 vph). Validation of the models developed in this research using field data might provide more definitive conclusions regarding the accuracy of the two sets of models.

Example Problem 2:

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

- Distance of from the end of the work zone to the downstream intersection is 500 ft
- Total number of lanes in the arterial = 2
- Number of lanes closed in the work zone = 1
- No right turn only lane
- Schematic of the arterial along with the lane channelization at the downstream intersection as given below:



- The number of through only lanes = 0
- Number of through right lanes = 1
- Left only lanes = 1
- Signal has exclusive left turn phase
- g/C ratio for through/right phase = 0.4
- g/C ratio for left turn phase = 0.1
- Fraction of vehicles in traffic stream that turn left = 0.15

Inputs:

$(g/C)_{TTR}$ (g/C Ratio of the Through, Through/Right and Right Turn Lanes) = 0.4

$(g/C)_{LT}$ (Left Phase g/C Ratio) = 0.1

D (Distance between the work zone and the intersection) = 500 ft

Model application:

The capacity can be estimated using model 2:

$C_{ALL} = 58.68 + (1581.31 \times (g/C)_{TTR}) + (0.12 \times D) + (521.55 \times (g/C)_{LT})$

Substituting above values:

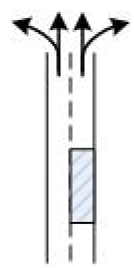
C_{ALL} = *58.68 + (1581.31 x* ***0.4****) + (0.12 x* ***500****) + (521.55 x* ***0.1****)*

C_{ALL} = *805 veh/hr.*

Example Problem 3:

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

- Total number of lanes in the arterial = 2
- Number of lanes closed in the work zone = 1
- No right turn lanes
- Schematic of the arterial along with the lane channelization at the downstream intersection as given below:



- The number of through only lanes = 0
- Number of through right lanes = 1
- Left only lanes = 1
- Signal has g/C ratio for entire arterial = 0.5
- Distance of from the end of the work zone to the downstream intersection is 500 ft

Inputs:

g/C (g/C ratio for entire arterial) = *0.5*

D (Distance between the work zone and the intersection) = 500 ft

Model application:

The capacity can be estimated using model 1:

$$C_{ALL} = 443.36 + (1685.78 \times g/C) + (0.21 \times D)$$

$$C_{ALL} = 443.36 + (1685.78 \times \mathbf{0.5}) + (0.21 \times \mathbf{500})$$

C_{ALL} = *1390 veh/hr.*

4. SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

The current FDOT arterial work zone capacity estimation procedure is an extension of the one used to estimate freeway work zone capacity, and does not account for various operating and work zone characteristics of the facility (i.e. speeds, the position of the closed lanes, etc.). A literature review found that there has been very little research on the capacity of arterial work zones. State policies use work zone capacity values ranging from 600 to 1520 vphpl, and it is not clear how these values were obtained, or what the relationship is between capacity and various work zone and operational characteristics at the site. Thus there is a need to assess the impact of various factors on the capacity of an arterial work zone, and to develop methods for estimating this capacity.

Field data were not available to conduct this research, therefore simulation was used to develop several intersection and work zone configurations and obtain relationships between various factors and the capacity of the arterial work zone. CORSIM (version 5.1) was selected to develop a comprehensive database for the model development. A set of appropriate scenarios was developed considering the capabilities of the simulator, the impacts various factors may have on arterial work zone capacity, as well as the sensitivity of those factors with respect to the simulated capacity. Five regression models were developed to predict the capacity of the entire approach, the capacity of the left turning lane group, and the capacity of the through and right turning group for various arterial work zone configurations. In those models, capacity is estimated as a function of various factors including the percent of left turning vehicles, the distance of the work zone to the downstream intersection, the g/C ratios of each lane group, etc.

The following were concluded from the research:

- There has been very little research on the capacity of arterial work zones, despite the fact that capacity is used as an important input in their evaluation.
- Existing simulators do not specifically model arterial work zones.
- Simulation of arterial work zones showed that the distance of the work zone to the downstream intersection affects the capacity of the entire arterial work zone. Increasing the available storage between the signal and the work zone models results in better utilization of the green at the intersection approach.
- The capacity of the arterial work zone is reduced when one of the movements are blocked by the other. The probability of such blockage increases when the g/C ratios are not optimal or when the channelization at the intersection is not optimal for the respective demands.
- Comparison of the arterial work zone capacity to the respective configurations with no work zones showed that there are selected cases when installing a work zone may increase capacity. Those increases typically occur when the intersection (prior to the work zone installation) is congested. In those cases the work zone funnels traffic through the work zone, and it becomes easier for vehicles to change lanes and reach their destination lane, because there is less blockage. This increase was observed mostly for scenarios with 3-6 lanes at the intersection approach.
- The capacity estimates obtained from the current FDOT procedure are based on an entirely different set of input variables and therefore cannot be directly compared to the capacity estimates obtained by the models developed in this research.
- Since this research was entirely based on simulation, the results and conclusions should be viewed with caution. It is likely that field observations would result in different capacity values and that additional factors would affect the results. The trends observed in the simulation however should generally be valid in the field.

The following are recommendations from this research:

- The models developed in this research should be applied on a trial basis to existing and upcoming arterial work zone projects, so that they can be tested and validated before being incorporated into the FDOT lane closure analysis procedure.
- Field data should be collected at various sites and with various work zone configurations, so that the procedures developed here can be thoroughly evaluated, and the simulated capacity estimates compared to field estimates.
- Specific guidance can be developed on traffic signal control strategies for intersections downstream of a work zone, so that capacity can be maximized.

- Research should be conducted to evaluate the capacity of an arterial work zone and its impact on the upstream intersection. In those cases, spillback would result in a reduction of the effective green for one or more of the upstream intersection approaches. Models can be developed to estimate the lost time and capacity reduction for each of these upstream approaches.

The following recommendations are provided regarding possible improvements to CORSIM with respect to arterial work zone simulation:

- The software should consider replicating the use of taper sections.
- The use of the "rubbernecking" factor in freeway work zone simulation could be applied to arterials as well, provided that there is a specific relationship between the rubbernecking factor and work intensity in the work zone.
- Various geometric elements (such as lane width and shoulder width) are currently not considered within CORSIM. Its algorithms should be modified to consider such factors generally, as well as with respect to work zones.

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