SIMULATION-BASED CAPACITY ESTIMATION OF ARTERIAL WORKZONES

By

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To my parents

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LIST OF ABBREVIATIONS

CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
DOT	Department of Transportation
FDOT	Florida Department of Transportation
FDOT PPM	Florida Department of Transportation Plans and Preparation Manual
FHWA	Federal Highway Administration
HCM	Highway Capacity Manual
MUTCD	Manual on Uniform Traffic Control Devices
ODOT	Oregon Department of Transportation
QUEWZ	Queue and User Cost Evaluation of Work Zones
Th/Rt Lanes	Lanes channelized as through and right lanes (shared lanes)
Th & Rt Lanes	Sum of lanes marked as Th/Rt Lanes and right-only lanes
WZATA	Work Zone Analysis Tool for the Arterial

Abstract of Thesis Presented to the Graduate School
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Numerous states have policies that provide guidance for the institution of short term lane closures on arterial streets based on capacity estimates; however, it is not clear how the existing values were developed, and there are currently no tools to estimate the capacity of arterial lane closures. This estimation is important because capacity is used to forecast queues and delays. In this research, simulation was used to develop several intersection and work zone configurations and to 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. Capacity is defined as a function of various factors including the percentage of left-turning vehicles, the distance of the work zone to the downstream intersection, and the g/C ratios of each lane group.

Simulation of arterial work zones showed that the distance from 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. The capacity of the arterial work zone is reduced when one of the movements is 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 are fewer blockages. This increase was observed mostly for scenarios with 3 to 6 lanes at the intersection approach.

CHAPTER 1
INTRODUCTION

1.1 Background

Many state transportation agencies are experiencing growing congestion and traffic delays because of work zones on arterial roads. This congestion results in delays for both motorists and commercial vehicles. The delays also result in driver frustration, making some drivers willing to take unsafe risks in an effort to bypass delays. The need to maintain adequate traffic flow through short term and long term arterial work zones is vital on today's heavily-traveled roadways. 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.

Numerous states (MassHighway, (2007), Missouri Department of Transportation (2004), Washington Department of Transportation (WDOT) (2006), Oregon Department of Transportation (ODOT) (2007), refer Sarasua et. al. (2004)) have policies that provide guidance for the installation of short term work zone (lane closures) including maximum allowable traffic flows, vehicle delays, and queue lengths. 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 for each state as a function of traffic stream characteristics, highway geometry, work zone location, type of construction activities, and work zone configuration (Sarasua, 2004).

There have been empirical observations of various factors that affect the operation and capacity of arterial work zones; however, literature lacks capacity estimation models.

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 obtain queues as well as delays. Currently, the FDOT procedure of estimating capacity on arterials is an extension of the one used to estimate freeway work zone capacity. The current methods have not been updated since 1995 and FDOT is interested in an improved method that will facilitate the scheduling and managing of short term work zone lane closures on arterials.

The existing procedure used by FDOT (PPM, 2000) for calculation of restricted capacity for open road (i.e., freeways, multilane highways, and two-lane highways) and signalized intersections 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 does not account for the operating characteristics of the facility (i.e., speeds, characteristics of downstream workzone, etc.).

1.2 Objectives and Scope

The objective of this research was to identify the various geometric and traffic factors that impact the capacity of an arterial work zone and to develop an analytical model to estimate work zone capacity. Capacity models are estimated for the approach to a signalized intersection. Additionally, models for predicting the maximum flow through left turn only and Through-right (Th/Rt) lane group were also estimated.

1.3 Report Overview

Chapter 2 reviews the literature pertaining to the topic. It discusses the state of the art in the field. Chapter 3 presents the methodology. It describes the scenario setup and the simulation. Model development is presented in the chapter 4 along with the models developed for all the scenarios. Chapter 5 presents the conclusions drawn from the research and the recommendations for future work.

CHAPTER 2
LITERATURE REVIEW

An extensive literature review was conducted to identify and evaluate existing research involving arterial work zone lane closures. Little research has been done to address the issue of capacity in arterial work zones.

The first section discusses the design of work zones in the Manual on Uniform Traffic Control Devices (FHWA, 2003). Review of the current FDOT methodology for capacity calculation of work zones and its limitations are presented next. The third section summarizes existing methods and approaches used by various states. It also provides an overview of work zone capacity research and other tools available for work zone analysis. The last section includes a brief summary of the findings and recommendations from the literature.

2.1 Arterial Work Zone Design

The 2003 version of the MUTCD provides guidance to transportation professionals on the design of arterial work zones. This section presents the various features of an arterial work zone based on these guidelines. Figure 2-1 presents a typical work zone implemented on an arterial. The barrier seen in the figure would only be implemented on a high speed, longer term project. In applications without barriers, the general layout would maintain the other characteristics as shown.

The work zone begins with an advance warning area which consists of various signs informing drivers of a imminent geometric change. 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 exist to calculate the length of this taper depending on the number of lanes closed, the length of work zone, and the speed of vehicles entering the work zone. The formulae are presented in Table 2-1 and are 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.

"Activity or work area" follows the "taper" which consist of workers and other equipment. 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 designating the end of road work. The lengths of and around the work area are based on the activity that is being conducted. The guidance from the MUTCD states that no work should be conducted in buffer areas.

The MUTCD provides typical applications for work zones at and within intersections however there are no guidelines for the minimum length of a work zone and its approaching taper zone if the speed and length of work zone are not known. Such guidelines can act as guiding values for safety norms. However there are guidelines for establishing the length of the taper as a function of the length of the work zone and the prevailing speeds only.

This section presented a brief overview of a typical work zone setup. The next section will detail the way work zone capacity is calculated by FDOT.

2.2 State Methodologies for Computing Work Zone Capacity

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). The threshold limits for these measures are defined on a state-by-state basis as a function of traffic stream characteristics, highway geometry, work zone location, type of construction activities, and work zone configuration (Sarasua, et. al., 2004).

There are several tools available for estimating work zone delay and queue length. These are estimated based on capacity estimates which are used as input to those tools (Jiang and Adeli, 2004). Specific values are suggested, however, there is little information available on the relative impacts of various work zone related factors on capacity. States provide suggested arterial work zone capacities as follows:

- Massachusetts: 1,170 to 1,490 vphpl; (MassHighway, 2007)
- Missouri: 1,000 vphpl; (Missouri DOT, 2004)
- Washington: 600 to 1,300 vphpl; (Washington DOT Design Manual, 2006)
- Oregon: 1,200 to 1,600 passenger cars per hour per lane (pcphpl); (ODOT, 2007)
- South Carolina: 800 vphpl. (Sarasua, et. al., 2004)

As shown there is wide variability in the values used, and there is no documentation on how these values were obtained.

2.3 Current FDOT Methodology

FDOT has a procedure to determine the capacity of Work Zone Lane Closures on Multi-Lane Signalized Arterials. Section 10.14.7 of FDOT PPM Volume I (1) (FDOT PPM, 2007) describes the lane-closure analysis.

The lane closure analysis is used to calculate the peak hour traffic volume and the restricted capacity for open road and signalized intersections. The analysis determines whether a lane closure should be allowed, and if it's allowed, then whether it should be implemented during the day or night. 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.

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

$$RC_{\text{open road}} = C \times OF \times WZF \qquad \text{(equation 1.1)}$$

where

C is the Base Capacity obtained from Table 2-1.

OF is obstruction Factor, which reduces the capacity of the remaining travel lane(s) by restricting one or both of the following components: Travel lane width less than 12 ft. and lateral clearance less than 6 ft.

WZF is Work Zone Factor, which is directly proportional to the length of the work zone. It applies only to closures converted to two-way, one-lane.

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

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

where

g/C is the Ratio of effective 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 FDOT procedure is based on the following:

- The "basic capacity" of the arterial. These capacities do 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. More 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 600 ft. roughly account for the taper, deceleration and storage for the intersection turning lane groups. However, the validity of the 600 ft value should be assessed in light of the large variability in traffic volumes, G/C ratios and queue lengths.
- 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 section 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.

Currently, three software products, *QUEWZ*, *QuickZone*, and *CA4PERS,* 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).

2.4.1 WZATA

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.

2.4.2 QUEWZ

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. It 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).

There are a few software packages that use queuing analysis to determine queue lengths and delay. These use capacity as either input or an intermediate variable. Absence of relevant literature lead to study of these packages to understand the factors affecting the capacity. Two software products, QuickZone and CA4PERS were studied for this project. Their algorithms and with the inputs and outputs are discussed below.

2.4.3 QuickZone Software

FHWA has developed QuickZone (FHWA, 2000), an analytical approach to estimate and quantify work zone delays. The software focuses on delays caused due to work zones but does not estimate the capacity of the work zone.

The software algorithm 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. (FHWA, 2000)

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. Queues on detour routes are also monitored. 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 on 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.

Regarding actuated signals, depending on the varying demand in the inbound and outbound directions, QuickZone will identify the smallest cycle time that supports the travel demand in each direction. This keeps the amount of delay to a minimum. Sometimes the maximum cycle length must be used in order to clear as many vehicles as possible.

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.

2.4.4 CA4PRS Software

In order to have an integrated analysis of design, construction, and traffic to provide a schedule baseline for highway rehabilitation projects, a construction production analysis model CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) software, was designed for the California Department of Transportation. It 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. (Lee and Ibbs, 2005)

CA4PRS is a production analysis tool designed to estimate the maximum probable length of highway pavement that can be rehabilitated or reconstructed given various project constraints. 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. (Lee and Ibbs, 2005)

2.5 Summary of Literature and Conclusions

Little research has been done to estimate the capacity of work zones on arterials. However, some factors affecting the capacity on both arterial and freeway work zones have been studied thus far. Some guidelines exist in FDOT PPM but they fail to consider the details of the work zone configuration. Some software programs look at the delays caused due to work zones and hence, account for some factors that might affect the capacity as well. QuickZone uses capacity as input and calculates the delays to the users based on queuing theory. It also looks at the effect of changing the cycle length on the delays and capacity. CA4PRS models looks at the rehabilitation production only, by comparing various input variables.

The issue of the capacity determination of the work zones on arterials has not been adequately addressed. It is not clear from the literature what factors affect the capacity of an arterial work zone. Capacity is used as input but there are no tools to calculate capacity which can be then used to estimate several other performance measures.

The next chapter discusses the proposed methodology for developing the models to estimate work zone capacity on arterial roads.

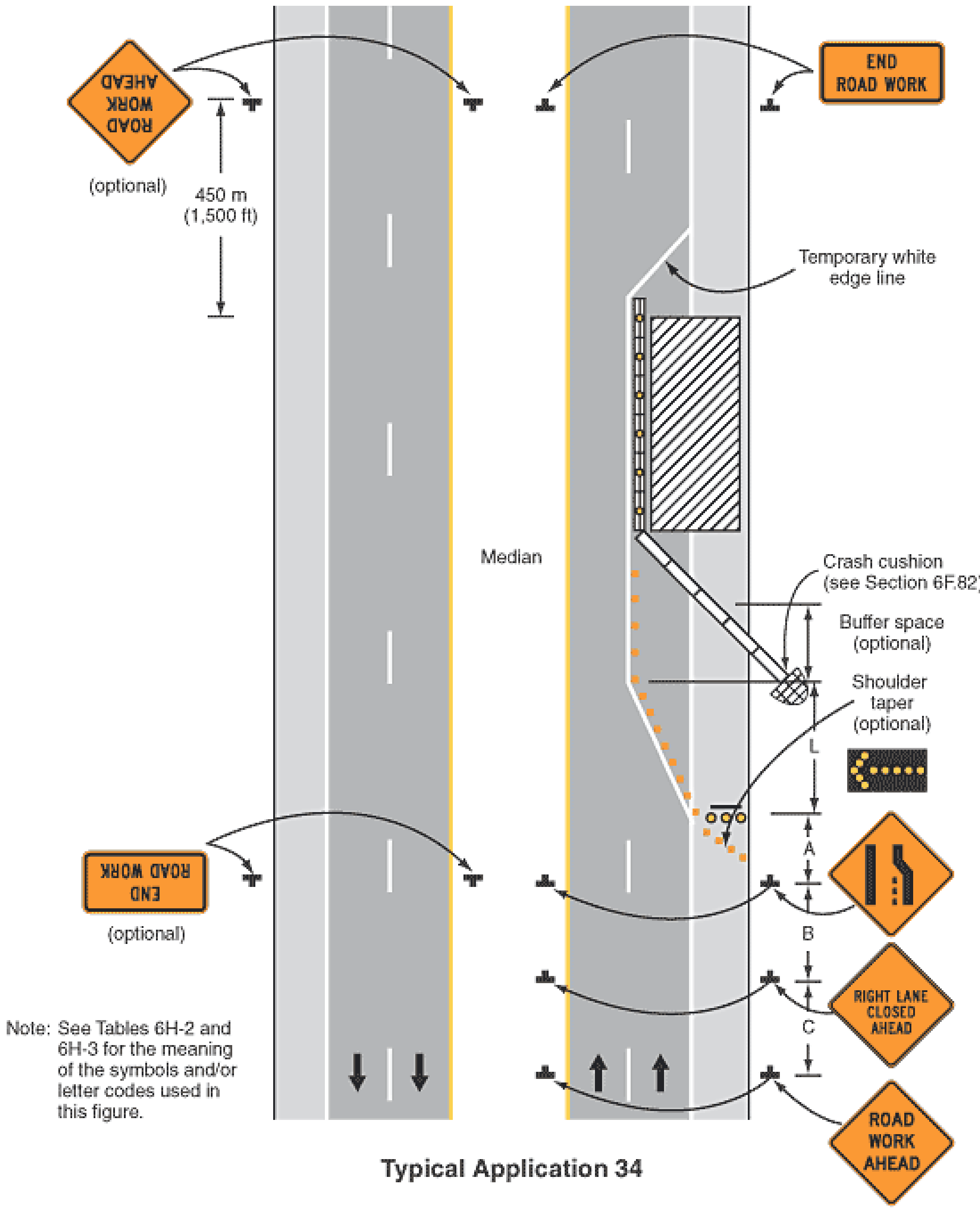

Figure 2-1 Work Zone Setup [Source: MUTCD 2003]

Table 2-1: Formulas for Determining Taper Lengths (MUTCD, 2003)

Speed Limit (S)	Taper Length (L) Feet
40 mph or less	$L = \frac{WS}{60}$
45 mph or more	$L = WS$

where
L = taper length in feet
W = width of offset in feet
S = posted speed limit, or off-peak 85th-percentile speed prior to work starting, or the anticipated operating speed in mph.

Table 2-2: 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

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents a discussion on the next step to develop a simulation that can accurately duplicate the effects of a work zone on the traffic stream. For this purpose, an appropriate tool should be used. This chapter starts with a discussion on the selection of the software package for simulation of the various scenarios involving work zones. Various software packages are discussed with their capabilities and limitations. CORSIM, the tool used for this project, is then discussed in particular. The reasons for selecting CORSIM, along with the specifics of the package are also discussed. The network configuration, the input variables and the factors that affect the capacity described next. The chapter concludes with a discussion on factors and sensitivity analysis with a description of the scenarios and the variables.

3.2 Simulator Selection

Simulation modeling cannot replace field data collection; it can, however, offer insights into the relative capacities under different geometric configurations and traffic stream scenarios.

Software packages available for simulating traffic do not capture all the features of the work zones on arterials. It has been found that most of the simulators do not have the capabilities to explicitly model work zones (Ben-Akiva, et al., 2004). Ten (namely: AIMSUN, CORSIM, MITSIMLab., VISSIM, Paramics, WATSIM, Cube Dynasim, DRACULA, INTEGRATION, Transmodeler) of the available simulators were studied by Ben-Akiva, et al. (2004) and their capabilities were assessed. The comparison is summarized below.

AIMSUN captures the effects of lane shifts, lane width reductions and reduced shoulder width through the link characteristics, which affects the car-following model and acceleration behavior. VISSIM also deals with these issues explicitly but the vehicular speeds are typically very low while they move through arterial work zones in congested conditions making speed related issues irrelevant.

MITSIMLab, Paramics, and WATSIM modify the link characteristics to change the free flow speeds. This can be done in CORSIM as well. Most of the simulators, including CORSIM can simulate weather conditions via proxy variables. Parameters that affect visibility and surface quality may be changed, which then affect acceleration and lane changing behavior. For the purpose of this project, weather characteristics that affect drivers have not been considered because of the time limitations.

Maximum and desired speeds mostly affect the acceleration of drivers in uncongested conditions and have much less impact on accelerations in congested conditions and on lane changing behaviors. (Ben-Akiva et al., 2004) Most of the simulators can model various vehicle types.

Ben-Akiva et al., 2003 surveyed (for comparison of their capabilities simulating work zones) AIMSUN, ARTEMIS, CORSIM, Cube Dynasim, DRACULA, INTEGRATION, MITSIM, Paramics, SimTraffic, TransModeler, VISSIM and WATSim. None of the surveyed simulators explicitly model work zones. Ten of the above simulators capture work zone effects by modeling it as a pre-defined incident. However, this approach does not necessarily capture all the effects of work zones.

The software package CORSIM was selected for simulating work zones on arterials for several reasons. First, the software, originally developed by FHWA, has been widely used and validated in the past twenty years. Second, this software is available to the University of Florida through McTrans, allowing for a high level of software support in understanding the software's algorithms. Third, CORSIM includes most of the features that are available with other simulation software at present. Some of the factors that are not available in CORSIM are not actually required for arterial work zones as indicated in the last section.

The literature suggests 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 vehicles did not behave in this manner 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, but the version used in this project is *CORSIM* version 5.1 release (McTrans, 2007).

This concludes the general discussion about all the simulation software packages and their comparison. The following section will discuss the specifics to work zone setup using CORSIM.

3.3 Modeling of Work Zones with CORSIM

CORSIM does not have specific parameters for modeling work zones on arterials. The software program does not consider merging operations within arterials, nor does it consider the effect of the presence of workers and equipment. Vehicle type is not considered as a variable because, even when CORSIM has capability to model heavy vehicles, it does not handle them properly. The way heavy vehicles move in the CORSIM simulations is not satisfactory. It would be better to let the model users to convert the heavy vehicles into passenger cars using standard guidelines and then use that as input for the models. The results will therefore be given in passenger vehicle units. Other software packages available at the TRC (such as AIMSUN), also do not model work zones on arterials. The next closest alternative evaluated was to insert a link with one or more lanes lesser than the upstream and downstream links, whose length would be equal to the work-zone length. Figure 3-1 shows a CORSIM animation snapshot with this type of configuration. As shown, the left (median) lane of the simulated work zone link is closed.

Approaching this simulated work zone (or lane drop), vehicles in CORSIM shift laterally, rather than merge, when the lane on which they are traveling is dropped. Without comparing the results with field data, it is impossible to say what effect this has on the performance of the network and the capacity of the work zone.

Similarly, it is not possible to simulate work zones that lie in the middle lane of 3 or 4 lane highways. If number of lanes in the dummy link that consists of the work zone is reduced then the rest of the lanes would appear together. There is no way to separate them without making two separate links with one lane each. This changes the way drivers would behave as compared to the field conditions, it is therefore expected to result in different values as opposed to the field conditions.

In conclusion, it is possible to replicate the presence of an arterial work zone in CORSIM for all the cases. The effect of the factors that were not included in the simulations is not known. If the left out variables are not very significant then the accuracy of the results would be better. This cannot be predicted without comparing the results with the field data.

3.4 Study Scenarios and Modeling Assumptions

This section will present general outline of the network that was set up in CORSIM to simulate all the work zones for this project.

3.4.1 Network Configuration

There is slight difference in each of the scenario but the basic outline remains same. The network (Figure 3-1) has work zone set up between the nodes 2 and 3. These nodes are dummy nodes.

The dummy nodes are set up 300 ft apart in the above network making work zone 300 ft in length. In this case, the link (2, 3) has only 1 lane while others have more lanes (Figure 3-2). The arterial has two lanes in normal working conditions; so link (10, 2) has 2 lanes. There is a turn pocket at the intersection resulting in three lanes in the link (3, 4). The nodes 8001 through 8004 represent virtual nodes for introducing and taking vehicles off the network. All the other links have 2 lanes which remain unaltered in other scenarios as it does not impact the results (except for links (4, 104) and (104, 8002) as these form receiving approach for the thorough traffic and should therefore accommodate the number of lanes in the approach containing work zone).

3.4.2 Input Variables

There may be various scenarios that can affect the capacity of the work zone. This section discusses the variables that were obtained from the literature. Since none of the literature surveyed explicitly pointed any variable to be either more or less effective, a comprehensive list of such variables was first made and then the suitable ones were selected from that list.

3.5 Factors That Affect Arterial Work Zone Capacity

This section presents the factors that have been found to affect the capacity of a work zone on freeways, along with the corresponding reference source. Some of the factors that cannot possibly affect the arterial work zone capacity have been skipped. These factors are grouped in four categories as given in Table 3-1.

3.6 Discussion on Factors

Given the constraints in obtaining field data, it is not always possible to obtain information for the entire range of possible scenarios that may occur. Simulation (or a combination of simulation and field data collection) can be used to address all factors that may impact the capacity and operational performance of an arterial work zone. These factors and the number of scenarios that should be considered while simulating work zones or collecting data are discussed below:

Signal control: The most important variable is the g/C (effective green to cycle length) ratio for the study approach. Whether the signal is pretimed or not does not matter as this research assumes the demand exceeds capacity of the work zone and in such a situation, actuated signals act as pretimed too. Pedestrian phases may also be evaluated. Three to four scenarios with varying g/C should be considered. The g/C ratios should also be varied for the protected left turn phase if it is present.

Work zone distances to adjacent intersections: Preliminary simulation experiments showed that the distance of the downstream intersection from the end of the work zone affects operational quality of the link. This happens because vehicles are often blocked in the work zone and cannot reach their target lane to take advantage of the green at downstream intersection. It is important to obtain data related with work zones with varying distances to the downstream intersection, and different locations of the work zone in the link. At least 4 to 5 scenarios can be modeled using CORSIM. This variable will be discussed later in the text along with the approach used for this project. It may be noted now that this factor turns out to be very significant among all the factors that are considered.

Presence of workers/equipment: The presence of workers and equipment is likely to affect traffic stream. Two scenarios should be analyzed: one without workers present and one with workers present. Because, this can only be observed in the field, this variable is not considered in this study and should be studied if field data becomes available.

Geometric factors: The impact of the terrain and the grade of the approach should be considered. Two to three scenarios with varying upgrades, in addition to one with level terrain, should be measured. This cannot be simulated with CORSIM and is important for field data collection only. The presence of turning pockets also eases out the congestion. This factor should also be considered with simulation as well as field data collection.

Driveway presence: The presence of a driveway within the work zone may impact operations mainly due to confusion or congestion within the work zone. While the confusion may sometimes be created because drivers fail to notice a driveway (either because of improper signs or because of visual distractions at the work zone site) may cause the capacity to go down.

Additional considerations: Factors such as signal coordination and the particular lane to be closed relative to the downstream movements' demand is likely to have an impact on the operation of work zone. Another factor that may impact operations is the presence of bicycles and bicycle facilities. These factors may be investigated if data is collected since they cannot be simulated.

Some of the factors were found to be infeasible with regards to simulation package being used (CORSIM). Hence, they were not included in the initial list of the factors to be considered for the pilot runs. All the factors discussed thus far are listed in Table 3-2. Heavy vehicles are not adequately dealt with by CORSIM, so they were not included in the simulation runs. Instead the capacity will simply be given out in terms of equivalent passenger vehicles. Similarly, other factors that could not be simulated are also presented in the table.

Sensitivity analysis on some of the above factors was conducted to see if they affect the capacity. This will be discussed in detail in the next section.

3.7 Sensitivity Analysis

Some of the factors that could be simulated were checked in terms of their impact on the capacity of the work zone. A base scenario was considered for this analysis. The Base scenario had two lanes in the approach with a left-only lane. Other features of the base scenario had default values which can be assumed to have the values mentioned here unless specified otherwise. The default value for length of the work zone is 300 ft. The distance from the downstream end of the work zone to the downstream intersection was taken to be 300 ft as well. The lateral position of work zone is the right lane. No driveways are present in the work zone. The posted speed limit is 25 mph. A sensitivity analysis was conducted only on those factors that were expected to have similar effects on the capacity as observed with the base scenario mentioned above. Depending on the results of the analysis, they were either included or excluded as variants in the proposed models. Each result is an average of five runs, which is the sample size for the study.

3.7.1 Length of Work Zone

The length of work zone was varied from 100 ft through 1000 ft in steps of 100 ft and the capacity of that scenario was found. Other factors were kept constant. Table 3-3 shows that the change in the length does not have any significant effect on the work zone capacity. Figure 3-3 shows that the effect is neither significant nor consistently increasing or decreasing. Because the length of the work zone was found not to have significant effect on the capacity, it was excluded from consideration. It may be noted that since work zone effects the capacity due to the additional lane changing at the start and end of the work zone area. Irrespective of the length (assuming it to be a minimum of 100 ft) this phenomenon remains the same. There is no reason to expect different results in other scenarios, so this factor can be excluded.

3.7.2 Work Zone Lateral Position

Work zones can be positioned at any of the lanes on the arterial. If one lane is closed on a two-lane arterial then it can either lie on the left lane or right lane. Those two configurations were simulated to determine whether the position of work zone has any effect on the capacity of the arterial. An average of 5 runs each, were conducted on several different work zone configurations. The results suggest that the position does not affect the capacity in the simulation. The vehicles change lanes to their destination lane with almost the same efficiency regardless of the position of the work zone. The capacity does not change significantly in this case, making it unnecessary to vary the position of the work zone for different scenarios.(Table 3-4)

3.7.3 Driveway Presence

Sometimes, there is a driveway in the middle of the work zone. This driveway may not be very easily seen because of equipment presence, improper signs, or drivers' inattentiveness. The presence of such a driveway may affect the capacity of the work zone. To determine whether any such effect is observable by CORSIM, the capacity of the work zone with a driveway was compared with the one without a driveway. The percentage of volume going into the driveway was also evaluated to determine whether it had an effect on the capacity.

As can be seen in Figure 3-4, the change in the capacity is not large and the effect is also not very uniform. Hence, it was concluded that the variable does not have significant effect on the capacity (Table 3-5). Since CORSIM does not handle vehicle turning in detail, it does not make a smooth transition in the speed of a vehicle while it makes a turn. First, vehicles do not slow down to make a turn in CORSIM. If a vehicle finds a gap then it makes a turn without stopping or slowing down, which is not realistic. Second, if the speed limit is different on the arterial and the destination street, then CORSIM instantly switches the speed of the vehicle without making a transition in the speed. Moreover, in case of driveways, the drivers in the major roadway do not yield to the drivers in the driveway which lessens the impact of the driveway. Therefore, this variable is not properly represented. Driveways were dropped out of the list of the variables to be considered. Based on the above discussion, it can be concluded that even multiple driveways would yield similar results when simulated in CORSIM. Therefore, multiple driveways were not considered.

3.7.4 Posted Speed Limit

Speeds of vehicles plying through the work zone may affect its capacity but the posted speed may or may not affect the same because at the intersection and in congested situation, the actual speeds are already very low. A sensitivity analysis was conducted to determine whether the posted speed affects the capacity. As it can be seen from Table 3-6, the speed limit increases the capacity slightly, but the increase is not significant and is not steady. Further, it can be seen in the simulation runs that the actual speed of the vehicles is very less as opposed to the posted speed. This makes the speed limit irrelevant for any scenario. For this reason the factor was excluded from the analysis.

Table 3-7 summarizes the results from the sensitivity analysis done in the last few segments. The results are given in the last column and the values which were tested are given in the middle column. Table 3-8 shows the changes in the network properties that were done so that the simulation properly replicates the observed traffic on the field. With these settings, the traffic produces much more realistic flows. The changes made are summarized in the table along with the effect that they produce.

The following sections will discuss the approaches planned for the simulation scenarios and the values of the factors that were used to finally simulate the work zone.

3.8 Simulation Scenarios

This section presents the scheme that was followed while developing the simulation scenarios for the study. The final scheme used for the project was arrived at after some alterations in the scheme that the project was started off with. The earlier approach to this project was that arterials with different number of lanes would be considered separately, i.e. there were separate scenarios for 2, 3 and 4 lane arterials. This approach did not deal properly with the turning pockets and the various possible channelization schemes. It was also noticed that there was a good relation between the distance of the work zone to the downstream intersection, available green time and the capacity. The distance between the work zone and intersection acted as storage for the vehicles queued up prior to the intersection. This relation was the reason for the change in the models and also the way simulations were conducted.

Secondly, the new approach also looks properly at the turning volumes of each lane group along with the capacity of the whole approach. It would result in better models and allow for better analysis of the situation. Lastly, it was realized that turning pockets cannot be tested for their impact on the basis of any single scenario. They may be important in one scenario and may not play a crucial role in affecting the capacity in other. So it is not possible to conduct a sensitivity analysis on them and claim either of the above for all the other cases. They had to be included in the simulation scenarios as variable. This would increase the number of cases and the difficulty in understanding them as well with the earlier approach. The new approach also allows for fewer models for all the cases and is easy to implement for the officials.

Scenarios were categorized on the basis of number of lanes at the intersection which include turn pockets along with normal lanes. Each scenario has different possible lane channelization schemes which are given in Figure 3-5. These channelization schemes are representative of most common configurations found in the U.S. The scenarios vary in terms of the geometry at the work zone. The total number of lanes in a normally working arterial may vary for the same number of lanes at an intersection. For example, if there are 3 lanes at intersection, then the arterial may have 2 lanes and the third may be a turn pocket. The arterial may have 3 lanes and hence there is no turn pocket. Further, in case of 3 lanes in the arterial, there are 2 possibilities: 1 lane open for traffic in the work zone or 2 lanes open for traffic in the work zone. All the possibilities considered in this study are listed in Table 3-9.

They were all simulated to obtain the capacity with regards to all the other variables which are listed in Table 3-10.

All of the combinations of the above variables were tried except for some of the specific combinations which were not reasonable. These are listed in Table 3-11

3.9 Required Number of Simulation Runs

The required number of simulation runs for each scenario was estimated using Equation 3.1.

$$n = \sqrt{\frac{sd \times z}{\varepsilon}} \qquad \text{(Equation 3.1)}$$

where
n = Sample Size
sd = Standard Deviation
ε = Error Tolerance

A network with two lanes in each direction was simulated 100 times to find the standard deviation in the capacity of the approach. Then the z-test was used at a confidence level of 95% with error tolerance of 100 veh/hr for the entire approach to find the sample size. The calculations are shown in Table 3-12.

The base case scenario consists of the same simulation files as in other scenarios but without the work zone. This means that for the same values of factors such as the number of open lanes in the work zone, g/C ratios etc.; the arterial is simulated without any work zone. The results of these scenarios will be used to compare the capacity of the work zone in normal conditions with its capacity after setting up a work zone. These comparisons can also be used to better analyze the effect of a particular factor on the extent to which it affects the normal capacity. They may later be used for purposes of modeling and charting. This will be discussed more in the text later. The next section outlines the outputs that are obtained from the simulations.

3.10 Output from Simulations

All the simulations produce 15-minute throughput for traffic that travels along the arterial past the intersection, by each lane. These represent the maximum flow rates that can travel through each lane group under the prevailing conditions. Given that there is demand starvation at the intersection due to the presence of the work zone, these maximum flows are technically not the capacity of each lane group. However, considering the system of the work zone and the intersection, the capacity of the system is the sum of these maximum flows. These definitions are used for the remainder of this thesis. “Work zone capacity” or just capacity indicates the capacity of the system, while maximum flows mean the maximum throughput that can pass through intersection from a particular lane group.

3.11 Summary

Various simulators are available for arterial simulation but none of them explicitly serve the purpose of this project. They do not take into consideration all the factors that may impact driver behavior and the way traffic moves through a work zone. CORSIM was found to be easier to work with given the available support for the software and researcher’s familiarity with it.

Some of the scenarios were developed based on the factors that were expected to impact the capacity. Minimal research has so far been done on the analysis of capacity through arterial work zone leaving only a tentative list of variables to be developed. It was not possible to simulate all of the variables because of the limitations of the software package being used. Other factors were removed from the list because the analysis showed that they do not affect the capacity in a significant manner. Then, a scheme was developed to properly accommodate the variation of all the factors with each other. Once completed, the sample size for the experiment was found out. The variation of the individual lane group flow that goes out of the arterial at the downstream intersection is expected to depend on different factors. The left-turning flow will depend more on the left-turning percentage in the traffic stream and on the green time of the left-turning phase but is expected to depend less on the percentage of vehicles turning right. On the other hand, Th/Rt flow will not depend much on the left-turning percentage. So these flows (left-turning and through right going) were also set as outputs along with the approach capacity. The list of the variables used for the simulation is preliminary and does not imply that the excluded variables do not impact the capacity. For example, the weather effects cannot be simulated in CORSIM properly without calibration. Further analysis of the results will reveal the correlation between the factors considered and the capacity. The next chapter summarizes the data from the simulation and presents the models developed from the outputs of the simulation runs.

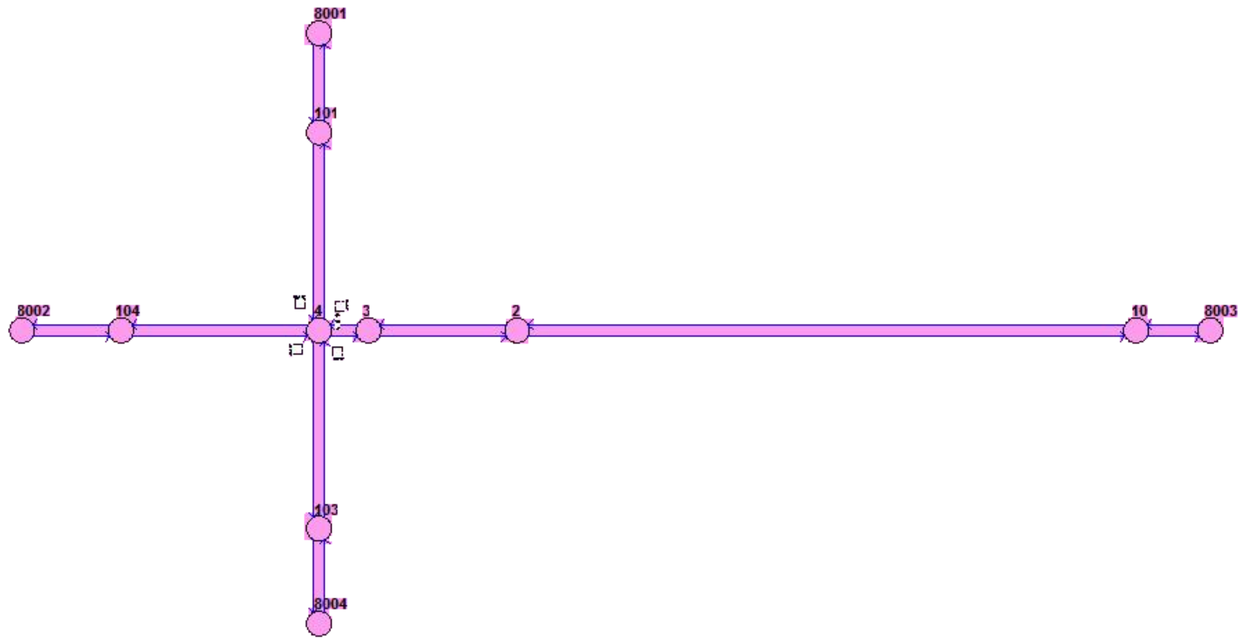

Figure 3-1: Network Configuration in CORSIM

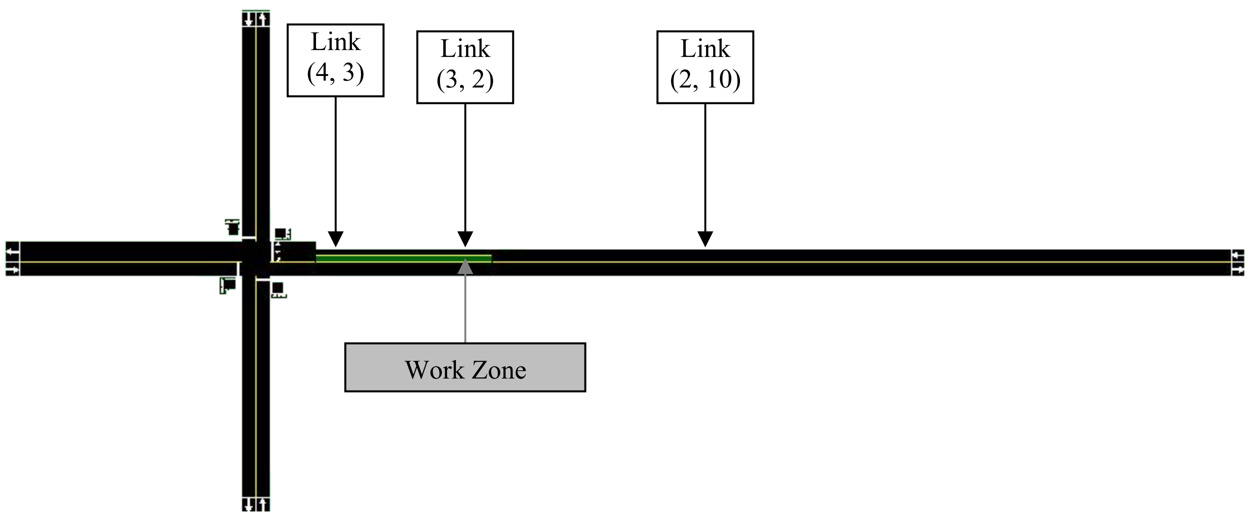

Figure 3-2: Network Map Showing Link Numbers

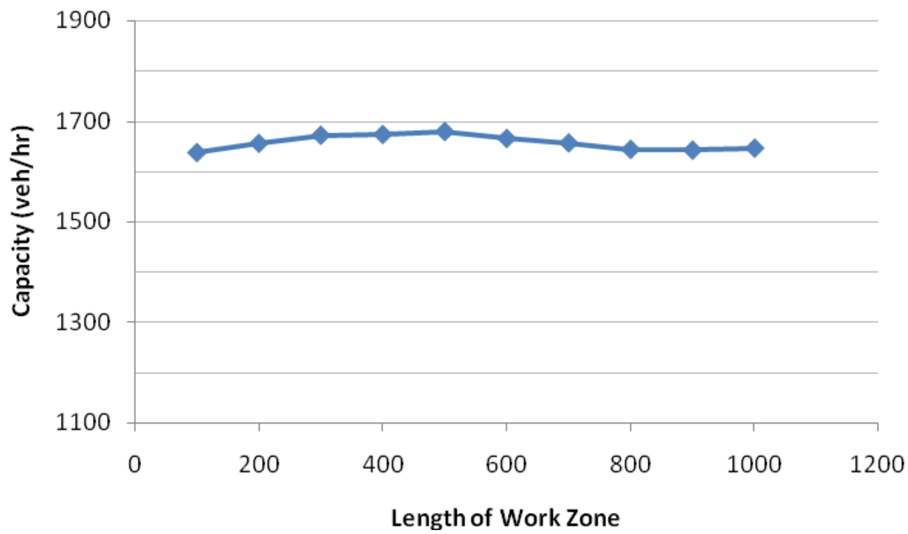

Figure 3-3: Work Zone Length Sensitivity

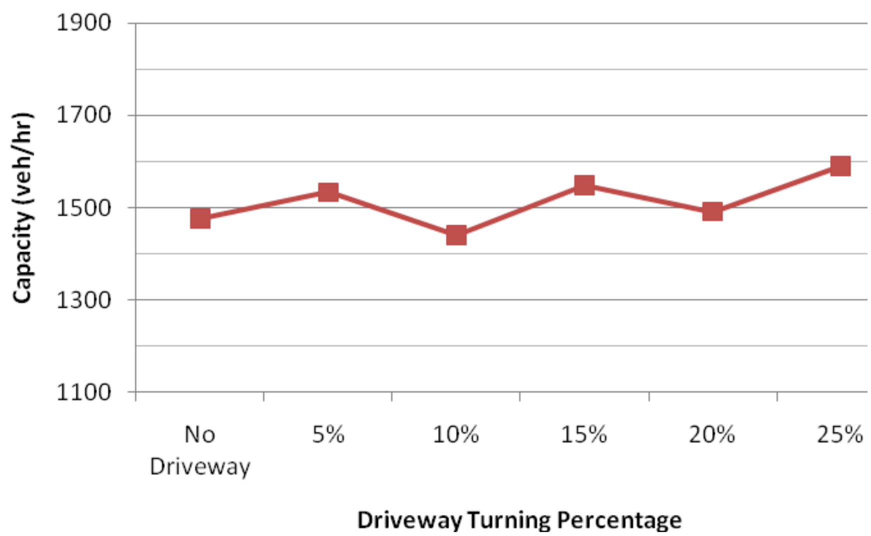

Figure 3-4: Driveway Flow vs. Capacity

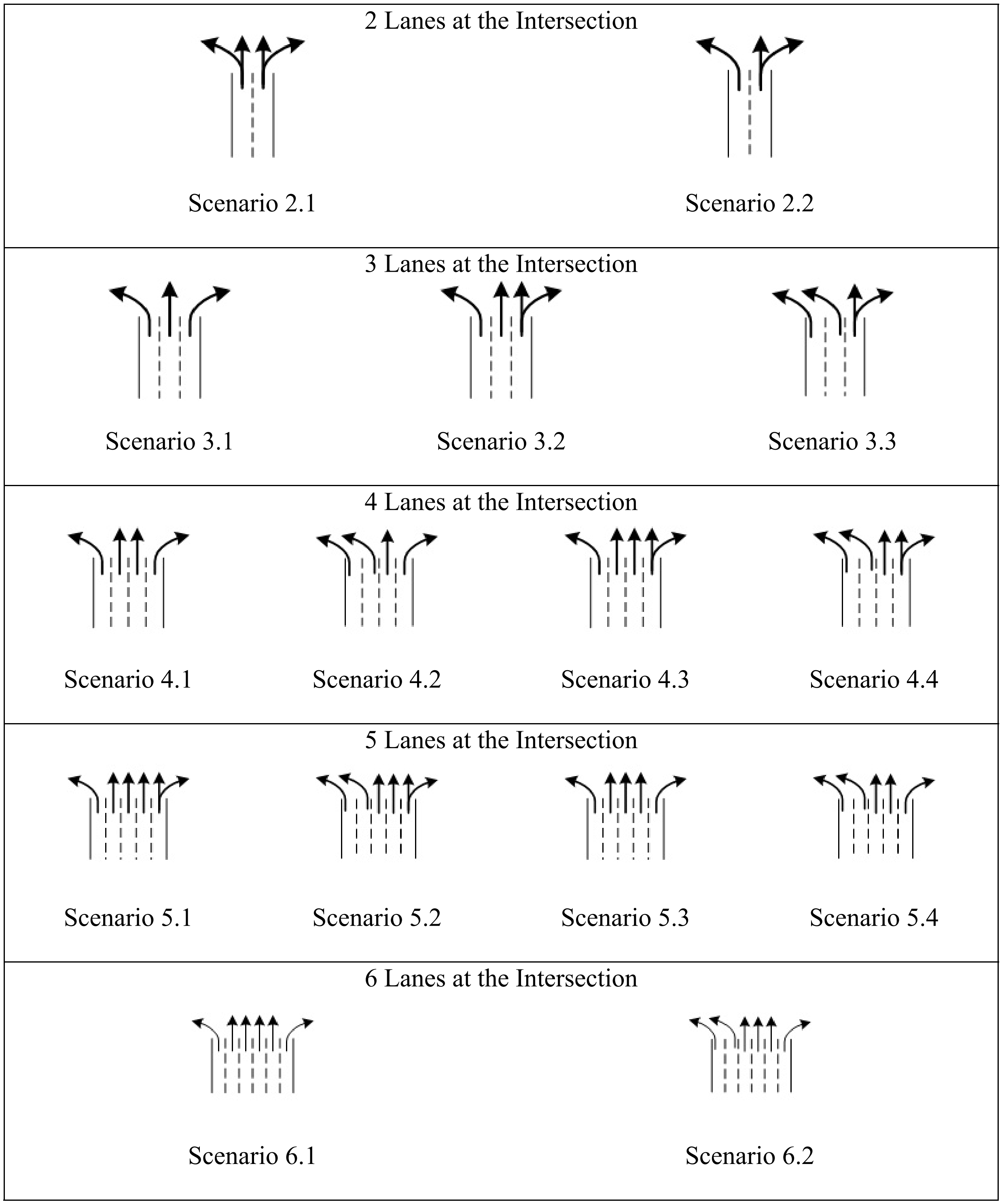

Figure 3-5: Lane Channelization Schemes for All Scenarios

Table 3-1: Grouped Factors Affecting Work Zone Capacity

Work Zone Factors:
Length of the work zone (ft) (Kim et al. , 2001)
Work zone sign distance upstream of the work zone (ft) (Arguea, 2006)
Work intensity (presence of equipment and workers) (HCM, 2000)
Police presence
Configuration of the work zone, including channelization of traffic (Arguea, 2006)
Geometric Data:
Terrain or grade of each approach (%) (Kim et al. , 2001)
Lane widths upstream, within, and downstream of the work zone (ft) (HCM, 2000 and FDOT PPM 2000)
Lateral clearance upstream, within, and downstream of the work zone (ft) (FDOT PPM, 2000)
Traffic Stream Data:
Volumes by lane for various times of day (am and pm peak periods), focusing on congested conditions (Arguea, 2006)
Percent heavy vehicles (HCM, 2000)
Other Environment-Related Factors:
Light conditions (daytime or nighttime with illumination)
Rain (no rain, light to moderate rain or heavy rain)

Table 3-2: Factors Affecting 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
Position of the Work Zone (Lane Closed)	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
Percentage of Heavy Vehicles	No
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

Table 3-3: Work Zone Length Sensitivity

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

Table 3-4: Work Zone Position Sensitivity

Position of Work Zone	Capacity (veh/hr)
Right lane	1667
Left lane	1697

Table 3-5: Driveway Sensitivity Analysis

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

Table 3-6: Posted Speed Limit Sensitivity

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

Table 3-7: Sensitivity Analysis

Factor	Values Tested	Included in Experimental Design?
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	0.1, 0.3, 0.5 (Left) 0.3, 0.5, 0.7 (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

Table 3-8: Changes in Network Properties

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.

Table 3-9: Geometric Variations

Total Lanes on arterial	Open lanes at Work Zone
2	1 Open (and 1 Closed)
3	1 Open (and 2 Closed) OR 2 Open (and 1 Closed)
4	2 Open (and 2 Closed) OR 3 Open (and 1 Closed)

Table 3-10: Variables in Simulation

Variable	Values
Distance of Downstream Intersection from end of the Work-Zone	100, 250, 500, 750, 1000 ft
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 Volume	10%, 25%, 40%
right-turning Volume	10%, 25%, 40%

Table 3-11: Constraints for Variables

Number	Constraints
1	0.7 g/C for Th/Rt phase only with 0.1 g/C for Left-turning phase
2	No double lefts with 0.1 g/C for Left-turning phase
3	0.5 g/C for Left-turning phase only with 0.3 Th/Rt phase
4	10% Left-turning percentage with only 0.1 and 0.3 g/C
5	40% Left-turning percentage with only 0.3 and 0.5 g/C
6	40% right-turning percentage with only 0.5 and 0.7 g/C

Table 3-12: Sample Size Calculations

Standard Deviation	098
z (95%)	001.96
ε (Error Tolerance)	100
n (Sample Size)	004

CHAPTER 4
CAPACITY MODEL DEVELOPMENT

4.1 Introduction

This chapter presents all the simulation scenarios in a combined fashion. First, the data from the simulation were analyzed to identify the cases exhibiting capacity increase followed by summary on the same. Mathematical relationships between various factors and the capacity of the arterial are presented next. The relationships between these factors and the flow getting through each lane group (Left-turning vehicles and Th/Rt turning vehicles) is also provided.

4.2 Simulation Results for Cases When a Work Zone is Present

Summary of the capacity values and maximum flow for the simulated work zone scenarios are presented in Table 4-1 through Table 4-3 tabulated by the total number of lanes at the intersection, the number of closed lanes, and the through movement g/C ratio. The g/C ratio and the number of lanes at downstream intersection were shown to have the largest effect on the work zone capacity.Table 4-1 presents the total capacity of the work zone in vehicles per hour, while Table 4-2 and Table 4-3 present the through/right-turning movement and the left-turning movement maximum flows respectively, in vehicles per hour per lane. The minimum and maximum values in these tables represent the lowest and highest values of capacity/flow 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 channelization schemes, with the total number of lanes at the intersection shown in the left most column. The number of open and closed lanes refers to the work zone upstream of the intersection. Table 4-1 indicates that 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 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 (i.e. segment of link stretching from the end of the work zone to the downstream intersection) 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 4-2 tabulates the maximum flow of the through/right movement per lane, which generally increases as a function of the respective g/C ratio. Per lane throughput is not affected much 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 4-3 presents the same information for the left turn movement. The g/C ratio for the left turn generally increases the movement's maximum flow, 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.

Appendix A describes the aggregate level trends of the capacity and individual lane group flow with respect to each variable step by step. These trends do not necessarily give an idea of how each factor may impact the capacity after controlling for others but the analysis provides insight into the effects of these variables.

4.3 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 Table 4-4 through Table 4-6. Table 4-4 presents the total capacity of the work zone in vehicles per hour, while Table 4-5 and Table 4-6 present the through/right-turning movement and the left-turning movement maximum flows 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 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 4-3, the 4, 5, and 6 lane scenarios include cases with dual left turns, and it is 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.

4.4 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. Table 4-7 through Table 4-9 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 highest decrease in capacity, the scenario that had the lowest decrease in capacity, 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 spillback 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 thepresence of a work zone results in a capacity increase, because it funnels (since there are lesser lanes in the work zone, it acts as a funnel) traffic through the work zone, and it becomes easier for vehicles to change lanes and reach their destination lane without being blocked. For example, on a three lane arterial, if two lanes are closed then the vehicles would find it very easy to reach their destination lane when they exit the work zone. They would not have to look for gaps as adjacent lanes would be empty. As said above, if adequate green is not allotted for each turning movement (which is the case in some scenarios) then the vehicles from that movement may block other traffic, but with the installation of a work zone, it becomes easier for vehicles to reach their destination lanes and hence the blocking effect is minimized. This increase was observed mostly for scenarios with 3 to 6 lanes at the intersection approach.

As Table 4-7 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 causing 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 4-8, which shows the change in maximum flow for through and right turns, the highest capacity drop is 39%, and the maximum increase was 376%, both for two lanes at the intersection approach. The 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 4-9 presents the change in the maximum left turn movement flow. The highest 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.

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.

4.5 Capacity Models

This section presents the capacity models for the 3.0 case through 6.0 cases first (i.e., the arterials with 3, 4, 5 and 6 lanes at intersection) (Figure 3-5). The models are all significant at the 99.9% confidence level. There are some other variables that were significant at the 90% confidence level but the R^2 value did not improve much by including them. The models developed are grouped into 3 sections. The first three models of the five apply to arterials with 3 through 6 lanes at the intersection including the turning pockets. The fourth and fifth models apply to arterials with two lanes at the intersection. These arterials will have one open and one closed lane through the work zone. The fourth model is applicable to those scenarios which have only one phase for both lanes. The fifth model applies to scenarios with a separate left turn phase. The two cases are considered separately for two reasons; the variables for Case 2.1 (Figure 3-5) are different than the rest of the cases because there is only one phase for the arterial. Another reason to separate the models was better accuracy of the models. When a unified model was developed for all the cases, its adjusted R^2 was very small and hence arterials with more than 2 lanes at the intersection were considered separately.

In Case 2, it was noticed that the capacity of the individual lane groups depend on the position of the work zone. So a model for the specific flows would not have good accuracy as position of work zone was not varied among various scenarios. It is for this reason that only total capacity models are given for Case 2. It may be noted that the total capacity of the arterial does not get affected by the lateral position (i.e. right or left) in any of the cases.

Since, the lateral position of work zone does not affect the individual lane group flows in all the other cases (except Case 2), separate lane group flow models are developed for the rest of the cases.

The next section presents the models for arterials with 3 through 6 lanes at the intersection along with the adjusted R^2 for the models. The adjusted R^2 statistic gives the probability of correct prediction of capacity from the model. Along with each coefficient, its standard error in prediction and t-statistic is also reported.

4.5.1 Models for 3 through 6 lanes at Downstream Intersection

This section presents the models that are applicable to arterials with 3 through 6 lanes at the downstream intersection to the work zone. There are three models which can be used to predict the maximum left-turning flow expected to pass through the intersection, the sum of the maximum of the throught as well as right-turning traffic and the capacity for the arterial.

4.5.1.1 Maximum Left-turning Flow

Table 4-10 gives the statistical details of the model, it can be written in equation form as in equation 4.1.

$$MLTF = -337.1 + (41.9 \times TTR) + (803.3 \times LTF) + (207.9 \times g/C_{TTR}) + (145.6 \times N_o/N_t) + (1262.1 \times LT \times LTF \times g/C_{LT}) + (0.1 \times L) \qquad \text{(Equation 4.1)}$$

where

MLTF : Maximum Left-turning Flow.

TTR: Sum of Th, Th/Rt and Rt Lanes.

LTF: Fraction of vehicles turning left at the intersection.

$(g/C)_{TTR}$: Green to Cycle time Ratio of the Th, Th/Rt and Rt Lanes.

N_o/N_t : Number of open lanes/ Total Number of Lanes.

LT : Number of Left-only Lanes.

$(g/C)_{LT}$: Left-turning Phase Green to Cycle time Ratio.

L: Length of the segment stretching from the end of the work zone till the downstream intersection.

All three models for cases 3.0 through 6.0 use the same set of factors (there is one additional factor in the capacity model). The through and right lane group has a positive impact on the capacity. Capacity goes up if the left-turning percentage goes up. It also increases with the ratio of (number of open lanes/total number of lanes on the arterial), Th/Rt phase g/C ratio, distance of the end of the work zone to the downstream intersection and left-only lanes.

4.5.1.2 Maximum Through and Right Flow

The model (Table 4-11) can be written as given in Equation 4.2.

$$MTRF = -629.4 + (359.2 \times TTR) - (2535.6 \times LTF) + (2168.2 \times g/C_{TTR}) + (602.2 \times N_o/N_t) + (1773.6 \times LT \times LTF \times g/C_{LT}) + (0.3 \times L) \quad \text{(Equation 4.2)}$$

where

MTRF: Maximum Through and Right Flow.

TTR: Sum of Th, Th/Rt and Rt Lanes.

LTF: Fraction of vehicles turning left at the intersection.

$(g/C)_{TTR}$: Green to Cycle time Ratio of the Th, Th/Rt and Rt Lanes.

N_o/N_t : Number of open lanes/ Total Number of Lanes.

LT : Number of Left-only Lanes.

$(g/C)_{LT}$: Left-turning phase Green to Cycle time Ratio.

L: Length of the segment stretching from the end of the work zone till the downstream intersection.

Through and right flow increases with increase in the through and right lanes, Th/Rt lane group g/C ratio as well as distance from the end of the work zone to the downstream intersection, left-only lanes and the left phase g/C ratio. The flow goes down with increase in the left-turning percentage.

4.5.1.3 Arterial Capacity

Statistical details of the model are given in Table 4-12. It can be written as in equation 4.3.

$$Cap = -947 + (422.4 \times TTR) - (1751.45 \times LTF) + (2378.5 \times g/C_{TTR}) + (755.4 \times N_o/N_t) + (3078 \times LT \times LTF \times g/C_{LT}) + (0.4 \times L) - (168.6 \times RT) \quad \text{(Equation 4.3)}$$

where

Cap : Capacity of the arterial (veh/hr)

TTR: Sum of Th, Th/Rt and Rt Lanes.

LTF: Fraction of vehicles turning left at the intersection.

$(g/C)_{TTR}$: Green to Cycle time Ratio of the Th, Th/Rt and Rt Lanes.

N_o/N_t : Number of open lanes/ Total Number of Lanes.

LT : Number of Left-only Lanes.

RT: Number of Right-only Lanes.

$(g/C)_{LT}$: Left-turning Phase Green to Cycle time Ratio.

L: Length of the segment stretching from the end of the work zone till the downstream intersection.

This model has one additional factor compared to the previous two models: right-only lanes, which has a negative impact on capacity. The increase in the through and right lanes increases the capacity while the left-turning percentage leads to a reduction in capacity. Capacity also increases with the Th/Rt phase g/C, *Number of open lanes/Total number of lanes*, left-only lanes and left phase g/C and the distance of the downstream intersection from the end of the work zone.

4.5.2 Models for arterials with 2 lanes at the Downstream Intersection

This section presents the models that can be used to predict the capacity for the arterials with 2 lanes at the intersection.

4.5.2.1 Capacity for 2-lane arterial with single phase (Case 2.1)

This model (Table 4-13) applies to those arterials which have one lane open through the work zone and a total of two lanes at the intersection without any turning pockets. Furthermore, the intersection downstream has one phase for the entire approach. It can be written as in equation 4.4.

$$Cap = 443.36 + (1685.78 \times g/C) + (0.21 \times L) \qquad \text{(Equation 4.4)}$$

where

Cap : Capacity of approach

g/C: Green to Cycle time ratio for the entire arterial

L: Length of the segment stretching from the end of the work zone till the downstream intersection.

This model has only two variables, it can be deduced from the coeffiecients that the capacity increases with the increases in g/C ratio predominantly and with the distance from the end of the work zone to the downstream intersection as well.

4.5.2.2 Capacity for 2-lane arterial with left turn phase (Case 2.2)

This model (Table 4-14) is applicable to arterials which have one lane open through the work zone and have a total of two lanes at the intersection without any turning pockets. In this case, the intersection should have separate left-turning phase. (Equation 4.5)

$$Cap = 58.68 + (1581.31 \times g/C_{TTR}) + (0.12 \times L) + (521.55 \times g/C_{LT}) \qquad \text{(Equation 4.5)}$$

where

Cap : Capacity of approach
$(g/C)_{TTR}$: Green to Cycle time Ratio of the Th, Th/Rt and Rt Lanes
$(g/C)_{LT}$: Left Phase Green to Cycle time Ratio
L: Length of the segment stretching from the end of the work zone till the downstream intersection.

This model implies that the capacity increases with the length of the section after the work zone till the downstream intersection, with the Th/Rt phase as well. It also increases with the left turn g/C ratio.

Above model is only applicable for a range of the values of each variable present in the models. The range of values for which the model can be used are given in Table 4-15.

4.6 Model Comparison

This section will discuss typical results from the models given in the earlier section. The models cannot be compared with the FDOT or the HCM methods on one to one basis because none of the variables that were considered in these models are common to either of the two.

The HCM model is meant for freeways only and so, comparing it with the models above does not make sense. The FDOT model has a extension for the arterials too. After calculating the capacity of the work zone, the g/C is used to adjust for the effect of the intersection. Calculations below give a typical range of capacity that can be obtained from the FDOT models:

Consider a 2 to 1 lane closure with base capacity of 1800vph. The following two cases can be used to obtain the maximum and the minimum possible obtainable capacities.

Travel Lane Width: 9 ft with no Lateral Clearance. g/C =0.3. This gives Obstruction Factor as 0.65. This yields the Restricted capacity = $(1800 \times 0.65 \times 0.3) = 351$ vph.

Travel Lane Width: 12ft and Lateral Clearance is 6ft, g/C = 0.7. This gives Obstruction Factor as 1.00. This yields the Restricted capacity = $(1800 \times 1.00 \times 0.7) = 1260$ vph.

For 3 to 2 lane closure with 3600 vph base capacity; following cases can be considered:

Travel Lane Width: 9 ft with no Lateral Clearance. g/C =0.3. This gives Obstruction Factor as 0.65. This yields the Restricted capacity = (3600 × 0.65 × 0.3) = 702 vph.

Travel Lane Width: 12ft and Lateral Clearance is 6ft, g/C = 0.7. This gives Obstruction Factor as 1.00. This yields the Restricted capacity = (3600 × 1.00 × 0.7) = 2520 vph.

With the model developed in this thesis, the range of values for the above scenarios can be found out for the same:

2-1 lane closure: Single phase for the entire arterial, Table 4-16 presents the results for case 2.1. For Case 2.2, the range is given in Table 4-17.

. So, for 2 to 1 lane closure, the capacity range is 598 to 1831 vph. 3-2 lane closure can be estimated by the model for capacity of 3 through 6 lanes at intersection given in .

The FDOT model for 2-1 lane closure under-estimates the capacity as compared to the estimated models. 3-2 model over estimates the maximum capacity of the work zone.

4.7 Sensitivity Analysis

This section evaluates the sensitivity of each variable used in the models with respect to the capacity/flows. It is useful to understand how change in each variable affects the capacity. Table 4-19 through Table 4-23 provide the results from this analysis. Each of these tables presents the sensitivity and results for each of the variables presented earlier. The "Initial Value" column under "Factor" determine the "Initial Cap". The "Final Value" column under "Factor" is used to find the "Final Cap" values. The "% Change" columns report the change in the values of capacity/flow and factor as a percentage of the intial values.

As can be seen from Table 4-19 the left-turning fraction results in the largest change in the maximum left-turning flow. The next most important factor is the number of the through, Th/Rt and right-only lanes, which has a positive impact on maximum flow.

The number of through, Th/Rt and right lanes, followed by the g/C for these lanes, are the factors affecting the Th/Rt maximum flow (Table 4-20) the most.

The sum of through, Th/Rt and right-only lanes greatly affects the capacity (Table 4-21) with a change of 69% when the factor is doubled. This is followed by the g/C ratio for the same group of lanes.

Some of the values in the "Percent Change" column under flow are negative. These signify that increasing those factors would reduce the maximum flow or capacity. Increasing the left turn fraction in traffic as well as the number of left-only lanes on the arterial reduces the maximum Th/Rt flow that can pass through the intersection (Table 4-20). This causes a negative change in percentage. Likewise, left turn fraction, number of left-only and right-only lanes on the arterial also have a negative impact on the arterial capacity (Table 4-21).

4.8 Example Problems

This section presents example problems of work zone capacity and lane group flow estimation. Each example illustrates the use of the models shown above.

4.8.1 Example Problem 1

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

- Total number of lanes in the arterial = 3
- Number of lanes closed in the work zone = 1
- Number of Left turn pocket = 1
- No right turn pocket
- Schematic of the Arterial along with the lane channelization at the downstream intersection is given in Figure 4-1:
- Number of through only lanes = 2
- Number of through right lanes = 1
- Number of right-only lanes = 0
- Left-only lanes = 1
- Signal has exclusive left turn phase with following g/C:
    - g/C for Th/Rt phase = 0.4
    - g/C for left turn phase = 0.1
- 15% vehicles turn left at the intersection

- Distance from the end of the work zone to the downstream intersection is 500 ft

Inputs:

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

LTF (Left-turning fraction) = 0.15

$(g/C)_{TTR}$ (Green to Cycle time Ratio of the Th, Th/Rt and Rt 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

L (Length of the section starting from the end of the work zone to the downstream intersection) = 500 ft

Model Application:

(i) The maximum flow through the left-only lane can be estimated with model given in equation 4.1:

$$MLTF = -337.1 + (41.9 \times TTR) + (803.3 \times LTF) + (207.9 \times g/C_{TTR}) + (145.6 \times N_o/N_t) + (1262.1 \times LT \times LTF \times g/C_{LT}) + (0.1 \times L)$$

Substituting the values:

$$MLTF = -337.1 + (41.9 \times \mathbf{3}) + (803.3 \times \mathbf{0.15}) + (207.9 \times \mathbf{0.4}) + (145.6 \times \mathbf{0.67}) + (1262.1 \times \mathbf{1} \times \mathbf{0.15} \times \mathbf{0.1}) + (0.1 \times \mathbf{500})$$

$MLTF = 185$ *veh/hr.*

(ii) The flow passing through the through, through/right and right-only lanes can be estimated with model as in equation 4.2:

$$MTRF = -629.4 + (359.2 \times TTR) - (2535.6 \times LTF) + (2168.2 \times g/C_{TTR}) + (602.2 \times N_o/N_t) + (1773.6 \times LT \times LTF \times g/C_{LT}) + (0.3 \times L)$$

Substituting the above values:

$MTRF = -629.4 + (359.2 \times \mathbf{3}) - (2535.6 \times \mathbf{0.15}) + (2168.2 \times \mathbf{0.4}) + (602.2 \times \mathbf{0.67}) + (1773.6 \times \mathbf{1} \times \mathbf{0.15} \times \mathbf{0.1}) + (0.3 \times \mathbf{500})$

$MTRF = 1504$ *veh/hr.*

(iii) The Capacity of the entire arterial can be calculated using the model given in equation 4.3:

$Cap = -947 + (422.4 \times TTR) - (1751.45 \times LTP) + (2378.5 \times g/C_{TTR}) + (755.4 \times N_o/N_t) + (3078 \times LT \times LTP \times g/C_{LT}) + (0.4 \times L) – (168.6 \times RT)$

Substituting the above values:

$Cap = -947 + (422.4 \times \mathbf{3}) - (1751.45 \times \mathbf{0.15}) + (2378.5 \times 0.4) + (755.4 \times \mathbf{0.67}) + (3078 \times \mathbf{1} \times \mathbf{0.15} \times \mathbf{0.1}) + (0.4 \times \mathbf{500}) – (168.6 \times \mathbf{0})$

$Cap = 1776$ *veh/hr.*

4.8.2 Example Problem 2

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 Left turn pocket
- No right turn pocket
- Schematic of the Arterial along with the lane channelization at the downstream intersection as given in Figure 4-2
- The number of through only lanes = 0
- Number of through right lanes = 1
- Number of right-only lanes = 0
- Left-only lanes = 1
- Signal has exclusive left turn phase with following g/C ratios:
    - g/C ratio for Th/Rt phase = 0.4
    - g/C ratio for left turn phase = 0.1
- 15% vehicles turn left at the intersection
- Distance from the end of the work zone to the downstream intersection is 500 ft

Inputs:

$(g/C)_{TTR}$ (g/C Ratio of the Th, Th/Rt and Rt Lanes) = 0.4

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

L (Length of the section starting from the end of the work zone to the downstream intersection) = 500 ft

Model application:

The capacity can be estimated using model given in equation 4.4:

$$Cap = 58.68 + (1581.31 \times g/C_{TTR}) + (0.12 \times L) + (521.55 \times g/C_{LT})$$

Substituting the values:

$$Cap = 58.68 + (1581.31 \times \mathbf{0.4}) + (0.12 \times \mathbf{500}) + (521.55 \times \mathbf{0.1})$$

$$Cap = 805 \ veh/hr.$$

4.8.3 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 Left turn pocket
- No right turn pocket
- Schematic of the Arterial along with the lane channelization at the downstream intersection as given in Figure 4-3
- The number of through only lanes = 0
- Number of through right lanes = 1
- Number of right-only lanes = 0
- Left-only lanes = 1
- Signal has g/C ratio for entire arterial = 0.5
- Distance 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

L (Length of the section starting from the end of the work zone to the downstream intersection) = 500 ft

Model Application (equation 4.5)

$$Cap = 443.36 + (1685.78 \times g/C) + (0.21 \times L)$$

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

$$Cap = 1390 \ veh/hr.$$

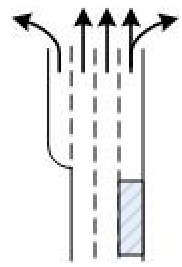

Figure 4-1: Schematic for Example 1

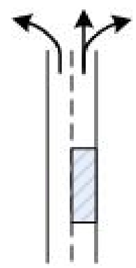

Figure 4-2: Schematic for Example 2

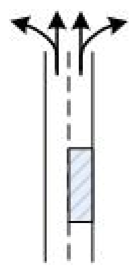

Figure 4-3: Schematic for Example 3

Table 4-1: 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	4128	3233
6	2	2	1243	2854	1880	1373	3994	2364	2545	4981	3251
	3	1	1547	3537	2157	1582	3816	2633	2782	3685	3382

Table 4-2: 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 4-3: 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

Table 4-4: 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 4-5: 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 4-6: 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

Table 4-7: 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

Table 4-8: Change in the Maximum Through/Right Flow 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 4-9: 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

Table 4-10: Maximum Left-turning Flow (MLTF)

	Variable Name	Coefficients	Standard Error	t-stat
1	Constant	-337.057	11.092	30.3
2	Number of Th, Th/Rt and Rt Lanes (TTR)	41.907	1.834	22.8
3	Left-turning Fraction (LTF)	803.356	20.912	38.4
4	Th/Rt Phase g/C Ratio ((g/C)TTR)	207.909	14.492	14.3
5	Number of Open Lanes / Total Number of Lanes (No/Nt)	145.634	11.052	13.1
6	(Left-only Lanes) x (Left-turning %) x (Left Phase g/C) [(LT*LTF*(g/C)LT]	1262.069	27.434	46.0
7	Distance of WZ from intersection (ft)	0.153	0.005	30.6
	adjusted $R^2 = 0.701$			

Table 4-11: Maximum Through and Right-turning Flow (MTRF)

	Variable Name	Coefficients	Standard Error	t-stat
1	Constant	-629.449	27.070	23.2
2	Number of Th, Th/Rt and Rt Lanes (TTR)	359.162	4.476	80.2
3	Left-turning Fraction (LTF)	-2535.577	51.033	49.6
4	Th/Rt Phase g/C Ratio ((g/C)TTR)	2168.250	35.366	61.3
5	Number of Open Lanes / Total Number of Lanes (No/Nt)	602.193	26.971	22.3
6	(Left-only Lanes) x (Left-turning %) x (Left Phase g/C) [(LT*LTF*(g/C)LT]	1773.573	66.950	26.4
7	Distance of WZ from intersection (ft)	0.282	0.012	23.5
	adjusted $R^2 = 0.724$			

Table 4-12: Arterial Capacity (Cap)

	Variable Name	Coefficients	Standard Error	t-stat
1	Constant	-946.955	32.789	28.8
2	Number of Th, Th/Rt and Rt Lanes (TTR)	422.389	5.562	75.9
3	Number of Right-only Lanes	-168.580	9.935	16.9
4	Left-turning Fraction (LTF)	-1751.447	61.788	28.3
5	Th/Rt Phase g/C Ratio ((g/C)TTR)	2378.501	42.812	55.5
6	Number of Open Lanes / Total Number of Lanes (No/Nt)	755.362	32.653	23.1
7	(Left-only Lanes) x (Left-turning %) x (Left Phase g/C) [(LT*LTF*(g/C)LT]	3078.002	81.083	37.9
8	Distance of WZ from intersection (ft)	0.435	0.015	28.8
	adjusted R^2 = 0.640.			

Table 4-13: Capacity for Arterials with Two Lanes and Single Phase

	Variable Name	Coefficients	Standard Error	t-stat
1	Constant	443.364	46.772	9.4
2	Distance of WZ from intersection (ft)	0.208	0.040	5.2
3	g/C Ratio for approach (*g/C)*	1685.778	79.710	21.1
	adjusted R^2 = 0.782			

Table 4-14: Capacity for Arterials with Two Lanes and Separate Left Turn Phase

	Variable Name	Coefficients	Standard Error	t-stat
1	Constant	58.682	73.550	0.7
2	Th/Rt Phase g/C Ratio ((g/C)TTR)	1581.307	119.964	13.1
3	Distance of WZ from intersection (ft)	0.124	0.042	2.9
4	Left Turn g/C Ratio((g/C)LT)	521.551	114.665	4.5
	adjusted R^2 = 0.542			

Table 4-15: Range of Applicable Values

Variable	Values
Distance of Downstream Intersection from end of the Work-Zone	100 to 1000 ft
g/C ratio of Left-turning Phase	0.1 to 0.5
g/C ratio of through and right Phase	0.3 to 0.7
Left-turning Fraction	0.10 to 0.40
Right-turning Fraction	0.10 to 0.40
# Open Lanes/ # Total Lanes	0.33 to 1.00
Right-only lanes	0 or 1
Left-only lanes	1 or 2
Sum of Th, Th/Rt and Rt Lanes	2 to 4

Table 4-16: Model Comaprison (Case 2.1)

	Variable Name	Coefficients	Min	Max
1	Constant	443.364	1	1
2	Distance of WZ from intersection (ft)	0.208	100	1000
3	g/C Ratio for approach (g/C)	1685.778	0.3	0.7
	Capacity (vph) =		970	1831

* Note that the values given here gives a typical range that may be expected. Some of the values from the models may be still lower or higher than given here.

Table 4-17: Model Comparison (Case 2.2)

	Variable Name	Coefficients	Min	Max
1	Constant	58.682	1	1
2	Th/Rt Phase g/C Ratio ((g/C)TTR)	1581.307	0.3	0.7
3	Distance of WZ from intersection (ft)	0.124	100	1000
4	Left Turn g/C Ratio((g/C)LT)	521.551	0.1	0.1
	Capacity (vph) =		598	1342

* Note that the values given here gives a typical range that may be expected. Some of the values from the models may be still lower or higher than given here.

Table 4-18: Model Comaparison (3 through 6 lanes)

	Variable Name	Coefficients	Min	Max
1	Constant	-946.955	1	1
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 (No/Nt)	755.362	1/3	1/3
7	(Left-only Lanes) × (Left-turning %) × (Left Phase g/C) [(LT ×LTF × (g/C)LT]	3078.002	0.32	0.005
8	Distance of WZ from intersection (ft)	0.435	100	1000
		Capacity (vph) =	769	2009

* Note that the values given here gives a typical range that may be expected. Some of the values from the models may be still lower or higher than given here.

Table 4-19: Sensitivity Analysis (Left-turning Flow Model)

	Factor			Flow			
Factor	Initial Value	Final Value	Percent Change	Initial Value	Final Value	Change in Flow	% Change in Flow
Number of Th, Th/Rt and Rt Lanes (TTR)	2	4	100	119	202	84	71%
Left-turning Fraction (LTF)	0.2	0.4	100	194	393	199	102%
Th/Rt Phase g/C Ratio ((g/C)TTR)	0.3	0.6	100	140	202	62	45%
Number of Open Lanes / Total Number of Lanes (No/Nt)	0.5	1	100	161	233	73	45%
(Left Phase g/C)	0.2	0.4	100	180	217	38	21%
Distance of WZ from intersection (ft)	300	600	100	130	176	46	35%
Left-only Lanes	1	2	100	161	218	57	36%

Table 4-20: Sensitivity Analysis (Maximum Th/Rt Flow)

Factor	Factor: Initial Value	Factor: Final Value	Factor: Percent Change	Flow: Initial Value	Flow: Final Value	Flow: Change in Flow	Flow: % Change in Flow
Number of Th, Th/Rt and Rt Lanes (TTR)	2	4	100	1045	1763	718	69%
Left-turning Fraction (LTF)	0.2	0.4	100	1268	814	-454	-36%
Th/Rt Phase g/C Ratio ($(g/C)_{TTR}$)	0.3	0.6	100	1187	1837	650	55%
Number of Open Lanes / Total Number of Lanes (N_o/N_t)	0.5	1	100	1404	1705	301	21%
(Left Phase g/C)	0.2	0.4	100	1430	1484	53	4%
Distance of WZ from intersection (ft)	300	600	100	1347	1432	85	6%
Left-only Lanes	1	2	100	1404	818	-586	-42%

Table 4-21: Sensitivity Analysis (Capacity)

Factor	Factor: From Value	Factor: To Value	Factor: % Change in Factor	Capacity: From *Cap.*	Capacity: To *Cap.*	Capacity: Change in *Cap.*	Capacity: % Change in *Cap.*
Number of Th, Th/Rt and Rt Lanes (TTR)	2	4	100	1228	2073	845	69%
Number of Right-only Lanes	0	1	*Plus One*	1650	1482	-169	-10%
Left-turning Fraction (LTF)	0.2	0.4	100	1547	1289	-258	-17%
Th/Rt Phase g/C Ratio ($(g/C)_{TTR}$)	0.3	0.6	100	1412	2126	714	51%
Number of Open Lanes / Total Number of Lanes (N_o/N_t)	0.5	1	100	1650	2028	378	23%
(Left Phase g/C)	0.2	0.4	100	1696	1789	92	5%
Distance of WZ from intersection (ft)	300	600	100	1563	1694	131	8%
Left-only Lanes	1	2	100	1650	1099	-551	-33%

Table 4-22: Sensitivity Analysis (Case 2.1)

Factor	Factor: From Value	Factor: To Value	Factor: % Change in Factor	Capacity: From *Cap.*	Capacity: To *Cap.*	Capacity: Change in *Cap.*	Capacity: % Change in *Cap.*
Distance of WZ from intersection (ft)	300	600	100	1180	1242	62	5%
g/C Ratio for arterial (*g/C)*	0.3	0.6	100	1053	1559	506	48%

Table 4-23: Sensitivity Analysis (Case 2.2)

Factor	Factor: From Value	Factor: To Value	Factor: % Change in Factor	Capacity: From *Cap.*	Capacity: To *Cap.*	Capacity: Change in *Cap.*	Capacity: % Change in *Cap.*
Th/Rt Phase g/C Ratio ($(g/C)_{TTR}$)	0.3	0.6	100	647	1122	474	73%
Distance of WZ from intersection (ft)	300	600	100	781	818	37	5%
Left Turn g/C Ratio($(g/C)_{LT}$)	0.2	0.4	100	858	962	104	12%

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

This chapter presents a summary of the findings and the analysis regarding work zone capacity. This is followed by a discussion on model applications. Conclusions from the research are presented next. The chapter concludes with suggestions on subsequent research on this topic.

5.1 Summary

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.). These models are not based on any field study on arterial work zone or any simulation study. Other state agencies also do not have any clearly defined methodology for calculating work zone capacities, although they use assumed capacity values as part of guidelines on work zone set up. Therefore, there is a need to develop an understanding of the factors that may affect the capacity of a work zone, and develop models to estimate it.

To address this need a list of factors was their developed from the literature on work zone capacity. A few factors were excluded from the study because of the limitations of simulation software. The selected factors were used for simulating scenarios with variations in values. Since no field data were available, simulation was used. A total of five models were then developed to estimate the maximum flow through different lane groups as well as the capacity of the arterial. Separate models had to be developed for arterials with two lanes at the downstream intersection because these arterials operate in a different manner. The proposed models showed that the downstream intersection has very significant effect on the capacity of the arterial work zone.

The proposed models are meant to be used for estimation purposes. These models can be used to estimate the capacity of a work zone, which can be used as input into other software packages, which estimate the delay through work zones. These models can help agencies plan their strategies on work zone implemention.

5.2 Conclusions

Conclusions drawn from this research are as follows:

a) 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. Work zone design documents such as the MUTCD identify some of the factors affecting capacity, but they do not specify their impact quantitavely.

b) Existing simulators do not specifically model arterial work zones.

c) The signalization of the intersection downstream of the work zone hugely affects the capacity of the work zone. Factors such as the g/C, percentage of traffic turning left as well as right, and the turning pockets were found to affect the capacity significantly.

d) 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 results in better utilization of the green at the intersection approach.

e) 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.

f) 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 are fewer blockages. This increase was observed mostly for scenarios with 3-6 lanes at the intersection approach.

g) 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.

h) 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.

5.3 Future Research

The following recommendations for further studies are made:

a) 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 used in the field.

b) 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.

c) Specific guidance can be developed on traffic signal control strategies for intersections downstream of a work zone, so that capacity can be maximized.

d) 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. In addition, the upstream intersection would affect the arrival pattern to the work zone. The analysis could answer the question: how many vehicles can pass through the system of an intersection followed by a work zone.

e) Some of the variables like the work intensity, presence of police and workers in the work zone and effect of warning signs could not be looked at due to lack of appropriate features in the existing simulation software packages. These factors and other additional factors may be examined when such a facility is available. The models presented in this report are based on simulation alone. Field data should be collected from various work zones to validate the models presented in this study. The data should have work zones with varying configurations as in this study so that the models can be validated thoroughly.

f) Another approach to the capacity calculation could be to design models which predict the capacity on installation of a work zone in terms of fraction of the present capacity of the approach. These fractions can then directly be applied to the capacity found by standard methods like the FDOT and the HCM. The calibration of that kind of model will require more field data, in addition to the data from the site with work zone, data from the same site without work zone would also be required.

g) It would be useful to develop simulation software with options to replicate the work zone features like taper, road signs, lane geometry. If the software packages incorporate these features then the effect of these on capacity may also be tested. Various geometric elements (such as lane width and shoulder width) are currently not considered in CORSIM. Its algorithms should be modified to consider such factors generally, as well as with respect to work zones.

APPENDIX A
ANALYSIS OF SIMULATION RESULTS

This appendix will discuss the results from the actual simulation runs. Results of each scenario will be analyzed sequentially in the next section. The possible lane channelization will be listed with the help of diagrams. Work zones might be set differently with each lane channelization; these will be presented with the channelization. Finally, the results of the simulation will be discussed in detail. The trends of the capacity of the approach with change in different variables like the g/C ratios of different lane groups are discussed. Similar trends are also explored for the hourly flows of each lane group (viz. left-turning and Th/Rt going traffic) if necessary. All the flows are given in veh/hr. unless stated otherwise. These include the separate Left-turning, Th/Lt, Th/Rt and the capacity of the approach as well. The analysis starts with 2 lanes at the intersection and goes through each scenario till 6 lanes at the intersection. It may be noted that these lanes also include the turn pockets.

A.1 Lanes at Intersection with one Phase Only (Figure A-1)

The scheme has a combined Th/Lt lane and single phase for the entire approach. One lane is closed and other is open to traffic. As discussed in the sensitivity analysis section (chapter 3), the position of the work zone does not matter.

Capacity increases slightly with the increase in distance up to 250 ft. It remains unchanged for distance up to 1000 ft. It may be concluded that the work zone affects the capacity up to 500 ft distance from the intersection, after that, its effect is not substantial (Figure A-2).

The capacity of the approach increases substantially as green increases (Figure A-3). This capacity increase is quite significant when green increases to 0.5 but remains constant after that. The reason for this is that g/C ratio of 0.5 satisfies the demand for vehicles and no green is wasted hence giving more green does not help. In fact, if in some cases the green is more than required which leads to wastage of green. Such inappropriate distribution of green leads to blocking of traffic.

Both the left and the right-turning percentages have almost no effect on the capacity, the figures for both look similar (Figure A-4 and Figure A-5). This is because there is no separate lane for left turns and hence they are equally distributed with the through traffic.

This completes the small analysis of effect of some variables applicable to this scenario on capacity.

A.2 Two Lanes at Intersection with a Left-only Phase (Figure A-6)

This scheme has a separate left turn lane instead of a Th/Lt lane. Figures representing aggregate level trends follow with discussion on the same.

The left-turning flow increases as the distance from the end of the work zone to the intersection increases from 100ft to 1000 ft (Figure A-7). It becomes constant after 500 ft. there is one outlier at the 750ft distance which has the maximum capacity while the majority of the data points show the trend discussed above. In cases with higher distances (500, 750 and 1000 ft); higher left-turning flow, 0.3 g/C for Lt turns and 0.5 g/C for Th/Rt traffic, the left turn lane suffers demand saturation because the left-turning vehicles get sufficient green time and hence the left-turning flow is the highest for this g/C ratio. In case of 0.5 g/C for left turns and 0.3 g/C for Th/Rt turns, the Th/Rt traffic blocks the left-turning traffic at the work zone and hence the left-turning flow is lower as compared to the former case.The left-turning vehicles may take more time to join the queue when they have to travel 1000ft as compared to 750ft. Those vehicles that do not find any queue because the green is still active when they reach the intersection will take more time to travel to the intersection if the distance to the end of the work zone is more which increases the left-turning flow.

The Th/Rt flow remains constant with respect to the distance (Figure A-8). There are two outliers here too; they occur at 250 ft distance, 0.1 g/C for left turns and 0.7 g/C for the Th/Rt turning traffic. It takes more time for vehicles in the queue to move if the queue is longer. But this difference is very slight and may not explain the phenomenon completely.

The capacity does not change much with distance in Figure A-9. It implies that the capacity of the work zone with the most favorable g/C and other suitable parameters does not optimize better with change in distance of intersection from the end of work zone. The reason for this is that in this scenario, the blockage is almost same regardless of the storage length available. It should be noted that major contribution of the Th/Rt flow to the capacity makes their trends look alike.

The approach capacity increases with the Th/Rt g/C because the major part of the traffic is the Th/Rt going traffic. (Figure A-10)

The left-turning flow goes on increasing as the percentage of traffic turning left increases in the traffic stream of the approach. (Figure A-11)

The Th/Rt flow first reduces and then remains constant with the increase in the left-turning traffic flow (Figure A-12). Even if the left-turning traffic increases, it does not block the Th/Rt traffic and in the later two conditions, the green time is just enough to let the Th/Rt traffic to get though and not block any traffic. Consequently, the entire green time is utilized in both those cases resulting in the same flows.

Figure A-13 is a combination of the above two effects as illustrated by: Figure A-11 and Figure A-12. The effect of the left-turning trend is suppressed by the Th/Rt trend because of the difference in the quantity.

Figure A-14 shows that the capacity remains almost constant with the increase in the right-turning traffic beyond 25%. The right-turning vehicles do affect the Th/Rt flow but their effect does not have much impact after they reach a particular percentage. This is because the combination of the traffic stream has almost the same number of through vehicles followed by the right-turning vehicles (and vice versa) for those percentages of right-turning vehicles.

A.3 Three Lanes at Intersection

Possible lane channelization of the three lanes is as shown (Figure A-15, Figure A-16 and Figure A-17). There are three possibilities that have been simulated. For each of the given scenarios, connecting arterial may have 2 or 3 lanes under normal functioning. Work zones can be set up in three ways as given in Table 3-9. (*viz.* 1 Open and 2 closed lanes, 2 open and 1 closed lane, 1 Open and 1 closed lane)

The approach capacity increases as the number of open lanes through the work zone increase. (Figure A-18)

Capacity decreases with the increase in left-only lanes because the left-turning flow is always less as compared with the combined through and right-turning flow (Figure A-19, Figure A-20) and if lanes are assigned for the left-turning traffic then it does not allow the majority of the traffic to pass through, so even if the left-turning flow goes up, the total capacity goes down. Further, it can be noticed that the left-turning flow also goes down for some cases because the Th/Rt traffic blocks it as the queue builds up in those lanes going through the work zone as well, not allowing enough left-turning vehicles to get through the work zone as the green time permits.

Th and Rt lanes include through only, Th/Rt lanes and right-only lanes. As these increase, the capacity of the approach also increases (Figure A-21). Since the Th/Rt flow is always greater than the left-turning flow, giving more passage to it helps increasing the capacity. It may be noted that both the Th/Rt and left-turning traffic increases with the increase in through lanes and right lanes. The increase in the left-turning traffic is caused due to its fewer blockages because of the queuing of the Th/Rt traffic when it has less passage. This variable has a positive effect on flows through all lane groups.

Most of the cases lose the capacity if a right-only lane is introduced (Figure A-22). It appears that a Th/Rt lane serves the purpose better than a right-only lane. In a few cases when the right-turning flow is too high, introducing a right-only lane just helps to keep the capacity the same, but it does not help in any of the cases. It may be concluded that introducing a right-only lane would in general, reduce the capacity.

With the increase in distance, the capacity increases a bit till 750 ft and remains almost the same thereafter (Figure A-23). Therefore, the effect of an upstream work zone is not significant at distances greater than 700ft (approx.)

Figure A-24 shows that the left-turning flow increases with more green time given to the left turns.

Figure A-25 and Figure A-26 show that both Th/Rt flow as well as the capacity decreases with the increase in the green time for left-turning vehicles. Since the left-turning flow is less the Th/Rt flow's trend is visible in the capacity the figure too.

Figure A-27 suggests that Th/Rt phase g/C ratio has a positive effect on the capacity of the approach, this follows the trends discussed earlier in scenario 2.2.

Figure A-28 and Figure A-29 show that the capacity goes down in many cases while it also comes up in some of the cases. The upper bound for both the figures has reduced in cases with higher distances and more green while the lower bounds are the cases with lesser distances and less g/C for the Th/Rt movements. The slight increase in the capacity of these cases is caused due to the separation of traffic according to the turning movements. If the traffic goes in different directions then the queuing is reduced in some of the cases with higher g/C.

This concludes the analysis of the factors that affect the capacity of the approach having three lanes at the intersection. Arterials having 4 lanes when they meet the intersection will be discussed next.

A.4 Four Lanes at Intersection

This section discusses the effect of various factors on the capacity as well as flows through each lane group if necessary. Four possible lane channelizations have been used for simulation purposes in this type of arterials. They are shown in following figures: Figure A-30, Figure A-31, Figure A-32 and Figure A-33.

As expected, the capacity of the entire approach increases as the number of open lanes through the work zone increase. (Figure A-34)

Capacity decreases with the increase in left-only lanes because the left-turning flow is always less as compared with the combined through and right-turning flow (Figure A-35) and more lanes are assigned for the left-turning traffic then it does not allow the majority of the traffic to pass through, so even if the left-turning flow increases, the total capacity decreases. Unlike scenario 3.0, increasing the left-only lanes does not have negative impact on the cases having maximum capacity.

Th and Rt lanes include through only, Th/Rt lanes and right-only lanes. As these increase, the capacity of the approach also increases (Figure A-37). Since the Th/Rt flow is always greater than the left-turning flow, giving more passage to it helps increasing the capacity. It may be noted that left-turning traffic decreases with the increase in through and right lanes. But this effect is not seen in the capacity trends because of less flow of left-turning traffic. (Figure A-36)

Most of the cases experience reduced capacity if a right-only lane is introduced (Figure A-38). It appears that a Th/Rt lane serves the purpose better than a right-only lane. In a few cases when the right-turning fraction is more, introducing a right-only lane just helps to keep the capacity constant, but it does not help in any of the cases. It may be concluded that introducing a right-only lane would in general, reduce the capacity.

With the increase in distance, the capacity remains almost same for 100 ft and 250 ft. It then starts to increase linearly from 500 ft till 1000 ft (Figure A-39). Unlike the previous cases, the distance has positive effect on the capacity in this scenario and it varies approximately linearly with distance. The increase is not significantly high.

Figure A-40 shows that the left-turning flow increases with more green time given to the left turns for g/C 0.3 but it goes down at g/C of 0.5. In former case, the highest left flow is given by the cases consisting two left-only lanes because they get sufficient passage time while in the later case, the through and right-turning green is not sufficient causing heavy queuing and blocking of the left-only lanes as well as the blockage of the work zone itself. This causes the left-turning flow to go down.

Figure A-41 and Figure A-42 show that both, Th/Rt flow, as well as the capacity, decrease with the increase in the green time for left-turning vehicles. Low left-turning fraction leads to the Th/Rt flow's trend being visible in the capacity the figure too.

Above chart (Figure A-43) suggests that Th/Rt phase g/C ratio has a positive effect on the capacity of the approach, this follows the trends discussed in all the earlier scenarios. The increase is fairly linear and is same for the Th/Rt lane group flow. The left-turning flow, however, experience steep reduction at 0.7 g/C for Th/Rt because of less g/C.

The charts showing the effect of the increase in the left-turning traffic's percentage on the various flows are given in Figure A-44, Figure A-45 and Figure A-46. More the fraction of left-turning vehicles in the traffic stream more will be the flow through the left-turning lanes and less will be the flow through the Th/Rt lane group. The last chart simply shows the combined effect of the two charts discussed above. It should be noted that the capacity can be better explained by looking at the individual trends rather than the final capacity value.

A fraction of right-turning traffic in the traffic stream has relatively less effect on the capacity (Figure A-47). The capacity reduced to 40% right-turning vehicles.

This completes the analysis of the factors that affect the capacity of the approach having three lanes at the intersection. Arterials having five lanes when they meet the intersection will be discussed next.

A.5 Five Lanes at Intersection

This section discusses the arterials with 5 lanes at the intersection. Possible lane channelization schemes are shown in the following figures: Figure A-48, Figure A-49, Figure A-50 and Figure A-51. With each of these channelization schemes, a work zone can be set up in 4 ways. These four ways are corresponding to the work zone setup on any arterial having 3 or 4 lanes under normal circumstances. (Refer Table 3-9: Geometric Variations) Let's look at how the variables affect the capacity of the arterial in this case.

Just like in Scenario 4.0, the capacity of the entire approach increases as the number of open lanes through the work zone increase. (Figure A-52)

Capacity decreases with the increase in left-only lanes because the left-turning flow is always less as compared with the combined through and right-turning flow (Figure A-53) and if more lanes are assigned for the left-turning traffic then it does not allow the majority of the traffic to pass through, so even if the left-turning flow goes up, the total capacity goes down. It may be noted that in this case too, similar to Scenario 4.0, the left-turning flow goes up but that increase is not huge in terms of fraction of the total capacity and does not have visible effect on the capacity.

Th and Rt lanes include through only, Th/Rt lanes and right-only lanes. As these increase, the capacity of the approach also increases (Figure A-55). Since the Th/Rt flow is always greater than the left-turning flow, giving more passage to it helps increasing the capacity. Left-turning traffic decreases by greater amounts as compared with the last scenario. But this effect is not seen in the capacity trends because of low flow of left-turning traffic (Figure A-54).

Introduction of a right turn only lane does not have any significant effect on the capacity (Figure A-56). In this case, it does not matter if there is a right-only or a Th/Rt lane.

With the increase in distance, the capacity starts to increase slightly till 500 ft. Thereafter, it remains almost constant till 1000 ft. Because there are too many lanes over which vehicles can distribute themselves the distance does not have effect on capacity after 500 ft. (Figure A-57)

In Figure A-58, the left-turning flow goes up dramatically at g/C ratio of 0.3 and then remains constant at g/C of 0.5. The Th/Rt flow (Figure A-59) goes down consistently with the same amount with the increase in g/C ratio. Finally, the capacity (Figure A-60) is same for the first two g/C ratios (0.1 and 0.3) and decreases at 0.5 g/C ratio because of the blockage of the traffic due to less g/C to Th/Rt traffic. This traffic queues up and blocks the left-turning traffic as well as itself causing the entire capacity to go down.

Figure A-62 suggests that Th/Rt phase g/C ratio has a positive effect on the capacity of the approach, this follows the trends discussed in all the earlier scenarios. The increase is fairly linear and is same for the Th/Rt lane group flow. The left-turning flow, however, falls down dramatically at 0.7 g/C for Th/Rt because it does not get any passage. (Figure A-61)

The effect of left-turning flow is same as was in scenario 4.0. The capacity of entire approach goes down with increase in the left-turning flow (Figure A-63, Figure A-64 and Figure A-65). More the fraction of left-turning vehicles in the traffic stream more will be the flow through the left-turning lanes and less will be the flow through the Th/Rt lane group. The last chart simply shows the combined effect of the two. It should be noted that the capacity can be better explained by looking at the individual trends rather than the final capacity value. But in this scenario, the capacity is decreasing more evenly as compared to scenario 4.0 so it may be possible to directly relate the effect to capacity rather than breaking it up into various flows.

A fraction of right-turning traffic in the traffic stream has relatively less effect on the capacity (Figure A-66). The capacity goes down slightly at 40% right-turning vehicles.

This concludes the analysis of the factors that affect the capacity of the approach having three lanes at the intersection. The next section is the last sub-section of the analysis. It will discuss the effect of the variables on those arterials which have six lanes at the intersection.

A.6 Six Lanes at Intersection (Figure A-67 and Figure A-68)

This scenario has two assumed lane channelization schemes. Majority of the lanes act as turn pockets (i.e, fixed channelization) leaving scope for less number of variations. Following channelization schemes are considered: Figure A-67 and Figure A-68. The arterials with these channelization schemes can have 3 or 4 lanes under normal functioning and hence a work zone can be set up in 4 ways as given in Table 3-9.

As usual, capacity increases with more open lanes through the work zone (Figure A-69). This is well explained in the earlier scenarios.

Capacity goes down, but not as much as the earlier scenarios with the increase in the left-only lanes because the through and right traffic has sufficient lanes to use (Figure A-70).

Capacity increases as more lanes are allocated to the through and right traffic, this trend is similar to the earlier trends (Figure A-71).

Except a few outliers at 100 ft distance, the capacity increases with the increase in distance. The increase is constant and is relatively very less (Figure A-72).

The capacity decreases with the increase in the g/C ratio for the left-turning vehicles (Figure A-73). The effect is more pronounced for the left-turning flow but the combined effect is more significant at 0.5 g/C for left-turning traffic. The decrease is because of more percentage of Th/Rt traffic than the left-turning traffic.

The Th/Rt g/C has a fairly linear effect on the capacity of the work zone with this kind of arterial (Figure A-74). The increase is expected because of the reasons cited in earlier scenarios.

With the increase in the percentage of the left-turning vehicles in the traffic, the entire capacity goes down (Figure A-75) because of the blockage of either the left-turning vehicles (at low g/C ratio for left turns) or the Th/Rt vehicles (at low g/C for Th/Rt phase). Other than this, the left-turning vehicles take more time to make the turns and hence lead to reduction in capacity.

The right-turning percentage inversely affects the capacity of the approach because of the less passage to the right-turning vehicles as they have only one lane and block the through going vehicles. (Figure A-76)

The next section will summarize the discussion of all the scenarios and conclude the appendix.

A.7 Summary and Conclusions

The aggregate level trends of the change in the capacity and individual lane group flows with respect to various factors was presented. This study does not suggest the trend that will appear after controlling for all the other factors. It simply indicates that, in general, it may be expected that the trend will be visible in the final models. It definitely gives an idea of how traffic flows through work zone, and how the changes in some of the values affect the traffic flow. This insight and analysis of each scenario separately will help define the final models better. Summary table (Table A-1) gives an overview of the findings of this section.

The trends may not be visible in all the cases necessarily but represent the most common trend in the data sets. It should be emphasized again that these are just typical aggregate level trends and not the individual trends which may appear after controlling for rest of the variables.

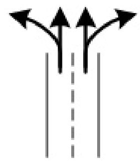

Figure A-1: Scenario 2.1 (Lane Channelization)

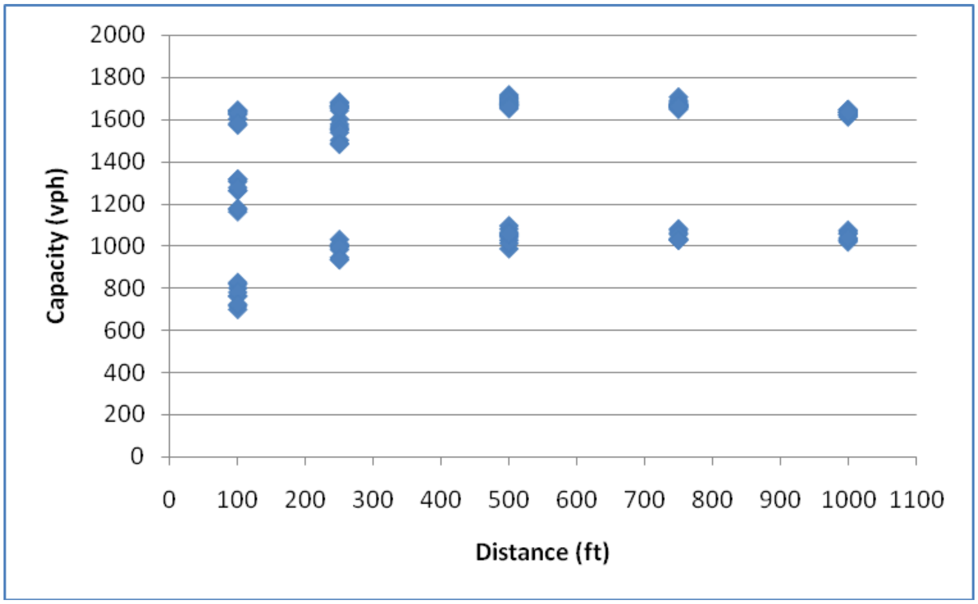

Figure A-2: Distance vs. Capacity (Scenario 2.1)

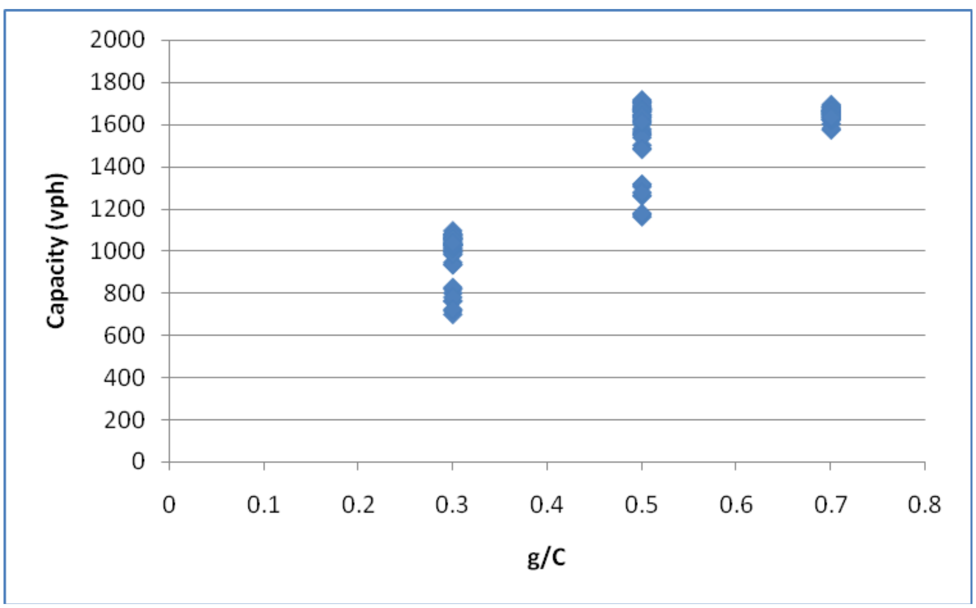

Figure A-3: g/C vs. Capacity (Scenario 2.1)

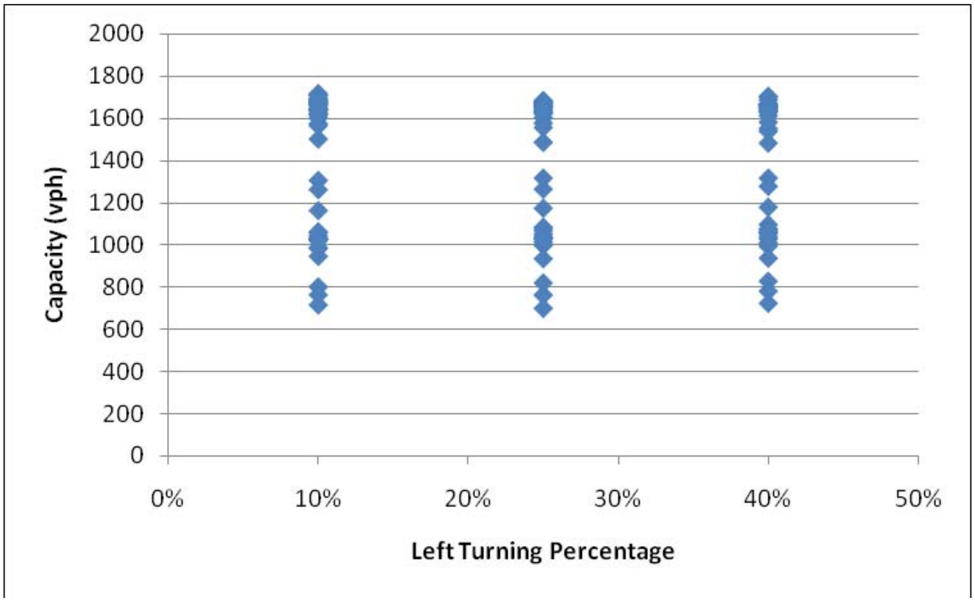

Figure A-4: Left-turning Percentage vs. Capacity (Scenario 2.1)

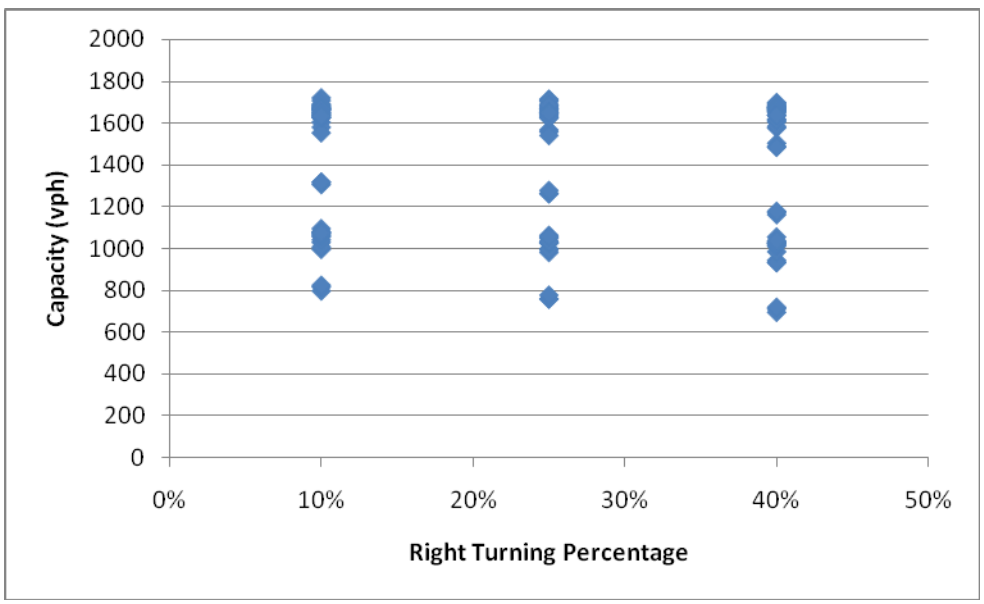

Figure A-5: Right-turning Percentage vs. Capacity (Scenario 2.1)

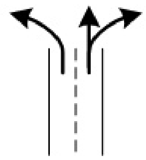

Figure A-6: Scenario 2.2 (Lane Channelization)

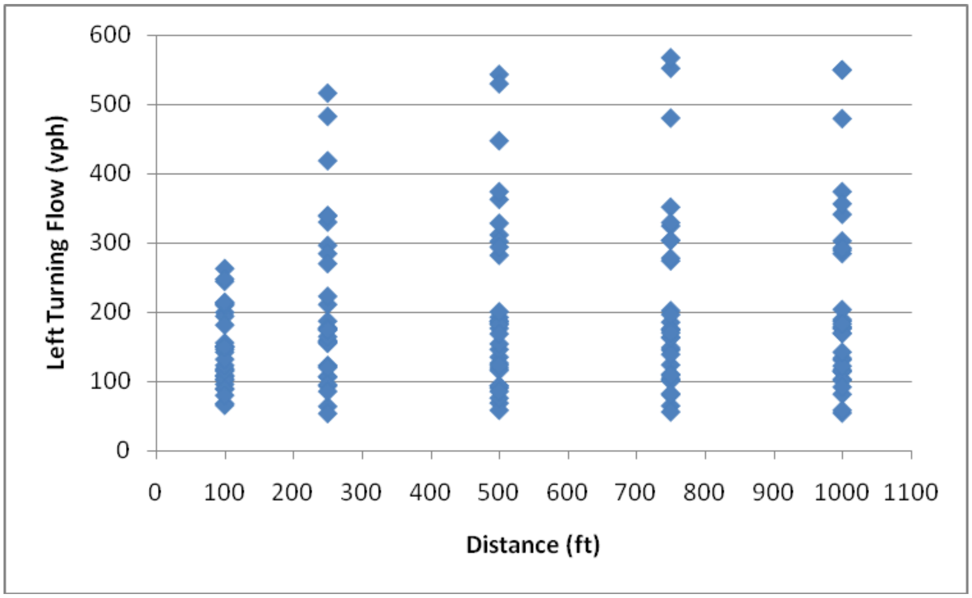

Figure A-7: Distance vs. Left-turning Flow (Scenario 2.2)

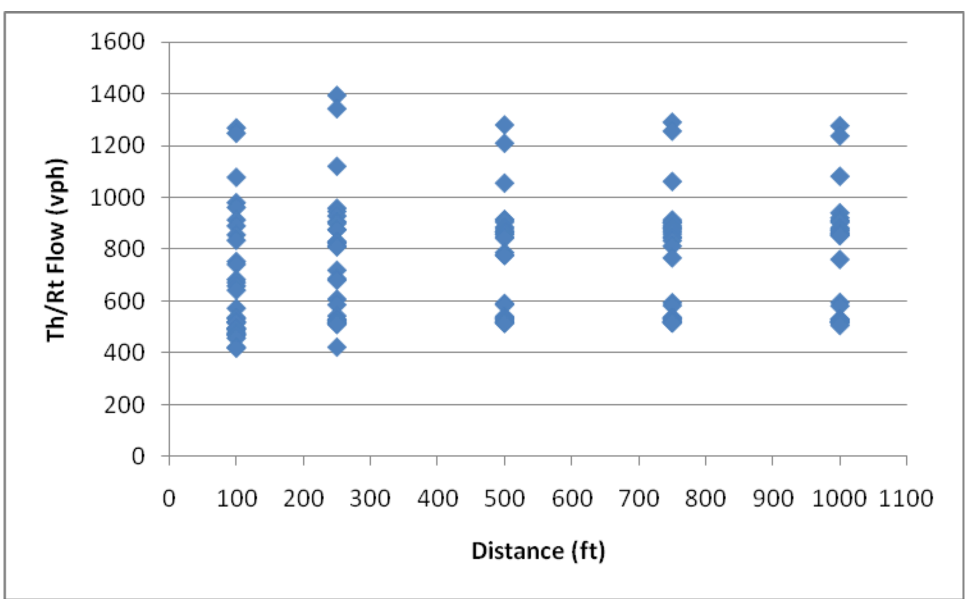

Figure A-8: Distance vs. Th/Rt Flow (Scenario 2.2)

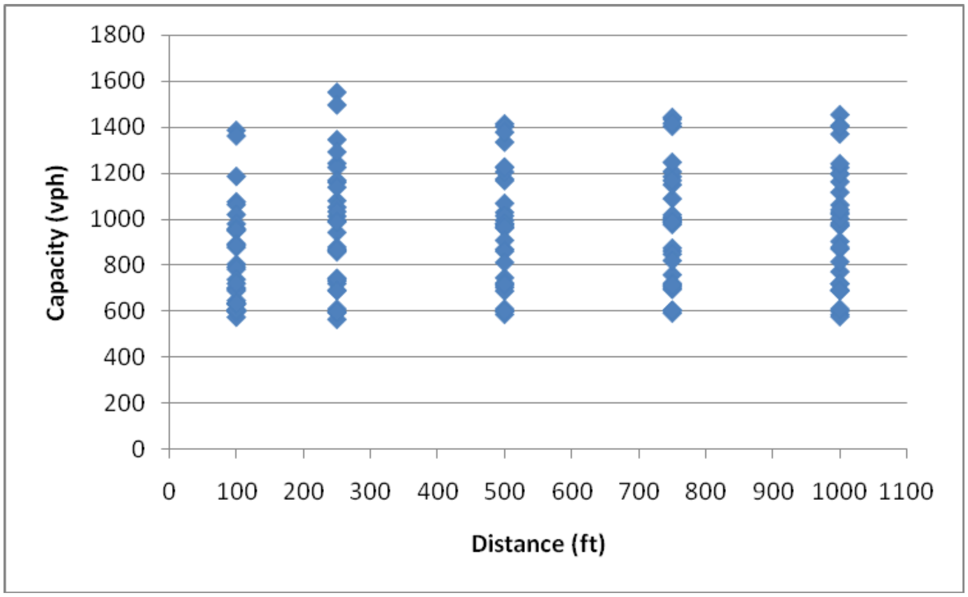

Figure A-9: Distance vs. Capacity (Scenario 2.2)

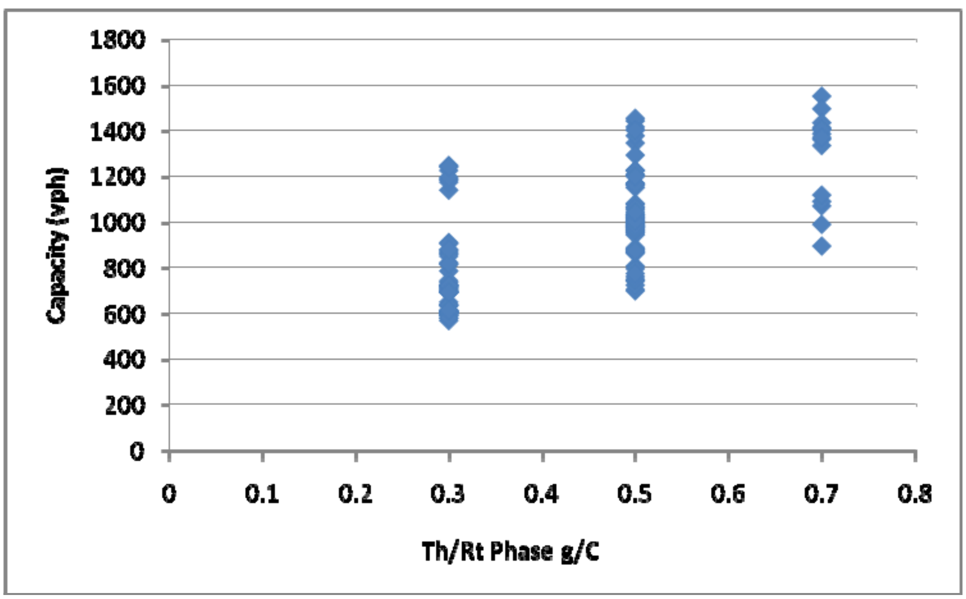

Figure A-10: Th/Rt g/C vs. Capacity (Scenario 2.2)

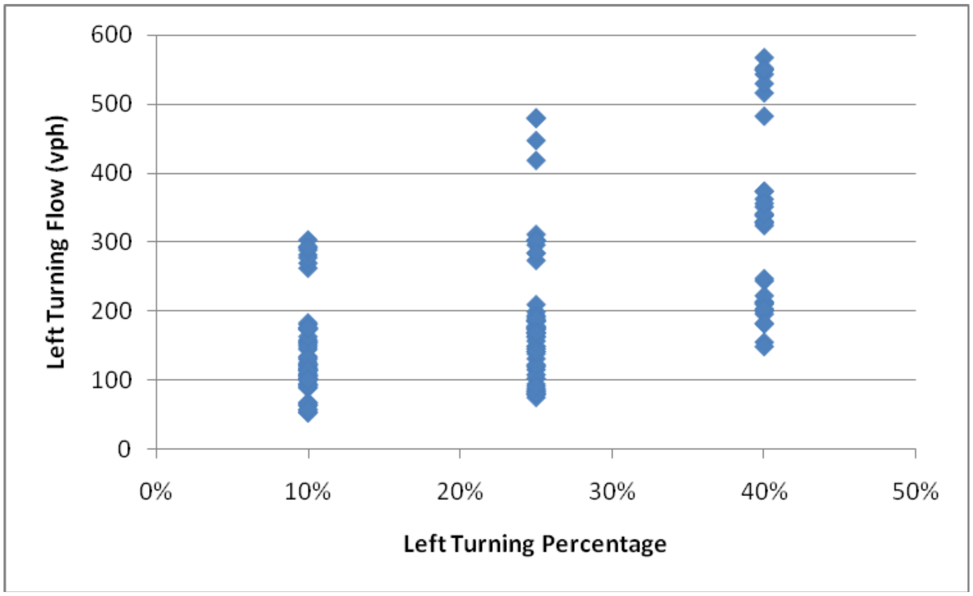

Figure A-11: Left-turning Percentage vs. Left-turning Flow (Scenario 2.2)

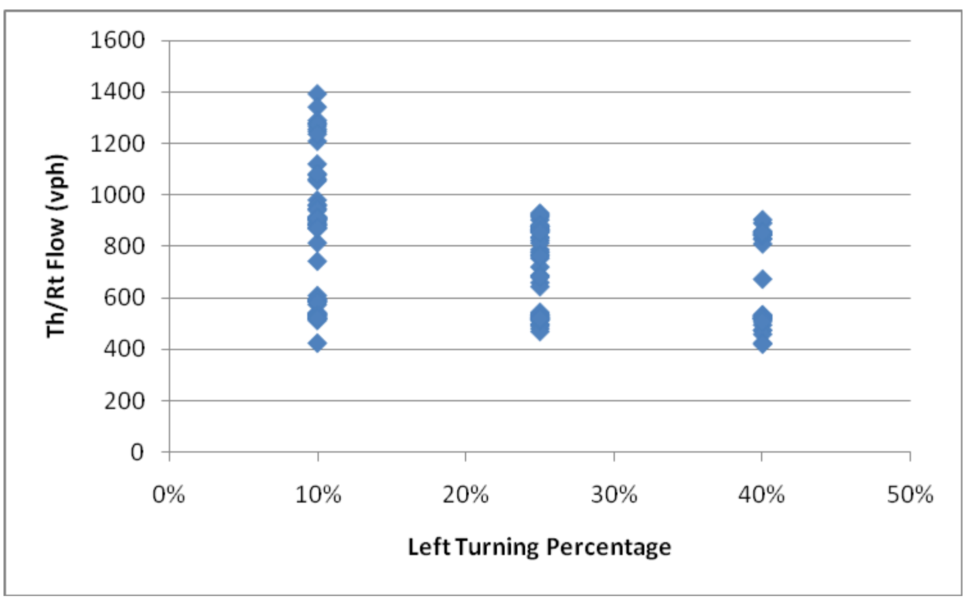

Figure A-12: Left-turning Percentage vs. Th/Rt Flow (Scenario 2.2)

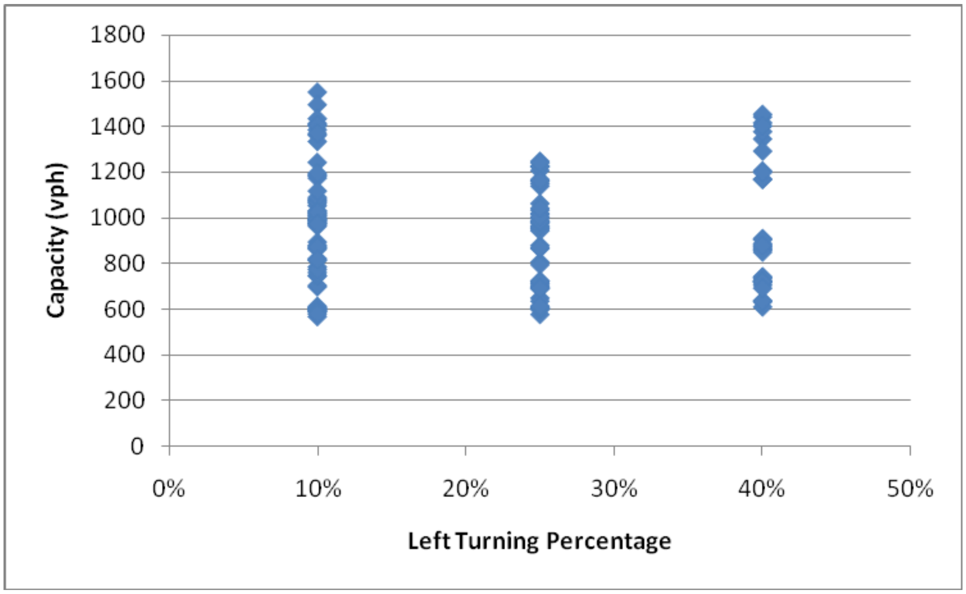

Figure A-13: Left-turning Percentage vs. Capacity (Scenario 2.2)

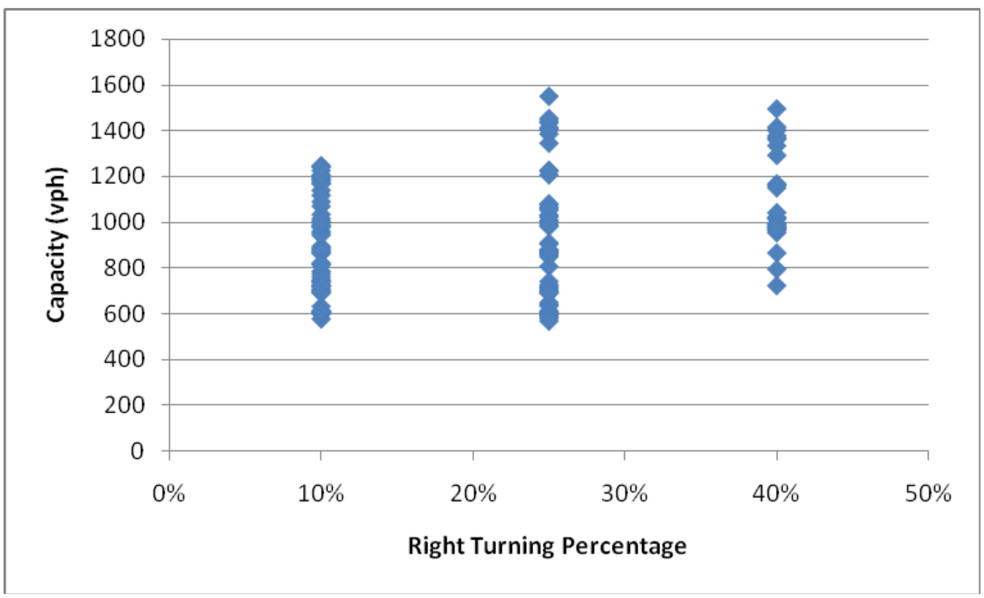

Figure A-14: Right-turning Percentage vs. Capacity (Scenario 2.2)

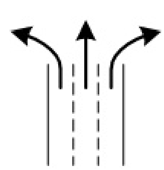

Figure A-15: Scenario 3.1
(Lane Channelization)

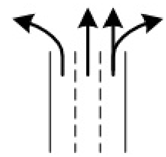

Figure A-16: Scenario 3.2
(Lane Channelization)

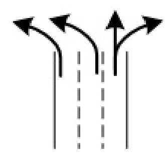

Figure A-17: Scenario 3.3
(Lane Channelization)

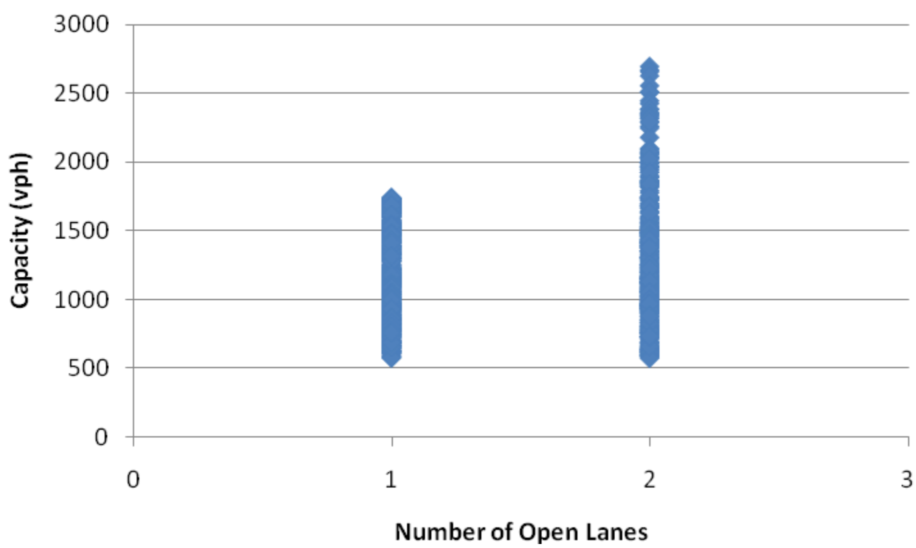

Figure A-18: Number of Open Lanes vs. Capacity (Scenario 3.0)

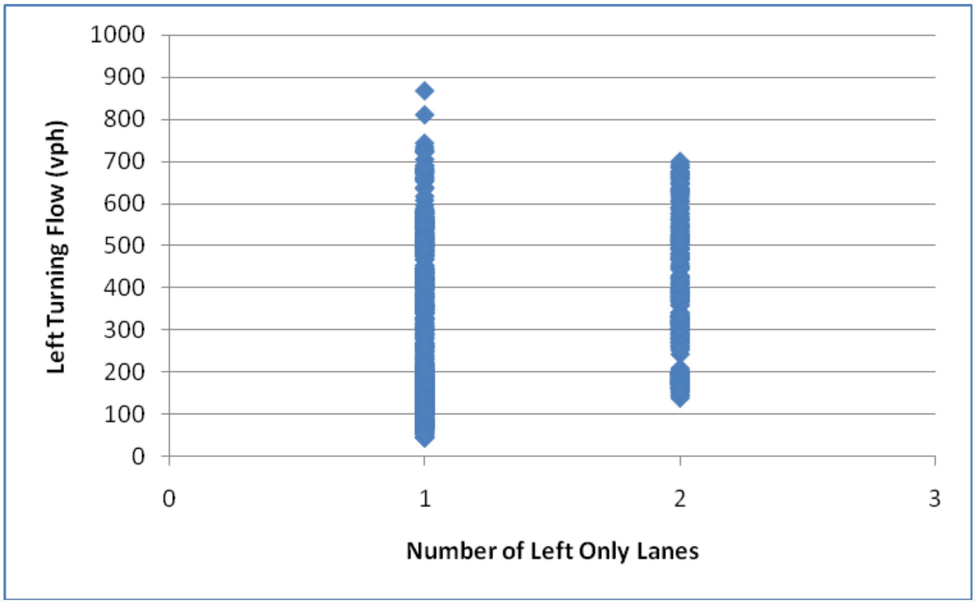

Figure A-19: Number of Left-only Lanes vs. Left-turning Flow (Scenario 3.0)

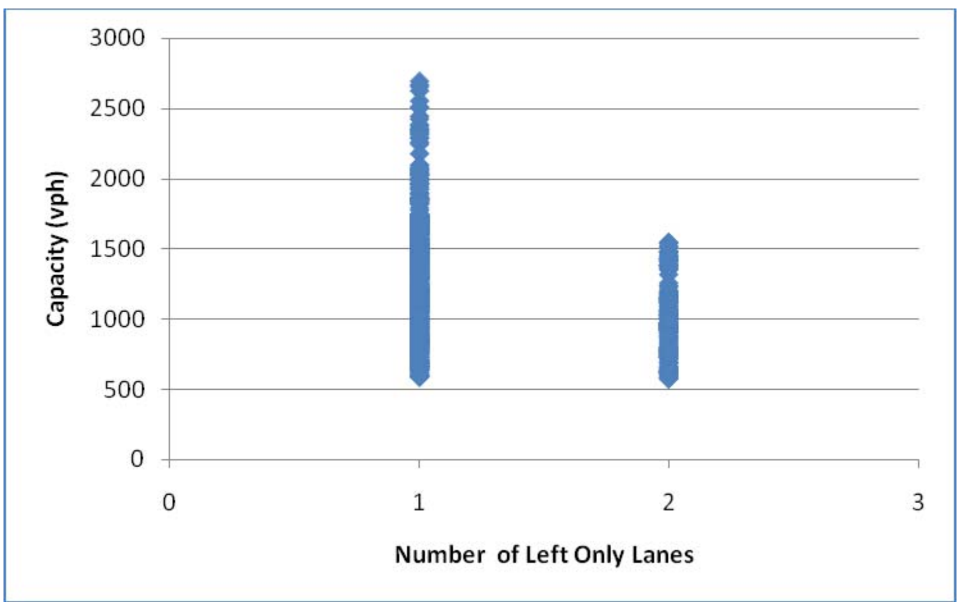

Figure A-20: Number of Left-only Lanes vs. Capacity (Scenario 3.0)

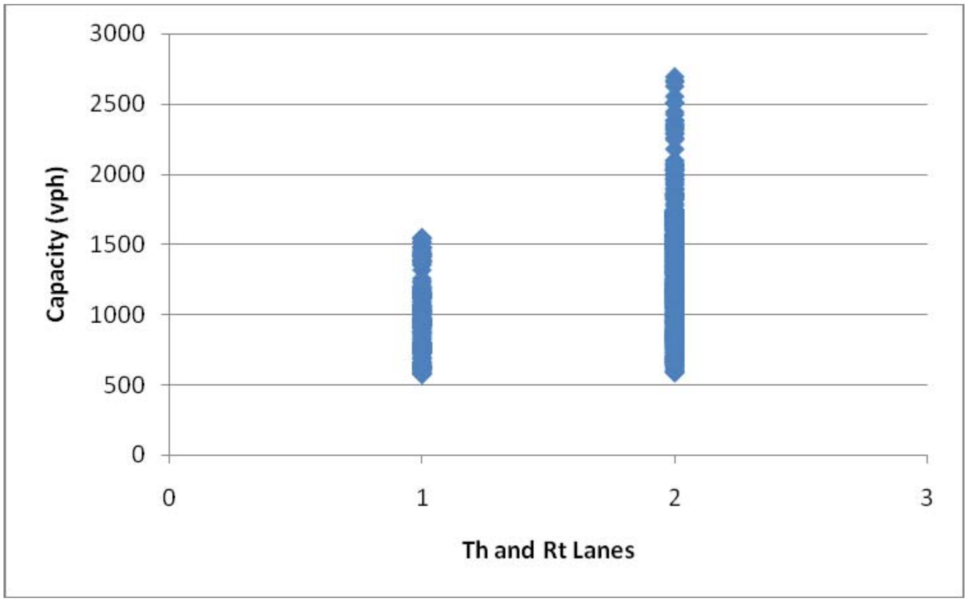

Figure A-21: Th and Rt Lanes vs. Capacity (Scenario 3.0)

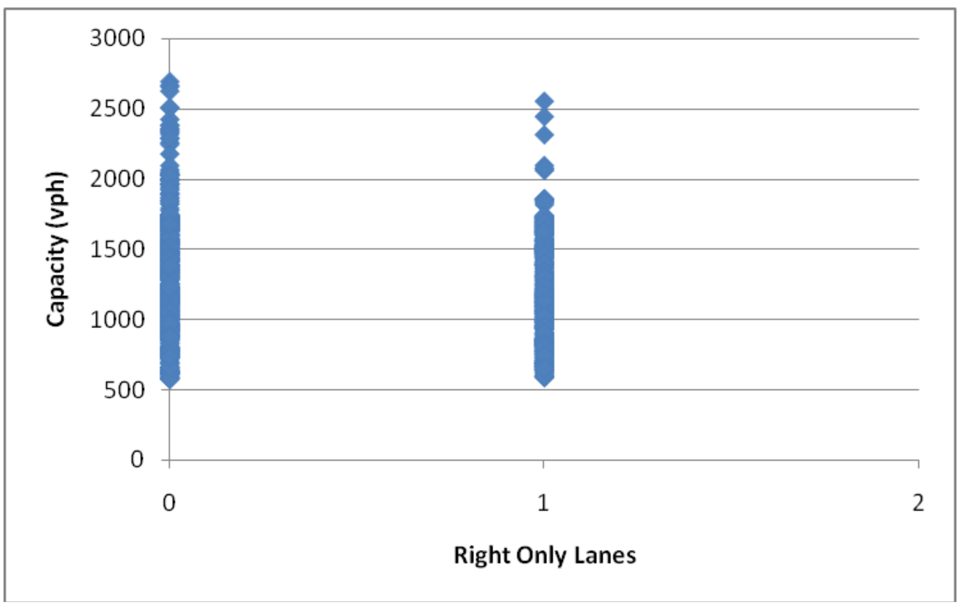

Figure A-22: Right-only Lanes vs. Capacity (Scenario 3.0)

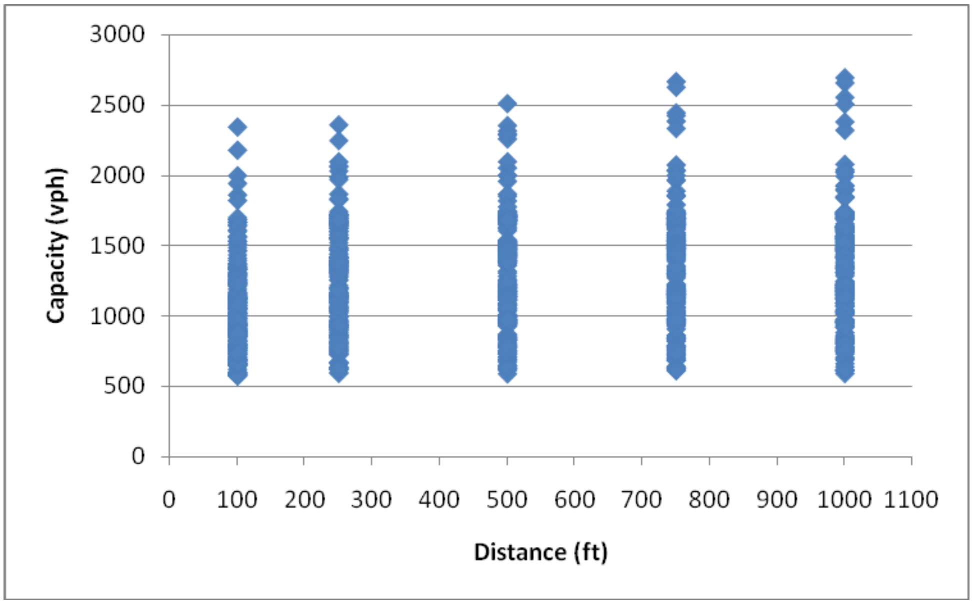

Figure A-23: Distance vs. Capacity (Scenario 3.0)

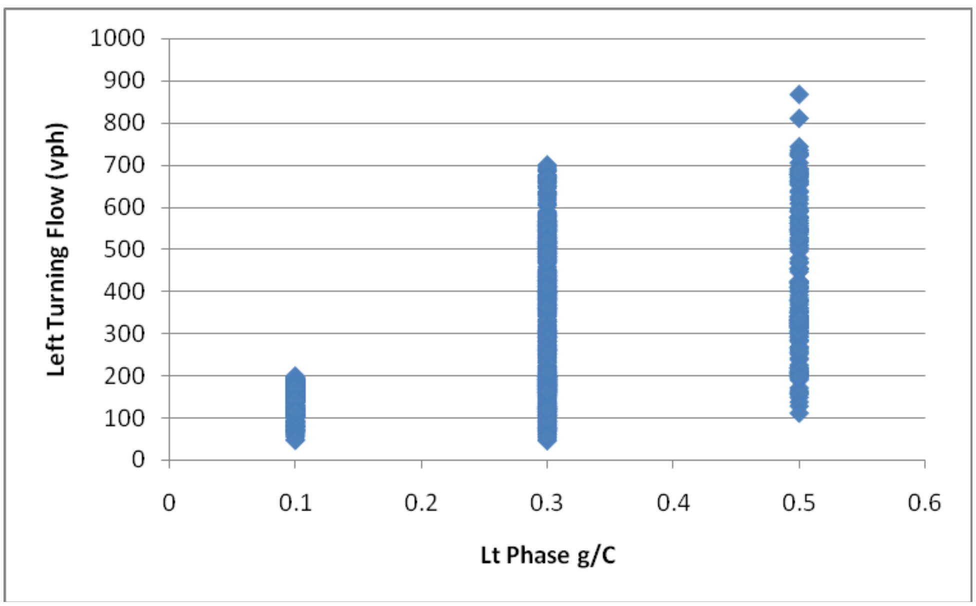

Figure A-24: Left-turning g/C vs. Left-turning Flow (Scenario 3.0)

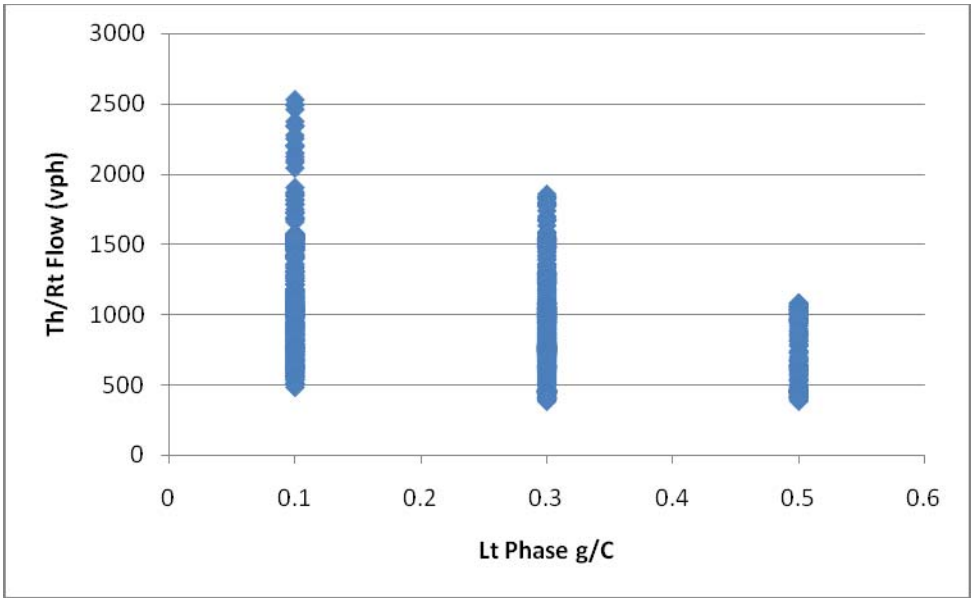

Figure A-25: Left-turning g/C vs. Th/Rt Flow (Scenario 3.0)

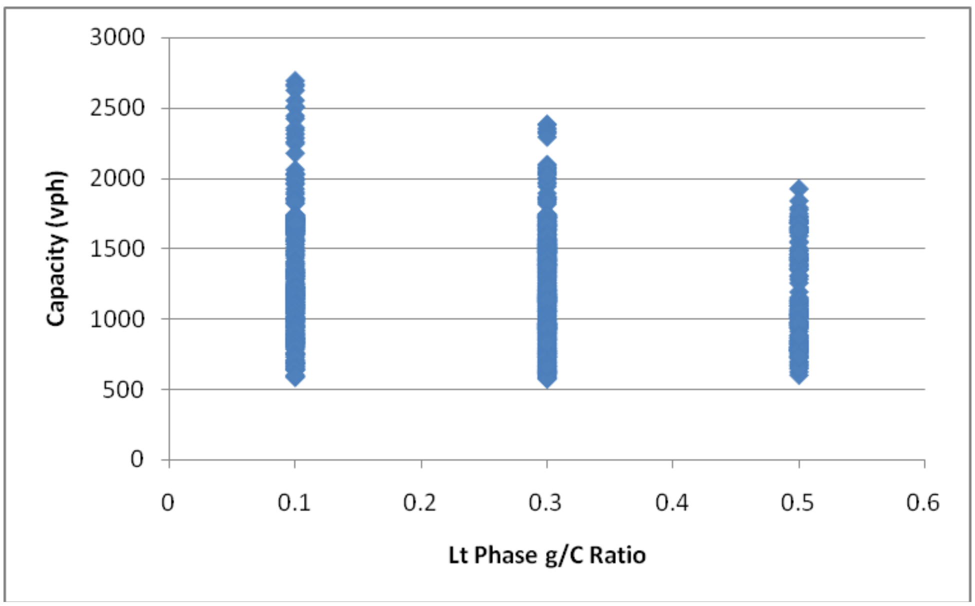

Figure A-26: Left-turning g/C vs. Capacity (Scenario 3.0)

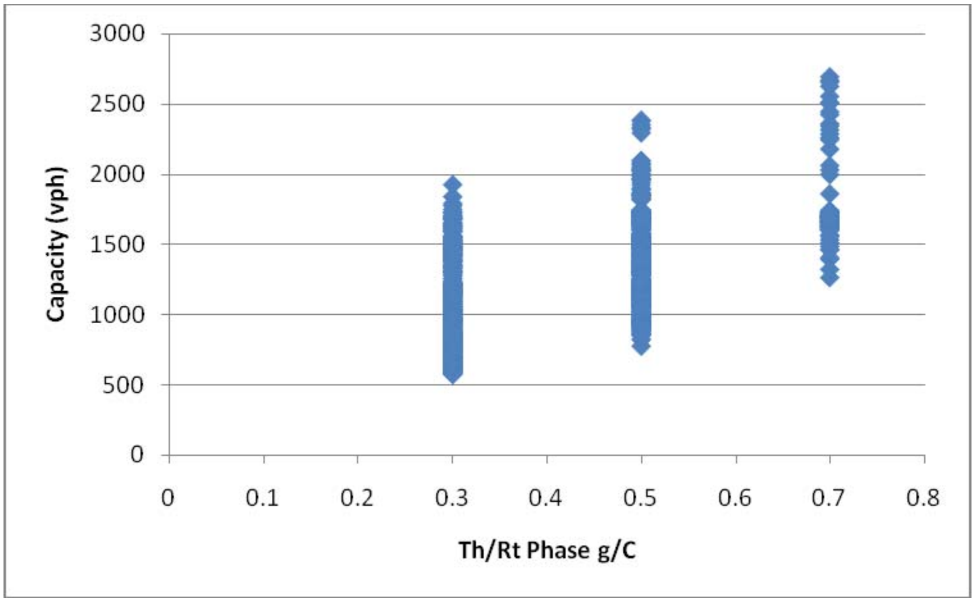

Figure A-27: Th/Rt Phase g/C vs. Capacity (Scenario 3.0)

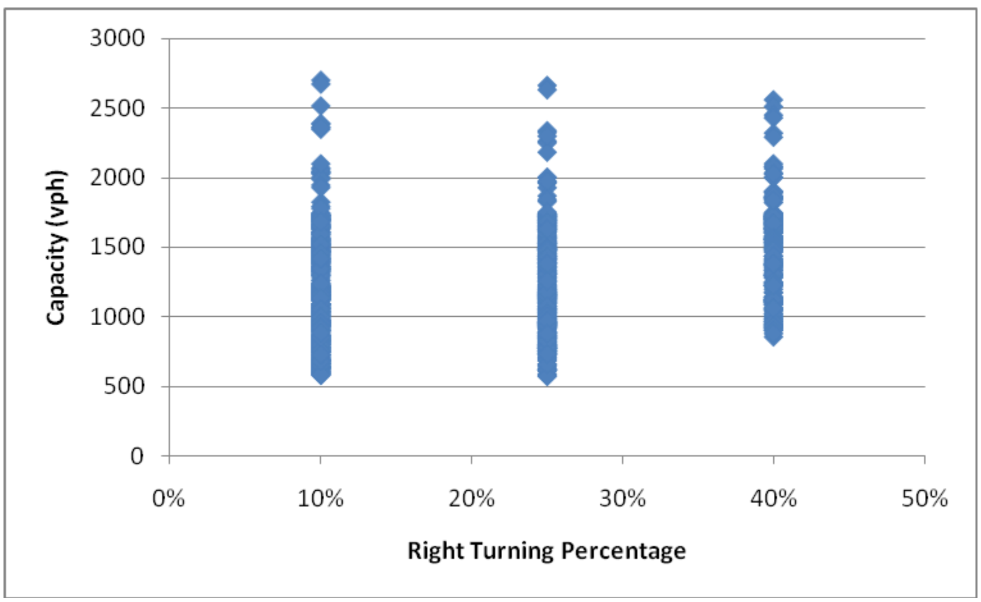

Figure A-28: Right-turning Percentage vs. Capacity (Scenario 3.0)

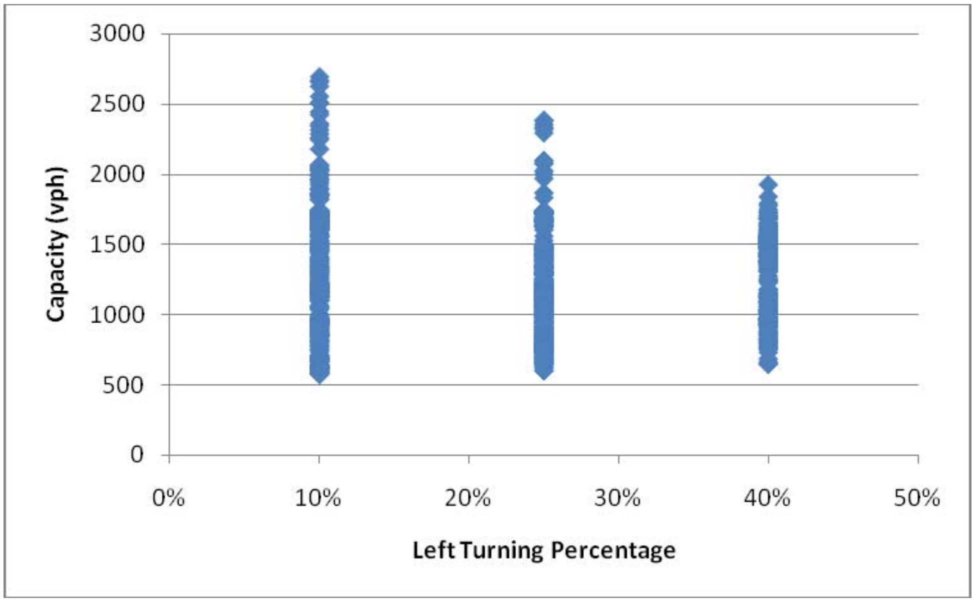

Figure A-29: Left-turning Percentage vs. Capacity (Scenario 3.0)

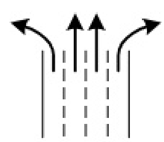

Figure A-30:Scenario 4.1 (Lane Channelization)

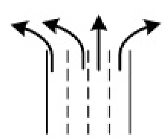

Figure A-31: Scenario 4.2 (Lane Channelization)

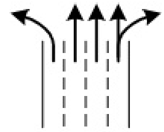

Figure A-32: Scenario 4.3 (Lane Channelization)

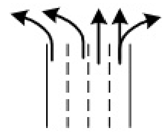

Figure A-33: Scenario 4.4 (Lane Channelization)

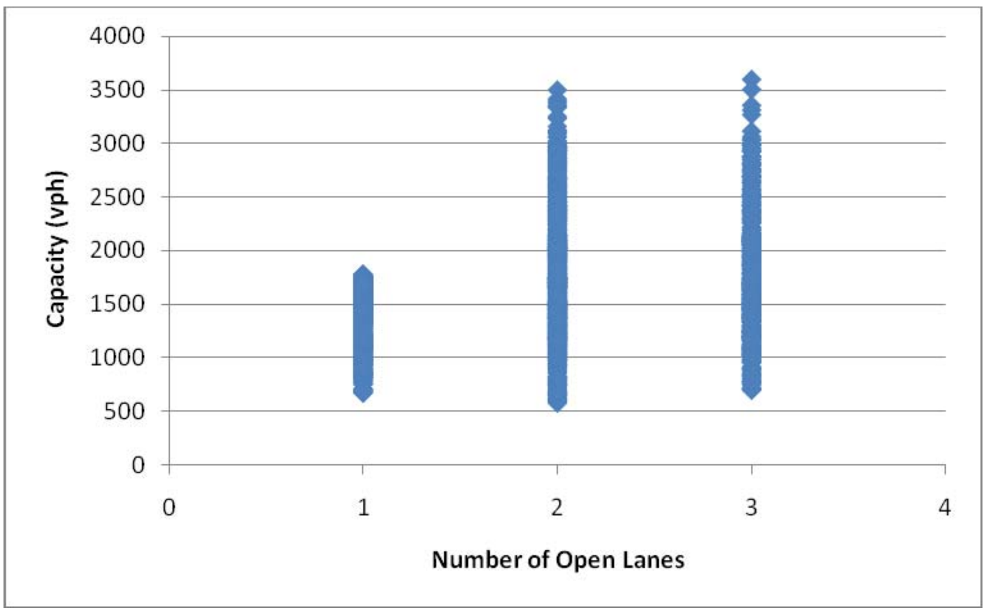

Figure A-34: Number of Open Lanes vs. Capacity (Scenario 4.0)

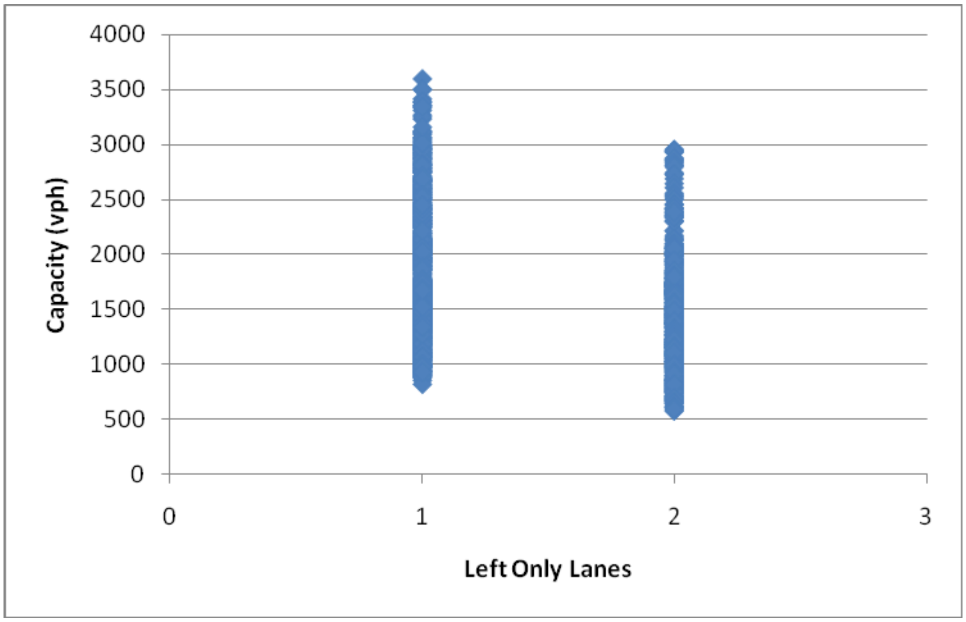

Figure A-35: Left-only Lanes vs. Capacity (Scenario 4.0)

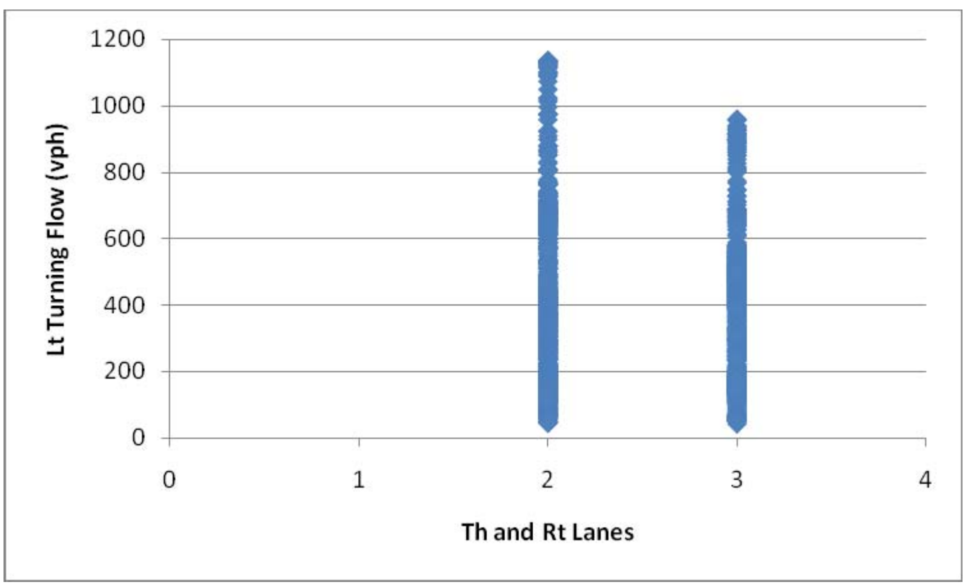

Figure A-36: Through and right Lanes vs. Left-turning Flow (Scenario 4.0)

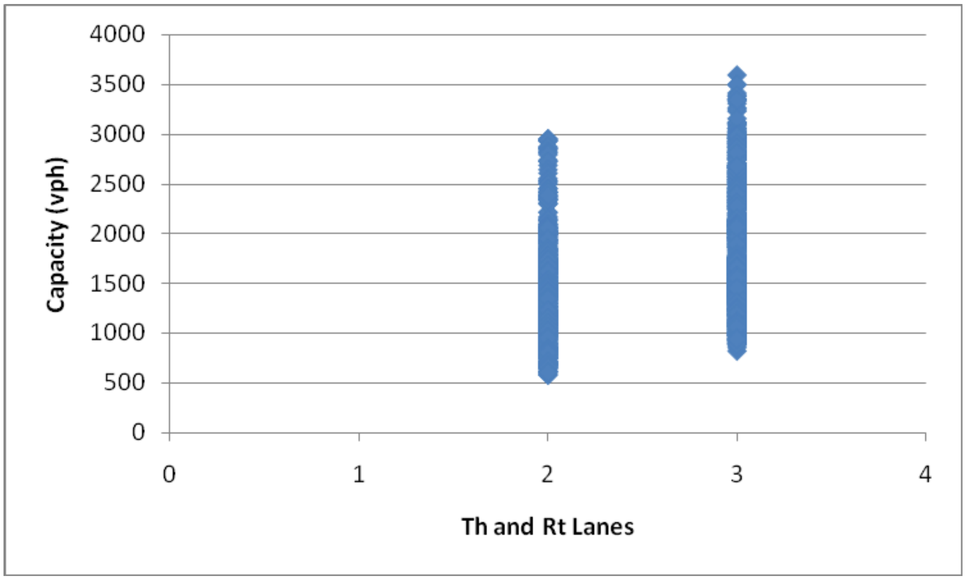

Figure A-37: Through and Right Lanes vs. Capacity (Scenario 4.0)

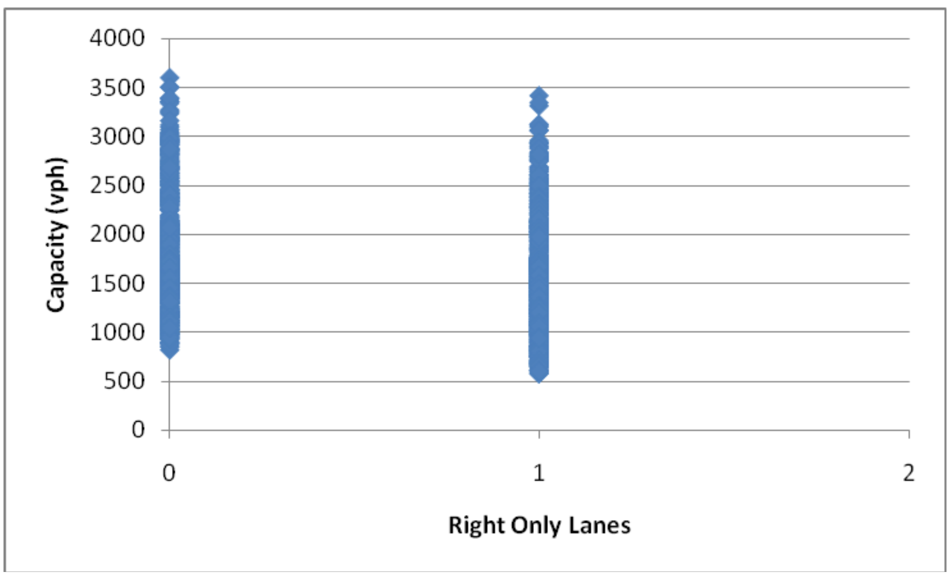

Figure A-38: Right-only Lanes vs. Capacity (Scenario 4.0)

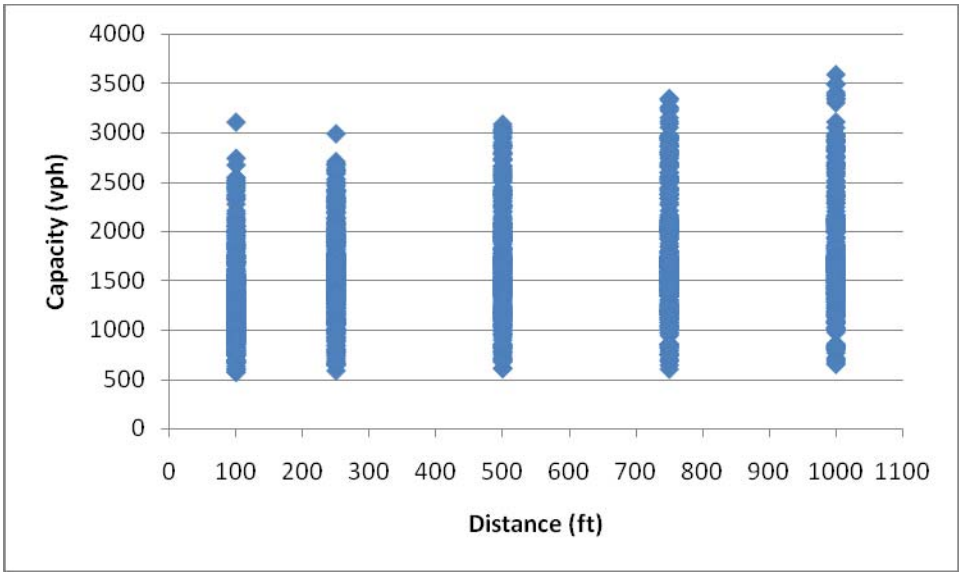

Figure A-39: Distance vs. Capacity (Scenario 4.0)

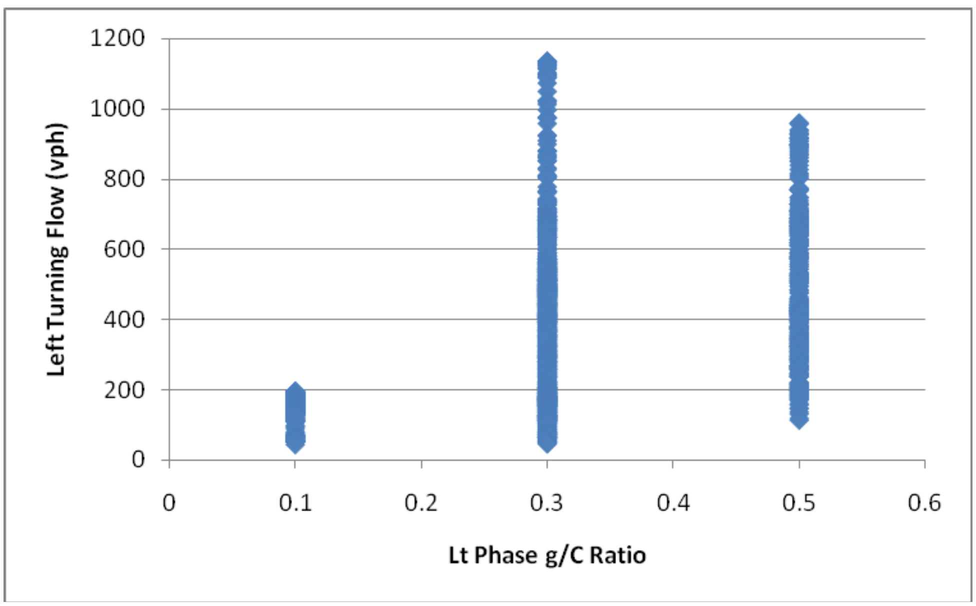

Figure A-40: Left Phase g/C vs. Left-turning Flow (Scenario 4.0)

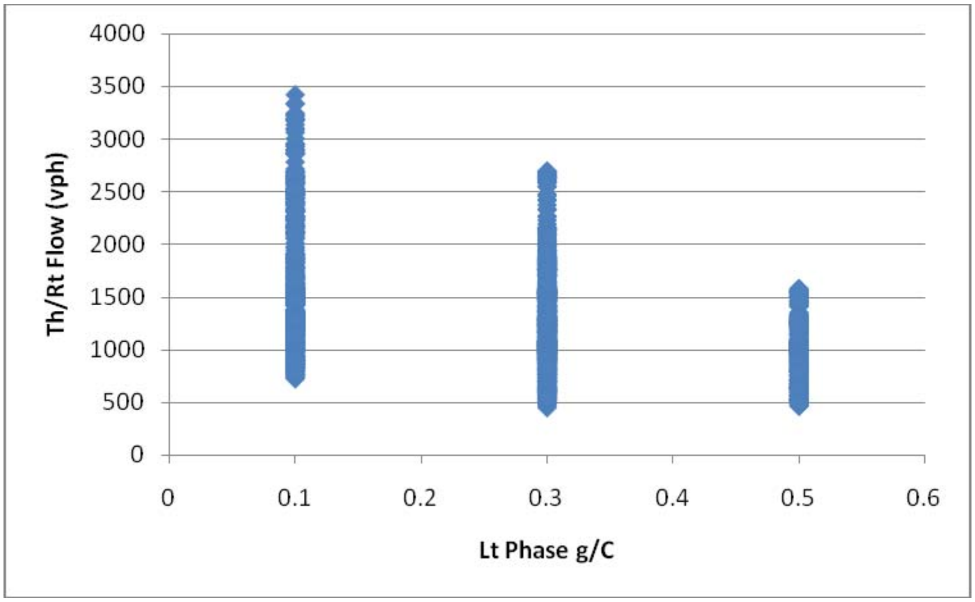

Figure A-41: Left Phase g/C vs. Th/Rt Flow (Scenario 4.0)

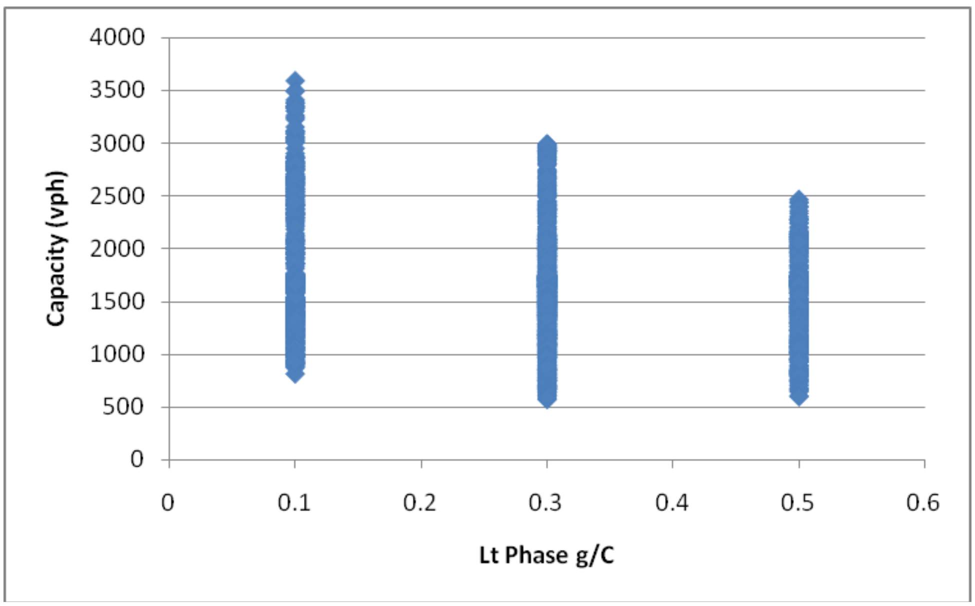

Figure A-42: Left Phase g/C vs. Capacity (Scenario 4.0)

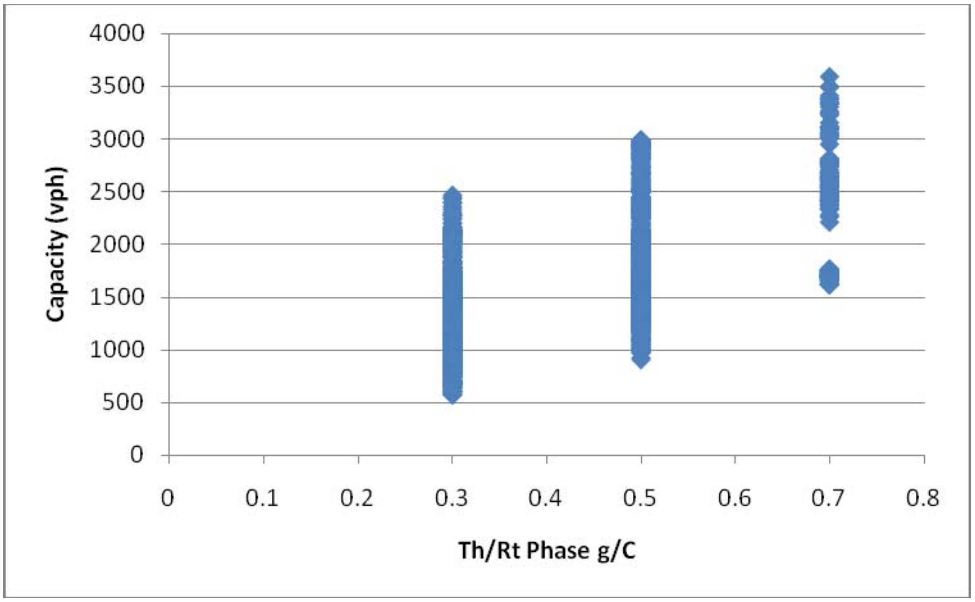

Figure A-43: Left Phase g/C vs. Capacity (Scenario 4.0)

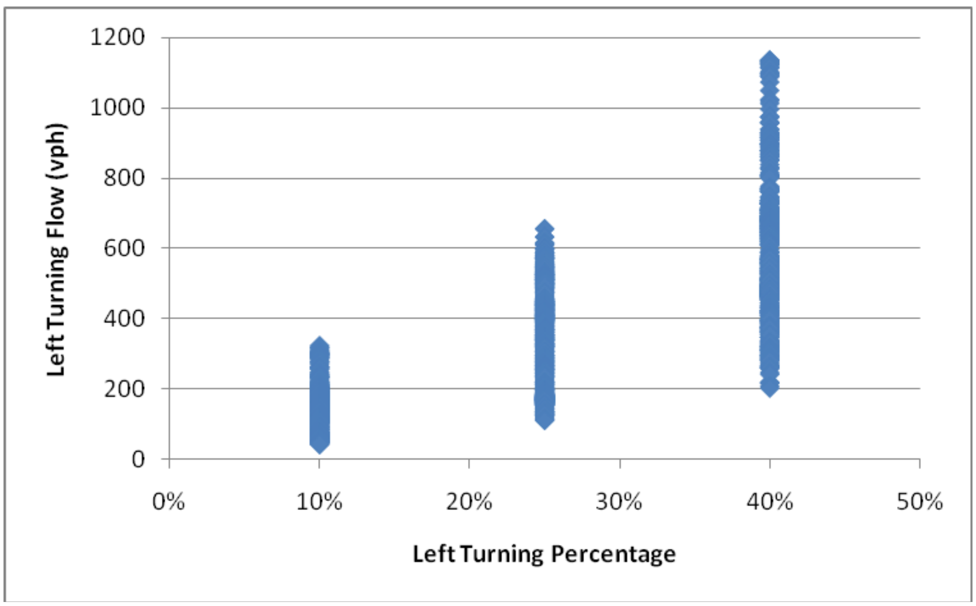

Figure A-44: Left-turning Percentage vs. Left-turning Flow (Scenario 4.0)

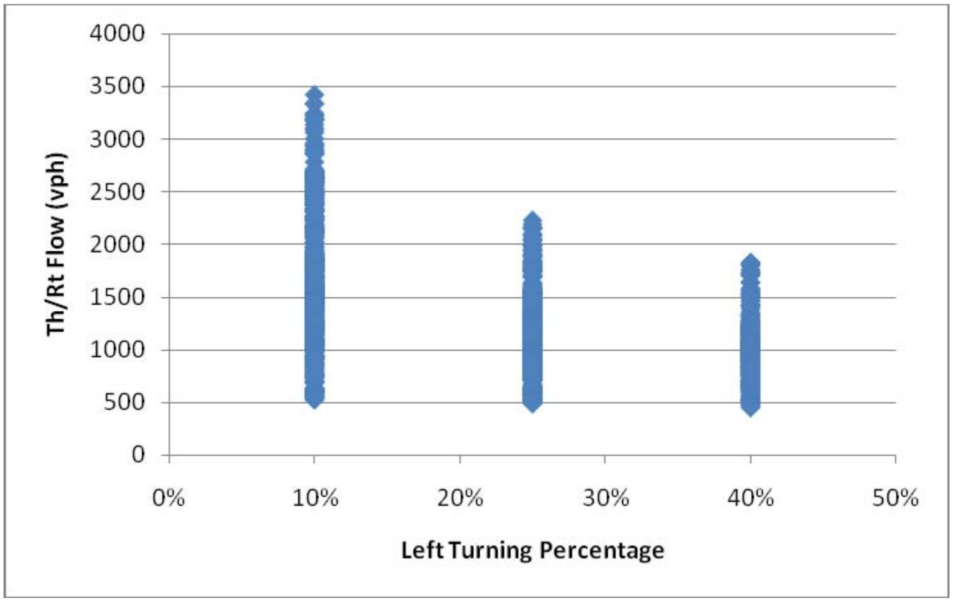

Figure A-45: Left-turning Percentage vs. Th/Rt Flow (Scenario 4.0)

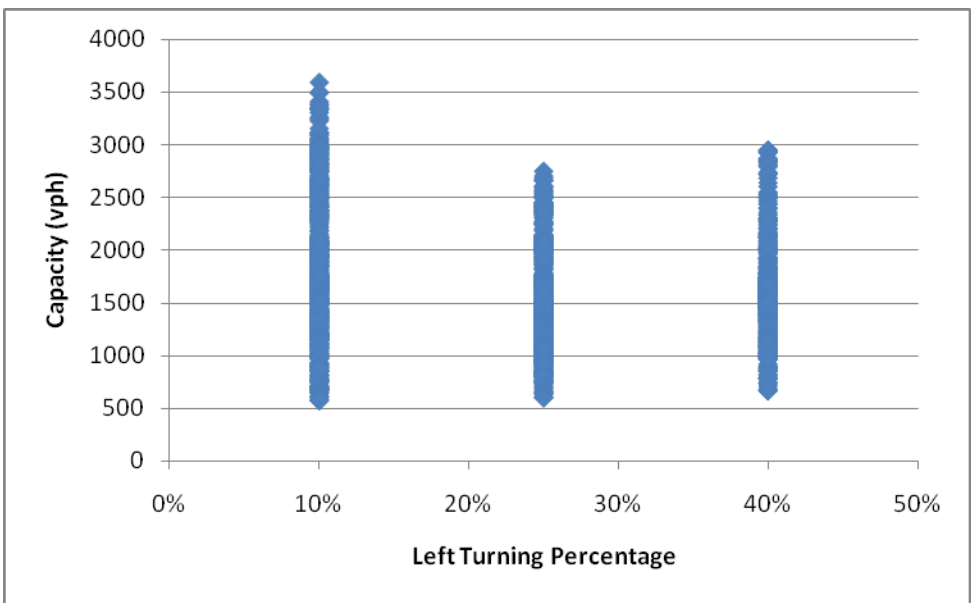

Figure A-46: Left-turning Percentage vs. Capacity (Scenario 4.0)

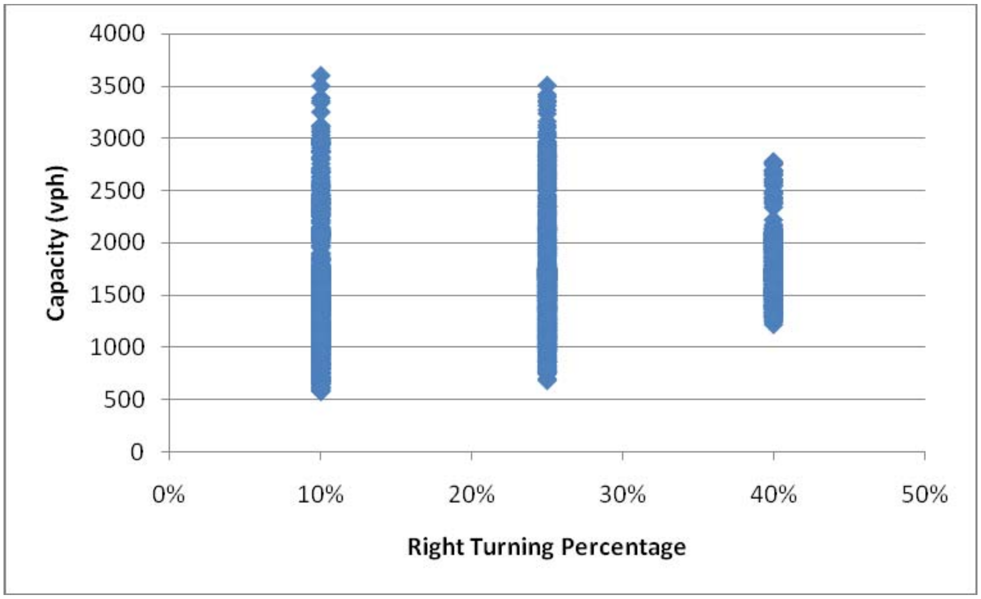

Figure A-47: Right-turning Percentage vs. Capacity (Scenario 4.0)

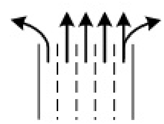

Figure A-48: Scenario 5.1 (Lane Channelization)

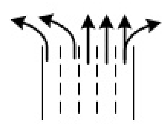

Figure A-49: Scenario 5.2 (Lane Channelization)

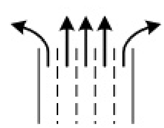

Figure A-50: Scenario 5.3 (Lane Channelization)

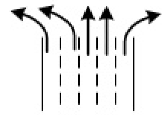

Figure A-51: Scenario 5.4 (Lane Channelization)

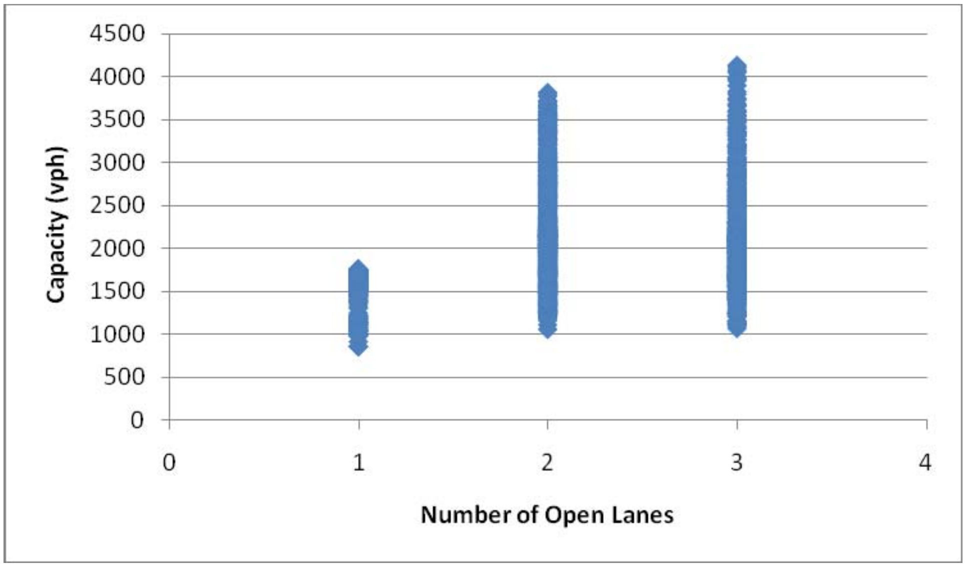

Figure A-52: Number of Open Lanes vs. Capacity (Scenario 5.0)

Figure A-53: Number of Left Turn Only Lanes vs. Capacity (Scenario 5.0)

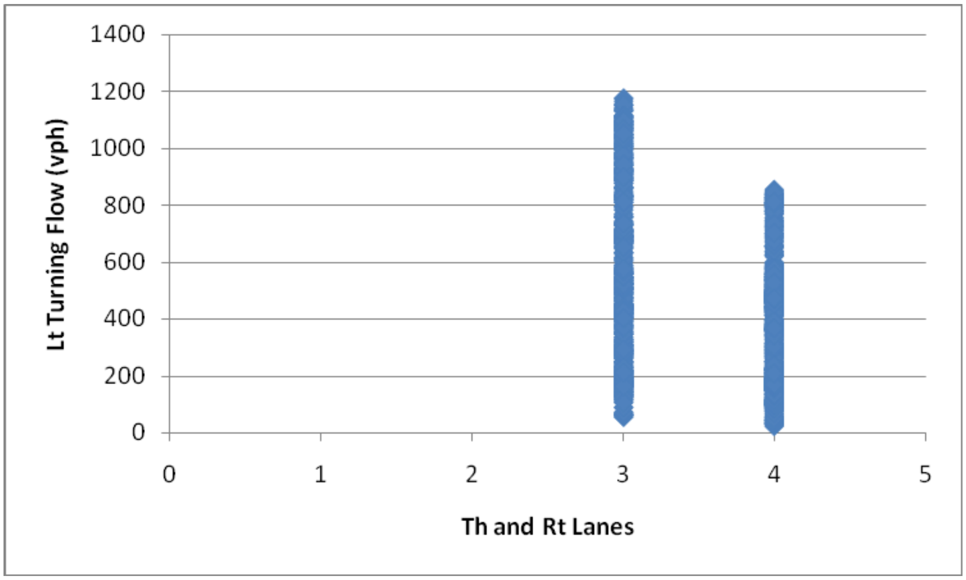

Figure A-54: Through and Right Lanes vs. Left-turning Flow (Scenario 5.0)

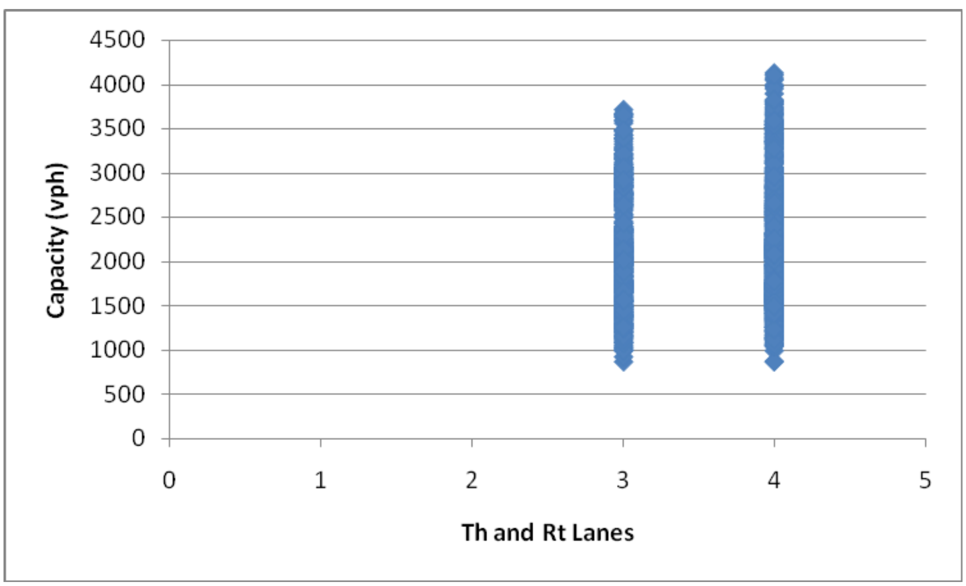

Figure A-55: Through and Right Lanes vs. Capacity (Scenario 5.0)

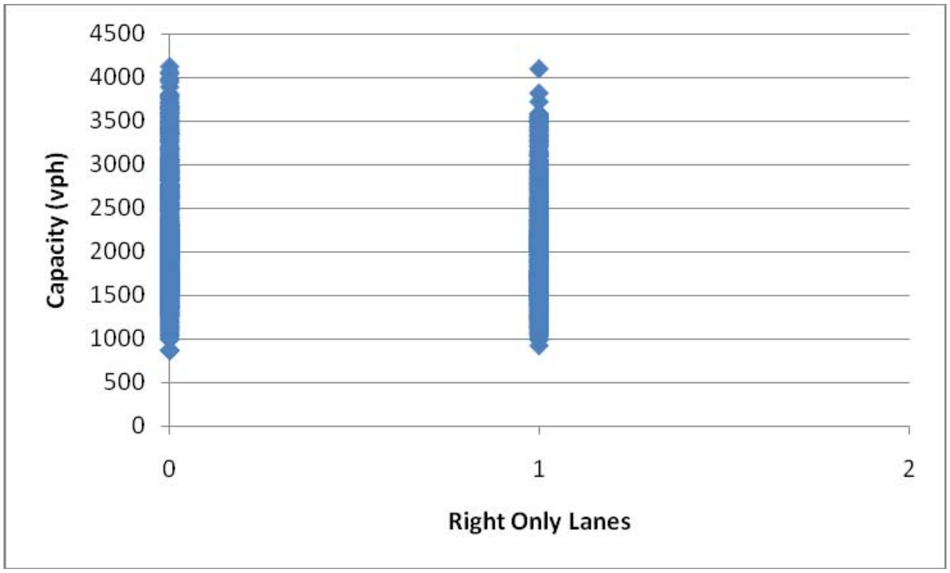

Figure A-56: Right-only Lanes vs. Capacity (Scenario 5.0)

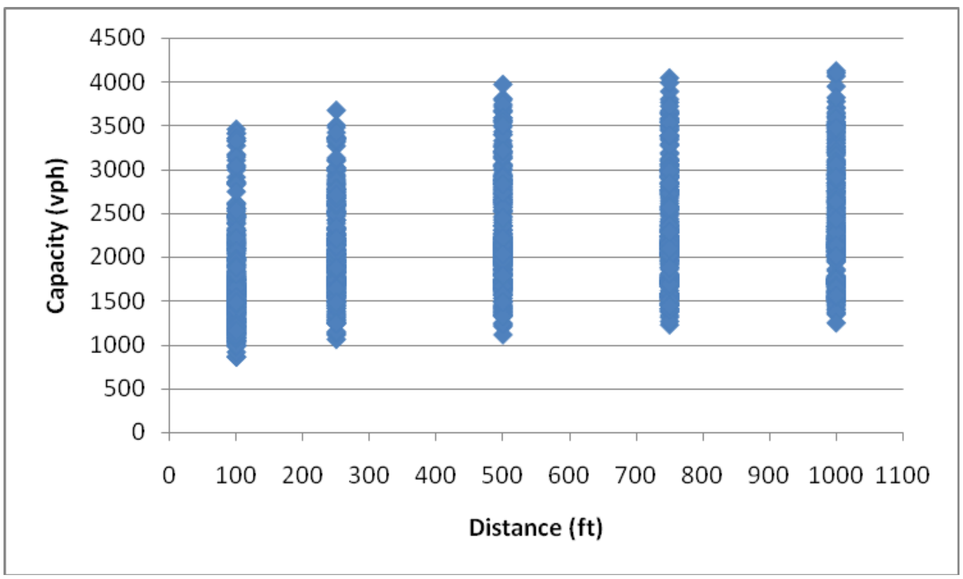

Figure A-57: Distance vs. Capacity (Scenario 5.0)

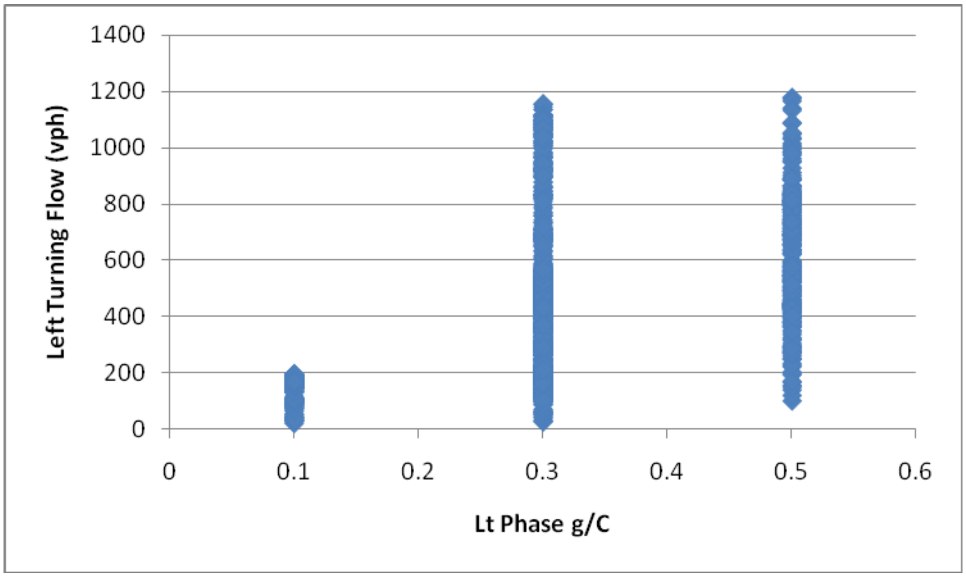

Figure A-58: Left Phase g/C vs. Lt Turning Flow (Scenario 5.0)

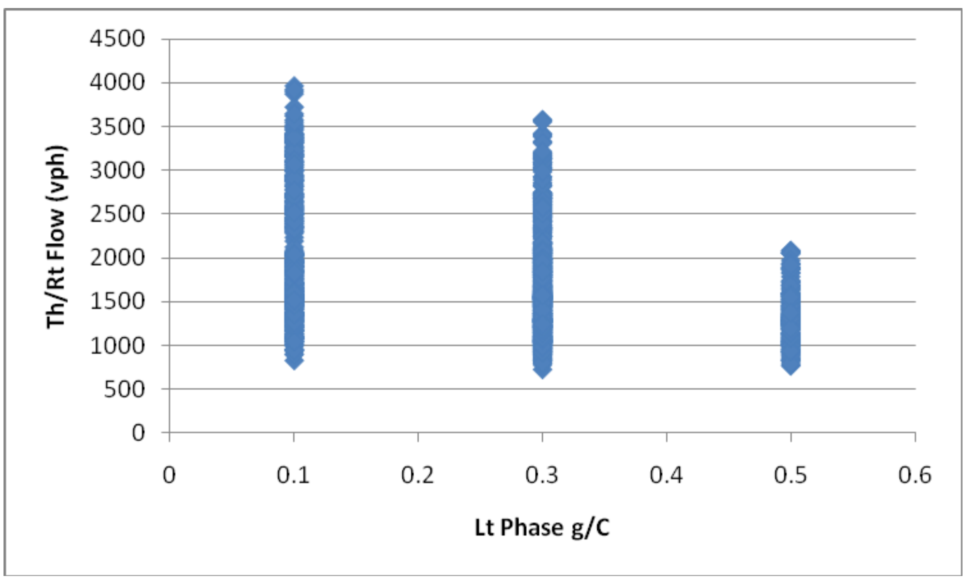

Figure A-59: Left Phase g/C vs. Right-turning Flow (Scenario 5.0)

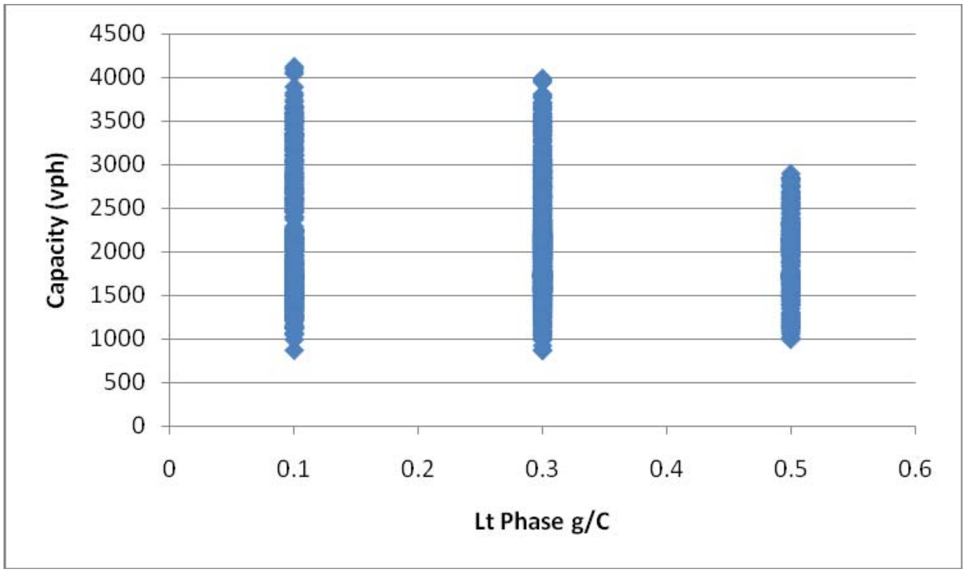

Figure A-60: Left Phase g/C vs. Capacity (Scenario 5.0)

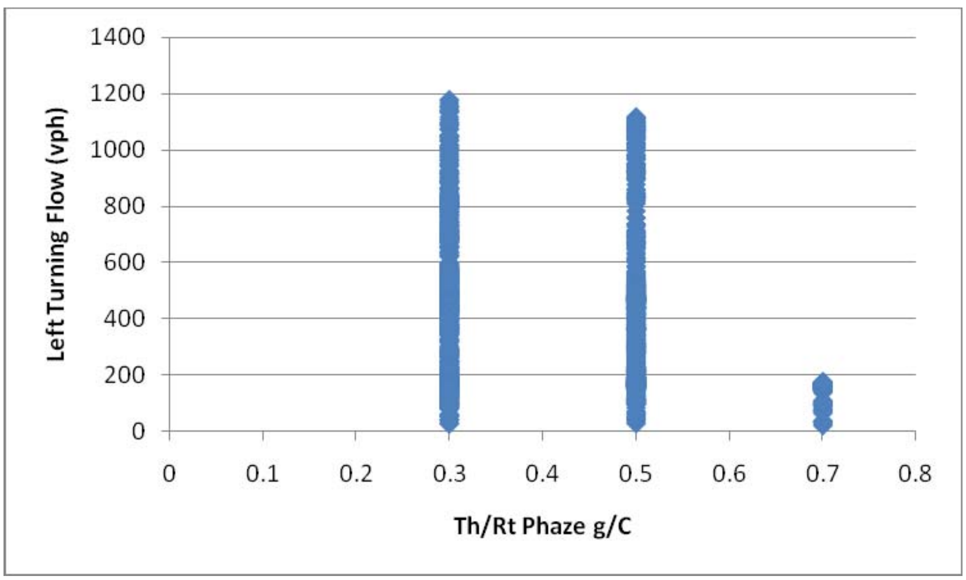

Figure A-61: Left Phase g/C vs. Left-turning Flow (Scenario 5.0)

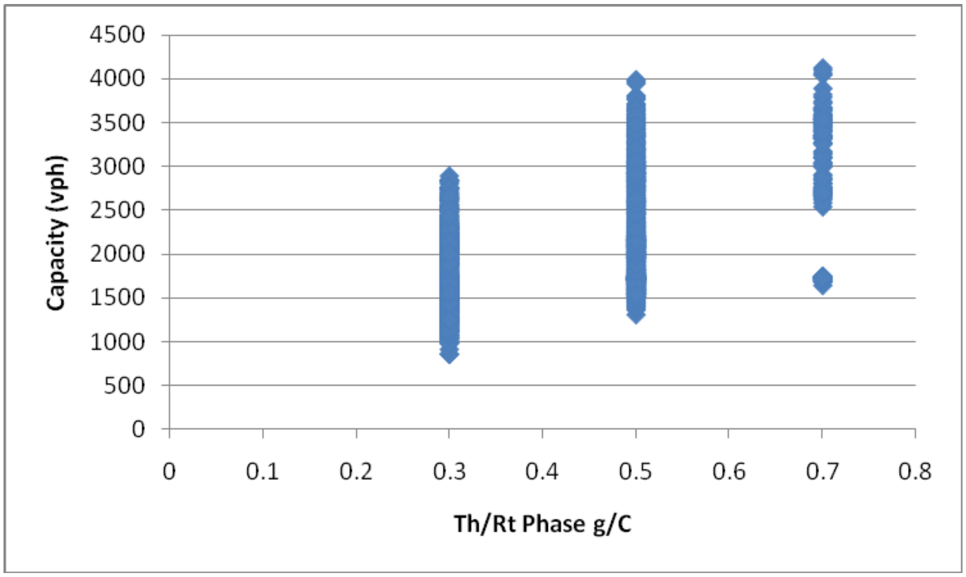

Figure A-62: Through Right Phase g/C vs. Capacity (Scenario 5.0)

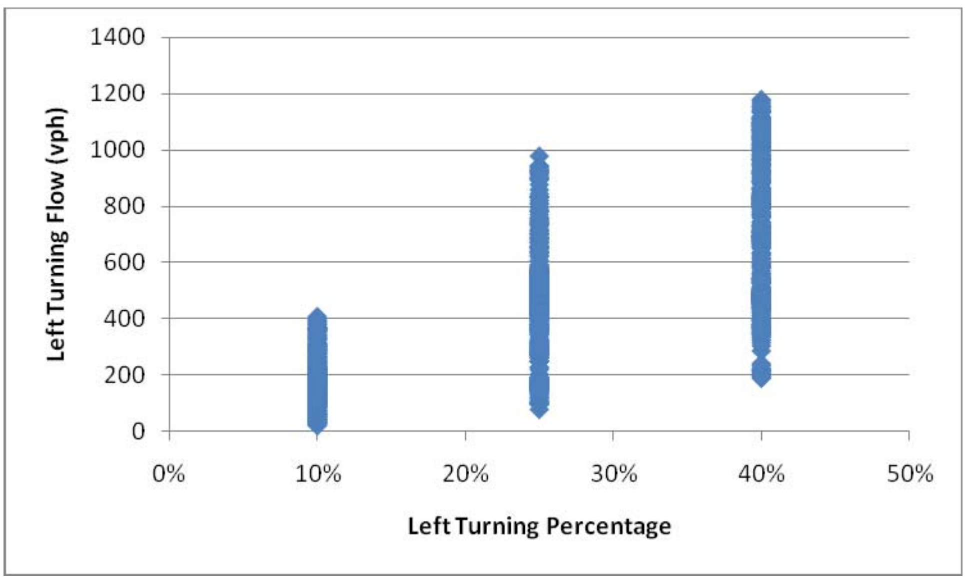

Figure A-63: Left-turning Percentage vs. Left-turning Flow (Scenario 5.0)

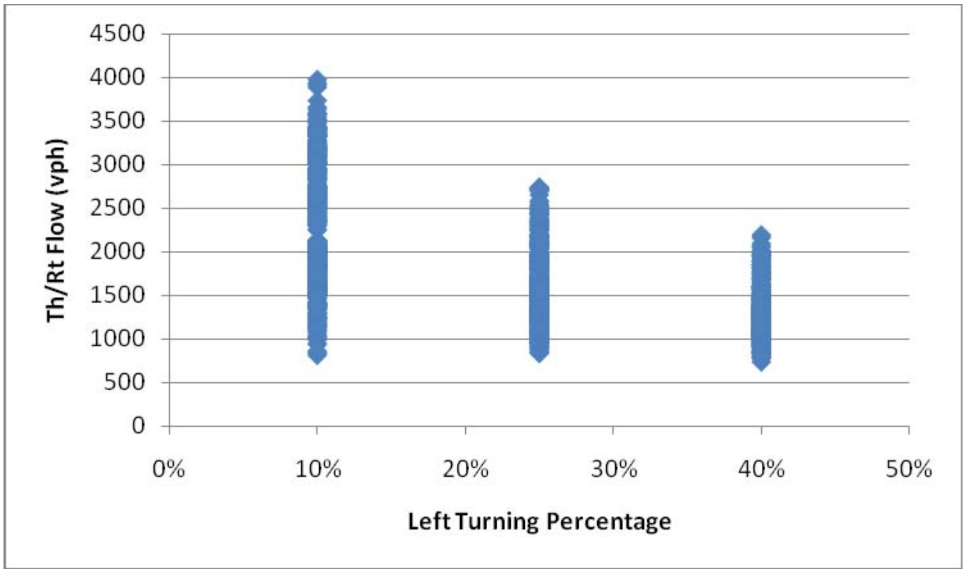

Figure A-64: Left-turning Percentage vs. Th/Rt Flow (Scenario 5.0)

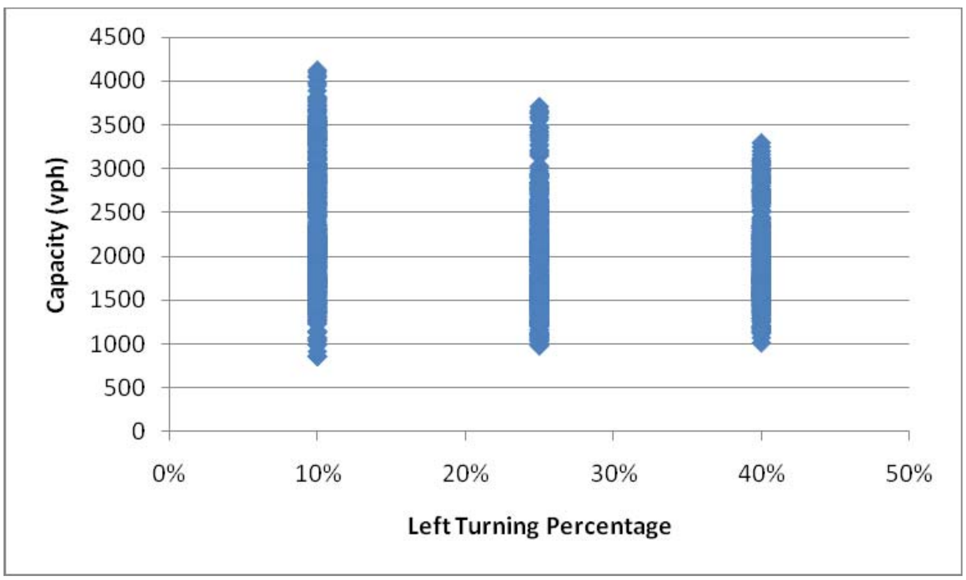

Figure A-65: Left-turning Percentage vs. Capacity (Scenario 5.0)

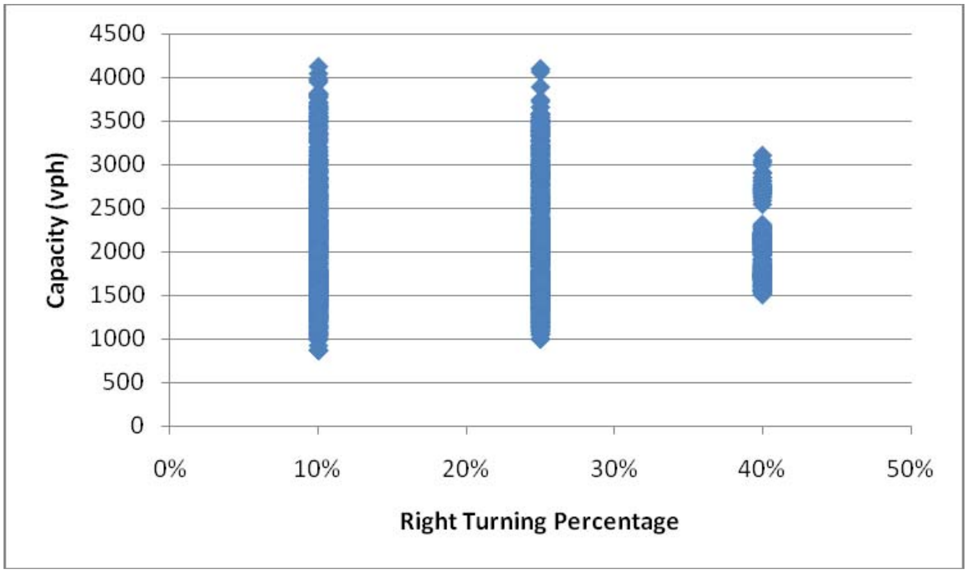

Figure A-66: Right-turning Percentage vs. Capacity (Scenario 5.0)

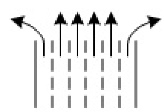

Figure A-67: Scenario 6.1 (Lane Channelization)

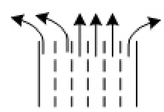

Figure A-68: Scenario 6.2 (Lane Channelization)

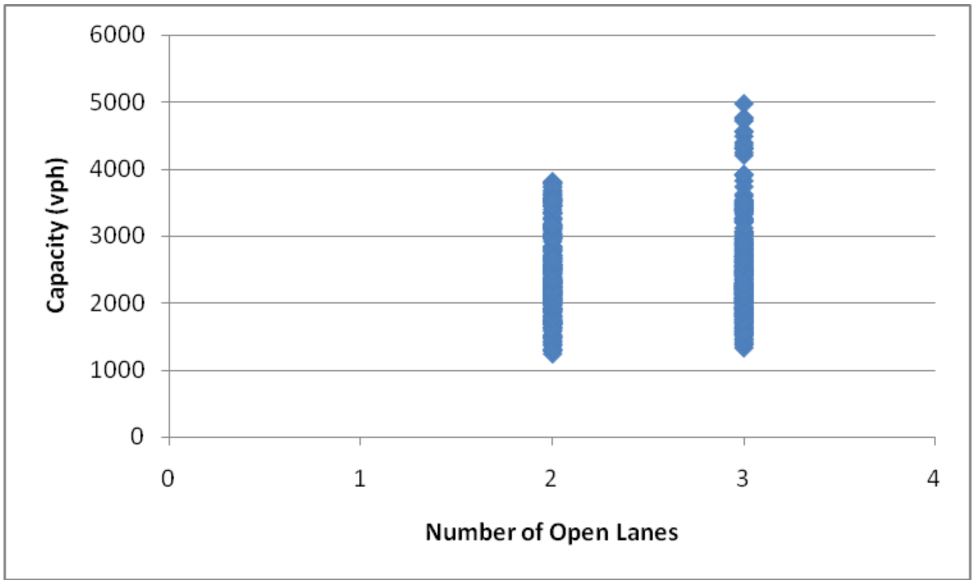

Figure A-69: Number of Open lanes vs. Capacity (Scenario 6.0)

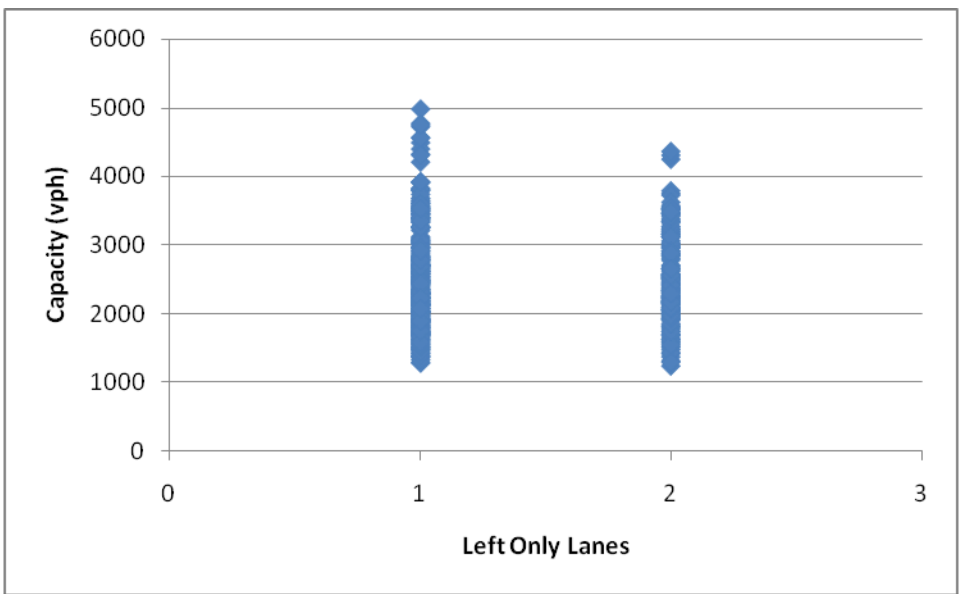

Figure A-70: Left-only Lanes vs. Capacity (Scenario 6.0)

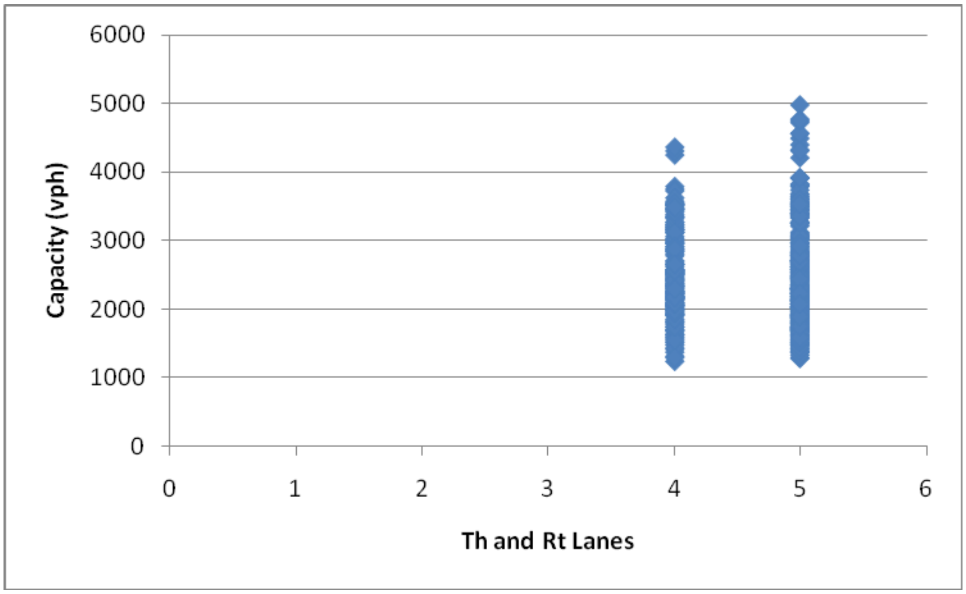

Figure A-71: Through and Right Lanes vs. Capacity (Scenario 6.0)

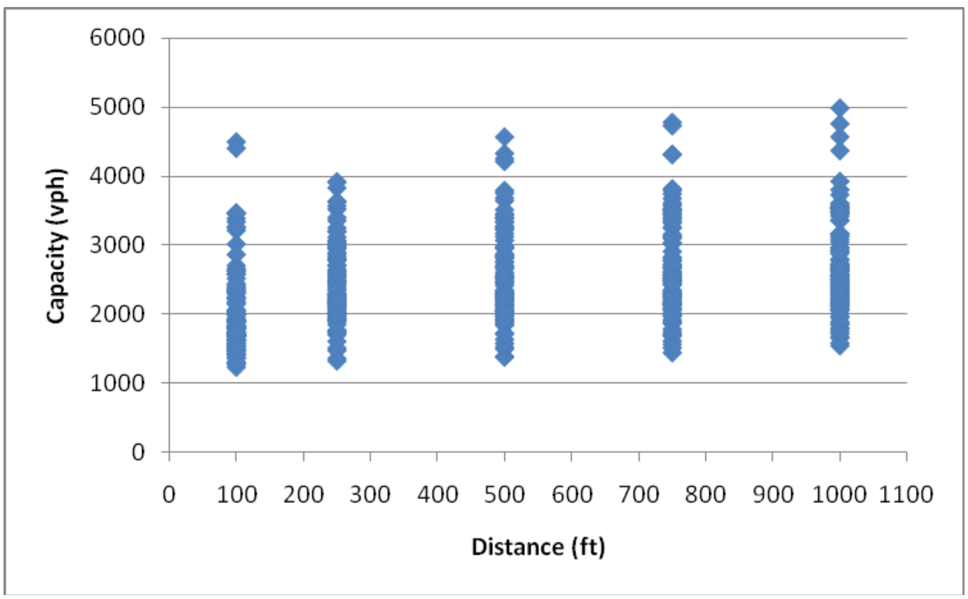

Figure A-72: Distance vs. Capacity (Scenario 6.0)

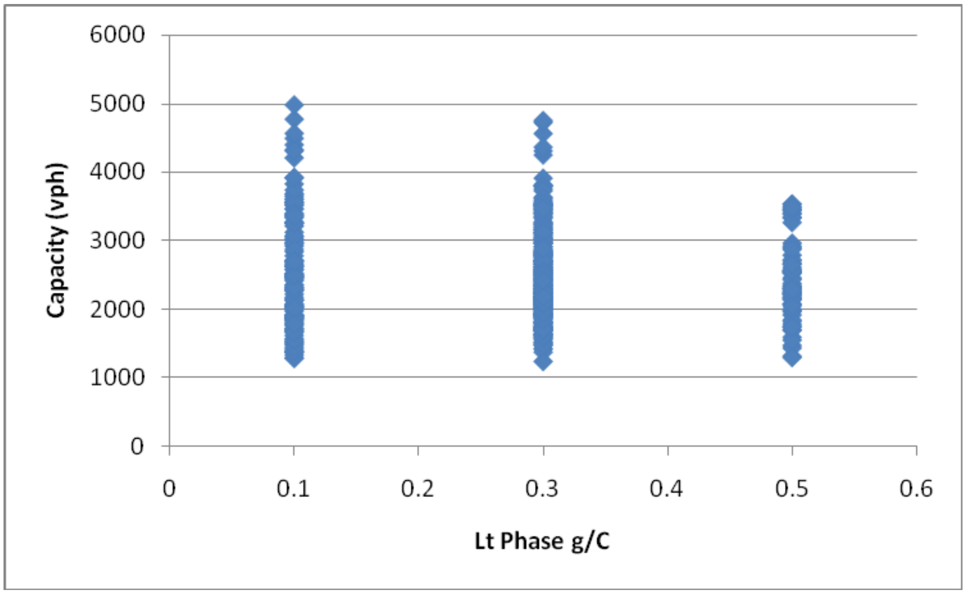

Figure A-73: Left Phase g/C vs. Capacity (Scenario 6.0)

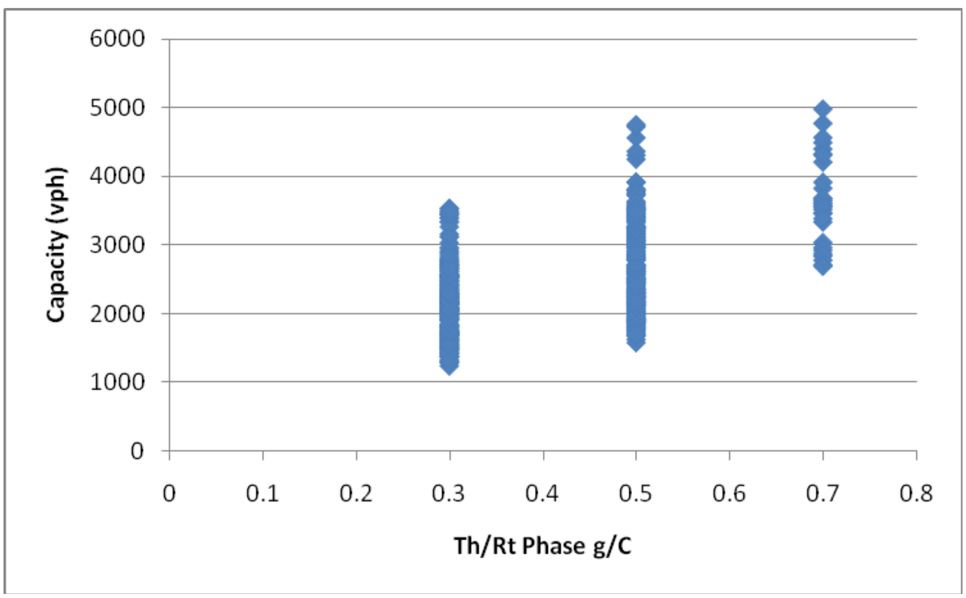

Figure A-74: Th/Rt Phase g/C vs. Capacity (Scenario 6.0)

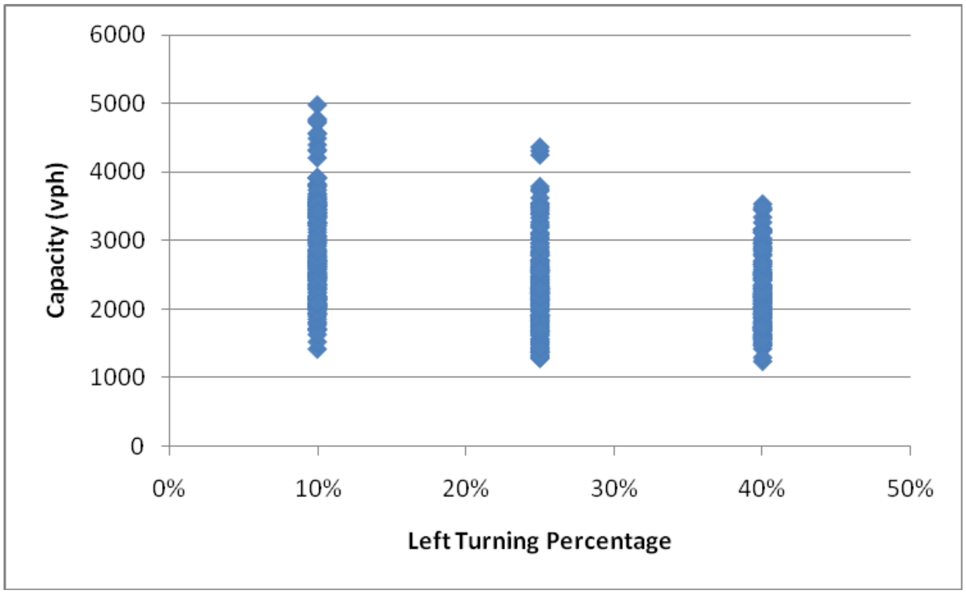

Figure A-75: Left-turning Percentage vs. Capacity (Scenario 6.0)

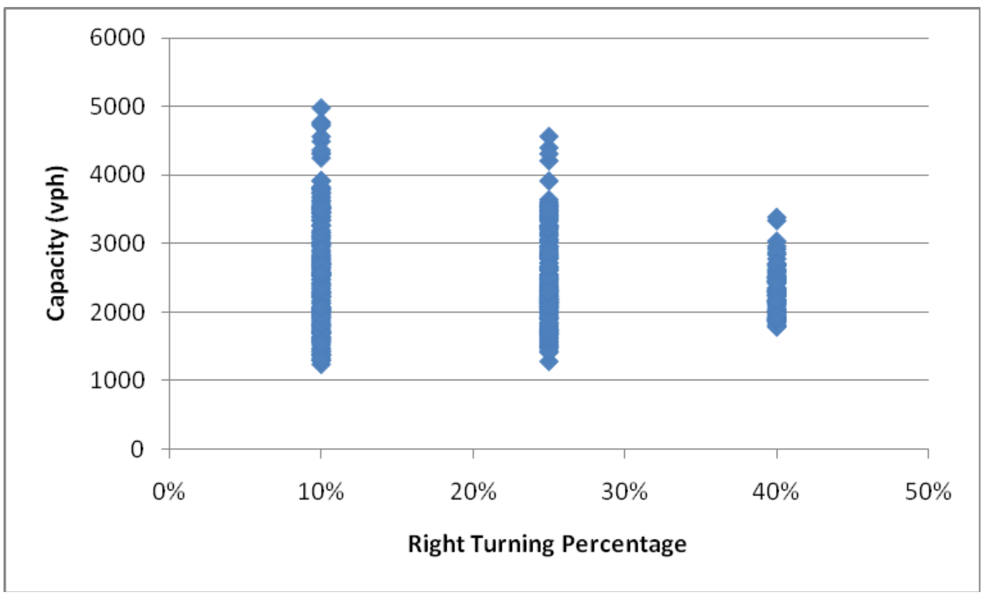

Figure A-76: Right-turning Percentage vs. Capacity (Scenario 6.0)

Table A-1: Aggregate Level Trends Summary

Factor	Trend for Capacity
Number of Open lanes	Maximum value increases, Minimum values remain same
Left-only Lanes	Maximum values decrease, minimum values remain almost same
Th and Rt lanes	Increase in capacity
right-only Lanes	No change
right-turning %	Goes down at very high values of 40% in some cases
Left-turning %	Capacity goes down
Distance	Increases till 500 ft and then remains almost constant
Left g/C	Capacity goes down
Th/Rt g/C	Increases almost linearly

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BIOGRAPHICAL SKETCH

Mayank Prakash Jain was born in the city of Udaipur in India. He belongs to the state of Rajasthan, the state with deserts. He went to high school in the city of lakes (Udaipur) and was brought up there. After his +2 he went to Kota to prepare for Joint Enterance Exam to get admission into one of the Indian Institutes of Technology. He completed his bachelor's degree in civil engineering at IIT Bombay. After that, he moved to University of Florida at Gainesville in Florida to complete his master's degree in civil engineering with specialization in transportation engineering.