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on Project

“Improvements and Enhancements to LOSPLAN 2007”

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Part B: Impact of left-turn spillover on through movement discharge at
signalized intersections



June 2009

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

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.388	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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16. Abstract <p>Signalized intersections are arguably the most critical components of an arterial. One of the major factors that affect the capacity of a signalized intersection is the presence of left-turning vehicles. Intersections that allow left turns usually have a left-turn bay to accommodate a certain amount of queuing. However, it is common to see the storage of a left-turn bay at a busy intersection exceeded during the peak periods. When this happens, the left-turning vehicles will spill over into the adjacent through lane and potentially reduce the discharge rate of through vehicles. The current Highway Capacity Manual (HCM) analysis procedure for signalized intersection operations does not explicitly account for left-turn bay spillover; thus, the assumption is that the through movement is unimpeded during the green phase of the through movement. For situations where left-turn spillover is prevalent, this can lead to overly optimistic estimates of signal delay for the through movement.</p> <p>This study developed predictive models for through movement discharge that consider the effects of left-turn traffic, phasing, and geometry, in addition to the through-movement characteristics. Therefore, potential left-turn spillover conditions are explicitly accounted for in the developed models. Simulation was used to generate the data on which the model development was based. The developed models will be incorporated into the Florida Department of Transportation's ARTPLAN software to provide for more accurate analysis of signalized arterial conditions during congested time periods.</p>					
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Report Organization

The content for this report is essentially the master's thesis prepared by Ms. Abigail Osei-Asamoah under the supervision of Dr. Scott Washburn. The front matter that was relevant only to the graduate school of the University of Florida was deleted, and some minor editorial and formatting revisions were also performed.

IMPACT OF LEFT-TURN SPILLOVER ON THROUGH
MOVEMENT DISCHARGE AT SIGNALIZED
INTERSECTIONS

EXECUTIVE SUMMARY

Signalized intersections are arguably the most critical components of an arterial. One of the major factors that affect the capacity of a signalized intersection is the presence of left-turning vehicles. Intersections that allow left turns usually have a left-turn bay to accommodate a certain amount of queuing. However, it is common to see the storage of a left-turn bay at a busy intersection exceeded during the peak periods. When this happens, the left-turning vehicles will spill over into the adjacent through lane and potentially reduce the discharge rate of through vehicles. The current Highway Capacity Manual (HCM) analysis procedure for signalized intersection operations does not explicitly account for left-turn bay spillover; thus, the assumption is that the through movement is unimpeded during the green phase of the through movement. For situations where left-turn spillover is prevalent, this can lead to overly optimistic estimates of signal delay for the through movement.

The objective of this study was to determine the factors that significantly affect left-turn lane spillover and develop a model, or models, to predict the expected through movement discharge rate as a function of this spillover. This objective was accomplished through the following supporting tasks: conducting a literature review; performing simple tests in the selected simulation tool to ensure the results were reliable; developing and executing a simulation experimental design based on the identified significant variables; and analyzing the simulation data and developing the model(s).

Simulation was used to generate the required data for this study. After some preliminary experimentation, the following factors were chosen for inclusion in the experimental design: left-turn bay length, left-turn percentage, through green time, left-turn green time, cycle length, approach demand, and number of through lanes.

A full factorial regression analysis was run on the data set obtained from the simulation runs to facilitate the consideration of variable interactions in the model development. Two different models were developed to predict the through movement discharge rate. One model is intended for application to signalized intersection approaches with only one through lane, in addition to the left-turn bay. The other model is intended for application to signalized intersection approaches with multiple through lanes.

The two developed models replicate the simulation results quite reasonably, as indicated by the goodness-of-fit measures. The relationship between the various model variables and their effect on through movement discharge rate are also reasonable and consistent with theoretical expectations. For intersections where left-turn spillover is a consistent problem, the models developed in this study can be applied to give a more accurate estimate of the expected through-movement flow rate than an analysis that ignores the left-turn spillover condition. The developed models will be incorporated into the Florida Department of Transportation's ARTPLAN software to provide for more accurate analysis of signalized arterial conditions during congested time periods.

While the results of this study present a significant improvement over the current condition; that is, a signalized intersection analysis methodology that ignores the effect of left-turn spillover on through movement discharge rates (i.e., the HCM), there are still areas that can be improved upon.

- Ideally, field data should be collected from a number of signalized intersections that experience left-turn spillover to use for calibrating and/or validating the regression models developed in this study.
- Further experiments should be conducted to investigate the effect of progression quality on left-turn spillover and through movement discharge rate. Once this relationship is established, this variable can be incorporated into the two models developed in this study to further improve its predictive capabilities over a wider range of traffic and control conditions.

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1. INTRODUCTION

Background

Signalized intersections are arguably the most critical components of an arterial. They can be a major source of delay on the arterial. This Highway Capacity Manual 2000 prescribes intersection delay (also referred to as control delay) as the service measure for signalized intersections; that is the performance measure upon which level of service is based. Effective traffic operations at a signalized intersection improve delay conditions and ultimately the level of service of the intersection.

Left-turn operations and their treatment are very important at a signalized intersection. Where left-turn demand is very high, a separate phase is usually created for the left-turning vehicles in the signal timing plan in addition to an exclusive left-turn lane. These left-turn lanes are usually shorter than the through lanes and are referred to as bays. If the length of the left-turn bay and phase timing are appropriate for the traffic conditions, there will be no adverse impact to through traffic operations (disregarding tradeoffs in green time due to adding a phase).

A common occurrence usually during the peak period however is when left-turn volumes are significantly high, left-turning vehicles spillover from the left-turn bay to the adjacent through lane as a result of inadequate signal timing and/or storage bay length. This situation can result in a reduction of the through vehicle discharge rate.

Problem Statement

The HCM traffic operations analysis procedure for signalized intersections assumes that through traffic is not impeded by turning movements. However, in urban settings, congestion is the norm and the probability of left-turning traffic spilling over from turn lanes and into the adjacent through lanes can occur frequently during the peak period. When the left-turn traffic spills over into the through lane, the discharge rate of the through lane is often reduced. If the

HCM methodology is used for an analysis under these conditions, the results will be overly optimistic in the estimation of capacity and delay at the signalized intersection. It is therefore necessary to determine the factors that significantly affect left-turn spillover and how these factors affect the discharge rate of the adjacent through lane(s).

Objective and Tasks

Our primary objective was to determine the factors that significantly affect left-turn lane spillover and develop a model, or models, to predict the expected through movement discharge rate as a function of this spillover. This objective was accomplished through the following supporting tasks:

- Conduct a literature review
- Perform simple tests in the selected simulation tool to ensure the results were reliable
- Develop and execute a simulation experimental design based on the identified significant variables
- Analyze the simulation data and develop the model(s)

Document Organization

Chapter 2 presents an overview of relevant studies found in literature. This review looks at the various methods proposed in the literature for identifying factors that significantly affect left-turn spillover, determining the probability of a left-turn spillover and the effect of the spillover on the discharge rate of the adjacent through lane(s).

Chapter 3 describes the research approach that was used to accomplish the objectives of this study. This chapter presents the tests of variables that significantly affect left-turn spillover, and the development and execution of an experimental design of these significant variables in a simulation tool. Chapter 4 presents the development of models that predict through vehicle discharge based on roadway, traffic, and control characteristics of the intersection approach.

Chapter 5 presents a summary of this study, conclusions drawn and recommendations for further study.

2. LITERATURE REVIEW

Introduction

This chapter provides an overview of previous studies and methodologies that deal with left-turn spillover. While a number of studies have been done on signalized intersections and their operation, only a limited number of them deal explicitly with the effect of left-turn spillover on through lane discharge rate.

Most previous studies on left-turn spillover focus on the determination of storage lengths of left-turn lanes to prevent left-turn spillover. A few studies deal with the complimentary issue of left-turn lane blockage due to through lane spillback. Some studies also involve determining the probability of the occurrence of left-turn lane spillover and determination of capacity of the through lane based on this probability.

Current Analysis Procedures

The HCM (2000) does provide a separate procedure in appendix G of the signalized intersection analysis methodology to calculate the back of queue. The HCM (2000) defines the back of queue as “the number of vehicles that are queued, depending on the arrival patterns of vehicles and on the number of vehicles that do not clear the intersection during the green phase (overflow)”. The back of queue calculation comprises of two terms; Q_1 ; defined as the first term queued vehicles and Q_2 ; defined as the second termed queued vehicles. This first term queued vehicles “ Q_1 ” is calculated using Equation 2-1.

$$Q_1 = PF_2 \times \frac{\frac{v_L C}{3600} \left(1 - \frac{g}{C}\right)}{1 - \left[\min(1.0, X_L)\right] \frac{g}{C}} \quad [2-1]$$

Where

Q_1 = first term queued vehicles (veh)

PF_2 = adjustment factor for effects of progression

v_L = lane group flow rate per lane (veh/h)
 C = cycle length (s)
 g = effective green time (s)
 X_L = ratio of flow rate to capacity (v_L/c_L ratio)

The second term “ Q_2 ” is calculated using Equation 2-2.

$$Q_2 = 0.25c_L T \left[(X_L - 1) + \sqrt{(X_L - 1)^2 + \frac{8k_B X_L}{c_L T} + \frac{16k_B Q_{bL}}{(c_L T)^2}} \right] \quad [2-2]$$

Where

Q_2 = second term of queued vehicles, estimate for average overflow queue (veh)
 c_L = lane group capacity per lane (veh/h)
 T = length of analysis period (h)
 X_L = v_L/c_L ratio
 k_B = second-term adjustment factor related to early arrivals
 Q_{bL} = initial queue at start of analysis period (veh)
 C = cycle length (s)

From these, the average back of queue can be determined as the sum of the terms; Q_1 and Q_2 . The back of queue measure is specified as useful for dealing with the blockage of available queue storage distance determined from the queue storage ratio; which is defined as the ratio of estimated queue length to the available storage space. The queue storage ratio uses the back of queue, queued vehicle spacing and available storage to determine if blockage will occur. The queue storage ratio is calculated using Equation 2-3. Blockage is defined to occur when this queue storage ratio equals or exceeds a value of 1.

$$Q_R = \frac{L_H Q}{L_a} \quad [2-3]$$

Where

Q_R = average queue storage ratio
 L_H = average queue spacing in a stationary queue (ft)
 L_a = available queue storage distance (ft)
 Q = average number of vehicles in queue (veh)

Although this procedure exists to compute the queue storage ratio, the results are not directly incorporated into the HCM signal analysis methodology. Furthermore, even though an analyst can use this calculation procedure to determine if through lane blockage may occur due to spillover, the HCM offers no guidance on how to determine the subsequent quantitative impact to the through movement discharge rate of the adjacent through lane(s).

Queue Length Model Comparisons

Viloria et al. (2000) compared queue length models. Queue length models from the following traffic analysis methodologies or programs were included in the study: SIDRA, NETSIM, TRANSYT-7F, SOAP, SIGNAL 97, HCM 2000, NCHRP Report 279, Oppenlander's method, and Teply's queuing criteria. A classification framework was developed for models from the above programs/methodologies and their behavior compared to that of the HCM 2000 queue model. The scope of analysis was limited to under saturated conditions.

A queue reach measure was defined in the study as a measure to determine adequacy of storage at the intersection. Some models were identified to predict the probability that the maximum queue reach will exceed the maximum storage requirements. Older queue models applied a constant of 2 as a factor of safety to account for the combination of factors that cause the queue to exceed its average length on some cycles causing overflow. More complex models dealt with overflow and assigned an explicit confidence percentile to a stochastic adjustment factor.

Of the models compared, NETSIM was the only model found to deal explicitly with effects of queue storage spillover on movement of traffic on adjacent lanes. Analytical models/methodologies just computed queue length, whereas NETSIM is a microscopic simulation tool that accounts for spillover through the vehicle movement modeling. NETSIM unlike the analytical models defined its queue length as queue accumulation and not queue reach.

Regression techniques were used to establish the type of relation and reliability between proposed HCM queue models and the other queue models. Queue estimates generated by each model were plotted against the HCM average back of queue, 90th and 98th percentile, queue confidence levels.

The HCM 2000 model and SIDRA provided higher queue length values than most of the other models because some models reported only the average values and applied no extension factor. Average values from other models before expansion (adjustment to account for the effect of overflow) did not reflect the possibility of overflow from previous cycles.

Simulation Studies

Messer and Fambro (1977) investigated the effect of signal phasing and length of left-turn bay on signal capacity and delay. Traffic operations were simulated on only one intersection approach with a protected left-turn lane and an adjacent through lane.

For their study of delay, two signal phasing arrangements were used in their simulation program; leading and lagging phase sequences. Two different cycle lengths of 60 s and 80 s were used in the study. Their results showed that leading and lagging phase sequences performed better for short bay lengths. Results of their simulation showed that delay increased, with increasing volume, nominal saturation ratio (defined as the ratio of the normal demand of the movement to the phase capacity when the left-turn storage is enough to prevent blockages) and cycle length. Delay also increased as the length of the bay decreased. Lagging left-turn operations resulted in a slightly reduced delay for the conditions studied.

For left-turn capacity investigations, two additional phase sequences were added; dual leading lefts and dual lagging lefts. Greater reductions in capacity occurred at higher volumes. Reductions in capacity also varied with the percentage of traffic turning left and the green splits for the left turn and through movements.

Left-turn bay lengths were also determined from a modified Poisson approach. Design lengths of left-turn lanes were provided based on results of the study.

Oppenlander and Oppenlander (1994) developed a Monte Carlo Simulation model for determining the design lengths of left-turn lanes with separate control. This simulation model was designed to model the interaction of vehicles arriving at the signalized intersection, the signal operation and the movement of vehicle through the intersection. Queue lengths over commonly observed ranges of left-turn volumes (50 to 400 veh/h, 50 veh/h intervals), green times (10 to 30 s, 5 s intervals) and cycle lengths (60 to 120 s, 15 s intervals) were generated using the model. Vehicle arrivals were modeled according to a Poisson relationship.

A total of 1000 signal cycles were simulated in the model for a single set of design parameters to produce queue length distributions. Design tables were developed to indicate the 50th, 85th and 95th percentile queue lengths for left turns with separate phases, at intersections with different left-turn volumes, cycle lengths and left-turn green times.

The 85th and 95th percentiles were specified to minimize the possibility of traffic demand exceeding storage requirements of the left-turn lane. The 50th percentile queue length provided a median point for the designer. Design storage lengths were to be sized in accordance with local design vehicles.

Analytical and Probabilistic Methods

Kikuchi et al. (1993) developed a probabilistic model for determination of lengths of left - turn lanes at signalized intersections based on left-turn overflow into through lanes and blockage of the entrance into the left-turn lane by the queued adjacent through vehicles. Left-turn overflow was determined to be dependent on left-turn volume, the protected phase duration, cycle length, opposing through volume and layout of the intersection; factors that affect the arrival and the

service rate of the left-turning vehicles. The left-turn blockage problem, however, was determined to be dependent on the through vehicle volume and through red time.

Models for computing the probabilities of lane overflow and blockage were developed. A threshold probability defined as “the tolerable frequency of occurrence of both problems” was specified for both cases. Selection of this threshold value depended on a number of factors including economic, capacity, safety, and site-specific conditions. This threshold affected the necessary length of left-turn lanes. Other factors affecting the length of left-turn lanes were traffic volumes, vehicle mix, signal timing, time required to make a left turn, and the space required for a stationary vehicle. The required left lane length in units of vehicles “ N^* ” from the lane overflow perspective were determined by Equation 2-4.

$$N^* = \min \left\{ N \left| \left(1 - \sum_{i=0}^N \pi_i \right) \leq \tau_i \right. \right\} \quad [2-4]$$

Where

N = number of vehicles in left-turn lane

π_i = steady state probability of a given queue existing in left-turn lane

τ_i = threshold probability

Left-turn lane lengths “ N^{**} ” from the blockage perspective were determined from Equation 2-5.

$$N^{**} = \min \{ N | P_B(N) \leq \tau_i \} \quad [2-5]$$

Where

$P_B(N)$ = probability of blockage when left-turn storage length is sufficient to store at most N vehicles

τ_i = threshold probability

Lane lengths determined from the blockage perspective usually had longer lengths than those determined from the overflow perspective. The recommended lane length “RL” is therefore determined from Equation 2-6.

$$RL = \max \{ N^*, N^{**} \} \quad [2-6]$$

Kikuchi et al. (2004) employed a probabilistic approach for determining the lengths of dual left-turn lanes (DLTL). Lengths of the left-turn lanes were determined based on two main considerations; first, minimizing the probability of overflow of left-turning vehicles into adjacent through lanes and second, minimizing the chance of queued through vehicles blocking the entrance to left-turn lanes. The arrival patterns of left-turning vehicles and through vehicles were directly related to the event of overflow and blockage of entrance to the dual left-turn lane as determined from surveys on lane selection in dual left-turn lanes.

A threshold probability was specified and defined in their approach as; the minimum value of probability that all the arriving vehicles can enter the dual left-turn lanes without spillover or blockage. Other factors considered included, signal timing and vehicle mix. Vehicle arrivals were assumed to follow a Poisson's distribution.

The probability of all left-turning vehicles arriving during the red phase, entering the dual left-turn lanes without blockage or spillover was determined as a function of the length of left-turn lanes and the average arrival rate of the left-turning vehicles and through vehicles. The above probability increased with the length of left-turn lane. It was also a function of the duration of the red phase for the left-turning and through vehicles.

Shorter red left-turn phases resulted in an increase in the probability of all left-turning vehicles entering the dual left-turn lanes without spillover. Also the probability of the queued through vehicles blocking the left-turn lanes decreased with an increase in the number of lanes. The required lengths of left-turn lanes were determined as the length for which this probability that all arriving vehicles can enter the DLTL without blockage or spillover is greater than the threshold value. Adequate lengths of the DLTL was also to take into account volume distribution among the DLTL and adjacent through lane and the vehicle mix.

Zhang and Tong (2007) developed models for left-turn and through movement capacity that account for the effects of left-turn bay length and signal timing strategy on the intersection capacity and signal operation investigated. The capacity models incorporate a term that represents the probability of blockage (of the left-turn or through lane(s)). The physical length of the left-turn bay was denoted as ‘ N ’ vehicles, but it was found from field observation that an additional two vehicles could enter the left-turn lane before the lane was completely blocked by through vehicles. The blockage by a through vehicle was determined to be equivalent the arrival of the $(N+2)$ th vehicle on the adjacent through lane at the start of the red interval. The probability of left-turn blockage by through traffic was calculated by Equation 2-7.

$$P_B = P(X_{TH} \geq N + 2) \cap P(X_{LT} \leq N + 2) \quad [2-7]$$

Where

P_B = probability of blockage

X_{TH} = number of through arrivals within the cycle at the intersection (veh)

X_{LT} = number of left-turn vehicles in the bay when blockage occurs (veh)

P = Probability

N = length of left-turn bay (veh)

Similarly, the probability of left-turn spillover is determined from Equation 2-8

$$P_S = P(X_{LT} \geq N + 3) \cap P(X_{TH} \leq N + 1) \quad [2-8]$$

Where

P_S = probability of spillover and the rest of the terms are defined the same as in Equation 2-7.

Left-turn capacity determined from the probability of blockage and is calculated using Equation 2-9.

$$c_{PROTECTED} = nP_B E(X_{LT}) + \frac{(1 - P_B)S_{LT}g_{LT}}{C} \quad [2-9]$$

Where

$c_{PROTECTED}$ = capacity of protected left turn (veh/h)

n = number of cycles in peak hour at designated intersection

C = cycle length (s)

S_{LT} = saturation flow rate for protected left-turn movement (veh/hg/ln)
 g_{LT} = effective green interval for protected left-turn movement (s), and the rest of the terms are as defined in Equation 2-7.

The adjacent through capacity model was developed assuming a lagging left-turn phase operation. The probability of left-turn spillover was defined to be the event of $(N+3)$ left-turn vehicle arrivals with no blockage of left-turn vehicles occurring after the start of the through red interval. Through capacity was estimated from the probability of spillover using Equation 2-10.

$$c_{THROUGH} = P_S \times \left(\frac{N_{TH} \times n - S_{TH}}{C} \right) + \frac{N_{LN} S_{TH} g_{TH}}{C} \quad [2-10]$$

Where

$c_{THROUGH}$ = through lane capacity (veh/h).

N_{LN} = the number of through lanes on the approach

g_{TH} = effective through green interval (s)

S_{TH} = through movement saturation flow rate (veh/hg/ln)

C = cycle Length (s)

n = number of cycles in peak hour and the remaining terms are defined as in Equation 2-9.

Kikuchi et al. (2007) used a probabilistic approach to determine the lengths of turn lanes, when a single lane approaches a signalized intersection and splits into a left, right and through lane. Probabilities of lane overflow and lane entrance blockage are computed. Probabilities of lane overflow and lane blockage are a function of the arriving volume, sequences of the movements during the red phase and length of turn lanes. Lengths of turn lanes were determined by volumes of vehicles for the turn lanes and vehicles wishing to move to other lanes due to the possibility of lane entrance blockage.

The probabilities that vehicles arriving at the intersection toward the end of the red phase will not experience lane overflow or lane entrance blockage (acceptable conditions), were derived based on the pattern of arrivals at the end of the red signal phase. The following conditions were identified as possible outcomes at the end of the red signal phase:

-
- The entrance to the desired lane is blocked so that vehicles cannot enter lane.
 - The entrance to the desired lane is not blocked and not overflowed.
 - The entrance to the desired lane is overflowed by vehicles having the same destination lanes as the arriving vehicle.
 - The entrance to the desired lane is overflowed by vehicles having different destination lanes as the arriving vehicle.

The required length of turn lanes is the length for which these probabilities are greater than a specified threshold value. Charts were provided for lane lengths computed in distance and units of vehicles for different threshold probabilities.

Qi et al. (2007) developed a method for estimating left-turn lane storage lengths lanes at signalized intersections. The length of the left-turn queue is estimated based on vehicle arrivals during the red phase and residual queues from previous cycles. Residual queues were analyzed based on discrete-time Markov chains. Factors taken into account included opposing traffic volume, cycle length, phasing, vehicle mix, and the turning vehicle's headways. The maximum length of the left-turn queue during the red phase was determined based on the probability of arrivals during the red phase; using a Poisson approach and is given by Equation 2-11.

$$P(A_R \leq Q_R) = \sum_0^{Q_R} P(N) = \sum_0^{Q_R} \frac{(\lambda_l R)^N e^{-\lambda_l R}}{N!} = \alpha_1 \quad [2-11]$$

Where

A_R = arrivals in the red phase

Q_R = maximum queue length during red phase (veh)

N = number of left-turn arrivals in red phase (veh)

λ_l = average arrival rate of left-turn vehicles (veh)

R = duration of red phase (s)

α_l = desired probability level

The residual queue at the length of the green phase is given by Equation 2-12.

$$P(N_O \leq Q_L) = \sum_0^{Q_L} \pi_i = \alpha_2 \quad [2-12]$$

Where

N_O = number of left over vehicles

Q_L = maximum left over queue length (veh)

π_i = stationary probability of “T” vehicles left over at the end of green phase

α_2 = desired probability level

The required storage length in units of vehicles is determined as the sum of Q_R and Q_L .

Summary of Literature Review

A comprehensive literature search was conducted in an effort to identify previous studies that examined the issue of left-turn spillover and its effect on through movement discharge. Nearly all of the studies found are focused only on queue length estimation, the probability of spillover, and/or the determination of appropriate left-turn storage lengths. Only one study examined the impact of left-turn lane spillover on through movement discharge. This study, however, still had limitations. For example, it only considers the much less common phasing situation of a lagging left turn and estimates just the capacity due to spillover (through movement discharge can still be reduced even if the demand is less than capacity).

3. RESEARCH APPROACH

Introduction

This chapter describes the approach taken to achieve the objectives of this study. It provides a detailed discussion of the variables identified that significantly affect the likelihood of left-turn lane spillover, tests performed in the simulation tool to verify its reliability, and the development and execution of a simulation experimental design.

Methodological Approach

As learned from the literature review, three main methodologies have been used in studies of left-turn spillover. The first approach involves various methods proposed for estimating and adjusting queue length models to account for left-turn spillover. The second methodological approach involves the use of simulation to analyze operations at signalized intersections with left-turn bays and determining relationships between left-turn spillover and elements of the signalized arterial, mainly geometric elements like left-turn bay length. These studies then, estimate required lengths of left-turn bays to prevent left-turn spillover. The last approach used involves determining the probability of left-turn spillover and determining required storage lengths to prevent spillover based on these probabilities and in one study, determination of the resulting through lane capacity when left-turn spillover happens.

Ideally, for a study such as this, an extensive amount of field data would be collected to base the model development upon. However, the time and cost requirements for this kind of data collection effort are extremely high. Furthermore, with the capabilities of current simulation tools, it was expected that good results could be obtained using simulation data as a surrogate for field data. Simulation was therefore used to generate the required data for this study. The methodological approach taken was to develop models for through vehicle discharge rate, as a function of traffic, roadway, and control factors for a signalized intersection approach, using

regression analysis. The remainder of this chapter discusses the selected simulation tool, the variables selected for inclusion in the experimental design and the development of the experimental design.

Selection of Simulation Tool

Several publicly available software programs are capable of simulating signalized arterial operations. For this project, the simulation program needed to be capable of simulating vehicle movements at the microscopic level (due to sensitivities with spillover conditions), allow for modification to a number of traffic flow parameters (such as queue discharge rate), have an animation viewing utility (to allow for visual verification of the simulation operation), and provide for efficient extraction of the pertinent performance measures

One simulation tool that met these criteria is CORSIM (CORridor SIMulation). This tool has previously undergone a tremendous amount of testing and validation and is generally recognized as a reliable simulation program with excellent modeling capabilities. The scripting capability for multiple runs and the comprehensive output processor provide for more efficient simulation runs and data processing than many other simulation tools. Additionally, the research team had direct access to the individuals that support and maintain CORSIM; thus, if any questions or issues were identified, they could be quickly resolved.

Testing the Operation of CORSIM

Despite all the previous studies that have used CORSIM, some basic tests were still conducted to make sure that it was functioning as expected and that its results could be considered as reliable. These tests involved identifying the relationships between key variables and left-turn spillover (and the corresponding through movement discharge rate). To perform these basic tests, an experimental signalized network was coded in CORSIM, with four approaches. All approaches had one through lane and one exclusive left-turn lane, except in the

case of the number of lanes test. The length of each approach was specified as 3000 ft., traffic arrivals were specified to be Erlang distributed with a parameter value of 1 (i.e., negative exponential headways).

Simulations were run for one, 3600 s (1 h) time period with sixty 60 s time intervals. The signal phasing for the left turns at the intersection were specified as lagging for the westbound and eastbound approaches and leading for the northbound and southbound approaches (but this was altered in the left-turn phasing sequence test). No right turns were included in the approach flow rates. Signal timings were determined based on the proportions of through and left-turn traffic volumes.

The traffic stream was composed of only passenger cars for all the variables investigated except in the case of the heavy vehicle composition test. Table 3-1 gives the various parameters and settings of the signalized intersection that was coded for the experimental network. Vehicle length of 25 ft was specified in all tests with the exception of the heavy vehicle percentage experiment. The performance measure of interest was the through vehicle discharge rate. The output processor was specified to extract this performance measure for the north bound and south bound approaches. Each of the individual numerical results represents an average of 50 replications. The individual tests and results are now described.

Left-Turn Storage Length

In this test, a left-turn percentage of 15% of a total approaching vehicular flow rate of 1600 veh/h was specified in CORSIM and kept constant during the simulation process. A cycle length of 120 s with through green time of 80 s and left-turn green time of 10 s was specified. The length of the left-turn bay was varied, at 50 ft increments with a minimum of 0 ft and a maximum of 1000 ft. The storage lengths were plotted against the through vehicle discharge rates extracted from the simulation results (Figure 3-1).

As the storage length of the left-turn lane increases, the through movement discharge rate increases sharply until a bay length of about 200 ft (Figure 3-1), with longer storage lengths resulting in modest increases in the discharge flow rate, until this rate equals the unimpeded capacity of the through lane (1200 veh/h/ln).

Left-Turn Phasing Sequence

The effect of left-turn phasing sequence (leading versus lagging) on through vehicle discharge was investigated. In this test, four different combinations of left-turn green time, through green time, cycle length, and approach flow rate were run. Each of the four different variable combinations was run with leading left-turn phasing and then lagging left-turn phasing. Left-turn bay lengths were specified as 125 ft while left-turn percentage was specified as 15% for all scenarios tested. Signal settings and approach flow rates specified are summarized in Table 3-2. The results of the experiment are also shown in Table 3-2.

Although the difference is generally small, lagging left-turn phasing generally resulted in slightly lower through vehicle discharge rates than leading left-turn phasing. Initially, it was hypothesized that the left-turn phasing sequence might be a significant factor to through movement discharge rate, but this was mostly from the perspective of treating each cycle independently. When considering a series of cycles, as would happen over an extended analysis period, cycles are not independent and an oscillating condition between spillover and spillback tends to occur. Thus, the issue of whether the left-turn movement goes before or after the adjacent through movement essentially becomes irrelevant. The small difference in the results (Table 3-2) from this test appear to be largely influenced by the first cycle during the simulation, where the left-turn spillover prevents discharge of the through vehicles since the through movement phase occurs before the left-turn phase. After the first cycle, it is expected that the

difference in through movement discharge rate between leading and lagging left-turn phasing would be negligible. Thus, this variable was dropped from further consideration in this study.

Left-Turn Percentage

This test was performed to investigate the relationship between the percentage of left-turn volume and the through vehicle discharge rate when left-turn spillover happens. A total approaching flow rate of 800 veh/h was specified. Signal settings were determined based on the volume split between left turns and through vehicles. Left-turn storage lengths were varied in relation to the percentage of left turns. Left-turn percentage was then varied at increments of 5% with a minimum value of 5% and a maximum value of 20%. Signal timings and the length of the left-turn bay were updated for each increment of left-turn percentage. Through vehicle discharge rate was plotted against the left-turn composition at each increment and is shown in Figure 3-2. It was hypothesized, that an increase in the left-turn percentage with all being equal would increase the probability of spillover and hence reduce the through movement discharge rate. For this experiment however, other variables; left-turn bay length, through green time, left-turn green time, and cycle length were varied for each increment in left-turn percentage to capture variance. Left-turn percentage had interactions with these variables used in the experiment leading to the resulting relationship (Figure 3-2).

Heavy Vehicle Percentage

This test was performed by coding the isolated signalized intersection with a total approaching flow rate of 1600 veh/h, a left-turn percentage of 15% and a left-turn bay length of 250 ft. The heavy vehicle percentage of the traffic stream was varied by 5% increments with a minimum value of 0% and a maximum value of 20%. The type of heavy vehicle was specified to be a medium truck; 35 ft in length. The relationship between through movement discharge rate and the heavy vehicle percentage is shown in Figure 3-3.

As the composition of heavy vehicles in the traffic stream increases, the through vehicle discharge rate decreases (Figure 3-3). Heavy vehicles are longer than passenger cars and fill up the left-turn bay faster and thereby increase the likelihood of left-turn queues spilling over to the adjacent through lane, thereby causing a reduction in through vehicle discharge.

Number of Through Lanes

To perform the test of the effect of the number of through lanes on left-turn spillover and hence through lane discharge rate, an average approach flow rate of 1600 veh/h was specified, with a left-turn percentage of 15% of the average approaching flow rate. Left-turn storage length was specified to be 250 ft .Signal settings were specified to be 10 s left-turn green time and 80 s through green time with a cycle length of 120 s. The number of through lanes was varied at increments of 1, with a minimum value of 1 and a maximum value of 3. Through vehicle discharge rates were extracted from the output processor Results of this test showing the relationship between the number of through lane at the approach of the intersection and through vehicle discharge rate are shown in Figure 3-4.

The through vehicle discharge rate increases with increasing number of approaching through lanes (Figure 3-4). This is consistent with expectations that, through vehicles will avoid queues from left-turn spillover by weaving around them if there are multiple through lanes, and hence reduce the impact of left-turn spillover to through movement discharge rates.

Identification of Significant Factors

A number of variables were considered for their potential impact on the probability of left-turn bay spillover. Through a combination of simulation testing and theoretical relationships, the following variables were identified as having a significant effect on left-turn spillover. The general relationship of these variables to the probability of spillover is also described:

-
- **Left-turn storage length:** The length of the left-turn bay determines its storage capacity. As the length of the left-turn bay increases, the more left-turning vehicles the bay can hold; thus, reducing the probability of spillover. As the length of the left-turn bay approaches the maximum number of queued left-turn vehicles expected during any one cycle, the maximum possible through movement discharge rate approaches that of the unimpeded capacity of the through movement.
 - **Percentage of left turns:** All else being equal, the higher the proportion of left-turning vehicles in the volume approaching the intersection, the higher the likelihood of spillover.
 - **Number of approaching through lanes:** As the number of through lanes increases, the less impact spillover conditions will have on through movement discharge rate due to the ability of through vehicles to move over into lanes further to the right or weave around the spillover condition.
 - **Left-turn green time:** For a given cycle length, more left-turn green time translates to less red time for the movement and thus less time for left-turn vehicles to queue—reducing the probability of spillover.
 - **Through green time:** For a given cycle length, more through green time results in more red time (assuming the cross street times are fixed) for the left-turn phase, which results in longer left-turn queues and an increased probability of spillover.
 - **Cycle length:** Assuming the phase split percentages are constant, a longer cycle length will increase the probability of spillover due to longer red times and consequently longer left-turn queue lengths per cycle.
 - **Approach demand:** For any given left-turn percentage (greater than zero), a larger approach demand flow rate will translate to a larger number of left turns; thus increasing the number of left-turn queued vehicles and the probability of spillover, as else being equal.
 - **Arrival type:** Arrival type represents the progression quality. Good progression (i.e., a higher percentage of vehicles arriving on green) generally leads to a reduced impact from spillover on through movement discharge. However, there are several complications that must be considered with this variable. For one, favorable progression is generally designed for only the through movement, and as such, the left-turn movement often suffers from poor progression. Thus, the probability of spillover can actually increase when the progression of the through movement is favorable. On the other hand, having a higher percentage of through vehicles arrive during the green provides more opportunities for vehicles to discharge the intersection that are not blocked by left-turn vehicles (even more so for multiple through lane intersection approaches).
 - **Heavy Vehicle Percentage:** Heavy vehicles generally have longer lengths than passenger cars and hence fill up the left-turn bay storage more quickly. The greater the proportion of heavy vehicles in the left-turning traffic volume, the higher the probability of spillover.

Experimental Design

An experimental design was developed for the purpose of generating a comprehensive data set to use for model development. The first step in the experimental design development was to select the independent variables, the second step was to select the number of levels to run each variable at and then the values for those levels, and then the last step was to determine the appropriate number of replications to run for each variable combination.

Selection of Variables

The following variables were included in the experimental design for this study.

- Left-Turn Bay Length
- Left-Turn Percentage
- Through Green Time
- Left-Turn Green Time
- Cycle Length
- Approach Demand
- Number of Through Lanes

Arrival type was not included in this study to prevent the experimental design from becoming too large and complex. The arrival type variable is quite complicated (as previously explained) and should really be incorporated into a second experimental design, rather than complicating this experimental design that has relatively straight forward relationships.

Rather than incorporating heavy vehicles directly into this experimental design (and subsequently the models) and making the required number of runs very large, heavy vehicles can be accommodated by applying the HCM passenger car equivalent (PCE) value and using the heavy vehicle factor to modify the approach demand flow rate. It should be noted, however, that with this simplification, different heavy vehicle percentages for left turns and through movements cannot be applied.

Variable Levels

Since each of the variable relationships with through discharge rate was linear (or approximately linear) throughout most of the range of discharge rate, just two levels were chosen for each variable. The variable levels were chosen such that a wide range of conditions would be tested; however, the majority of the scenarios had large demand to capacity ratios for the left-turn movement such that many of the cases would experience some level of left-turn bay spillover. The selected values for the two levels for each variable are shown in Table 3-3. A comprehensive list of the combinations of factor levels for the experimental design is given in appendix A.

Number of Replications

The necessary number of replications to run for each of the experimental design scenarios was estimated with Equation 3-1.

$$N = \left(\frac{Z_{\alpha/2} \times s}{\varepsilon} \right)^2 \quad [3-1]$$

Where

$Z_{\alpha/2}$ = user specified probability level

s = standard deviation of sample

ε = user specified allowable error

For the various simulation test scenarios that were run and from the variances obtained from the scenario runs, it was found that 10 replications was sufficient based on a 5% allowable error and a 95% probability level. Each replication of each scenario used a different random number seed. The total number of runs required is calculated according to Equation 3-2.

$$TR = 2^K \times NR \quad [3-2]$$

Where

TR = total number of runs

K = number of factors

NR = number of replications

Two experiments were developed and executed: single through lane and multiple through lanes. This was done because the operation at a single through lane approach is somewhat unique and different from that with multiple through lanes. At signalized intersections with a single through lane, vehicles do not have the option of weaving around queues to avoid left-turn spillover conditions. Thus, the impact of left-turn spillover on through movement discharge is typically greater for intersections with single through lane approaches than for those with multiple through lanes approaches.

The single through lane experiment had six factors, each investigated at two levels, and with 10 replications for each variable combination. Therefore, the number of required runs is 640 ($2^6 \times 10$). Similarly, the multiple through lanes experiment had seven factors each investigated at two levels and with 10 replications, resulting in 1280 ($2^7 \times 10$) required runs.

Network Configuration for Experimental Design

The network was coded as an isolated intersection with four approaches. For the single through lane experiment, each approach had one through lane and one left-turn lane, while the multiple through lanes experiment had either two or four through lanes and one left-turn lane. Data was however extracted for only the north bound approach

Saturation headways of 2 s (saturation flow rate of 1800 veh/hg/ln), were specified on each approach of the isolated intersection. Free flow speeds were specified as 40 mi/h on each approach. Random arrivals were specified (i.e., specifying the Erlang distribution with a parameter of 1, resulting in the negative exponential distribution for headways). The signal settings for the experimental design are given in Table 3-4.

Only leading left turns were considered in this study because they comprise the very large majority of left-turn phasing in the field. A screen capture of the CORSIM output processor is shown in Figure 3-5.

The output processor enables the user to select performance measures to be extracted at the end of simulation and from which lanes. The performance measure extracted in this study was the through vehicle discharge rate (through vehicles discharge per hour). It also gives the user the flexibility to select the frequency at which output processing should be done by specifying which interval to extract performance measure. The multi run tab when clicked, allows the user to select the number of runs to be done for each simulation. Finally, the format and options tab allows the selection of the format (Microsoft excel, Comma Separated value) in which output processor reports the results of simulation and which statistical measures to be extracted for the performance measure specified.

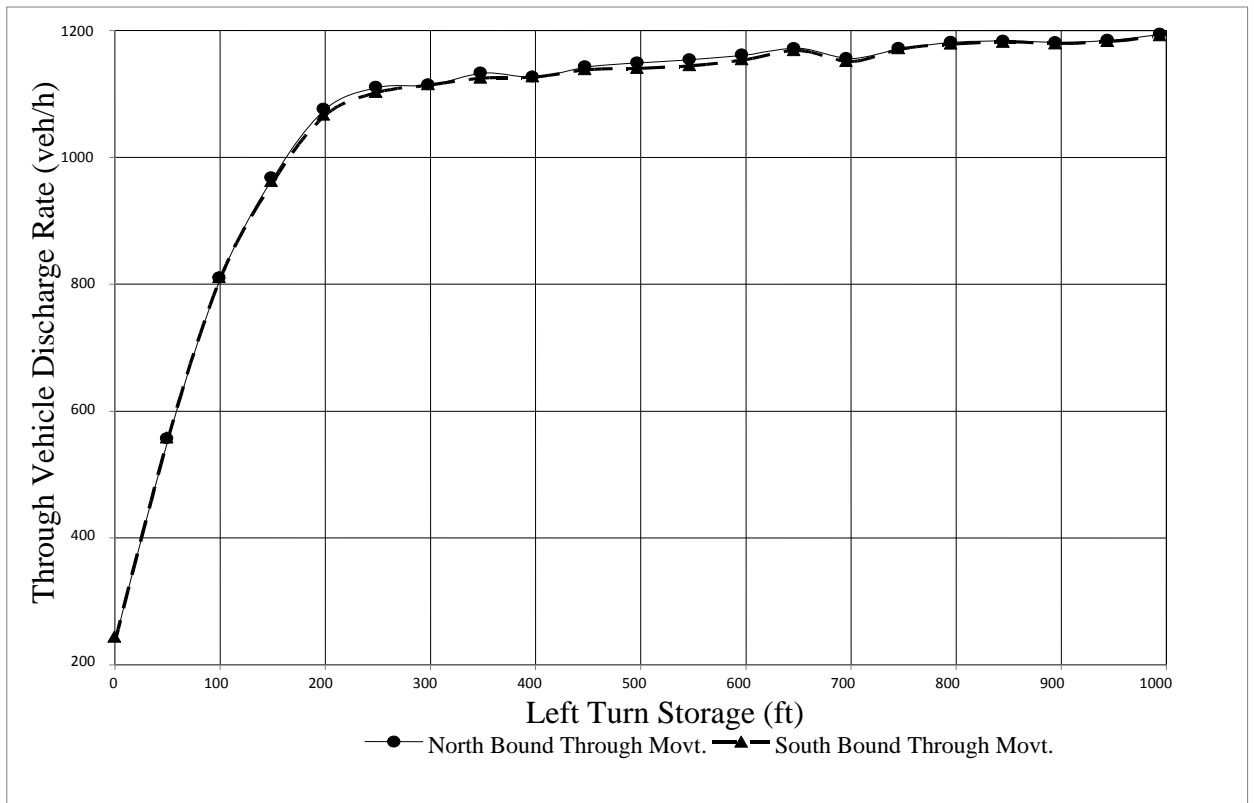


Figure 3-1. Relationship between left-turn storage and through vehicle discharge rate

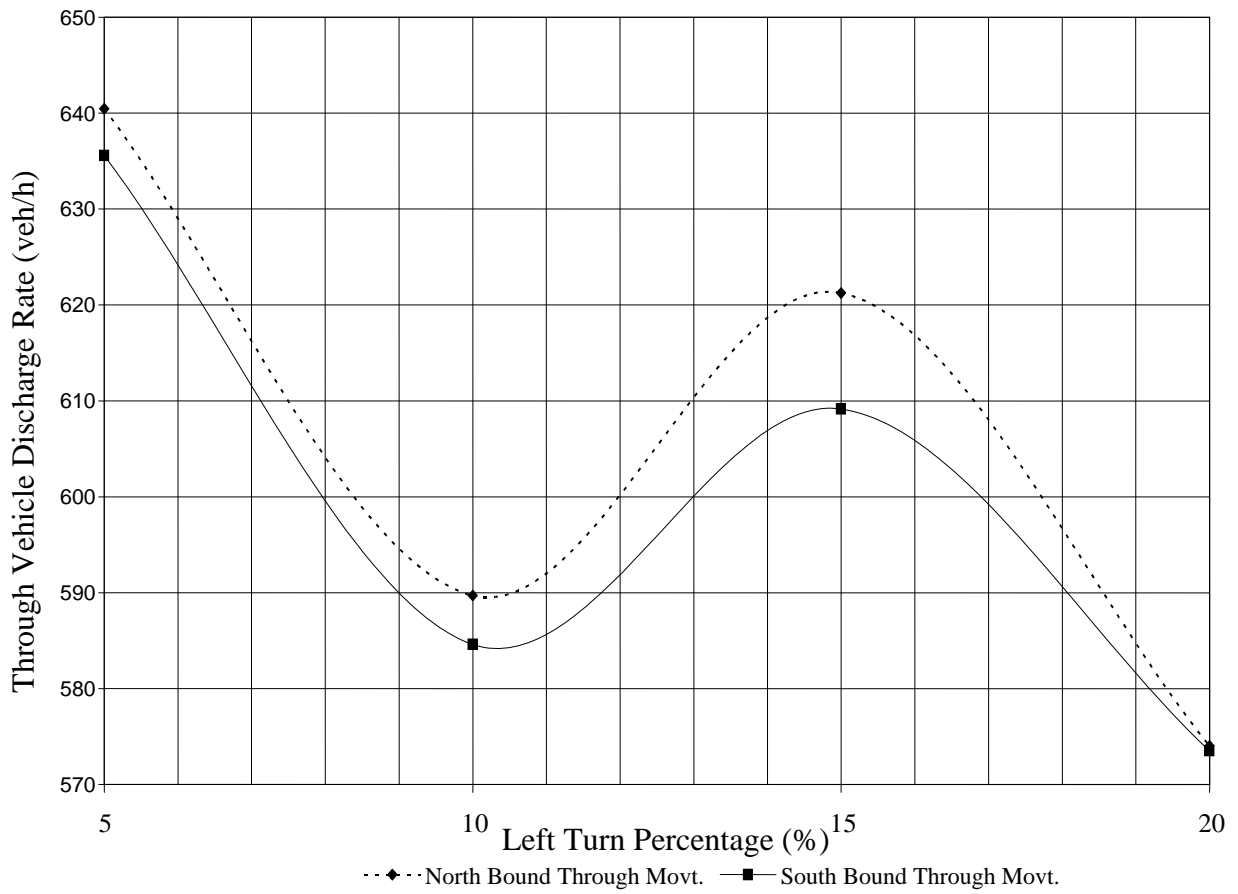


Figure 3-2. Relationship between left-turn percent and through vehicle discharge rate

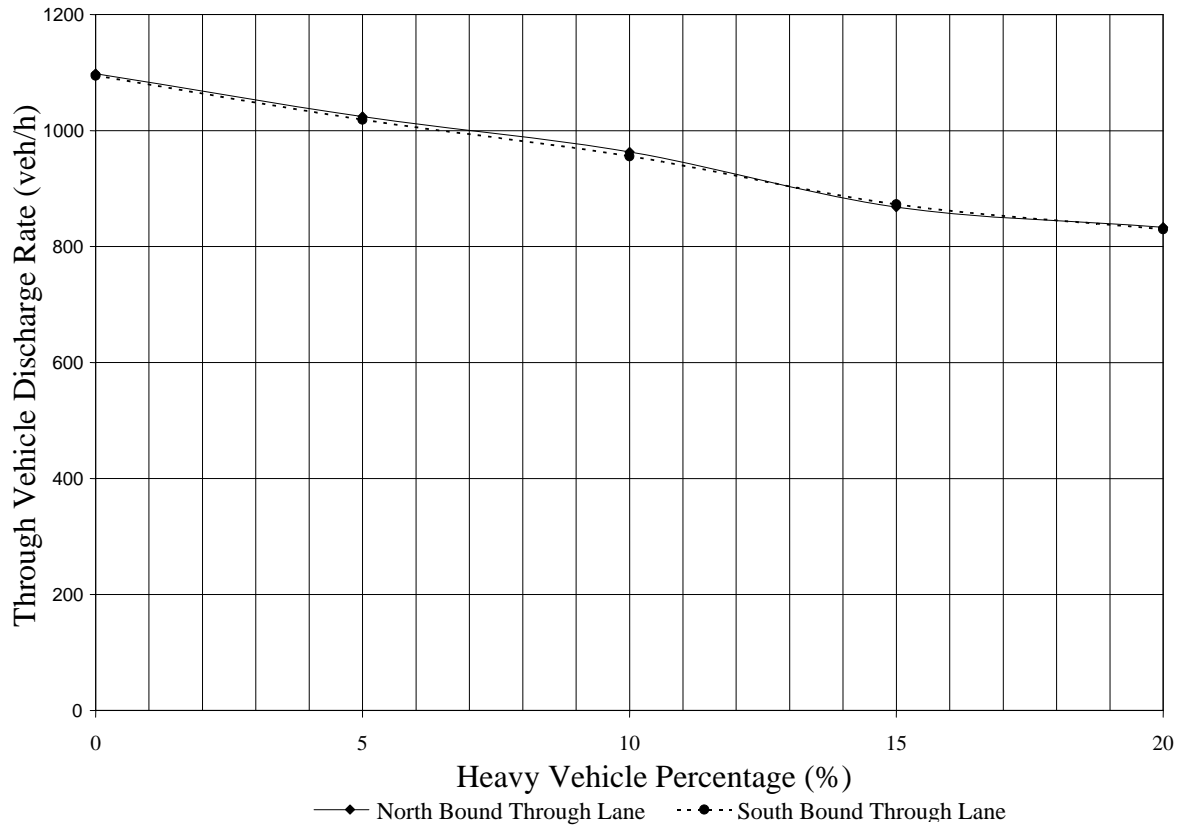


Figure 3-3. Relationship between heavy vehicle percent and through discharge rate

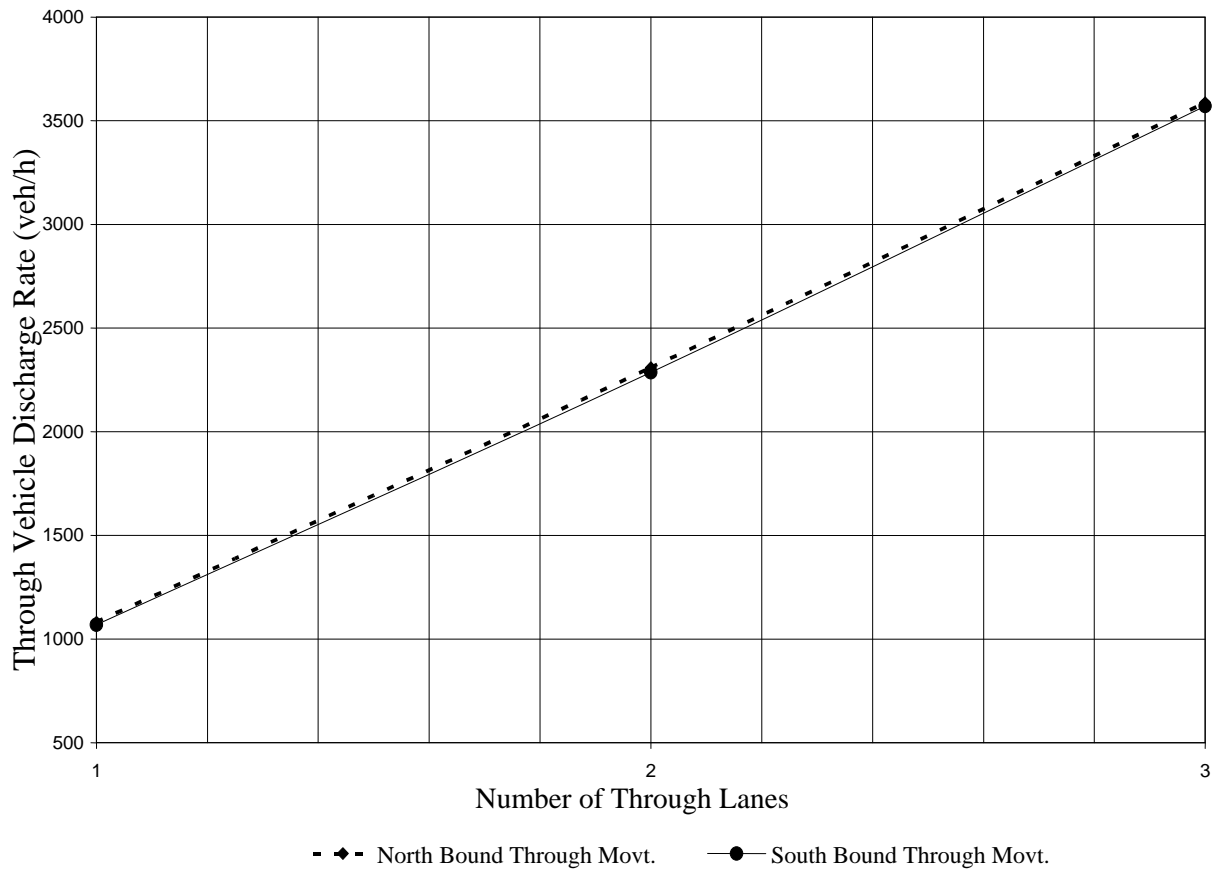


Figure 3-4. Relationship of through discharge rate to number of approaching through lanes

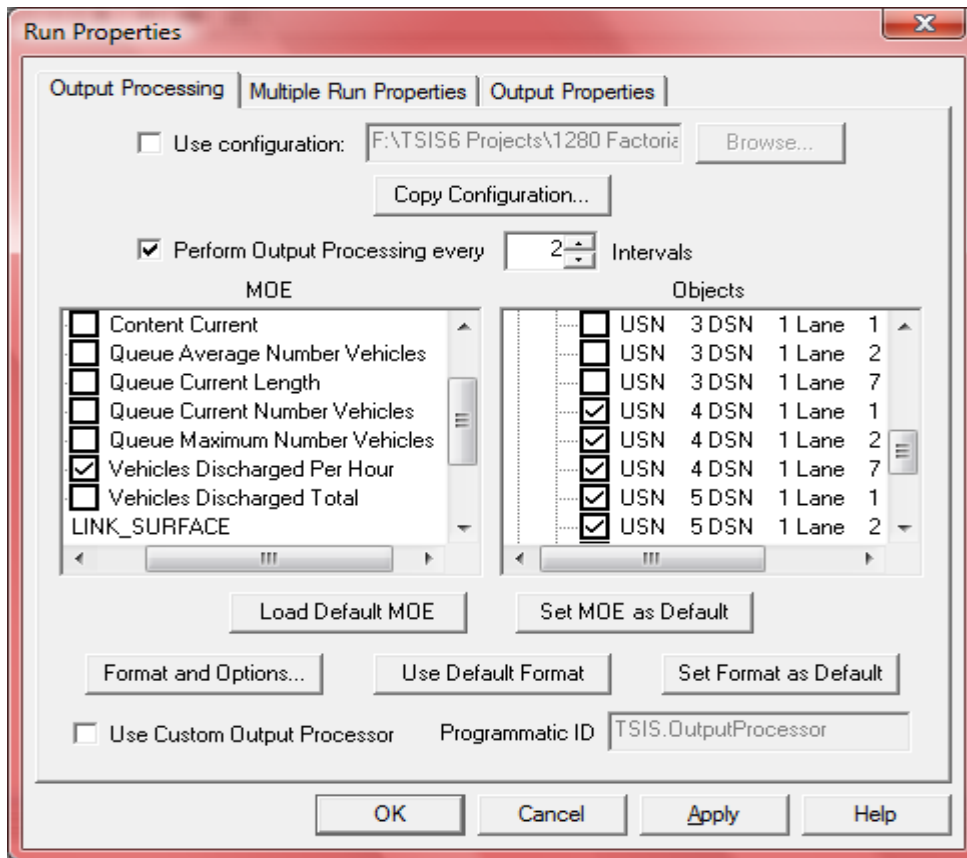


Figure 3-5. Screen shot of CORSIM output processor settings

Table 3-1. Settings coded into experimental network

<i>Parameters</i>	<i>Value</i>
Saturation flow rate (veh/hg/ln)	1800
Free flow speed (mi/h)	40
Amber time (s)	3
All red period (s)	1
Vehicle lengths (ft)	25 ¹

¹ 22 ft vehicle length plus 3 ft intervehicle spacing

Table 3-2. Summary of inputs and results for left-turn phasing sequence experiment

Left-Turn Phasing	Left-Turn	Through	Cycle Length (s)	Approach Flow Rate (veh/h)	North Bound	South Bound
	Green Time (s)	Green Time (s)			Through Discharge Rate (veh/h)	Through Discharge Rate (veh/h)
Leading	10	54	180	800	519	526
Lagging	10	54	180	800	489	485
Leading	10	54	180	1200	516	516
Lagging	10	54	180	1200	499	500
Leading	10	60	120	1000	782	785
Lagging	10	60	120	1000	765	763
Leading	10	60	120	1400	793	794
Lagging	10	60	120	1400	772	773

Table 3-3. Factor levels for experimental design

Factor	Levels	
	Low	High
Left-Turn Percentage (%)	15	30
Left-Turn Bay Length (veh)	5	10
Left-Turn Green Time (s)	10	20
Through Green Time (s)	54	81
Cycle Length (s)	120	180
Average Approach Demand Per Lane (veh/h/ln)	800	1200
Number of Lanes ²	2	4

²This variable is only used in the multiple through lane experiment.

Table 3-4. Signal settings used specified in simulation tool for experimental design

		NB		SB	
		Left	Through	Left	Through
Phase Sequence	Leading left-turn phase	Leading left-turn phase			
Phase		1	6	5	2
All Red Interval (s)		1	1	1	1
Yellow Interval (s)		3	3	3	3
Cycle Length(s)	Low	120		120	
	High	180		180	
Green Times(s)	Low	10	54	10	54
	High	20	81	20	81

4. MODEL DEVELOPMENT AND ANALYSIS

Introduction

This chapter describes the developed models for estimating through vehicle discharge rate as a function of left-turn lane spillover. This includes a summary of model coefficient values, t-statistics, and goodness-of-fit results. Finally, sample applications of the models are presented, along with guidelines for the application of the models.

Model Development

A full factorial regression analysis was run on the data set obtained from the simulation runs to facilitate the consideration of variable interactions in the model development. Only two-way interactions between variables were included in the regression model, as it was found that the improvement in model predictive accuracy was negligible with the consideration of higher level interactions and model complexity would be significantly increased. Two different models were developed to predict the through movement discharge rate, which are described in the following sections.

Single Through Lane Model

This model predicts the through movement discharge rate from the through lane at an isolated, signalized intersection with only one through lane. It captures the impact of left-turn percentage, left-turn bay length, left-turn green time, through green time, cycle length and average per lane approach demand. The general specification of the single through lane model is shown in Equation 4-1, the model has a good fit (Figure 4-1) with an adjusted R^2 value of 0.9380. A summary of coefficients and t-statistics of variables in the model are shown in Table 4-1. All variables included in the model were statistically significant at the 95% or greater confidence level.

$$\begin{aligned}
\text{Thruput} = & 799.0094 - 6.8054 \times \%LT - 43.8500 \times L - 30.9825 \times G_{LT} + 1.3245 \times G_{TH} \\
& + 0.9251 \times C + 0.4918 \times D + 0.6805 \times \%LT \times L + 0.9152 \times \%LT \times G_{LT} - 0.2896 \\
& \times \%LT \times G_{TH} + 0.0338 \times \%LT \times C - 0.0161 \times \%LT \times D + 0.6493 \times L \times G_{LT} + 0.1148 \\
& \times L \times G_{TH} + 0.0241 \times L \times D + 0.0571 \times G_{LT} \times G_{TH} + 0.0109 \times G_{LT} \times D + 0.0056 \times G_{TH} \\
& \times D - 0.0045 \times C \times D
\end{aligned} \quad [4-1]$$

Where

Thruput = through lane vehicle discharge rate (veh/h)

%LT = percent of the approach demand turning left

L = left-turn storage length (veh)³

G_{LT} = green time for left-turn movement (s)

G_{TH} = green time for through movement (s)

C = cycle length (s)

D = approach demand (veh/h/ln)

The contribution of each variable to the through movement discharge rate was logical based on an interpretation of variable signs. Note that the effect of variable interactions must be considered in addition to the main effects when making this assessment.

Multiple Through Lane Model

This model captures the impact of left-turn percentage, left-turn bay length, left-turn green time, through green time, cycle length, average per lane approach demand, and the number of through lanes on the through movement discharge rate. All variables included in the model were statistically significant at the 95% or greater confidence level. The model has a good fit (Figure 4-2) with an adjusted R^2 value of 0.9606. The general form of the model is shown in Equation 4-2 and Table 4-2 summarizes the coefficients and t-statistics of the multiple through lane model.

³ This includes vehicle length plus spacing between vehicles. Twenty five feet per vehicle was used in this study.

$$\begin{aligned}
Thruput = & 932.6415 - 21.6749 \times \%LT - 41.9322 \times L - 100.4621 \times G_{LT} - 39.4056 \\
& \times G_{TH} + 8.8626 \times C + 0.5795 \times D + 731.7854 \times NumLanes + 0.9569 \times \%LT \times L \\
& + 1.5033 \times \%LT \times G_{LT} - 0.5604 \times \%LT \times G_{TH} + 0.0732 \times \%LT \times C - 0.0314 \times \%LT \\
& \times D - 5.0604 \times \%LT \times NumLanes + 0.2749 \times L \times C + 0.5900 \times G_{LT} \times G_{TH} + 0.0281 \\
& \times G_{LT} \times D + 5.5910 \times G_{LT} \times NumLanes + 0.0586 \times G_{TH} \times C + 0.0293 \times G_{TH} \times D + 6.8871 \\
& \times G_{TH} \times NumLanes - 0.0151 \times C \times D - 3.9624 \times C \times NumLanes + 0.1671 \times D \times NumLanes
\end{aligned} \tag{4-2}$$

Where:

Thruput = through lanes vehicle discharge rate (veh/h)

%LT = percent of the average per lane approach demand turning left

L = left-turn storage length (veh)

G_{LT} = green time for left-turn movement (s)

G_{TH} = green time for through movement (s)

C = cycle length(s)

D = average approach demand (veh/h/ln)

NumLanes = number of through lanes

Model Application and Comparisons with Simulation Results

This section gives sample applications of the single through lane and multiple through lane models. These applications involve sample calculations using the general model specifications; Equations 4-1 and 4-2. Three sample calculations are given for each model—one that results in a relatively low estimated through movement discharge rate, one that results in a medium discharge rate, and one that results in a relatively high discharge rate.

The variable values chosen for the three scenarios were values that were also used in the simulation runs so the model estimation results could be compared directly with the simulation results (the average value for the 10 replications).

Sample Calculations for the Single Through Lane Model

A summary of inputs used in the sample calculations for this model are given in Table 4-3. Comparison of the single through lane model sample calculation results with simulation results obtained for the same set of inputs is shown in Table 4-4.

Sample Calculation 1

$$\begin{aligned} \text{Thruput} = & 799.0094 - 6.8054 \times 30 - 43.8500 \times 5 - 30.9825 \times 10 + 1.3245 \times 54 \\ & + 0.9251 \times 180 + 0.4918 \times 1200 + 0.6805 \times 30 \times 5 + 0.9152 \times 30 \times 10 - 0.2896 \\ & \times 30 \times 54 + 0.0338 \times 30 \times 180 - 0.0161 \times 30 \times 1200 + 0.6493 \times 5 \times 10 + 0.1148 \\ & \times 5 \times 54 + 0.0241 \times 5 \times 1200 + 0.0571 \times 10 \times 54 + 0.0109 \times 10 \times 1200 + 0.0056 \times 54 \\ & \times 1200 - 0.0045 \times 180 \times 1200 \end{aligned}$$

$$\text{Thruput} = 192 \text{ veh/h}$$

Sample Calculation 2

$$\begin{aligned} \text{Thruput} = & 799.0094 - 6.8054 \times 15 - 43.8500 \times 5 - 30.9825 \times 10 + 1.3245 \times 81 \\ & + 0.9251 \times 180 + 0.4918 \times 800 + 0.6805 \times 15 \times 5 + 0.9152 \times 15 \times 10 - 0.2896 \\ & \times 15 \times 81 + 0.0338 \times 15 \times 180 - 0.0161 \times 15 \times 800 + 0.6493 \times 5 \times 10 + 0.1148 \\ & \times 5 \times 81 + 0.0241 \times 5 \times 800 + 0.0571 \times 10 \times 81 + 0.0109 \times 10 \times 800 + 0.0056 \times 81 \\ & \times 800 - 0.0045 \times 180 \times 800 \end{aligned}$$

$$\text{Thruput} = 607 \text{ veh/h}$$

Sample Calculation 3

$$\begin{aligned} \text{Thruput} = & 799.0094 - 6.8054 \times 15 - 43.8500 \times 10 - 30.9825 \times 20 + 1.3245 \times 81 \\ & + 0.9251 \times 120 + 0.4918 \times 1200 + 0.6805 \times 15 \times 10 + 0.9152 \times 15 \times 20 - 0.2896 \\ & \times 15 \times 81 + 0.0338 \times 15 \times 120 - 0.0161 \times 15 \times 1200 + 0.6493 \times 10 \times 20 + 0.1148 \\ & \times 10 \times 81 + 0.0241 \times 10 \times 1200 + 0.0571 \times 20 \times 81 + 0.0109 \times 20 \times 1200 + 0.0056 \times 81 \\ & \times 1200 - 0.0045 \times 120 \times 1200 \end{aligned}$$

$$\text{Thruput} = 1015 \text{ veh/h}$$

Sample Calculation for the Multiple Through Lanes Model

Similarly, sample calculations were performed with the general specification of the multiple through lanes model using inputs from Table 4-5. A comparison of the multiple through lanes model sample calculation results with simulation results obtained for the same set of inputs is shown in Table 4-6.

Sample Calculation 4

$$\begin{aligned} \text{Thruput} = & 932.6415 - 21.6749 \times 30 - 41.9322 \times 10 - 100.4621 \times 10 - 39.4056 \\ & \times 81 + 8.8626 \times 180 + 0.5795 \times 1200 + 731.7854 \times 2 + 0.9569 \times 30 \times 10 + 1.5033 \\ & \times 30 \times 10 - 0.5604 \times 30 \times 81 + 0.0732 \times 30 \times 180 - 0.0314 \times 30 \times 1200 - 5.0604 \\ & \times 30 \times 2 + 0.2749 \times 10 \times 180 + 0.5900 \times 10 \times 81 + 0.0281 \times 10 \times 1200 + 5.5910 \times 10 \\ & \times 2 + 0.0586 \times 81 \times 180 + 0.0293 \times 81 \times 1200 + 6.8871 \times 81 \times 2 - 0.0151 \times 180 \\ & \times 1200 - 3.9624 \times 180 \times 2 + 0.1671 \times 1200 \times 2 \end{aligned}$$

$$\text{Thruput} = 1007 \text{ veh/h}$$

Sample Calculation 5

$$\begin{aligned} \text{Thruput} = & 932.6415 - 21.6749 \times 15 - 41.9322 \times 10 - 100.4621 \times 10 - 39.4056 \\ & \times 54 + 8.8626 \times 120 + 0.5795 \times 800 + 731.7854 \times 2 + 0.9569 \times 15 \times 10 + 1.5033 \\ & \times 15 \times 10 - 0.5604 \times 15 \times 54 + 0.0732 \times 15 \times 120 - 0.0314 \times 15 \times 800 - 5.0604 \\ & \times 15 \times 2 + 0.2749 \times 10 \times 120 + 0.5900 \times 10 \times 54 + 0.0281 \times 10 \times 800 + 5.5910 \\ & \times 10 \times 2 + 0.0586 \times 54 \times 120 + 0.0293 \times 54 \times 800 + 6.8871 \times 54 \times 2 - 0.0151 \times 120 \\ & \times 800 - 3.9624 \times 120 \times 2 + 0.1671 \times 800 \times 2 \end{aligned}$$

$$\text{Thruput} = 1454 \text{ veh/h}$$

Sample Calculation 6

$$\begin{aligned} \text{Thruput} = & 932.6415 - 21.6749 \times 30 - 41.9322 \times 5 - 100.4621 \times 10 - 39.4056 \times 81 \\ & + 8.8626 \times 120 + 0.5795 \times 1200 + 731.7854 \times 4 + 0.9569 \times 30 \times 5 + 1.5033 \times 30 \times 10 \\ & - 0.5604 \times 30 \times 81 + 0.0732 \times 30 \times 120 - 0.0314 \times 30 \times 1200 - 5.0604 \times 30 \times 4 \\ & + 0.2749 \times 5 \times 120 + 0.5900 \times 10 \times 81 + 0.0281 \times 10 \times 1200 + 5.5910 \times 10 \times 4 + 0.0586 \\ & \times 81 \times 120 + 0.0293 \times 81 \times 1200 + 6.8871 \times 81 \times 4 - 0.0151 \times 120 \times 1200 - 3.9624 \\ & \times 120 \times 4 + 0.1671 \times 1200 \times 4 \end{aligned}$$

$$\text{Thruput} = 3195 \text{ veh/h}$$

Comparison of Reductions in Through Vehicle Discharge as Predicted By Single Through Lane and Multiple Through Lane Models

To verify whether having separate models for a single through lane and multiple through lanes was warranted, the reduction of through vehicle discharge rates was compared (on a per lane basis), using the same input values. The input values are given in Table 4-7. Three calculations were performed for each model, as follows.

Sample Calculations for Single Through Lane Model Reduction

Calculation 1

$$\begin{aligned} \text{Thruput} = & 799.0094 - 6.8054 \times 15 - 43.8500 \times 5 - 30.9825 \times 10 + 1.3245 \times 81 \\ & + 0.9251 \times 120 + 0.4918 \times 1200 + 0.6805 \times 15 \times 5 + 0.9152 \times 15 \times 10 - 0.2896 \\ & \times 15 \times 81 + 0.0338 \times 15 \times 120 - 0.0161 \times 15 \times 1200 + 0.6493 \times 5 \times 10 + 0.1148 \\ & \times 5 \times 81 + 0.0241 \times 5 \times 1200 + 0.0571 \times 10 \times 81 + 0.0109 \times 10 \times 1200 + 0.0056 \\ & \times 81 \times 1200 - 0.0045 \times 120 \times 1200 \end{aligned}$$

$$\text{Thruput per lane} = \frac{890 \text{ veh/h}}{1 \text{ lane}} = 890 \text{ veh/h/ln}$$

$$\text{Thruput Reduction (\%)} = \left(1 - \frac{\text{Thru Discharge (veh/h/ln)}}{\text{Thru Demand (veh/h/ln)}} \right) \times 100 = \left(1 - \frac{890}{1020} \right) \times 100 = 12.74$$

Calculation 2

$$\begin{aligned} \text{Thruput} = & 799.0094 - 6.8054 \times 15 - 43.8500 \times 5 - 30.9825 \times 10 + 1.3245 \times 81 \\ & + 0.9251 \times 180 + 0.4918 \times 800 + 0.6805 \times 15 \times 5 + 0.9152 \times 15 \times 10 - 0.2896 \\ & \times 15 \times 81 + 0.0338 \times 15 \times 180 - 0.0161 \times 15 \times 800 + 0.6493 \times 5 \times 10 + 0.1148 \\ & \times 5 \times 81 + 0.0241 \times 5 \times 800 + 0.0571 \times 10 \times 81 + 0.0109 \times 10 \times 800 + 0.0056 \times 81 \\ & \times 800 - 0.0045 \times 180 \times 800 \end{aligned}$$

$$\text{Thruput per lane} = \frac{607 \text{ veh/h}}{1 \text{ lane}} = 607 \text{ veh/h/ln}$$

$$\text{Thruput Reduction (\%)} = \left(1 - \frac{\text{Thru Discharge (veh/h/ln)}}{\text{Thru Demand (veh/h/ln)}} \right) \times 100 = \left(1 - \frac{607}{680} \right) \times 100 = 10.70$$

Calculation 3

$$\begin{aligned} \text{Thruput} = & 799.0094 - 6.8054 \times 30 - 43.8500 \times 10 - 30.9825 \times 20 + 1.3245 \times 54 \\ & + 0.9251 \times 120 + 0.4918 \times 1200 + 0.6805 \times 30 \times 10 + 0.9152 \times 30 \times 20 - 0.2896 \\ & \times 30 \times 54 + 0.0338 \times 30 \times 120 - 0.0161 \times 30 \times 1200 + 0.6493 \times 10 \times 20 + 0.1148 \\ & \times 10 \times 54 + 0.0241 \times 10 \times 1200 + 0.0571 \times 20 \times 54 + 0.0109 \times 20 \times 1200 + 0.0056 \\ & \times 54 \times 1200 - 0.0045 \times 120 \times 1200 \end{aligned}$$

$$\text{Thruput per lane} = \frac{673 \text{ veh/h}}{1 \text{ lane}} = 673 \text{ veh/h/ln}$$

$$\text{Thruput Reduction (\%)} = \left(1 - \frac{\text{Thru Discharge (veh/h/ln)}}{\text{Thru Demand (veh/h/ln)}} \right) \times 100 = \left(1 - \frac{673}{840} \right) \times 100 = 19.88$$

Sample Calculations for Multiple Through Lane Model Reduction

Calculation 1

$$\begin{aligned} \text{Thruput} = & 932.6415 - 21.6749 \times 15 - 41.9322 \times 5 - 100.4621 \times 10 - 39.4056 \\ & \times 81 + 8.8626 \times 120 + 0.5795 \times 1200 + 731.7854 \times 2 + 0.9569 \times 15 \times 5 + 1.5033 \\ & \times 15 \times 10 - 0.5604 \times 15 \times 81 + 0.0732 \times 15 \times 120 - 0.0314 \times 15 \times 1200 - 5.0604 \\ & \times 15 \times 2 + 0.2749 \times 5 \times 120 + 0.5900 \times 10 \times 81 + 0.0281 \times 10 \times 1200 + 5.5910 \times 10 \\ & \times 2 + 0.0586 \times 81 \times 120 + 0.0293 \times 81 \times 1200 + 6.8871 \times 81 \times 2 - 0.0151 \\ & \times 120 \times 1200 - 3.9624 \times 120 \times 2 + 0.1671 \times 1200 \times 2 \end{aligned}$$

$$\text{Thruput per lane} = \frac{2001 \text{ veh/h}}{2 \text{ lanes}} = 1001 \text{ veh/h/ln}$$

$$\text{Thruput Reduction (\%)} = \left(1 - \frac{\text{Thru Discharge (veh/h/ln)}}{\text{Thru Demand (veh/h/ln)}} \right) \times 100 = \left(1 - \frac{1001}{1020} \right) \times 100 = 1.86$$

Calculation 2

$$\begin{aligned} \text{Thruput} = & 932.6415 - 21.6749 \times 15 - 41.9322 \times 5 - 100.4621 \times 10 - 39.4056 \\ & \times 81 + 8.8626 \times 180 + 0.5795 \times 800 + 731.7854 \times 2 + 0.9569 \times 15 \times 5 + 1.5033 \\ & \times 15 \times 10 - 0.5604 \times 15 \times 81 + 0.0732 \times 15 \times 180 - 0.0314 \times 15 \times 800 - 5.0604 \\ & \times 15 \times 2 + 0.2749 \times 5 \times 180 + 0.5900 \times 10 \times 81 + 0.0281 \times 10 \times 800 + 5.5910 \times 10 \\ & \times 2 + 0.0586 \times 81 \times 180 + 0.0293 \times 81 \times 800 + 6.8871 \times 81 \times 2 - 0.0151 \times 180 \times 800 \\ & - 3.9624 \times 180 \times 2 + 0.1671 \times 800 \times 2 \end{aligned}$$

$$\text{Thruput per lane} = \frac{1253 \text{ veh/h}}{2 \text{ lanes}} = 627 \text{ veh/h/ln}$$

$$\text{Thruput Reduction (\%)} = \left(1 - \frac{\text{Thru Discharge (veh/h/ln)}}{\text{Thru Demand (veh/h/ln)}} \right) \times 100 = \left(1 - \frac{627}{680} \right) \times 100 = 7.79$$

Calculation 3

$$\begin{aligned} \text{Thruput} = & 932.6415 - 21.6749 \times 30 - 41.9322 \times 10 - 100.4621 \times 20 - 39.4056 \\ & \times 54 + 8.8626 \times 120 + 0.5795 \times 1200 + 731.7854 \times 4 + 0.9569 \times 30 \times 10 + 1.5033 \\ & \times 30 \times 20 - 0.5604 \times 30 \times 54 + 0.0732 \times 30 \times 120 - 0.0314 \times 30 \times 1200 - 5.0604 \\ & \times 30 \times 4 + 0.2749 \times 10 \times 120 + 0.5900 \times 20 \times 54 + 0.0281 \times 20 \times 1200 + 5.5910 \times 20 \\ & \times 4 + 0.0586 \times 54 \times 120 + 0.0293 \times 54 \times 1200 + 6.8871 \times 54 \times 4 - 0.0151 \times 120 \times 1200 \\ & - 3.9624 \times 120 \times 4 + 0.1671 \times 1200 \times 4 \end{aligned}$$

$$\text{Thruput per lane} = \frac{3096 \text{ veh/h}}{4 \text{ lanes}} = 774 \text{ veh/h/ln}$$

$$\text{Thruput Reduction (\%)} = \left(1 - \frac{\text{Thru Discharge (veh/h/ln)}}{\text{Thru Demand (veh/h/ln)}}\right) \times 100 = \left(1 - \frac{774}{840}\right) \times 100 = 7.86$$

The results are also summarized in Table 4-8. The percentage reduction in through vehicle discharge, on a per lane basis, is greater for the single through lane case than for the multiple through lane case (Table 4-8). Again, this was expected since through vehicles do not have the opportunity to weave around a left-turn spillover condition in the case of a single through lane. Many other input conditions were also tested beyond those shown here, and the results from these additional tests were consistent with those shown here. Thus, having separate models for the single through lane and multiple through lane cases is justified.

Guidelines for Application of Model

For nearly all situations where *reasonable* variable values are used, and over a very wide range of input values, the models can be expected to give reasonable results. Certainly, for situations where unreasonable input values are used (e.g., a negative cycle length or green time), unreasonable model results will be obtained. Furthermore, for unreasonable combinations of input values (e.g., a green time greater than the cycle length), unreasonable model results can be expected. In the very infrequent case where reasonable input values are used, yet the model-predicted value is still unreasonable, use the following guidelines to adjust the model value:

- If the model predicts a through movement discharge rate greater than the approaching through demand flow rate, use the approaching through demand rate as the limiting value.
- If the model predicts a through movement discharge rate greater than the capacity of the through movement (as unaffected by left-turn spillover), use the through movement capacity as the limiting value.

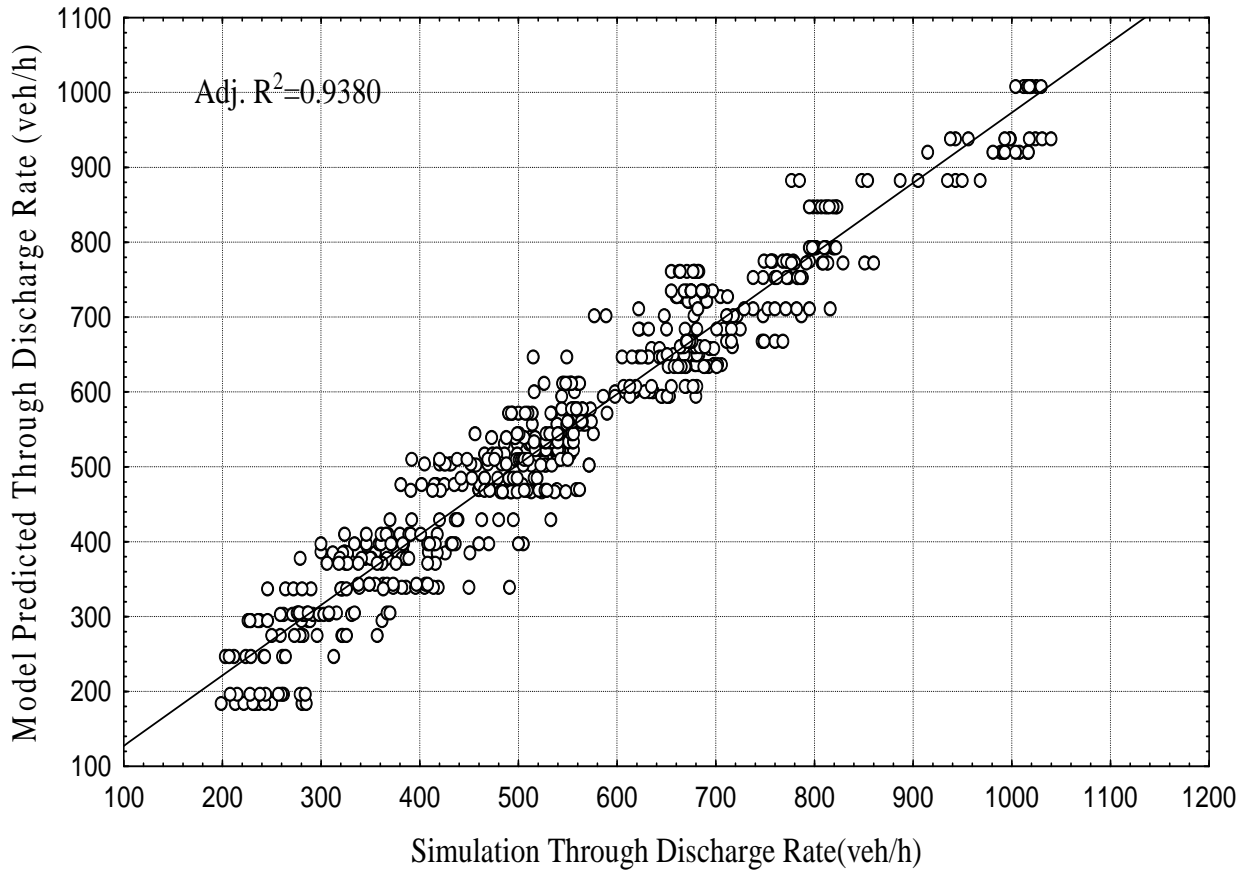


Figure 4-1. Comparison of simulation and model estimation results for single-through lane model

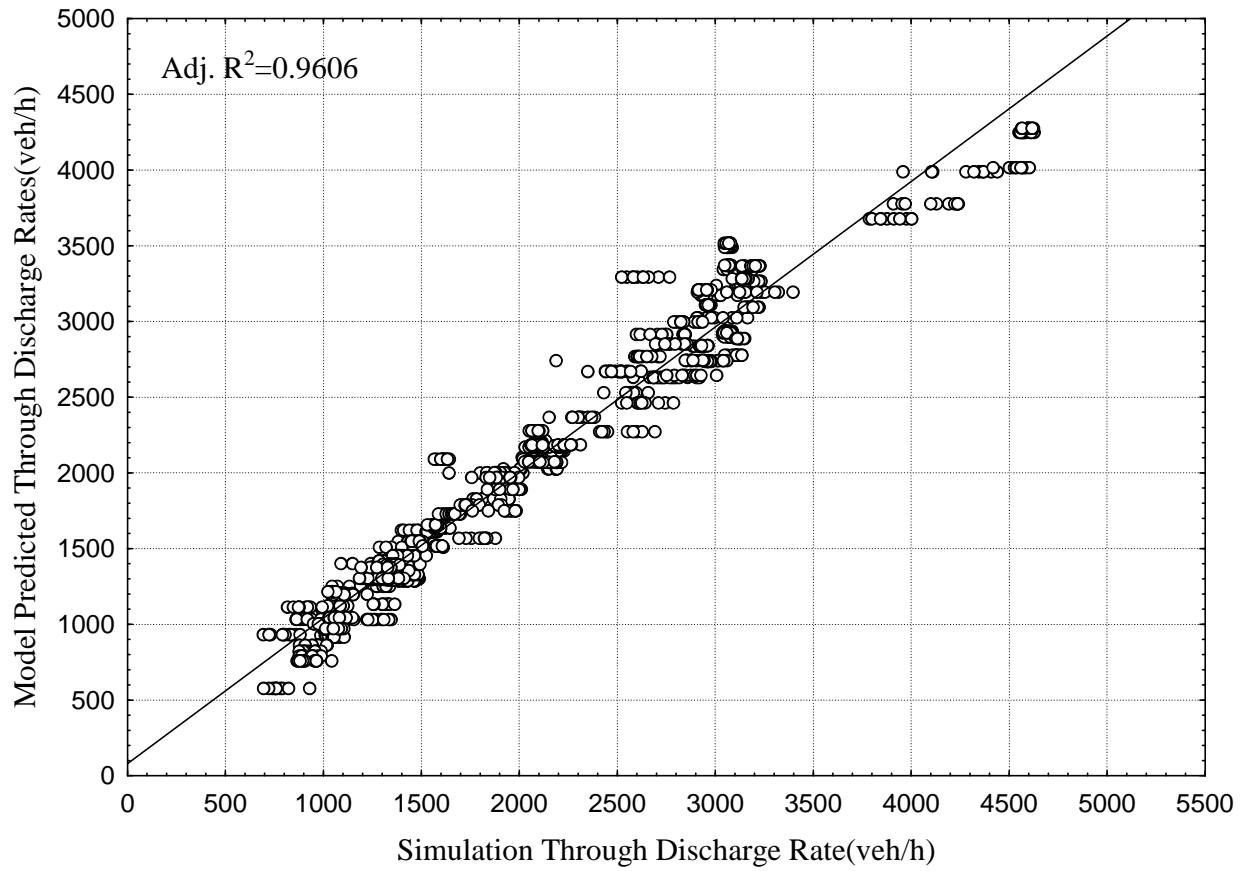


Figure 4-2. Comparison of simulation and model estimation results for multiple through lanes model

Table 4-1. Summary of Single through lane model parameters

Variable	Co-efficient	t-stat
Constant	799.0094	7.5912
$\%LT$	-6.8054	-2.8165
L	-43.8500	-7.0606
G_{LT}	-30.9825	-9.9774
G_{TH}	1.3245	1.3141
C	0.9251	2.5098
D	0.4918	5.9585
$\%LT \times L$	0.6805	6.8263
$\%LT \times G_{LT}$	0.9152	18.3606
$\%LT \times G_{TH}$	-0.2896	-15.6873
$\%LT \times C$	0.0388	4.6763
$\%LT \times D$	-0.0161	-12.9053
$L \times G_{LT}$	0.6493	4.3419
$L \times G_{TH}$	0.1148	2.0731
$L \times D$	0.0241	6.4535
$G_{LT} \times G_{TH}$	0.0571	2.0614
$G_{LT} \times D$	0.0109	5.8533
$G_{TH} \times D$	0.0056	8.0351
$C \times D$	-0.0045	-14.5521

Table 4-2. Summary of Multiple through lane model parameters

Variable	Co-efficient	t-stat
Constant	932.6415	2.8136
%LT	21.6749	3.1820
<i>L</i>	-41.9322	-3.5200
G_{LT}	-100.4621	-12.0127
G_{TH}	-39.4056	-11.9657
<i>C</i>	8.8626	5.9804
<i>D</i>	0.5795	2.6070
<i>NumLanes</i>	731.7854	14.9939
%LT × <i>L</i>	0.9569	3.5644
%LT × G_{LT}	1.5033	11.1991
%LT × G_{TH}	-0.5604	-11.2717
%LT × <i>C</i>	0.0732	3.2737
%LT × <i>D</i>	-0.0314	-9.3505
%LT × <i>NumLanes</i>	-5.0604	-7.5394
<i>L</i> × <i>C</i>	0.2749	4.0962
G_{LT} × G_{TH}	0.5900	7.9119
G_{LT} × <i>D</i>	0.0281	5.5744
G_{LT} × <i>NumLanes</i>	5.5910	5.5534
G_{TH} × <i>C</i>	0.0586	4.7109
G_{TH} × <i>D</i>	0.0293	15.6866
G_{TH} × <i>NumLanes</i>	6.8871	18.4700
<i>C</i> × <i>D</i>	-0.0151	-18.0165
<i>C</i> × <i>NumLanes</i>	-3.9624	-23.6142
<i>D</i> × <i>NumLanes</i>	932.6415	6.6395

Table 4-3. Values of parameters used in sample calculations for single through lane approach model

Sample Calculations	%LT	<i>L</i> (veh)	G_{LT} (s)	G_{TH} (s)	<i>C</i> (s)	<i>D</i> (veh/h/ln)
1	30	5	10	54	180	1200
2	15	5	10	81	180	800
3	15	10	20	81	120	1200

Table 4-4. Comparison of sample single through lane model predictions with simulation results

Sample Model Calculation Results (veh/h)	Simulation Results (veh/h)
192	199
607	608
1015	1025

Table 4-5. Values of parameters used in sample calculations for multiple through lanes model

Sample Calculations	%LT	L (veh)	G_{LT} (s)	G_{TH} (s)	C (s)	D (veh/h/ln)	NumLanes
4	30	10	10	81	180	1200	2
5	15	10	10	54	120	800	2
6	30	5	10	81	120	1200	4

Table 4-6. Comparison of sample multiple through lanes model predictions with simulation results

Sample Model Calculation Results (veh/h)	Simulation Results (veh/h)
1007	1005
1454	1474
3195	3198

Table 4-7. Summary of inputs used in sample calculations for through discharge reduction model comparisons

Calculation	%LT	L (veh)	G_{LT} (s)	G_{TH} (s)	C (s)	D (veh/h/ln)	NumLanes	Through Flow Rate (veh/h/ln)
1	15	5	10	81	120	1200	2	1020
2	15	5	10	81	180	800	2	680
3	30	10	20	54	120	120	4	840

Table 4-8. Comparison of reduction in through discharge rates for both models

Calculation	Single Through Lane Model Reduction (%)	Multiple Through Lane Model Reduction (%)
1	12.74	1.86
2	10.70	7.79
3	19.80	7.86

5. CONCLUSIONS AND RECOMMENDATIONS

Summary

The HCM signalized intersection analysis methodology does not explicitly account for the impact to through movement flow rate due to left-turn spillover. This study developed two models to estimate the through movement flow rate as impacted by left-turn spillover, as a function of traffic, roadway, and control factors for the left-turn and through movements. The models were developed from regression analysis and used simulation data as a surrogate for field data. One model is specific to intersections with only a single through lane on the approach while the other is specific to intersections with multiple through lanes on the approach.

Conclusions

The two developed models replicate the simulation results quite reasonably, as indicated by the goodness-of-fit measures. The relationship between the various model variables and their effect on through movement discharge rate are also reasonable and consistent with theoretical expectations. For intersections where left-turn spillover is a consistent problem, the models developed in this study can be applied to give a more accurate estimate of the expected through movement flow rate than an analysis that ignores the left-turn spillover condition.

Recommendations for Further Research

While the results of this study present a significant improvement over the current condition; that is, a signalized intersection analysis methodology that ignores the effect of left-turn spillover on through movement discharge rates (i.e., the HCM), there are still areas that can be improved upon.

- Ideally, field data should be collected from a number of signalized intersections that experience left-turn spillover to use for calibrating and/or validating the regression models developed in this study.

-
- Further experiments should be conducted to investigate the effect of progression quality on left-turn spillover and through movement discharge rate. Once this relationship is established, this variable can be incorporated into the two models developed in this study to further improve its predictive capabilities over a wider range of traffic and control conditions.

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APPENDIX A:
EXPERIMENTAL DESIGN COMBINATIONS

Table A-1. Experimental design combinations for single through lane experiment

SCENARIO	%LT	L (veh)	G _{LT} (s)	G _{TH} (s)	C (s)	D (veh/h)
1	15	5	10	54	120	800
2	15	5	10	54	120	1200
3	15	5	10	54	180	800
4	15	5	10	54	180	1200
5	15	5	10	81	120	800
6	15	5	10	81	120	1200
7	15	5	10	81	180	800
8	15	5	10	81	180	1200
9	15	5	20	54	120	800
10	15	5	20	54	120	1200
11	15	5	20	54	180	800
12	15	5	20	54	180	1200
13	15	5	20	81	120	800
14	15	5	20	81	120	1200
15	15	5	20	81	180	800
16	15	5	20	81	180	1200
17	15	10	10	54	120	800
18	15	10	10	54	120	1200
19	15	10	10	54	180	800
20	15	10	10	54	180	1200
21	15	10	10	81	120	800
22	15	10	10	81	120	1200
23	15	10	10	81	180	800
24	15	10	10	81	180	1200
25	15	10	20	54	120	800
26	15	10	20	54	120	1200
27	15	10	20	54	180	800
28	15	10	20	54	180	1200
29	15	10	20	81	120	800
30	15	10	20	81	120	1200
31	15	10	20	81	180	800
32	15	10	20	81	180	1200
33	30	5	10	54	120	800
34	30	5	10	54	120	1200
35	30	5	10	54	180	800
36	30	5	10	54	180	1200

Table A-1 Continued.

SCENARIO	%LT	L (veh)	G_{LT} (s)	G_{TH} (s)	C (s)	D (veh/h)
37	30	5	10	81	120	800
38	30	5	10	81	120	1200
39	30	5	10	81	180	800
40	30	5	10	81	180	1200
41	30	5	20	54	120	800
42	30	5	20	54	120	1200
43	30	5	20	54	180	800
44	30	5	20	54	180	1200
45	30	5	20	81	120	800
46	30	5	20	81	120	1200
47	30	5	20	81	180	800
48	30	5	20	81	180	1200
49	30	10	10	54	120	800
50	30	10	10	54	120	1200
51	30	10	10	54	180	800
52	30	10	10	54	180	1200
53	30	10	10	81	120	800
54	30	10	10	81	120	1200
55	30	10	10	81	180	1200
56	30	10	10	81	180	800
57	30	10	20	54	120	800
58	30	10	20	54	120	1200
59	30	10	20	54	180	800
60	30	10	20	54	180	1200
61	30	10	20	81	120	800
62	30	10	20	81	120	1200
63	30	10	20	81	180	800
64	30	10	20	81	180	1200

Table A-2. Experimental design combinations for multiple through lanes experiment

SCENARIO	%LT	L (veh)	G_{LT} (s)	G_{TH} (s)	C (s)	D (veh/h)	TOT DEMAND (veh/h)	$NumLanes$
1	15	5	10	54	120	800	1600	2
2	15	5	10	54	120	1200	2400	2
3	15	5	10	54	180	800	1600	2
4	15	5	10	54	180	1200	2400	2
5	15	5	10	81	120	800	1600	2
6	15	5	10	81	120	1200	2400	2
7	15	5	10	81	180	800	1600	2
8	15	5	10	81	180	1200	2400	2
9	15	5	20	54	120	800	1600	2
10	15	5	20	54	120	1200	2400	2
11	15	5	20	54	180	800	1600	2
12	15	5	20	54	180	1200	2400	2
13	15	5	20	81	120	800	1600	2
14	15	5	20	81	120	1200	2400	2
15	15	5	20	81	180	800	1600	2
16	15	5	20	81	180	1200	2400	2
17	15	10	10	54	120	800	1600	2
18	15	10	10	54	120	1200	2400	2
19	15	10	10	54	180	800	1600	2
20	15	10	10	54	180	1200	2400	2
21	15	10	10	81	120	800	1600	2
22	15	10	10	81	120	1200	2400	2
23	15	10	10	81	180	800	1600	2
24	15	10	10	81	180	1200	2400	2
25	15	10	20	54	120	800	1600	2
26	15	10	20	54	120	1200	2400	2
27	15	10	20	54	180	800	1600	2
28	15	10	20	54	180	1200	2400	2
29	15	10	20	81	120	800	1600	2
30	15	10	20	81	120	1200	2400	2
31	15	10	20	81	180	800	1600	2
32	15	10	20	81	180	1200	2400	2
33	30	5	10	54	120	800	1600	2
34	30	5	10	54	120	1200	2400	2
35	30	5	10	54	180	800	1600	2
36	30	5	10	54	180	1200	2400	2
37	30	5	10	81	120	800	1600	2
38	30	5	10	81	120	1200	2400	2

Table A-2 Continued

SCENARIO	%LT (s)	L (veh)	G_{LT} (s)	G_{TH} (s)	C (s)	D (veh/h)	TOT DEMAND (veh/h)	$NumLanes$
39	30	5	10	81	180	800	1600	2
40	30	5	10	81	180	1200	2400	2
41	30	5	20	54	120	800	1600	2
42	30	5	20	54	120	1200	2400	2
43	30	5	20	54	180	800	1600	2
44	30	5	20	54	180	1200	2400	2
45	30	5	20	81	120	800	1600	2
46	30	5	20	81	120	1200	2400	2
47	30	5	20	81	180	800	1600	2
48	30	5	20	81	180	1200	2400	2
49	30	10	10	54	120	800	1600	2
50	30	10	10	54	120	1200	2400	2
51	30	10	10	54	180	800	1600	2
52	30	10	10	54	180	1200	2400	2
53	30	10	10	81	120	800	1600	2
54	30	10	10	81	120	1200	2400	2
55	30	10	10	81	180	1200	2400	2
56	30	10	10	81	180	800	1600	2
57	30	10	20	54	120	800	1600	2
58	30	10	20	54	120	1200	2400	2
59	30	10	20	54	180	800	1600	2
60	30	10	20	54	180	1200	2400	2
61	30	10	20	81	120	800	1600	2
62	30	10	20	81	120	1200	2400	2
63	30	10	20	81	180	800	1600	2
64	30	10	20	81	180	1200	2400	2
65	15	5	10	54	120	800	3200	4
66	15	5	10	54	120	1200	4800	4
67	15	5	10	54	180	800	3200	4
68	15	5	10	54	180	1200	4800	4
69	15	5	10	81	120	800	3200	4
70	15	5	10	81	120	1200	4800	4
71	15	5	10	81	180	800	3200	4
72	15	5	10	81	180	1200	4800	4
73	15	5	20	54	120	800	3200	4
74	15	5	20	54	120	1200	4800	4
75	15	5	20	54	180	800	3200	4
76	15	5	20	54	180	1200	4800	4

Table A-2 Continued

SCENARIO	%LT (s)	L (veh)	G_{LT} (s)	G_{TH} (s)	C (s)	D (veh/h)	TOT DEMAND (veh/h)	<i>NumLanes</i>
77	15	5	20	81	120	800	3200	4
78	15	5	20	81	120	1200	4800	4
79	15	5	20	81	180	800	3200	4
80	15	5	20	81	180	1200	4800	4
81	15	10	10	54	120	800	3200	4
82	15	10	10	54	120	1200	4800	4
83	15	10	10	54	180	800	3200	4
84	15	10	10	54	180	1200	4800	4
85	15	10	10	81	120	800	3200	4
86	15	10	10	81	120	1200	4800	4
87	15	10	10	81	180	800	3200	4
88	15	10	10	81	180	1200	4800	4
89	15	10	20	54	120	800	3200	4
90	15	10	20	54	120	1200	4800	4
91	15	10	20	54	180	800	3200	4
92	15	10	20	54	180	1200	4800	4
93	15	10	20	81	120	800	3200	4
94	15	10	20	81	120	1200	4800	4
95	15	10	20	81	180	800	3200	4
96	15	10	20	81	180	1200	4800	4
97	30	5	10	54	120	800	3200	4
98	30	5	10	54	120	1200	4800	4
99	30	5	10	54	180	800	3200	4
100	30	5	10	54	180	1200	4800	4
101	30	5	10	81	120	800	3200	4
102	30	5	10	81	120	1200	4800	4
103	30	5	10	81	180	800	3200	4
104	30	5	10	81	180	1200	4800	4
105	30	5	20	54	120	800	3200	4
106	30	5	20	54	120	1200	4800	4
107	30	5	20	54	180	800	3200	4
108	30	5	20	54	180	1200	4800	4
109	30	5	20	81	120	800	3200	4
110	30	5	20	81	120	1200	4800	4
111	30	5	20	81	180	800	3200	4
112	30	5	20	81	180	1200	4800	4
113	30	10	10	54	120	800	3200	4
114	30	10	10	54	120	1200	4800	4

Table A-2 Continued

SCENARIO	%LT	<i>L</i> (veh)	<i>G_{LT}</i> (s)	<i>G_{TH}</i> (s)	<i>C</i> (s)	<i>D</i> (veh/h)	TOT DEMAND (veh/h)	<i>NumLanes</i>
115	30	10	10	54	180	800	3200	4
116	30	10	10	54	180	1200	4800	4
117	30	10	10	81	120	800	3200	4
118	30	10	10	81	120	1200	4800	4
119	30	10	10	81	180	1200	4800	4
120	30	10	10	81	180	800	3200	4
121	30	10	20	54	120	800	3200	4
122	30	10	20	54	120	1200	4800	4
123	30	10	20	54	180	800	3200	4
124	30	10	20	54	180	1200	4800	4
125	30	10	20	81	120	800	3200	4
126	30	10	20	81	120	1200	4800	4
127	30	10	20	81	180	800	3200	4
128	30	10	20	81	180	1200	4800	4