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I am submitting herewith a dissertation written by Mohammad A. Qureshi entitled "A Delay Model for Exclusive Right-turn Lanes at Signalized Intersections with Uniform Arrivals and Right Turns on Red." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

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A Delay Model for Exclusive Right-turn Lanes at Signalized Intersections with Uniform Arrivals and Right Turns on Red

A Dissertation Presented For The Doctor Of Philosophy Degree
The University Of Tennessee, Knoxville

Mohammad A. Qureshi

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Dedicated to my mom and dad
for their many years of love, support, and,
most importantly, patience.

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ABSTRACT

Right turn on red (RTOR) is an established part of today's driving patterns. However, despite several revisions of the *Highway Capacity Manual* (HCM), the procedures for estimating delay at signalized intersections do not adequately incorporate the effects of RTOR. The HCM currently removes RTOR from the analysis.

This dissertation has developed models of uniform delay that incorporate RTOR based on queuing theory. Queuing accumulation polygons (QAP) were developed that include RTOR. The research developed a classification system for describing any signal phasing into one of 4 classes based on the sequence of 3 red regimes and one green regime.

It was further demonstrated that these 4 classes of signal phasings resulted in one of 2 general QAP patterns. The first pattern consists of two conflicting regimes followed by two non-conflicting regimes. The other pattern consists of alternating conflicting and non-conflicting regimes. Models to calculate delay for each basic pattern were developed.

The performance of the proposed models was evaluated with both field data and simulated data. The proposed model predicted delays that were different from both the observed delays and the delays based on the HCM method. A review of the intermediate calculations and videotape data suggests that variations in driver behavior may may partially account for the difference between the observed delay and the predicted delay.

Data sets were generated by varying volume parameters and signal timing parameters. The first data set simulated a variety of traffic conditions at the study intersection. The second data set represents as a variety of volumes under different signal timing patterns for a 4 phase timing plan. The proposed model predicted reductions in delay over a wide range of conditions when compared to the HCM approach under both sets of conditions.

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LIST OF ABBREVIATIONS/SYMBOLS

ABBREVIATIONS

ASSA	Adjusted Stop Sign Analogy
HCM	Highway Capacity Manual
QAP	Queuing Accumulation Polygon
RTOR	Right Turn(s) On Red
SSA	Stop Sign Analogy
TRIS	Transportation Research Information Services
TWSC	Two-Way Stop Controlled
VPH	Vehicles Per Hour

SYMBOLS

d	Average delay
d_1	uniform control delay component assuming uniform arrivals
PF	uniform delay progression factor that accounts for the affects of signal progression on delay
d_2	incremental delay component to account for the effect of random and oversaturation queues
d_3	residual demand delay to account for initial queues at the beginning of the analysis period
V	Arrival rate of right turning vehicles both with and without RTOR
Q_r	Number of vehicles in queue at the end of the effective red period
S	Departure rate of right turning vehicles
c_p	Potential capacity of RROR from the TWSC models
c_c	Actual capacity for RTOR from the TWSC models
r_u,,U	Unsaturated red time
C	Cycle length
f_{ped}	Pedestrian adjustment factor
E	Expected number of right turning vehicles arriving before a blocking vehicle during a cycle length
P_r	Proportion of right turning vehicles in a shared lane
c_{sl}	RTOR capacity for a shared lane based on TWSC models
c_R	RTOR capacity for the SSA approach
V_c	Volume of conflicting traffic
t_g	Critical gap time
t_f	Follow-up time
c_A	RTOR capacity for the ASSA approach
c_{RTOR}	RTOR capacity as calculated by Liu
G,g	Effective green time
X	Volume to capacity ratio
T	Duration of the analysis period
k	Incremental delay factor that is dependent on controller settings
I	Upstream filtering/metering adjustment factor
c	Lane group capacity

Q_b	Initial queue at the start of period *T*
t	Duration of unmet demand in period *T*
u	Delay parameter
$T_1, T_2, T_3, T_4, T_5, T_6$	Time points
$Q_1, Q_2, Q_3, Q_4, Q_5, Q_6$	Length of queue at corresponding time point
S_1, S_2, S_3, S_4	Departure rates of vehicles
$RTOR_p$	Predicted number of RTOR
RT	Right turn volume
s	Saturation flow rate for an exclusive right turn lane
so	Ideal saturation flow rate
f_w, f_{HV}, f_{bb}, f_{LU} ,f_g, f_p, f_a	Adjustment factors to account for deviations from ideal saturation flow conditions
t_q	Queue clearance time
$q_{r,c}$	Platoon ratio for the conflicting traffic
t_L	Lost time
R	Platoon ratio for the conflicting traffic stream
V_{rt}	Right turn volume including RTOR

1. INTRODUCTION

1.1 BACKGROUND

Legislation has existed since the 1970's in every state of the union that permits drivers to make right turns on red when it is safe to do so. In the past two decades, a number of studies have been conducted to quantify the consequences and benefits from permitting right turn on red (RTOR). These studies have shown that RTOR reduces delay and conserves fuel. The studies have been inconclusive on the safety impacts of permitting RTOR.

Right turn on red is an established part of today's driving patterns. However, despite several revisions of the *Highway Capacity Manual* (HCM) since 1985, the procedures for estimating delay at signalized intersections do not adequately incorporate the benefits of RTOR. In fact the HCM states that when RTOR are present, the RTOR volume should be removed from the analysis volume.

The HCM presumes that vehicles will arrive and depart as depicted in Figure 1. Vehicles arrive and the queue builds while the signal is red. No vehicles depart during the red phase. Upon the light turning green, vehicles depart and the queue dissipates.

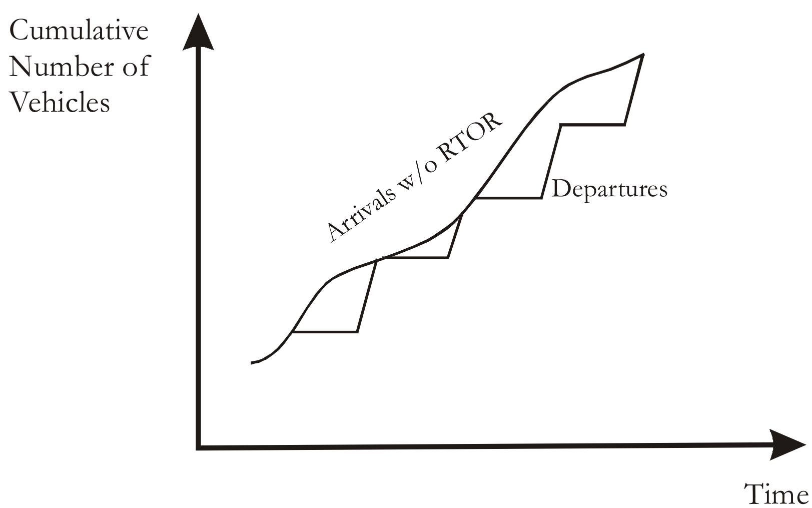

Figure 1: Queuing diagram for under the current HCM model

The HCM further separates the delay into 3 components. The first component represents delay assuming uniform arrival of vehicles (Figure 2). The second component adds an incremental delay to account for randomness and occasional oversaturation (i.e. failure to clear the queue under green). The third component adds delay as the result of an initial queue at the beginning of the analysis period.

When RTOR are incorporated in the analysis, the picture changes slightly as depicted in Figure 3. Vehicles still arrive and form a queue. However, the rate of arrivals is greater. During the red phase, some vehicles depart. Departures under green occur as before.

The difference in these approaches is shown in Figure 4. The two approaches yield the same delay only when shaded area 1 is equal to shaded area 2 in Figure 4. While it is possible that a set of volumes and signal timing may produce such an occurrence, the equality of these areas cannot be assumed as a general rule.

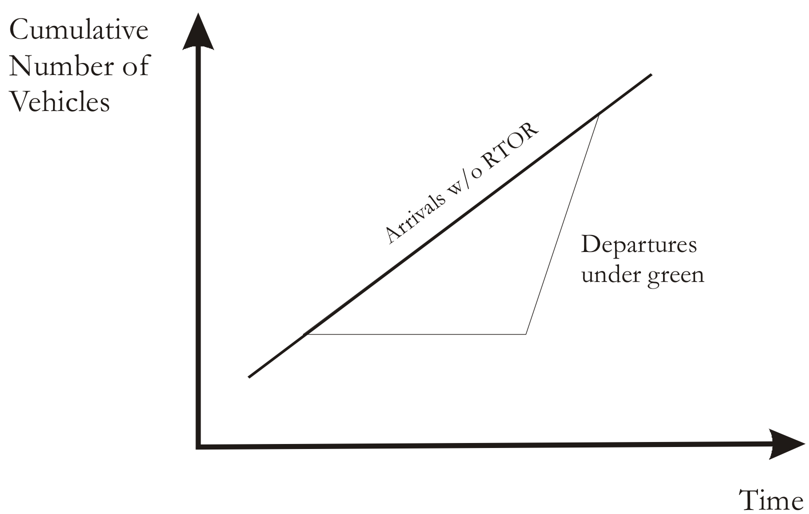

Figure 2: Conceptual uniform delay model under existing HCM treatment of RTOR

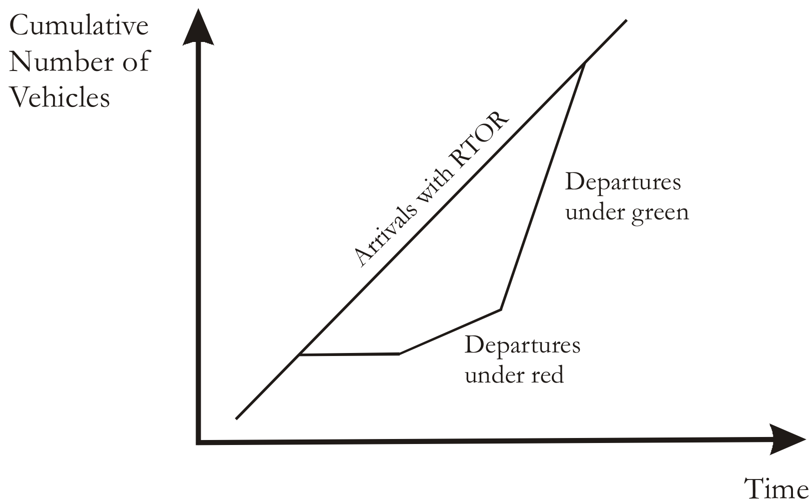

Figure 3: Conceptual delay model incorporating RTOR

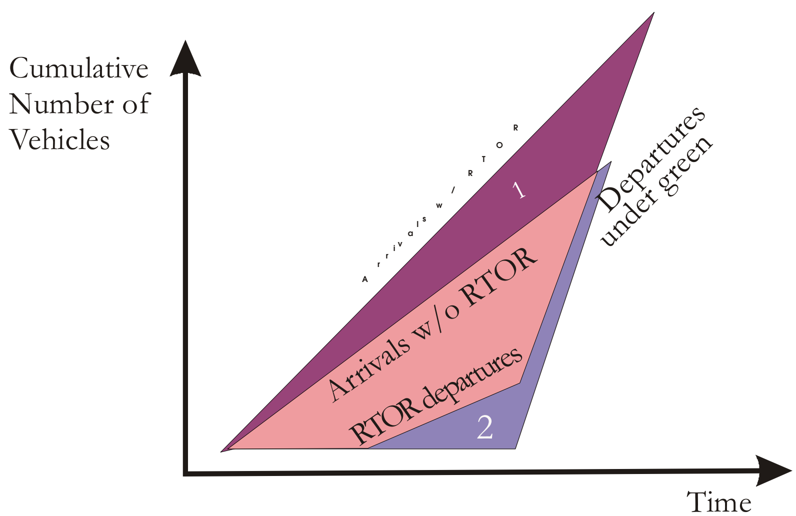

Figure 4: Difference between the HCM and RTOR inclusive delay models

1.2 OBJECTIVE

The objective of this research is to account for the effects of right turns on red in the current *Highway Capacity Manual's* model for delay at signalized intersections.

1.3 SCOPE

This dissertation will develop queuing diagrams for the different signal phasing patterns under which RTOR may occur. From these diagrams, delay equations will be derived.

Following the derivation of the delay equations, estimates for parameters in these equations will be identified and discussed. However, this dissertation will not validate or enumerate the parameter estimates. Finally, this dissertation will evaluate the performance of the proposed models with RTOR using a combination of field data and simulated data.

2. LITERATURE REVIEW

As noted earlier the objective of this research is to develop a model for delay at signalized intersections that incorporates right turns on red. The literature review, therefore, has focused on the analysis of right turns on red. A keyword search was conducted on the TRIS bibliographic database[1]. In addition, searches were conducted of recent dissertations and on the catalogs of established transportation libraries such as the Harmer E. Davis Transportation Library at the University of California, Berkeley.

No literature addressing the existence of a delay model that incorporates right turns on red was found. The literature found can be divided into four categories: literature on delay models for signalized intersections, studies on the safety and operational effects of right turns on red, studies on the capacity or flow of right turns on red, and studies on the prediction of RTOR volumes.

2.1 DELAY MODELS FOR SIGNALIZED INTERSECTIONS

The primary source on the treatment of delay at signalized intersections is Transportation Research Board *Special Report 209: The Highway Capacity Manual* (HCM). The 1997 revision of the HCM adopted control delay as the measure of performance for both signalized and un-signalized intersections. Control delay includes "initial deceleration delay, queue move up time, stopped delay, and final acceleration delay."

For a given lane group, the average control delay, d, is given by:

$$d = d_1 PF + d_2 + d_3$$

where

d_1= uniform control delay component assuming uniform arrivals;

[1] The Transportation Research Information Services (TRIS) Database is the world's largest and most comprehensive bibliographic resource on transportation information. TRIS is produced and maintained by the Transportation Research

PF = uniform delay progression factor that accounts for the effects of signal progression on delay;

d_2= incremental delay component to account for the effect of random and oversaturation queues;

d_3= residual demand delay to account for initial queues at the beginning of the analysis period.

The HCM documents the equations and procedures to estimate each of these parameters and will not be reproduced in this discussion. The models currently implemented in the HCM were proposed as part of Project 3-48 in the National Cooperative Highway Research Program, which developed a *Capacity Analysis for Traffic Actuated Intersections*. The authors of the project report contend that their delay formulation adopts "the traditional delay formulation used by virtually all analytical models" and is based on "two terms, which are added together to produce the total delay." The first term is mainly based on the uniform delay, which assumes all vehicles arrive in a completely uniform manner. The uniform delay is computed as the area contained in the queuing accumulation polygon (QAP). The second term is an incremental delay, which adds a correction factor for stochastic arrivals and occasional oversaturation. The second incremental term was derived from calibration with simulation data.

The QAP is an alternative means of showing arrivals and departures and is analogous to Figure 2. The QAP tracks the number of vehicles in queue as a function of time. A QAP for a simple two-phase operation is shown in Figure 5.

2.2 OPERATIONAL AND SAFETY EFFECTS OF RTOR

A second category of literature found during the database searches pertains to quantifying

Board (TRB) at the National Academies of Sciences. TRIS contains almost a half million records of published and ongoing research on all modes and disciplines in the field of transportation. Each year over 20,000 new records are added to TRIS.

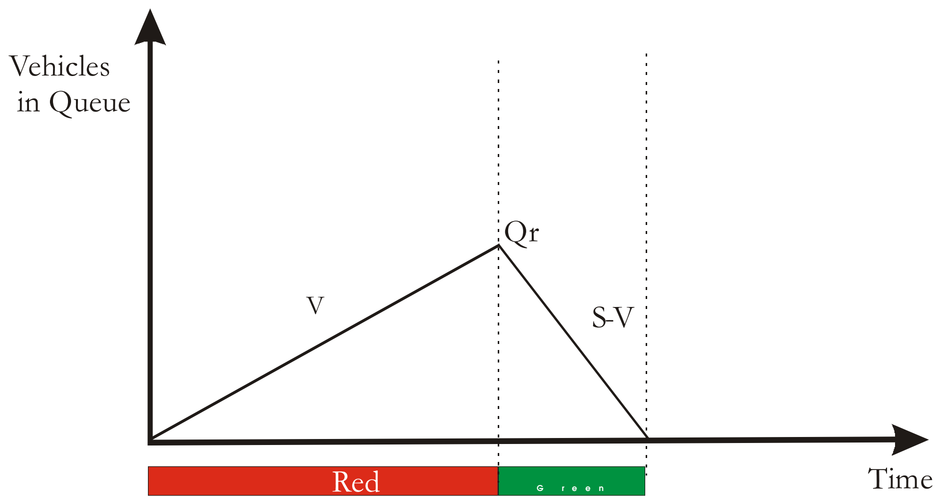

Figure 5: A Queuing Accumulation Polygon for simple two-phase operation

the impacts of the RTOR operation. Most of these studies were conducted in the late 1970's following the adoption of RTOR as a Federal Highway rule and focus on the safety impacts in terms of increases or decreases in accident rates. Since this dissertation is interested in delay and not in evaluating the policy of RTOR, safety studies were only given a cursory review. Some studies found no noticeable difference in rates after permitting RTOR while most found an increase in crashes.

An operational study was conducted in 1984 by the New Jersey Department of Transportation (Mullowney and Davis, 1984). This study concluded that as result of RTOR in New Jersey:

- Stopped vehicles saved an average of 3.0 second/vehicle;
- Approach vehicles saved an average of 1.4 seconds/vehicle;
- 5% of pedestrians were delayed in some way;
- Intersections with state highways had approximately 3,000 more accidents per year from 1978-1981 as result of RTOR; and
- Intersections involving only county or local roads exhibited no change in accidents.

2.3 RTOR CAPACITY AND SATURATION FLOW

Most of the recent work on RTOR has focused on calculating the capacity for RTOR. In 1985, Lin examined the characteristics of RTOR and use of auxiliary right-turn lanes. Lin collected counts at 16 sites on the proportion of right turns on red. In addition, data were collected on lane use for RTOR (traffic lane vs. shoulder), gap acceptance behavior, and dwell time for RTOR. This data was used to develop a simulation model that tested 3 combinations of geometric design and RTOR policy. Lin concluded that an auxiliary right turn lane is indispensable in facilitating RTOR.

While this conclusion is not surprising, several findings are quite interesting. Lin found that the critical gap for RTOR was 8.4 seconds. When a long gap is present and multiple RTOR maneuvers are made, the RTOR maneuver takes about 4.7 seconds to complete for the vehicles after the first vehicle. Lin found in his study that RTOR from an auxiliary lane may not reduce delay if the right turn delay without RTOR is under 15 seconds per vehicle. RTOR was effective in reducing delay when the cross traffic had saturation ratio under 0.6 and right turn delays without RTOR exceed 30 seconds per vehicle.

In 1990, Luh and Lu proposed estimating capacity based on existing models in the HCM. They observed that the RTOR drivers are required to come to a stop and select a gap in the conflicting traffic flow. These requirements are similar to those of a right turn from a minor street onto a major street at a two-way stop controlled (TWSC) intersection. The authors were unable to find evidence supporting their hypothesis. Consequently, they simulated RTOR capacity in NETSIM[2]. NETSIM does not explicitly model this maneuver and had to be manipulated to simulate RTOR. The results of the simulation for various conflicting traffic flows were compared to the capacity predicted by the models in the HCM for right turns at TWSC intersections. While the authors did not conduct any statistically based comparisons, they nevertheless concluded that the TWSC models did reasonably estimate capacity for RTOR.

[2] NETSIM is simulation software that is part of the TSIS software package developed by the Federal highway Admin.

Luh and Lu propose a 7-step procedure for computing RTOR capacity for an exclusive right-turn lane:

1. Identify conflicting traffic
2. Compute unsaturated red time (the portion of green time for the conflicting approach for which the volume to saturation flow rate is less than 1)
3. Find the critical gap
4. Compute the conflicting flow rate
5. Find potential capacity from TWSC models, c_p
6. Find adjustment factor for pedestrians
7. Compute actual capacity, $c_c = c_p(\frac{r_u}{C}) * f_{ped}$ where r_u is the unsaturated red time; C is the cycle time; and f_{ped} is a pedestrian adjustment factor.

If the right turns are made from a shared lane, Luh and Lu provide 4 additional steps as follows:

1. Compute actual capacity for an exclusive lane, $c_c = c_p(\frac{r_u}{3600}) * f_{ped}$
2. Compute portion of right-turning flow rate in the shared lane
3. Compute the expected number of leading right-turning vehicles $E = (\frac{1}{1-P_r}) - 1$ where E is the expected number of right-turn vehicles arriving before a blocking vehicle arrives and P_r is the proportion of right turn vehicles in the shared lane
4. Compute actual RTOR, $c_{sl} = \min(c_c, E)(\frac{3600}{C})$

In 1995, Virkler and Maddela compared the stop sign analogy (Luh and Lu approach) and the shadowing approach with data from 40 intersections. The shadowing method assumes that the number of RTOR is equivalent to the number of protected left turns on the cross street with a reduction factor for shared lanes if necessary. The shadowing method allows for the reduction of RTOR from the right-turn volumes while the stop sign analogy adds capacity to the right turns. Based on their analyses, the authors conclude that both approaches are better than assuming zero RTOR.

From a theoretical perspective, neither of these approaches is correct. They adjust either the arrival rate or the departure rate uniformly rather than using a step function approach to estimating the departures (see Figure 3). However, refinements are needed in both approaches to estimate delay and level of service. The stop sign analogy requires a modification of the delay model in the HCM since this approach adds capacity during the red phase while the delay model is based on capacity during the green phase. The shadowing approach presumes that all RTOR that could occur are made. This assumption is unrealistic. Also the shadowing approach removes vehicles from the analysis and consequently does not consider the reduced delays for these vehicles as part of the overall delay.

In 1998, Virkler and Krishna studied the treatments of RTOR in the HCM (shadowing), SIDRA (analysis software from Australia) and the stop sign analogy (SSA) approaches. SIDRA models RTOR using a gap acceptance behavior during the red phase and relies on user-specified critical gaps and follow-up times. The authors note that a potential problem from both the SSA and SIDRA approaches is the overestimation of capacity. Both models utilize a gap size distribution based on the negative exponential distribution. The problem is that gaps larger than the red time are not usable for RTOR. Therefore, both of these approaches overestimate the capacity. The authors propose an adjusted stop sign analogy (ASSA) method that reduces the SSA estimate of capacity for the gaps that are larger than the unsaturated red time.

The SSA capacity is calculated as:

$$c_R = \frac{3600}{t_f} e^{-\frac{V_c\left(t_g - \frac{t_f}{2}\right)}{3600}}$$

where,

c_R= capacity for RTOR

V_c= hourly volume of the conflicting traffic stream

t_g= critical gap

t_f= follow up time

The ASSA modifies the capacity from the SSA in the following manner:

$$c_A = \frac{3600}{t_f} e^{-\frac{V_c\left(t_g - \frac{t_f}{2}\right)}{3600}} - \frac{3600}{t_f} e^{-\frac{V_c\left(U - \frac{t_f}{2}\right)}{3600}}$$

where,

c_A = adjusted capacity for RTOR

V_c = hourly volume of the conflicting traffic stream

U = unsaturated red time.

The authors collected data at 7 sites for both RTOR and channelized right-turn movements. For each site, data were collected on:

1. Times for the rear wheels of vehicles in conflicting approaches to cross to the approach stop line (to determine saturation flow rates for the conflicting through and left-turn traffic);

2. Gaps in conflicting traffic streams accepted and rejected to determine critical gaps and follow-up times for yielding right turns;
3. Gaps in each conflicting flow stream (to determine the gap distribution available to right turns);
4. Conflicting volumes during each phase; and,
5. Phase lengths.

The authors used these data to compare the SSA and ASSA approaches. The authors found that the ASSA approach underestimated gap capacity while the SSA approach over estimated gap capacity. The shadowing approach also underestimated capacity for RTOR.

In 1995, Stewart and Hodgson examined the saturation flow rates for RTOR in Canada. The authors measured saturation flow for 6 intersections in the Greater Kingston, Ontario area. The authors compared the measured data with two methods for estimating saturation flow rates. One method was based on gap acceptance behavior and the arrival probability distribution of the conflicting traffic. The other approach establishes a relationship between conflicting traffic flow and RTOR saturation flow through curvilinear regression. Both methods produced estimates similar to the field data. However, a hold out sample was not used to test the accuracy of the two models.

The authors concluded:

1. The average critical gap was 6.59 seconds.
2. The average additional gap for multiple right turns was 4.7 seconds.
3. The average unopposed saturation flow for RTOR was 800 passenger car equivalents per hour of green.
4. The size of the critical gap was affected by environmental variables such as geometric conditions, surrounding land use, and roadway type.

5. The additional gap required for multiple discharges does not appear to be affected by location.

6. Gap acceptance behavior did not vary by day of the week.

7. The gap acceptance behavior did appear to be influenced by the time of day, number of conflicting lanes, and/or the turn radius.

8. Saturation flow rates for average conditions could be estimated by either the gap acceptance approach or by the regression approach.

Liu, also in 1995, produced a dissertation on the characteristics of RTOR. Liu utilized the TEXAS simulation model to simulate RTOR behavior at an isolated signalized intersection. The TEXAS model is capable of handling each driver-unit separately during simulation. Driver response is a function of driver-vehicle characteristics, roadway geometry, traffic control, and the action of other driver-vehicle units in the system. Simulations were conducted for two intersections. One was a 4-legged intersection with 2 lanes on each approach and a shared right-turn lane. The second was a 4-legged intersection with a single lane approach and an exclusive right turn-lane. The simulations used 12 classes of vehicles and 3 classes of drivers. The signal phasing was a 60 second cycle with a 50/50 split. The simulation run-time was 2700 seconds with 1-second increments and was replicated 8 times.

From these simulations, Liu determined the RTOR capacity for each approach. Regression analysis was used to model capacity as a function of the conflicting volume. Liu estimated the following piece-wise linear function:

$$\begin{aligned} c_{rtor} &= 206 - 0.22V_c, \text{ if } 0 \leq V_c \leq 300 \\ &= 183 - 0.18V_c, \text{ if } 300 \leq V_c \leq 650 \end{aligned}$$

Liu evaluated the sensitivity of this model to cycle length and cycle split: Increasing the cycle length to 90 seconds did not significantly affect RTOR capacity. Both a 60/40 and 40/60 cycle split were evaluated. The RTOR capacity was found to increase as the cycle split (first value in the ratio) decreases because a smaller split implies more red time for the subject approach.

Diegel (1995) in another dissertation applied queuing theory to analyze RTOR. The objective of this research was to apply waiting line analysis to the design and control of intersections. In simple terms, waiting line analysis says that a unit is immediately serviced upon its arrival to a processing point unless there are other units waiting to be processed in which case it waits until its turn. Thus in order to characterize the operation of the process the only information required is the arrival distribution, the service time distribution, and the number of service channels.

Therefore, the focus of Diegel's research was on identifying the arrival and service time distributions and classifying the queuing system. Data were collected at two intersections with simple two-phase timing. The cycle time was 60 seconds with a 50/50 split for the first intersection. At this intersection there were no exclusive right-turn lanes on any of the four legs of the intersection and all legs had 2 through lanes and a left-turn lane. The second intersection had an 80 second cycle with 50 seconds of green plus yellow time for the major leg of the intersections. All legs had two through lanes and a left-turn lane. In addition, the major leg of the intersection had exclusive right-turn lanes on each side.

Based on the data collected, the distribution of inter-arrival times was determined to be negative exponential. The service time distribution was identified as a shifted negative exponential. Consequently, properties of an M/M/1 distribution could be used to identify measures of performance such as the expected number of vehicles in the queue and the expected waiting time for queued vehicles.

2.4 RTOR VOLUME PREDICTION

Historically, the RTOR volume has not been modeled but rather observed as part of a turning movement count. However, often times RTOR are not disaggregated from the right-turn volume to simplify the counting process and to minimize costs. In 1997, Abu-Lebdeh, developed a model to estimate the volume of RTOR as a function of the right-turn volume, the g/C ratio of the subject approach, conflicting traffic volume, and the type of conflict. Type of conflict was a categorical variable to indicate if conflicts occurred from either the intersecting traffic or both the intersecting and opposing traffic. Regression analysis was used to estimate a model with main effects and two-way interaction effects with type of conflict. The authors found a linear regression model to be most suitable. All effects were found to be significant except for an interaction effect between conflicting volume and type of conflict.

In addition, the authors evaluated the impact of removing RTOR on delay. The authors computed two sets of delay based on the HCM procedures. The first delay uses an analysis volume that includes both right turns and RTOR. The second delay is based on only the right turns. The difference is the benefit of removing RTOR from the analysis as currently recommended by the HCM. For the 11 intersections in the study, the delay with RTOR included in the analysis volume were from 0% to 130% higher than the delays without RTOR in the analysis volume. On average, the difference was about 12%.

3. RESEARCH METHODOLOGY

3.1 HCM DELAY

Recall that the *Highway Capacity Manual* defines the average delay, d, for a lane group as:

$$d = d_1 PF + d_2 + d_3$$

where,

d_1= uniform control delay component assuming uniform arrivals;

PF = uniform delay progression factor that accounts for the affects of signal progression on delay;

d_2= incremental delay component to account for the effect of random and oversaturation queues;

d_3= residual demand delay to account for initial queues.

3.1.1 UNIFORM CONTROL DELAY

The uniform delay is derived from the queuing accumulation polygon under uniform, or constant, arrivals (Figure 5). Therefore,

$$d_1 = \frac{0.5C\left(1 - \frac{g}{C}\right)^2}{1 - Min(1, X)\frac{g}{C}}$$

where,

C = cycle length

g = the effective green tine

X = the volume to capacity ratio

3.1.2 INCREMENTAL DELAY

The incremental delay accounts for stochastic arrivals and for unmet demand at the end of the analysis period (i.e. arrivals exceed capacity). So,

$$d_2 = 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}\right]$$

where,

T = duration of the analysis period

X = the volume to capacity ratio

k = incremental delay factor that is dependent on controller settings

I = upstream filtering/metering adjustment factor

c = lane group capacity

3.1.3 RESIDUAL DEMAND DELAY

The residual demand accounts for the additional delay incurred by arriving vehicles during the analysis period because of initial queue at the beginning of the analysis period. Thus,

$$d_3 = \frac{1800Q_b(1+u)t}{cT}$$

where,

Q_b =initial queue at the start of period T

c = lane group capacity

T = duration of the analysis period

t = duration of unmet demand in period T

u = delay parameter

3.2 INFLUENCE OF RTOR ON HCM DELAY

In determining the impact of RTOR on delay, there are 2 questions that need to be determined.

1. Which of these delay terms is affected by RTOR?
2. How are these delay terms affected by RTOR?

An examination of the treatment of left turns provides the key to the first question. All three terms are applied to left-turns made under either protected (i.e. an exclusive phase) or permitted (i.e. when traffic conditions provide a sufficient gap under green light conditions). However, when both protected plus permitted phasing exists, the HCM introduces a supplemental uniform delay. This supplemental uniform delay accounts for the fact that the queuing accumulation polygons are not simple triangles (Figure 6). However, the incremental and residual delay terms are not adjusted.

RTOR are similar to left turns under protected plus permitted phasing in that the queuing accumulation polygons for both situations are not simple triangles. Consequently, RTOR should be treated in an analogous manner to left turns under protected plus permitted phasing.

3.3 IMPACT OF LANE ALLOCATION ON HCM DELAY

When right turns share a lane with through traffic, the potential exists that RTOR traffic may be blocked by a through vehicle that is unable to proceed under red. Luh and Lu presented an approach based on probability theory to account for this operational characteristic of shared lanes. Their method identifies the number of right turn vehicles that arrive prior to the arrival of a blocking vehicle based on the assumption that the number of unblocked right turns is geometrically distributed. Once the proportion of right-turning traffic in the shared lane is known, the expected number of right-turning vehicles arriving before a blocking vehicle is given by:

$$E = \frac{1}{1-P_r} - 1$$

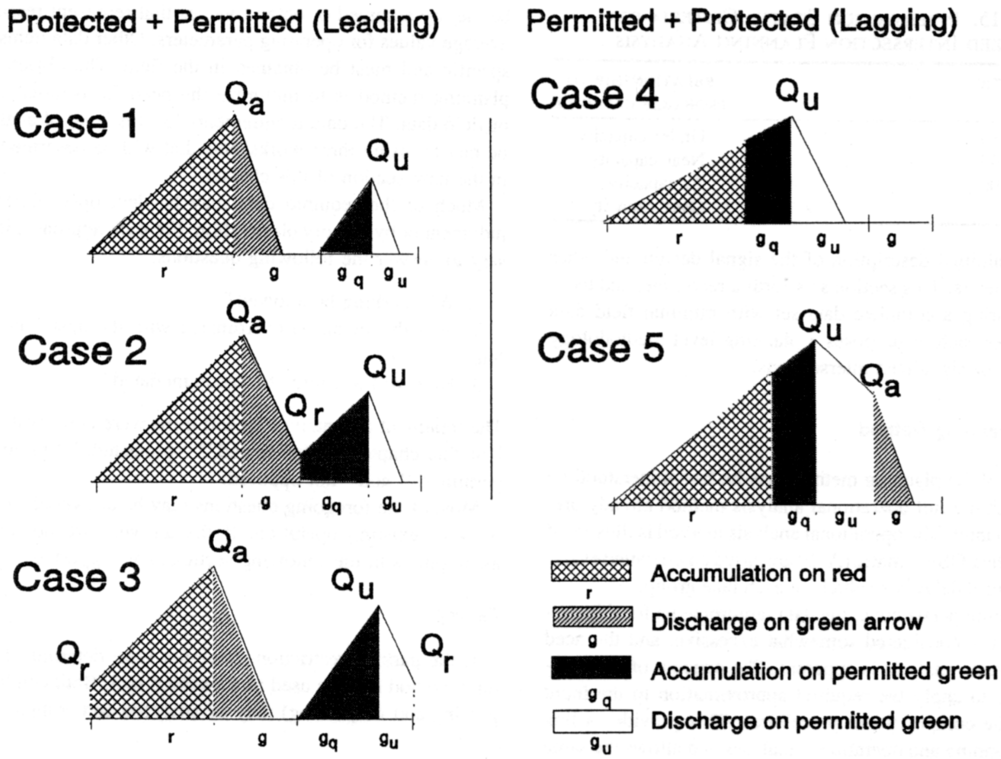

Figure 6: Queuing accumulation polygons for protected plus permitted phasing.
Source: Transportation Research Board, Special Report 209: The Highway Capacity Manual, 1997, pg. 9-31.

As can be seen in Figure 7, with as many as 80% of the vehicles in a lane making right turns, only 4 vehicles are expected prior to the arrival of a blocking vehicle during a red phase. Consequently, only these 4 vehicles would have the opportunity to make a right-turn-on red if appropriate gaps were available. Under most shared lane conditions, therefore, the probability of a blocking vehicle limits the number of RTOR maneuvers allowed. By the time a significant number of RTOR maneuvers arrive before the appearance of a blocking vehicle, the proportion of right turns is so high that the lane should be analyzed as a de facto exclusive right-turn lane.

Given the limited opportunities of RTOR under shared lane conditions, the remainder of this dissertation will not specifically address the shared lane condition. While the existing delay models, which exclude RTOR, adequately incorporate the impact of RTOR from a shared lane, the

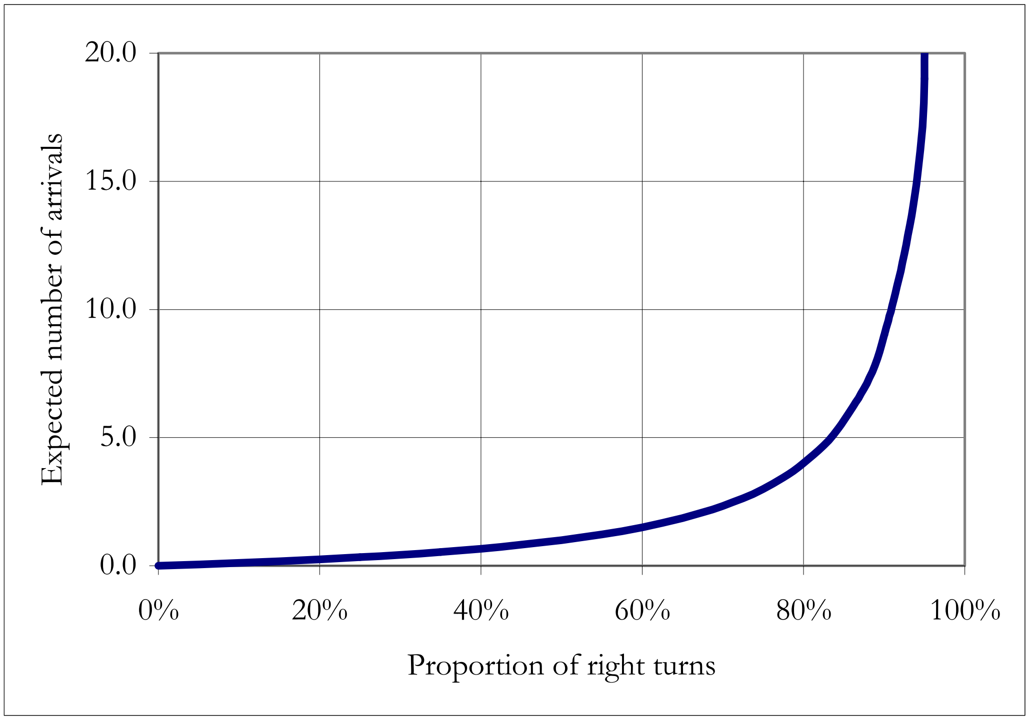

Figure 7: Expected Number of RTOR Arrivals Before a Blocking Vehicle

methodology developed in the proceeding sections may be modified to analyze delays under shared lane conditions.

4. INCORPORATING RTOR IN UNIFORM CONTROL DELAY

The HCM states that the number of vehicles able to turn right during a red phase is the function of several complex variables:

- Demand for right-turn movements,
- Sight distance at the intersection,
- Degree of saturation of the conflicting through movement,
- Arrival patterns over the signal cycle,
- Left-turn signal phasing on the conflicting street, and
- Conflicts with pedestrians.

While the complexity of these variables may imply that RTOR are unique to a given set of conditions, the use of QAPs allows for the development of versatile analytical models of delay to analyze RTOR. Each QAP involving RTOR may be classified by the sequence of signal phasing at an intersection. Within each classification, the effect of the variables listed above may be captured in the parameters of the analytic model.

4.1 INFLUENCE OF SIGNAL PHASING ON QAP

Consider the situation shown in Figure 8, a vehicle (labeled S in Figure 8) arrives during red phase and comes to a stop. Three regimes during the red phase affect this vehicle's ability to turn right during the red phase. During one regime, the red light gives priority to through vehicles on the intersecting street that conflict with the subject vehicle's ability to turn right. (Figure 8, labeled A). In the second regime, the red light prioritizes vehicles on the intersecting street that do not conflict with the subject vehicle's ability to turn right (Figure 8, labeled B). The final regime provides priority to opposing left-turns that also may restrict the ability of the subject vehicle to turn right (Figure 8, labeled C). When the light turns green, the right-turning vehicle has priority. The lengths of these red and green regimes are effective times and include appropriate adjustments for the yellow and lost times.

Therefore, any phasing plan can be described by a simple sequence of these 3 red regimes and the green phase. Furthermore, the two regimes prioritizing the intersecting traffic streams occur sequentially, and more specifically, occur only once during a cycle. Similarly, the regime prioritizing the opposing left-turns and the green phase occur sequentially and occur only once during a cycle.

Therefore, for the intersecting street, the following sequences are possible:

- R_{ic}, a single phase where all movements occur at once. Thus, the only regime of concern protects conflicting traffic on the intersecting street (Figure 8, labeled A);
- R_{inc}, a single phase that protects only non-conflicting traffic on the intersecting street. (Figure 8, labeled B);
- R_{ic} followed by R_{inc}; and,
- R_{inc} flowed by R_{ic}.

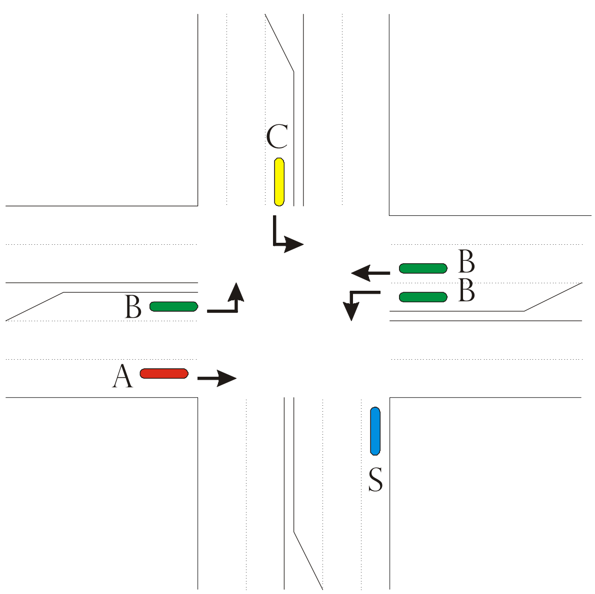

Figure 8: Typical 4 leg intersection

While a sequence is possible that would allow a single R_{inc} phase, such an event can only occur at a fully actuated signal when left turning traffic is present and through traffic is not present. The probability of such an event is very low and the significance of such an event is also very low.

Meanwhile for the subject approach, the following sequences are possible:

- G, a single phase where all movements occur at once. Thus, the only regime of concern prioritizes the subject approach;
- R_{oc}, a single phase that protects the opposing left-turning traffic. (Figure 8, labeled C);
- G followed by R_{oc}; and,
- R_{oc} flowed by G.

As with the intersecting streets, a single R_{oc} phase, while theoretically possible, is highly improbable and has little significance.

Consequently, complex intersection phasing sequences can be classified into 4 general classes of red and green regime phasing as shown in Table 1. Table 2 describes the phasing sequences for these 4 classes in an alternate manner that highlights the sequence of phases. Subclasses of phasing sequences can be derived by recognizing that all 3 red regimes do not need to be present in a signal phasing sequence. Table 3 shows 5 common subclasses of phasing sequences. Figure 9 shows some common intersection phasing plans and their associated RTOR phasing classification.

A queuing accumulation polygon can be developed for each of these classes and subclasses. However, the general shape and corresponding delay model are not necessarily unique. Differences in QAP result because of the specific timing and traffic volumes for a given situation. By recognizing the similarities in the characteristics among the 3 red regimes and the green regime, 2 basic QAP patterns can be identified to describe the 4 classes.

Table 1: Classification of Phasing Sequences for RTOR

SUBJECT APPROACH INITIAL PHASE		INTERSECTING APPROACH INITIAL PHASE	
		R_{inc}	R_{ic}
	R_{oc}	I	II
	Green	III	IV

Table 2: Alternate Representation of Signal Phasing Classifications for RTOR

CLASS	INTERSECTING APPROACH	SUBJECT APPROACH	DESCRIPTION
I	R_{inc} , R_{ic}	R_{oc} , G	4 phase plan with leading lefts
II	R_{ic} , R_{inc}	R_{oc} , G	4 phase plan with leading lefts on the subject approach and lagging lefts on the intersecting approach
III	R_{inc} , R_{ic}	G , R_{oc}	4 phase plan with lagging lefts on the subject approach and leading lefts on the intersecting approach
IV	R_{ic} , R_{inc}	G , R_{oc}	4 phase plan with lagging lefts

Table 3: Subclasses of Signal Phasing Sequences for RTOR

SUBCLASS	INTERSECTING APPROACH	SUBJECT APPROACH	DESCRIPTION
1	R_{ic}	G	2 phase plan
2	R_{ic}	R_{oc} , G	3 phase plan with leading lefts on the subject approach
3	R_{ic}	G , R_{oc}	3 phase plan with lagging lefts on the subject approach
4	R_{ic} , R_{inc}	G	3 phase plan with lagging lefts on the intersecting approach
5	R_{inc} , R_{ic}	G	3 phase plan with leading lefts on the intersecting approach

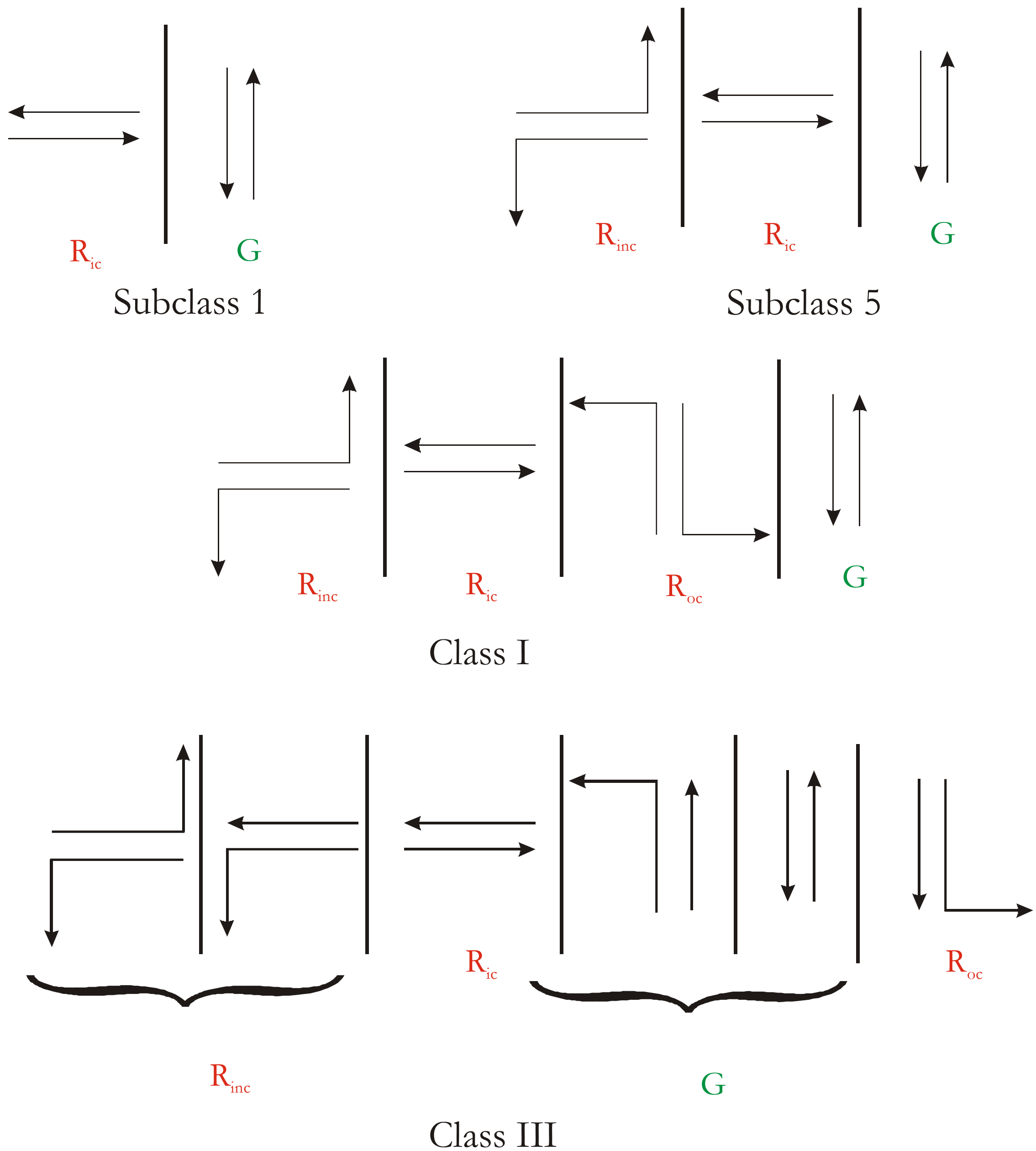

Figure 9: Sample intersection phasing sequences and their associated RTOR Phasing Classification

The two regimes that provide priority to conflicting traffic with respect to RTOR exhibit a similar queuing accumulation pattern. Initially, the RTOR queue builds while the queue in the conflicting stream dissipates. Once the queue in the conflicting stream has discharged, the RTOR queue discharges. The green regime and the red regime that provides priority to the non-conflicting traffic stream do not show a period of time where the RTOR queue builds but immediately progress to the queue discharge stage. The rates of discharge may vary in each regime and the length of time that the queues build or discharge may vary. However, the general shape of the resulting sections of the QAP will either follow the pattern of a conflicting phase or a non-conflicting phase.

Assuming that a QAP begins with a conflicting phase, then the 4 classes of phasing sequences result in QAPs that consist of two basic patterns. The first pattern consists of 2 conflicting phases followed by 2 non-conflicting. The second pattern consists of alternating conflicting phases.

In the following sections, QAP and analytic solutions for average delay will be derived for the HCM approach, which consists of a simple two phase sequence, and for the two basic patterns found in QAP with RTOR.

4.2 QAP FOR THE HCM APPROACH

The uniform delay for right turns as calculated by the HCM is based on a simple phasing that consists of two phases. Either a red light prohibits right turns or a green light permits right turns. The QAP for this phasing is a simple triangle, as shown in Figure 10, where the queue builds during the red phase and then discharges during the green phase. It is important to remember that the arrival rate under this approach only considers the turns made under green and excludes RTOR.

The average delay for this QAP is then defined as:

$$d = \frac{\int_0^C Q(t)dt}{\int_0^C V dt}$$

$$d = \frac{\text{area of the QAP}}{\text{VC}}$$

$$d = \frac{1}{VC}\left(\frac{rQ_r}{2} + \frac{Q_r^2}{2(S-V)}\right)$$

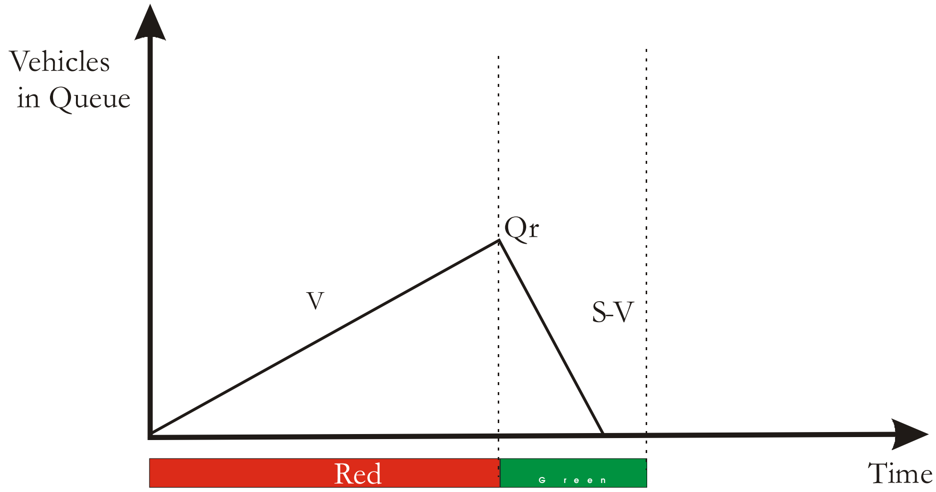

Figure 10: QAP for a two-phase sequence

where,

C = cycle length

V = arrival rate of vehicles

r = the effective red period

Q_r = number of vehicles in queue at the end of the effective red period

S = departure rate of vehicles

4.3 RTOR QAP WITH 2 CONSECUTIVE CONFLICTING PHASES

Of the 4 classes of RTOR phasing sequences identified above, both classes I and IV exhibit this pattern of 2 consecutive conflicting phases. For class I the phasing is defined as R_{inc}, R_{ic}, R_{oc}, & Green, However, the first conflicting phase is the R_{ic} phase and if the sequence initiates from this phase, the sequence becomes R_{ic}, R_{oc}, Green, & R_{inc}. For class IV, the phasing is Green, R_{oc}, R_{ic}, & R_{inc}. Using the same logic of initiating the sequence with the first conflicting phase, the rearranged sequence is R_{oc}, R_{ic}, R_{inc}, & Green. The resulting QAP for both of these sequences is shown in Figure 11.

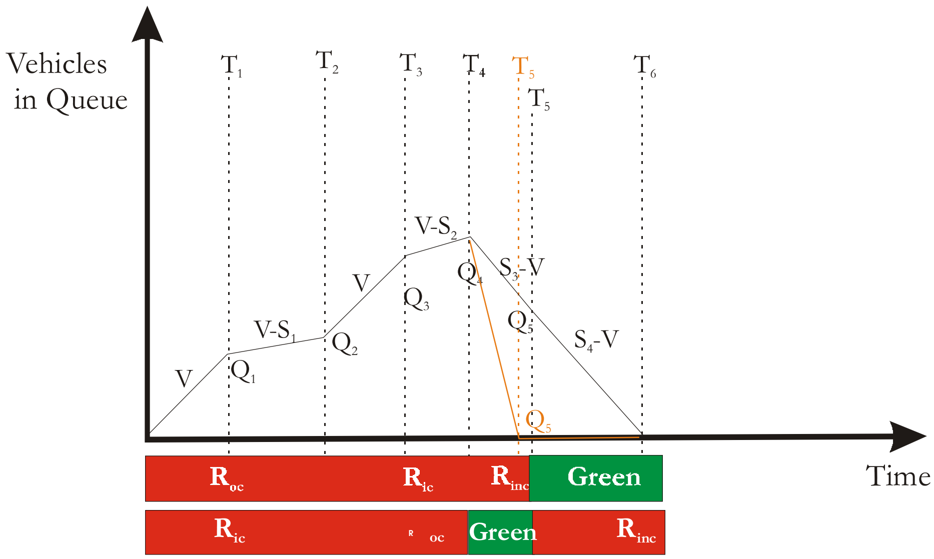

Figure 11: QAP for two consecutive conflicting phases

The first increment of time to T_1 is the time for the queue of the conflicting movement to clear. T_2 marks the end of the initial phase and the beginning of the second conflicting phase. Between, T_1 and T_2 right turns on red may occur and change the rate of queue accumulation. T_3 ends the queue clearance for the second conflicting phase. T_4 ends the second conflicting phase and begins a discharge phase. Between T3 and T4, right turns may occur and affect the rate of queue accumulation. The next two phases, from T_4 to T_5 and from T_5 to T_6, should discharge the queue. It should be noted that the queue may clear before end of the cycle.

Again, the average delay is calculated as the area of the polygon divided by the total number of right turns (this time including RTOR). The versatility of this solution lies in the fact that the parameters for arrival and departure rates characterize the specifics of the situation analyzed.

The average delay is then:

$$d = \frac{\int_C Q(t)dt}{\int_C Vdt}$$

$$d = \frac{1}{VC}\left(\begin{array}{l} \frac{Q_1 T_1}{2} + (T_2 - T_1)\frac{Q_1 + Q_2}{2} + (T_3 - T_2)\frac{Q_2 + Q_3}{2} + (T_4 - T_3)\frac{Q_3 + Q_4}{2} \\ + (T_5 - T_4)\frac{Q_4 + Q_5}{2} + (T_6 - T_5)\frac{Q_5}{2} \end{array} \right)$$

where,

Q_i = number of vehicles in queue at time period T_i

C = cycle length

V = arrival rate of vehicles including RTOR

4.4 QAP FOR ALTERNATING CONFLICTING PHASES

Class II and III phasing sequences result in a QAP pattern as shown in Figure 12. The sequences after rearranging become R_{oc}, Green, R_{ic}, R_{inc} and R_{ic}, R_{inc},Green, R_{oc}. Again T_1 represents the initial portion of the conflicting phase during which the queue in the conflicting traffic stream clears. After the end of the conflicting phase at T_2, a non-conflicting phase begins. This pattern is then repeated beginning at T_3.

The solution for the average delay is identical to the consecutive conflicting phases and is given by:

$$d = \frac{\int_C Q(t)dt}{\int_C V dt}$$

$$d = \frac{1}{VC}\left(\begin{array}{l} \frac{Q_1 T_1}{2} + (T_2 - T_1)\frac{Q_1 + Q_2}{2} + (T_3 - T_2)\frac{Q_2 + Q_3}{2} + (T_4 - T_3)\frac{Q_3 + Q_4}{2} \\ + (T_5 - T_4)\frac{Q_4 + Q_5}{2} + (T_6 - T_5)\frac{Q_5}{2} \end{array} \right)$$

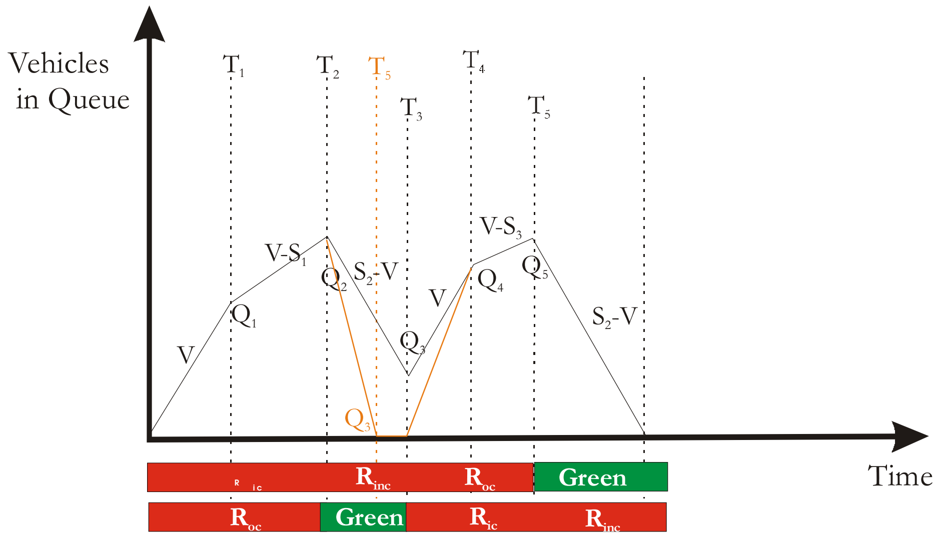

Figure 12: QAP for alternating conflicting phases

4.5 QAP FOR SUB CLASSES AND SPECIAL CASES

The key to solving subclasses and special cases is to recognize that the basic building blocks for the QAP are the sequence of conflicting and non-conflicting phases. The analytic solutions for the subclasses are variants of the general solutions derived above with some terms dropping out and simplifying the solution. For example, consider the case of simple two-phase sequence of red and green as shown in Figure 13. The delay for this case is given by:

$$d = \frac{1}{VC}\left(\frac{Q_1 T_1}{2} + (T_2 - T_1)\frac{Q_1 + Q_2}{2} + +(T_3 - T_2)\frac{Q_2}{2} \right)$$

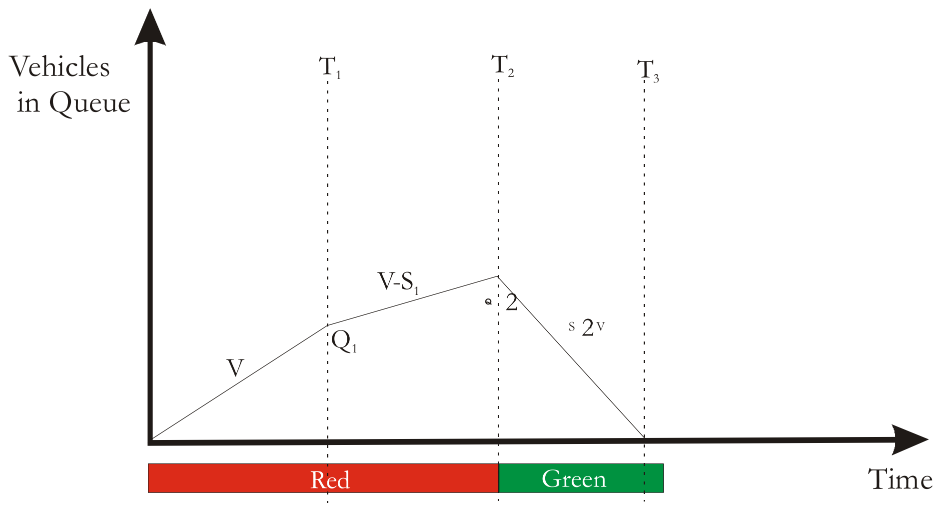

Figure 13: Two-phase sequence with RTOR

5. PARAMETER ESTIMATES

The versatility of analyzing delay through QAPs lies in the fact that parameter estimates for arrival and departure rates may be estimated with field data or by models or some combination of both. In the solutions detailed in the previous chapter, calculating the delay requires knowledge of the number of vehicles in queue at specific points during the cycle. These queues can be calculated if the arrival rate, departure rates under the different phases, the queue clearance times for conflicting phases, and the length and sequence of both conflicting and non-conflicting phases are known. Alternatively, they can be directly observed as well.

5.1 VOLUME ARRIVAL RATE ESTIMATES

Arrival rates are most commonly based on volume counts. Prior to analyzing an intersection, a turning movement count is required. In some cases, the count will be conducted explicitly for the analysis. However, turning movements are often counted as part of an overall effort to track changes in traffic patterns.

During a turning movement count, RTOR volumes are counted. However, the results are not always disaggregated. That is to say, the RTOR may be included as part of the general right turn volume rather than as a separate category.

For the proposed delay equations derived in the previous chapter, the volume arrival rate should be the total volume for the lane group. For an exclusive right turn lane, this would be the sum of the right turns on green and RTOR.

If, however, a comparison with the existing HCM method, which excludes RTOR, is desired, then the RTOR volume must be disaggregated. If RTOR are not counted separately during the turning movement count, then the study by Abu-Lebdeh in 1997 provides a means for estimating RTOR. Abu-Lebdeh proposed two models depending on the types of conflicting volumes. If the conflicting volume is only from the intersecting approach, then

$$RTOR_p = 79 + 0.339RT - 165\frac{G}{C} - 0.0559V$$

However, if the conflicting traffic is from both intersecting and opposing approaches, then

$$RTOR_p = 28.7 + 0.447RT - 22\frac{G}{C} - 0.0559V$$

where,

RT = total right turn volume on the subject approach

G/C = green time to cycle time ratio for the subject approach

V = the conflicting traffic volume.

5.2 SATURATION FLOW RATES

In the previous chapter, 4 flow regimes (3 during the red phase and 1 during the green) were identified for RTOR. The ability to make a right turn and the rate at which rights may be serviced can vary during each of these periods. These flow rates can be measured in the field or estimated based on existing models of behavior.

5.2.1 FLOW RATE UNDER GREEN

The flow rate during green is the simplest to estimate since the procedure comes directly from the HCM. The general form of the model for an exclusive right turn lane is:

$$s = 0.85 s_o f_w f_{HV} f_g f_p f_{bb} f_{LU} f_a$$

where,

s_o = a saturation flow rate for a given set of lane characteristics representing ideal conditions

f = adjustment factors for lane characteristics deviating from the ideal.

For a detailed discussion of this method, consult the HCM.

5.2.2 FLOW RATE UNDER RED WITHOUT CONFLICTING TRAFFIC

During this regime, RTOR are protected from conflict. Consequently, flows under this regime can be high. In many cases, right turns could be given a green signal. Therefore, the saturation flow rate under green, as described above, should be a very close approximation.

However, a modification may be required to account for drivers having to come to a stop prior to completing the RTOR. This modification can be achieved by measuring the proper ideal saturation flow rate, s_0.

5.2.3 FLOW RATE UNDER RED WITH CONFLICTS FROM THE INTERSECTING TRAFFIC

During the red phase when there is a conflicting and intersecting traffic stream, the RTOR behavior relies on the acceptance of an available gap for completing the right turn maneuver. This behavior is identical to making a right turn at a stop sign. Therefore, the stop sign analogy method of Luh and Lu (1990) or the adjusted stop sign analogy proposed by Virkler and Krishna (1998) may be used to estimate the departure rate. As shown by Virkler and Krishna, their method tends to underestimate while the Luh and Lu approach overestimates the rate of departures. Both of these methods rely on the HCM critical gap and follow-up times of 5.5 and 2.6 seconds, respectively. However, Stewart and Hodgson (1995) observed longer critical gap and follow-up times.

Alternatively, the regression-based approach of Stewart and Hodgson may also be used. Detailed comparative studies are needed to identify whether the Luh and Lu model:

$$s = \frac{3600}{t_f} e^{-\frac{V_c(t_g - 0.5t_f)}{3600}}$$

or the Virkler and Krishna model:

$$s = \frac{3600}{t_f} e^{-\frac{V_c(t_g - 0.5t_f)}{3600}} - \frac{3600}{t_f} e^{-\frac{V_c(U - 0.5t_f)}{3600}}$$

or the Stewart and Hodgson model:

$$s = 849.82e^{-.00129V_c} - 31$$

best estimate the departure flow rate. It is worth noting that all three models are forms of the negative exponential distribution and consistent with Diegel's findings about the departure rate of RTOR.

All 3 models rely on an estimate of the conflicting volume. To properly calculate the saturation flow rates, the appropriate conflicting volume is only the traffic in the lane that will receive the right turns, usually the right most lane of the receiving approach.

5.2.4 FLOW RATE UNDER RED WITH CONFLICTS FROM OPPOSING TRAFFIC STREAMS

RTOR operation when the red signal provides priority to the left turns of the opposing approach is similar to that of RTOR under red signal that provides priority to the intersecting approach. Therefore, the previous discussion remains valid. RTOR with conflicts from the opposing approach, however, may result in slightly different critical gap and follow-up times. Observational studies are needed to identify if this is the case.

5.3 QUEUE CLEARANCE TIMES

While the queue for the conflicting traffic stream clears, the gaps are relatively small and insufficient for a RTOR to be completed. Therefore, the final piece of the puzzle required to estimate queue lengths is the time for queues to clear and gaps appear in the conflicting traffic stream.

Regression models have been developed in the HCM for protected plus permitted phasing for left turns that may be utilized. For a given period of red time (i.e. one of the two regimes in which conflicting traffic has priority – R_{inc} or R_{oc}) the time to clear, t_q, is defined as

$$t_q = \frac{V_c q_{r,c}}{0.5 - \frac{V_c(1-q_{r,c})}{red}} - t_L$$

where,

V_c=the volume of the conflicting traffic stream;

$q_{r,c}$=the queue ratio for the conflicting stream defined as $q_{r,c} = 1 - R\frac{g}{C}$ where R is the platoon ratio for the conflicting stream and g/C is the ratio of effective green for the conflicting stream; and

t_L=the lost time for the conflicting stream.

5.4 EXAMPLE OF QUEUE ESTIMATION

Given the estimates of arrival rate, departure rate, phasing sequences, and queue clearance times, the queue lengths can be estimated. In Figure 13, there are two queue lengths needed for estimating delay, Q_1 and Q_2. Using parameter estimates, they can be computed as:

$$\begin{aligned} Q_1 &= V_{rt}T_1 \\ &= V_{rt}t_c \end{aligned}$$

and,

$$\begin{aligned} Q_2 &= Q_1 + (V_{rt} - s_R)(T_2 - T_1) \\ &= V_{rt}t_c + (V_{rt} - s_R)(red - t_c) \end{aligned}$$

where,

V_{rt} = the arrival rate of all right turns including RTOR;

t_c = the time to clear the queue in the conflicting traffic stream; and

s_R = the saturation flow rate for RTOR during the red phase.

6. MODEL PERFORMANCE AND SENSITIVITY

To evaluate the proposed model, field data and simulated data were utilized to compare the proposed model against observed delays and the existing HCM model.

6.1 FIELD DATA

Students at the University of Tennessee in a graduate course on traffic operations chose a term project that compared field observations of delay against delays calculated by the HCM method as implemented by the Highway Capacity Software. A subset of data relevant to this study of right turns on red was extracted from their efforts.

Data were collected for the morning and evening peak period during the month of April, 2000 at the intersection of Broadway and Washington Avenues in Knoxville, Tennessee. Delay for the right turn lane was measured using two different procedures. One method observed the elapsed time of vehicles (travel time method) by identifying the times a right-turning vehicle passed an upstream point on Washington Avenue and the time a vehicle departed the stop line at Broadway. The other method observed the number of vehicles in queue every 10 seconds (incremental method) in the right turn lane. Video was also collected to perform counts of right turns from Washington and conflicting traffic in the rightmost lane of northbound Broadway Avenue (Figure 14).

The left turn from Broadway onto Washington is an actuated phase. To account for this variability, only cycles in which the left turn phase was not actuated or in which the left turn phase was actuated by a single vehicle were selected for the evaluation of the proposed model. At this location, an exit-only driveway for a Post Office abuts the right turn lane on Washington. Since the upstream observer for the travel time method was located upstream of the driveway, the travel time method data tended to overestimate observed delays. However, the incremental method did capture the delay for the post office's exiting vehicles. Therefore, for the purposes of this evaluation the

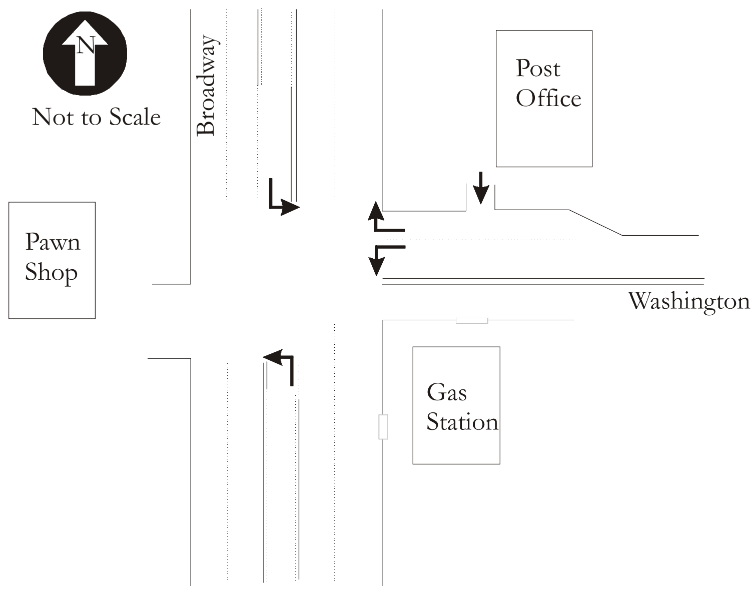

Figure 14: Schematic of the intersection of Broadway and Washington Avenues

delays observed with the incremental method were utilized. Table 4 summarizes the characteristics of the data set utilized for this evaluation.

6.2 MODEL PERFORMANCE RELATIVE TO FIELD DATA

For each of the 42 cycles included in this evaluation, the uniform delay based on the HCM method was calculated. The delay based on the proposed model was calculated only for those cycles in which a RTOR was observed. For the proposed model, delays were based on two different QAP. Cycles without a left turn phase utilized the QAP in Figure 15 while the cycles with a left-turn actuation utilized the QAP in Figure 16. The saturation flow rate for RTOR, S_1, in both QAP was calculated based on the Stewart and Hodgson model. This model was chosen for its simplicity and its ability to produce results similar to the stop-sign analogy approaches. In the QAP with a left turn actuation, the saturation flow rate, S_3, during the left turn phase was assumed to be the same as the saturation flow under green, S_2. In order to calculate the effective green and red times, a lost time of 4 seconds per phase was utilized in conjunction with the signal timings provided by the City of Knoxville.

Table 4: Characteristics of data collected at Broadway & Washington Avenues

	AM	PM
CYCLE LENGTH	100 seconds	120 seconds
NUMBER OF CYCLES	25	17
NUMBER OF CYCLES WITH RTOR	18	12
NUMBER OF CYCLES WITH AN ACTUATED LEFT TURN PHASE	4	9
RATE OF RIGHT TURNS ON GREEN	0 to 144 vehicles per hour	0 to 210 vehicles per hour
RATE OF RTOR	0 to 180 vehicles per hour	0 to 150 vehicles per hour
RATE OF CONFLICTING TRAFFIC	108 to 432 vehicles per hour	450 to 870 vehicles per hour

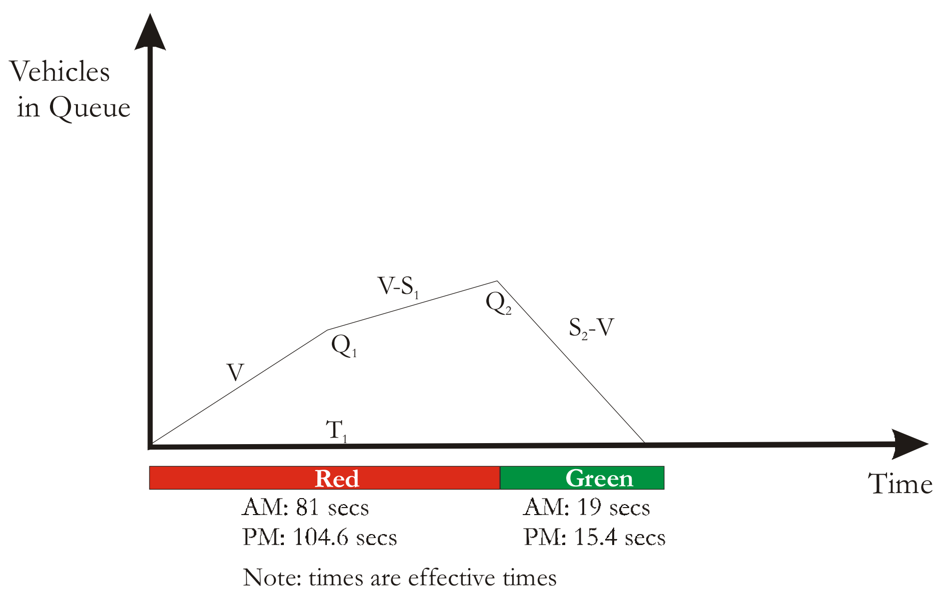

Figure 15: QAP without a left-turn phase actuation on Broadway

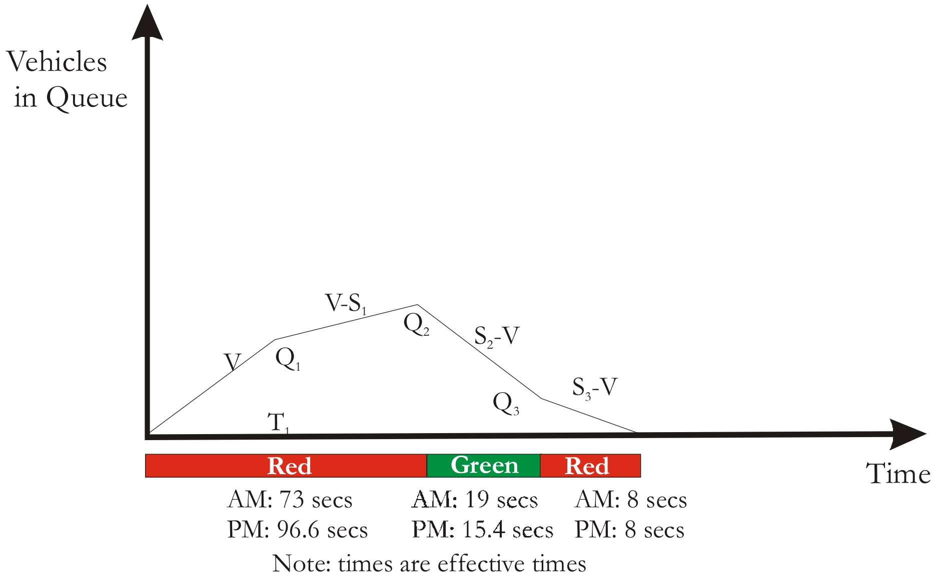

Figure 16: QAP with left-turn phase actuation on Broadway

Comparisons were made between the proposed model and the observed delay, the HCM model and the observed delay, and between the proposed model and the HCM model for the AM and PM period. To avoid restrictive assumptions about the underlying distributions of delays, the Wilcoxon signed rank test was conducted to test for bias in the 3 pair-wise comparisons between the two models and the observed delay. Based on these tests of bias, the proposed model predicts delays that are smaller than the observed and HCM model delays (Table 5). Meanwhile, the HCM model predicts delays similar to the observed delay.

It is not surprising that the proposed model predicts smaller delays than the HCM model. A vehicle that is able to complete a RTOR maneuver should have a smaller delay than if the same vehicle had not been able to complete a RTOR maneuver. Since the average delay for the right turn lane is a weighted average of the all the right turning vehicles, the inclusion of RTOR vehicles with smaller delays should then reduce the overall delay for the lane.

Table 5: Summary of Wilcoxon Signed rank Tests using SAS PROC Univariate

COMPARISON	AM	PM	SAMPLE SIZE (AM/PM)
HCM vs. Observed	38 (p=.1617)	3.5 (p=.8808)	25/17
Proposed vs. Observed	-85.5 (p<.0001)	-39 (p=.0005)	18/12
Proposed vs. HCM	-24.5 (p=.0098)	--36 (p=.0024)	18/12

However, it would be desirable to find that the proposed model was not distinguishable from the observed delays. Since this was not the case, a bootstrap analysis was used to corroborate the findings of the Wilcoxon signed rank test. The procedure was applied to the difference in delay for each of the 3 comparisons above. For each difference, 5000 samples of size N (i.e. 25 or 18 for the AM and 17 or 12 for the PM as appropriate) were generated by randomly drawing (with substitution) from the original sample. Next the means of the differences for these 5000 samples were calculated. The 5000 estimates were ranked from lowest to highest. Finally an interval estimate for the mean difference for each comparison was developed based on the rankings. As summarized in Table 6, the proposed model predicted significantly lower delays than either the observed delays or the HCM method delays. Using the PM period as an example, Table 6 shows that the proposed model predicted a mean delay that was between 31.7 and 49.5 seconds per vehicle smaller than the observed mean delay. The proposed model also predicted a mean delay that was between 27.3 and 48.3 seconds/vehicle smaller than the mean delay predicted by HCM method. The magnitudes of the differences in the AM period are smaller than the PM. However, the pattern remains similar.

Table 6: 95% confidence intervals for the bias in the mean differences

COMPARISON	AM	PM	SAMPLE SIZE (AM/PM)
HCM vs. Observed	(-2.1,13.4)	(-10.3,10.4)	25/17
Proposed vs. Observed	(-15.2,-7.5)	(-49.5,-31.7)	18/12
Proposed vs. HCM	(-22.8,-7.5)	(-48.3,-27.3)	18/12

The results of the bootstrap analysis are identical to the signed rank test analysis. However, the interval estimates indicate that the proposed model predicts drastically lower delays than either the HCM model or the observed delays. A review of the intermediate calculations and the video of the intersection indicates that driver behavior may be a leading cause for the discrepancies. A number of drivers exhibited a tendency to wait for extended periods of time prior to completing a RTOR, while others exhibited faster responses.

6.3 MODEL PERFORMANCE BASED ON SIMULATED DATA

Thus far the performance of the model has focused on the data available from direct observation. However, the field data characterizes only a small portion of the conditions that are observable. Therefore, to examine the proposed model's performance over a greater range of conditions, data were generated for the PM period's QAPs by simulating the values of the 3 flow parameters. The right-turn volume ranged from 20 to 900 vehicles per hour (vph) in increments of 40 vph. The proportion of RTOR varied from 10% to 90% in increments of 10%. Lastly, the conflicting volume ranged from 50 to 1100 vph by increments of 50. For each combination of these 3 parameters, the HCM delay and the proposed model delay were calculated. Observations where the queue was not cleared by the end of the cycle were dropped.

Figure 17 summarizes the difference in delay between the proposed model and the HCM model as a function of the volume to capacity (v/c) ratio for the exclusive right turn lane and the rate of RTOR. This representation is particularly useful in that it offers practical guidance on potential savings from an application of the proposed model. The v/c ratio is defined under the same parameters as the HCM model in that volume does not include RTOR and the capacity is capacity under green. A practitioner could use existing software to calculate the v/c ratio for a given set of conditions. If the number of RTOR that were removed from the analysis were known, then the corresponding reduction in delay can be found. Since delay is influenced by the level of conflicting

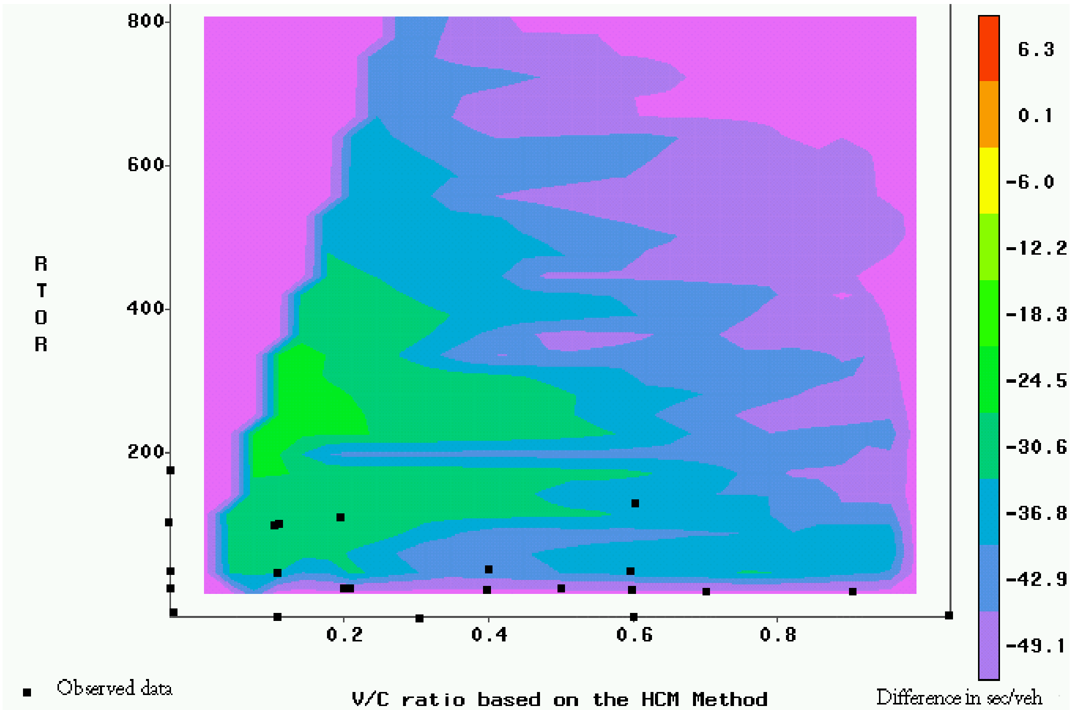

Figure 17: Reduction in delay from application of the proposed model with PM phasing at Washington & Broadway

traffic volumes, it is important to recognize that the delays shown in Figure 17 are average values over a range of conflicting volumes. Note also that Figure 17 also shows the relationship of the observed data to the simulated data. These observations cover only small portion of the conditions under which the proposed model predicts lower delays. Based on this analysis, the proposed model estimates delays that are 30-40 seconds/vehicle lower than the HCM approach. These findings are consistent with the interval estimates from the bootstrap analysis.

Recall that variations in driver behavior were significant in explaining the difference between the observed and predicted delays. To evaluate the sensitivity of such variations, the time until the queue on the conflicting approach clears, T_1, was increased by a factor of 2, 4, and 8. For delays averaged over a range of conflicting traffic volumes, increasing the time before the conflicting queue clears and RTOR may begin to occur does not appear to significantly alter the average reductions in delay (Figure 18). This does not mean that a reduction in delay from a specific combination of

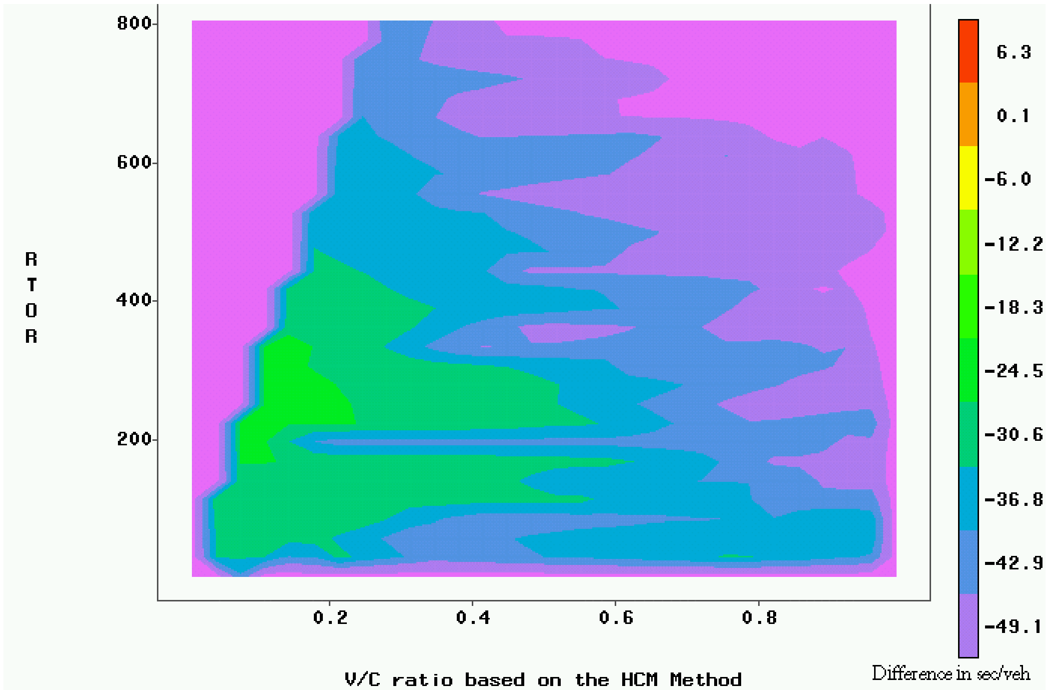

Figure 18: Decrease in delay with an expansion factor of 8 times T_1

volumes would not be affected by different driver behavior. However, over a range of conditions, the average reduction in delay is fairly stable.

While the reductions in delay are significant for this particular intersection when incorporating RTOR into the delay calculation, these savings are based on a unique signal-timing plan. Consequently, a second simulated data set was generated to examine the effects of different signal-timing plans. This data set is based on the QAP for the case where two consecutive conflicting phases. Specifically, for this data set,

- Right turn volumes varied from 100 to 900 vph by 100 vph;
- Intersecting conflicting traffic varied from 100 to 1100 vph by 200 vph;
- Opposing conflicting traffic varied from 0 to 250 vph by 50 vph;
- RTOR proportion varied from 10% to 50% by 10%;
- Green time varied from 20 to 60 seconds by 10 seconds

- Red time to prioritize the intersecting traffic varied from 30 to 60 seconds by 10seconds
- Red times to prioritize the opposing conflicting traffic and the intersecting but non-conflicting traffic streams both varied from 0 to 30 second by 10 seconds.

With so many combinations of variables, it is difficult to show the effects of these variables on the difference in delay. However, Figure 19 provides one perspective on the possible reductions in delay as function of the right turn volume which includes both right turns on green and RTOR. Not surprisingly, the majority of scenarios simulated result in reductions in delay. Given that RTOR vehicles should wait a shorter period of time as a result of a red light, it is to be expected that the delay for the right turn lane should be lower when RTOR are included. However, it is interesting to note that under some high right turn volume conditions, the inclusion of RTOR increases delay. These are scenarios under which the HCM approach assumes that RTOR occur when in fact conditions do not allow RTOR maneuvers to be completed. The HCM approach under most scenarios is a more conservative estimate of delay. However, in these situations with high right turn volumes and the inability to complete RTOR, the HCM is underestimating delays. The black lines in **Error! Reference source not found.** indicate outliers with respect to the mean reduction in delay. The observations represented by the black symbols identify reductions in delay that are larger than at least 96% of the all the scenarios evaluated. The majority of the scenarios result in reductions in delay between 15 and 30 seconds as indicated by the large boxes showing the 25^{th} and 75^{th} percentiles.

6.4 SUMMARY OF MODEL PERFORMANCE

The performance of the proposed models was evaluated with both field data and simulated data. The proposed model predicted delays that were different from both the observed delays and the delays based on the HCM method. A review of the intermediate calculations and videotape data suggests that variations in local driver behavior may be the cause of the difference between the observed delay and the predicted delay.

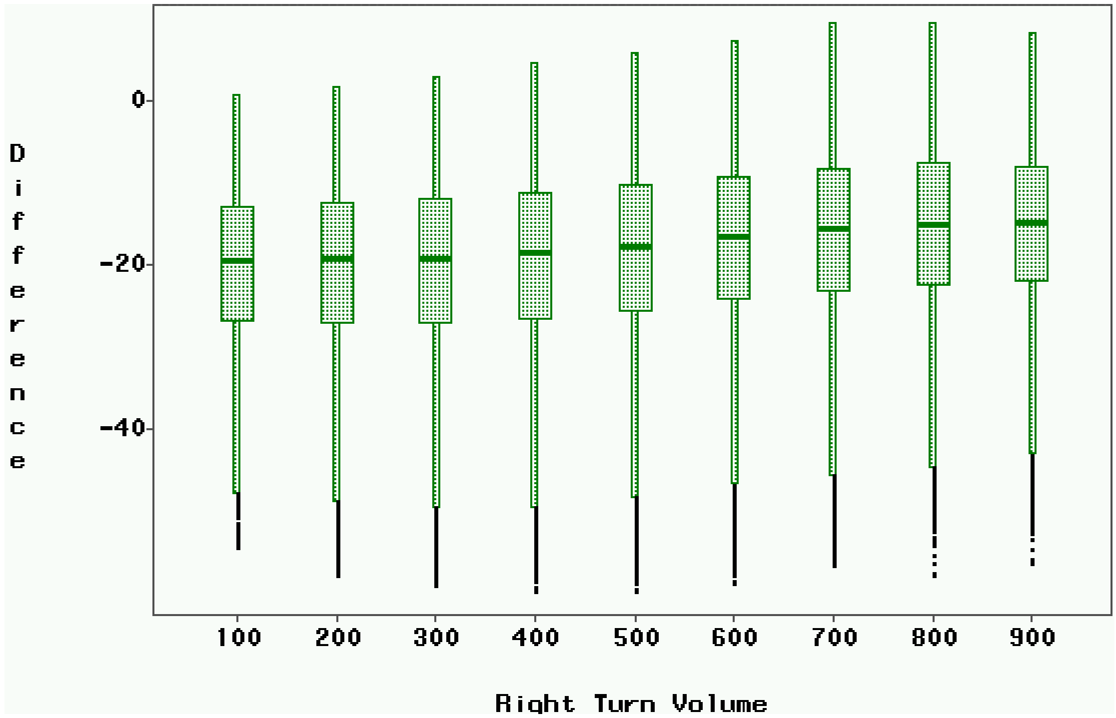

Figure 19: Reductions in delays as a function of total right turn volume

6.4 SUMMARY OF MODEL PERFORMANCE

The performance of the proposed models was evaluated with both field data and simulated data. The proposed model predicted delays that were different from both the observed delays and the delays based on the HCM method. A review of the intermediate calculations and videotape data suggests that variations in local driver behavior may be the cause of the difference between the observed delay and the predicted delay.

Data sets were generated by varying volume parameters and signal timing parameters. The first data set simulated a variety of traffic conditions at the study intersection. The second data set represents as a variety of volumes under different signal timing patterns for a 4 phase timing plan. The proposed model predicted reductions in delay over a wide range of conditions when compared to the HCM approach under both sets of conditions.

7. SUMMARY AND RECOMMENDATIONS

7.1 SUMMARY OF RESEARCH

Right turn on red is an established part of today's driving patterns. However, despite several revisions of the *Highway Capacity Manual* (HCM), the current procedures for estimating delay at signalized intersections simply removes RTOR from the analysis and, hence, do not adequately reflect the benefits of RTOR.

This dissertation has developed models of uniform delay that incorporate RTOR based on queuing theory. Queuing accumulation polygons (QAP) were developed to include RTOR operations. The research developed a classification system for categorizing any signal phasing scheme into one of 4 classes based on the sequence of 3 red regimes and one green regime. The 3 red regimes are characterized by the traffic stream that is prioritized over the RTOR during that portion of the red phase. One regime provides priority to the intersecting conflicting traffic. Another regime provides priority to the intersecting but non-conflicting traffic. The final regime prioritizes the opposing conflicting traffic.

It was further demonstrated that these 4 classes of signal phasings resulted in one of 2 general QAP patterns. The first pattern consists of two conflicting regimes followed by two non-conflicting regimes. The other pattern consists of alternating conflicting and non-conflicting regimes. Models to calculate delay for each basic pattern were developed.

The performance of the proposed models was evaluated with both field data and simulated data. The proposed model predicted delays that were different from both the observed delays and the delays based on the HCM method. A review of the intermediate calculations and videotape data suggests that variations in driver behavior may partially account for the difference between the observed delay and the predicted delay.

A data set was generated by varying both the right turn volumes and the conflicting volumes for the signal timing at the study intersection. The proposed model predicted reductions in delay over a wide range of conditions when compared to the HCM approach. Contour diagrams for reductions in delay were developed as a function of the v/c ratio for the right turn lane and the number of RTOR. A sensitivity analysis of the model to variations in driver behavior was conducted and found that average reductions in delay are stable with respect to driver behavior.

A second data set was generated to simulate conditions beyond the study intersection. A number of traffic volume and signal timing parameters were varied to simulate a larger population of conditions. Reductions in delay are possible over a wide range of conditions. However the mean difference is relatively stable as a function of the total right turn volume.

7.2 SIGNIFICANCE OF RESEARCH

The Highway and Quality of Service committee of the Transportation Research Board is responsible for updating the *Highway Capacity Manual*. While a new edition of the HCM is scheduled to be released in the fall of 2000, discussions are under way to identify research topics that may lead to revisions in future versions. The analysis of right turns on red is one among many other items that are under consideration.

This research has provided a well-defined starting point for these discussions by:

- Conducting a review of the current research related to right turns on red. From this review comes a better understanding of the deficiencies in the understanding of RTOR behavior.
- Developing a methodology that provides an understanding of RTOR operation and a model for estimating delay. This methodology is consistent with the existing procedures and represents an incremental update rather than a drastic overhaul.

- Providing an estimate of reductions in delay compared to the existing procedure. This estimate can serve as the basis for quantifying the benefits and costs associated with adopting this methodology in future revisions of the HCM.

While the methodology is relatively straight forward, it does require a certain degree of basic familiarity with queuing diagrams. In particular if one were to implement this procedure, the key element would be to properly relate the timing plan to the associated shape of the QAP. Given the shape of the QAP, computing the delay is a function of identifying the appropriate points in time when the rate of queue accumulation changes. Consequently, widespread implementation should not be encouraged until the procedure is automated into a software-based solution.

7.3 RECOMMENDATIONS FOR FUTURE RESEARCH

To provide direction for future research, several areas of research resulting from extensions of this dissertation as well as areas outside the scope of this dissertation have been identified:

1. As the HCM strives to incorporate quantitative perceptions of roadway performance by drivers, the variability in driver behavior should be examined with more breadth. In this research, variations in driver behavior may have affected and exacerbated the difference between the predicted delay and the observed delay. Collecting video data from representative locations throughout the U.S. should provide ample opportunity to document the degree of variability. This may be especially significant if the proposed model is to be customized to specific geographical locations.

2. In the analysis of left turns under protected permitted phasing, the HCM utilizes a methodology that is similar to the methodology presented in this dissertation. Both procedures rely on developing special QAP and estimating a uniform delay component that replaces the d_1 component based on a simple diagram. Both of

these approaches do not adjust either the incremental or residual delay terms, d_2 and d_3 respectively. It is desirable to verify if the existing methods for estimating the incremental delay adequately address the effects of stochastic arrivals.

3. Three models for predicting the service rate of RTOR were developed prior to the undertaking of this dissertation. The models predict similar estimates of RTOR capacity. It would be desirable to conduct a comprehensive analysis to identify which of these models is the most accurate predictor.

4. While the proposed model provides lower estimates of delay under both the observed conditions and the simulated conditions, it would be desirable to perform a more extensive evaluation of the model's performance. In particular it would be very informative to see to assess the magnitude of changes in delay when the proposed model is applied to the data that were used to validate the current HCM model.

5. The methodology presented in this dissertation is applicable to exclusive right turn lanes. However, not all intersections have exclusive right turn lanes. Therefore, it is desirable to evaluate if the costs associated with modifying the HCM are warranted given the potential benefits from the reduced delays in exclusive right turn lanes.

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REFERENCES

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APPENDICES

APPENDIX 1: FIELD AND CALCULATED DELAY DATA

	Volume in veh/cycle				Volume in veh/hr			
Begin Cycle	RT	RTOR	Total	Conflicting	RT	RTOR	Total	Conflicting
16:34:40	6	0	6	18	180	0	180	540
16:36:40	0	1	1	19	0	30	30	570
16:42:40	5	1	6	23	150	30	180	690
16:44:40	3	0	3	29	90	0	90	870
16:46:40	4	1	5	20	120	30	150	600
16:50:40	2	2	4	23	60	60	120	690
17:02:40	4	5	9	19	120	150	270	570
17:04:40	7	0	7	24	210	0	210	720
17:06:40	4	0	4	27	120	0	120	810
17:10:40	2	0	2	25	60	0	60	750
17:24:40	2	0	2	25	60	0	60	750
17:26:40	2	0	2	24	60	0	60	720
17:28:40	0	2	2	15	0	60	60	450
17:30:40	3	2	5	29	90	60	150	870
17:32:40	3	2	5	21	90	60	150	630
17:34:40	4	2	6	18	120	60	180	540
17:36:40	3	1	4	18	90	30	120	540
7:26:40	1	2	3	3	36	72	108	108
7:30:00	0	0	0	5	0	0	0	180
7:31:40	0	1	1	9	0	36	36	324
7:33:20	2	1	3	8	72	36	108	288
7:38:20	0	0	0	10	0	0	0	360
7:40:00	0	2	2	7	0	72	72	252
7:43:20	2	1	3	9	72	36	108	324
7:48:20	1	2	3	9	36	72	108	324
7:50:00	0	3	3	12	0	108	108	432
7:51:40	0	0	0	7	0	0	0	252
7:55:00	0	2	2	6	0	72	72	216
8:00:00	0	2	2	3	0	72	72	108
8:03:20	0	2	2	6	0	72	72	216
8:06:40	0	0	0	8	0	0	0	288
8:08:20	2	3	5	10	72	108	180	360
8:16:40	1	0	1	7	36	0	36	252
8:18:20	0	0	0	8	0	0	0	288
8:21:40	0	5	5	8	0	180	180	288
8:23:20	1	3	4	9	36	108	144	324
8:28:20	0	2	2	5	0	72	72	180
8:30:00	1	3	4	10	36	108	144	360
8:31:40	0	5	5	5	0	180	180	180
8:33:20	0	2	2	6	0	72	72	216
8:35:00	1	0	1	5	36	0	36	180
8:36:40	4	1	5	6	144	36	180	216

	Delay in sec/veh				HCM vs. Proposed	
Begin Cycle	Incremental	Travel Time	HCM	Proposed	Difference	Relative Difference
16:34:40	65.0	6.3	41.0			
16:36:40	60.0	54.0	0.0	0.4	-0.4	#DIV/0!
16:42:40	31.7	0.0	49.9	2.4	47.5	95%
16:44:40	50.0	49.0	48.2			
16:46:40	62.0	49.0	49.0	1.6	47.4	97%
16:50:40	47.5	67.3	47.3	2.5	44.9	95%
17:02:40	30.0	73.7	49.0	1.4	47.7	97%
17:04:40	25.7	66.3	51.6			
17:06:40	27.5	41.3	49.0			
17:10:40	60.0	0.0	47.3			
17:24:40	35.0	0.0	47.3			
17:26:40	70.0	72.5	47.3			
17:28:40	20.0	85.3	0.0	0.5	-0.5	#DIV/0!
17:30:40	42.0	96.0	48.2	4.5	43.6	91%
17:32:40	50.0	63.7	48.2	1.9	46.3	96%
17:34:40	28.3	96.0	49.0	1.1	47.9	98%
17:36:40	17.5	69.3	48.2	1.1	47.0	98%
7:26:40	3.3	0.0	33.6	0.0	33.6	100%
7:30:00	0.0	0.0	0.0	0.0		
7:31:40	20.0	0.0	0.0	0.1	-0.1	#DIV/0!
7:33:20	6.7	0.0	34.3	0.0	34.3	100%
7:38:20	0.0	0.0	0.0	0.0		
7:40:00	15.0	13.0	0.0	0.0	0.0	#DIV/0!
7:43:20	6.7	21.0	34.3	0.1	34.2	100%
7:48:20	6.7	24.7	33.6	0.1	33.5	100%
7:50:00	36.7	36.0	0.0	0.8	-0.8	#DIV/0!
7:51:40	0.0	0.0	0.0	0.0		
7:55:00	10.0	16.5	0.0	0.0	0.0	#DIV/0!
8:00:00	5.0	12.0	0.0	0.0	0.0	#DIV/0!
8:03:20	10.0	10.5	0.0	0.0	0.0	#DIV/0!
8:06:40	0.0	1.0	0.0	0.0		
8:08:20	8.0	9.3	34.3	0.3	34.0	99%
8:16:40	0.0	0.0	33.6	0.0		
8:18:20	0.0	11.0	0.0	0.0		
8:21:40	20.0	18.2	0.0	0.0	0.0	#DIV/0!
8:23:20	15.0	27.3	33.6	0.1	33.5	100%
8:28:20	5.0	90.0	0.0	0.0	0.0	#DIV/0!
8:30:00	12.5	57.0	33.6	0.3	33.2	99%
8:31:40	10.0	4.7	0.0	0.0	0.0	#DIV/0!
8:33:20	5.0	7.0	0.0	0.0	0.0	#DIV/0!
8:35:00	0.0	5.0	33.6			
8:36:40	6.0	9.0	35.8	0.0	35.8	100%

APPENDIX 2: RESULTS OF THE WILCOXON SIGNED RANK TEST

The SAS System

The UNIVARIATE Procedure
Variable: hcmdiff (HCM minus Observed)

Moments

N	25	Sum Weights	25
Mean	5.53955557	Sum Observations	138.488889
Std Deviation	20.1636267	Variance	406.571841
Skewness	-0.0738715	Kurtosis	-1.0438263
Uncorrected SS	10524.8911	Corrected SS	9757.72418
Coeff Variation	363.993581	Std Error Mean	4.03272534

Basic Statistical Measures

Location		Variability	
Mean	5.539556	Std Deviation	20.16363
Median	0.000000	Variance	406.57184
Mode	0.000000	Range	70.21785
		Interquartile Range	36.88451

Tests for Location: Mu0=0

Test	-Statistic-		-----p Value------	
Student's t	t	1.373651	Pr > |t|	0.1822
Sign	M	0	Pr >= |M|	1.0000
Signed Rank	S	38	Pr >= |S|	0.1617

Location Counts: Mu0=0.00

Count	Value
Num Obs > Mu0	10
Num Obs ^= Mu0	20
Num Obs < Mu0	10

The SAS System

The UNIVARIATE Procedure
Variable: propdiff (Proposed minus Observed)

Moments

N	18	Sum Weights	18
Mean	-11.098623	Sum Observations	-199.77522
Std Deviation	7.94952894	Variance	63.1950104
Skewness	-1.9879872	Kurtosis	4.748281
Uncorrected SS	3291.5451	Corrected SS	1074.31518
Coeff Variation	-71.626261	Std Error Mean	1.87372194

Basic Statistical Measures

Location		Variability	
Mean	-11.0986	Std Deviation	7.94953
Median	-8.8481	Variance	63.19501
Mode	-10.0000	Range	32.52333
		Interquartile Range	8.90016

NOTE: The mode displayed is the smallest of 2 modes with a count of 3.

Tests for Location: Mu0=0

Test	-Statistic-		-----p Value------	
Student's t	t	-5.9233	Pr > |t|	<.0001
Sign	M	-9	Pr >= |M|	<.0001
Signed Rank	S	-85.5	Pr >= |S|	<.0001

Quantiles (Definition 5)

Quantile	Estimate
100% Max	-3.33333
99%	-3.33333
95%	-3.33333
90%	-5.00000
75% Q3	-6.00000
50% Median	-8.84813
25% Q1	-14.90016
10%	-20.00000
5%	-35.85667
1%	-35.85667
0% Min	-35.85667

The SAS System

The UNIVARIATE Procedure
Variable: moddiff (Proposed minus HCM)

Moments

N	18	Sum Weights	18
Mean	-15.064542	Sum Observations	-271.16175
Std Deviation	17.4409846	Variance	304.187944
Skewness	-0.2471396	Kurtosis	-2.1920304
Uncorrected SS	9256.12248	Corrected SS	5171.19505
Coeff Variation	-115.77508	Std Error Mean	4.1108795

Basic Statistical Measures

Location		Variability	
Mean	-15.0645	Std Deviation	17.44098
Median	0.0000	Variance	304.18794
Mode	0.0000	Range	36.59972
		Interquartile Range	33.55118

Tests for Location: Mu0=0

Test	-Statistic-		-----p Value------	
Student's t	t	-3.66455	Pr > |t|	0.0019
Sign	M	-3	Pr >= |M|	0.1094
Signed Rank	S	-24.5	Pr >= |S|	0.0098

Quantiles (Definition 5)

Quantile	Estimate
100% Max	0.8100000
99%	0.8100000
95%	0.8100000
90%	0.0691463
75% Q3	0.0000000
50% Median	0.0000000
25% Q1	-33.5511806
10%	-34.2973612
5%	-35.7897223
1%	-35.7897223
0% Min	-35.7897223

The SAS System

The UNIVARIATE Procedure
Variable: hcmdiff (HCM minus Observed)

Moments

N	17	Sum Weights	17
Mean	-0.0881358	Sum Observations	-1.4983081
Std Deviation	23.4752252	Variance	551.086198
Skewness	-0.9369255	Kurtosis	1.05496816
Uncorrected SS	8817.51122	Corrected SS	8817.37916
Coeff Variation	-26635.297	Std Error Mean	5.69357841

Basic Statistical Measures

Location		Variability	
Mean	-0.08814	Std Deviation	23.47523
Median	-0.18359	Variance	551.08620
Mode	-1.81947	Range	90.68053
		Interquartile Range	32.00000

Tests for Location: Mu0=0

Test	-Statistic-		-----p Value------	
Student's t	t	-0.01548	Pr > |t|	0.9878
Sign	M	-0.5	Pr >= |M|	1.0000
Signed Rank	S	3.5	Pr >= |S|	0.8808

Location Counts: Mu0=0.00

Count	Value
Num Obs > Mu0	8
Num Obs ^= Mu0	17
Num Obs < Mu0	9

The SAS System

The UNIVARIATE Procedure
Variable: propdiff (Proposed minus Observed)

Moments

N	12	Sum Weights	12
Mean	-38.113936	Sum Observations	-457.36724
Std Deviation	14.9498789	Variance	223.498879
Skewness	-0.1882477	Kurtosis	-1.2196263
Uncorrected SS	19890.5535	Corrected SS	2458.48767
Coeff Variation	-39.22418	Std Error Mean	4.3156583

Basic Statistical Measures

Location		Variability	
Mean	-38.1139	Std Deviation	14.94988
Median	-35.2145	Variance	223.49888
Mode	.	Range	44.02058
		Interquartile Range	22.59247

Tests for Location: Mu0=0

Test	-Statistic-		-----p Value------	
Student's t	t	-8.83155	Pr > |t|	<.0001
Sign	M	-6	Pr >= |M|	0.0005
Signed Rank	S	-39	Pr >= |S|	0.0005

Quantiles (Definition 5)

Quantile	Estimate
100% Max	-16.3668
99%	-16.3668
95%	-16.3668
90%	-19.4852
75% Q3	-27.9110
50% Median	-35.2145
25% Q1	-50.5035
10%	-59.5842
5%	-60.3874
1%	-60.3874
0% Min	-60.3874

The SAS System

The UNIVARIATE Procedure
Variable: moddiff (Proposed minus HCM)

Moments

N	12	Sum Weights	12
Mean	-37.769836	Sum Observations	-453.23803
Std Deviation	18.0670862	Variance	326.419602
Skewness	1.95677868	Kurtosis	2.37011255
Uncorrected SS	20709.3417	Corrected SS	3590.61563
Coeff Variation	-47.834696	Std Error Mean	5.21551853

Basic Statistical Measures

Location		Variability	
Mean	-37.7698	Std Deviation	18.06709
Median	-45.5806	Variance	326.41960
Mode	-43.6451	Range	48.41522
		Interquartile Range	6.54347

Tests for Location: Mu0=0

Test	-Statistic-		-----p Value------	
Student's t	t	-7.24182	Pr > |t|	<.0001
Sign	M	-4	Pr >= |M|	0.0386
Signed Rank	S	-36	Pr >= |S|	0.0024

Quantiles (Definition 5)

Quantile	Estimate
100% Max	0.514823
99%	0.514823
95%	0.514823
90%	0.415809
75% Q3	-40.912506
50% Median	-45.580629
25% Q1	-47.455978
10%	-47.677624
5%	-47.900397
1%	-47.900397
0% Min	-47.900397

APPENDIX 3: SAS CODE FOR GENERATING SIMULATED DATA FOR THE BROADWAY INTERSECTION

```
data diss.broad;
do left= 0,1;
do k= 1,2,4,8;
do volic= 50 to 1100 by 50;
do rvol=20 to 900 by 40;
do prtor= 0.1 to 0.9 by .1;

if left=0 then do;
       c=120;
       green=15.4;
       red=c-green;
         reda=red;end;
  else do;
    c=120;
    green=26;
    red=c-green;
      reda=red-8;end;


/* calc sat flow,arrival rate, cycle*/
  sg=1900*.85/3600;
  v=rvol*(1-prtor)/3600;
  cap=green/c*sg;
  vcratio=v/cap;
/*calculate di for HCM approach*/
  Qr=v*red;
  tc= Qr/abs(v-sg);
  HCMAD1= Qr*(red+min(tc,green))/(2*v*c);
  if tc>green then continue;

/*calculate D1 for proposed approach*/

/*calc queue clear time for first section - red*/
  vlic=volic*c/3600;
  qroic=1-red/c;
  t1=k*max(0, min(red,(vlic*qroic)/(0.5-(vlic*(1-qroic)/reda))-3.0));

  /*calc rtor volume*/
  v1=rvol/3600;
  rtor=rvol*prtor;
  /* calc rtor sat flow */
   s1=(849.82*exp (-.00129*volic)-31)/3600;

  /*calc delay for first section*/
   q1=v1*t1;
   tc1=q1/abs(v1-s1); /*clearnce time*/
   q2=q1+(v1-s1)*min(red-t1,tc1);
   pd1=q1*t1 +(q2+q1)*min(red-t1,tc1);

/*calc queue clearance for green time & rinc*/
   tg=q2/abs(v1-sg);
   pd3=q2*min(tg,green);
   if tg>green then continue;

   PAD1=(pd1+pd3)/(2*v1*c);
   diff=PAD1-HCMAD1;
```

```
   eff=-(HCMAD1-PAD1)/HCMAD1;
   output;
end;
end;
end;
end;
end;
label rvol="Right Turn Volume"
      volic="Opp. Volume"
        eff="Relative Difference"
      diff="Difference in Seconds"
      rtor="RTOR"
      vcratio="V/C ratio based on the HCM Method";
format eff percent10.0;
run;
```

APPENDIX 4: SAS CODE FOR GENERATING DATA FOR THE TWO CONSECUTIVE CONFLICTING PHASE CASE

```
data diss.classalt;
do volic= 100 to 1100 by 200;
do voloc=0,50,100,150,200,250;
do rvol=100 to 900 by 100;
do prtor= 0.1 to 0.5 by .1;
do ric=30 to 60 by 10;
do rinc=0,10,20,30;
do roc=0,10,20,30;
do green=20 to 60 by 10;

/* calc sat flow,arrival rate, cycle*/
  sg=1900*.85/3600;
  v=rvol*(1-prtor)/3600;
  rtor=rvol*(1-prtor);
  red=ric+roc+rinc;
  c=red+green;
  cap=green/c*sg;
  vcratio=v/cap;
/*calculate di for HCM approach*/
  Qr=v*red;
  tc= Qr/abs(v-sg);

  HCMAD1= Qr*(red+min(tc,green))/(2*v*c);
  if tc>green then continue;

/*calculate D1 for proposed approach*/

/*calc queue clear time for first section - Ric*/
  vlic=volic*c/3600;
  qroic=1-ric/c;
  t1=max(0, min(ric,(vlic*qroic)/(0.5-(vlic*(1-qroic)/ric))-3.0));

  /*calc rtor volume*/
  v1=rvol/3600;

  /* calc rtor sat flow */
   s1=(849.82*exp (-.00129*volic)-31)/3600;

  /*calc delay for first section*/
   q1=v1*t1;
   tc1=q1/abs(v1-s1); /*clearnce time*/
   q2=q1+(v1-s1)*min(ric-t1,tc1);
   pd1=q1*t1 +(q2+q1)*min(ric-t1,tc1);

/*calc queue clearance for second section roc*/
  vloc=voloc*c/3600;
  qrooc=1-roc/c;
  t2=max(0, min(roc,(vloc*qrooc)/(0.5-(vloc*(1-qrooc)/roc))-3.0));

  /* calc rtor sat flow */
   s2=(849.82*exp (-.00129*voloc)-31)/3600;
   q3=q2+v1*t2;
   tc2=q3/abs(v1-s2);
   q4=q3+(v1-s2)*min(tc2,roc-t2);
   pd2=(q2+q3)*t2 + (q3+q4)*min(tc2,roc-t2);
/*calc queue clearance for green time & rinc*/
```

```
   tg=q4/abs(v1-sg);
   pd3=q4*min(tg,green+rinc);
   if tg>green+rinc then continue;

   PAD1=(pd1+pd2+pd3)/(2*v1*c);
   diff=PAD1-HCMAD1;
   eff=-(HCMAD1-PAD1)/HCMAD1;
   oppvol=volic+voloc;
   output;
end;
end;
end;
end;
end;
end;
end;
end;
label rvol="Right Turn Volume"
      eff="Relative Difference"
        vcratio="V/C Ratio based on HCM Method"
      rtor="RTOR"
      diff="Difference";
format eff percent10.0;
run;
```

VITA

Mr. Qureshi began his academic career at the University of California, Berkeley in the mid 1980's. He received his Bachelor of Science in Civil Engineering form the University of California in 1988 and proceeded directly to graduate studies at the University of California, Berkeley, where he completed the requirements for a Master of Science degree in Civil Engineering.

Following his graduate career at Berkeley. Mr. Qureshi joined the staff of Resource Systems Group, Inc in White River Junction, Vermont. There he developed an expertise in the analysis of traffic impacts. During this period he was involved in several studies for both private and public entities. In addition he participated in developing several Excel based templates that implemented procedures for the operational analysis of signalized and un-signalized intersection as wells as several templates to evaluate signal, stop sign, and turning lane warrants.

In 1997, Mr. Qureshi returned to graduate studies at the University of Tennessee to pursue his doctorate. After a year as student, he joined the staff of the Center for Transportation Research. During his tenure with the CTR, he was involved in several safety related research projects. He also conducted research on distance estimates for the commodity flow survey for Oak Ridge National Laboratory.

Mr. Qureshi is a registered Civil Engineer in the state of Vermont. He is an active member of ITE and has held office in student chapters of ITE at the University of California, Berkeley and the University of Tennessee. Mr Qureshi is also active in TRB and serves a member of committee A5011 on Statistical Methodology And Statistical Computer Software In Transportation Research.

Dr. Qureshi looks forward to continuing his academic career as an Assistant Professor wit the University of Missouri-Rolla.