ABSTRACT OF DISSERTATION

F. Thomas Creasey

The Graduate School

University of Kentucky

2010

RIGHT-TURN-ON-RED VOLUME ESTIMATION AND INCREMENTAL CAPACITY MODELS FOR SHARED LANES AT SIGNALIZED INTERSECTIONS

ABSTRACT OF DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Engineering at the University of Kentucky

by

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Lexington, Kentucky

Director: Dr. Nikiforos Stamatiadis, Professor of Civil Engineering
Lexington, Kentucky

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The Highway Capacity Manual (HCM) is one of the most widely used transportation references in the world. It provides methods for the analyses of transportation system components such as freeways, multilane highways, two-lane highways, urban streets, signalized intersections, and others. The Signalized Intersections Methodology is used to estimate capacity and average control delay for individual lane groups and for intersections. The current method does not estimate control delay for vehicles that are permitted to turn right on red, nor does it include these vehicles in the computation of capacity. Furthermore, it provides limited guidance for estimating the number of right-turns-on-red (RTORs) when the actual number is unknown.

It is recognized that RTORs do increase the capacity of individual lane groups and the intersection as a whole. The result is that capacity, delay and level of service may not be predicted accurately when RTORs occur. This research focused on the specific case where RTORs occur from a shared lane. While RTORs in both cases are limited by the frequency of available gaps in conflicting traffic streams, the number and incremental capacity of RTORs from a shared lane are further affected by the proportion of through and right-turning vehicles. The objective of this research was to develop models that predict the number of RTOR vehicles and estimate their incremental capacity.

The RTOR Volume Estimation Model is a deterministic model that produced reasonable results and incorporates the probabilistic nature of RTORs from shared lanes. The model compared favorably with results obtained through simulating the anticipated number of RTORs that occurred at actual study sites. The RTOR Incremental Capacity Model demonstrated that greater capacity is realized when RTORs occur from shared lane approaches compared to the current HCM method. Both models developed are consistent with the current deterministic models contained in the HCM and have been validated with actual field data, enhancing their potential acceptance into future updates to the method. Finally, recommendations for adapting these models to intersection approaches with exclusive right-turn lanes were provided.

KEYWORDS: Right-Turns-on-Red (RTORs), Volume Estimation, Capacity, Shared Lanes, Signalized Intersections

May 3, 2010

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Director of Dissertation

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I. INTRODUCTION

The Highway Capacity Manual (HCM) is one of the most widely used transportation documents in the world. It provides references and methods for the analyses of transportation system components such as freeways, weaving sections, ramp junctions, multilane highways, two-lane highways, urban streets, signalized intersections, and others. Originally published in 1950, the current version of the document, the 2000 HCM, contains almost 1,200 pages. The Transportation Research Board has sold over 16,000 copies of the 2000 HCM.

Chapter 16 of the 2000 HCM, which contains the Signalized Intersections Methodology, is the most frequently used portion of the manual. The methodology is used to estimate capacity and average control delay for individual lane groups and for intersections as a whole. Control delay is defined to be the component of delay that results when a control signal causes a lane group to reduce its speed or stop; it is measured by comparison to the uncontrolled condition. Average control delay per vehicle is a function of capacity and intersection level of service (LOS) is directly related to the average control delay.

The current method does not estimate control delay for vehicles that are permitted to turn right on red, nor does it include these vehicles in the computation of capacity. When right turns on red (RTORs) are permitted, the right-turn volume for analysis may be reduced by the volume of right-turning vehicles moving on the red phase. This reduction is generally done on the basis of hourly volumes (i.e. vehicle per hour) before the conversion to flow rates.

Within the transportation engineering profession, it has been recognized that RTOR vehicles increase the capacity of an individual lane group and the intersection as a whole as they enter the intersection on a red signal display. The result is that capacity, delay and level of service may not be predicted accurately when RTORs are permitted.

A good deal of research has been performed previously on the issue of right turns on red. Almost all of that research has been focused on the case where an exclusive right-turn lane exists. This research instead focuses on the very specific case where right turns on red are permitted from a shared through/right-turn lane. While right turns on red in both cases are limited by the frequency of available gaps in conflicting traffic streams, the number and incremental capacity of RTORs from a shared lane are further affected by the proportion of through and right-turning vehicles.

The objective of this research was to develop a model that predicts the number of RTOR vehicles (when actual field data are not available) and estimates their incremental capacity for potential inclusion in future updates to the Signalized Intersection methodology.

II. THE HIGHWAY CAPACITY MANUAL

History

The first edition of the Highway Capacity Manual (HCM) [1] was published by the Bureau of Public Roads in 1950. It was approximately 150 pages in length and included an analytical section on signalized intersections. The concept of average delay (in minutes per vehicle) was presented, but it was not directly correlated with any service measure.

Capacity of signalized intersections was defined and a classification scheme was used to differentiate three capacity types: 1) basic capacity; 2) possible capacity; and 3) practical capacity. Computational methods were limited to making adjustments to pre-determined capacity values for specific conditions or factors such as turning movements, commercial vehicles and bus stops.

The HCM was first updated in 1965 [2] and incorporated a considerable amount of research that had been conducted since the 1950 Manual. The concept of capacity was redefined in the 1965 HCM and level of service (LOS) was first introduced. The capacity classification scheme was eliminated and intersection capacity was defined simply as the maximum number of vehicles that can be accommodated given the particular geometrics, environment, traffic characteristics, and controls.

In the 1965 HCM, the concept of load factor was introduced to describe the degree of utilization of an individual intersection approach. It was defined as the ratio of the number of "loaded" or fully utilized green signal phases of an intersection approach during one hour of peak traffic flow. Load factor values ranged from 0.0 (free flow) to 1.0 (unstable flow, where all cycles were "loaded" or fully utilized during a peak hour).

Correspondingly, levels of service were correlated with load factor values, with LOS A being represented by a load factor of 0.0 and LOS E corresponding to a load factor of 1.0. Capacity was determined to be the service volume at LOS E (load factor = 1.0). Computational procedures for capacity involved a series of nomographs containing service volumes, load factors, and adjustment factors for parameters such as metropolitan area size, turning volume percentages, presence of parking, street width, peak hour factor, and buses.

Transportation Research Circular (TRC) 212 [3], published in 1980, served as a bridge for selected chapters between the 1965 Manual and the next update. For signalized intersections, the Critical Movement Analysis was introduced as a method for determining LOS based on the sum of critical volumes for each of the signal phases. The method incorporated the effects of geometry and traffic signal operation in determining LOS for the intersection as a whole. A correlation was made between LOS, volume-to-capacity ratio, and delay, but delay was based on "stopped delay" as measured in the field. No method was presented for estimating stopped delay. TRC 212 maintained the definition and computational methods for capacity from the 1965 HCM.

The second complete update to the Manual in 1985 [4] marked the introduction of the modern signalized intersection method. While capacity and level of service were central to the method, they were not as strongly correlated for signalized intersections as for other facility types. The two measures were analyzed separately for signalized intersections and level of service was based on average vehicular delay. Average stopped delay was predicted for each of the critical lane groups as a function of the degree of saturation (i.e., the ratio of flow or volume to capacity) and effective green-to-cycle length ratio (g/C).

In 1997, the Signalized Intersections chapter underwent an update, though technically the document was still considered to be the 1985 version of the Manual. One of the most significant changes was the change in the primary performance measure from stopped delay to control delay. This did not change the method itself, only the performance measure and its application.

Some other changes that were part of the 1997 update included a new model for oversaturated delay, new treatment for the affects of actuated/coordinated signal control along an arterial street, a change in the application of the lane utilization factor, a third delay term that accounted for a residual queue from the previous time period, and some other minor changes. While these changes collectively resulted in a significant enhancement to the signalized intersections method, the overall model framework remained the same as it was introduced in the 1985 Manual.

Current Signalized Intersection Method

In the 2000 Highway Capacity Manual [5], the Signalized Intersections method (detailed in Chapter 16) remained basically the same, with some minor enhancements. The analytical process for the current signalized intersection method is comprised of five basic modules. The first is the determination of input parameters, followed by lane grouping and demand flow rate, and saturation flow rate. These two are performed concurrently. The fourth module involves computation of capacity and volume-to-capacity ratio, followed by calculation of performance measures such as delay and level of service.

Several input parameters are required to conduct the operational analysis for signalized intersections. These include parameters describing geometric conditions such as number of lanes, presence of left turn and/or right turn lanes, and storage length. Traffic volumes (or demand if conditions are oversaturated) must be specified for each movement on each approach of an intersection. The quality of traffic progression is an important input parameter and is reflected in an arrival type, AT, for each lane group. Arrival type has a significant impact on delay estimates and LOS determination.

Complete information on signalization is required to perform an intersection analysis. This information includes the phasing scheme, cycle length, green times, and change-and-clearance intervals. Information on the type of signal operation – actuated, semi-actuated, or pretimed – also must be input. While the procedure is based on pretimed signal control, a method for actuated control is included in which average green times that would approximate pretimed control are predicted.

The signalized intersection method is disaggregate, meaning that it is designed to consider individual intersection approaches and individual lane groups within those approaches. Lane grouping considers both the geometry of the intersection and traffic movements dictated by the signal phasing. The Manual offers guidelines for determination of lane groups. Lane groups can include combinations of movements when a lane is shared (a combined through/right turn lane, for example).

The third part of the process, determining the flow rate, occurs parallel to the establishment of lane groups. For the desired analysis period, traffic movement volumes are adjusted to average flow rates (in vehicles per hour). These are determined for each of the lane groups that have been established.

It is at this juncture that the adjustment is made for right turn on red. The Manual states:

> *"When right turn on red (RTOR) is permitted, the right-turn volume for analysis may be reduced by the volume of right-turning vehicles moving on the red phase. This reduction is generally done on the basis of hourly volumes before conversion to flow rates."*

The Manual directs that RTOR volumes should be determined by field observation at an existing intersection. For future intersections, it is necessary to estimate the number of RTOR vehicles. For both shared and exclusive right turn lanes, the number of RTOR vehicles may be subtracted from the right turning volume before analysis of lane group capacity or level of service. If there are no field data available, it is preferable to not reduce for RTOR except when an exclusive right turn movement runs concurrent with the protected left-turn phase from the adjacent cross-street. The Manual advises, under that scenario, that the right turn volume can be reduced by the number of "shadowed" left turners. It also advises that free-flow right turns not under signal control should be removed from the analysis entirely.

For each lane group, saturation flow rate is determined. It is the product of the base (formally referred to as "ideal") saturation flow rate and multiplicative adjustment factors to account for various parameters such as number of lanes, lane width, percentage of heavy vehicles in the traffic stream, approach grade, presence of on-street parking, blocking effect of transit buses, geometric effects on left and right turns, and others.

The fourth step in the process involves the computation of capacity and the volume-to-capacity (*v/c*) ratio. Capacity at signalized intersections is based on the saturation flow and saturation flow rate concepts. Flow ratio is defined to be the ratio of the actual or projected demand flow rate for a lane group (v_i) and the saturation flow rate (s_i). The flow ratio is expressed by the symbol $(v/s)_i$ for lane group *i*. The capacity of the lane group, therefore, is expressed as:

$$c_i = s_i \frac{g_i}{C}$$

where

c_i = capacity of lane group *i* (in vehicles per hour)
s_i = saturation flow rate of lane group *i* (in vehicles per hour)
C = cycle length (seconds)
g_i/C = effective green ratio ("green to cycle length ratio") for lane group *i*

The ratio of flow rate to capacity (*v/c*), referred to as the volume-to-capacity ratio, is expressed by the symbol *X* for an intersection analysis. It is also referred to as the degree of saturation. For a given lane group *i*, X_i is computed as:

$$X_i = \left(\frac{v}{c}\right)_i = \frac{v_i}{s_i\left(\frac{g_i}{C}\right)} = \frac{v_i C}{s_i g_i}$$

Values for X_i greater than 1.0 indicate that the demand exceeds the capacity (i.e. there is oversaturation).

The concept of critical *v/c* ratio, X_c, is the *v/c* ratio for the intersection as a whole. X_c does not account for every lane group that makes up the intersection, but rather only those lane groups that have the highest flow ratio (*v/s*) for a given signal phase. The critical *v/c* ratio is expressed,

$$X_c = \sum \left(\frac{v}{s}\right)_{ci} \left(\frac{C}{C-L}\right)$$

where each signal phase has a critical lane group. Lost time, L, is defined to be the time during which an intersection is not used effectively by any movement. It is the sum of clearance (end of phase) lost times plus start-up (beginning of phase) lost times.

The signalized intersection methodology predicts or estimates average control delay incurred by all vehicles arriving during the analysis period. Control delay, which is the delay experienced by a vehicle as a result of a traffic control device, includes stopped time, plus movements at slower speed and stops on intersection approaches as vehicles move up in a queue or slow down in advance of an intersection. Average control delay for a lane group is expressed by Equation 16-9 of the HCM [5]:

$$d = d_1(PF) + d_2 + d_3 \tag{16-9}$$

where

d	=	control delay per vehicle (s/veh)
d_1	=	uniform control delay (s/veh) assuming uniform arrivals
PF	=	uniform progression adjustment factor, which accounts for the effects of signal progression
d_2	=	incremental delay (s/veh) to account for the effect of random arrivals and oversaturation queues, adjusted for the duration of the analysis period and type of signal control; this delay assumes no initial queue for the lane group at the start of the analysis period
d_3	=	initial queue delay (s/veh), which accounts for the delay to all vehicles in the analysis period due to an initial queue at the start of the analysis period

The progression adjustment factor, PF, applies to all coordinated lane groups in semi-actuated control systems, as well as in circumstances where coordinated control is explicitly provided for actuated lane groups. It is a function of the proportion of vehicles arriving on the green signal phase and the proportion of green time available. The progression factor primarily affects uniform delay and therefore is applied only to the d_1 term.

The uniform delay term, d_1, is based on the first term of Webster's classic delay equation [6] and it is widely accepted as an accurate model for delay under the ideal case of uniform arrivals. In additional to uniform arrivals, it assumes stable flow and no initial queue. Lane group capacity is included in the computation of v/c, or X, and values of X greater than 1.0 are not used in the uniform delay equation, which is expressed by Equation 16-11 of the HCM [5]:

$$d_1 = \frac{0.5C\left(1-\frac{g}{C}\right)^2}{1-\left[\min(1,X)\frac{g}{C}\right]} \tag{16-11}$$

The incremental delay term, d_2, is used to estimate the delay resulting from non-uniform arrivals, temporary cycle failures, and sustained periods of oversaturation. The term is sensitive to the degree of saturation of the lane group, the duration of the analysis period, lane group capacity, and type of signal control. The term assumes there is no unmet demand (i.e. no initial queue) at the beginning of the analysis period and is valid for all values of X, including lane groups that are highly oversaturated. The incremental delay term is expressed as Equation 16-12 of the HCM [5]:

$$d_2 = 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}\right] \qquad (16\text{-}12)$$

where

d_2	=	incremental delay (s/veh) to account for the effect of random arrivals and oversaturation queues, adjusted for the duration of the analysis period and type of signal control; this delay assumes no initial queue for the lane group at the start of the analysis period
T	=	duration of the analysis period (in hours)
k	=	incremental delay factor that is dependent on controller settings
I	=	upstream filtering/metering adjustment factor
c	=	lane group capacity (in veh/h)
X	=	lane group *v/c* ratio or degree of saturation

The third term of the delay equation, the initial queue delay, d_3, results when there is an initial queue at the start of the analysis period from vehicles arriving prior to the period. When there is an initial queue, three possible cases exist:

1. The queue is dissipated during the analysis period;
2. The queue remains at the end of the analysis period but is smaller than the initial queue; or
3. The queue remains at the end of the analysis period and grows larger.

The general form of the initial queue delay equation is expressed as Equation 16-14 of the HCM [5]:

$$d_3 = \frac{1800Q_b(1+u)t}{cT} \qquad (16\text{-}14)$$

where

Q_b	=	initial queue at the start of period T (veh)
c	=	adjusted lane group capacity (veh/h)
T	=	duration of analysis period (h)
t	=	duration of unmet demand in T (h)
u	=	delay parameter

Parameters *t* and *u* are determined according to one of the three prevailing cases above. For an expanded discussion of the unmet demand and delay parameters, Appendix F of Chapter 16 of the Manual should be consulted.

In all three terms of the delay equation, capacity or the volume-to-capacity ratio, X, can be found. Thus, an accurate determination of capacity is necessary to produce an accurate estimation of control delay and subsequent level of service.

Level of service, the qualitative measure describing operational conditions at an intersection, is a function of average control delay and is based on the following criteria:

LOS	Control Delay per Vehicle (s/veh)
A	≤ 10
B	> 10 – 20
C	> 20 - 35
D	> 35 - 55
E	> 55 - 80
F	> 80

Note: Presented as Exhibit 16-2, LOS Criteria for Signalized Intersections, in the 2000 Highway Capacity Manual.

As stated previously, capacity is a component of each of the three terms in the average control delay equation. Regardless of whether made from an exclusive lane or a shared lane, accounting for right turns on red increases the capacity of an intersection and therefore yields a lower delay compared to the case where RTORs are ignored. To accurately account for the effects of RTOR enables the analyst to make a more accurate estimation of capacity, delay and level of service.

III. LITERATURE REVIEW

A comprehensive literature review was performed to identify the extent to which prediction of right-turn-on-red (RTOR) volumes and computation of RTOR incremental capacity has been addressed. The Transportation Research Information Services (TRIS) database was queried to identify current, relevant research on these topics. Additional articles were identified from sources referenced in the TRIS database.

Previous related research efforts are divided into two groups within this literature review: (1) prediction of RTOR volumes; and (2) estimation of saturation flow, capacity and delay of RTOR movements.

Prediction of RTOR Volumes

Two early efforts provided suggestions for estimating RTOR volumes. The 1985 HCM advised that during a protected left-turn phase, a parallel, "shadowed" RTOR movement can take place because there is no conflicting traffic. The estimated RTOR volume then equates to the parallel protected left-turn volume on a per lane basis (for the case where protected left turns occur from more than a single lane). The 1994 update to the HCM clarified that if the RTOR approach has a shared through/right-turn lane, then the number is reduced according to the likelihood that the RTOR will be blocked by a through vehicle.

Luh and Lu [7] recognized that RTOR opportunities can be utilized only when a leading right-turning vehicle arrives before a non-right-turning vehicle when the lane is shared. They claimed that the number of right-turning vehicles arriving before a non-right-turning vehicle is geometrically distributed and can be computed by the following equation:

$$E = 1/(1 - P_R) - 1$$

where

E	=	Expected number of leading right-turning vehicles per cycle
P_R	=	Proportion of right-turn traffic in a shared lane

On an hourly basis, the expected RTOR volume would equal E times (3600/C), where C is the cycle length in seconds.

The definitive work on the subject was performed by Abu-Lebdeh, Benekohal and Al-Omari [8]. The study focused on predicting RTOR volumes; it addressed delay only in a cursory manner. The researchers applied the HCM signalized intersection method at study sites with and without observed RTOR volumes and computed the delay difference at each site. All of the subject approaches contained exclusive right-turn lanes. It was determined that the delay difference is proportional to both right-turn on green (RTOG) and RTOR volumes. From the results, the following rule-of-thumb was developed: If the right-turning volume on the subject approach exceeds 100 vehicles per hour (veh/h) or if the RTOR volume exceeds 40 veh/h, then RTOR may not be ignored and a reasonably accurate estimate should be made.

Two types of conflicting traffic were identified – Type 1 conflicting traffic, approaching the subject intersection from the left (referred to as the intersecting approach), and Type 2, conflicting traffic, which includes both intersecting and opposing left-turning traffic. The following formulas estimate conflicting traffic volumes:

Type 1 conflict: $V_c = (V_t + V_r)/n$
Type 2 conflict: $V_c = (V_t + V_r)/n\ V_{ol}$

where

n	=	number of through lanes on the intersecting approach
V_c	=	total conflicting volume (veh/h)
V_t	=	through volume on the intersecting approach (veh/h)
V_r	=	right-turning volume (if made from a shared lane) on the intersecting approach (veh/h)
V_{ol}	=	protected left-turning volume (veh/h) on the opposite approach

Right turns made from exclusive lanes on the intersecting approach were not considered as conflicting volumes.

Abu-Lebdeh et al. developed a multiple regression model of the following general form:

$$RTOR_p = 79.0 + 0.339RT - 165g/C - 0.0559V_c - 50.3T + 0.108T \text{ x } RT + 143T \text{ x } g/C$$

where

$RTOR_p$	=	potential or predicted RTOR (from exclusive right-turn lane) (veh/h)
RT	=	total right-turn volume (veh/h)
g/C	=	green-to-cycle length ratio
V_c	=	total conflicting volume (veh/h)
T	=	categorical conflict variable (T = 0 if conflict is from intersecting approach only; T = 1 if conflict is from both intersecting and opposite approaches)

The model can be simplified for the two types of conflicting traffic conditions, as such:

Type 1 conflict (T = 0, conflict is from intersecting approach only):

$$RTOR_p = 79 + 0.339RT - 165g/C - 0.0559V_c$$

Type 2 conflict (T = 1, conflict is from intersecting and opposing approaches):

$$RTOR_p = 28.7 + 0.447RT - 22g/C - 0.0559V_c$$

Whereas Abu-Lebdeh et al. assumed no blockage of right-turning vehicles on the subject approach, Tarko [9] accounted for blocking of right-turning vehicles as a result of (1) through vehicles in front of right-turning vehicles in a shared lane; or (2) through vehicles in front of right-turning vehicles in advance of the beginning of a right-turn lane. Tarko concluded that the number of vehicles turning right on red depends on:

1. Volume of right-turning vehicles blocking right turns during the red signal;
2. Queue of same-approach vehicles blocking right turns during the red signal; and
3. Vehicles and pedestrians in the cross-street blocking RTOR vehicles.

Tarko determined that the expected number of right-turning vehicles arriving at the intersection approach during a red signal can be predicted by the following equation:

$$a_r = \frac{V_r(C - R_p \cdot f_r)}{3{,}600}$$

where

a_r	=	expected number of right-turning vehicles arriving on the subject intersection approach during a single red signal
V_r	=	flow rate of right turns (veh/h)
C	=	signal cycle length (s)
R_p	=	platoon ratio from the HCM corresponding to type of right-turning vehicle arrivals (R_p = 1 for isolated intersections)
f_r	=	phase time for right turns (s)

An intersection approach has either an exclusive right-turn lane or has a lane where right turns are shared with non-right turn (through and possible left-turn) movements. For approaches having a shared lane, a single vehicle can block the right-turning movement. Tarko postulated that this was equivalent to having a right-turn bay for one vehicle. In his proposed method, a right-turn bay for one vehicle represented the case where there was no exclusive right-turn lane.

For approaches having a separate right-turn lane, two distinct situations are possible:

1. All right-turning vehicles arriving during a red signal reach the right-turn bay, regardless of how they arrive. The total number of non-right-turning vehicles arriving on red is not large enough to block the right-turn lane.

2. The total number of non-right-turning vehicles arriving during the red phase is large enough to block the right-turn bay for at least some of the right turns. It is possible in this situation for all of the right-turning vehicles to enter the right-turn bay, but they must arrive before the bay becomes blocked.

Tarko used the variables x, t and k to mathematically represent these scenarios, where

x	=	number of right-turning vehicles arriving during a red signal
t	=	total number of vehicles arriving on red
k	=	length of right-turn bay (in vehicles)

In the first situation (all right-turning vehicles make it into the turn bay), the following condition for the number of non-right-turning vehicles applies: $t - x < k$, which means that $x > t - k$. Tarko determined that the number of unblocked right turns (x) can be considered a result of independent experiments (number of vehicle arrivals) with the likelihood of success p (proportion of right turns in the right-most lane). He used a binomial distribution to calculate P_B, the likelihood that x right-turning vehicles are not blocked:

$$P_B(x) = \binom{t}{x} p^x (1-p)^{t-x}$$

In the second case, where there is a separate right-turn lane, the number of non-right-turning vehicles arriving on red is sufficiently large so that right-turning vehicles arriving after the k^{th} vehicle are blocked and cannot reach the turn bay before the green begins. Tarko determined that a Negative Binomial distribution can be used to predict the likelihood of the number of unblocked right turns (x) that will arrive before the k^{th} vehicle that blocks the right-turn lane. The likelihood of "success" in this case is the proportion of non-right-turning vehicles in the right-most lane ($1 - p$) and fits the relationship:

$$P_{NB}(x) = \binom{x+k-1}{k-1} (1-p)^k p^x$$

Thus, the value of x, the number of right-turning vehicles arriving on red, determines which case occurs:

Case	Description	Condition	Distribution
1	All RT vehicles make it into the right-turn bay	$x > (t - k)$	Binomial
2	Some RT vehicles are blocked by non-RT vehicles	$x \leq (t - k)$	Negative Binomial

Tarko concluded that the average value of right-turning vehicles arriving on red, which he denoted as b, can be calculated by using the definition of expected value:

$$b = \sum_{x=0}^{t-k} x P_{NB}(x) + \sum_{x=t-k+1}^{t} x P_{B}(x)$$

The volume of right-turning vehicles arriving at the stop bar, under the absence of impedance from the perpendicular or intersecting stream, is

$$V_o = b \cdot m$$

where m is the number of cycles in one hour. This is the predicted value that would serve as the input parameter in the HCM method.

Tarko made reference to impedance from the perpendicular traffic stream, but did not specifically address conflicts from opposing left turns. It is implied that the impedance could include intersecting or perpendicular traffic flows approaching from the left and opposing left turns combined, but this issue was not addressed directly in the research.

Dixon and Gangula [10] evaluated the different methods for estimating RTOR volumes, identified their limitations, and developed an improved RTOR volume estimation model. The Tarko and Abu-Lebdeh models were selected for further testing because they seemed more promising. The researchers concluded that the Tarko analytical model has a wider range of applicability than the Abu-Lebdeh et al. regression model, but that the Tarko model does not address situations where the non-right-turning volume in the (shared) outermost lane is zero. They also noted that the Tarko model is guaranteed to yield positive estimates; if the Abu-Lebdeh et al. regression model yields a negative value due to some unusual combination of input variables, then the estimated RTOR volume should be set to zero.

Dixon and Gangula also developed an improved RTOR model, based on a recalibrated Abu-Lebdeh et al. model, with additional variables added to consider the effects of exclusive and shared lanes, (k), and another for the effects of the proportion of right turns in the outside lane (V_{ol}). That model was:

$$RTOR_p = -1.221 + 0.387RT - 86.002g/C + 0.021V_c + 4.549k + 8.322(RT/V_{ol})$$

where

$RTOR_p$	=	potential or predicted RTOR (from exclusive right-turn lane) (veh/h)
RT	=	total right-turn volume (veh/h)
g/C	=	green-to-cycle length ratio
V_c	=	total conflicting volume (veh/h)
k	=	length of right-turn bay in number of vehicles
V_{ol}	=	outer lane volume on subject approach from which right-turn vehicle enters the right-turn bay

Dixon and Gangula compared their modified regression model with the Tarko model. They concluded that the new regression model and the Tarko model were not significantly different in predicting RTOR volumes for different lane configurations, but from a practical standpoint, there was a difference in the following situations:

- The subject approach has a shared through/right-turn lane configuration and the ration of right turns to outer lane volume is greater than 0.74, the new regression model performed better.

- There can be a combination of independent variables that can be input into the new regression model that might yield negative values, in which case the RTOR volume should be set to zero.

Estimation of Saturation Flow, Capacity and Delay

Abu-Lebdeh1 et al. [8] defined $RTOR_{Cap}$ as the capacity of the RTOR movement; i.e., the maximum number of right turns that can be processed on red. This was predicted according to the following model:

$$RTOR_{Cap} = \alpha\{Max[((1-g/C)s - V_c),0]\}$$

where

α	=	ratio of saturation headway of intersecting through traffic to that of RTOR traffic. Values of α range from 0.73 (which corresponds to a right-turn lane saturation headway of 2.6 seconds per vehicle) to 0.85 (which corresponds to a right-turn lane saturation headway of 2.2. seconds per vehicle)
g/C	=	green-to-cycle length ratio
s	=	saturation flow rate (veh/h)
V_c	=	total conflicting volume (veh/h)

Several other researchers have addressed the estimation of RTOR saturation flow, capacity and delay as a function of gap acceptance behavior. Tarko [9] also addressed RTOR capacity in his research. He recognized that vehicles may turn right on red during two different periods of the red cycle:

a. The period when right-turning vehicles are impeded by other traffic; and
b. The period when right-turning vehicles are not impeded.

There are two capacities for right-turning vehicle flow, c_1 and c_2, that correspond to these two periods respectively. For the first period, the c_1 capacity is influenced by impeding traffic flows from the left in the right-most lane or by pedestrians crossing the subject approach under a "Walk" signal indication. Tarko postulated that these two impeding factors can be modeled by using properly modified equation from the HCM Unsignalized Intersections method. Capacity c_1 can be computed as:

$$c_1 = \left(1 - \frac{v_p}{2{,}100}\right) \cdot \frac{v_i \cdot \exp\dfrac{-v_i \cdot t_o \cdot C}{3{,}600 \cdot f_i}}{1 - \exp\dfrac{-v_i \cdot t_f \cdot C}{3{,}600 \cdot f_i}} \cdot \frac{f_i}{C}$$

where

v_p	=	pedestrian volume across approach with right turns (pedestrians/h)
v_i	=	impeding vehicular flow (veh/h)
C	=	expected signal cycle (s)
t_o	=	critical gap for right turns (6.9 s)
t_f	=	follow-up time (3.3 s) and
f_i	=	phase time for impeding flow (s)

This equation is a modified version of the HCM equation for potential capacity of movement at unsignalized intersections. The term f_i/C translates an hourly flow rate to capacity based on the proportion of the cycle during which display is red on the subject approach.

For the second period, when right-turning vehicles are not impeded, the capacity is estimated with the assumption that a right-turning vehicle needs t_f seconds to leave the first position in the queue. The equation for capacity c_2 is:

$$c_2 = \frac{3{,}600}{t_f} \cdot \frac{C - f_r - f_i}{C}$$

where

f_r = phase time for right turns (s)
f_i = phase time for impeding flow (s)

Lin [11] identified several RTOR flow parameters:

- Use of RTOR opportunities
- Gap-acceptance behavior of RTOR drivers
- Dwell times of unopposed RTOR vehicles
- Efficiency in executing multiple right-turns-on-red

He noted a 16 percent rejection rate of those drivers having RTOR opportunities, postulating that drivers' ignorance of the RTOR regulation was a likely cause. (Note: Lin conducted his research more than 20 years ago. As RTOR is commonplace nationwide today, this author hypothesizes that the current rejection rate would be lower.)

Lin determined that the rate of RTOR use was also governed by the size of gaps in cross traffic and the ability of right-turners to accept those gaps. He found that a gap in cross traffic smaller than 5 seconds was unlikely to be accepted, while a gap greater than 15 seconds was unlikely to be rejected. For the RTOR movement, Lin computed the critical gap (that is, the minimum gap that a driver will accept) to be 8.4 seconds. This is considerably larger than typical critical gaps of 4.0 to 5.5 seconds that had been observed previously for drivers making left turns through opposing traffic streams.

Lin observed that every RTOR vehicle incurs a dwell time, that is, the elapsed time from the moment a driver reaches the position from which he can make a right turn on red until he begins executing the RTOR. The average dwell time was observed to be 4.4 seconds, but approximately 40 percent of the drivers executed the maneuver within 2 seconds of their arrival (thus, they did not stop completely). Lin also observed that multiple RTORs may occur when the gap is long. He concluded that because of dwell times, the red phase of a signal is only about 60 percent as useful (in discharging RTOR traffic where allowed) as a green phase of the same length, even when conflicting traffic does not exist. He cautioned that assuming every driver will use RTOR opportunities could lead to a slight overestimation of the impact of RTOR.

Lin determined that average discharge headways stabilize at 2.1 seconds for through vehicles and 2.4 seconds for right-turning vehicles on an intersection approach. This corresponds to saturation flow rates of 1,700 veh/h for through vehicles and 1,500 veh/h for right-turning vehicles. He also found that when conflicting (cross) flow is heavy and its saturation ratio approaches 1.0, acceptable gaps in that flow hardly exist. Lin determined that average right-turn delays vary in an approximately linear manner with the saturation ratio of cross-flow traffic. He also concluded:

- RTOR has a negligible impact on delay if the average delay to right-turning vehicles is less than 15 s/veh; and

- RTOR is not likely to reduce right-turn delays significantly if the saturation ratio of cross-flow traffic is greater than 0.6 and delays to right-turning vehicles are less than 30 s/veh.

Luh and Lu [7] developed models to compute RTOR capacity in both exclusive and shared right-turn lanes. They recognized that right-turn lane use (exclusive vs. shared) and the proportion of right turns using a shared lane were major factors influencing RTOR capacity.

Luh and Lu stated that requirements for RTOR drivers to select a gap in conflicting traffic flow are similar to the requirements for drivers turning right from a minor street onto a major street at a STOP-sign-controlled intersection. They postulated that the unsignalized intersection capacity computation in the HCM may be used to estimate RTOR capacity.

Luh and Lu noted that, according to the HCM method, potential capacity (i.e. capacity under ideal conditions) for STOP-sign-controlled right turns is expressed in units of vehicles per hour per lane. They distinguished that, for RTOR, potential capacity should be expressed in vehicles per hour of *unsaturated* red because only the unsaturated portion of a phase can be utilized by RTOR traffic. Under the saturated portion of a red phase, conflicting traffic flow is at saturation and there are no available gaps for RTORs.

The researchers used microscopic simulation (NETSIM) to support their assumptions that RTOR behavior during unsaturated red is similar to that of STOP-controlled right turns. They developed the following model to compute actual capacity:

$$c_i = c_p (r_u / C) f_{RT}$$

where

c_i	=	actual capacity in the i^{th} signal phase (veh/h)
c_p	=	RTOR potential capacity in an exclusive right-turn lane (veh/h)
r_u	=	unsaturated red time (s), which is in fact the unsaturated green time for conflicting traffic
C	=	cycle length (s)
f_{RT}	=	HCM adjustment factor for pedestrians

At this point, the methodology assumes that RTOR is made from an exclusive right-turn lane. As noted previously in this literature review, they recognized that RTOR opportunities can be utilized only when a leading right-turning vehicle arrives before a non-right-turning vehicle when the lane is shared. The authors claimed that the number of right-turning vehicles arriving before a non-right-turning vehicle is geometrically distributed and can be computed by the following equation:

$$E = 1/(1 - P_R) - 1$$

where

E	=	Expected number of leading right-turning vehicles per cycle
P_R	=	Proportion of right-turn traffic in a shared lane

The number of RTOR chances provided in the conflicting traffic stream is computed as:

$$c_c = c_p (r_u / 3{,}600) f_{RT}$$

Finally, the RTOR capacity in a shared lane in a single phase is the smaller value of the RTOR opportunities and the number of leading right-turning vehicles, as expressed by the following equation:

$$c_{ai} = Min(c_{c,} E)\left(\frac{3600}{C}\right)$$

where

c_{ai} = Actual RTOR capacity in the shared lane in the i^{th} phase

For each phase, the RTOR capacity from the shared lane can be summed for all values of c_{ai}.

Virkler and Maddela [12] examined the two procedures for analyzing RTOR that were commonly accepted at that time:

1. Shadowing of RTOR by a protected left turn phase, under the assumption that the parallel RTOR movement can take place because there is no conflicting traffic; and

2. The RTOR movement is analogous to the movement of right-turning vehicles at a STOP-sign-controlled intersection and that the HCM procedure for a right turn at an unsignalized intersection can be modified to estimate RTOR capacity.

Virkler and Maddela acknowledged that if the shadowed RTOR occurs from a shared lane, then the number of RTOR occurrences is reduced according to the likelihood that RTOR will be blocked by a through vehicle. They found that the shadowing procedure can indicate that all right turns occur on red, which is unrealistic. In reality, both right-turn-on-green (RTOG) and RTOR vehicles experience some stopped delay, but less than what would be determined if there were no RTOR.

The researchers noted that the HCM delay equation is based on the assumption that the vehicles depart from an intersection during the green phase. Application of the stop sign analogy (SSA) adds intersection capacity during the red phase as RTOR is included. However, though intersection delay is reduced by RTOR, the amount of this reduction cannot be modeled correctly by the HCM method.

Virkler and Krishna [13] examined several methods for estimating capacity for right turns into gaps at signalized intersections through RTOR and free rights (with yield control). They examined the HCM signalized intersection method (where the RTOR volume are subtracted from the approach volume), the 1996 version of the Australian software SIDRA, in which there are two “green” periods (the second “green” period represents RTOR during all non-green phases), and the HCM Stop Sign Analogy (SSA).

Virkler and Krishna noted similar drawbacks as did other researchers with the HCM signalized intersection method, that is:

- If the RTOR volume is not known, subtracting a RTOR volume equal to the per-lane volume of a shadowing left turn movement may not provide an accurate estimate; and

- By subtracting RTOR vehicles from the approach volume, their delay is ignored, when in fact RTOR vehicles do experience delay.

The authors noted that the SIDRA method called for user-supplied critical gap, follow-up time, and gap acceptance parameters. They determined that a disadvantage to the SIDRA approach was that it combined flow rates for all opposing phases, which could lead to a different capacity than when phases are considered individually.

Virkler and Krishna expanded upon the previous research by Virkler and Maddela, which applied the SSA procedure to traffic signal and volume data from 132 exclusive and shared right-turn lane groups at 40 intersections in Missouri. They noted that the HCM unsignalized intersection equation used to represent capacity for gap acceptance is based on a negative exponential distribution of arrivals in the conflicting traffic stream and can be written as:

$$c_R = \frac{3{,}600}{t_f} \cdot e^{\frac{-v_c t_o}{3{,}600}}$$

where

c_R	=	capacity (veh/h unsaturated time)
v_c	=	hourly volume of conflicting traffic stream (veh/h)
t_o	=	$t_g - (t_f/2)$
t_g	=	critical gap (s)
t_f	=	follow-up time (s)

The capacity then would be:

$$c = c_R\left(R_u / C\right)$$

where

c = capacity from the interval during an hour (veh/h)
R_u = unsaturated red time of interval (s)
C = cycle length (s)

Virkler and Krishna made an adjustment to the capacity equation in order to eliminate capacity derived from gaps greater than the unsaturated portion of the phase time. This modification was referred to by the authors as the Adjusted Stop Sign Analysis (ASSA). The following equation is equivalent to saying that gaps greater than the unsaturated period are not available for use by right-turning traffic, as shown:

$$c_A = \frac{3{,}600}{t_f} \cdot e^{\frac{-v_c t_o}{3{,}600}} - \frac{3{,}600}{t_f} \cdot e^{\frac{-v_c U_o}{3{,}600}}$$

where

c_A = adjusted capacity during an individual red interval (veh/h unsaturated red)
U_o = $U - (t_f/2)$
U = unsaturated red time (s)

Virkler and Krishna concluded that the SSA tends to overestimate gap capacity, while the ASSA tends to underestimate gap capacity.

Follmer and Janson [14] examined the use of separate saturation flow rates and capacities for right turns made during both the red and green signal phases. Their approach was to develop a modified uniform delay equation (i.e. the d_1 term of the HCM delay equation) to include both RTOR and RTOG saturation flow rates. They also included the effects of the revised total capacity estimate on the incremental (d_2) and initial queue (d_3) delay terms.

Follmer and Janson applied the HCM Stop Sign Analogy, which estimates the potential capacity of exclusive right-turn lanes at unsignalized intersections, to estimate RTOR capacity at signalized intersections. They noted that flows conflicting with RTOR movements in the SSA include both opposing left turns and cross-street through and right-turn movements.

The researchers determined that if the RTOR volume is known and a RTOR queue generally exists for the analysis period, then the RTOR volume is a good estimate for the RTOR saturation flow rate. Right-turn capacities can be computed individually for the red and green signal phases:

$$RTOR\ capacity = S_r(1\text{-}g/C)$$
$$RT\ capacity = S_g(g/C)$$

where

S_r = Right-turn saturation flow during the red phase (veh/h)
S_g = Right-turn saturation flow during the green phase (veh/h)

The total right-turn capacity then becomes:

$$Total\ Right\ Turn\ Lane\ Capacity = S_r(1\text{-}g/C) + S_g(g/C)$$

Follmer and Janson modified the d_1 equation accordingly:

$$Modified\ d_1 = 0.5(C/v)(1\text{-}g/C)^2[(v\text{-}S_r)+(v\text{-}S_r)^2/(S_g\text{-}v)]$$

where

v = total right-turn volume (veh/h), with a maximum value of $S_r(1\text{-}g/C)$ + $S_g(g/C)$, and a minimum value of S_r

The d_2 term also was modified as such:

$$d_2 = 225\left[(X-1)+\sqrt{(X-1)^2 + mX/capacity}\right]$$

where

d_2 = estimated incremental (oversaturated) delay (s/veh)
X = volume-to-capacity ratio, with no restrictions on minimum or maximum value of total right-turn volume

m = incremental delay adjustment factor
$capacity$ = $S_r(1\text{-}g/C) + S_g(g/C)$

It should be noted that the d_2 equation was modified to its current form after the research by Follmer and Janson was conducted, to include the upstream filtering/metering adjustment factor, I.

Follmer and Janson also modified the HCM unsignalized intersection model for estimating right-turn capacity versus the number of conflicting vehicles, to include opposing left turns as an additional conflicting flow, as represented in the following equation:

$$V_c = V_2/N + V_{10}/N_L + 0.5V_3$$

where

- V_c = total conflicting volume per hour of red time (veh/h red time) for RTOR movements
- V_2/N = cross-street through volume per hour of red time (veh/h red time) divided by the number of through lanes N
- V_{10}/N_L= opposing left-turn volume per hour of red time (veh/h red time) divided by the number of left-turn lanes N_L
- V_3 = cross-street right-turn volume per hour of red time (veh/h); this term is used if right turns on the conflicting cross-street are from a shared through/right-turn lane and is removed from the equation if a separate right turn lane exists on the conflicting cross-street

Pedestrian movements were dropped from the modified equation as the HCM included a comprehensive method to estimate the effects of pedestrian on right-turn capacity at signalized intersections.

The RTOR conflicting flow V_c was used to estimate the potential RTOR saturation flow rate S_r based on the following equation:

$$S_r = V_c[e^{(-VcTc)/3,600}]/[1-e^{(-VcTf)/3,600}]$$

where

- S_r = potential RTOR saturation flow rate (veh/h red time)
- T_c = critical gap (s) for RTOR movement

T_f = follow-up time (s) for RTOR movement

Qureshi and Han [15] posed two questions in determining the impact of RTOR on delay:

a. Which of the (HCM) delay terms is affected by RTOR?
b. How are the delay terms affected by RTOR?

Qureshi and Han point to the treatment of left turns as the answer to these questions. They claimed that all three terms are applied to left turns that are either protected by an exclusive phase or permitted when traffic conditions allow for a sufficient gap in the opposing traffic stream. However, when protected-plus-permitted phasing exists, the HCM introduces a supplemental uniform delay to account for queuing accumulation polygons (QAPs) that are not simple triangles; the incremental and initial queue delay terms are not adjusted. Five separate cases of QAPs for protected-plus-permitted phasing are shown in **Figure III.1**.

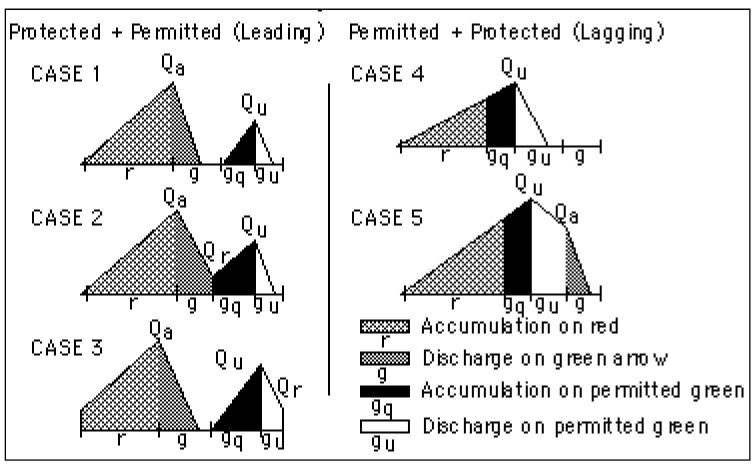


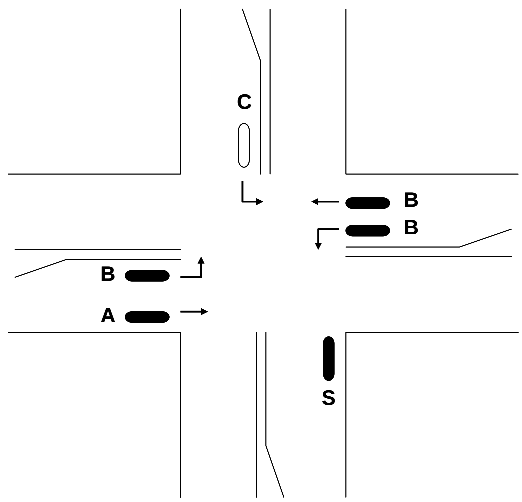
Figure III.1. Queue Accumulation Polygons (source: Highway Capacity Manual)

The researchers hypothesized that RTOR is similar to a left turn under protected-plus-permitted phasing in that QAPs for both situations are not simple triangles and therefore RTOR should be treated in a similar fashion.

Qureshi and Han determined that each QAP involving RTORs may be classified according to a sequence of signal phases at an intersection. They identified three regimes during a red phase that affect a vehicle's ability to turn right:

Regime	Conflicting Movement
A	Red light gives priority to through vehicles on the intersecting street
B	Red light prioritizes vehicles on the intersecting street that do not conflict with the ability to conduct the RTOR maneuver
C	Priority is given to opposing left turns that may restrict RTOR maneuver

For a typical four-legged intersection, these regimes are illustrated in **Figure III.2**. The subject approach is denoted by 'S.'



(Source: Qureshi and Han)

Figure III.2. Phasing Plan Regimes - Typical Four-Legged Intersection

Qureshi and Han developed a classification scheme for four general classes of red (RR-A, RR-B, and RR-C) and green regime phasing, as shown in **Figure III.3**.

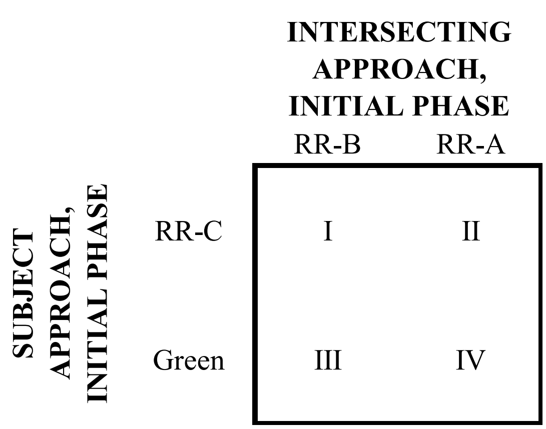


Figure III.3. Classification of Phasing Sequences for RTOR

Based on this scheme, QAPs are developed for each class. For any combination of phasing sequences, the average delay for each QAP becomes the area of the polygons, that is:

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

where

C = cycle length (s)
$Q(t)$ = number of vehicles in queue at time, t
V = arrival rate of vehicles (veh/s)

The research of Qureshi and Han addressed only the uniform delay component of control delay; it did not address the incremental and initial queue delay components. The QAP method was not tested or validated on field data.

Stewart and Hodgson [16] conducted research on the estimation of RTOR saturation flow rates. They recognized that site-specific measurement of saturation flow is not always practical or even possible. Stewart and Hodgson developed two methods for estimating flow rates:

1. A microscopic approach using gap acceptance techniques to determine the probability of accepting a gap for each individual vehicle; and

2. A macroscopic approach utilizing regression equations.

Stewart and Hodgson derived their microscopic model based on a commonly-accepted theory that saturation flow rates for RTOR movements are accurately represented by a Poisson distribution, that is:

$$P(x) = \frac{m^x e^{-m}}{x!}$$

where

$P(x)$	=	probability of exactly x vehicles arriving in time interval t
m	=	average number of vehicles arriving in time interval t
x	=	number of vehicles arriving during the selected time interval being investigated

When a gap in the conflicting traffic stream occurs (i.e. $x = 0$), a negative exponential distribution of vehicle headways, h, results. When V is defined as an hourly flow rate of conflicting traffic, the probability that the headways will be greater than some time, t, can be expressed as:

$$P(h \geq t) = e^{(Vt/3,600)}$$

The saturation flow rates then can be estimated according to the following formula:

$$S = V \sum P(h \geq t)$$

The researchers also developed a macroscopic model using linear regression. They hypothesized that the relationship between conflicting through flow and RTOR saturation flow rates can be estimated by regressing observed conflicting flow rates against observed RTOR saturation flow rates. Assuming negatively exponentially distributed inter-arrival times for opposed through flow, the general form of the regression equation is:

$$S_R = ce^{dV'_o} - \lambda$$

where

S_R	=	RTOR saturation flow rate (veh/h)
c,d,λ	=	calibration parameters
V_o'	=	$V_o \cdot (c/G)$
g	=	effective green time (s)
C	=	cycle length (s)

Fitted to observed data, the final form of the regression equation is:

$$S = 849.82e^{-0.00129v} - 31$$

where

S = saturation flow rate (veh/h)
v = conflicting flow rate (veh/h)

The researchers determined that the coefficients were significant at a 95 percent confidence level. Correspondence with the principal author revealed that the conflicting flow rate, v, applied only to through intersecting traffic coming from the left and did not include opposing left turn traffic.

Stewart and Hodgson concluded from their research:

- The average critical gap size was 6.59 seconds;
- The average additional size of gap required for multiple discharges was 4.7 seconds;
- The average unopposed saturation flow rate for RTOR was 800 vehicles (passenger cars) per hour of green;
- Critical gap size was affected by differences in geometric conditions, surrounding land use and roadway type; and
- Gap acceptance behavior may be affected by time of day, number of conflicting lanes and/or turn radius.

Tian and Wu [17] developed a capacity estimation model for signalized intersection approaches containing short right-turn lanes. The model was developed to overcome one of the major shortcomings of the current capacity estimation method by considering the probabilistic nature of traffic flow and its effect of queue blockage to short-turn lane sections.

When an approach contains a short, exclusive right-turn lane, the researchers recognized two general cases where blockage of either the through or right-turning vehicles can occur:

1. When a through vehicle or vehicles blocks the right-turn lane; and
2. When the short right-turn lane becomes filled and subsequent right-turning vehicles waiting to enter the right-turn lane spill back and block the through lane.

It was recognized that the length of the short right-turn lane (i.e., its storage capacity) directly affects the capacity of the through and right-turn lanes for the subject approach. Furthermore, the probability of blockage to right-turning vehicles by through vehicles was noted to be equivalent to the proportion of through traffic to the total traffic.

Tian and Wu generalized their approach such that 2N+1 through vehicles would be necessary to block right-turning vehicles (and thus prevent the RTOR movement), under the assumption that N equals the storage length of the short right-turn lane and one vehicle in addition to the Nth vehicle would be able to use the transition area to enter the right-turn lane. The probability density function for the number of blocking through vehicles was determined to follow a Negative Binomial distribution, as given by the following equation:

$$f(n_t) = \binom{2N+1}{n_t} (1 - p_t)^{2N+1-nt} \cdot p_t^{nt}$$

where

n_t = number of through vehicles arriving during a signal cycle
N = length of short right-turn lane (in vehicles)
p_t = proportion of through vehicles

Thus, the probability of blockage due to a through vehicle, Pr_t, can be calculated according to the following equation:

$$Pr_t = \sum_{n_t=N+1}^{2N+1} f(n_t)$$

An approach containing a shared through/right-turn lane was considered to be a special case of a short right-turn lane with a length equal to zero vehicles (and no transition area). Tian and Wu demonstrated that the probability of blockage due to a through vehicle increased as the proportion of through vehicles increased.

Conclusions

Significant research has been conducted on the RTOR issue since the 1985 Highway Capacity Manual. However, nothing conclusive has been reached to the point that the current methodology has been modified to better address the issue.

While the work done by Abu-Lebdeh et al. [8] appears to be the most recognized research so far, the resulting empirical regression model for predicting RTOR volumes has limitations (for example, it’s theoretically possible to predict negative values) and it is not applicable to shared lanes. While Tarko [9] did account for blocking of right-turning vehicles in shared lanes, his research did not specifically address impedance to RTORs from opposing left-turn movements, only those from the intersecting (perpendicular) traffic stream. As Dixon and Gangula [10] offered an improved regression model based on previous research by Abu-Lebdeh et al., theirs was subject to the same limitations.

Regarding RTOR capacity, several researchers acknowledged gap acceptance behavior by drivers performing the RTOR maneuver and its similarity to driver behavior at STOP-controlled cross-street approaches. Furthermore, they recognized the probabilistic nature of RTORs from shared lanes and the blocking effect of through vehicles. Their efforts, however, were primarily theoretical and stopped short of comparing predicted RTOR volumes or capacities with observed RTOR volumes or capacities computed using the HCM methodology.

Qureshi and Han [15] offered a useful scheme for classifying the signal phasing regimes under which RTORs can occur. A similar scheme was employed as part of this research. Qureshi and Han, however, only addressed the uniform delay component of control delay. In the review of the HCM method, it was demonstrated that capacity is a component of all three terms in the delay model (uniform delay, incremental delay and initial queue delay). Thus, the Qureshi and Han research did not fully address the effect of RTORs on capacity and delay, and their method was not tested or validated using field data.

Finally, none of the previous research has produced RTOR volume and capacity models that could be applied to exclusive or shared lane approaches. Ultimately the objective should be to produce such a model that is easily understood and applied, produces reasonable results, and is incorporated into a future version of the Signalized Intersection methodology.

IV. METHODOLOGY

To accomplish this research, a series of tasks was undertaken. With the exception of the review of the Highway Capacity Manual and other relevant literature, which have been performed already, the details of the approach to the subsequent tasks are provided in the following section. The tasks were:

1. Review of the Highway Capacity Manual
2. Review of Other Literature
3. Objectives
4. Study Design
    a. Shared Lanes vs. Exclusive Right-Turn Lanes
    b. Right-Turn-on-Red (RTOR) Regimes
    c. RTORs from Shared Lanes – A Probabilistic Approach
    d. Study Sites
    e. RTOR Volume Prediction Model
    f. RTOR Incremental Capacity Model
5. Conclusions

Objectives

The objectives of this research were:

- To develop RTOR volume and RTOR incremental capacity estimation models based on actual field data that account for the probabilistic nature of blocking by through vehicles in shared lanes;
- To develop models that are easily understood by practitioners and produce reasonable results; and
- To develop deterministic models that are consistent with the HCM Signalized Intersection methodology and that can be incorporated into future updates to the method.

Study Design

Shared Lanes Versus Exclusive Right-Turn Lanes

It is recognized that shared through/right turn lanes pose a limitation on the volume of RTOR maneuvers that can occur due to the fact that, during any given cycle of the traffic signal, a through vehicle on the subject approach during a red signal display serves to block any following vehicles from completing a RTOR maneuver, even if there are sufficient gaps in the conflicting traffic stream(s). Furthermore, the occurrence of this blocking event varies from one cycle to the next and is a function of the proportion of through vehicles to right-turning vehicles. Where the subject approach contains one or more through lanes in addition to the shared through/right-turn lane, the volume of through vehicles in the shared lane must be determined. If actual field data are not available, common practice is to divide the total approach volume by the number of through and shared lanes, with the through volume in the shared lane being half the total approach volume minus the right-turn volume. Ideally, methods to estimate RTOR volumes and the incremental capacity achieved by allowing RTORs should be applicable to both situations. While this research focused on RTORs from shared lanes, guidance for application of these models to approaches with exclusive right-turn lanes is offered.

Right-Turn-on-Red Regimes

The most common type of signalized intersection is a four-legged intersection where the legs intersect at 90-degree angles. With regard to the subject approach where right turns on red are permitted, RTORs may occur during any of three regimes, as illustrated in **Figure IV.1**. In Figure IV.1, the subject approach is oriented in the northbound or upward direction. The RTOR regimes are:

1. ***Intersecting***, where traffic approaches from the left. RTORs can be made when there are sufficient gaps in the through traffic stream on the intersecting approach. When the intersecting approach contains two or more through lanes, it is assumed that only through traffic in the curb or outside lane conflicts with drivers on the subject approach desiring to perform the RTOR maneuver. In Figure IV.1, the eastbound approach is the intersecting approach. When the intersecting approach contains a shared through/right-turn lane, right-turn volumes from the shared lane are subtracted from the intersecting approach volume as they do not conflict with potential RTOR vehicles on the subject approach.

2. ***Opposing***, where left turns occurring from the approach opposite the subject approach conflict with drivers desiring to turn right on red. Similar to the Intersecting regime, RTORs can be made during the Opposing regime when there are available gaps within the opposing traffic stream. The Opposing regime occurs only when the Opposing left turns operate during an exclusive or protected (i.e. a “green arrow” signal display) left turn phase. If the Opposing left turns are permitted (i.e. a “green ball” signal display), it is assumed that the right turns on the subject approach have the right of way. It is also assumed that Opposing left turns are made into the inside or near lane when there are two or more downstream lanes and that RTORs on the subject approach are not constrained

when this is the case. In Figure IV.1, Opposing left turns are made from the southbound approach.

3. ***Shadowed Left Turns***, which occur from the approach opposite the Intersecting approach and do not conflict with RTORs from the subject approach. This regime occurs only when the left turns occur during a protected or exclusive phase, thus the name "shadowed." This research did not include U-turns as part of Shadowed Left Turns. In Figure IV.1, Shadowed Left Turns occur from the westbound approach.

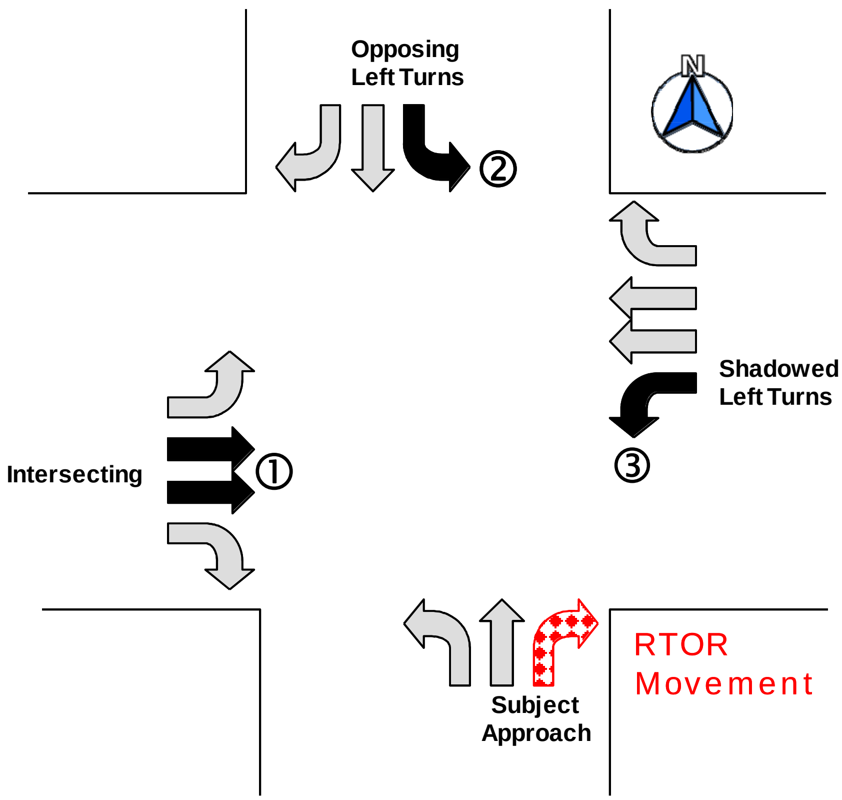


Figure IV.1. Right-Turn-on-Red Regimes

Both the Intersecting and Opposing regimes are considered to be conflicting regimes in that RTORs must yield to through or left-turning movements that have right of way during their respective signal phases.

These regimes can be applied to a three-legged or T-intersection as well. Depending on the orientation of the subject approach, either the Intersecting or Opposing regime would not exist. All of the intersections studied as part of this research were four-legged intersections. However, the Opposing Left Turn regime does not exist if the approach opposite the subject approach does not have an exclusive left turn phase. This was the case for two of the five intersections studied.

Pedestrian crossing movements affect RTOR maneuvers by reducing the available portion of the intersecting movement phase interval (Regime ①) during which RTORs can be made. The models developed as part of this research do not incorporate pedestrian crossing activities.

RTORs from Shared Lanes – A Probabilistic Approach

A unique condition exists for the case where there is a shared through/right-turn lane in that if during the red phase RTORs are permitted, this maneuver is impeded or blocked if the vehicle at the STOP bar is not a right-turning vehicle. Thus, during this portion of the cycle, there are two possible outcomes for each vehicle approaching the STOP bar:

- The vehicle is a right-turning vehicle and the driver has the potential to make the RTOR movement; or
- The vehicle is a through vehicle and the driver must wait until there is a green signal display. In this case, the through vehicle would block any subsequent right-turning vehicles from making the RTOR maneuver.

For the sake of estimating the number of right-turning vehicles during the red portion of the cycle, the interest lies in identifying the number of RTOR vehicles that pass the STOP bar before the first through or blocking vehicle arrives. If a through vehicle arriving at the STOP bar on red is considered as a "success," there are then two possible binary outcomes:

- 1 = Through or Blocking Vehicle = "Success"
- 0 = RTOR Vehicle = "Failure"

For the purpose of predicting the number of RTOR maneuvers, *Y*, that could occur and the incremental capacity that can be realized when RTORs are allowed, the objective therefore is to identify the number of "failures" (i.e. RTORs) that occur before the arrival of the first through or blocking ("success") vehicle. Statistically, this relationship takes the form of a Negative Binomial Distribution having the general form:

$$P(Y = y) = \binom{y + r - 1}{r - 1} p^r (1 - p)^y$$

where

y = The number of RTORs that are observed during a given red signal phase (y = 0, 1, 2, ...).

r = The number of through vehicles required to block the shared lane and prevent further RTORs during the given red signal phase. For r

= 0, a vehicle is able to make the RTOR maneuver. For $r = 1$, one through vehicle in the shared lane blocks a subsequent RTOR vehicle.

p = The proportion of through vehicles to total vehicles in the shared lane.

For each "experiment" (i.e. one signal cycle), there are two possible outcomes for vehicles on the subject approach – either the vehicle is a right-turning vehicle and makes the RTOR maneuver if an acceptable gap is present or the vehicle is a through vehicle and blocks any subsequent RTOR vehicles until the next cycle. At this point, the "experiment" ends and is repeated upon the onset of red in the next cycle. The Negative Binomial Distribution models this "experiment," the parameter Y constitutes a RTOR vehicle.

In the case of a shared through/right-turn lane where there is no shoulder for which right-turning vehicles can bypass a stopped through vehicle, it only takes one through vehicle to block a potential RTOR maneuver. This represents a Geometric Distribution, which is a Negative Binomial Distribution with $r = 1$. For a Geometric Distribution, the Expected Value, $E[Y]$, is the average number of leading right-turning vehicles arriving before a through vehicle. On a per cycle basis, it is expressed:

$$E[Y] = r\left(\frac{1-p}{p}\right) = \frac{1-p}{p}$$

where p is the proportion of through vehicles in the shared lane. Thus, the term $(1-p)/p$ becomes an important parameter in estimating the number of RTORs and corresponding incremental capacity for the condition where there is a shared lane on an intersection approach.

Study Sites

Field data from actual study sites were collected for the purpose of validating the RTOR volume and incremental capacity estimation models. The study locations were:

- Part of actual traffic studies conducted in various urban areas in Kentucky; and
- Signalized intersections that contained a shared through/right-turn lane on the subject approach.

A list of study sites, including the metropolitan area, size, and characteristics of the intersecting streets is provided in **Table IV.1**.

Table IV.1. List of Study Sites

Site No.	Urban Area	2008 Population*	Major Street Name	Major Street Functional Class	Major Street ADT**	Cross Street Name	Cross Street Functional Class	Cross Street ADT**
1	Lexington	282,114	Man o' War Blvd.	Minor Arterial	41,600	Todds Rd.	Minor Arterial	11,000
2	Lexington	282,114	S. Limestone (US 27)	Principal Arterial	39,000	Cooper Dr./Waller Ave.	Minor Arterial	16,000
3	Georgetown	21,589	Cincinnati Rd. (US 25)	Minor Arterial	7,500	Champion Way (KY 32)	Collector	7,000
4	Shelbyville	11,294	Frankfort Rd. (US 60)	Principal Arterial	15,000	Mt. Eden Rd. (KY 53)	Principal Arterial	6,300
5	Owensboro	55,516	Frederica St. (US 431)	Principal Arterial	17,500	9th Street	Collector	8,200

* Source: Kentucky State Data Center
** ADT - Average Daily Traffic; Source: Kentucky Transportation Cabinet

At each location, peak period intersecting turning movement counts were collected for each approach on a "typical" weekday (where a "typical" weekday was considered to be a Tuesday, Wednesday or Thursday when schools were in session and there were no known incidents or special events that affected normal traffic patterns). The counts were collected in 15-minute intervals and are summarized in **Table IV.2**. Additionally, for the subject approach at each intersection where there was a shared through/right-turn lane, observed RTOR maneuvers were recorded.

Traffic signal timing plans for each of the locations were obtained from the Kentucky Transportation Cabinet. The plans were input into traffic simulation models that were developed to validate the RTOR volume estimation model and were input into the HCM computations that were used to validate the RTOR incremental capacity estimation model.

The HCM establishes 15 minutes as the fundamental analysis period length. This is based on the assumption that traffic demand flow rates remain relatively constant over a 15-minute period during peak traffic conditions. For this research, based on the field data that were collected, there were a total of 28 15-minute intervals during which observed RTOR volumes were deemed significant for use in model validation.

Schematic diagrams for each of the study sites are located in the Appendix. Each of the diagrams includes the approach lane configurations, lane use, and signal phasing schemes.

Table IV.2. 15-Minute Traffic Count Summary

				Southbound				Westbound				Northbound				Eastbound			
Site	Location	Period	Start	LT	TH	RT_{Total}	RTOR	LT	TH	RT_{Total}	RTOR	LT	TH	RT_{Total}	RTOR	LT	TH	RT_{Total}	RTOR
1	Man o' War at Todds Road	AM	7:30	32	17	5	1	8	279	42	12	160	82	51	5	8	260	11	2
1	Man o' War at Todds Road	AM	7:45	51	21	4	1	18	322	58	11	147	81	40	2	9	305	22	0
1	Man o' War at Todds Road	AM	8:00	50	36	5	1	13	318	36	15	100	58	37	1	8	267	12	4
1	Man o' War at Todds Road	PM	16:45	59	50	50	0	60	356	76	18	41	27	34	13	20	421	77	25
1	Man o' War at Todds Road	PM	17:00	72	61	64	3	52	374	57	24	50	40	21	2	19	369	99	37
1	Man o' War at Todds Road	PM	17:15	62	53	53	0	59	346	63	16	53	38	22	4	14	433	97	28
1	Man o' War at Todds Road	PM	17:30	64	50	50	0	78	383	79	23	55	25	23	2	26	431	93	25
1	Man o' War at Todds Road	PM	17:45	67	64	64	0	71	306	61	21	64	31	37	3	14	332	93	21
2	S. Limestone at Cooper/Waller	AM	7:15	23	91	6	5	27	42	49	30	14	396	108	17	36	87	16	4
2	S. Limestone at Cooper/Waller	AM	7:30	46	118	21	17	49	54	55	30	17	400	112	17	37	89	17	1
2	S. Limestone at Cooper/Waller	AM	7:45	48	122	17	8	37	54	72	32	29	455	102	24	42	77	22	4
2	S. Limestone at Cooper/Waller	AM	8:00	27	101	26	18	33	70	53	31	28	368	85	17	34	67	13	4
3	US 25 at Champion Way	AM	8:15	31	53	15	4	14	65	46	1	40	30	10	0	33	56	11	0
3	US 25 at Champion Way	PM	15:30	13	69	9	9	19	79	66	0	49	65	18	3	13	38	16	2
3	US 25 at Champion Way	PM	16:00	17	69	9	3	21	46	35	0	21	90	20	1	12	39	17	0
3	US 25 at Champion Way	PM	16:15	13	78	10	4	14	42	33	1	40	111	13	5	4	34	29	2
3	US 25 at Champion Way	PM	16:30	15	62	12	3	16	71	43	2	43	137	20	1	12	50	41	0
4	US 60 at KY 55/KY 53	AM	8:00	23	70	41	26	53	79	35	1	42	57	72	21	55	89	28	12
4	US 60 at KY 55/KY 54	AM	8:15	15	68	40	24	43	114	31	2	53	73	35	16	52	66	23	14
4	US 60 at KY 55/KY 55	AM	8:30	17	75	45	25	50	91	32	4	41	48	23	12	33	71	29	22
4	US 60 at KY 55/KY 56	PM	17:00	32	92	30	20	58	117	44	5	51	115	52	28	69	104	81	47
4	US 60 at KY 55/KY 57	PM	17:15	39	94	28	21	31	85	42	11	57	116	49	26	72	103	62	40
4	US 60 at KY 55/KY 58	PM	17:30	35	72	48	22	39	96	29	1	48	114	33	12	56	105	46	31
5	US 431 at 9th Street	AM	7:00	1	43	7	1	8	29	3	1	5	66	12	2	3	28	8	4
5	US 431 at 9th Street	AM	7:15	5	52	5	1	12	41	5	2	8	69	17	2	11	44	12	5
5	US 431 at 9th Street	AM	8:00	12	108	2	0	13	49	10	5	18	121	15	0	11	43	19	3
5	US 431 at 9th Street	AM	8:15	11	87	6	0	13	33	12	9	11	100	17	0	10	41	18	5
5	US 431 at 9th Street	PM	16:45	11	134	5	1	17	66	14	9	11	92	9	2	9	65	20	6

KEY

LT - Left Turn
TH - Through
RT_{Total} - Total Right Turns
RTOR - Right Turns on Red

Subject Approach

RTOR Volume Estimation Model

Fundamental to the development of a RTOR Volume Estimation Model that can be applied for shared lane approaches is the incorporation of the probabilistic nature of this event due to blocking through vehicles and how this event can vary from one signal cycle to the next. However, in order to develop a deterministic model that is consistent with the Signalized Intersection method in the HCM, the model must consider the *average* number of RTORs that would be expected to occur from a shared lane during the analysis period, based on the proportions of through and right-turning vehicles. The model also must consider the ratio of demand to capacity for the shared lane on the subject approach so that it does not over-predict the number of RTORs that actually occur.

For all of the study sites, vehicle arrivals on the subject approaches occurred randomly; that is, they were not influenced by platooning or bunching of vehicles resulting from closely-spaced upstream intersections. Although actual RTOR volumes for these subject approaches were included in the traffic counts that were collected, it was decided that computer simulation would be used to determine the average number of "observed' RTORs during each analysis period and that the field counts would be used as a "check." Use of computer simulation would allow for this randomness to be extended beyond the analysis period for which each of the counts were made, thus simulating the randomness that actually occurs from one day to the next.

The Traffic Software Integrated System (TSIS) CORridor SIMulation (CORSIM) computer program was used to simulate intersection operations at the study locations for each of the analysis periods. Individual CORSIM models were created for each analysis period at each location, incorporating observed approach demand volumes, lane use, and signal timing parameters. CORSIM also simulates the randomness that occurs under actuated signal control, where signal phases vary in length based on the variability in vehicle arrivals.

The CORSIM software includes a series of random number seeds that vary from one run to the next in order to account for randomness in entry headways (i.e., arrival times from one vehicle to the next), driver and vehicle characteristics, and driver acceptance of available gaps in the conflicting traffic streams. Thus, through the use of simulation, the cycle-to-cycle and day-to-day variance that actually occurs was accounted for more fully in estimating the average number of RTORs from shared lanes that could be anticipated given a particular set of demand parameters.

For each study site, 10 runs of the CORSIM model were made and, for each run, the random number seeds were varied. Ten was selected as the number of simulation runs to be performed for each scenario based on guidance provided within the CORSIM user community. While increasing the number of runs beyond 10 would have provided increased accuracy in estimating the average number of RTORs per 15-minute analysis period, guidance provided on the application of the software advises that the mean for discrete variables such as the number of RTORs is usually constrained within 7 to 10 runs [18]. Supporting this guidance, when the Multiple Run option for the program is selected, the default number of runs is 10. It was determined that 10 CORSIM runs would be sufficient the purpose of validating the RTOR Volume Estimation Model.

The TRAFVU visualization utility then was used and the number of observed RTORs was counted. The average number of observed RTORs was then compared to the predicted value obtained from the deterministic model that was developed.

The development of the RTOR Volume Estimation Model, comparison of predicted to observed volumes, conclusions, and limitations of the model are discussed in the subsequent Chapter V.

<u>RTOR Incremental Capacity Model</u>

This part of the research was focused on the incremental capacity that is realized when RTORs are allowed, specifically, for approaches that contain shared through/right-turn lanes. In other words, it does not attempt to invalidate the HCM method for computing approach capacity during the green portion of the cycle, but instead accounts for the incremental capacity that is realized when RTORs can be made.

For a subject approach where RTORs are permitted, the total capacity consists of three components, as presented:

$$c = c_1 + P_{RTOR}(c_2 + c_3)$$

where

c	=	Total approach capacity (veh/h), where the approach contains a shared through/right-turn lane;
c_1	=	Approach capacity (veh/h) during the green signal phase
c_2	=	Approach capacity (veh/h) during which conflicting movements (intersecting through from the left) and opposing left turns receive an exclusive green signal display;
c_3	=	Approach capacity (veh/h) during which shadowed left turns from the right receive an exclusive green signal display; and
P_{RTOR}	=	The probability that a RTOR movement will occur from the shared lane, assuming that there are available gaps in the conflicting traffic streams.

The term P_{RTOR} is computed as follows:

$$P_{RTOR} = \frac{\frac{(1-p)}{p} \cdot \frac{3600}{C}}{Vol_{SharedLane}}$$

where

p	=	The proportion of through vehicles to the total approach volume in the shared lane, expressed in vehicles per hour;
C	=	Average cycle length, in seconds; and
$Vol_{SharedLane}$	=	Total approach volume in the shared lane, in vehicles per hour.

The c_1 component of the capacity model is the same as that used in the current HCM Signalized Intersection method. The c_2 component applies the same principles used in the current HCM Unsignalized Intersection method for two-way STOP-controlled (TWSC) approaches, under the assumption that drivers performing the RTOR maneuver behave in a similar manner as drivers at a STOP-controlled approach entering the intersection from a minor street, when acceptable gaps in the conflicting traffic streams exist. For the Unsignalized Intersection method, drivers on the STOP-controlled approach can perform left-turn, through and right-turn movements when available gaps exist in conflicting traffic streams. For the purpose of this research, only the right-turn-on-red movement is considered.

The c_3 component also is based on the HCM Unsignalized Intersection method, but the capacity during this regime is based on the time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same gap under a condition of continuous queuing. During this regime, there is one continuous "gap" that equals the duration of the protected, shadowed left turn phase. This time is known as the follow-up time.

The c_2 and c_3 components of the capacity model for shared lane approaches are affected by the proportion of through and right-turning vehicles; that is, the higher the proportion of right-turning vehicles, the greater the probability that RTORs will occur and the higher the incremental capacity that can be achieved when RTORs are permitted. The term P_{RTOR} accounts for this probability.

The development of the RTOR Incremental Capacity Model, the computation of total capacity for the study site subject approaches, comparison with HCM-predicted capacities when RTORs are excluded (as they are handled in the current HCM method), and limitations of the model, are presented in Chapter VI.

V. RTOR VOLUME ESTIMATION MODEL

The current Signalized Intersection method chapter of the Highway Capacity Manual advises the analyst that, where right turns on red are permitted, the approach demand volumes may be reduced by the number of right-turning vehicles moving on the red phase. The HCM directs that RTOR vehicles should be determined by field observation at existing intersections. Often the analyst does not have this information; either RTOR movements were not observed during data collection or the analysis is being performed for a future or hypothetical scenario where the data do not exist. In such cases, this parameter must be estimated.

The HCM provides some guidance on estimating RTOR volumes. If no field data exist, the HCM advises that it is not preferable to reduce for RTOR except when an exclusive right-turn movement runs concurrent with the protected left-turn phase from the adjacent cross-street, at which point the right-turn volume can be reduced by the number of "shadowed" left turners. However, this guidance does not take into account that RTORs can and do occur during intersecting through and opposing left-turn phases of the cycle. The guidance also accounts for the degree of saturation of the shadowed left-turn phase only indirectly under the presumption that the volume of shadowed left turns is proportional to the demand-to-capacity ratio for this movement. Depending on signal timing parameters (pre-timed vs. actuated control, phase duration, clearance intervals and lost time), the volume of RTORs that could occur during the shadowed left-turn phase may be significantly different than the shadowed left-turn volume.

The HCM provides no guidance on estimating RTOR volumes for shared lanes. Instead, it merely groups exclusive right-turn lanes and shared lanes together and it is left up to the analyst to determine how to address the case where there is a shared lane. As was stated previously, RTOR volumes from a shared lane can be significant when the proportion of right-turning vehicles to through vehicles is high. It can be argued that the current HCM method discourages the analyst from considering RTORs altogether where actual field data do not exist, which ultimately leads to an underestimation of capacity and a resulting incorrect computation of delay.

It is desirable to have a deterministic model for estimating RTORs that is consistent with the overall HCM Signalized Intersection method, that is easily understood by analysts, that produces reasonable results, and that accounts for the probabilistic nature of RTORs occurring from shared lane approaches. Furthermore, the method should be adaptable so that it can be applied for exclusive right-turn lane approaches as well.

As discussed in Chapter IV. Methodology, for the case where there is a shared through/right-turn lane, the interest lies in identifying the number of RTOR vehicles that pass the STOP bar before the first through or blocking vehicle arrives. Statistically, if a through vehicle arriving at the STOP bar is considered as a "success," then there are two possible binary outcomes:

- 1 = Through or Blocking Vehicle = "Success"
- 0 = RTOR Vehicle = "Failure"

In order to predict the number of RTOR movements, *Y*, that will occur during the red signal phase, the objective is to identify the number of "failures" (i.e., RTORs) that can occur before the arrival of the first through or blocking ("success") vehicle. Statistically, this relationship takes the form of a Negative Binomial Distribution having the general form

$$P(Y = y) = \binom{y + r - 1}{r - 1} p^r (1 - p)^y$$

where

y	=	The number of RTORs that are observed during a given red signal phase (y = 0, 1, 2, ...)
r	=	The number of through vehicles required to block the shared lane and prevent further RTORs during the given red signal phase. For $r = 0$, a vehicle is able to make the RTOR maneuver. For $r = 1$, one through vehicle in the shared lane blocks a subsequent RTOR vehicle.
p	=	The proportion of through vehicles to total vehicles in the shared lane.

In case of a shared through/right-turn lane where there is no shoulder for which right-turning vehicles can bypass a stopped through vehicle, it only takes one through vehicle to block a potential RTOR maneuver. This represents a Geometric Distribution, which is a Negative Binomial Distribution with $r = 1$. For a Geometric Distribution, the Expected Value, *E[Y]*, is the average number of leading right-turning vehicles arriving before a through vehicle. On a per cycle basis, it is expressed:

$$E[Y] = r\left(\frac{1-p}{p}\right) = \frac{1-p}{p}$$

where *p* is the proportion of through vehicles in the shared lane. Thus, the average number of vehicles per cycle that can be expected to turn right on red, assuming that available RTOR opportunities exist, is *(1-p)/p*.

As discussed in Chapter IV, RTORs can occur during one of three regimes. These regimes also include start-up and clearance lost times for their respective phases; that is, the portion of the signal change and clearance intervals (yellow and all-red) that are not used for vehicular movement at saturation flow. Observation of RTOR maneuvers at intersections revealed that RTOR drivers do indeed utilize lost times from other phases as part of acceptable gaps into which RTOR maneuvers can be made. In the HCM, start-up lost time is designated as l_1 and clearance lost time is designated as l_2. The total lost time, L, is defined as the sum of clearance lost times plus start-up lost times. The HCM advises the analyst to measure lost times in the field; however, in the absence of field data, default values of 2.0 seconds each for both l_1 and l_2 per phase are suggested.

For shared lanes, the *average* number of RTORs that can be expected per cycle can be estimated by the term $(1-p)/p$, where p is the proportion of through vehicles in the shared lane. As the HCM Signalized Intersection methodology deals in hourly flow rates, this parameter must be converted to an hourly flow by multiplying it by the term 3600/C, where:

- 3600 is the number of seconds per hour; and
- C equals the average cycle length in seconds

The number of RTOR vehicles per hour that would be expected to occur from a shared lane, assuming a continuous demand on the subject approach and assuming available gaps in the conflicting traffic streams, can be expressed as:

$$\left(\frac{1-p}{p}\right)\cdot\frac{3600}{C}$$

It is important to note the significance of the parameter C and how it can affect the estimation of RTORs. Under pre-timed signal control, all phase durations are the same for each cycle and the cycle length does not vary. Similarly, under actuated-coordinated control, the cycle length remains constant, although individual phase durations may vary in response to variable demands for green time during these phases.

Under actuated-isolated control, where the signal is not part of a coordinated system, the cycle length may vary (and usually does unless all approaches are “saturated” and the maximum green interval is realized for all phases). In this case, it is important to estimate the average cycle length that would approximate an equivalent pre-timed cycle length during the analysis period.

The HCM Signalized Intersection method includes a procedure for estimating timing plans for traffic-actuated control. This is an iterative process that incorporates approach-specific data such as how left turns are treated (exclusive, permitted, or exclusive + permitted), turn bays lengths, and approach speed. The method also incorporates phase-specific data such as minimum and maximum green times, passage (the incremental time extension added to the minimum green duration for subsequent actuations), and phasing schemes. For this research, the HCM method was used to estimate the average cycle length, *C*, for those locations where the signal operated under actuated-isolated control.

As stated previously, the average of RTORs per hour can be expressed by *(1-p)/p* times 3600/*C*, assuming a continuous demand on the subject approach. For the case where the demand is not continuous over the analysis period (i.e., the approach is not saturated), this must be taken into consideration or else the result will be an over-estimation of RTOR volumes. An adjustment must be made that accounts for the potential under-saturation of the approach demand.

A simple deterministic model was developed that estimates the number of RTORs per hour that can be expected for a shared through/right-turn lane. The model incorporates the proportion of through and right-turning vehicles in a shared lane, the degree of saturation on the subject approach, and the average cycle length during the analysis period. The RTOR Volume Estimation Model is expressed as:

$$No._{RTOR} = Min(X_r, 1.0) \cdot \left(\frac{1-p}{p} \right) \cdot \frac{3600}{C}$$

where

$No._{RTOR}$	=	The expected number of RTORs expressed as an hourly flow rate for the analysis period
X_r	=	The demand volume-to-capacity ratio for the shared lane subject approach
p	=	The proportion of through vehicles to the total approach volume in the shared lane, expressed in vehicles per hour
C	=	Average cycle length (in seconds) during the analysis period

The term $Min(X_r, 1.0)$ limits the shared lane demand volume-to-capacity ratio to 1.0. For cases where this parameter exceeds 1.0, the demand volume is greater than the capacity during the analysis period and the incremental demand that exceeds capacity is served during the subsequent period(s).

The Traffic Software Integrated System (TSIS) CORridor SIMulation (CORSIM) computer program was used to simulate intersection operations at the study locations. Individual CORSIM models were created for each study location for each of the analysis periods, incorporating geometric and operational parameters along with observed demand volumes. For each analysis period, 10 model runs were performed for which random number seeds were varied in order to simulate the day-to-day variability that occurs. Modeled intersection operations were then "observed" using the TRAFVU visualization utility and the number of RTORs on the subject approaches was counted. The mean RTOR volume was computed for each analysis period at each site and the mean was compared to the estimated RTOR volume that was computed using the deterministic model.

The results of the estimated RTOR volumes from the deterministic model as compared with the mean RTOR observed volumes from the simulation runs are summarized in **Table V.1**. For the 15-minute analysis periods at the five study sites (of which there were 28 total data points), the comparison between estimated and observed RTOR volumes for the subject shared lane approaches is shown in **Table V.2**.

Table V.1. RTOR Volume Estimation Model Results

		Start	Ave. Cycle		Subject Approach		Right Turns on Red (RTORs)					Confidence Interval[7]	
Site	Period	Time	Length, C (sec)	(1-p)/p	Dir	X_r[1]	Estimated[2]	Observed[3]	Obs_{StdDev}[4]	Δ[5]	Count[6]	Lower	Upper
1	AM	7:30	150	0.622	NB	1.66	3.7	4.0	1.76	0.3	5	2.1	5.9
1	AM	7:45	150	0.494	NB	1.50	3.0	2.9	2.13	0.1	2	0.6	5.2
1	AM	8:00	150	0.638	NB	1.19	3.8	4.3	2.11	0.5	1	2.0	6.6
1	PM	16:45	160	1.259	NB	1.16	7.1	6.2	4.29	0.9	13	1.6	10.8
1	PM	17:00	160	0.525	NB	1.12	3.0	2.7	2.16	0.3	2	0.4	5.0
1	PM	17:15	160	0.579	NB	1.11	3.3	3.9	3.00	0.6	4	0.7	7.1
1	PM	17:30	160	0.920	NB	0.90	4.7	3.6	1.96	1.1	2	1.5	5.7
1	PM	17:45	160	1.194	NB	1.29	6.7	7.4	3.37	0.7	3	3.7	11.1
2	AM	7:15	180	0.451	EB	0.80	1.8	2.0	2.21	0.2	4	0.0	4.4
2	AM	7:30	180	0.472	EB	0.81	1.9	2.0	1.76	0.1	1	0.1	3.9
2	AM	7:45	180	0.800	EB	0.79	3.2	2.6	1.96	0.6	4	0.5	4.7
2	AM	8:00	180	0.481	EB	0.74	1.8	1.8	1.62	0.0	4	0.0	3.6
3	AM	8:15	56	0.283	SB	0.43	2.0	4.0	1.63	2.0	4	2.2	5.8
3	PM	15:30	69	0.130	SB	0.45	0.8	1.5	1.08	0.7	9	0.3	2.7
3	PM	16:00	47	0.130	SB	0.41	1.0	1.7	1.25	0.7	3	0.3	3.1
3	PM	16:15	44	0.128	SB	0.45	1.2	1.2	1.03	0.0	4	0.1	2.3
3	PM	16:30	72	0.194	SB	0.36	0.9	2.2	0.92	1.3	3	1.2	3.2
4	AM	8:00	114	1.062	WB	0.39	3.3	5.3	1.42	2.0	1	3.8	6.8
4	AM	8:15	116	0.645	WB	0.49	2.5	3.5	2.51	1.0	2	0.8	6.2
4	AM	8:30	112	0.776	WB	0.36	2.2	4.5	2.42	2.3	4	1.9	7.1
4	PM	17:00	132	1.101	WB	0.62	4.7	6.0	3.40	1.3	5	2.3	9.7
4	PM	17:15	137	1.421	WB	0.51	6.6	4.1	2.01	2.5	11	1.9	6.3
4	PM	17:30	119	0.776	WB	0.43	2.5	3.0	2.31	0.5	1	0.5	5.5
5	AM	7:00	54.1	0.286	EB	0.50	2.4	3.4	1.35	1.0	4	1.9	4.9
5	AM	7:15	57	0.273	EB	0.57	2.5	3.2	1.62	0.7	5	1.4	5.0
5	AM	8:00	58	0.442	EB	0.58	4.0	4.7	1.64	0.7	3	2.9	6.5
5	AM	8:15	57.5	0.439	EB	0.58	4.0	4.8	1.40	0.8	5	3.3	6.3
5	PM	16:45	61.5	0.308	EB	0.64	2.9	3.7	1.89	0.8	6	1.7	5.7

Footnotes

[1] Demand-to-capacity ratio, X, for the subject approach

[2] Estimated number of RTORs for 15-minute analysis period using RTOR Volume Prediction Model

[3] Mean RTORs observed from simulation during 15-minute analysis period

[4] Standard deviation of RTORs observed from simulation during 15-minute analysis period

[5] Absolute value of difference (Δ) between Estimated RTORs and Observed RTORs

[6] RTORs from field traffic counts during 15-minute analysis period

[7] Confidence interval using *t*-statistic at α = 0.01 and n-1 degrees of freedom

Table V.2. Difference Between Estimated and Observed RTOR Volumes

Difference* Between Estimated & Observed RTOR Volumes (Δ vehicles)	No. of Analysis Periods**
$\Delta \leq 1.0$	21
$1.0 < \Delta \leq 2.0$	5
$2.0 < \Delta \leq 3.0$	2
Total	28

* *Absolute value*
** *15-minute analysis period*

One other test was performed to compare the reasonableness of the estimation model with the actual traffic count data. From the simulation results, confidence intervals were constructed using the mean observed value (from the simulation), standard deviation, and *t*-statistic. The confidence intervals were constructed using a 99 percent level of confidence and nine (i.e., n -1) degrees of freedom.

It is recognized that, for a given analysis period, the actual number of RTORs on a subject approach that would be counted will vary from one "typical" day to the next due to the variability in arrivals, distribution of available gaps in the conflicting traffic streams, and variability of driver types (i.e., aggressiveness) in accepting gaps. Where the counted number of RTORs fits within the computed confidence interval, it can be concluded that the RTOR Volume Estimation Model reflects the day-to-day variation in driver behavior and traffic parameters within a 99 percent level of confidence.

Of the 28 data points, the counted number of RTORs fit within the computed confidence interval 18 times. However, while confidence interval limits are computed as continuous values, the actual counted RTOR volumes are discrete values. If the confidence interval limits are rounded to the nearest integer to reflect the discrete nature of the counts, then three additional data points would fit within the confidence intervals. Given the likelihood that counting errors in field data may exist, it can be concluded that the RTOR Volume Estimation Model does a reasonable job in accounting for the day-to-day variability that exists when compared to actual field traffic counts.

The RTOR Volume Estimation Model is an analytical model. The CORSIM software was used to validate the model by comparing "observed" RTORs in simulation with predicted RTORs using the model. The simulations were not hypothetical examples but instead were based on actual traffic and operational data at five locations across Kentucky. To support the use of simulation in validating the analytical model, confidence intervals for the simulated RTORs were constructed in order to account for the daily variation that occurs in the field. For the subject approaches containing a shared lane, the number of RTORs that were recorded in the field on the day that the counts were collected fit within the computed confidence interval 75 percent of the time, indicating that simulation was a reasonable alternative (to collecting field data on multiple days) for use in validating the analytical model. The relationship among the analytical model, simulation and field traffic count data is expressed conceptually in **Figure V.1**.

Figure V.1. Relationship Among RTOR Volume Estimation Model, Simulation and Field Traffic Counts

Assumptions and Limitations

The model developed is a theoretical models based on methods employed in the HCM. The intent was to develop a model that is consistent with HCM technique that can be integrated into future revisions to the Signalized Intersection Methodology. The RTOR Volume Estimation Model included limited validation through the use of simulation and comparison with actual field data for a total of 28 analysis periods at five study sites. The model that was developed is subject to the following assumptions and limitations:

1. When the intersecting approach contains two or more through lanes, it is assumed that only vehicles in the outside (curb) lane will conflict with potential RTOR movements from the subject approach. It is assumed that vehicles in the non-curb lane(s) on the intersecting approach do not conflict with subject RTOR movements.

2. When the opposing left-turn approach contains two or more lanes, it is assumed that only vehicles in the right-most (outside) left-turn lane will conflict with potential subject approach RTOR movements.

3. The model developed from this research does not include potential limiting effects of pedestrian crossings on the subject approach, as there was no pedestrian activity at the study sites from which the inhibiting effects could be quantified. Furthermore, little previous research has been done to address this issue, as was discovered in the literature review.

4. The model does not address bicycles as part of the traffic streams on either the subject approach or one of the conflicting approaches.

5. The model developed assumes random arrivals on all approaches. Mathematically, the negative exponential distribution is used to represent the distribution of random arrivals such as vehicle headways [17]. Headway is defined to be the time, in seconds, between two successive vehicles as they pass a point on a roadway, measured form the same common feature such as the front axle or bumper [5]. It is commonly accepted that vehicles generally do not travel at a constant headway unless intersection spacing and/or signal coordination result in compact platoons [18]. For those study locations that were part of coordinated signal systems (Sites 1 and 2), it was determined that the subject intersections were located far enough downstream such that vehicle platoons were dispersed to the point that arrivals were random. CORSIM models created to simulate traffic conditions at field study sites were set to model arrival headways using a negative binomial distribution. Departure distributions for RTORs were assumed to be constant (on the basis that adequate gaps in the conflicting traffic streams were present), with the average departure headway equal to the follow-up time, t_f.

6. The model was developed based on exclusive conflicting signal phases – intersecting through movements, opposing left turns and shadowed left turns. Combined protected/permitted left turn phases were not addressed specifically as part of this research.

7. The model assumes that there is adequate sight distance between drivers at the STOP bar on the subject approach and approaching vehicles in the intersecting traffic stream, such that RTOR drivers can clearly identify the size and distribution of gaps in the intersecting traffic stream.

8. The model assumes that there is no room on the shoulder for right-turning vehicles to bypass blocking through vehicles.

Adaptation for Exclusive Right-Turn Lanes

The RTOR Volume Estimation Model accounts for the probabilistic nature of blocking RTORs by though vehicles in a shared lane through the inclusion of the term *(1-p)/p* (where *p* is the proportion of through vehicles in a shared lane) as a multiplicative term. When the subject approach contains an exclusive right-turn lane instead of a shared lane, this blocking effect is removed. This research was focused on the specific case where a shared through/right-turn lane exists. However, ideally, the model should be adaptable to approaches with exclusive right-turn lanes. An adaptation of the RTOR Volume Estimation Model for exclusive right-turn lanes is offered as follows:

$$No._{RTOR} = Min(X_r, 1.0) \cdot \left[1 - \left(\frac{g_r}{C} + Min(X_c, 1.0) \cdot \frac{g_c}{C}\right)\right] \cdot \frac{3600}{C}$$

where

$No._{RTOR}$	=	The expected number of RTORs expressed as an hourly flow rate for the analysis period
X_r	=	The demand volume-to-capacity ratio for the subject approach
g_r	=	The effective green time for the subject approach
X_c	=	The demand volume-to-capacity ratio for the conflicting approach(es), including both the intersecting approach from the left and the opposing left turn approach
g_c	=	The effective green time for the conflicting approach(es)
C	=	Average cycle length (in seconds) during the analysis period

When the conflicting movements contain exclusive intersecting and opposing left turn phases, the term $Min(X_c, 1.0) \cdot \frac{g_c}{C}$ is expanded to $Min(X_i, 1.0) \cdot \frac{g_i}{C} + Min(X_o, 1.0) \cdot \frac{g_o}{C}$ to address the separate conflicting (Intersecting, i and Opposing, o) phases. The demand volume-to-capacity ratio, X, is limited to saturation (i.e., $X = 1.0$). In other words, when a conflicting phase is saturated, the green time for that phase is fully utilized by the conflicting movement and there is no unused green time that could be used for RTORs from the subject approach during the phase.

Thus, for an exclusive right-turn approach, the term *(1-p)/p* is replaced by the term [1-$Min(X_c, 1.0) \cdot \frac{g_c}{C}$]. On a per cycle basis, the number of RTORs that can be expected is a function of the available green time during the unutilized portion of the conflicting (intersecting plus opposing left turn) phases and the demand-to-capacity ratio, X_r, for the subject approach. This alternative RTOR Volume Estimation Model is offered, but was not validated as part of this research.

VI. RTOR INCREMENTAL CAPACITY MODEL

The Highway Capacity Manual Signalized Intersection methodology ignores that portion of the cycle during which RTORs may occur; that is, during the three RTOR regimes - ① Intersecting, ② Opposing Left Turns, and ③ Shadowed Left Turns (refer to Figure IV.1 in Chapter IV). For a given lane group *i*, HCM-based capacity is computed as:

$$c_i = s_i \frac{g_i}{C}$$

where

c_i = capacity of lane group *i* (in vehicles per hour)
s_i = saturation flow rate of lane group *i* (in vehicles per hour)
g_i/C = effective green ratio ("green-to-cycle length ratio") for lane group *i*

Thus, in the current method, capacity is a function of the adjusted saturation flow rate for the subject approach and the proportion of available green time to the total cycle length allocated to serving the lane group demand. This research demonstrates that additional, incremental capacity is realized during the RTOR regimes of the cycle and that this incremental capacity should be added to the capacity for the green portion of the cycle, assuming that RTORs are permitted and that available gaps in the conflicting traffic streams exist.

For a subject approach where RTORs are permitted, the RTOR Incremental Capacity Model is expressed as follows:

$$c = c_1 + P_{RTOR}(c_2 + c_3)$$

where

c = Total approach capacity (veh/h), where the approach contains a shared through/right-turn lane;
c_1 = Approach capacity (veh/h) during the green signal phase
c_2 = Approach capacity (veh/h) during which conflicting movements (intersecting through from the left) and opposing left turns receive an exclusive green signal display (Regimes ① and ②);
c_3 = Approach capacity (veh/h) during which shadowed left turns from the right receive an exclusive green signal display (Regime ③); and

P_{RTOR}	=	The probability that a RTOR movement will occur from the shared lane, assuming that there are available gaps in the conflicting traffic streams.

The model as presented applies to approaches containing a shared through/right-turn lane, but also can be adapted to the case where an exclusive right-turn exists.

The c_1 component is the same as the capacity computation used in the current HCM method. However, RTORs are not subtracted from the demand volume as they are with the HCM method. The adjusted saturation flow rate includes a factor to adjust for right turns, including those made from a shared lane.

The c_2 component applies the same principles used in the current HCM Unsignalized Intersection method for two-way STOP-controlled approaches, assuming that drivers performing the RTOR maneuver behave in a manner similar to drivers at a STOP-controlled approach entering the intersection from a minor street, when acceptable gaps in the conflicting traffic stream exist. The difference is that RTOR maneuvers at a signalized intersection can occur only during the portion of the cycle when the subject approach receives a red signal display and there are conflicting (i.e., intersecting and opposing left turn) traffic flows that have right-of-way. These occur during Regimes ① and ②.

The c_2 term of the capacity model is expressed as follows:

$$c_2 = V_C \cdot \frac{e^{\frac{-Vc \cdot tc}{3600}}}{1 - e^{\frac{-Vc \cdot tf}{3600}}} \cdot \frac{g_c - g_q}{C}$$

where

c_2	=	Capacity during the conflicting flow (intersecting plus opposing left turns) portion of the cycle (in vehicles per hour), where opposing left turns receive an exclusive signal display
V_c	=	Conflicting (intersecting plus opposing left turn) flow rate (in vehicles per hour)
t_c	=	Critical gap (in seconds), which is defined in the HCM to be the minimum time interval in the conflicting traffic stream(s) that allows intersection entry for one minor-street vehicle
t_f	=	Follow-up time (in seconds), which is defined as the departure time for one vehicle from the minor street (i.e. RTOR lane group) and the departure of the next RTOR vehicle using the same gap in the

conflicting traffic stream, under a condition of continuous queuing on the RTOR approach

g_c = Effective green time (in seconds) for the conflicting traffic movement

g_q = Portion of the effective green for a conflicting movement (intersecting or opposing left turns) that is blocked by the clearance of a conflicting queue of vehicles

C = Average cycle length (in seconds)

The c_2 term is based upon the model used to estimate potential capacity for minor-street movements at two-way stop-controlled intersections in the HCM. This is a gap acceptance method that estimates potential capacity as a function of the flow rate for a conflicting movement, V_c, the critical gap, t_c, and the follow-up time, t_f. It is hypothesized that drivers performing RTOR maneuvers exhibit the same characteristics as those entering an intersection from minor-street approaches at two-way stop-controlled intersections.

Tarko [9] included the potential capacity term from the HCM in his research, but he modified it to include a multiplicative term, C/f, to account for flow compression caused by traffic signals. He also did not account for the queue clearance time, g_q, that reduces the available portion of the conflicting phase during which RTORs can be made due to vehicles initially queued at the onset of the phase. Finally, Tarko considered only the intersecting flow from the left as conflicting flow; he did not include opposing left turns in the quantification of conflicting flow and the estimation of RTOR capacity.

The c_2 term developed as part of this research has three components. The term V_c is the conflicting flow rate. The term $(g - g_q)/C$ adjusts the portion of the cycle during which RTORs can be made by subtracting the time that it takes to dissipate an initial queue in the conflicting traffic stream at the onset of green. The middle term estimates the number of vehicles that can be expected to perform the RTOR maneuver per hour, based on the critical gap size and the follow-up time, given the rate of conflicting flow. The c_2 term is computed separately for intersecting and opposing left-turn flows that receive an exclusive signal phase, then these capacities are combined.

The term g_q adjusts for the dissipation of an initial queue in the intersecting and opposing left-turn traffic streams at the onset of the green displays. This is illustrated in **Figure VI.1**. As these movements have right-of-way at the onset of green during Regimes ② and ③, the portion of the conflicting green phases during which RTORs can be made is reduced by the time it takes to clear the initial queue.

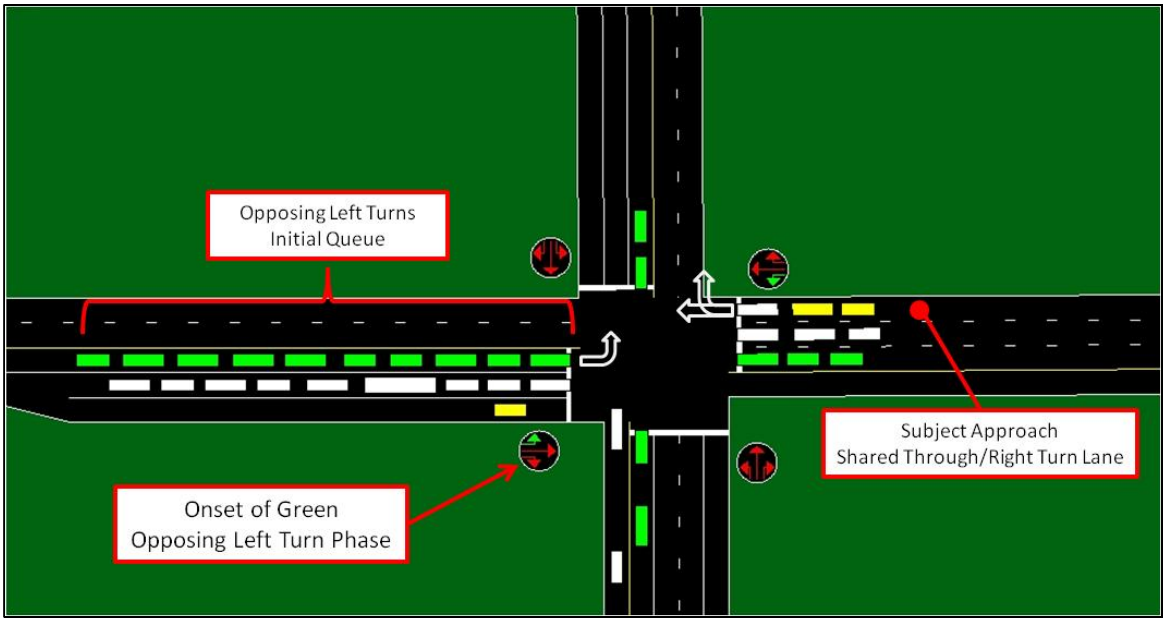


Figure VI.1. Conflicting Flow (Opposing Left Turn) Initial Queue

Fundamental to the estimation of g_q is the assumption that drivers desiring to perform a RTOR maneuver behave in a manner similar to drivers performing a permitted left turn into gaps into an opposing through traffic stream. The same model used in the HCM to account for queue clearance time for opposing through vehicles is used for the RTOR movement:

$$g_q = \frac{V_{c/c} \cdot qr_c}{0.5 - \frac{V_{c/c}(1 - qr_c)}{g_c}} - t_L$$

where

g_q	=	Portion of the effective green that is blocked by the clearance of a conflicting queue of vehicles (in seconds)
$V_{c/c}$	=	Conflicting flow rate per lane per cycle
qr_c	=	Opposing queue ratio, that is, proportion of opposing flow rate originating in opposing queues, computed as $1 - R_{po}(g_o/C)$; $qr_c \geq 0$
R_{po}	=	Platoon ratio for opposing flow, obtained from HCM Exhibit 16-12 [5] based on opposing arrival type
g_o	=	Effective green for opposing flow(s), in seconds
C	=	Average cycle length, in seconds
g_c	=	Effective green for opposing flow(s)
t_L	=	Lost time for opposing lane group(s), in seconds

While the term g_q was developed initially for application with permitted left turns, the same principle applies here, that RTORs can occur only after an initial queue in the conflicting traffic stream, either intersecting or opposing, has cleared. If the conflicting movement initial queue is not dissipated before the end of the phase, there is no time available for which RTORs can be made and the c_2 term becomes zero.

The c_3 term occurs during Regime ③, when shadowed left turns from the right occur during a protected phase. During this regime, there is no conflicting flow, thus the number of RTORs that can occur is a function of the signal interval for the shadowed left turn and the follow-up time. Where the subject approach contains a shared lane, this volume also is affected by the probability that the RTOR maneuver would be blocked by a through vehicle. The c_3 term is defined as follows:

$$c_3 = \frac{g_{SHLT}}{C} \cdot \frac{3600}{t_f}$$

where

c_3	=	Capacity during Regime ③ (shadowed left turns), in vehicles per hour
g_{SHLT}	=	Effective green time (in seconds) for a protected, shadowed left-turn phase
t_f	=	Follow-up time (in seconds)

The HCM offers guidance for estimating the number of RTORs as the equivalent number of shadowed left turns that occurs during this protected phase, but does not address the RTOR capacity component during Regime ③. Tarko [9] and Qureshi and Han [15] acknowledged that this RTOR regime has a unique capacity. The Tarko research, however, did not validate the capacity that can be realized during this portion of the cycle and the Qureshi and Han research focused on the prediction of delay, not capacity.

Because there are no conflicting vehicles during this phase of the cycle, there is a single, continuous gap into which RTORs from the subject approach can be made and the magnitude of this gap is the duration of this exclusive signal phase. The number of RTORs per cycle that can be expected is determined by the duration of the phase divided by the follow-up time.

In the development of the RTOR Incremental Capacity Model, HCM-recommended default values for the critical gap, t_c, and the follow-up time, t_f, were assumed. Where the conflicting approach has one lane, a value of 6.2 seconds was used for the critical gap; for a two-lane conflicting approach, the default value of 6.9 seconds was used. As the RTOR maneuver is considered to be "minor" compared to conflicting flows, the recommended default value of 3.3 seconds for the follow-up time was assumed for right turns on red. The HCM recommends the use of default values in the absence of actual field data.

A summary of the incremental capacities for each of the three capacity terms and the total capacity for each of the 28 data points is presented in **Table VI.1**. The total capacity includes the effect of the P_{RTOR} term, which accounts for the blocking of RTOR vehicles in a shared lane by a preceding through vehicle.

Table VI.1. RTOR Incremental Capacity Model Results

Site	Period	Start	Subject Approach	c_1	c_{2Int}	c_{2Opp}	c_3	P_{RTOR}	Estimated Capacity	HCM Capacity	Ratio**
1	AM	7:30	NB	344	233	26	73	0.0281	353	320	1.10
1	AM	7:45	NB	347	186	0	73	0.0245	353	323	1.09
1	AM	8:00	NB	344	225	0	73	0.0403	356	320	1.11
1	PM	16:45	NB	264	0	47	160	0.1161	288	211	1.37
1	PM	17:00	NB	264	25	45	158	0.0484	275	218	1.26
1	PM	17:15	NB	263	0	47	160	0.0543	275	217	1.27
1	PM	17:30	NB	256	0	47	160	0.1078	279	214	1.30
1	PM	17:45	NB	255	64	46	160	0.0987	281	211	1.33
2	AM	7:15	EB	267	254	133	87	0.0438	288	258	1.12
2	AM	7:30	EB	273	187	78	87	0.0445	288	263	1.10
2	AM	7:45	EB	261	182	108	87	0.0808	291	250	1.16
2	AM	8:00	EB	227	248	118	87	0.0602	255	217	1.17
3	AM	8:15	SB	689	339	0	0	0.0669	711	670	1.06
3	PM	15:30	SB	742	292	0	0	0.0218	748	609	1.23
3	PM	16:00	SB	834	299	0	0	0.0320	843	746	1.13
3	PM	16:15	SB	891	286	0	0	0.0298	900	761	1.18
3	PM	16:30	SB	876	248	0	0	0.0327	884	766	1.15
4	AM	8:00	WB	600	258	61	87	0.1290	652	502	1.30
4	AM	8:15	WB	598	199	61	62	0.0641	619	516	1.20
4	AM	8:30	WB	688	262	65	68	0.0878	723	516	1.40
4	PM	17:00	WB	521	155	48	108	0.0873	548	471	1.16
4	PM	17:15	WB	497	144	44	125	0.1404	541	458	1.18
4	PM	17:30	WB	581	186	58	119	0.0889	613	487	1.26
5	AM	7:00	EB	388	605	0	0	0.1320	467	339	1.38
5	AM	7:15	EB	457	559	0	0	0.0769	500	410	1.22
5	AM	8:00	EB	471	466	0	0	0.1106	523	427	1.22
5	AM	8:15	EB	461	500	0	0	0.1165	519	417	1.24
5	PM	16:45	EB	548	397	0	0	0.0530	569	506	1.13

** Subject approach shared lane capacity computed using current HCM Signalized Intersection method*
*** Ratio Total Capacity computed using RTOR Incremental Capacity Model to HCM-Based Capacity*

For comparison, the computed capacity using the HCM method is shown in Table VI.1 as well. The HCM-based capacity, denoted in the table as "*HCM Capacity*," is less than the c_1 value, though they are computed in a similar fashion, because RTORs are subtracted from the approach demand volume before the HCM-based capacity is computed.

In all cases, the estimated capacities computed using the RTOR Incremental Capacity Model are greater than the HCM-based capacity. This is illustrated in **Figure VI.2**, where the dashed red line represents the case where capacities computed using the

RTOR Incremental Capacity Model would equal the HCM-based capacity for the same scenario. All of the data points in Figure VI.2 lie above the dashed line, which supports the hypothesis that the RTOR Incremental Capacity Model results in higher capacities than the HCM method where a shared through/right-turn lane exists. It can be postulated that the same holds true for the case where there is an exclusive right-turn lane, though the research did not address this specifically.

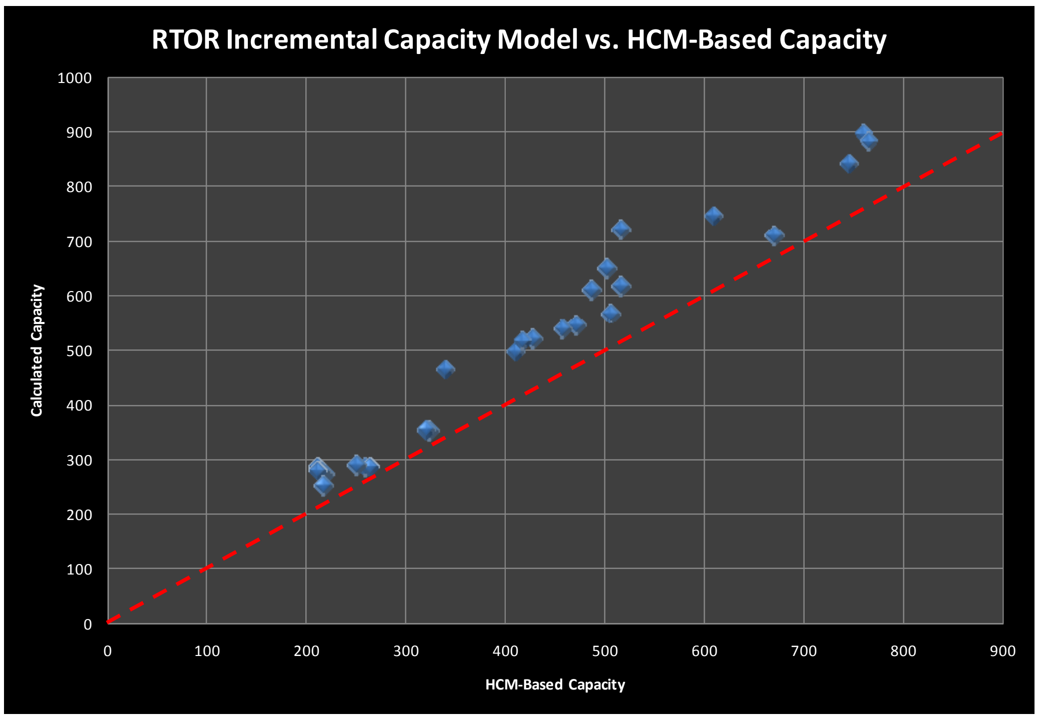


Figure VI.2. Comparison of RTOR Incremental Capacity Model Results vs. HCM-Based Capacities

The RTOR Incremental Capacity Model builds upon previous research, with enhancements made to reflect this researcher's approach to solving the problem and with specific application to shared through/right-turn lanes. The c_1 term applies the HCM approach for computing capacity on the green signal phase, except that RTORs are not subtracted from the demand volume as they are using the HCM method. The RTORs are accommodated during the red signal phases that make up Regimes ①, ② and ③. Subtracting RTORs from the demand volume (per the HCM method) yields a lower volume-to-capacity ratio (X) when compared to the RTOR Incremental Capacity Model c_1 term, but the additional capacity gained by including the c_2 and c_3 terms ultimately yields a lower (and more correct) volume-to-capacity ratio than the HCM method does for the green portion of the phase on the subject approach.

Several previous research efforts ([7], [9], [12], [13]) have supported using the HCM Unsignalized Intersection Method for computing potential capacity the way it is used in the c_2 term of this model, where available gaps in the conflicting traffic streams are the determining factor. The other models did not discount the portion of the signal phase for a conflicting movement that is blocked by an initial queue of vehicles. This term, g_q, can have a significant effect on the c_2 term and even can cause the term to be zero if the conflicting movement is saturated.

The c_3 term is similar to the one used by Tarko [9] and both employ the follow-up time, t_f, in computing capacity during the shadowed left-turn regime. By incorporating the effective green time (which is the green display plus yellow plus all-red, minus lost time), the RTOR Incremental Capacity Model directly includes the signal clearance interval (yellow and all-red displays) as part of the "continuous gap" during which RTORs can be made and field observations have confirmed that drivers do indeed use this portion of the cycle for making RTORs. The clearance intervals of the cycle provide significant opportunities for RTORs. Tarko's research did not specifically address the clearance interval in computing capacity for unimpeded RTORs.

The P_{RTOR} parameter provides a deterministic estimate of a probabilistic variable where a shared lane exists. It offers a simple approach for approximating a stochastic event and fits neatly within the framework of the Highway Capacity Manual. No other known research efforts have simplified the variable in this manner.

Assumptions and Limitations

The model developed is a theoretical models based on methods employed in the HCM. The intent was to develop a model that is consistent with HCM technique that can be integrated into future revisions to the Signalized Intersection Methodology. The RTOR Incremental Capacity Model included limited validation through comparison with actual field data for a total of 28 analysis periods at five study sites. The model that was developed is subject to the following assumptions and limitations:

1. When the intersecting approach contains two or more through lanes, it is assumed that only vehicles in the outside (curb) lane will conflict with potential RTOR movements from the subject approach. It is assumed that vehicles in the non-curb lane(s) on the intersecting approach do not conflict with subject RTOR movements.

2. When the opposing left-turn approach contains two or more lanes, it is assumed that only vehicles in the right-most (outside) left-turn lane will conflict with potential subject approach RTOR movements.

3. The model developed from this research does not include potential limiting effects of pedestrian crossings on the subject approach, as there was no pedestrian activity at the study sites from which the inhibiting effects could be quantified. Furthermore, little previous research has been done to address this issue, as was discovered in the literature review. Tarko [9] did include a multiplicative term in his capacity model, ($1\text{-}V_p/2100$), where V_p is the hourly pedestrian volume on the subject approach. However, the Tarko research did not include any actual pedestrian data from which the term could be validated.

4. The model does not address bicycles as part of the traffic streams on either the subject approach or one of the conflicting approaches.

5. The model developed assumes random arrivals on all approaches. Mathematically, the negative exponential distribution is used to represent the distribution of random arrivals such as vehicle headways [19]. Headway is defined to be the time, in seconds, between two successive vehicles as they pass a point on a roadway, measured form the same common feature such as the front axle or bumper [5]. It is commonly accepted that vehicles generally do not travel at a constant headway unless intersection spacing and/or signal coordination result in compact platoons [20]. For those study locations that were part of coordinated signal systems (Sites 1 and 2), it was determined that the subject intersections were located far enough downstream such that vehicle platoons were dispersed to the point that arrivals were random. CORSIM models created to simulate traffic conditions at field study sites were set to model arrival headways using a negative binomial distribution. Departure distributions for RTORs were assumed to be constant (on the basis that adequate gaps in the conflicting traffic streams were present), with the average departure headway equal to the follow-up time, t_f.

6. The model is based on exclusive conflicting signal phases – intersecting through movements, opposing left turns and shadowed left turns. Combined protected/permitted left turn phases were not addressed specifically as part of this research.

7. The model assumes that there is no room on the shoulder for right-turning vehicles to bypass blocking through vehicles.

Adaptation for Exclusive Right-Turn Lanes

The RTOR Incremental Capacity Model accounts for the probabilistic nature of blocking RTORs by though vehicles in a shared lane through the inclusion of the term $(1\text{-}p)/p$ (where p is the proportion of through vehicles in a shared lane) as a multiplicative term. When the subject approach contains an exclusive right-turn lane instead of a shared lane, this blocking effect is removed. This research was focused on the specific case where a shared through/right-turn lane exists. However, ideally, the model should be adaptable to approaches with exclusive right-turn lanes. An adaptation of the RTOR Incremental Capacity Model for exclusive right-turn lanes is offered as follows:

$$c = c_1 + c_2 + c_3$$

where

c	=	Total approach capacity (veh/h), where the approach contains a shared through/right-turn lane;
c_1	=	Approach capacity (veh/h) during the green signal phase
c_2	=	Approach capacity (veh/h) during which conflicting movements (intersecting through from the left) and opposing left turns receive an exclusive green signal display (Regimes ① and ②);
c_3	=	Approach capacity (veh/h) during which shadowed left turns from the right receive an exclusive green signal display (Regime ③)

In this case, the term $P_{RTOR,}$ which is the probability that a RTOR movement will occur from the exclusive lane, becomes 1.0 and therefore is removed from the equation. This proposed model also has not been validated using actual field data.

VII. CONCLUSIONS

Although the Highway Capacity Manual (HCM) is one of the most widely used transportation references in the world, there are limitations and opportunities for improvements to some of its methods. This is particularly true for the Signalized Intersections Methodology and especially with the way the procedure deals with right turns on red (RTORs).

The current method dictates the analyst determine the number of RTORs that occur during an analysis period. If actual traffic count data are not available, the HCM provides limited guidance for estimating this parameter. This guidance, however, does not address the specific case where a shared through/right-turn lane exists on a subject approach. In many cases, the RTOR volume is not available – either RTOR counts were not obtained or the analysis is for a hypothetical scenario. In either case, there is the need for a better method to estimate the RTOR volume for both exclusive right-turn lanes and shared through/right-turn lanes.

The HCM method also has been criticized for the manner in which it deals with RTOR demand volumes, whether estimated or from actual counts. Instead of including RTORs in capacity and delay calculations, the number of RTORs per hour is simply subtracted from the demand volume in the current method. The result is that, where RTORs are permitted and do occur, there is an under-estimation of capacity and an over-estimation of delay for those approaches that contain right-turn lanes of either type.

This research was focused on the development of models to estimate RTOR volumes and the incremental capacity this is realized when RTORs are permitted, for the specific case where the subject approach contains a shared through/right-turn lane. The primary objectives in developing these models were:

1. To develop RTOR volume and RTOR incremental capacity estimation models that account for the probabilistic nature of blocking by through vehicles in shared lanes;
2. To develop models that are easily understood by practitioners and produce reasonable results; and
3. To develop deterministic models that are consistent with the HCM Signalized Intersection Methodology and that can be incorporated into future updates to the method.

One final objective was to develop models that could be adapted to the case where the subject approach contained an exclusive right-turn lane.

The following conclusions are drawn from this research:

- The Signalized Intersection Methodology in the Highway Capacity Manual under-estimates capacity on approaches where right-turns-on-red (RTORs) are permitted, as the current capacity model includes only that portion of the cycle where a green signal display is given for the subject approach. This is true for both exclusive right-turn lanes and shared through/right-turn lanes. Furthermore, an under-estimation of capacity leads to an over-estimation of delay and potentially an incorrect determination of level of service.

- The HCM Signalized Intersection Methodology is deterministic, but RTORs from shared lanes are probabilistic (i.e. stochastic) in nature, as the number of RTORs per cycle and the shared lane capacity are a function of both the proportion of through vehicles in the shared lane *and* that point in the cycle when a blocking through vehicle arrives. A Geometric Distribution can be used to estimate the number of leading right-turning vehicles that will arrive before a blocking through vehicle. The Geometric Distribution is a special form of the Negative Binomial Distribution where only one through vehicle is required to block subsequent RTOR vehicles, which is the case for shared lanes. Accounting for this distribution as the probability that RTORs will occur from the shared lane (P_{RTOR}), this stochastic parameter can be applied in deterministic models that are consistent with those currently applied in the HCM.

- The HCM method requires the number of RTORs as an input parameter, but provides limited guidance for estimating this parameter for exclusive right-turn lanes when actual RTOR counts are not available. The Manual provides virtually no guidance for estimating this parameter when the approach contains a shared lane. The RTOR Volume Estimation Model is a deterministic model that produces reasonable results and incorporates the probabilistic nature of RTORs from shared lanes. The Volume Estimation Model compared favorably with results obtained through simulating the anticipated number of RTORs that occurred at actual study sites.

- The RTOR Incremental Capacity Model demonstrated that greater capacity is realized when RTORs occur from shared lane approaches compared to the current HCM method.

- While the RTOR Volume Estimation Model and RTOR Incremental Capacity Model were addressed to develop the specific scenario where there is a shared lane on the subject approach, they are both adaptable to exclusive right-turn lane approaches. Alternative forms of these models for application on approaches with exclusive right-turn lanes were offered, though not tested.

The models developed as part of this research are theoretical models that were validated through simulation of actual intersections at five locations across Kentucky. Intersection turning movement counts collected as part of actual traffic studies (conducted by the author) were used to create a total of 28 analysis scenarios. Computer simulation was used to replicate the cycle-to-cycle and day-to-day variation in RTORs that occurs on subject intersection approaches containing a shared through/right-turn lane. For each of the 15-minute intervals, the mean value of the observed RTORs from the simulation was compared to the predicted number of RTORs.

Sites 1, 3 and 5 contained multiple approaches with shared lanes. While these sites offered the potential to expand the data set to include a greater number of study approaches, it is believed that there would be a potential influence on RTORs at one shared-lane approach by other shared-lane approaches at the same intersection. The desire was to isolate the effect on RTORs by shared-lane approaches for the sake of model validation, which limited the number of analysis scenarios that were used.

Ideally, more study approaches and analysis periods would have been included in the validation data set upon which the simulation models were constructed. While additional 15-minute periods at these five sites were considered, they were dropped from the analysis due to low RTOR volumes counted in the field. Locating similar available data from other traffic studies at isolated intersections proved to be an unsuccessful endeavor, in spite of earnest attempts. However, though limited, the data used in the model validation were "real-world" data obtained in other traffic studies conducted by this author and their validity is assured.

Benefits to Practitioners

This research supports the hypothesis that the current HCM method under-predicts capacity for those approaches where RTORs occur. This results in an over-prediction of control delay, the performance measure on which level of service for signalized intersections is based. The practical implication is that decisions related to signal timing and intersection geometry typically are based on delay and level of service; thus, the ability to accurately determine capacity, delay and level of service plays an important role in the decision-making process where capital intersection improvements are concerned.

Where RTORs from shared lanes are concerned, the research provides a simple way to estimate the average number of RTORs that can be expected when a shared lane exists and the additional capacity this is realized. The current version of the HCM offers essentially no guidance for quantifying this parameter. The models developed also fit within the deterministic framework of the current HCM method, yet account for the probabilistic nature of RTORs where shared lanes are present.

The current HCM Signalized Intersection Method requires the number of RTORs as an input parameter, only to subtract them from the demand volume, which in turn produces an inaccurate computation of the demand volume-to-capacity ratio for the subject approach. Right-turns-on-red should be included in the demand volume. The ability to accurately estimate the average number of RTORs during an analysis period is especially useful to the practitioner when considering intersection improvements that include potentially adding an exclusive right-turn lane.

Finally, the computation of capacity and delay may or may not change the level of service for a particular scenario, depending on where the delay computation falls in relation to the level-of-service threshold. In general, computing a higher capacity and corresponding lower delay using the RTOR Incremental Capacity Model will result in a better level of service (by about one grade), which has practical implications in the decision-making process where intersection improvements are being considered.

Recommendations for Further Research

As mentioned previously, the development of the RTOR Volume Estimation Model and RTOR Incremental Capacity Model did not address the impact of pedestrian crossings on RTORs. At four of the five study sites, pedestrian crossings during the analysis periods were non-existent. At Site 2, which borders the University of Kentucky campus, pedestrian activity does occur but pedestrian crossings were not modeled. At that site, the subject (eastbound) approach was on the side of the street opposite the University campus and the counted number of RTORs did not vary significantly from the predicted value using the RTOR Volume Estimation Model, indicating that the pedestrian effect on this particular approach was minimal.

For locations where pedestrian crossing activity is significant, such as downtown areas and on college campuses, a more significant impact on RTOR volume and capacity is expected. The anticipated effect is that RTOR volumes and capacities will be lower when pedestrian crossings are present. Further research in this area should include quantifying there impacts.

The models developed also do not address bicycles within the traffic stream. Although there is a tendency to lump bicycles and pedestrians together, there is a very distinct difference, as bicycles on the road move with traffic while pedestrians cross the traffic stream. Furthermore, bicycles travel either within the traffic lane or in a separate bicycle lane where those facilities exist. Because bicycles tend to accelerate more slowly and travel at lower speeds than autos, their characteristics are markedly different and they should be treated separately. Their impacts on RTORs can be significant.

Site 2 was the only location where bicycles constituted more than a random occurrence within the traffic stream and bicycle volumes were not recorded during data collection. As with pedestrian activity for this site, the comparison of predicted RTORs with counted RTORs was close, indicating that bicycle impacts on RTORs for this specific approach were not significant. Further research should include sites where bicycles have a significant and quantifiable effect on RTORs.

This research provided a basic framework for models that estimate RTOR volumes and capacities at signalized intersections for approaches that contain a shared through/right-turn lane. Further research is recommended to expand the ability of these models to address factors and scenarios that were not addressed as part of this research, but may be found in a "typical" urban environment. Those recommendations are:

- Test the alternative models offered for the case where the approach contains an exclusive right-turn lane;

- Expand the models to include the effects of pedestrian crossings on the subject approach where RTORs may occur;

- Expand the models to include the effects of bicycles, both on the subject approach and in the conflicting traffic streams;

- Test the models over a wider range of subject approach and conflicting traffic stream volumes, particularly when volumes are relatively low;

- Address scenarios where there is complex signal phasing such as protected/permitted left turns and lead-lag left-turn phasing; and

- Incorporate the effects of non-random arrivals on both the subject approach and in the conflicting traffic stream, particularly where closely spaced upstream signals create a platooning effect for downstream arrivals at the subject intersection.

Contributions to the Practice

While the current Signalized Intersection Methodology of the Highway Capacity Manual has been updated since it was first introduced in the 1985 version, there has been no universally accepted research that has satisfactorily addressed the method's deficiencies in addressing right-turns-on-red, either from exclusive right-turn lane or shared lane approaches. While several researchers have developed models to estimate the number of RTORs that can be expected or the additional capacity that is realized when RTORs occur, the Highway Capacity and Quality of Service Committee of the Transportation Research Board, which is responsible for the upkeep of the Manual, has not incorporated any of this past research in past updates to the method.

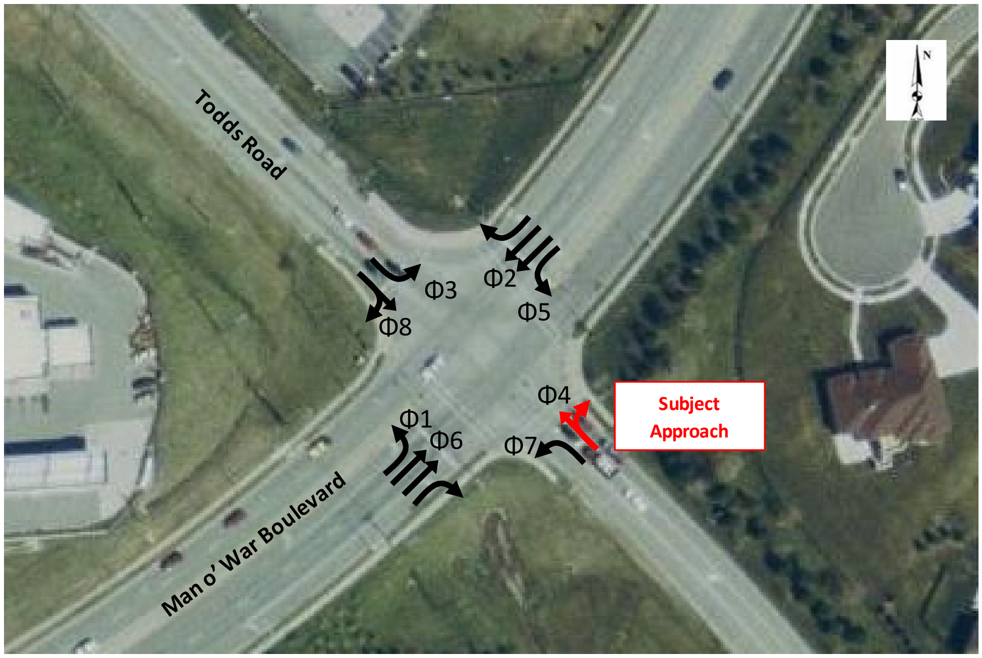
This research has resulted in models to estimate RTOR volumes and incremental capacity for the specific case where a shared through/right-turn lane exists on a subject approach, with additional recommendations for adaptation of these models to exclusive right-turn lane approaches. Furthermore, the models offered through this research are consistent with the current deterministic models contained in the HCM and have been validated with actual field data, enhancing their potential acceptance into future updates to the method.

Finally, the research has demonstrated that additional capacity is realized when RTORs occur, that this capacity can be quantified, and that the stochastic nature of RTORs occurring from shared through/right-turn lanes can be approximated and accounted for in deterministic models that are consistent with models current employed in the Highway Capacity Manual.

APPENDIX

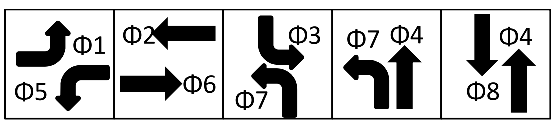
Intersection Site Diagrams

Site 1. Man o' War Boulevard at Todds Road
Lexington, Kentucky

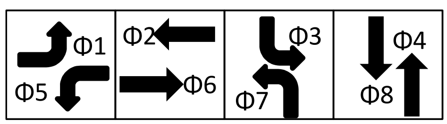


Signal Phasing

A.M. Peak



P.M. Peak



Signal Timing

A.M. Peak

Phase	Φ1 + Φ5	Φ2 + Φ6	Φ3 + Φ7	Φ4 + Φ7	Φ4 + Φ8
Min Green	5.0	---	5.0	5.0	5.0
Ext	3.0	4.0	3.5	3.5	3.5
Max Green	13.9	42.6	29.3	15.0	30.0
Yellow	3.9	5.0	---	---	3.6
All Red	2.5	1.7	---	---	2.5

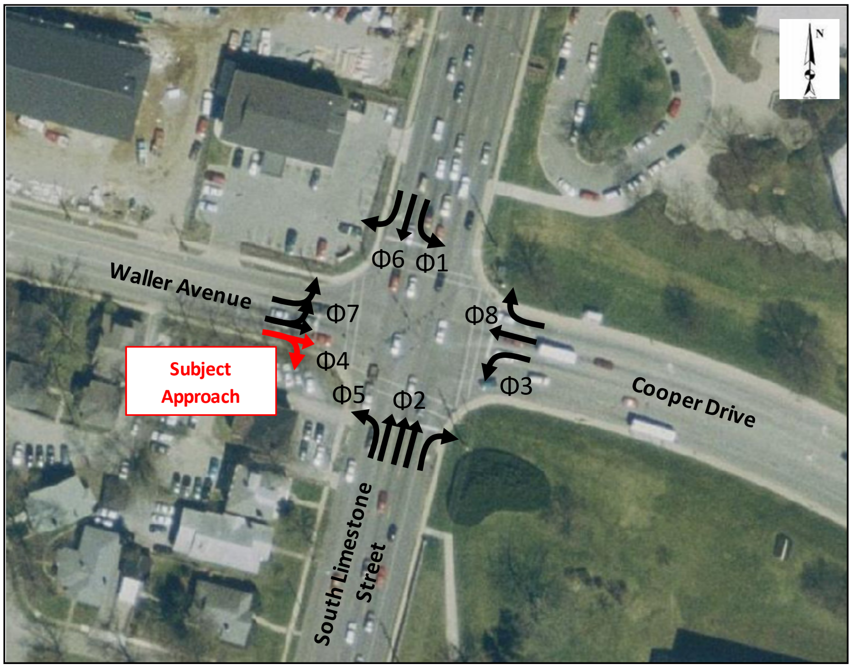
C = 150

P.M. Peak

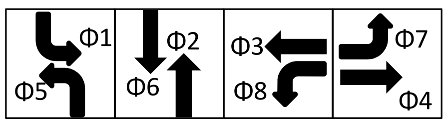
Phase	Φ1 + Φ5	Φ2 + Φ6	Φ3 + Φ7	Φ4 + Φ8
Min Green	5.0	---	5.0	5.0
Ext	3.0	4.0	3.5	3.5
Max Green	20.9	61.6	32.3	19.9
Yellow	3.9	5.0	3.6	3.6
All Red	2.5	1.7	2.5	2.5

C = 160

Site 2. South L:imestone Street at Waller Avenue/Cooper Drive
Lexington, Kentucky



Signal Phasing

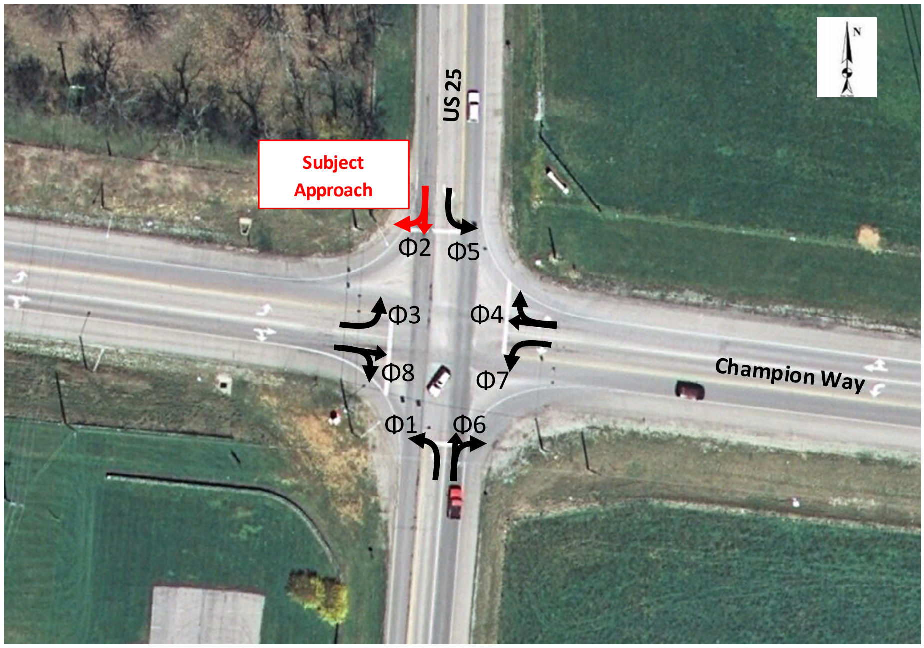


Signal Timing

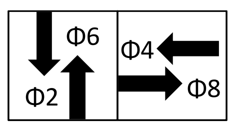
Phase	Φ1 + Φ5	Φ2 + Φ6	Φ3 + Φ8	Φ4 + Φ7
Min Green	5.0	---	5.0	5.0
Ext	3.0	---	3.0	3.0
Max Green	21.9	58.9	43.5	30.9
Yellow	3.6	4.3	3.6	3.6
All Red	2.5	2.2	2.5	2.5

C = 180

Site 3. US 25 at Champion Way
Georgetown, Kentucky



Signal Phasing



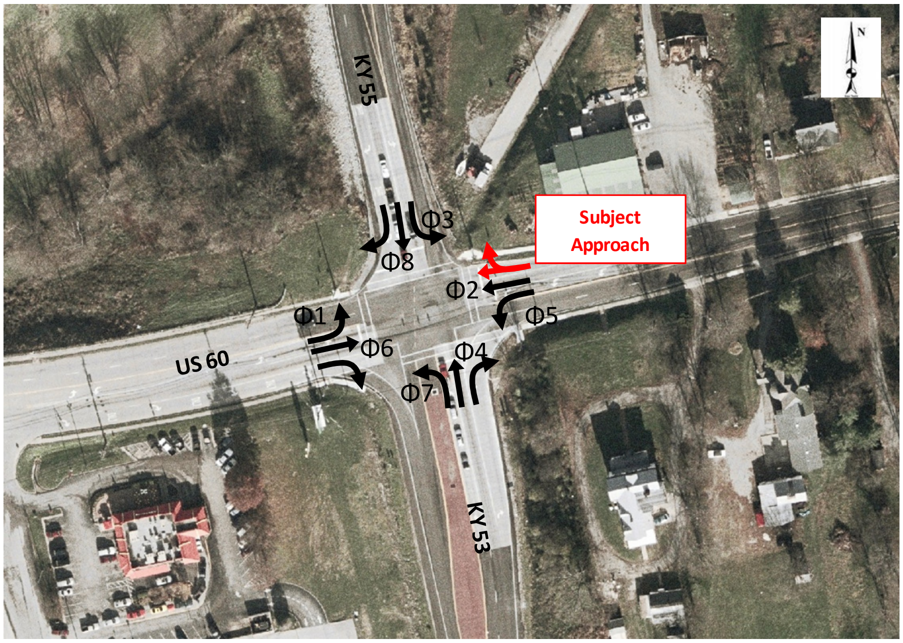
Signal Timing

Phase	Φ2 + Φ6	Φ4 + Φ8
Min Green	20.0	5.0
Ext	2.2	3.0
Max Green	60.0	45.0
Yellow	4.6	4.6
All Red	1.6	1.0

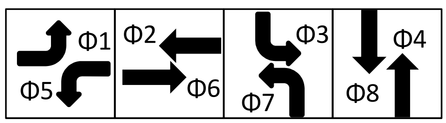
C = 44 -72*

* Fully actuated signal; cycle length varies, depending on traffic demand

Site 4. US 60 at KY 55/KY 53
Shelbyville, Kentucky



Signal Phasing



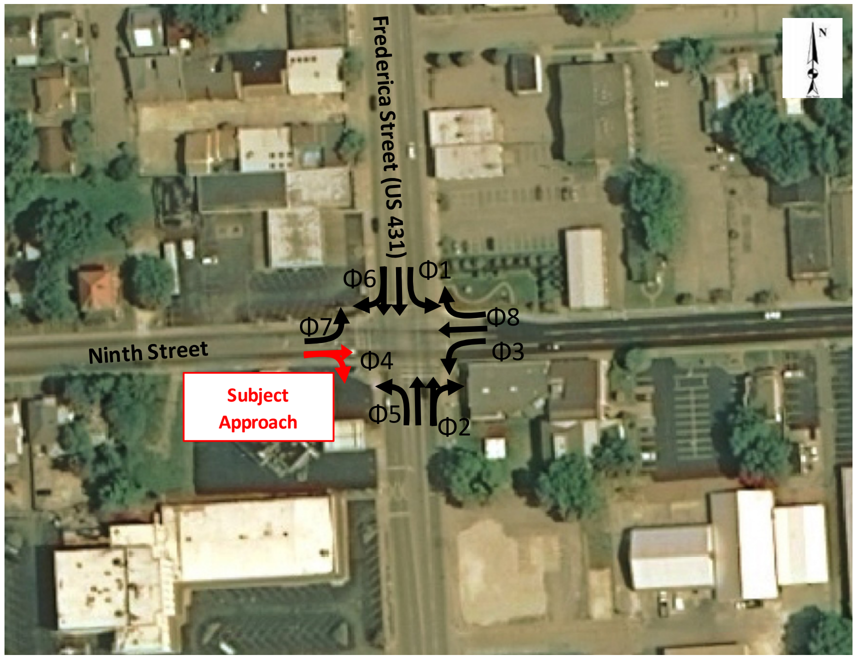
Signal Timing

Phase	Φ1 + Φ5	Φ2 + Φ6	Φ3 + Φ8	Φ4 + Φ7
Min Green	5.0	40.0	5.0	5.0
Ext	4.0	4.0	4.0	4.0
Max Green	25.0	40.0	25.0	35.0
Yellow	4.3	4.3	4.3	4.3
All Red	1.0	2.0	1.0	1.0

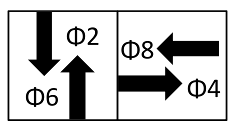
C = 112 - 137*

* Fully actuated signal; cycle length varies, depending on traffic demand

Site 5. Frederica Street (US 431) at Ninth Street
Owensboro, Kentucky



Signal Phasing



Signal Timing

Phase	Φ2 + Φ6	Φ4 + Φ8
Min Green	5.0	10.0
Ext	1.0	3.0
Max Green	35.0	30.0
Yellow	3.5	3.5
All Red	0.0	2.0

C = 54 - 62*

* Fully actuated signal; cycle length varies, depending on traffic demand

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