Right-Turn-on-Red Flow Profile Impacts on Urban Street Capacity Analysis

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The *Highway Capacity Manual 2010* (HCM 2010) contains computational procedures for evaluating traffic operational efficiency of urban street segments. These procedures have been implemented within several commercial software packages and are likely used by thousands of engineers and planners across the United States. The procedures for urban street capacity analysis contain no logic for handling right turns on red (RTORs) or for handling special cases of RTORs such as shielded and free right turns. A new proposed RTOR modeling framework is described for urban streets in the HCM 2010. When significant upstream RTOR flows exist, the proposed logic is designed to generate more realistic flow profiles. Three types of experimental results are presented: they demonstrate the improved modeling accuracy of the proposed logic. First, it is shown that macroscopic flow profile shapes are now more visually sensible because they now illustrate RTOR flows moving at the appropriate times. Second, macroscopic flow profile shapes are now more consistent with microscopic vehicle trajectories. Third, a statistical analysis shows that when the proposed logic is used, HCM 2010 performance measures become more consistent with the performance measures generated by microsimulation. Finally, case study results show that when the proposed RTOR logic is not used, control delays are sometimes be inaccurate by more than 30%. Given the experimental evidence presented, it is urgent that the proposed improvements be adopted and implemented so that RTOR corridors can be accurately analyzed by the HCM 2010 procedures.

The *Highway Capacity Manual 2010* (HCM 2010) contains computational procedures designed to evaluate traffic operational efficiency of urban street segments, signalized intersections, and interchange ramp terminals (*1*). The HCM 2010 is one of the world's most important transportation documents. These procedures are implemented by commercial software packages including the Highway Capacity Software (HCS) 2010, Synchro, Vistro, and Transmodeler. There has been a natural interest in integrating these interrupted-flow procedures because they all require detailed analysis of signalized intersection operation. The TRB Standing Committee on Highway Capacity and Quality of Service, which maintains computational engines to test and demonstrate their procedures, has worked on integrating their engines related to urban streets and signalized intersections. In recent years the McTrans Center, at the University of Florida, integrated three procedures (i.e., urban streets, signalized intersections, and interchange ramp terminals) into a single software module within HCS.

This integration presented various challenges, including the treatment of right turn on red (RTOR). For many years, HCM 2010 procedures for signalized intersections have required the analyst to specify an expected number of RTOR vehicles per time period. Subsequently, RTOR volumes would be subtracted from right-turn volumes before the full procedure was executed. Although the signalized intersection procedures continue to support this treatment of RTOR, computational engines for urban streets and ramp terminals do not support RTOR. Some calculations related to flow profiles within the urban street and ramp terminal engines become even less accurate when the signalized intersection treatment occurs. Ideally, the HCM 2010 signalized procedures would be expanded to include methods for explicit analysis of permissive right turns. However, this expansion would not resolve problems with the flow profile model, which currently has no logic for addressing RTOR.

Flow profiles should properly address RTOR to allow accurate computation of the percentage of downstream vehicles arriving on green (PVG). When the discharge flow rate of RTOR vehicles is determined, the procedures should account for conflicting flow rates. PVG values significantly affect performance measures including control delay and level of service (LOS). It is also desirable that the signalized procedures reflect operation of free right turns, in which right-turning vehicles move freely throughout the cycle. The operation of shielded right turns, in which exclusive left-turn phases allow right turns on the conflicting approach to move without yielding, should also be explicitly recognized.

The objective of this research was to develop improvements to the RTOR treatment for the HCM 2010 and to test their accuracy. The next section summarizes existing HCM 2010 treatment of RTOR, including free and shielded right turns. Next, shortcomings of the existing treatment are demonstrated, and the following section proposes corresponding improvements. The subsequent section provides a statistical comparison of existing and proposed logic in terms of consistency with microsimulation. The final section provides a case study to demonstrate the impacts of the proposed logic.

BACKGROUND

HCM 2010 Computational Engines

Certain chapters of the HCM 2010 refer to computational engines that implement the HCM 2010 methodologies (*1*). Although these methodologies have improved since the publication of HCM 2000,

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some issues have not been addressed. One example is that RTOR is fully supported in the engine for signalized intersections but not in the one for urban streets. A unified engine should accurately model RTOR movements on all major- and minor-street approaches. Until then, users of unified engines will face compromised results when RTOR conditions exist. The ramp terminal procedures also require modeling of PVG at downstream intersections. So although there is nothing erroneous within the chapter on ramp terminals regarding RTOR, urban street RTOR deficiencies compromise the accuracy of ramp terminal analysis in a unified engine.

From 2011 to 2014, the McTrans Center received problem reports from users of the HCS software (*2*), which implements the HCM 2010 procedures. Heavy RTOR input volumes caused analysis volumes to be incorrect by 10% to 50%. In 2014, the TRB Standing Committee on Highway Capacity and Quality of Service eliminated RTOR-related flow balancing problems in the computational engine by making appropriate changes to the programming logic. Flow profile and PVG errors caused by RTOR, free rights, and shielded rights were not reported by HCS users during the period from 2011 to 2014. However, the complexity of PVG calculations made it difficult to detect problems. Thus, users were likely accepting performance measures (and LOS) compromised by PVG errors.

Permissive Movement Models

The HCM 2010 chapter on two-way stop control provides a reasonable model for permissive right turns from the minor street, a prerequisite to modeling upstream intersection RTOR effects on downstream intersection flow profiles. Upstream intersection flow profiles also affect sign-controlled movement capacity, but such analysis is outside the scope of this paper. HCM 2010 equations 19-4 through 19-9 determine conflicting flows as a function of conflicting lanes. Exhibits 19-10 and 19-11 suggest critical headway and follow-up values, respectively, for right turns made from a minor street. Equation 19-32 (shown here as Equation 1) then uses conflicting flow rate, critical headway, and follow-up values to determine permissive right-turn maximum flow rate (S_{RT}). For permissive maximum flow rates, HCM 2010 computational engines use the S_{LT} or S_{RT} terminology, whereas the HCM 2010 chapters use the $c_{p,x}$ terminology. The signalized intersection procedure already prescribes Equation 19-32 (Equation 1 here) to estimate permissive left-turn maximum flow rates (S_{LT}). Extending this logic to S_{RT} is thus easily accomplished by applying right-turn values of t_c and t_f; and by obtaining v_c from the 90-degree conflicting approach, instead of the 180-degree opposing approach, as follows:

$$c_{p,x} = v_{c,x} \frac{e^{\frac{-v_{c,x}t_{c,x}}{3,600}}}{1 - e^{\frac{-v_{c,x}t_{f,x}}{3,600}}} \tag{1}$$

where

$c_{p,x}$ = potential capacity of movement x [vehicles per hour (vph)];
$v_{c,x}$ = conflicting flow rate for movement x (vph);
$t_{c,x}$ = critical headway for minor movement x (s), typically 4.5 s for left turns and 6.9 s for right turns; and
$t_{f,x}$ = follow-up headway for minor movement x (s), typically 2.5 s for left turns and 3.3 s for right turns.

When RTOR maximum flow from shared lanes is estimated, the HCM 2010 prescribes an extra adjustment. Creasey (*3*) and Creasey et al. (*4*) noted that RTOR research was lacking in shared lanes, and they developed a shared-lane probability model. Creasey et al. also summarized methods to estimate RTOR maximum flow ($RTOR_{Cap}$) from exclusive lanes (*4*), such as Equation 2 from work by Abu-Lebdeh et al. (*5*):

$$RTOR_{Cap} = a\left\{\max\left[\left(\left(1 - \frac{g}{C}\right)s - V_c\right), 0\right]\right\} \tag{2}$$

where

α = ratio of saturation headway of intersecting through traffic to that of RTOR traffic; values of α range from 0.73 (corresponding to a right-turn saturation headway of 2.6 s per vehicle) to 0.85 (corresponding to 2.2 s per vehicle);
g/C = ratio of green to cycle length;
s = saturation flow rate on green (vph); and
V_c = total conflicting volume (vph).

Portions of the HCM 2010 platoon dispersion logic are based on Robertson's original algorithms (*6–8*) within the TRANSYT-7F arterial analysis software (*9*). TRANSYT-7F estimates RTOR maximum flow rate by applying the FHWA-TRC (*10*) regression model shown in Equation 3, with special coefficients developed for minor-street right turns:

$$MFR(t)_i = A_i \cdot \exp\left(-B_i \cdot v_o(t)^{C_i}\right) \tag{3}$$

where

$MFR(t)_i$ = maximum flow rate for permitted traffic at time t for minor-street rights;
A_i = statistically derived intercept, MFR at zero opposing flow, for minor-street rights;
B_i, C_i = statistically derived model parameters; and
$v_o(t)$ = opposing flow rate at time t.

Problem Scenario: Upstream Right Turns Made from Minor Street

Flow profiles from the urban street computational engine are not yet designed to reflect incoming flows from special-case right turns (RTORs, shielded, free). When special-case right turns exist, PVG becomes less accurate at the downstream intersection. Accuracy of the downstream PVG is inversely proportional to the volume of minor-street vehicles serving as special-case right turns. Moreover, PVG is known to have a significant effect on delay and LOS in many situations.

Summary of Background Information

In summary, the existing HCM 2010 computational engines for urban streets and ramp terminals have significant shortcomings related to RTOR, some of which have been reported by HCS users. Several modeling methods for permissive right turns exist in the literature, and three of them were summarized in this section. Permissive right-turn models are a prerequisite in generating flow profiles that account for RTOR vehicles. A new flow profile methodology is needed so that all RTOR corridors can be accurately analyzed by the HCM 2010 procedures.

PROPOSED METHODOLOGY

Maximum Flow Rates

The proposed methodology requires exactly the same input data as the current HCM methodology. For free right turns and shielded right turns, saturation flow rates are provided by the analyst. Units of measurement are typically vehicles per lane per hour of green. However for RTOR, permissive-period maximum flow rates are needed. "Unadjusted" maximum flow rate estimates can be obtained from models available in the literature, as described earlier in the section on permissive movement models. Subsequently, HCM 2010 procedures and computational engines contain logic for making final adjustments. These final adjustments for pedestrian, bicycle, lane utilization, and other effects, which were previously implemented for the permissive left-turn maximum flow rate, should now be applicable to the maximum flow rate for RTOR.

The computational engines classify 14 cases of combined lane geometry and signal phasing. Cases 1 through 4 denote protected left-turn cases under various geometries. Cases 5 through 8 cover permissive left turns, whereas Cases 9 through 12 involve split phasing. Cases 13 and 14 cover protected–permitted left turns made from a shared lane. The RTOR adjustments should be applied to Case 3 (exclusive right turns moving while left turns are not allowed to move), Case 5 (exclusive right turns moving during a permissive left-turn phase), and Case 9 (exclusive right turns moving during an unopposed split phase). When an RTOR made from a shared lane is modeled, the adjustment for lane utilization would be omitted.

Discharge Flow Rates

The urban street computational engine does not yet recognize the effect of special-case right turns (RTOR, shielded, free) on flow profiles, and the chapter on urban streets does not mention their influence. To address this deficiency, adjusted maximum flow rate from the previous section can now be used to synthesize more accurate flow profiles. To accomplish this, new logic is needed to transform upstream maximum flow rates into an improved upstream discharge profile. The computational engine currently contains logic for four types of discharge profiles, but a new category, for special-case upstream right turns, is now suggested. The new category is suggested as Option 3, because these options are typically checked in a first-to-last sequence. Options at the top of the list capture the most specific and complex cases. Options toward the bottom of the list contain simpler and more generalized logic; they catch all scenarios not already addressed by the earlier options:

1. Upstream left turns made from an approach with protected–permitted left-turn phasing;
2. Upstream left turns made from an approach with permitted-only left-turn phasing;
3. Upstream right turns made from an approach with RTOR, free right turns, and shielded right turns (new);
4. Upstream through movements and right turns made from an approach with permitted-only left-turn phasing and no exclusive left-turn lanes; and
5. All other upstream phase and movement combinations.

Figure 1 illustrates discharge flow rates for up to eight periods within the cycle in the most complex case of protected–permissive right turns.

Durations of these eight periods are determined by the HCM 2010 signalized intersection procedure, which is essentially a subset of the urban street procedure. It is fairly simple to determine discharge profiles for upstream free right turns made from the minor street. Their discharge rate remains unchanged throughout the cycle, and they do not yield to major-street vehicles. The discharge rate should reflect their saturation flow rate (S) or demand volume (Q_G), whichever is lower. For shielded right turns, queue service times are needed to synthesize more accurate flow profiles. The computational engine computes shielded right-turn queue service time (T_Que_1), but this value should now be used to determine discharge flow rates. Additional logic is needed to identify green windows in which shielded right turns can move. The green window should account for T_Que_1 as

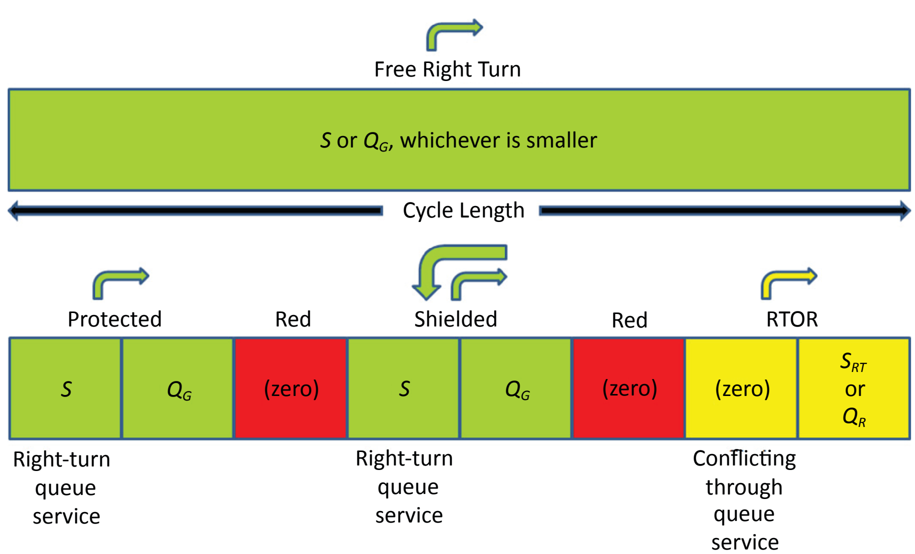
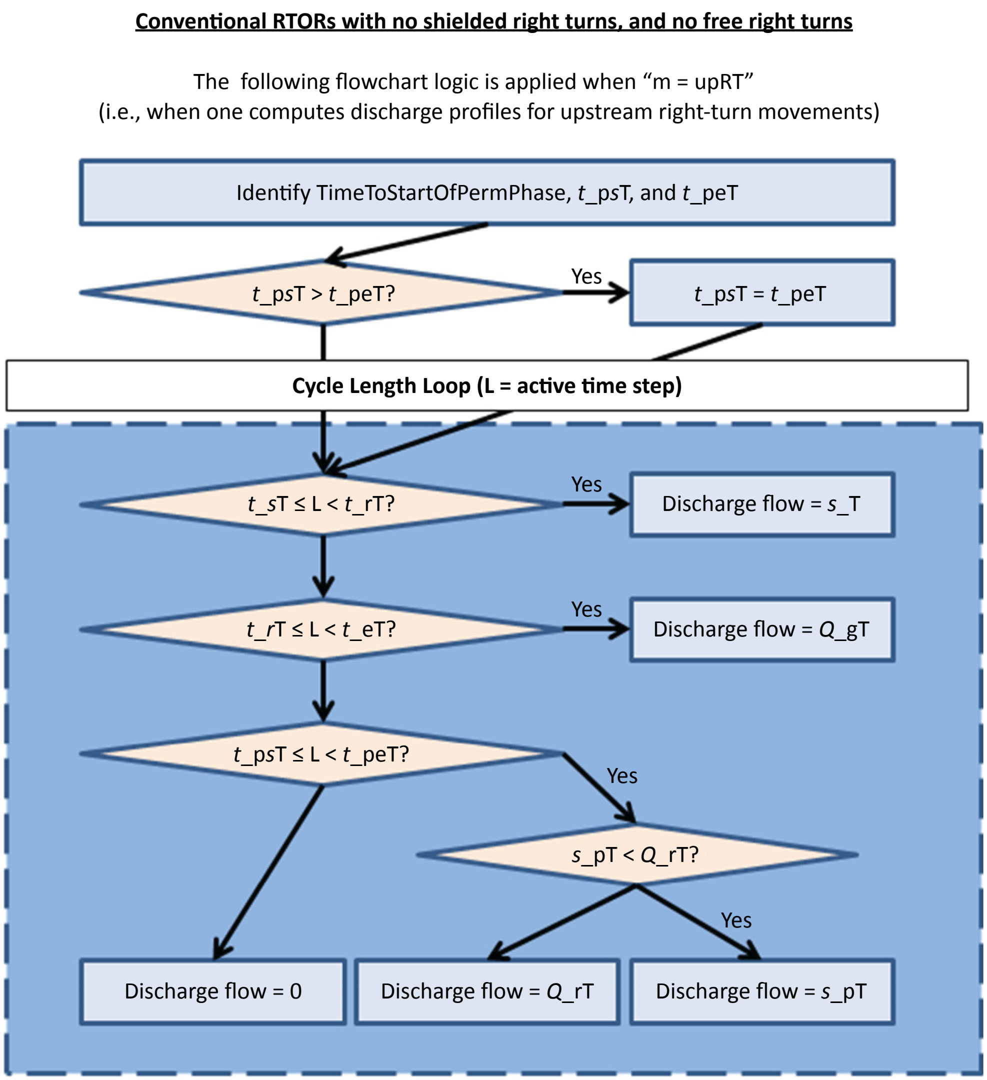


FIGURE 1 Right-turn discharge flow rates for up to eight periods within cycle [S = protected right-turn saturation rate (vehicles per second; vps); S_{RT} = permissive right-turn saturation flow rate (vps; from section on background); Q_G = protected right-turn arrival flow rate during green (vps); Q_R = protected right-turn arrival flow during red (vps)].

well as phase start and end times for the complementary left turn. Finally, it is necessary to define discharge profiles in a similar manner to that for protected–permitted left turns, because shielded right turns also have multiple green phases. Discharge profile values during the shielded phase should reflect saturation flow (S) while the queue is being served and arrival rate on red (Q_R) after the queue is served.

For upstream RTORs made from the minor street, it is first necessary to identify the green window in which RTORs are allowed to move. The green window is affected by queue service times and phase start and end times for conflicting movements (this research focused on conflicting through movements instead of opposing left-turn movements). Then it is necessary to convert adjusted RTOR maximum flow rates into discharge profile flow rates. Finally, it is necessary to define discharge profiles in a similar manner to that for protected–permitted left turns, because RTOR movements also have protected and permissive phases. The discharge rate during the RTOR period should be equal to the arrival rate on red (Q_R) or the adjusted RTOR maximum flow rate (S_{RT}), whichever is lower. The most complex case involves both RTOR and shielded right turns, causing up to three green windows (protected, shielded, RTOR) within the cycle. Figures 2 through 4



TimeToStartOfPermPhase = time until beginning of permissive right-turn phase (new)
t_psT = start of queue service during permissive phase (new)
t_peT = start of permissive phase effective red time (new)
t_sT = start of queue service during protected phase
t_rT = end of queue service during protected phase
t_eT = start of red time after protected phase
s_T = saturation flow rate of protected phase
s_pT = maximum flow rate of permissive phase (new)
Q_gT = flow rate during protected phase
Q_rT = flow rate arriving on red

FIGURE 2 RTOR-only discharge flow rate methodology.

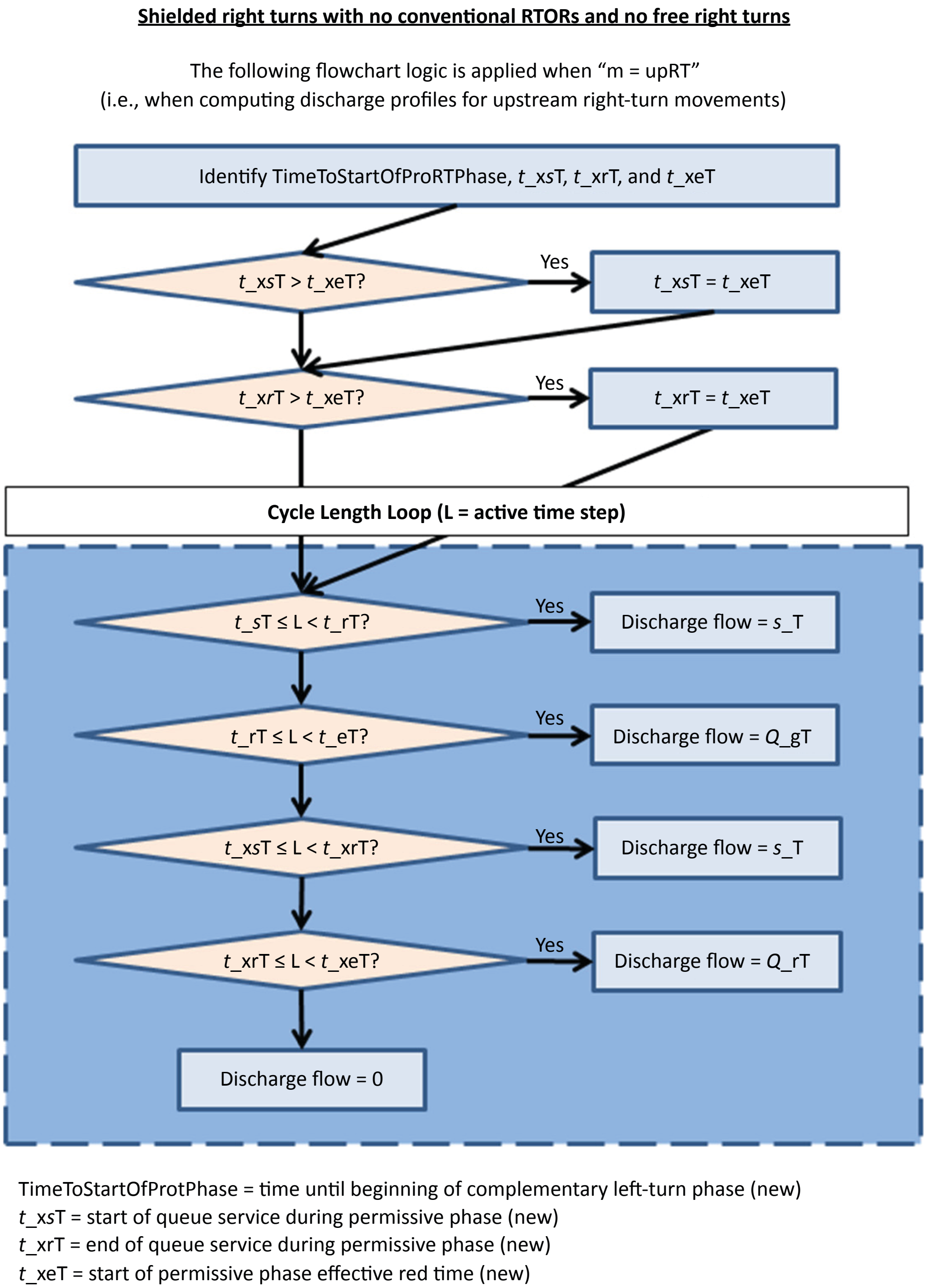


FIGURE 3 Shielded-only discharge flow rate methodology.

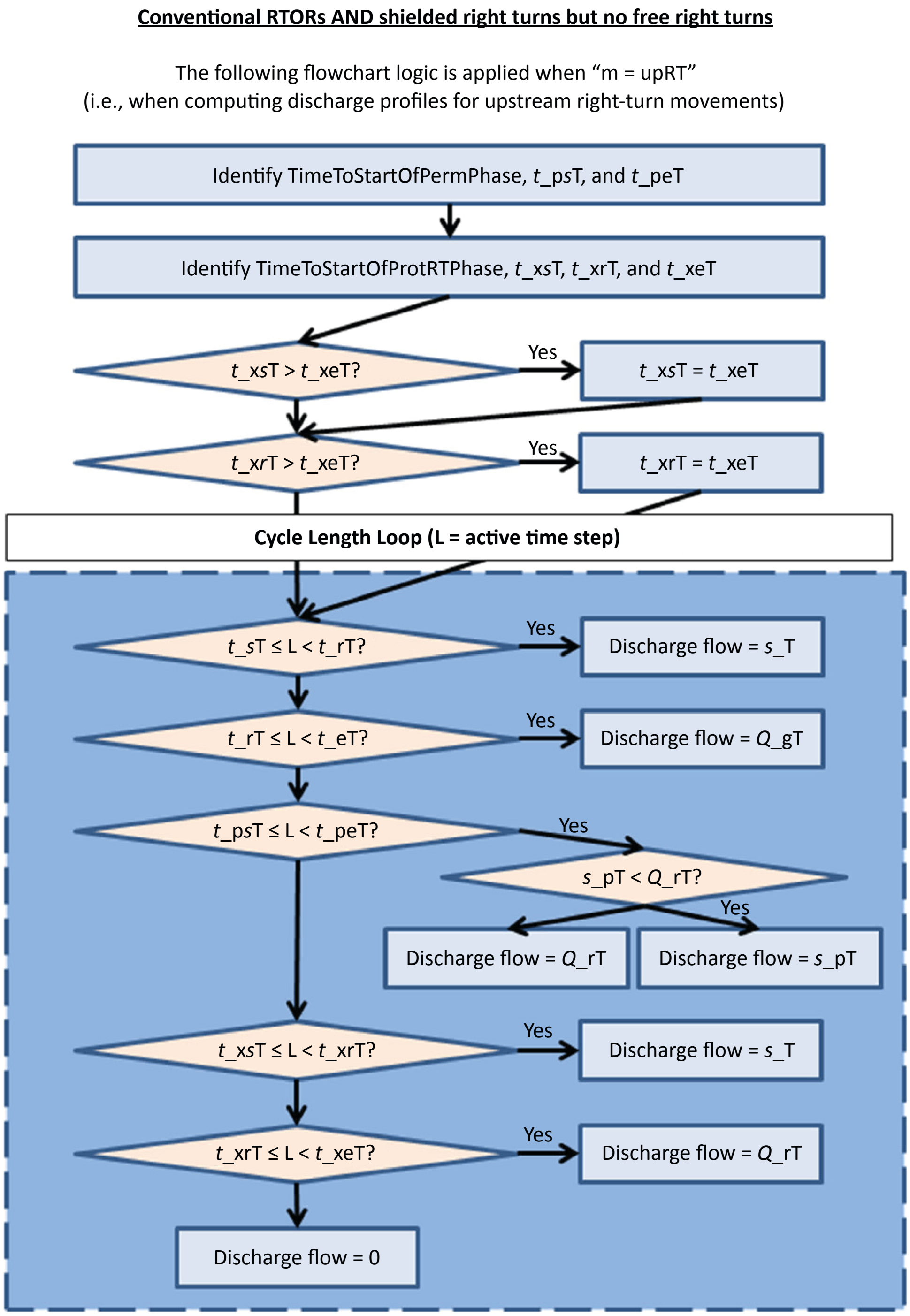


FIGURE 4 RTOR-plus-shielded discharge flow rate methodology.

illustrate the RTOR-only methodology, shielded methodology, and RTOR-plus-shielded methodology, respectively.

Summary of Proposed Improvements

The proposed improvements are summarized next. In the event that the TRB Standing Committee on Highway Capacity and Quality of Service develops an explicit RTOR permissive movement model, Items 1 and 2 would become unnecessary but proposed Items 3 through 5 would still be needed:

1. Base maximum flow calculation for upstream RTOR from the minor street (section on permissive movement models) (provides necessary maximum flow values for RTOR discharge flow profile calculations),
2. Maximum flow rate adjustment for upstream RTOR from the minor street (section on maximum flow rates) (unadjusted maximum flow rates should be adjusted by typical HCM 2010 methods),
3. Discharge flow logic for upstream free right turns from the minor street (section on discharge flow rates) (generates free right arrival profile and prevents flow profiles from ignoring free rights),
4. Discharge flow logic for upstream shielded right turns from the minor street (section on discharge flow rates) (generates shielded arrival profile and prevents flow profiles from ignoring shielded rights), and
5. Discharge flow logic for upstream RTOR from the minor street (section on discharge flow rates) (generates RTOR arrival profile and prevents flow profiles from ignoring RTOR).

COMPARISON OF ORIGINAL AND PROPOSED LOGIC

This section provides three categories of evidence to show that the proposed logic improves modeling accuracy. First, flow profiles are visibly shown to reflect upstream RTOR more realistically. Second, a statistical analysis of performance measures shows significantly reduced error between the HCM 2010 and microsimulation when the proposed logic is in effect. Third, vehicle trajectories from microsimulation exhibit improved pattern matching when compared with flow profiles under the proposed logic. Finally, case study results demonstrate the potential impact of these changes.

To test the proposed logic, a synthetic traffic network was created in HCS and exported to CORSIM (*11*). Figure 5 illustrates the synthetic traffic network and upstream signal phasing. Comparisons were then made between a new HCS (containing the proposed corrections), the old HCS, and CORSIM Version 6.3. The synthetic network was designed so upstream RTORs from an exclusive lane made from the northbound minor street onto the eastbound major street would significantly affect flow profiles at the downstream signal with a 152-m distance between signals. Signal spacing exceeding 300 m would smooth out flow profiles and reduce their impact. Signal spacing of less than 100 m would cause downstream flow profiles to match upstream saturation flows; this outcome would make it difficult to assess the proposed logic. Similarly, an RTOR flow rate of 500 vph was chosen for the experiments to illustrate that the proposed logic has significant impacts under typical conditions. RTOR flow rates of less than 500 vph would produce less impressive impacts, and more than 500 vph is considered uncommon.

The synthetic network scenarios are as follows:

SN1. No RTOR allowed, no shielded right-turn phase exists;
SN2. RTOR allowed, no shielded right-turn phase exists;
SN3. No RTOR allowed, shielded right-turn phase does exist; and
SN4. RTOR allowed, shielded right-turn phase exists.

Visual Assessment of Flow Profiles

Figures 6 through 8 illustrate arrival profiles for the downstream through movement. PVG values generated by these profiles significantly affect control delay and other performance measures. In the complex case (SN4) of both RTORs and shielded right turns, the first platoon spike (far left) shown in Figure 8*a* is caused by vehicles from the protected right-turn phase. The second spike is caused by vehicles from the shielded phase, but it dissipates after the right-turn queue is served. The third spike is caused by major-street through phase vehicles but dissipates into combined through plus right-turn arrivals after the through queue is served. In contrast, flow profiles from the original logic ignore RTOR and shielded right-turn vehicle movements.

Proposed Improvement 1 (out of 5) involves base maximum flow calculation for upstream RTOR from the minor street. Under the traffic conditions that generated Figures 6 through 8, performance measures are identical when either the HCM 2010 two-way stop control

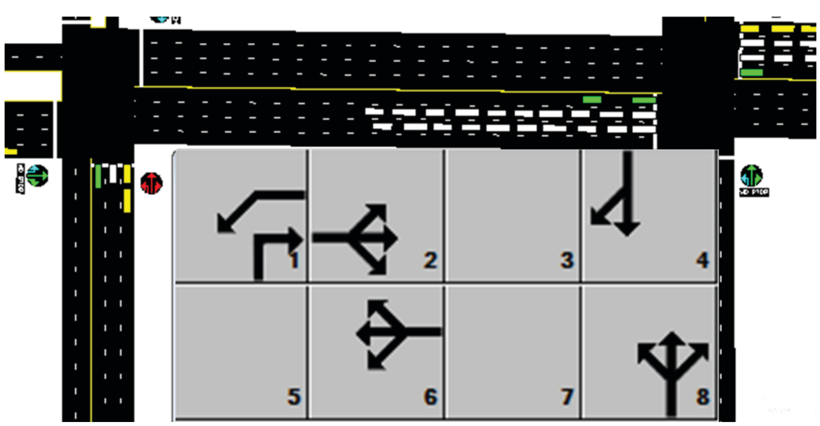
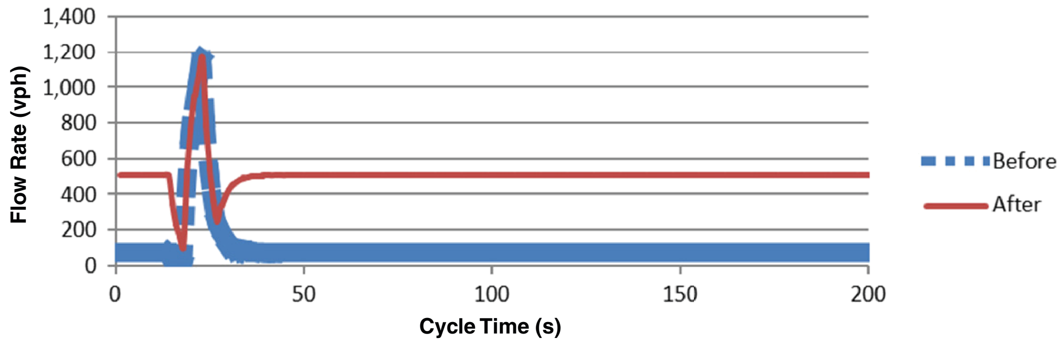
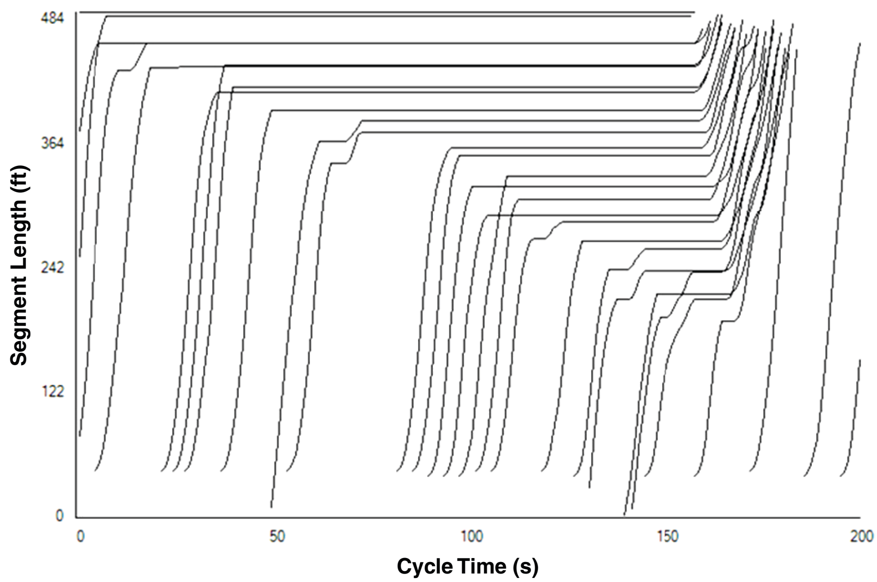


FIGURE 5 Testing conditions for RTOR and shielded right turns as shown in CORSIM.

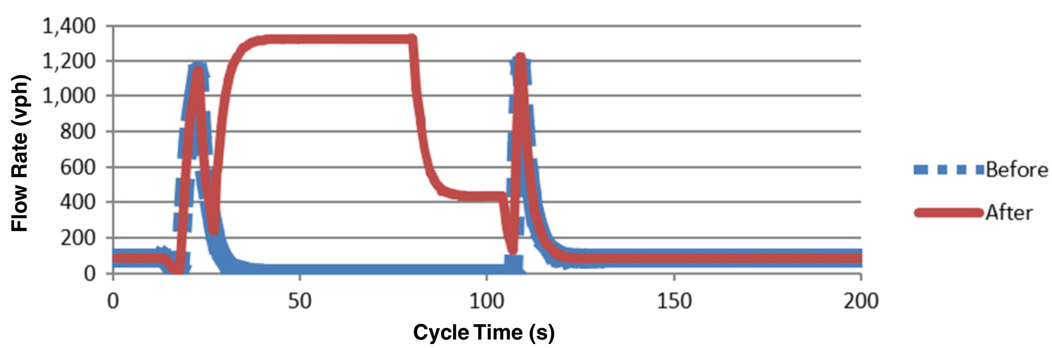


(a)



(b)

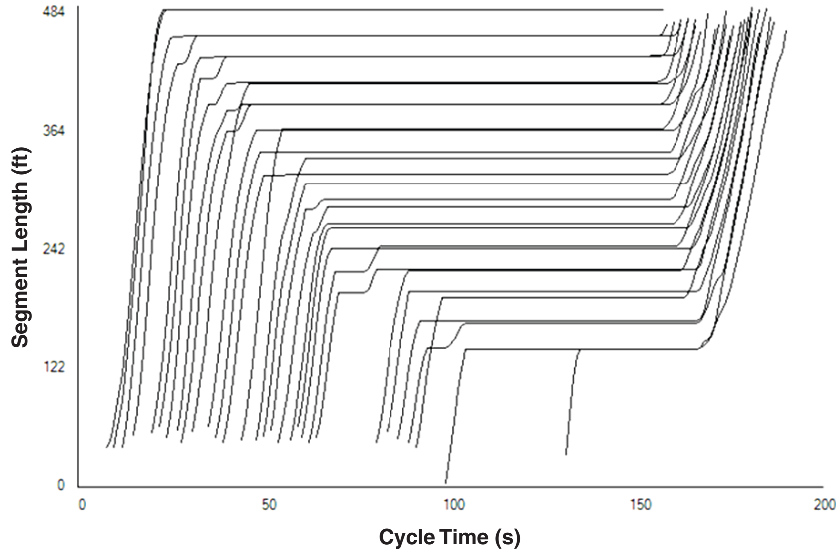
FIGURE 6 Case SN2 (RTOR only): (*a*) macroscopic flow profiles and (*b*) microscopic vehicle trajectories.



(a)

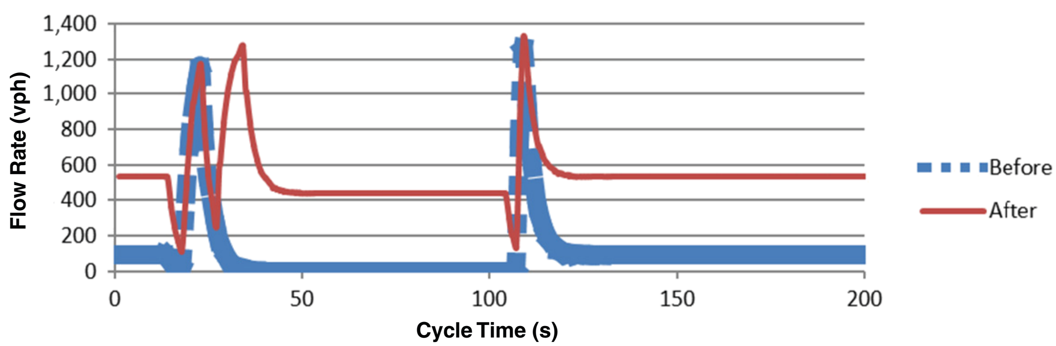
FIGURE 7 Case SN3 (shielded only): (*a*) macroscopic flow profiles.

(continued)

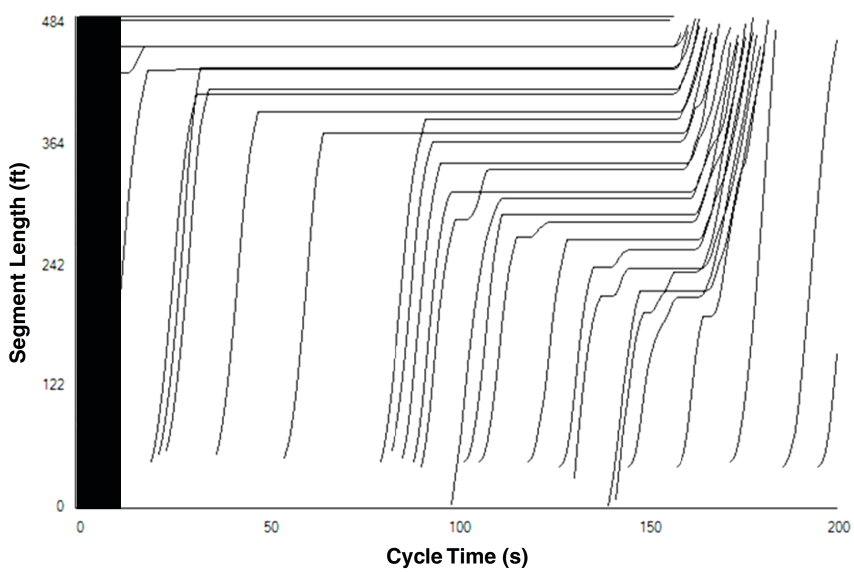


(b)

FIGURE 7 *(continued)* Case SN3 (shielded only): (*b*) microscopic vehicle trajectories



(a)



(b)

FIGURE 8 Case SN4 (both RTOR and shielded): (*a*) macroscopic flow profiles and (*b*) microscopic vehicle trajectories.

calculation or the calculation by Abu-Lebdeh et al. (*5*) shown in Equation 2 is used. This result is because base maximum flow rates predicted by the HCM 2010 (943 vph) and by Abu-Lebdeh et al. (1,234 vph) both exceed the arrival rate on red (500 vph):

HCM 2010 (*1*):

$$S_{\mathrm{RT}} = v_{c,x}\frac{e^{\frac{-v_{c,x}t_{c,x}}{3{,}600}}}{1-e^{\frac{-v_{c,x}t_{f,x}}{3{,}600}}} = 100 * \frac{e^{\frac{-100*6.9}{3{,}600}}}{1-e^{\frac{-100*3.3}{3{,}600}}} = 943 \text{ vph}$$

Abu-Lebdeh et al. (*5*):

$$S_{\mathrm{RT}} = a\left\{\max\left[\left(\left(1-\frac{g}{C}\right)s - V_c\right), 0\right]\right\} = \left(\frac{1{,}525}{1{,}714}\right)$$
$$* \left[\left((1-0.025)*1{,}525\right)-100\right] = 1{,}234 \text{ vph}$$

Thus the discharge flow rate is 500 vph during the RTOR phase, regardless of which model is in effect. Although this study did not investigate the ideal model for Proposed Improvement 1, results shown in Figures 6 through 8 imply that flow profiles under the proposed logic are more consistent with commonsense RTOR operation. Moreover, the new flow profiles are more consistent with vehicle trajectories from microscopic simulation. Vehicle trajectories from Figures 6 through 8 sometimes cross because there were two through lanes, and some vehicles passed others by selecting the lane with the shortest queue.

In Case SN2 (Figure 6), RTOR movements occur throughout the signal cycle except during the protected green phase, when right-turners briefly move at a higher flow rate. Thus under the proposed logic, the SN2 flow profile remains flat throughout the cycle, at a flow rate reflecting the combined upstream through and right-turning vehicles. Microscopic vehicle trajectories also reflect steady vehicle arrivals throughout the cycle. In Case SN3 (Figure 7), only the proposed logic correctly reflects right-turning vehicles flowing heavily between Time Steps 25 and 75. Most microscopic vehicle trajectories also reflect vehicle arrivals during the first half of the cycle. Finally, in Case SN4, right-turning vehicles flow steadily throughout the cycle under the proposed logic. However, the flow rate during the shielded phase (Steps 25 through 75) is significantly lower in SN4 than in SN3 because so much demand volume has already been served as RTOR during other parts of the cycle. Microscopic vehicle trajectories, which show steady vehicle arrivals throughout the cycle, are again more consistent with the proposed logic.

Statistical Analysis of Performance Measures

Visual analysis demonstrates that the proposed logic better reflects real-world traffic flow. However, statistical analysis can demonstrate that under the proposed logic, performance measures are more consistent with microsimulation. In addition, microsimulations provide a much larger sample size of results than field data; this size produces more confidence in the findings. In this experiment, the four basic scenarios (SN1 through SN4) were examined at 20 evenly spaced offsets (10-s intervals) throughout the 200-s cycle. Evenly distributed offsets throughout the cycle make it possible to analyze the full shape of the flow profile. For each of 80 total scenarios, an HCM 2010 analysis was performed with and without the proposed logic. In addition, 10 CORSIM simulations were performed with 10 sets of random seed numbers to generate a reliable average result for each scenario. Thus a total of 160 HCM 2010 and 800 CORSIM runs was conducted for the statistical analysis experiment.

A paired *t*-test compares two population means in which observations in one sample are paired with observations in the other sample (*12*). In this experiment, two samples of observations were derived from the same scenarios and should thus be paired for comparison. The primary performance measure was the percentage of difference between HCM 2010 and CORSIM results. For the combined set of four basic scenarios (SN1 through SN4) and for each individual scenario, the data in Table 1 imply that the proposed logic produces statistically better results when CORSIM results are considered as the ground truth. On average, differences between the HCM 2010 and CORSIM were approximately 5.2% lower under the proposed logic for both control delays (5.25%) and travel times (5.22%).

TABLE 1 Statistical Analysis Results for Control Delay and Travel Time

				Difference Between Old and New Methods (95% confidence interval)		
Scenario	*t*-Statistic	Degrees of Freedom	*P*-Value	Mean	Lower Bound	Upper Bound
Percentage of Difference in Control Delay						
Overall	2.0172	79	.0471	0.0525	0.0007	0.1043
SN1	na	19	na	0	0	0
SN2	2.7804	19	.0119	0.0360	0.0089	0.0631
SN3	1.8474	19	.0803	0.1757	–0.0234	0.3747
SN4	–0.0526	19	.9586	–0.0016	–0.0661	0.0629
Percentage of Difference in Travel Time						
Overall	3.0893	79	.0027	0.0522	0.0185	0.0857
SN1	na	19	na	0	0	0
SN2	1.3981	19	.1782	0.0155	–0.0077	0.0387
SN3	2.6922	19	.0144	0.1569	0.0349	0.2789
SN4	1.7741	19	.0920	0.0362	–0.0065	0.0789

NOTE: na = not applicable.

Overall *P*-values less than .05 imply a 95% confidence level for both of these improvements (control delay and travel time).

In the data analysis, control delay and travel time improved the most under Scenario SN3 (shielded right turns only), by 17.6% and 15.7%, respectively. However control delays improved by 3.6% for Scenario SN2 (RTOR only), and travel times improved by 3.6% under Scenario SN4 (both RTOR and shielded right turns). This finding appears consistent with flow profiles observed in Figures 6 through 8 because the shielded right-turn scenario experiences the biggest shape change, whereas the RTOR-plus-shielded scenario exhibits the biggest cycle-wide magnitude change. According to the HCM 2010 urban street procedure, flow profile shapes and magnitudes are converted into PVG and segment flow rates, respectively. Subsequently, the HCM 2010 signalized intersection procedure uses PVG to determine control delay, and the urban street procedure uses segment flow rates to compute travel time.

According to various microsimulation guidelines, a statistical check can determine the appropriate sample size (*13, 14*). If the formula from the Virginia Department of Transportation (*13*) is applied to the data in Table 1, the appropriate sample size for control delay would be 5.1 simulations, and for travel time it would be 3.6 simulations. Thus, it can be concluded that 10 simulations per scenario produced reliable results.

Impact of Flow Profiles on Performance Measures

Although the statistical analysis illustrated flow profile impacts on performance measures, a case study of the same RTOR flow rate (500 vph) at only one offset point can illustrate these impacts. In the abstract, it is stated that omission of RTOR in the flow profiles can cause vehicle delays to be inaccurate by more than 30%. According to Table 2, vehicle delays were more than 30% different (67 versus 96 s per vehicle) under the original procedure and the proposed logic in Case SN3. Because HCM 2010 control delay is considered an important performance measure by decision makers and is used to determine LOS, the significant change implies an incentive to incorporate the proposed logic sooner rather than later.

Two observed values of PVG results under two random seed numbers were obtained by time-consuming inspection of CORSIM animation, because PVG statistics were not provided by the software. Each observed PVG result was the average of 18 PVG results observed during a 1-h simulation. Under the proposed logic, special-case right turns (RTORs, shielded, free) changed the PVG result and travel time (TT) by less than 10% and 6 s, respectively. These changes are more consistent with those in CORSIM, in which special-case right turns change PVG and TT by less than 6% and 6 s, respectively. Although absolute TT correlates better under the old logic, the impact of special-case right turns on PVG and TT results correlates better under the new logic. Eliminating absolute differences between the HCM 2010 and microsimulation is beyond the scope of this paper, but special-case right-turn effects were more consistent with microsimulation under the new logic.

CONCLUSIONS

There has been natural interest in integrating HCM 2010 procedures for signalized intersections, urban street segments, and interchange ramp terminals because they all require detailed signal analysis. This integration has presented various challenges, including the treatment of RTORs. The treatment of RTORs by the signalized intersection procedure causes urban street and ramp terminal procedures to lose accuracy. Rather than remove RTOR support from the unified computational process, it would be preferable to improve RTOR support. Five specific modeling enhancements are proposed; they allow the urban street procedure and computational engine to model RTORs, free right turns, and shielded right turns more accurately in a way that does not change preexisting support for RTORs in the signalized intersection procedure. In a unified engine, the five enhancements will also improve the accuracy of ramp terminal analysis.

These computational software improvements could facilitate acceptance of the HCM 2010. They have been shown to affect delays and LOS greatly, by making the status quo less acceptable and change more desirable. A case study is used to demonstrate how significant the impacts can be when a reasonable RTOR methodology is implemented instead of a nonexistent RTOR methodology.

As for possible future enhancements, the interrupted-flow procedures and engines could be expanded for explicit analysis of “channelized” right turns, which yield to conflicting through vehicles. Unlike RTORs, the channelized rights would not have a protected green phase. The new logic could therefore be a hybrid of RTOR and free right-turn logic, with new input parameters to indicate the existence of channelized right turns. Interrupted-flow procedures could also be expanded to model RTOR explicitly as a permissive movement and make left-turn and right-turn treatments more consistent. Engineers would no longer need to estimate the number of RTOR vph. Finally, it would help to incorporate adjustments recommended by Creasey et al. (*4*) and Chen et al. (*15*), such as RTORs made from a shared lane or a dual right-turn lane or yielding to opposing left-turners.

TABLE 2 Downstream Performance Under Original and Proposed Logic

	Control Delay (s/vehicle)		Arrivals on Green (%)				Travel Time (s)			
	HCS		HCS		CORSIM		HCS		CORSIM	
Scenario	Old	New	Old	New	Run No. 1	Run No. 2	Old	New	Run No. 1	Run No. 2
None (SN1)	92	92	10	10	13	18	105	105	91	88
RTOR (SN2)	69	88	38	19	11	18	82	101	95	85
Shielded (SN3)	67	96	40	8	18	17	77	110	88	90
Both (SN4)	69	89	39	18	12	15	82	102	88	90

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