Capacity for Right Turn on Red

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Right turn on red (RTOR) can have a significant effect on intersection operation, but RTOR volume data are seldom collected and are not available for solving intersection design problems. Two techniques have been suggested for analyzing RTOR in the absence of field data. The first is to assume that during a protected left-turn phase, the RTOR movement that is "shadowed" by the protected left turn can have a volume equal to the per-lane volume of the shadowing left turn. The second technique suggests that the movement of an RTOR vehicle is analogous to the movement of a right-turning vehicle at a stop sign–controlled, unsignalized intersection. Extra capacity is present for an RTOR vehicle to move through the unsaturated green portions of movements that currently have a green indication. These two approaches are examined with data from 40 intersections to determine ways to provide a more realistic estimate of intersection operations when significant RTOR volumes may occur. Both approaches yield significant changes in reported intersection operation. For instance, shadowing improved the reported level of service for almost a third of the exclusive right-turn lanes. The stop sign analogy drastically reduced the number of right-turn lanes reported as over capacity. Neither approach is modeled correctly by the *Highway Capacity Manual* delay equation used for estimating level of service, but modeling of RTOR with the stop sign analogy could lead to a more realistic description of intersection performance and a more efficient use of green time as well as eliminate the construction of unneeded lanes.

The 1985 *Highway Capacity Manual* (HCM) states that when right turn on red (RTOR) is allowed at a signalized intersection, the analyst may reduce the right-turn volume by the RTOR volume (*1*). To implement this concept in the HCM operational analysis, one needs an estimate of the RTOR volume. However, such data are seldom collected during intersection traffic counts and would not be available for the design or retiming of an intersection.

While analyzing existing traffic counts with the HCM operational procedure, Virkler and Chen (*2*) found that RTOR may have a significant influence on the resulting flow-to-capacity ratios (v/c) and level of service (LOS). In several cases, right-turn volumes were much greater than the estimated capacity on green. Since actual volume cannot exceed capacity, the most likely explanation was that a significant RTOR volume was present. In these cases a good estimate of RTOR flow could dramatically change the estimated v/c and LOS.

Two techniques have been suggested for analyzing RTOR in the absence of field data. The first is to assume that during a protected left-turn phase, a parallel RTOR movement can take place because there is no conflicting traffic (e.g., during a protected left-turn phase for traffic approaching from the south and turning to the west, RTOR traffic approaching from the west and turning to the south will have no conflicting traffic). This approach is included in the updated version of the HCM intersection operational procedure (*3*). The second technique, proposed by Luh and Lu, suggests that the movement of an RTOR vehicle is analogous to the movement of a right-turning vehicle at stop sign–controlled, unsignalized intersection (*4*). The HCM's procedure for a right-turn at an unsignalized intersection can therefore be modified to estimate the RTOR capacity.

The objective of this research was to examine these procedures to determine how to provide a more realistic estimate of intersection operations when significant RTOR volumes may occur. The procedures were applied to the data on 40 intersections used by Virkler and Chen. The procedures, data, analysis, results, and conclusions are described.

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ALTERNATIVE PROCEDURES

New HCM Signalized Intersection Operational Analysis (Shadowing)

An analyst can estimate an expected RTOR volume with the revised signalized intersection operational analysis. This expected volume is recommended for use if the field-counted RTOR volume is not available. The protected left-turn volume (on a per-lane basis) is deducted from the "shadowed" RTOR volume, if an exclusive right-turn lane is available. For example, if dual left-turn lanes carry 300 left-turning vehicles from the northbound approach (150 left turns per lane) during a protected left-turn phase, then 150 RTOR vehicles can be subtracted from the eastbound approach right-turn lane volume. If the RTOR approach has a shared right/through lane, then this number is reduced according to the likelihood that the RTOR will be blocked by a through vehicle (*3*).

HCM Stop Sign Analogy

Luh and Lu (*4*) demonstrated that the RTOR movement is similar to a right turn made at a stop sign–controlled approach. The HCM procedure for an unsignalized intersection can therefore be used to estimate the capacity for RTOR. An abbreviated version of the steps are shown in the list. Since a complete description of the steps would be lengthy, the reader is referred to specific tables and figures of the HCM (as cited) for more detailed discussion of the concepts.

1. *Identify conflicting traffic.* During the red phase, the right-turn vehicle can make an RTOR maneuver after stopping (if it is controlled by a red ball) or it can turn right by yielding to other movements that have the right of way (if it is controlled by a yield sign). The traffic to which the RTOR vehicle yields is called conflicting traffic (HCM, Figure 10-2). This conflicting traffic could be through traffic from the left side approach, protected left turns from the opposite approach, or no traffic (e.g., during a shadowed phase). Depending on the signal phasing, RTOR might be made during one

or two or all of these conflicting flows during a cycle. Each phase would be analyzed separately.

2. *Compute unsaturated red time.* If the conflicting movements have unsaturated green time during their phases (i.e., they are not operating at capacity), then the RTOR becomes possible. The amount of the time that could be used for RTOR movements is the unsaturated green time of the conflicting traffic (referred to as the "unsaturated red time" for RTOR). The calculation for unsaturated green time is demonstrated in Figure 9-9 of the HCM.

3. *Find critical gap.* Critical gap is the 50th-percentile gap used for the right turn at a stop or yield sign, as provided by HCM Table 10-2.

4. *Compute conflicting flow rate.* The conflicting traffic rate of flow during each phase's unsaturated red time is determined. The RTOR maneuver will be similar to a right turn from a stop or yield sign onto a street having this rate of flow. The conflicting flow will equal the arrival flow rate of the subject movement, since these conflicting vehicles will not have been part of an approach queue at the intersection (i.e., these conflicting vehicles arrived at the intersection during the green for their phase when no queue was present).

5. *Find potential capacity during each unsaturated red time.* The potential capacity is the capacity under ideal conditions (HCM, Figure 10-3). Each part of the red time (i.e., through traffic from the left side, left turns from the opposite approach, and no conflicting traffic during a shadowed phase) can have a potential capacity.

6. *Find adjustment factor for pedestrians.* The HCM adjustment for pedestrians blocking the right turn (HCM, Table 9-11) is applied to the potential capacity. Use the pedestrian volume that would interfere with the RTOR vehicle because of the signal indication

7. *Compute actual capacity.* The potential capacity for RTOR during each unsaturated red time is summed. This is the RTOR capacity of an exclusive right-turn lane.

For a shared right/through lane this number is reduced according to the likelihood that the RTOR will be blocked by a through vehicle.

Updated HCM Stop Sign Analogy

The HCM procedure for unsignalized intersections, like that for signalized intersections, is being revised. The newer unsignalized approach (*5*) is similar to the earlier version, but the resulting capacity numbers are different. Therefore the stop sign analogy was also applied using the new the HCM unsignalized intersection analysis procedure.

DESCRIPTION OF DATA AND DATA ANALYSIS

Virkler and Chen (*2*) examined pretimed and actuated signals for 40 typical intersections of the Missouri state highway system. Half of the data were from a large city (St. Louis), and the other half were from three smaller cities (Columbia, Jefferson City, and Sedalia). The data included 15-min turning movement counts, phase plans, and intersection condition diagrams. No RTOR volumes were available. The data contained both a.m. and p.m. peak-hour traffic counts, so 80 peak-period data sets were available.

Application of Shadowing Procedure

The 1994 HCM RTOR treatment can be applied to the right-turn lane groups that are shadowed by protected left-turn phases. The data set included 45 intersections with 112 approaches having shadowing phases. Of the 112 approaches, 71 approaches had exclusive right-turn lanes and 41 had shared right/through lanes.

The expected RTOR volumes for the lane groups were calculated by the shadowing procedure. In some cases the RTOR volume exceeded the field-counted right-turn volume. The *Highway Capacity Software* (*6*) would not allow an RTOR volume greater than the right-turn volume. In such cases the expected RTORs were set equal to the right-turn volume. Occasionally with a right-turn volume equal to 0, the software gave inconsistent values for delay (i.e., different answers were provided by subsequent runs of the software, apparently due to a memory problem caused by a volume equal to 0). To gain consistent output, a minimum value of 1 was assigned to the right-turn volume on green.

Application of HCM Stop Sign Analogy

Although the shadowing procedure applies only to shadowed RTOR, the stop sign analogy can be applied to right turns with or without a shadowing phase. The stop sign analogy was applied to all the exclusive right-turn lanes in the data. Because of the large time requirement for data analysis, shared right-turn lanes were omitted from this application. There were 99 exclusive right-turn lanes in the data. In cases in which the conflicting flow was very low–potential capacity values beyond 1,000 passenger cars per hour (pcph)—the HCM nomographs did not show potential capacity values. In these cases the curves were extrapolated.

Application of Updated HCM Stop Sign Analogy

The updated HCM stop sign analogy was applied to the 99 exclusive right-turn lanes. The updated unsignalized intersection parameters gave higher potential capacities in most of the cases.

RESULTS

The different effects of the procedures complicates the comparison of results. The shadowing method reduces the right-turn volume; the HCM stop sign analogies increase the capacity of the right-turn lane group. These effects are described separately.

Right-Turn Volume Reduction from Shadowing

The right-turn volume reduction from the shadowing procedure ranged from 0 to 100 percent. In exclusive right-turn lanes the mean reduction was 67 percent, and in shared through/right-turn lanes the mean reduction was 36 percent. Figures 1 and 2 are comparisons of lane group v/c ratios with and without the right-turn volume reduction. Figure 1 deals with exclusive right-turn lanes. Many exclusive right-turn lane groups showed large v/c reductions. Figure 2 shows shared right-turn lane groups. The v/c reduction was dramatic for only a few shared lanes. Since the original lane group volumes (without shadowing) were actual flows, no v/c ratio should have exceeded unity if the no-RTOR assumption was correct. The shadowing procedure appears to make the large v/c ratios more reasonable. On the other hand, not all right turns will occur on red. With the shadowing procedure, the right-turn volume reductions can equal 100 percent of the original right-turn volume.

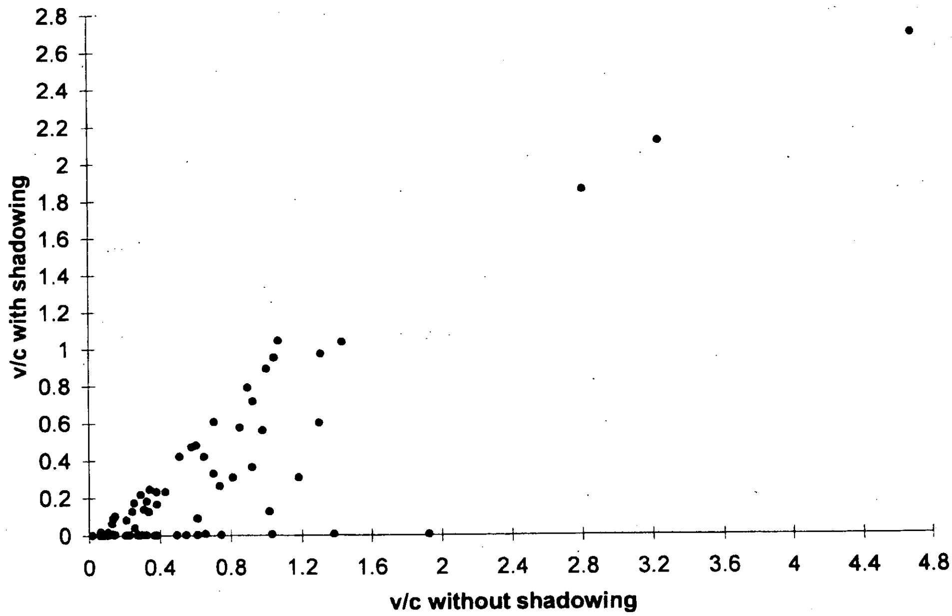

FIGURE 1 Effects of shadowing on exclusive right-turn lane groups.

The HCM average stopped delay equation is applicable for a 15-min period when v/c is less than 1 and can be applied to somewhat higher v/c ratios if the resulting queue would clear during the next 15-min period. If the v/c is too high, the delay and LOS (which is based on average stopped delay) are both reported as an asterisk (*) rather than in seconds and in an LOS category. A description of delay reductions would be incomplete because of the large number of situations in which the delay equation was not calculated because the v/c ratios exceeded the allowable maximum. However, the impact of shadowing on reported LOS is clearly visible. After the right-turn volume reductions from shadowing, many LOS results changed and many asterisks were replaced by a calculated LOS.

The delay equation used to determine LOS was not developed to consider RTOR. The shadowing procedure simply eliminates RTOR vehicles from the analysis. The following results should be read as a description of what the procedure will calculate, rather than as an accurate picture of the true LOS situation.

Figure 3 shows the changes in LOS for the 45 intersections (based on the average delay of all vehicles said to use the intersection and, therefore, not including subtracted RTOR vehicles). Four of the intersections, which originally included right-turn lane groups having v/c ratios too high for use of the delay model (in the before condition), were changed to LOS B, C, D, and E by shadowing (the after condition). Two intersections improved from LOS C to B, and one inter-

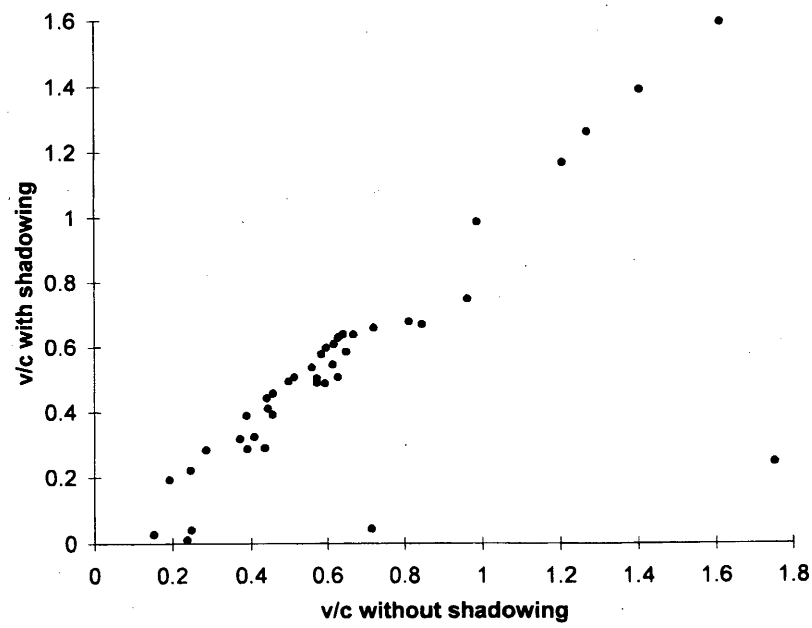

FIGURE 2 Effects of shadowing on shared right-turn lane groups.

	AFTER							
BEFORE	A	B	C	D	E	F	*	TOTAL
A	0							0
B		6	1					7
C		2	10					12
D				2				2
E					1			1
F						0		0
*		1	1	1	1		19	23
TOTAL	0	8	12	3	2	0	19	45

FIGURE 3 Changes in intersection LOS due to shadowing.

section regressed from B to C. This negative impact on LOS was due to the reduction in the right-turn volume in a low-delay right-turn lane. The average delay of all vehicles included in this intersection's analysis increased from 14.7 to 15.1 sec (LOS C begins at 15.0 sec). Intersection delay sometimes increased because of the removal of low-delay right-turning vehicles, but the increases were all small.

The LOS impact of shadowing on the 112 intersection approaches (based on the average delay of all left through and right-turning vehicles said to use the approach and, therefore, not including subtracted RTOR vehicles) is shown in Figure 4. The top portion of the figure shows that for the 71 approaches with exclusive right-turn lanes, LOS improved in 12 cases (including 3 cases in which LOS could now be calculated because the v/c ratio had been reduced to within the range of the delay model). Two approaches jumped from LOS F to D, and one approach improved from E to C. The 41 approaches with shared right-turn lanes are described in the bottom half of Figure 4. LOS improved in seven cases (including three cases in which LOS could now be calculated because of the right-turn volume reduction). One approach leaped from LOS F to LOS D.

The impact on LOS was most dramatic within exclusive right-turn lane groups, as shown at the top of Figure 5. Among the 71 right-turn lanes, 22 (or 31 percent had improved LOS (including 5 that were now within the range of the delay model). Five lanes improved by two levels and two lanes improved from LOS F to LOS C.

The 41 shared right-turn lane groups are described at the bottom of Figure 5. Two of the five that originally were not within the range of the delay model could now be categorized. Three lane groups improved by one LOS.

	AFTER							
BEFORE	A	B	C	D	E	F	*	TOTAL
A	0							0
B		8	1					9
C		1	16					17
D			3	10	1			14
E			1	2	0			3
F				2		6		8
*				1	1	1	17	20
TOTAL	0	9	21	15	2	7	17	71

	AFTER							
BEFORE	A	B	C	D	E	F	*	TOTAL
A	0							0
B		8						8
C			12					12
D				5				5
E				3	4			7
F				1		0		1
*		1	1			1	5	8
TOTAL	0	9	13	9	4	1	5	41

FIGURE 4 Changes in approach LOS due to shadowing: *top*, exclusive right-turn lanes; *bottom*, shared right-turn lane groups.

	AFTER							
BEFORE	A	B	C	D	E	F	*	TOTAL
A	0							0
B		14						14
C		2	23					25
D		1	4	9				14
E			2	3	0			5
F			2	2	1	0		5
*				3	1	1	3	8
TOTAL	0	17	31	17	2	1	3	71

	AFTER							
BEFORE	A	B	C	D	E	F	*	TOTAL
A	0							0
B		11						11
C			15					15
D				4				4
E				2	3			5
F					1	0		1
*			1			1	3	5
TOTAL	0	11	16	6	4	1	3	41

FIGURE 5 Changes in lane group LOS due to shadowing: *top*, exclusive right-turn lanes; *bottom*, shared right-turn lane groups.

Capacity Increase from Stop Sign Analogies

The capacity increase from the HCM stop sign analogy ranged from 3 to 483 percent (with a mean of 113 percent) and from 22 to 875 vehicles. The capacity increase from the updated HCM stop sign analogy ranged from 4 to 561 percent (with a mean of 130 percent) and from 23 to 1,328 vehicles. No direct means to estimate the change in delay (and therefore LOS) caused by the capacity increase was apparent. The HCM delay equation is based on the assumption that vehicles depart from the intersection during their green phase. The stop sign analogies add capacity during the red phase. Whereas delay will be reduced by RTOR, the amount of the reduction cannot be modeled correctly by the HCM delay equation. Therefore, the discussion of results focuses on the change in v/c ratios.

Figure 6 shows the before and after v/c ratios for lane groups that originally had v/c ratios between 0 and 1.0. Data points are shown for the HCM stop sign analogy, the updated HCM stop sign analogy, and the shadowing procedure. However, the shadowing procedure results have been changed from volume reductions to capacity increases. Consider a right-turn lane group with a volume of 200 right turns, a capacity of 400 right turns on green, and a volume reduction from shadowing of 100 right turns during red. The v/c without shadowing would be 200/400, or 0.5. The v/c with the volume reduction from shadowing would be (200 − 100)/400, or 0.25. If the shadowing were interpreted as a capacity increase rather than a volume decrease, then the v/c would be 200/(400 + 100), or 0.40. The latter interpretation is used in Figure 6. Many of the changes in v/c from shadowing appear small, but almost all of the stop sign analogy changes appear fairly large.

The results are most dramatic for the 12 lane groups that originally had v/c ratios greater than unity (Figure 7). Three lane groups that originally had incredible v/c ratios of 2.8, 3.2, and 4.7 were reduced to ratios below 1.7 by all three applications. The shadowing procedure left six lane groups significantly above unity, while the stop sign analogies each left three significantly above unity.

Critical v/c Ratios for Intersections

Five of the 80 original intersection analyses indicated that the critical v/c for the intersection was greater than unity. In such cases the present intersection and timing arrangement would be judged to be incapable of serving the demand. The analysis of RTOR, however, indicated that some of these intersection v/c values were too high. Table 1 presents the intersection v/c values before and after consideration of RTOR. In Case 1 the v/c was reduced moderately. In Cases 2 and 3 all three methods gave a result below or nearly below capacity. In Case 4 no change occurred because the right-turn lane group was not a critical movement. In Case 5 no shadowing protected left turn was present, so only the stop sign analogies led to indications of below-capacity operation.

CONCLUSIONS

The results indicate that many right-turn lane groups and intersections will be deemed to be over capacity unless RTOR is considered explicitly. It is likely that in some of these cases, analysts would consider adding unneeded lanes, providing unnecessary green time, prohibiting left turns, or implementing other measures when demand could be handled without these actions.

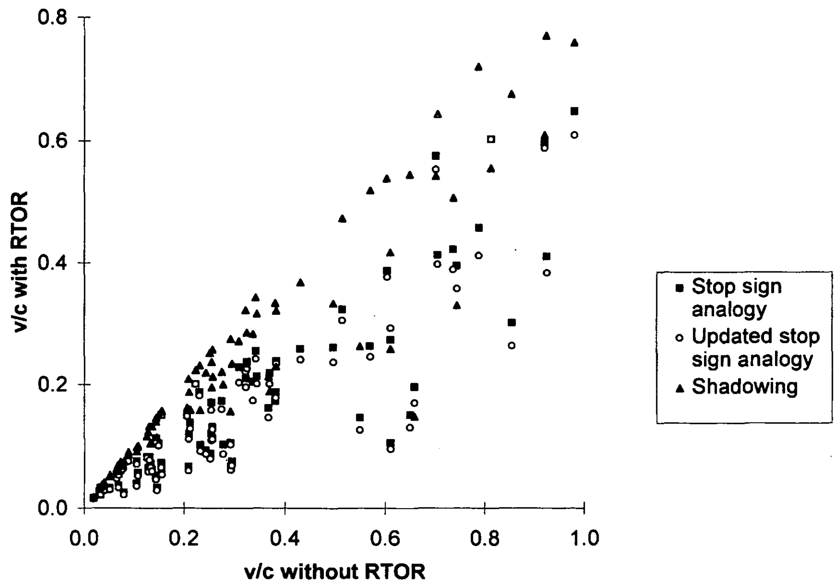

FIGURE 6 RTOR effect on lane group v/c (v/c without RTOR < 1).

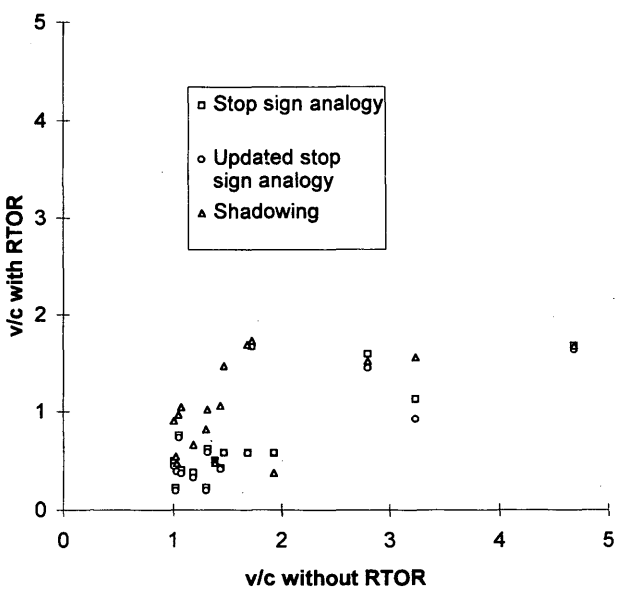

FIGURE 7 RTOR effect on lane group v/c (v/c without RTOR > 1).

Two rational approaches are available to consider RTOR. The shadowing procedure is conservative in its logic, simple to implement, and available with the new HCM signalized intersection procedure. The stop sign analogy is consistent with the HCM analysis of unsignalized intersections and yields higher RTOR capacity, but it would require a significant effort to be placed within a computer application of the HCM. Either approach would probably be better than assuming zero RTOR volumes. However, both methods need refinements for estimating delay and LOS.

The shadowing procedure eliminates 0 to 100 percent of right-turning vehicles from demand. The procedure can underestimate the RTOR volume by ignoring RTOR through a conflicting stream having significant unsaturated green time. On the other hand, the shadowing procedure can indicate that all right turns occur on red, which is unrealistic. In reality, the right turn on green and RTOR vehicles will experience some stopped delay, but less than that which would be determined by assuming no RTOR.

The stop sign analogy increases the right turn capacity. Since this extra capacity would be available during the red phase, the HCM delay equation is not directly applicable. The stop sign analogy also does not indicate how much of the demand will use RTOR. Since the unsaturated red time (unsaturated green of the conflicting flow) is not uniform throughout the red phase, estimating RTOR volume

TABLE 1 Changes in Intersection Critical v/c Ratio

	Intersection Critical v/c Ratio			
CASE	Without RTOR	With Shadowing	With Stop Sign Analogy	With Updated Stop Sign Analogy
1	1.68	1.55	1.55	1.55
2	1.31	1.00	0.97	0.97
3	1.31	0.99	0.96	0.96
4	1.18	1.18	1.18	1.18
5	1.01	1.01	0.86	0.86

and delay becomes a complicated task. However, it appears likely that a procedure could be created to estimate delay with RTOR.

A computer version of the updated stop sign analogy should be developed. Until this is available, an analyst should apply the shadowing procedure when a right-turn lane group, without RTOR, is found to be over capacity. If the shadowing procedure leaves a right-turn lane group significantly over capacity, then the analyst should manually apply the updated stop sign analogy (at least to the nonshadowed phases) to estimate the capacity situation, if there is unsaturated green time within the conflicting flows.

A procedure for estimating delay under the stop sign analogy should be developed and tested. HCM users familiar with the treatment of protected plus permitted left turns can appreciate the complexity of a procedure to estimate RTOR flows. However, this effort could lead to a more realistic description of intersection performance. In many cases it will yield more efficient use of green time and avoid the construction of unneeded lanes.

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