Right-Turn-on-Red Characteristics and Use of Auxiliary Right-Turn Lanes

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ABSTRACT

Right-turn-on-red (RTOR) as a means of expediting traffic movements can be complemented with auxiliary right-turn lanes. In this study the characteristics of several RTOR flow parameters are identified from field observations. These and other flow characteristics are analyzed with a simulation model to examine alternative designs and operations relating to RTOR and the use of auxiliary right-turn lanes. To allow an auxiliary right-turn lane to fully serve its function, AASHO recommended that the storage length of such a lane be long enough to prevent a blockage of the traffic in an approach lane. Based on this design requirement, an analytical method for determining the storage lengths is developed.

Intersections are potential bottlenecks in a street network. Searching for ways to improve the operating efficiency of a street network has become an urgent problem because streets are becoming more crowded. Recent efforts in this connection have overwhelmingly focused on the development of better signal control systems. Although this undertaking is necessary, it cannot remove the constraints imposed on traffic movements by the geometric design of an intersection. There are situations where the use of an auxiliary right-turn lane in conjunction with right-turn-on-red (RTOR) can achieve a much needed improvement in the operating efficiency of an intersection.

RTOR is intended primarily as an energy conservation measure. Previous studies (1,2) have indicated that RTOR on urban streets has the potential of reducing fuel consumption by about 5 percent. The implications of RTOR for traffic safety, however, have received more attention in the past (3,4). Several studies (5,6) have also examined the general impact of RTOR on vehicle delays. But current understanding of this subject is still not sufficient to assist traffic engineers in making planning, design, and operating decisions.

The impact of RTOR on the operating efficiency of an intersection can be expected to be small if no auxiliary right-turn lanes are provided. The beneficial effects of an auxiliary right-turn lane can be fully realized only if the lane is sufficiently long. Otherwise, straight-through vehicles arriving during a red phase may block the entrance to the right-turn lane. Similarly, right-turn vehicles may block straight-through vehicles. To prevent such a blockage from occurring, AASHO (7) recommended that the storage length of an auxiliary lane be based on 1.5 to 2 times the average number of vehicles that would be stored per signal cycle. This recommendation is convenient to follow but is vague in the methods needed to obtain an estimate of the average number of stored vehicles per cycle. It may not lead to a proper design in terms of intersection operation or resource allocation. A better method of determining the storage requirements of auxiliary right-turn lanes is needed.

To provide a better understanding of the potential and limitations of using auxiliary right-turn lanes with RTOR to improve intersection operations, several observed RTOR flow characteristics are first described. This is followed by a discussion of the potential impact of auxiliary right-turn lanes with or without RTOR on vehicle delays. Finally, an analytical method for determining required lengths of auxiliary right-turn lanes is presented.

CHARACTERISTICS OF RTOR FLOWS

RTOR flows are associated with a greater variability of driver behavior than other types of directional flows at an intersection. They are also subject to the influence of a greater variety of signal control and traffic flow conditions. As a result, it is difficult to rely entirely on field observations to identify the complex relationships between RTOR and its related variables. An alternative approach is to identify the basic characteristics of RTOR flows from field observations and use them to develop a simulation model as an analysis tool.

For this reason data on various RTOR characteristics were collected in downtown Syracuse, New York, and its suburban area. These data made it possible to quantify several RTOR flow parameters. Included among them are the use of RTOR opportunities, the gap-acceptance behaviors of RTOR drivers, the dwell times of unopposed RTOR vehicles, and the efficiency in executing multiple right-turns-on-red. These parameters are described in the following sections.

Use of RTOR

The data in Table 1 give the proportions of right turns made during red intervals from 16 right lanes with mixed directional flows. The traffic flows at these sites were regulated with signal controls that have cycle lengths that range from 75 to 110 sec. The green phases for the right lanes accounted for 20 to 30 percent of the cycle lengths. The cross-traffic volumes were about 150 to 350 vehicles per hour (vph), with approach speeds less than 35 mph.

Although the red phases accounted for 70 to 80 percent of the cycles, the number of RTOR vehicles as a percentage of the right-turn vehicles was low in most of the lanes examined. In 12 out of the 16 lanes, for example, less than 30 percent of the

TABLE 1 Rates of RTOR

Lane	Flow Rate (vph)	Right-Turn Percentage	Percentage of Right Turns Making RTOR from: Traffic Lane	Shoulder
1	150	43	20	7
2	345	63	31	5
3	162	43	29	0
4	162	45	35	3
5	166	15	38	1
6	331	47	41	3
7	376	42	5	36
8	265	35	77	3
9	413	45	17	0
10	272	44	21	0
11	298	54	25	5
12	513	39	11	68
13	431	16	20	0
14	240	22	9	1
15	466	22	11	0
16	135	50	10	4

Note: vph = vehicles per hour.

right turns were made from regular traffic lanes during red phases. The average for the 16 lanes was only 21.8 percent of the right turns.

When the circumstance permitted, a driver made RTOR from a shoulder. It is interesting to note that a small increase in the approach width of an intersection can drastically raise the rate of RTOR use. This phenomenon is exemplified by the RTOR flow rates of Lanes 7 and 12 given in Table 1. Both lanes have an unpaved shoulder area about 6 ft wide. The shoulders are not intended to carry traffic, but a large proportion of the right-turn drivers in either lane pulled onto the shoulder and subsequently executed RTOR. This demonstrates the need to provide exclusive right-turn lanes to accommodate RTOR vehicles.

In contrast, many drivers may elect not to use RTOR opportunities. Based on observations of 359 leading right-turn drivers in 10 right lanes, it was found that the rate of rejection for using RTOR opportunities was 16 percent among the drivers. One major reason for rejecting RTOR is likely to be drivers' ignorance of the RTOR regulation. Current lack of uniformity in RTOR signing may be another factor that contributes to some drivers' reluctance to execute RTOR at certain intersections. The existing rejection rate can be expected to dwindle to a negligible level in the future when drivers become more familiar with RTOR regulation and signing.

Gap-Acceptance Behavior

The rate of RTOR use is also governed in part by the sizes of the gaps (headways) in the cross traffic and by the ability of the right-turn drivers to accept such gaps. To quantify the gap-acceptance behavior of the RTOR drivers, field data on leading right-turn driver movements during red intervals were collected from 10 right lanes.

This task was tedious and difficult mainly because of the lack of suitable intersections where a large sample of data could be obtained in a short period of time. RTOR driver behavior and the existence of mixed directional flows in every lane examined further aggravated the situation. As mentioned previously, some right-turn drivers chose not to execute RTOR even when there was ample opportunity to do so. Other right-turn drivers were blocked by straight-through or left-turn vehicles. And some leading right-turn drivers were able to make RTOR without opposition.

From the 10 right lanes chosen for the study, a total of 359 leading right-turn drivers was observed. Out of this total only 202 rejected at least one gap before merging into the cross traffic. The behavior of these drivers indicates that a gap of less than 5 sec has little chance of being accepted and a gap of greater than 15 sec is unlikely to be rejected. The critical gap of these drivers, as shown in Figure 1, was found to be about 8.4 sec. This gap is considerably longer than the typical critical gaps of 4 to 5.5 sec of opposed left-turn drivers (8,9,10).

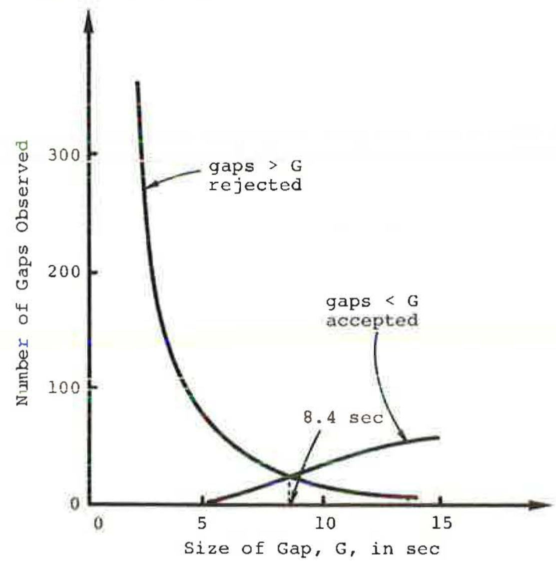

FIGURE 1 Gap-acceptance characteristics of RTOR drivers.

An RTOR driver who accepts a gap will consume a portion of the gap. This is because the turning vehicle has to wait until after the leading cross-traffic vehicle that forms the gap passes the conflicting point. On average, it took the observed RTOR drivers 3.1 sec after the passing of the leading cross-traffic vehicle to execute RTOR. This magnitude of the elapsed time has an adverse impact on the RTOR capacity of a right lane.

Dwell Time of Unopposed RTOR Drivers

RTOR drivers are required to come to a stop before making the turn. This requirement incurs a dwell time for every RTOR driver. The dwell time is defined as the elapsed time from the moment a driver reaches a position from which he can make RTOR until he starts executing the turn. In the field investigation a total of 246 right-turn drivers who made RTOR without any opposition were observed. The average dwell time of these drivers was 4.4 sec. Approximately 40 percent of these drivers executed RTOR within 2 sec of their arrivals at the merging position. This represents the proportion of drivers who violate the requirement to come to a stop.

Multiple RTOR

When a long gap is available in the cross traffic, several drivers may be able to use this gap to execute multiple right-turns-on-red. The time required to do so can affect delays, number of stops, fuel consumption, and the capacity of a right-turn lane. Figure 2 shows the observed relationship of this time requirement to the number of right-turns-on-red made in a gap by a queue of right-turn vehicles. The time requirement was measured from the moment the first RTOR vehicle was in a position to move until the last RTOR vehicle started the turn. The figure shows that two consecutive executions of RTOR would require an average of 10.5 sec. With five multiple turns, the average total time requirement reaches approximately 23.5 sec. This time requirement is long compared with an average of about 14 sec needed for the first five right-turn queuing vehicles to enter an intersection during a green phase. It is obvious that a red phase is only about 60 percent as useful as a green phase of the same length, even when cross traffic does not exist.

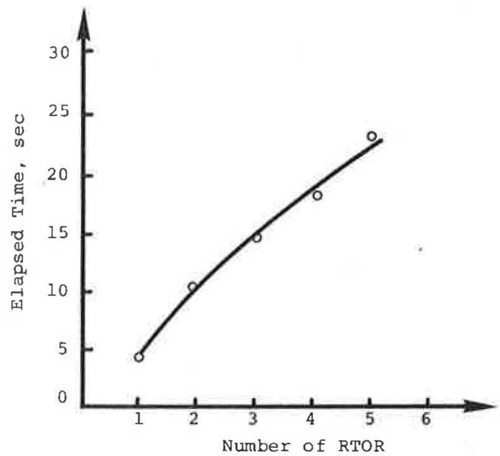

FIGURE 2 Time requirements for multiple RTOR.

EFFECTS OF RIGHT-TURN LANES

The ability of an auxiliary right-turn lane to reduce vehicle delays depends on a number of factors. These factors include the storage length of the right-turn lane, right-turn percentage of the approaching vehicles, flow rates, RTOR policy, type of signal control and signal timing settings, pedestrian flows. The large number of influencing factors precludes a comprehensive analysis of the impact of right-turn lanes. Nevertheless, insight into the potential impact of right-turn lanes can be obtained with an analysis of limited scope. An analysis of this nature is presented herein. The analysis is based on an intersection controlled with a two-phase pretimed signal. Furthermore, pedestrian interferences with the right-turn vehicles are assumed to be negligible and the rightturn lane has a sufficiently long length to avoid blockage of the traffic lanes.

To facilitate the analysis, a simulation model is calibrated in part on the basis of the RTOR data described previously. Field data on straight-through and right-turn queuing flows are also used in the calibration. However, one deviation from the observed RTOR flow characteristics is allowed in the model. This deviation stems from an implicit assumption in the model that every driver will use RTOR opportunities. This assumption could lead to slight overestimates of the impact of RTOR.

The operating efficiency of a signalized intersection is governed to a large extent by the discharge headways of dissipating queuing vehicles. Therefore, such headways are carefully treated in the simulation model. The data in Table 2 give the representative averages of observed queue discharge headways for three types of turning movements. It can be noted from the data in this table that the average discharge headways stabilize at a value of about 2.1 sec for straight-through vehicles and about 2.4 sec for right-turn vehicles. The corresponding saturation flow rates are approximately 1,700 vph for straight-through flows and 1,500 vph for right-turn flows. The variations among individual discharge headways are large.

TABLE 2 Representative Average Queue Discharge Headways

Queuing Position	Avg Discharge Headways (sec) ST	RT	Mixed ST and RT
1	3.3	3.6	3.2
2	2.6	2.8	2.7
3	2.4	2.6	2.5
4	2.3	2.5	2.5
5	2.2	2.5	2.3
6	2.2	2.5	2.2
7	2.1	2.4	2.2
8	2.1	2.4	2.2
9	2.1	2.4	2.2
10	2.1	2.4	2.2

Note: ST = straight through and RT = right turn.

The discharge headways of those vehicles in the same queuing position can be represented in terms of the percentages of their average. With this transformation, it was found that the discharge headways have a distribution that conforms to the one shown in Figure 3. This distribution is applicable to all types of turning movements and to all queuing positions.

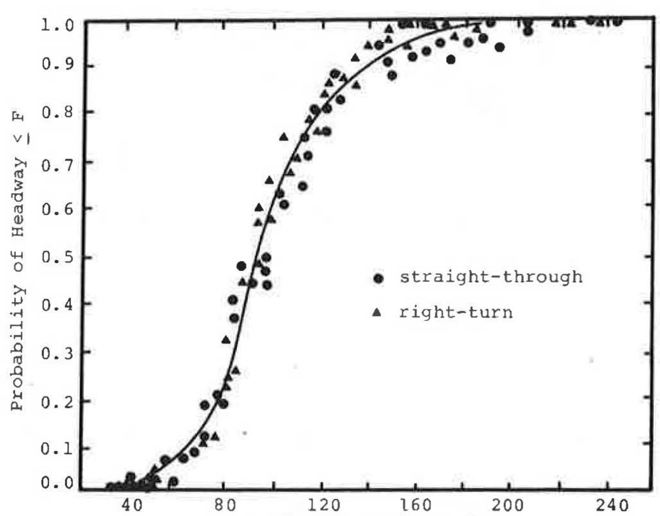

FIGURE 3 Normalized cumulative distribution of headways.

Figure 3 shows that the discharge headways may vary from about 40 percent to more than 240 percent of the averages. The upper bounds of the variations are not the same for all queuing positions. Field data indicate that such upper bounds can be approximated by the following equation:

$$U = 163 + 14.5i + 3i^2 - 0.5i^3 \leq 240 \quad (1)$$

where U is the upper bound and i is the queuing position of a vehicle. The queue discharge characteristics, as represented by Table 2, Figure 3, and Equation 1, are incorporated into the simulation model.

The model is used to examine delays associated with three alternative combinations of geometric design and RTOR policy. The first alternative has an approach lane without an auxiliary right-turn lane and RTOR is not permitted. The second alternative has an approach lane that diverges into a straight-through lane and an auxiliary right-turn lane without RTOR. The last alternative has the same geometric design as the second alternative, but RTOR is allowed.

Without RTOR

Figure 4 shows the average delays of vehicles in a mixed straight-through and right-turn flow under a specific signal control condition. The signal has a cycle length of C = 60 sec and a green phase of G = 26 sec for the arriving vehicles. The figure reveals that the availability of a right-turn lane decreases the average delays by about 20 percent when right-turn vehicles account for 10 percent of the arriving vehicles. When right-turn vehicles account for 40 percent of the arriving vehicles, the delays can be reduced by 20 to 50 percent, depending on the arriving flow rate.

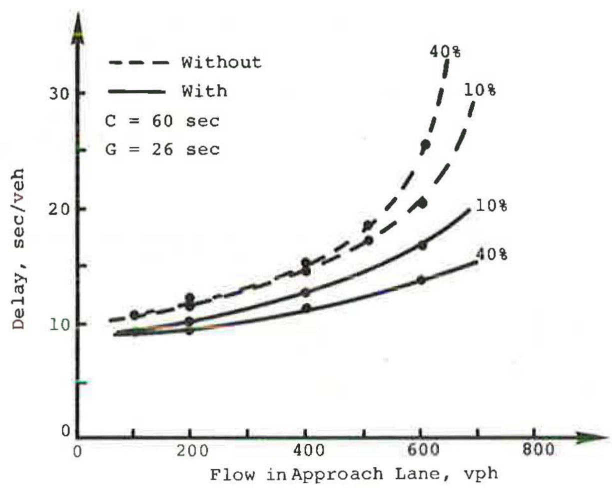

FIGURE 4 Vehicle delays with and without right-turn lanes at two levels of right-turn percentages.

The reductions in delays attributable to the presence of an auxiliary right-turn lane are also affected by signal timing settings. Figure 5 shows that the amount of reduction in delays would usually be less than 5 sec per vehicle under varied flow and signal conditions if the saturation ratio of the approach flow is less than 0.7. The saturation ratio is defined as

$$r = QC/SG_e \quad (2)$$

where

r = saturation ratio;
Q = approach flow rate;
C = cycle length;

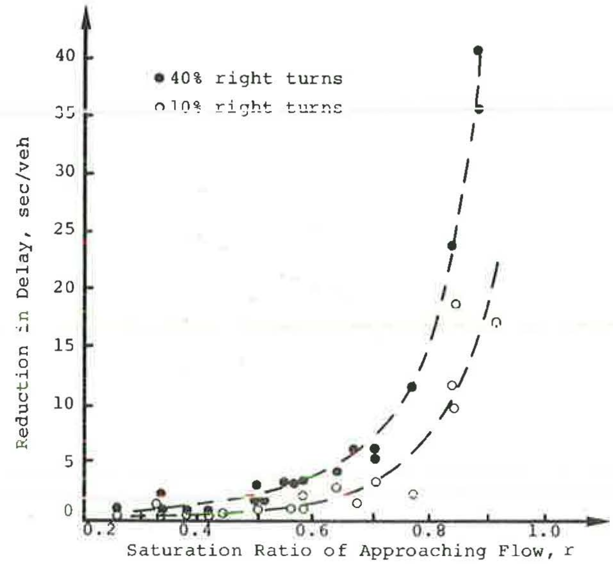

FIGURE 5 Reductions in average delays attributable to auxiliary right-turn lanes without RTOR.

G_e = effective green phase for the arriving vehicles, equal approximately to the green phase (G); and
S = saturation flow rate.

Figure 5 also shows that when the saturation ratio exceeds 0.8, even a right-turn percentage of only 10 percent could reduce delays substantially. This is not an unexpected result. Under pretimed control, the delays rise rapidly when the saturation ratio is greater than 0.8. At this level of the saturation ratio, the delays are about 25 sec or more per vehicle.

With RTOR

When RTOR is allowed from an auxiliary right-turn lane, right-turn delays may be further reduced. The extent of the reduction depends on the cross flow. When the cross flow is heavy and its saturation ratio approaches or exceeds 1.0, the gaps in this flow that are acceptable to the RTOR drivers would hardly exist. Consequently, RTOR would become virtually impossible. Under such circumstances RTOR cannot reduce right-turn delays. On the other hand, if the cross flow does not exist or is light, then the right-turn vehicles in a queue can execute multiple right-turns-on-red at a rate of about 1 vehicle per 4.7 sec (Figure 2). This could lead to a significant reduction in the delays.

The reductions in the right-turn delays attributable to RTOR also rest on the right-turn percentage. For example, with only 10 percent right turns in the approaching flow, RTOR has little influence on right-turn delays. With 40 percent right turns, then the availability of RTOR opportunities may reduce the delays substantially. This impact of RTOR at a 40 percent right-turn percentage is shown in Figure 6. Each of the curves in the figure represents the delays of a given right-turn flow under various cross-flow conditions. It can be seen from this figure that the average right-turn delays vary approximately in a linear manner with the saturation ratio of the cross flow. In this figure the average delays at a saturation ratio of 1.0 correspond closely to the average delays of right-turn vehicles

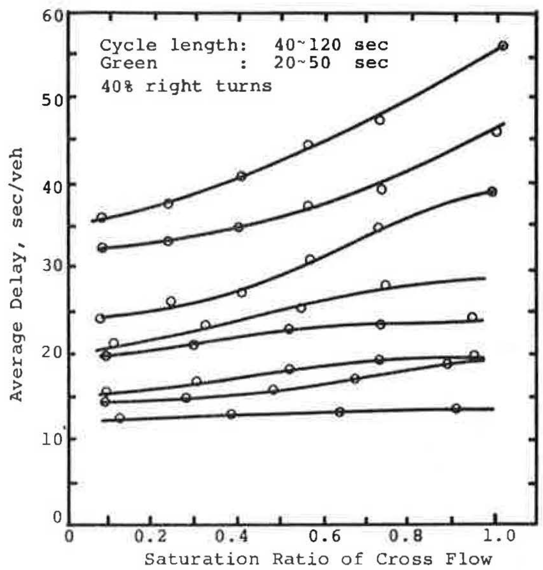

FIGURE 6 Effects of RTOR on right-turn delays.

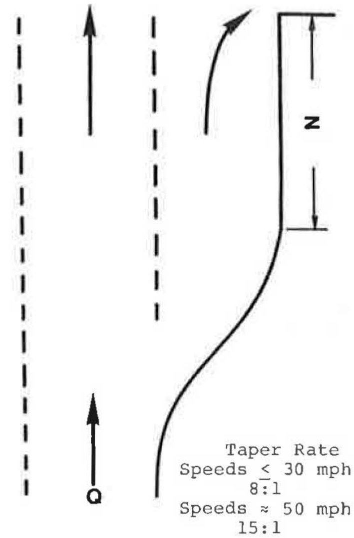

FIGURE 7 Schematic of auxiliary right-turn lane.

when RTOR is not allowed. These delays can also be conveniently estimated from Webster's formula (11) by using a saturation flow rate of 1,500 vph for a right-turn flow.

On the basis of the data in Figure 6, possible reductions in right-turn delays for an approaching flow with 40 percent right-turns are determined (Table 3). The data in this table indicate that RTOR has a negligible impact on delays if the average right-turn delays without RTOR are less than 15 sec per vehicle. Generally, RTOR is not likely to reduce right-turn delays significantly if the saturation ratio of the cross flow is greater than 0.6 and the delays without RTOR are less than 30 sec per vehicle.

TABLE 3 Reductions in Average Right-Turn Delays Due to RTOR, with 40 Percent Right Turns

Saturation Ratio[a]	Avg Delay Without RTOR (sec/vehicle)				
	0~15	15~20	20~30	30~45	>45
<0.2	0~2	0~5	5~8	8~15	>15
0.2~0.4	0	0~3	3~6	6~14	>14
0.4~0.6	0	0~2	2~4	4~12	>12
0.6~0.8	0	0~1	1~3	2~9	>9
0.8~1.0	0	0	0	0~5	>5

[a]Cross flow.

Approach lanes with rather high percentages of right turns are common. For example, out of the 16 lanes listed in Table 1, 12 had right-turn percentages in the range of 35 to 63 percent. The average for the 16 lanes was 39 percent. Note that none of these lanes has an auxiliary right-turn lane.

STORAGE REQUIREMENTS OF RIGHT-TURN LANES

Figure 7 shows an approach lane diverging into a straight-through lane and an auxiliary right-turn lane. The right-turn lane has a full-width section and a taper. As mentioned previously, AASHO recommended that neither the straight-through lane nor the right-turn lane be blocked. This requires that the queue lengths in both lanes and during any red phase be less than the storage length of the right-turn lane. The following variables should be considered when determining the minimum storage length of the right-turn lane needed to satisfy this requirement:

- Q = average flow rate in the approach lane that serves both straight-through and right-turn vehicles;
- R = length of red phase faced by the vehicles in the approach lane;
- λ = average number of arrivals during a red phase in the approach lane, equal to Q times R for a flow pattern with random arrivals;
- f = average right-turn flow rate as a proportion of Q ($0 < f < 1$); and
- N = number of vehicles that can be stored in the full-width section of the right-turn lane during a red phase.

Assume that vehicles arrive randomly; therefore the probability of having x arrivals (x = 0,1,2,...) during a red phase can be approximated by the Poisson distribution (12):

$$P(x) = \lambda^x e^{-\lambda}/x! \qquad (3)$$

where P(x) is the probability of having x number of vehicles arriving during a red phase in the approach lane.

Given that there are x arrivals during a red phase, the probability of having y straight-through vehicles among these x arrivals is

$$F = \{x!/[(x-y)!y!]\}(1-f)^y f^{x-y} \qquad (4)$$

where x - y represents the number of right-turn vehicles.

For a right-turn lane with a full-width of 12 ft and a taper rate of 10:1, the taper would have a length of 120 ft. With this design feature, a blockage will rarely occur if the number of arrivals (x) is less than or equal to N + 2. By using this relationship as a basis for analysis, it can be assumed that a blockage will not occur if $x \leq N + 2$.

When $x > N + 2$, the straight-through vehicles will block the approach lane if $y > N + 2$. On the other hand, if $x - y > N + 2$, or if $y < x - N - 2$, the right-turn vehicles will do the blocking. For a given x, the probability of a blockage by the straight-through vehicles is

$$P_s = \sum_{y=N+3}^{x} \{x!/[(x - y)!y!]\} (1 - f)^y f^{x - y} \quad (5)$$

The probability of a blockage by the right-turn vehicles is

$$P_r = \sum_{y=0}^{x-N-3} \{x!/[(x - y)!y!]\} (1 - f)^y f^{x - y} \quad (6)$$

Equations 5 and 6 may share the same event. This event is associated with x = 2 (N + 3). In such a case the upper bound of y in Equation 6 is the same as the lower bound of y in Equation 5. This event has the following probability of occurring:

$$P_e = \sum_{y=0}^{N+3} \{(2N + 6)!/[(2N + 6 - y)!y!]\} \times (1 - f)^y f^{2N + 6 - y} \quad (7)$$

To determine the total probability of blockage, P_e should be accounted for only once. Therefore the total probability of blockage, taking into consideration all possible values of x greater than N + 2, is

$$P_t = \left[\sum_{x=N+3}^{\infty} P(x) (P_s + P_r) \right] - P_e \quad (8)$$

Because P_e is small in comparison with the sum of the probabilities of other events, it may be deleted from the equation.

To determine the storage requirement of a right-turn lane, different values of N in Equation 8 can be used to determine the probabilities of blockage. The smallest N that reduces the probability of blockage to an acceptable level is the minimum required storage capacity. Figure 8 shows the minimum storage capacities determined from Equation 8 for various combinations of λ and f to limit the probability of blockage to less than 0.1 percent. The same results can also be obtained through computer simulation.

Figure 8 shows that the required capacity for a given number of arrivals during a red phase is smallest when the right-turn vehicles account for 50 percent (i.e., f = 0.5) of the approaching flow. A larger capacity is needed when there is an uneven mix of straight-through and right-turn vehicles. The figure can be used easily to determine the minimum storage requirement of a right-turn lane.

For example, consider a case that involves the following signal control and traffic flow conditions: (a) total approach flow = 600 vph with 30 percent right turns, (b) cycle length = 60 sec, and (c) red phase faced by the right turns = 30 sec. Based on these data, the average combined number of straight-through and right-turn vehicles per red phase is λ = 600 x 30/3,600 = 5 vehicles. With λ = 5 and f = 0.3, the data in Figure 8 indicate that a minimum storage requirement of 8 vehicles is required for the full-width section of the right-turn lane.

The cost of providing an auxiliary right-turn lane varies with a number of factors. Therefore it was estimated that a right-turn lane with a 500-ft full-width section and a 20-ft taper would cost about $25,000. (Note that these data are from 1983

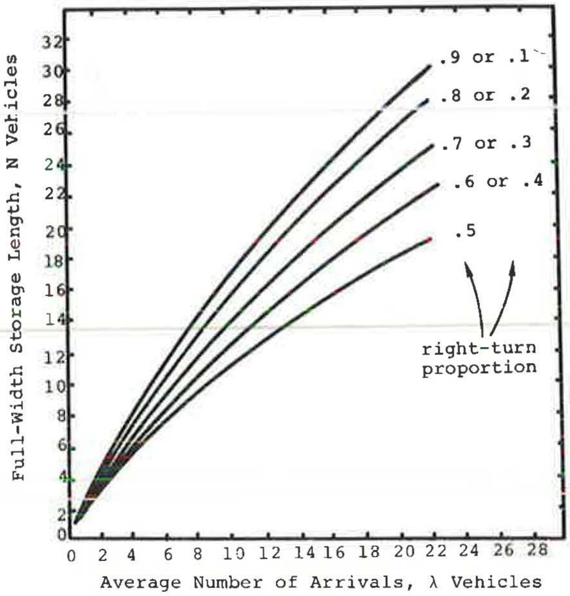

FIGURE 8 Minimum storage length requirements of auxiliary right-turn lanes.

correspondence with L. Raymond Powers, assistant engineer to the regional director of the Region 7 office of the New York State Department of Transportation in Watertown, New York.) This lane would have a 12-ft-wide flexible pavement with a 4-ft shoulder. The cost estimate allows a certain amount of earthwork. It reflects the probable cost of construction if the crews of a regional office of New York State Department of Transportation do the work.

As shown in Figure 8, the storage length of a right-turn lane can vary substantially with λ and f. For most urban intersections, the required lengths could be much shorter than the one mentioned previously.

It should be noted that Figure 8 is strictly valid only if the arrivals of vehicles are random. Nevertheless, it is adequate for most applications as long as the average number of arrivals (λ) is based on expected arrivals during a red phase. If the design flows are light (e.g., less than 200 vph per lane during red phases), the arrivals could have larger variations than those in a random arrival pattern. As a result, storage lengths longer than those shown in Figure 8 may be needed. This is not a serious problem because an insufficient storage length under a light flow condition would not have a significant adverse impact on the traffic operation. Besides, the storage lengths for such a case may be lengthened slightly from the lengths shown in Figure 8. If the design flows are heavy (e.g., more than 700 vph per lane during red phases), the arrivals could have smaller variations. The use of Figure 8 in such events could lead to conservative storage lengths.

CONCLUSIONS

The use of auxiliary right-turn lanes to accommodate RTOR can complement improved signal controls to increase the efficiency of traffic operations in a street network. Current practices in intersection traffic operations often require straight-through vehicles to share a lane with right-turn vehicles. Field data indicate that in such a lane it is not unusual for right turns to constitute more than 35 percent of the traffic. If the average delay of vehicles in a mixed straight-through and right-turn flow exceeds approximately 25 sec per vehicle, the provision of an auxiliary right-turn lane can substantially reduce the delays even if the right-turn percentage is only 10 percent.

To facilitate RTOR, the availability of auxiliary right-turn lanes is indispensable. Without an auxiliary right-turn lane, it has been observed that a limited shoulder area can allow more than 6 times as many vehicles to turn on red as a regular traffic lane. This signifies the desirability of providing auxiliary right-turn lanes to accommodate RTOR.

The critical gap of RTOR drivers was found to be approximately 8.4 sec. This is about 70 percent longer than the critical gap of opposed left-turn drivers. When a long gap is available in the cross flow, multiple RTOR requires an average of about 4.7 sec per vehicle to complete. As a result, a red phase is only 60 percent as useful as a green phase of the same length even when the cross flow does not exist.

RTOR from an auxiliary right-turn lane may not reduce right-turn delays significantly. When the right-turn delays without RTOR are less than 15 sec per vehicle, allowing RTOR would have negligible effects on the delays. RTOR could effectively reduce right-turn delays if the saturation ratio of the cross flow is less than 0.6 and the right-turn delays without RTOR exceed 30 sec per vehicle.

The storage length of an auxiliary right-turn lane should be long enough to prevent a blockage of traffic lanes during a red phase. The minimum storage requirements depend primarily on the flow rate and the right-turn percentage of an approach flow. A design chart that relates the minimum storage requirements to these influencing factors is presented in this paper.

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