Detector Delay for Right Turn on Red

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Delayed actuation at a right-turn-on-red (RTOR) location allows a driver to turn right onto the cross street without requiring green time. This increases the efficiency of the signal and reduces delay to cross-street motorists. However, there are no analytically based guidelines to assist the traffic engineer in selecting the appropriate length of delay for RTOR applications. A questionnaire sent to city transportation departments indicated that 100 percent based the length of RTOR delay on engineering judgment, field observation, or both. An analytical process used to determine the appropriate values of RTOR delay is described. Equations of motion and statistical relationships are applied to the three maneuvers of an RTOR. The calculations indicate that RTOR delay settings are primarily dependent on the loop length and the traffic volume in the outside lane of the cross street. The speed of cross-street traffic also impacts the length of delay but to a lesser extent than loop length or traffic volume. The resulting guidelines for RTOR settings are based on total loop length, traffic volume in the outside lane of the cross street, and speed of the cross-street traffic. The guidelines indicate that 7 to 10 sec is appropriate for locations with low cross-street traffic volumes and 9 to 13 sec, for locations with higher cross-street traffic volumes. The higher delay values in these ranges should be used for longer loop lengths and higher cross-street speeds.

The first traffic-actuated signal was installed in Baltimore in February 1928; it used a sound box as the detector (*1*). A driver sounded the vehicle's horn to obtain a green indication. Fortunately for those living near signalized intersections, detector technology has advanced considerably in the intervening years. Today, traffic engineers use the many advantages offered by actuated signals to improve traffic operations at signalized intersections.

The induction loop detector is currently the most common type of detector used with actuator traffic signals; it provides a great deal of flexibility in operating traffic signals. The loop detector consists of a loop of wire placed in the pavement and connected to a detector unit. The detector unit sends either a pulse or presence actuation call to the controller when a vehicle is detected in the space above the loop. In pulse detection, a short-duration actuation call is sent when a vehicle first occupies the loop. In presence actuation, the actuation call is maintained for as long as the vehicle occupies the loop.

One of the most useful features of the standard NEMA detector unit is the ability to delay a presence actuation call. With delayed actuation, the actuation call is dropped if the vehicle leaves the loop before the delay time expires. The delay value can be set at 1-sec increments between 0 and 15 sec and at 2-sec increments between 16 and 30 sec (*2*). Delayed actuation is especially effective at locations where a vehicle may turn right on red within a few seconds of arriving at the intersection. Delaying the call allows a right-turning vehicle to stop, select a gap, and turn right without calling an unnecessary green indication. This increases the efficiency of the signal and results in reduced delay to cross-street traffic. Heavy right-turn movements will bring up a green indication anyway, because the loop will continue to be occupied by the following vehicles.

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Optimizing the use of the delay feature in a right-turn-on-red (RTOR) location depends on selecting the appropriate delay setting. However, there are no published guidelines to assist the traffic engineer in determining the value of the delay setting. Therefore, a questionnaire was sent to city transportation departments in Texas to identify how they determined RTOR delay settings. A total of 23 questionnaires were mailed, and 15 were returned. Thirteen of the 15 respondents utilized delay at RTOR locations. Table 1 presents the values of RTOR delay identified in the survey. Delay settings ranged between 2 and 20 sec; 5 to 10 sec was the most common. In general, cities with longer loop lengths use longer delay settings, but there were exceptions. For instance, RTOR delay settings in one city ranged from 3 to 6 sec for a 50-ft-long loop, whereas the delay settings in another city ranged from 12 to 20 sec for the same size loop. Of the 13 agencies that use delay at RTOR locations, all cited field observation, engineering judgment, or both as the basis for selecting the delay setting. The size of this sample is too small to draw any statistically significant conclusions about the appropriate value of delay, but the results do indicate the variation in delay values and the lack of analytically based guidelines for determining the appropriate delay.

Although field observation and engineering judgment are vital to effective traffic signal operations, it is possible to determine mathematically the appropriate RTOR delay setting from the time needed to execute the maneuver. There are three distinct movements or elements in the RTOR maneuver, and the time needed to complete each one can be calculated from readily available information. The three movements and the associated delay (in seconds) are

1. Decelerating while in the detection area (referred to as deceleration delay, t_d),
2. Finding and accepting an adequate gap in the cross-street traffic stream (referred to as waiting delay, t_w), and
3. Accelerating out of the detection area (referred to as acceleration delay, t_a).

The deceleration and acceleration delays can be calculated easily from equations of motion and typical values for deceleration and acceleration rates. Additionally, there is little variation in these values for a given situation. However, determining the waiting delay is more complicated because it

TABLE 1 Summary of Loop Delay Timings in Texas

	Average	Minimum	Maximum	Number
Size of RTOR Loops	6' × 47'	6' × 20'	6' × 100'	13
Avg. Length of RTOR Delay (sec)	8.6	2.0	20.0	13
Delay for 6'×20' Loop (sec)	7.5	5.0	10.0	1
Delay for 6'×30' Loop (sec)	10.0	10.0	10.0	1
Delay for 6'×40' Loop (sec)	8.8	4.0	15.0	5
Delay for 6'×50' Loop (sec)	9.9	3.0	20.0	4
Delay for 6'×60' Loop (sec)	6.0	2.0	10.0	1
Delay for 6'×100' Loop (sec)	5.0	5.0	5.0	1

depends not only on the occurrence of gaps in the traffic stream, but also on an individual driver's accepting or rejecting each gap that occurs. The calculations for determining the time needed to complete each of these maneuvers are described in the following sections. Adding the individual delays provides an analytical measure of the value of the total RTOR delay setting. As with most procedures, the following assumptions have been made to simplify the calculation of the RTOR delay setting:

- Level roads,
- No sight distance restrictions,
- Intersection isolated from platooning effects (random flow),
- Vehicle makes a complete stop before turning,
- Vehicle makes RTOR into outside lane of cross street, and
- Vehicle comes to a stop before the driver searches for an acceptable gap.

DECELERATION DELAY

The first element of the RTOR delay setting is the length of time that a vehicle occupies the detection area while decelerating to a stop. This period, the deceleration delay, begins when the front of the vehicle enters the detection zone and ends when the vehicle comes to a stop. The deceleration delay is based on the following parameters:

1. Deceleration rate of the vehicle in feet per second squared $(-a)$.
2. Length of the loop in the deceleration area in feet (L_d).
3. Speed of the vehicle when it begins decelerating in feet per second (V_i).

The deceleration delay is calculated from the equations of motion shown in Equations 1 and 2. Setting V_f equal to 0 and solving for t_d in Equation 2 results in Equation 3.

$$V_f^2 = V_i^2 + 2 \times -a \times L_d \quad (1)$$

$$V_f = V_i + -a \times t_d \quad (2)$$

$$t_d = \frac{\sqrt{2 \times a \times L_d}}{a} \quad (3)$$

where V_f is 0, final speed (ft/sec).

The deceleration rate $(-a)$ controls the time required to come to a stop. Previous research has indicated the mean deceleration rate for vehicles approaching a yellow signal is 9.5 ft/sec^2 (*3*). This represents a maximum comfortable deceleration rate. For this analysis, it is assumed that a driver approaching a red indication will decelerate at a more comfortable rate before attempting to turn right on red. Table 2 presents the passenger vehicle deceleration rates used in this analysis.

The loop deceleration length, L_d, is the distance from the back of the loop to the point where the vehicle should stop, typically the stop line, as shown in Figure 1. Often the loop will extend beyond the stop line. However, the part of the loop beyond the stop line should not be included in the loop deceleration length. Table 3 presents the deceleration delay based on Equation 3 for loop deceleration lengths of 5, 10, 15, 20, 30, 40, and 50 ft and speeds of 30, 40, and 50 mph. Figure 2 graphically shows this relationship.

TABLE 2 Passenger Vehicle Deceleration Rates $(-a)$ For Level Terrain (ft/sec^2) (*4*)

Final Speed, V_f (mph)	Initial Speed, V_i (mph)					
	15	30	40	50	60	70
0	7.8	6.7	6.2	5.9	5.7	5.6

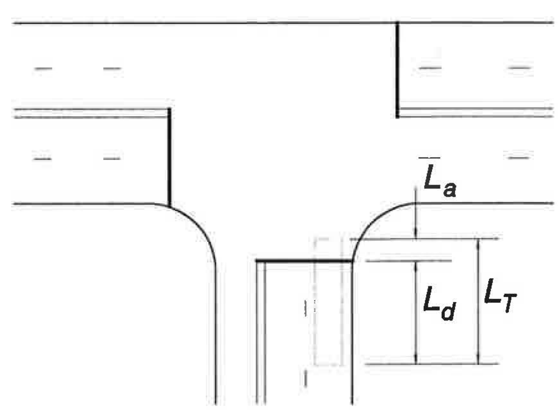

FIGURE 1 RTOR loop location.

TABLE 3 Deceleration Delay, t_d (sec)

Loop Deceleration Length, L_d, (feet)	Initial Speed, V_i, (mph)		
	30	40	50
5	1.2	1.3	1.3
10	1.7	1.8	1.8
15	2.1	2.2	2.3
20	2.4	2.5	2.6
30	3.0	3.1	3.2
40	3.5	3.6	3.7
50	3.9	4.0	4.1

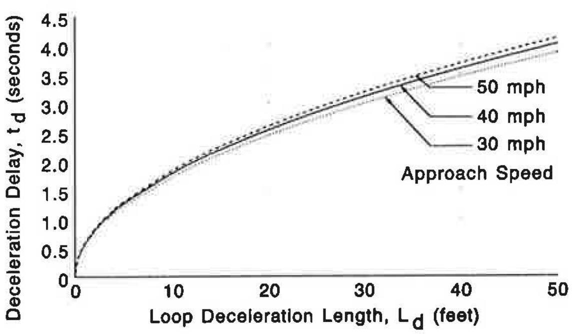

FIGURE 2 Deceleration delay, t_d.

Table 3 shows that there is little difference between the deceleration delay at speeds of 30, 40, and 50 mph for a given loop deceleration length. The deceleration delay for the 40-mph speed is ±0.1 sec from the 30- and 50-mph deceleration delay. Because the delay is set in 1-sec increments, a difference of 0.1 sec is not significant; the deceleration delay for the 40-mph speed is used to represent all speeds.

WAITING DELAY

The major and most complex element in the selection of an appropriate delay setting is the length of time that a vehicle occupies the loop while waiting for an acceptable gap in the cross-street traffic. This time is a function of two factors: the size of the critical gap and the length of time before the critical gap occurs in the cross-street traffic.

The critical gap for an RTOR maneuver at a signalized intersection can be approximated with the critical gap for a right-turn at a stop-controlled intersection. The 1985 *Highway Capacity Manual* shows the critical gap for a stop-controlled right turn from a minor to a major street to be 5.5 and 6.5 sec for major street speeds of 30 and 50 mph, respectively (*5*). From these, the critical gap for a major street speed of 40 mph can be interpolated as 6.0 sec.

The delay associated with waiting for the critical gap can be calculated from a statistical distribution of gap occurrence. Actuated signals are most effective at isolated intersections at which random arrivals are a reasonable approximation of the traffic distribution. Random vehicle arrivals can be approximated to the Poisson distribution, with the use of negative exponential distribution to represent the occurrence of gaps between the vehicle arrivals. The waiting delay is the length of time a driver must wait for the critical gap to occur in the cross-street traffic. It can be calculated from Equation 4 (*6*). Table 4 presents the waiting delay for major street outside lane volumes of 100, 300, and 500 vehicles per hour (vph) and speeds of 30, 40, and 50 mph as calculated from Equation 4. Table 4 also indicates the waiting delay for an unopposed RTOR maneuver. The unopposed waiting delay was calculated from a volume of 1 vph, because zero volume cannot be inserted into Equation 4. Figure 3 graphically shows the relationships of Equation 4.

$$t_w = \frac{3{,}600}{v e^{-vt/3{,}600}} - \frac{t}{1 - e^{-vt/3{,}600}} \quad (4)$$

where

t_w = waiting delay (sec),
t = critical gap size (sec), and
v = volume of traffic in outside lane (vph).

Gap acceptance of RTOR drivers has been addressed in a previous research study (*7*). A part of this study evaluated 359 drivers making an RTOR, of which only 202 rejected at least one gap before turning right onto the cross street. The behavior of these drivers indicated that a gap of fewer than 5 sec had little chance of being accepted and that a gap of greater than 15 sec was unlikely to be rejected. The critical gap for these drivers was found to be about 8.4 sec, as compared to the critical gaps between 5.5 and 6.5 sec used in this analysis. However, this study did not identify the effects of

TABLE 4 Waiting Delay, t_w (sec)

Major Street Volume, Outside Lane, v, (vph)	Major Street Speed (mph)			
	30	40	50	N/A
	Critical Gap, t, (seconds)			
	5.5	6.0	6.5	8.4
1	2.8	3.0	3.3	4.2
100	3.1	3.4	3.8	5.1
300	4.0	4.5	5.1	7.5
500	5.2	6.0	6.8	10.9

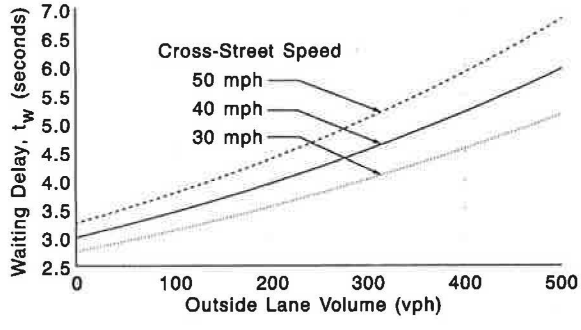

FIGURE 3 Waiting delay, t_w.

platoon flow and the cross-street speed on the critical gap. Therefore, the 8.4-sec gap is probably an overestimation of the critical gap for random flow. The waiting delay that results from a gap of 8.4 sec is shown in Table 4 for comparison purposes. Using a gap of 8.4 sec adds approximately 2 to 6 sec to the waiting delay.

ACCELERATION DELAY

The final movement in the RTOR maneuver is the acceleration off the loop into the cross-street traffic. The time required to accelerate off the loop is dependent on the length of the loop in front of the vehicle in feet (L_a), the length of the vehicle in feet (L_v), and the acceleration rate of the vehicle in feet per second squared (a).

Acceleration delay calculations are also based on Equations 1 and 2 with the following changes: the deceleration rate becomes the acceleration rate and changes from a negative value to a positive value, the initial speed becomes 0, the final speed becomes the speed of cross-street traffic, and the deceleration length becomes the acceleration length. The acceleration length is the distance from the stop line to the front of the loop. The vehicle length must be added to the loop acceleration length because the detection period will not end until the rear of the vehicle has cleared the loop. Solving for t_a yields Equation 5.

$$t_a = \frac{\sqrt{2 \times a \times (L_a + L_v)}}{a} \quad (5)$$

Acceleration rates from a stop can range from 3 to 15 ft/sec^2 depending on the vehicle type and the desired speed. Table 5 presents typical acceleration rates for passenger vehicles accelerating from a stop to various speeds.

If the loop extends beyond the stop line, then the vehicle must travel an additional distance to get off the loop. The distance from the stop line to the front of the loop is referred to as the loop acceleration length, L_a, as shown in Figure 1. In this analysis, loop acceleration lengths of 0, 5, and 10 ft are used. The length of the vehicle must also be included in the acceleration delay calculation. Although the design length of a passenger vehicle is 19 ft, actual vehicle lengths are considerably less (*8*). Vehicle lengths for domestic 1991 model passenger cars range from 11.7 to 18.2 ft, averaging 15.4 ft (*9*). The average of 15.4 ft is used in the following calculations. It should be noted that the total length of the loop (L_T) is the sum of the loop deceleration length (L_d) and the loop acceleration length (L_a) as shown in Figure 1 and Equation 6.

$$L_T = L_d + L_a \quad (6)$$

TABLE 5 Passenger Vehicle Acceleration Rates, a, for Level Terrain (ft/sec^2)

Initial Speed, V_i, (mph)	Final Speed, V_f, (mph)				
	15	30	40	50	60
0	4.8	4.8	4.8	4.5	4.3

Inserting the values for acceleration (a), loop acceleration length (L_a), and vehicle length (L_v) into Equation 5 yields the delay associated with a vehicle accelerating out of the detection area. Table 6 shows the acceleration delay calculated from Equation 5 for loop acceleration lengths of 0, 5, and 10-ft and desired speeds of 30, 40, and 50 mph for a vehicle length of 15.4 ft. Figure 4 graphically shows the relationship. Table 6 presents that the acceleration delay for the 40-mph final speed is the same as the 30-mph speed and 0.1 sec less than the 50-mph speed. This difference is not significant because the total delay is set in 1-sec increments. Therefore, the acceleration delay for the 40-mph final speed is used to represent all speeds. If the vehicle length is increased to 19 ft, the acceleration delay increases by 0.2 to 0.3 sec.

DELAY SETTING FOR RTOR

The minimum delay setting for an RTOR location assumes that the driver selects a gap before stopping the vehicle and that the gap is immediately available. The minimum RTOR delay can be determined by adding the deceleration and acceleration delays as shown in Equation 7. Table 7 presents the minimum delay setting for various total loop lengths (L_T) and loop acceleration lengths (L_a). For loops between 5 and 50 ft, the minimum delay setting ranges between 3.8 and 6.9 sec.

$$t_m = t_d + t_a \quad (7)$$

where t_m is the minimum delay (sec).

Table 7 shows that although there is a difference of 0.8 sec between the acceleration delays for the various loop accel-

TABLE 6 Acceleration Delay, t_a (sec)

Acceleration Loop Length (feet)	Final Speed (mph)		
	30	40	50
0	2.5	2.5	2.6
5	2.9	2.9	3.0
10	3.3	3.3	3.4

t_a based on vehicle length of 15.4 feet.

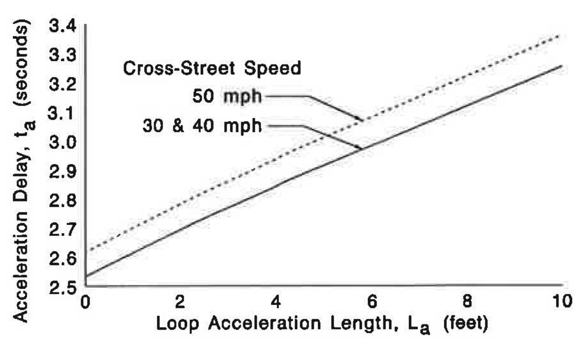

FIGURE 4 Acceleration delay, t_a.

TABLE 7 Minimum Delay Setting for RTOR (sec)

Total Loop Length, L_T (feet)	Loop Acceleration Length[a], L_a (feet)		
	0	5	10
5	1.3+2.5=3.8	N/A	N/A
10	1.8+2.5=4.3	1.3+2.9=4.2	N/A
15	2.2+2.5=4.7	1.8+2.9=4.7	1.3+3.3=4.6
20	2.5+2.5=5.0	2.2+2.9=5.1	1.8+3.3=5.1
30	3.1+2.5=5.6	2.8+2.9=5.7	2.5+3.3=5.8
40	3.6+2.5=6.1	3.4+2.9=6.3	3.1+3.3=6.4
50	4.0+2.5=6.5	3.8+2.9=6.7	3.6+3.3=6.9

[a]First number is the deceleration delay from Table 3 for 40 mph speed, second number is the acceleration delay from Table 6 for 40 mph speed.

eration lengths, the minimum delay setting exhibits a maximum difference of only 0.4 sec for the range of loop acceleration lengths. Therefore, the minimum delay setting for a loop acceleration length of 5 ft is used to represent all loop acceleration lengths for loops with a total length of 10 ft or more. A loop acceleration length of 0 ft is used for a 5-ft-long loop.

The RTOR study also evaluated the dwell or minimum delay of RTOR drivers (7). A total of 246 right-turn drivers who made a RTOR without any opposing volume were observed. The average dwell time of these drivers was 4.4 sec. This value compares favorably to the minimum RTOR delay for short loops shown in Table 7. The RTOR study did not address the increase in dwell time due to a longer loop. Therefore, it is not appropriate to compare the minimum delay for longer loops with the dwell time determined in the RTOR study. Approximately 40 percent of the drivers in the RTOR study executed the RTOR within 2 sec of their arrival at the turning position. This represents the proportion of drivers who violated the requirement to come to a stop.

The appropriate value of the delay setting for an RTOR detector can be determined by adding time to the minimum delay setting, as shown in Equation 8, to account for the waiting delay that a driver would encounter while selecting an acceptable gap after coming to a stop. The amount of waiting delay is obtained from Table 4 and is based on the cross-street speed and the volume of traffic in the outside lane of the cross-street. Values range from a minimum of 2.8 sec for a speed of 30 mph and no opposing volume in the outside lane to a maximum of 6.8 sec for a speed of 50 mph and a volume of 500 vph in the outside lane. When added to the minimum delay setting, the total delay for the given conditions ranges from 6.6 to 13.5 sec. Table 8 presents the total RTOR delay settings for various combinations of total loop length, cross-street speed, and traffic volume in the outside lane of the cross street.

$$t_{delay} = t_m + t_w = t_d + t_a + t_w \qquad (8)$$

where t_{delay} is total delay (sec).

CONCLUSIONS

One of the useful features of loop detectors is the ability to delay an actuation. This feature is most often used at locations with heavy RTOR volumes. Delaying actuation allows a right-turning vehicle to complete the maneuver without calling an unnecessary green indication, thereby increasing the efficiency of the signal. A procedure for calculating the value of the RTOR delay on the basis of the length of the loop and the speed of cross-street traffic is described. The suggested values for RTOR delay apply to actuated traffic signals at isolated intersections where random flow exists.

The procedure described suggests that the delay setting for RTOR locations should be approximately 7 to 10 sec at locations with low volumes in the outside lane of the cross street. As the volumes increase, the delay setting should also increase. Delay settings in the range of 9 to 14 sec are appropriate for higher-volume cross streets. The higher values in these ranges should be used for longer loop lengths. The delay setting for 10-ft-long loops should be approximately 7 to 11 sec, and the delay setting for 50-ft loops should be about 10 to 14 sec.

Adjustments to the delay setting may be appropriate to account for factors such as grade, vehicle types and lengths,

TABLE 8 Right-Turn-On-Red Delay Settings (sec)

Total Loop Length (feet)	Volume[a] (vph) for 30 mph[b]				Volume[a] (vph) for 40 mph[b]				Volume[a] (vph) for 50 mph[b]			
	1[c]	100	300	500	1[c]	100	300	500	1[c]	100	300	500
5	6.6	6.9	7.8	9.0	6.8	7.2	8.3	9.8	7.1	7.6	8.9	10.6
10	7.0	7.3	8.2	9.4	7.2	7.6	8.7	10.2	7.5	8.0	9.3	11.0
15	7.5	7.8	8.7	9.9	7.7	8.1	9.2	10.7	8.0	8.5	9.8	11.5
20	7.9	8.2	9.1	10.3	8.1	8.5	9.6	11.1	8.4	8.9	10.2	11.9
30	8.5	8.8	9.7	10.9	8.7	9.1	10.2	11.7	9.0	9.5	10.8	12.5
40	9.1	9.4	10.3	11.5	9.3	9.7	10.8	12.3	9.6	10.1	11.4	13.1
50	9.5	9.8	10.7	11.9	9.7	10.1	11.2	12.7	10.0	10.5	11.8	13.5

[a]Volume in outside lane of cross-street traffic.
[b]Speed of cross-street traffic.
[c]Represents no opposing cross-street traffic.

vehicle acceleration rates, and driver patience and impatience, or to change the response time of the signal operation. In particular, RTOR locations with a large percentage of older drivers may require a longer delay setting. The RTOR delay setting should be increased up to 6 sec if an 8.4-sec critical gap is used, as suggested in the RTOR study (*7*). It is now common to use several short loops as a replacement for one long loop. When this type of segmented loop is used, the delay setting should be based on the length of the loop closest to the intersection. The use of the suggested RTOR delay values, combined with engineering judgment and field observation, will enable the traffic engineer to optimize the use of the loop detector delay option at RTOR locations.

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