Effect of Radius of Curvature for Right Turning Vehicles on Through Traffic Delay

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ABSTRACT

This paper looks at the delay to through vehicles due to right turning vehicles at intersections. This type of delay is part of the geometric delay of the intersection and is part of the total delay experienced by vehicles using the intersection. The authors collected data at 15 intersections for this research. The results show that as the radius of curvature of the traveled way the right turning vehicle speed decreases, and the potential for delay to following vehicles increases. This work will be of most use in helping to design intersections in congested areas and to determine the geometric delay due to right turning vehicles at intersections.

1. INTRODUCTION

In 1993, Americans made 190 million trips each day in metropolitan areas. This has created substantial traffic loads on the urban networks, which are becoming increasingly more congested. Many existing roadways in the United States have design limitations, which impact their capacity. These limitations include: curb radius, right-of-way constraints, grade, and sight distance. At present, traffic engineers try to increase roadway capacity without major construction. The major constraint on the capacity of an urban roadway is the intersection, which causes traffic to slow down due to turning movements and traffic control. By decreasing the delay per vehicle, it is possible to increase the flow through the intersection. One method to decrease vehicle delay at intersections is to decrease the delay caused by the geometric design of the intersection. By reducing geometric delay, the total delay at the intersection will also decrease allowing an increase in the capacity of the intersection without the addition of lanes. The focus of this paper is the geometric delay on through vehicles caused by right turning traffic. By examining the impacts of curb radius on turning vehicle speed it is possible to develop guidelines for designing curb radii that will eliminate the geometric delay caused by the right turning vehicles. Minor adjustments such as this will increase the capacity of existing roads.

2. STATE OF THE ART

Currently, no research is conducted on the delay caused by right turning traffic. The right turn movement is considered a rank 1 movement, not impeded by other movements. Because the right turn is not required to yield to other traffic streams, vehicles making right turns are not considered to cause delay or be delayed at intersections unless there is a traffic control device controlling right turn movements or there are conflicting pedestrians. Total delay is the delay caused by traffic control devices, geometric characteristics, incidents, and traffic. Geometric delay is the only part of the total delay, which has an effect on right-turn movements and can be remedied. Geometric delay is created by the design characteristics of intersection geometry. The focus of this paper is the geometric delay to through moving vehicles caused by vehicles making an unimpeded right turn movement. The delay to the through moving vehicles is due to the decrease in speed and increase in travel time of a vehicle making a right turn. The decrease in speed of the vehicle making the right turn is a factor of the radius of curvature of the turn. As the radius of curvature increases, the speed of a vehicle negotiating the turn increases which decreases the travel time through the curve. This is true even though the distance traveled increases as the radius of curvature increases.

3. STUDY OVERVIEW

For this study 15 intersections were selected. This provided a maximum of 60 different right-turn movements. The selection process was started by using a road map of Northern Virginia to locate potential intersections in the Alexandria, Virginia, area. The potential intersections were then visually inspected and the 15 most suitable intersections were selected. The selection criteria were:

- 90 degree corners
- level intersection - minimal grades
- good sight lines for videotaping the intersections

The raw data was collected using a Sony Handycam set up between 3 and 14 meters from the intersection. The majority of the data was taken for turning radii of 1.6 m to 20 m. The camera was set up so that all four right turn movements were visible from the camera location. Right turn data was collected at each intersection for two hours. This method of data collection was selected because it provides a permanent record of each intersection allowing for additional analysis of traffic flows to calibrate the models.

4. DATA

Data was collected at 15 intersections in the Alexandria, Virginia, area. Both signalized and unsignalized intersections were used in the study. Care was taken to ensure that vehicles timed at signalized intersections were not in the stopped queue and were at running speed before starting the turning maneuver. The 15 intersections were videotaped for two hours during which each intersection yielded 50 to 250 turning movements for each right turning movement. This provided a sufficient number of observations to get a good statistical representation travel time. The 50 to 250 turning movement times were averaged yielding the average time of the vehicles to complete the right turn movement. The average speed for each right turn was then plotted against its respective radius of curvature. Figure 1 shows the relationship between speed and curb radius for the study intersections. This figure shows the how the turning speed increases as the radius of curb on the right turn is increased.

The intersection geometry was found using a measuring wheel. No plans of the intersections were available through the state or county engineering offices. To calculate the speed of each vehicle, the distance traveled by the vehicle through the turn was needed. The lane width was measured to find the distance traveled by a turning vehicle. All vehicles were assumed to travel in the center of each lane which effectively increases the turning radius by half the distance of the lane width.

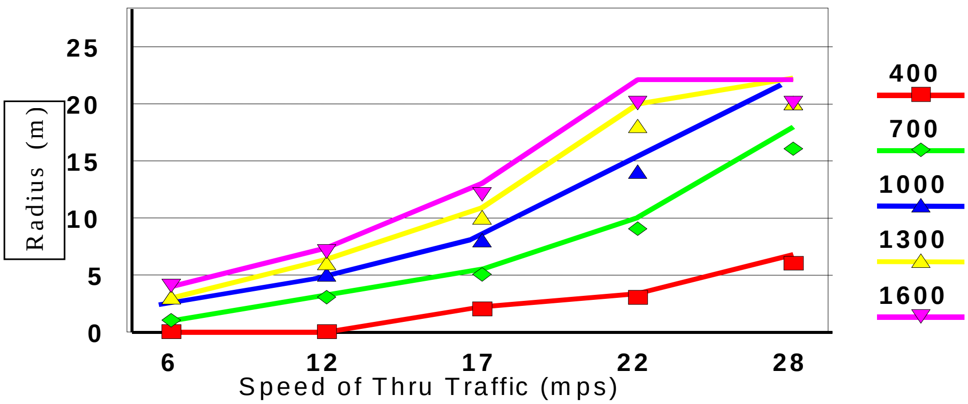

FIGURE 1 Relationship between volume, speed, and radius of curb showing threshold values.

5. METHODOLOGY

To determine the delay caused by vehicles making right turns it is necessary to determine the speed of vehicles as they maneuver through a turn. The speed of the vehicles was determined by timing the vehicles over a distance. The distance traveled by the vehicle through the curve was found by first determining the radius of the curb. An offset, usually half the lane width, was then added to the radius, from this value it was possible to determine the arc traveled by the vehicle through the curve. To find the radius of the curb (R) of a right turn, the arc length of the curb and the chord of the arc were measured. From these measurements the radius of the curb could be geometrically calculated.

$$R = \frac{4(d_a)}{2\pi} \tag{1}$$

$$R = \frac{d_c/2}{\sin 45^\circ} \tag{2}$$

where:

d_a is the arc distance
d_c is the chord distance
R is the radius.

The two values for the radius were compared and the average was used to determine the distance traveled.

$$D = \frac{2\pi R}{4} \tag{3}$$

To determine the speed of the vehicle through the curve, the traveled distance was divided by the time to complete the maneuver.

$$V = \frac{D}{t} \qquad \text{in meters per second}$$

Given the speed and the curb radius data it was possible to determine a relationship between speed and radius with an R^2 of 0.766.

$$S = 2.2678809 + 0.451631R + 0.078901R^2 - 0.007308R^3 + 0.0001811R^4 \qquad (4)$$

To determine the amount of delay to the through traffic, it was first necessary to determine the time and distance necessary to complete the turning maneuver given the radius of the curb. The time to complete the turning maneuver was found by determining the braking distance, time to clear the through street and time for the through vehicle to accelerate back to operating speed. The braking distance is found using Equation 5.

$$t_b = \frac{V_o - V}{a_d} \qquad (5)$$

where:

t_b is the braking time
V_o is the velocity of through traffic
S is the velocity needed to maneuver around the turn found in Equation 4
a_d is the deceleration rate, 2.5 mps^2.

The clearance time is the time it takes a right turning vehicle to leave the traveled way of the through vehicles. It was assumed that the vehicles would be 2 meters wide. The vehicle is considered to be clear of the traveled way when it is past the edge of the traveled way. The distance and angle can be determined

$$\theta = Arc\cos\left(\frac{R-1}{R+1}\right) \qquad (6)$$

$$D_c = \frac{2\pi R\theta}{360} \qquad (7)$$

the clearance time is then found from the clearance distance, the vehicle length (6 m), and the turn velocity.

$$t_c = \frac{D_c + 6}{S} \qquad (8)$$

Combining the braking time, t_b, and the clearance time, t_c, gives the total time necessary to complete the turning maneuver.

$$t_m = t_b + t_c \tag{9}$$

This total movement time, t_m, is compared to the time it would take an unimpeded through vehicle to travel the same distance. To determine the unimpeded travel time of the through vehicle it is first necessary to determine the distance traveled by the turning vehicle during deceleration.

$$x_m = V_o t_b - 0.5 a_d t_b^2 \tag{10}$$

Given the distance traveled by the turning vehicle during braking, it is possible to determine the unimpeded travel time of the through vehicle.

$$t_t = \frac{x_m}{V_o} \tag{11}$$

The acceleration time is the time required for a vehicle to accelerate back to operating speed after the turning vehicle has exited the roadway.

$$t_a = \frac{V - V_o}{a_a} \tag{12}$$

It was necessary to determine the potential for through vehicles to be delayed by a right turning vehicle. The impacts were compared to headways between vehicles for five different traffic volumes, 400 vehicles/hour, 700 vph, 1000 vph, 1300 vph, 1600 vph, to determine if the turning maneuver could be accomplished without delaying the following vehicle.

$$t_m - n\frac{3600}{v_i} \overset{?}{>} 0 \tag{13}$$

If Equation 13 is true, then there is an impact on the following *n* vehicles. Otherwise the turning vehicle does not impact the following *n*th vehicle. The delay to the through traffic due to the turning vehicle can be determined.

$$t_d = 1.25\frac{t_m}{V_o} \tag{14}$$

The acceleration time necessary to resume operating speed is determined.

$$t_a = \frac{a_d\left(t_m - 3600/v_i\right)}{a_a} \tag{15}$$

The total time the vehicle is impacting traffic is found by taking the deceleration time, clearance time, acceleration time of the through vehicle, the headway between adjacent vehicles, and the minimum headway, 1.9 seconds, into consideration.

$$t_d = t_b + t_c - t_a - h + 1.9 \tag{16}$$

This gives the time span of the vehicle impact on through traffic.

6. RESULTS

The results presented are in the form of a graphical representation of the threshold radius of curb where there is delay to through vehicles. Table 1 shows the deceleration time and clearance time for right turning vehicles for a given curb radius and through traffic speed. As would be expected as speed increases the deceleration and clearance time increases, while the deceleration and clearance time decrease as the curb radius increases. Table 2 shows the delay time caused by the right turning vehicle. This delay time is the difference between the deceleration and clearance time and the time it would take an unimpeded vehicle to travel the same distance. If the delay time is less than the difference between the actual headway and the minimum headway between vehicles then there is no delay to following through vehicles. The actual headway is based on the given through volume and the minimum headway, based on the saturation flow of a signalized intersection, is 1.9 seconds. With this information it is possible to develop tables showing the number of impacted through vehicles due to a right turning vehicle for the range of volumes, speeds, and curb radii. Figure 2 shows the expected number of through vehicles impacted by the

TABLE 1 Deceleration and Clearance Time (sec/veh)

Radius	Speed (mps)				
(m)	6	12	17	22	28
1	4.00	6.40	8.40	10.40	12.80
2	3.49	5.89	7.89	9.89	12.29
3	2.94	5.34	7.34	9.34	11.74
4	2.41	4.81	6.81	8.81	11.21
5	1.91	4.31	6.31	8.31	10.71
6	1.65	3.86	5.86	7.86	10.26
7	1.53	3.44	5.44	7.44	9.84
8	1.44	3.07	5.07	7.07	9.47
9	1.37	2.74	4.74	6.74	9.14
10	1.32	2.45	4.45	6.45	8.85
11	1.28	2.20	4.20	6.20	8.60
12	1.25	1.98	3.98	5.98	8.38
13	1.23	1.79	3.79	5.79	8.19
14	1.21	1.63	3.63	5.63	8.03
15	1.20	1.48	3.48	5.48	7.88
16	1.19	1.34	3.34	5.34	7.74
17	1.18	1.19	3.19	5.19	7.59
18	1.16	1.16	3.02	5.02	7.42
19	1.14	1.14	2.81	4.81	7.21
20	1.11	1.11	2.56	4.56	6.96

TABLE 2 Increase in Travel Time for Right Turning Vehicles

Radius (m)	Speed (mps)				
	6	12	17	22	28
1	3.33	4.26	5.18	6.14	7.31
2	2.57	3.62	4.58	5.56	6.75
3	1.80	2.97	3.96	4.96	6.16
4	1.21	2.41	3.41	4.41	5.61
5	0.76	1.94	2.93	3.93	5.12
6	0.56	1.55	2.52	3.51	4.70
7	0.49	1.23	2.18	3.15	4.32
8	0.43	0.98	1.89	2.84	4.00
9	0.39	0.78	1.65	2.58	3.73
10	0.36	0.63	1.46	2.36	3.50
11	0.34	0.50	1.30	2.18	3.30
12	0.33	0.41	1.17	2.03	3.14
13	0.32	0.34	1.06	1.91	3.00
14	0.31	0.28	0.97	1.80	2.88
15	0.30	0.23	0.89	1.71	2.77
16	0.30	0.19	0.82	1.62	2.67
17	0.29	0.15	0.75	1.53	2.57
18	0.28	0.14	0.67	1.43	2.46
19	0.27	0.13	0.58	1.32	2.32
20	0.26	0.13	0.48	1.18	2.16

right turning vehicles. Figure 3 shows the total delay expected due to a right turning vehicle on following through vehicles. These values are based on one right turning vehicle and uniform distribution. From these tables a curb radius threshold value for each speed and volume can be determined. The threshold value representing the curb radius where through traffic is delayed. Figure 3 presents this threshold for each of the traffic volumes, through traffic speeds, and curb radii. As would be expected the impacts of right turning traffic on through traffic is dependent upon the time for a right turning vehicle to complete its maneuver. This time is related to the curb radius of the turn and the operating speed of the vehicle before it begins the turning maneuver. As traffic volume increases the headway between vehicles decrease causing right turning traffic to have a greater impact on through traffic. This is shown in Figure 3 where low volume (400–700 vph), low speed (6–12 mps) roads will not be impacted by small radius curbs. As speed increases the impact of curb radius is more significant for traffic volumes between 700 vph and 1600 vph. With Figure 3 it is possible to determine the smallest radius curb which will allow right turning traffic to move without impeding through traffic at a given speed and density.

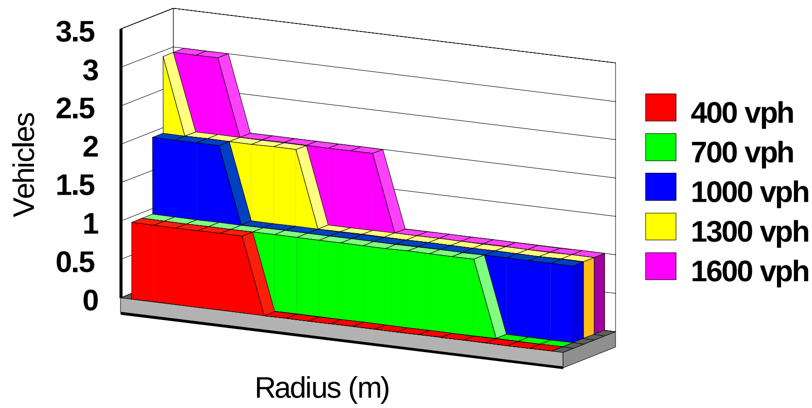

FIGURE 2 Through vehicles impacted by right turning vehicles.

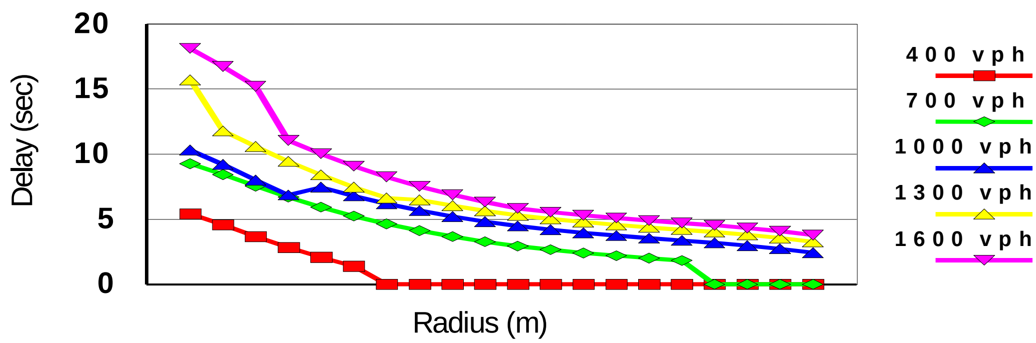

FIGURE 3 Delay caused by one right turning vehicle.

7. SUMMARY

The research presented here deals with the issue of increasing capacity at an intersection by decreasing the geometric delay. To accomplish this decrease in geometric delay, the radius of curve of the traveled path of right turning vehicles need to be increased. This may be constrained in urban areas due to development, pedestrian considerations, and available space. In all cases it will become possible to determine the delay to through vehicles caused by the geometric delay to right turning vehicles. This adds one more piece of information for the engineer to use in determining the capacity of an intersection and the methods available to increase its capacity.

With the information presented it should be possible to determine the delay equation for through vehicles. Development and calibration of this delay equation will be addressed in the next phase of this research.

REFERENCES

1. Transportation Research Board. (1998). *Special Report 209: Highway Capacity Manual*, 1997 Update, 3rd Ed., TRB, Washington, D.C.