Guidelines for Right-Turn Lanes on Urban Roadways

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Guidelines for the use of right-turn lanes at access points on urban two-lane and four-lane roadways were developed. The guidelines define the design-hour traffic volumes for which the benefits of right-turn lanes exceed their costs. The benefits used in the analysis were the operational and accident cost savings that right-turn lanes provide road users. The operational cost savings were those associated with the reductions in stops, delays, and fuel consumption experienced by through traffic. The accident cost savings were those associated with the reduction in accidents expected from the lower speed differentials between right-turning and through traffic. The guidelines define the right-turn design-hour volume required to justify a right-turn lane as a function of the following factors: (a) directional design-hour volume, (b) roadway speed, (c) number of lanes on the roadway, and (d) right-of-way cost. Comparison with guidelines developed by others indicates that the guidelines developed in the research are within the range of existing guidelines. In addition they are more definitive than the other guidelines because they account for the effects of roadway speed and right-of-way costs.

Right-turn movements from roadways can cause safety and operational problems. Vehicles slowing to turn right increase the potential for rear-end collisions involving the through vehicles following behind them that fail to slow down. It has been estimated that vehicles turning right into driveways account for 15 percent of all driveway accidents (*1*). About 7 percent of all traffic accidents in urban areas in Nebraska are collisions at driveways, and another 1 percent involve right-turn movements at intersections (*2*). Of course, the numbers of accidents related to right turns may be substantially underreported because some rear-end and sideswipe collisions occurring upstream of driveways and intersections as a result of right turns into them do not involve the right-turning vehicles. Vehicles slowing to turn right also increase the delay to through vehicles behind them and reduce the capacity of the highway. The delay experienced by the through traffic can range from a few seconds to over 20 sec per right turn, depending on the speed and volume of traffic (*3*). It has been estimated that the capacity of a four-lane arterial street with a 72-km/hr speed limit is reduced by 1 percent for every 2 percent of the traffic that turns right into driveways (*4*).

Right-turn lanes remove decelerating right-turn vehicles from the through lanes and thereby improve the safety and efficiency of traffic operations on the roadway. However, there are few guidelines available for determining when right-turn lanes should be provided at driveways and intersections on urban roadways. The national design guides do not include definitive warrants for right-turn lanes. AASHTO merely acknowledges in *A Policy on Geometric Design of Highways and Streets* (*5*) the potential benefits of right-turn lanes, particularly at intersections on high-speed, high-volume roadways, and suggests that the decision to provide right-turn lanes requires the consideration of several factors such as speeds, traffic volumes, capacity, type of highway, service provided, arrangement and frequency of intersections, and accident experience. Likewise, the ITE *Guidelines for Driveway Design and Location* (*6*) does not contain warrants for the use of right-turn lanes. Although the benefits of right-turn lanes are apparent, current nationally recognized highway design and access control guidelines do not define the prevailing roadway and traffic conditions for which these lanes are cost-effective on urban highways.

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OBJECTIVE

The objective of the research presented in this paper was to develop guidelines for the use of right-turn lanes on uncontrolled approaches to intersections and driveways on urban two-lane and four-lane roadways. The guidelines developed define the circumstances for which the costs of right-turn lanes are justified by the operational and accident cost savings they provide to road users.

EXISTING GUIDELINES

A few studies have developed guidelines for right-turn lanes. Alexander (*7*) developed warrants for right-turn lanes at intersections on two-lane highways solely on the basis of delay cost savings. Alexander compared the delay cost savings provided by right-turn lanes with the cost of constructing and maintaining them and identified the combinations of right-turn and approach volumes for which right-turn lanes would provide delay cost savings exceeding the cost of constructing and maintaining the right-turn lanes for average roadway speeds of 48, 64, and 81 km/hr.

The access control guidelines for urban streets and highways developed by Stover et al. (*3*) suggest that right-turn lanes be provided on uncontrolled intersection approaches when the average daily traffic (ADT) on the intersecting roadway is 500 vehicles per day (vpd) or greater. Right-turn lanes are also recommended at commercial and industrial driveways along primary and secondary streets. However these guidelines were simply based on a general assessment of the operational and safety effects of right-turn lanes with respect to the level of service implied by the functional classification of the streets. A benefit-cost analysis was not concluded.

Glennon et al. (*8*) conducted a benefit-cost analysis of right-turn deceleration lanes at driveway entrances. The analysis was based on data from the literature and some assumptions about the operational and safety effects of right-turn lanes. The results of the analysis indicated that right-turn lanes are cost-effective at driveways when (a) the driveway volume is at least 1,000 vpd with at least 40 right turns into the driveway during peak periods and (b) the roadway ADT is at least 10,000 vpd and the roadway speed is at least 56 km/hr.

Cottrell (*9*) developed guidelines for the treatment of right-turn movements at intersections on rural highways. The treatments considered were (a) no special treatment other than the radius, (b) a taper, and (c) a full-width lane. The guidelines were a synthesis of information obtained from a survey of state practices and field studies. Traffic conflict studies were conducted on 21 rural intersection approaches in Virginia in an effort to determine the relationship between right-turn conflicts, traffic volume, and type of right-turn treatment. Right-turn lanes were found to reduce right-turn conflicts, but the data were not sufficient for the development of guidelines. Therefore, the guidelines developed by Cottrell (*9*) were a synthesis of other states' guidelines adjusted to reflect the nature of traffic conditions in Virginia as determined from the field studies. Similar guidelines have been adopted by the state of Washington (*10*).

Stover and Koepke (*11*) recommend driveway designs for access to arterial streets that include right-turn lanes. They suggest that continuous right-turn lanes be provided when the driveway spacing is less than that necessary to accommodate right-turn lanes at individual driveways. Also, on streets where the speed is over 56 km/hr, they recommend the use of right-turn lanes at driveways when there are more than 1,000 right turns per day and 40 right turns during the peak hour.

In a national study of roadway access management practices, Koepke and Levinson (*12*) cite the right-turn lane warrant used by the Colorado Department of Transportation. The warrant recommends the provision of right-turn deceleration lanes at access points on the basis of the right-turn volume, the roadway's single-lane volume, and roadway speed.

The existing guidelines use several factors to determine the need for right-turn lanes, such as right-turn and through traffic volumes, traffic speed, roadway classification, number of roadway lanes, and capacity. Although many of the guidelines use the same factors, there is considerable variation among the threshold values and the units applied to them. For example, traffic volumes are expressed in terms of ADTs in some of the guidelines, design-hour volumes in others, and peak-hour volumes in others. Some of the guidelines use right-turn volumes and some use right-turn percentages. Some of the guidelines are based primarily on experience and engineering judgment, whereas others are based on benefit-cost analyses. Even among those based on benefit-cost analyses, however, different benefits and costs were used in the analyses. Both operational and safety benefits were used in some cases, whereas only operational benefits were included in others. None of the guidelines have been widely adopted by practitioners.

OPERATIONAL EFFECTS

Right-turn lanes remove the decelerating right-turning vehicles from the through traffic lanes and thereby eliminate the need for through traffic to slow down or change lanes behind them. Consequently, right-turn lanes improve the operational efficiency of the roadway by eliminating the through-vehicle delay and operating costs associated with the speed-change cycle. To quantify these operational improvements, the TRAF-NETSIM (*13*) model was used to simulate traffic operations on uncontrolled approaches to intersections and driveways with and without right-turn lanes. Multiple regression analysis of the simulation output was then conducted to derive equations for the operational benefits of right-turn lanes.

Simulation

The TRAF-NETSIM model was used to simulate traffic operations at four T-intersection configurations: (a) uncontrolled intersection approach without a right-turn lane on a two-lane, two-way roadway, (b) uncontrolled intersection approach with a right-turn lane on a two-lane, two-way roadway, (c) uncontrolled intersection approach without a right-turn lane on a four-lane, two-way roadway, and (d) uncontrolled intersection approach with a right-turn lane on a four-lane, two-way roadway. In each case the intersecting roadway was a two-lane, two-way roadway that was controlled by a stop sign.

Link-Node Diagram

The link-node diagram used to represent the four intersection configurations is shown in Figure 1. Node 4 is the intersection. The roadway is represented by the links between Nodes 801, 1, 4, 2, and 802. Link 1–4 is the uncontrolled intersection approach that was simulated with and without a right-turn lane. The intersecting roadway or driveway is represented by the links between Nodes 803, 3, and 4. Link 3–4 is controlled by a stop sign. The roadway links each had one lane when operations on a two-lane, two-way roadway were being simulated, and they each had two lanes when a four-lane roadway was being simulated. The links on the intersecting roadway or driveway each had one lane in all cases. The TRAF-NETSIM performance measures output for Links 1–4 and 4–2 before and after the addition of a right-turn lane on Link 1–4 were compared to determine the operational effects of the right-turn lanes.

Experimental Design

The inventory of urban highways maintained by the Nebraska Department of Roads (NDOR) was reviewed to determine the

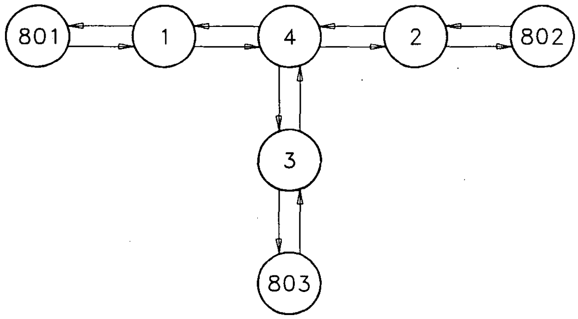

FIGURE 1 Link-node diagram.

range in traffic volumes that should be considered in the simulation. The ADTs on two-lane sections ranged from around 1,000 to 25,000 vpd. The ADTs on four-lane sections ranged from about 5,000 to 60,000 vpd. Since ADTs are two-way volumes and the peak-hour traffic represents about 10 percent of the ADT (*14*), the link volumes used in the simulation ranged from 100 to 1,200 vehicles per hour (vph) for the two-lane, two-way roadway and from 600 to 3,000 vph for the four-lane, two-way roadway. Zero percent trucks was used in all cases, because the effects of trucks were accounted for in the road user cost factors used in subsequent benefit-cost analysis.

Data defining the range of the right-turn percentages at driveways on urban highways in Nebraska were not available. Of course the percentage of right turns would depend on the nature and intensity of the abutting land use and would vary by time of day. For example driveways serving an office building may generate higher right-turn percentages during the morning peak hours, whereas shopping center driveways may generate higher right-turn percentages during off-peak hours. Therefore to maximize the applicability of the guidelines to be developed, a wide range of right-turn percentages was used in the simulation. The right-turn percentages simulated ranged from 7.5 to 90 percent at 7.5-percent increments.

Four roadway speeds and three driveway speeds were simulated. The roadway speeds were 40, 56, 72, and 89 km/hr. The driveway speeds were 16, 24, and 32 km/hr.

A total of 8,640 simulations were made. Three runs were made for each combination of the following variables:

1. Number of roadway lanes (two levels: two and four lanes),
2. Right-turn lane (two levels: with and without),
3. Approach volume (five levels),
4. Right-turn percentage (12 levels: 7.5 to 95 percent at 7.5-percent increments),
5. Approach speed (four levels: 40, 56, 72, and 89 km/hr), and
6. Driveway speed (three levels: 16, 24, and 32 km/hr).

The five levels of approach volume simulated for two-lane roadways were 100, 300, 600, 900, and 1,200 vph. For four-lane roadways, they were 600, 1,200, 1,800, 2,400, and 3,000 vph.

Data Analysis

The delay, stops, and fuel consumption for the through vehicles simulated by TRAF-NETSIM for Links 1–4 and 4–2 shown in Figure 1 were recorded from the output for each simulation. For the conditions simulated it was found that right-turning vehicles on roadways without right-turn lanes caused through vehicles to slow but not stop. Therefore there were no differences in the number of through-vehicle stops with and without right-turn lanes. Consequently the only operational effects of right-turn lanes obtained from the results of the simulation were reductions in delay and fuel consumption.

A total of 8,640 delay and fuel consumption values were obtained from the TRAF-NETSIM output, 4,320 for each roadway type. The data for each roadway type were then split randomly into two sets. One set, which contained two-thirds of the original data, was used to conduct a multiple regression analysis to develop delay and fuel consumption models. The other set, which contained one-third of the original data, was used to validate the models.

Model Formulation

The first step in the formulation of the delay and fuel consumption models was to determine the nature of the relationships. Scattered diagrams were plotted with delay and fuel consumption as the dependent variables and volume as the independent variable. Diagrams were plotted for various combinations of right-turn percentage, roadway speed, and driveway speed for two-lane and four-lane roadways with and without right-turn lanes. Examination of these diagrams suggested the nature of the functional relationships that should be investigated in the multiple regression analysis. Linear relationships were indicated for the fuel consumption models. Both linear and exponential relationships were indicated for the delay models.

Next multiple regression analysis was used to develop delay and fuel consumption models for both the two-lane and the four-lane roadways. Several models were considered. The alternative models were compared on the basis of the following: (a) the extent to which they explained the variation in the dependent variable, as indicated by their coefficients of determination (R^2 values); (b) the statistical significance of the independent variables, as indicated by their "F" values; (c) the extent to which they exhibited the lack of multicollinearity, as indicated by their variance inflation factors; and (d) their appropriateness, as indicated by their residual plots.

Four linear models were found to best describe the delay and fuel consumption on two-lane and four-lane roadways. The coefficients of determination were 0.77 and 0.80 for the two-lane and four-lane delay models, respectively, and 0.99 for both of the fuel consumption models. All four of the models were statistically significant (p = .0001), and the regression coefficients of all the independent variables in the models were also statistically significant (p = .0001). The residual plots indicated that the variance of the error terms was constant, indicating that the relationships were appropriate.

According to the models right-turn lanes reduced delay and fuel consumption as a function of right-turn volume as follows:

$$\Delta D_{2L} = 0.0388\ V_{RT} \quad (1)$$

$$\Delta FC_{2L} = 0.0125\ V_{RT} \quad (2)$$

$$\Delta D_{4L} = 0.0200\ V_{RT} \quad (3)$$

$$\Delta FC_{4L} = 0.00435\ V_{RT} \quad (4)$$

where

ΔD_{2L} = delay savings on a two-lane roadway (sec/through vehicle),
ΔFC_{2L} = fuel consumption savings on a two-lane roadway (L/15 min),
ΔD_{4L} = delay savings on a four-lane roadway (sec/through vehicle),
ΔFC_{4L} = fuel consumption savings on a four-lane roadway (L/15 min), and
V_{RT} = right-turn volume (vehicles/15 min).

Model Validation

The delay and fuel consumption models were validated by conducting a multiple regression analysis of the data that were set aside for model validation and comparing the results with those of the initial regression analysis. A comparison of the results of the initial and validation regression analyses indicated that there was no statistically significant ($p = .01$) difference between the regression coefficients obtained from the two analyses. Therefore it was concluded that the delay and fuel consumption models developed initially are valid for the purpose of the study.

SAFETY EFFECTS

Right-turn lanes improve the safety of traffic operations by removing the deceleration of right-turning vehicles from through traffic lanes, thereby reducing the potential for rear-end collisions involving through vehicles that fail to slow down. Previous research, however, has not adequately quantified the safety effects of right-turn lanes on uncontrolled approaches to intersections and driveways on urban roadways because of the limitations of the accident data available. Therefore as suggested by Stover et al. (*3*), the relationship between speed differential and accidents established by Solomon (*15*) was used to estimate the safety effects of right-turn lanes, because the primary effect of a right-turn lane is to reduce the speed differential in the through lanes.

Speed Differential

To estimate accidents from the relationship between speed differential and accidents established by Solomon (*15*), it was first necessary to estimate the difference between the speed of right-turning vehicles and the average speed of vehicles on the roadway. The average speed of right-turning vehicles during deceleration was then assumed to be equal to the average of the speeds of the vehicles on the roadway and driveway entrance. On the basis of the driveway entrance speed data collected by Richards (*16*) and Stover et al. (*3*), it was assumed that the turning speed of right-turning vehicles is 24 km/hr.

The average roadway speed is the average speed of all vehicles on the roadway, both right-turning and non-right-turning vehicles. The average roadway speed was computed as follows:

$$S_{avg} = P_{RT}S_{RT} + (1 - P_{RT})S_R \tag{5}$$

where

S_{avg} = average roadway speed (km/hr),
P_{RT} = portion of right-turning vehicles,
S_{RT} = average speed of right-turning vehicles (km/hr), and
S_R = roadway speed (km/hr).

The speed differentials used to estimate the accidents associated with right turns from through lanes were the differences between the average speeds of right-turning vehicles and the average roadway speeds.

Number of Accidents

The number of accidents per year caused by vehicles turning right from through traffic lanes was computed as follows:

$$A = 55.6(P_D I_D + P_N I_N)\ \mathrm{ADT} \cdot P_{RT} \cdot L \tag{6}$$

where

A = annual number of accidents caused by right-turning vehicles,
P_D = portion of daytime traffic,
I_D = daytime accident involvement rate (accidents/vehicle km),
P_N = portion of nighttime traffic,
I_N = nighttime accident involvement rate (accidents/vehicle km),
ADT = annual average daily traffic (vpd),
P_{RT} = portion of right turns, and
L = right-turn deceleration distance (m).

The daytime and nighttime accident involvement rates were determined from the relationship between speed differential and accidents established by Solomon (*15*). The portions of daytime and nighttime traffic used in Equation 6 were the averages of those found at the continuous traffic counting stations on urban arterial sections of the state highway system in Nebraska (*14*). On average the portion of daytime traffic is 0.76 and the portion of nighttime traffic is 0.24. The right-turn deceleration distance in Equation 6 is the distance over which the right-turning vehicles are assumed to decelerate, and the length of the roadway over which the speed differential used to determine the accident involvement rate was assumed to apply. The deceleration distances used are those recommended by AASHTO (*5*).

BENEFITS-COSTS

The development of the right-turn lane guidelines was based on the results of a benefit-cost analysis. The benefits used in the analysis were the road user cost savings associated with the operational and safety effects of right-turn lanes. The costs used in the analysis were those of constructing and maintaining right-turn lanes.

Operational Cost Savings

The operational cost savings were the road user cost savings resulting from the reductions in delay and fuel consumption provided by right-turn lanes. Using the delay and fuel consumption savings models (Equations 1 to 4), the hourly operational cost savings associated with these savings in delay and fuel consumption are computed as follows:

$$\mathrm{HOCS}_{2L} = \frac{0.0338}{3600} V_{RT}V_TC_T + (0.0125)(4)V_{RT}C_F \tag{7}$$

$$\mathrm{HOCS}_{4L} = \frac{0.0200}{3600} V_{RT}V_TC_T + (0.00435)(4)V_{RT}C_F \tag{8}$$

where

HOCS_{2L} = hourly operational cost savings on a two-lane roadway ($/hr),
HOCS_{4L} = hourly operational cost savings on a four-lane roadway ($/hr),
V_{RT} = right-turn volume (vehicles/15 min),
V_T = through traffic volume (vph),

C_T = unit value of time (\$/hr), and
C_F = cost of fuel (\$/L).

To facilitate the ultimate application of the guidelines to be developed, the through and right-turn volumes in Equations 7 and 8 were expressed in terms of ADTs as follows:

$$V_{RT} = P_{RT} \frac{P_i}{4} \frac{ADT}{2} \quad (9)$$

$$V_T = (1 - P_{RT})\, P_i \frac{ADT}{2} \quad (10)$$

where

V_{RT} = right-turn volume (vehicles/15 min),
V_T = through traffic volume (vph),
P_{RT} = portion of right turns,
P_i = portion of ADT in ith hour of the day, and
ADT = annual average daily traffic (vpd).

Substituting these volume expressions into Equations 7 and 8, the hourly operational cost savings equations in terms of ADT become:

$$\text{HOCS}_{2L} = \left[\frac{0.0338}{57{,}600}(1 - P_{RT})P_i\text{ADT}\, C_T + \frac{0.0125}{2} C_F\right] P_{RT}P_i\text{ADT} \quad (11)$$

$$\text{HOCS}_{4L} = \left[\frac{0.0200}{57{,}600}(1 - P_{RT})P_i\text{ADT}\, C_T + \frac{0.00435}{2} C_F\right] P_{RT}P_i\text{ADT} \quad (12)$$

The portion, P_i, of daily traffic during each hour of the day used to compute the operational cost savings was determined from the traffic count data collected at the continuous traffic counting stations on urban arterial sections of the state highway system in Nebraska (*14*).

The annual operational cost savings were then computed by summing the hourly operational cost savings for each of the 24 hr in the day to obtain the daily operational cost savings and then multiplying the daily operational cost savings by 365 days per year.

The unit value of time, C_T, used to compute the operational cost savings was \$9.53/hr. This value is the 1975 unit value of time established by AASHTO (*17*) updated to 1992 in accordance with changes in the consumer price index. This value represents an average unit value of time for all trip purposes, relatively low (less than 5 min) time savings, an average vehicle occupancy of 1.56 persons, and a vehicle mix of 97 percent passenger cars, 2 percent single-unit trucks, and 1 percent combination trucks. The vehicle mix was the average composition of traffic at the continuous traffic counting stations on urban arterial sections of the state highway system in Nebraska (*14*). The cost of fuel used in the calculation of operation cost savings was \$0.32/L.

Accident Cost Savings

The number of accidents per year caused by vehicles turning right from through-traffic lanes was computed by using Equation 6. This number represents the number of rear-end accidents likely to be caused by vehicles decelerating to turn right from through-traffic lanes. Therefore, it was assumed that this number of accidents would be eliminated by providing a right-turn lane.

According to the NDOR revised relative severity index figures (*18*), the cost of a rear-end collision on an urban section of the state highway system in Nebraska is \$9,300. Thus the annual accident cost savings provided by right-turn lanes were computed as follows:

$$\text{AACS} = \$9{,}300A \quad (13)$$

where AACS is the annual accident cost savings (\$/year), and A is the annual number of accidents caused by right-turning vehicles.

Right-Turn Lane Costs

The costs of right-turn lanes were estimated from cost data provided by the NDOR for the construction of right-turn lanes on typical urban sections of the state highway system in Nebraska. The costs included fixed costs, variable costs, and right-of-way cost. The fixed costs included the costs of preliminary engineering, mobilization, field laboratory, general clearing and grubbing, and traffic control devices. The variable costs were a function of the pavement area of the right-turn lane and included the costs of excavation, paving, sodding, and sidewalks. The total variable cost was computed by multiplying the pavement area of the right-turn lane by the unit variable cost. The area of the right-turn lane was calculated by using a width of 3.66 m and a length that included the approach-taper deceleration-lane distances recommended by AASHTO (*5*).

The cost of right-of-way can vary considerably. The experience of the NDOR indicates that it can range from \$0.093 to \$0.93/m^2 along urban roadways, depending on the location. Also in some cases there may be no cost of right-of-way because the existing right-of-way is sufficient to accommodate the construction of a right-turn lane. Therefore the guidelines were developed for four cases. One case represented the situation in which the existing right-of-way was sufficient so that the right-of-way cost was zero. The other three cases were representative of low (\$0.093/m^2), medium (\$0.465/m^2), and high (\$0.93/m^2) right-of-way costs.

GUIDELINES

The guidelines were developed by comparing the benefits and costs of right-turn lanes at uncontrolled intersections and driveways on urban roadways. The guidelines indicate the design-hour traffic volumes for which the costs of right-turn lanes are justified by the benefits they provide to road users. The benefits and costs of right-turn lanes on two-lane and four-lane roadways were compared over a range of traffic volumes. The benefits used were the sum of the annual operational and accident costs savings, which were computed for annual traffic growth rates of 2 percent. The costs of right-turn lanes were annualized by using a 4-percent interest rate, a 20-year service life, and a zero residual or salvage value. Annual costs were computed for the four right-of-way cost cases: (a) none, construction within existing right-of-way; (b) low, \$0.093/m^2; (c) medium, \$0.465/m^2; and (d) \$0.93/m^2.

The ADTs and right-turn percentages at which the benefits and costs of right-turn lanes are equal were determined for each combination of roadway speed and right-of-way cost. The breakeven ADTs and right-turn percentages were then converted to design-hour volumes by using the relationship between design-hour volume and ADT on urban roadways in Nebraska (*14*) as follows:

$$\text{DDHV} = 65.11 + 0.0958 \frac{\text{ADT}}{2} \quad (14)$$

$$\text{RTDHV} = P_{\text{RT}}\text{DDHV} \quad (15)$$

where

DDHV = directional design hour volume (vph),
RTDHV = right-turn design hour volume (vph), and
ADT = annual average daily traffic (vpd).

RTDHV represents the minimum design-hour right-turn volume necessary to justify the construction of a right-turn lane on an urban roadway with a directional design-hour volume equal to DDHV.

The guidelines for right-turn lanes on urban two-lane roadways are given in Table 1. The guidelines for right-turn lanes on urban four-lane roadways are given in Table 2. In each case, guidelines are shown for each combination of roadway speed and right-of-way cost. It should be noted that both the directional and right-turn design-hour volumes in the guidelines are existing, or base year, traffic volumes.

The guidelines developed in this research are within the range of those developed by others. The guidelines for right-turn (RT) lanes on urban two-lane and four-lane roadways are compared with the right-turn lane guidelines developed by others in Figures 2 and 3, respectively. The ranges of the guidelines developed in this research are defined by two cases. The upper limits of the ranges are defined by the guidelines for the 40-km/hr roadway speed and high ($0.93/m^2) right-of-way cost, and the lower limits are defined by the guidelines for the 89-km/hr roadway speed and zero right-of-way cost. As shown in Figures 2 and 3, the guidelines developed in this research are bounded by the existing guidelines. The Colorado (*12*) guidelines are the lower boundary, and the Virginia (*9*) and Washington State Department of Transportation (*10*) guidelines are the upper boundary. The guidelines developed by Alexander (*7*) and Glennon et al. (*8*) are within the range of those developed in the present research.

CONCLUSION

The guidelines presented in this paper define the right-turn design-hour volume required to justify a right-turn lane at access points on urban two-lane and four-lane roadways as a function of the following factors: (a) directional design-hour volume, (b) roadway speed, (c) number of lanes on the roadway, and (d) right-of-way cost. The guidelines indicate that the right-turn design-hour volume that warrants a right-turn lane is lower on roadways with higher directional design-hour volumes and higher roadway speeds, because the road user costs associated with the operational and safety effects of right turns are greater on higher-volume, higher-speed roadways. Consequently the road user cost savings provided by right-turn lanes are greater on these roadways. Likewise the right-turn design-hour volume required to justify a right-turn lane on a two-lane roadway is lower than that required to

TABLE 1 Right-Turn Lane Guidelines for Urban Two-Lane Roadways

Roadway DDHV (vph)	Minimum Right-Turn DHV (vph)															
	Within Existing ROW				ROW Cost = $0.093/m^2				ROW Cost = $0.465/m^2				ROW Cost = $0.93/m^2			
	Roadway Speed (km/hr)				Roadway Speed (km/hr)				Roadway Speed (km/hr)				Roadway Speed (km/hr)			
	40	56	72	89	40	56	72	89	40	56	72	89	40	56	72	89
100			65	30			70	40								
125	65	60	40	25	70	65	50	25			75	45				
150	60	50	35	20	65	55	40	20	75	75	60	35	95	95	90	50
200	50	45	30	15	55	45	30	15	65	65	40	25	80	80	60	30
400	40	35	20	10	40	35	20	10	40	40	30	20	55	55	40	20
600	35	30	15	10	35	30	15	10	35	35	25	15	45	45	35	15
800	30	25	15	10	30	25	15	10	30	30	20	10	35	35	30	15
1000	25	20	15	10	30	25	15	10	30	30	20	10	35	35	30	15
1200	25	20	15	10	30	25	15	10	30	30	20	10	35	35	30	15

TABLE 2 Right-Turn Lane Guidelines for Urban Four-Lane Roadways

Roadway DDHV (vph)	Minimum Right-Turn DHV (vph)															
	Within Existing ROW				ROW Cost = \$0.093/m²				ROW Cost = \$0.465/m²				ROW Cost = \$0.93/m²			
	Roadway Speed (km/hr)				Roadway Speed (km/hr)				Roadway Speed (km/hr)				Roadway Speed (km/hr)			
	40	56	72	89	40	56	72	89	40	56	72	89	40	56	72	89
100				35				60								
150	80	65	40	25	85	70	45	25			70	40				60
200	70	55	35	20	75	60	35	20	85	75	50	30	110	100	70	40
500	45	40	25	15	50	45	25	15	60	50	35	25	70	60	40	30
1000	35	30	20	10	35	30	20	10	40	40	25	15	45	45	35	20
1500	30	25	15	5	30	25	15	5	35	35	20	10	40	40	30	15
2000	25	20	15	5	25	20	15	5	30	30	20	10	35	35	25	15
2500	20	20	15	5	20	20	15	5	25	25	20	10	30	30	20	15
3000	20	20	15	5	20	20	15	5	25	25	20	10	25	25	20	15

justify one on a four-lane roadway, because the road user costs associated with the operational and safety effects of right turns are higher on two-lane roadways. On the other hand, the warranting right-turn design-hour volume increases with higher right-of-way cost, because more road user cost savings are needed to offset the higher cost of the right-turn lane.

The guidelines developed in this research are within the range of those developed by others. Comparison with other guidelines indicates that the guidelines developed in this research are reasonable. In addition, they are more definitive than the other guidelines because they account for the effects of roadway speed and right-of-way costs.

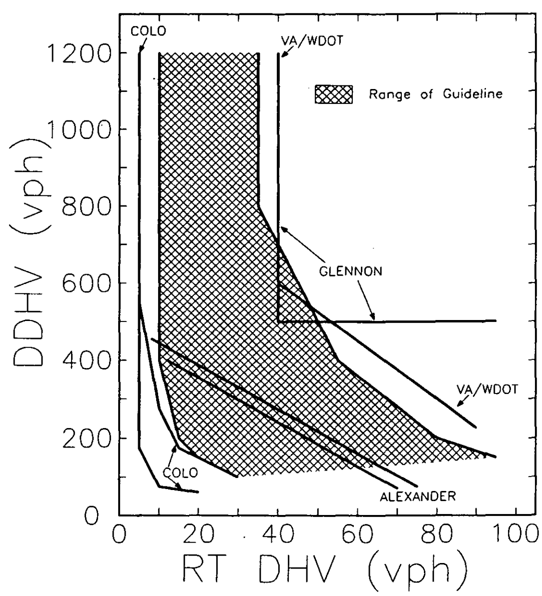

FIGURE 2 Comparison of right-turn lane guidelines for urban two-lane roadways.

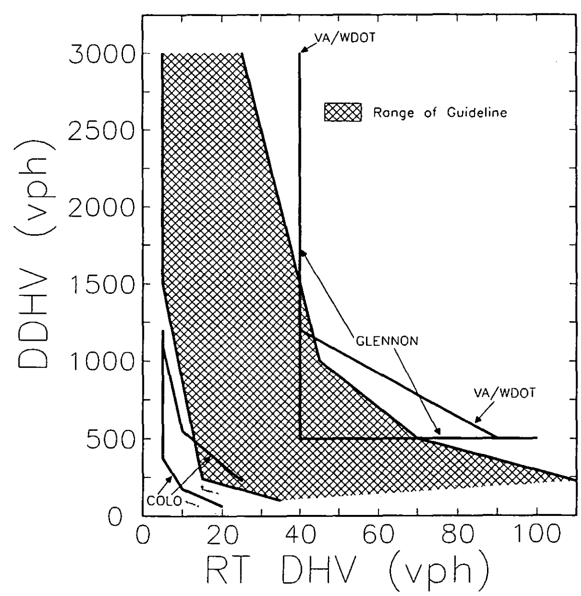

FIGURE 3 Comparison of right-turn lane guidelines for urban four-lane roadways.

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