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Right-turn Traffic Volume Adjustment in Traffic Signal Warrant Analysis

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Cui Zhou and Zong Tian

An intersection with heavy right-turn volumes, without any reduction, might mislead a signal warrant analysis, and a different conclusion may be reached on whether a signal is warranted. Previous right-turn volume reduction methods based mostly on engineering judgment lack specific theoretical backgrounds. Therefore, this paper proposes a new method with theoretical justification. The method focuses on traffic operation principles centered on finding the delay equivalent relationship between right-turn and through traffic, that is, to equate the right-turn volume to through vehicles to produce the same control delay on a minor street. Equivalent factor tables were constructed on the basis of four geometric configurations. Combining with the various traffic volume distributions, more than 12,000 scenarios were analyzed. The volume ratio in the two directions of the main street was especially considered. The analysis showed that the uneven volume distribution in the main street had a greater effect on the minor-street right-turn movement. To use the equivalent factors efficiently, statistical regression models were developed. Last, the proposed method was applied to one signal warrant case and demonstrated promising results for its practical application in traffic signal warrant analysis.

Traffic signals are the most restrictive intersection control types compared with unsignalized intersections. When installed appropriately, signals may reduce certain types of accidents, most notably angle collisions. However, unjustified traffic signals may cause an increase in other types of accidents (such as rear-end collisions), excessive delay, congestion, and disobedience toward signals. Traffic signals should be installed only when they alleviate more problems than they induce. The decision for traffic signals should be based on competent engineering studies and field observations to ensure that a signal is warranted and will enhance the safety and efficiency of the intersection. In that context, to avoid the unnecessary use of signals, signal warrant analysis is the first and most important step in the signal installation process.

When a signal is considered for capacity reasons, it is customary to adjust minor-street right-turn volumes to acknowledge the fact that a certain percentage of vehicles can make right turns without the aid of a traffic signal. High volumes of right-turn vehicles on the minor street can skew a signal warrant analysis and indicate an incorrect need for a signal; therefore, how to adequately consider the right-turn volume is crucial in signal warrant analysis. Section 4.1 of the *Manual on Uniform Traffic Control Devices* clearly states that “the study should consider the effects of the right-turn vehicles from the minor-street approach and engineering judgment should be used to determine what, if any, portion of the right-turn traffic is subtracted from the minor-street traffic count when evaluating the count against the signal warrants” (*1*). The above statements provide justifications for reducing right-turn traffic volume.

Right-turn adjustments can be based on engineering judgment, field observation, or a right-turn adjustment method. Right-turn vehicles should be reduced if a portion of the right-turning traffic is able to make the movement without experiencing significant delay. However, if queued vehicles prevent right-turning traffic from flowing freely or main-line volumes are high enough that even right-turning vehicles experience significant delay, the reduction should be carefully considered and full right-turn volumes may be used in signal warrant analysis.

Mozdbar et al. emphasized the importance of including right-turn traffic in the signal warrant studies and expanded the guidelines developed by the city of Austin, Texas (*2*). They considered a right-turn volume adjustment under one of three conditions: accident experience, sight distance obstruction, and delay. The highest adjusted right-turn volume would be used in a combination of left-turn and through traffic to conduct the signal warrant analysis. Engineers at the Illinois Department of Transportation (DOT) District 1 developed a process called the Pagones theorem to reduce the number of right turns on the minor street (*3*). It is a two-step method that uses a minor-street equivalent factor and a main-line congestion factor to estimate the reduced portion of right-turn volumes. The minor-street equivalent factor reflects minor-street geometry and traffic volume, while the main-line congestion factor adjusts to account for the amount of congestion on the main street. NCHRP Report 457 provides a right-turn reduction method, which was originally proposed by the Utah DOT (*4*). According to this method, the actual right-turn volume is reduced on the basis of the consideration of the main-line volume conflicting with the right-turn movement. The relationship between the reduced right-turn volumes and the conflicting main-line volume is illustrated in a graph. The Wisconsin DOT uses three right-turn inclusion percentages based on the effect of the right turns on the operation of the intersection (*5*). The Oregon DOT suggests that 85% of the right-turn lane or shared lane capacity be subtracted from the right-turn volume (*6*). The Arizona DOT recommends that the adjusted right-turn volume equal the total right-turn volume minus the right-turn volume experiencing a stopped-delay measurement of 5 s or less on the higher-volume minor-street approach (*7*).

To gather more information on the reduction of right-turn vehicles in signal warrant analysis in current practice, a survey was posted on the ITE community discussion section in October 2013. Eight

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Transportation Research Record: Journal of the Transportation Research Board, No. 2562, Transportation Research Board, Washington, D.C., 2016, pp. 28–35.
DOI: 10.3141/2562-04

responses were received in this survey. They are presented and summarized below.

Traffic engineers from the Wisconsin DOT and the Illinois DOT mentioned that their states had written policies about right-turn reduction. A transportation planner from a consulting firm stated his office used the recommendations based on NCHRP 457. For DOTs that have no written policy on this matter, traffic engineers apply their own procedures. A traffic engineer from the city of Federal Way commented that he did not include right-turn volume if the level of service (LOS) for that movement was Level A, but would otherwise include all of it. A senior engineer from the Lee County DOT indicated that if there was a right-turn-only lane, he would deduct the number of left turns from the right-turn volume with the justification that if there was enough of a gap for a left turn, then there was a gap for a right turn. Another traffic engineer from Lee County said that if there was no right-turn lane, he used the entire approach volume for the warrant analysis and he did not consider the effect of a small right-turn channel. Particularly, if there were a high number of U-turns that conflicted with the right turns, then he might want to consider a greater percentage of the right-turning traffic in the count. A traffic engineer at the Virginia DOT recommended the Pagones theorem, which was used by the Illinois DOT District 1, and found it useful in reduction calculations. The president of Yarger Engineering, Inc., posted a particularly long comment about the right-turn inclusion in the signal warrant analysis. In the comment, he expressed that this topic was a gray area and disagreed with the practice of including or otherwise excluding all right-turn volume purely on the basis of an analyst's subjectivity.

All of the methods mentioned above are means of estimating the volume of right-turning traffic that would not benefit from the provision of a signal. However, most of them are based on engineering judgments with no theoretical studies to support them. Methods based on field observation seem appropriate but are hard to realistically implement. The Pagones theorem and the NCHRP method seem to be more robust, but no published literature was found to document the algorithms and theories behind these two methods. Besides, even though the Pagones theorem has considered the main-street volume, it does not take into account the uneven volume distribution in two directions. The NCHRP method reduces right-turn volume purely on the basis of the conflicting major-road volume and whether a right-turn bay is provided. It does not consider the minor-street through traffic at all, but in reality, through traffic can block right-turn traffic. Further, this method does not provide the inherent relationship between minor-street right-turn volume reduction and conflicting major-street volume except for a graph.

PROPOSED METHOD

The proposed approach is based on traffic operation principles (i.e., delay or LOS) that have been successfully applied to determine intersection control types (*8, 9*). The control delay estimation is based on the 2010 *Highway Capacity Manual* (HCM) procedure for two-way stop-controlled intersections (*10*). To expedite the data analysis process, the HCM analysis procedure is implemented in Microsoft Excel with Visual Basic, which allows quick analysis of multiple scenarios.

An isolated intersection shown in Figure 1 is used for the analysis in this paper. The subject movements are northbound through and right turn. Both movements have a direct crossing or merging conflict with all of the main-street movements, except the right turn into the subject approach. It is assumed that all traffic on the main street is through movement in both directions. In the analysis, the volume distribution in the two directions of the main street is considered and defined in Equation 1.

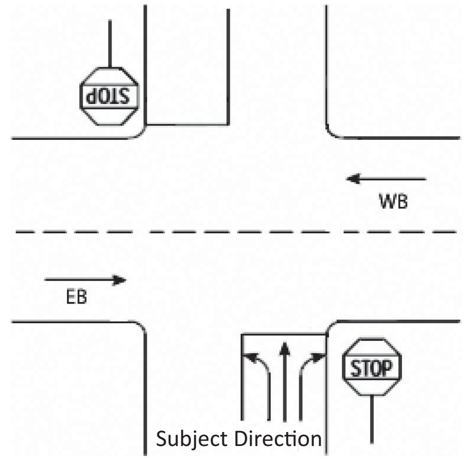

FIGURE 1 Study intersection (EB = eastbound; WB = westbound).

$$\mathrm{VR} = \frac{V_1}{V_2} \tag{1}$$

where

VR = volume ratio of main street,
V_1 = far side of main street to subject minor street, and
V_2 = near side of main street to subject minor street.

Specifically, the volume ratio is the volume of the westbound divided by that of the eastbound (see Figure 1). Furthermore, according to the minor-street lane configurations, four configurations are discussed, as shown in Figure 2.

Configuration 1

Configuration 1 depicts a shared-lane geometry on the minor street. The volume ranges covered in the analysis are listed in Table 1. These volume combinations yield a total of 12,096 scenarios. Each main-street volume and volume ratio are combined as one study situation. In one study situation, all the minor-street volume conditions are calculated and the maximum value of the entire minor-street volume scenarios is defined as the situation equivalent factor. There are 63 study situations in total for all configurations. Under each study situation, there are 192 minor-street volume scenarios. For the minor-street left and through movements, 20% left turns are assumed.

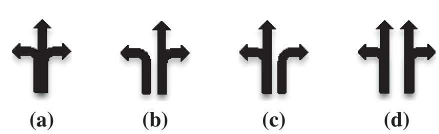

FIGURE 2 Minor-street lane configurations: (*a*) 1, (*b*) 2, (*c*) 3, and (*d*) 4.

TABLE 1 Scenarios Evaluated in Configuration 1

Item	Range
Main street (9)	400, 500, 600, 700, 800, 900, 1,000, 1,100, 1,200 vph
Volume ratio (7)	1:1, 1:2, 1:3, 1:4, 2:1, 3:1, 4:1
Minor-street right turn (8)	50, 100, 150, 200, 250, 300, 350, 400 vph
Minor-street left turn and through (24)	40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 500 vph

In the analysis, the right-turn equivalent factor (equivalent factor, for short) is defined in Equation 2. By means of equivalence, the amount of right-turn traffic is equivalent to the amount of through traffic in order to yield the same control delay.

$$\text{EF} = \frac{T_2 - T_1}{R} \qquad (2)$$

where

EF = right-turn equivalent factor,
T_1 = through volume before equivalence,
T_2 = through volume after equivalence without right-turn traffic, and
R = right-turn volume before equivalence.

The adjusted right-turn volume could be estimated by the equivalent factor as follows:

$$R_{\text{adj}} = R \times \text{EF} \qquad (3)$$

where R_{adj} is the adjusted right-turn volume. It is obvious that the larger the equivalent factor, the more right-turn volume would be used for a warrant check.

For example, Table 2 shows the computation of the equivalent factor of one volume scenario with a main-street volume of 600 vehicles per hour (vph), volume ratio of 1:2, minor-street right-turn (RT) volume of 200 vph, and minor-street left-turn (LT) and through (T) volume of 132 vph. In this condition, the shared lane delay is 22.2 s/vehicle (veh). Then, all the right-turn traffic is eliminated, and the through traffic volume is increased until the control delay reaches 22.2 s/veh.

Figure 3 shows equivalent factors for one specific study situation in which the main-line volume is 500 vph with a 1:1 volume ratio

TABLE 2 Equivalent Factor Calculation Example for Configuration 1

Main Street		Subject Minor Street			
EB	WB	LT	T	RT	Delay
Before Reduction					
400	200	24	108	200	22.2
After Reduction					
400	200	24	188	0	22.2

NOTE: Major volume = 600; volume ratio = ½; equivalent factor (188 – 108)/200 = 0.4; adjusted right-turn volume, 200 × 0.4 = 80.

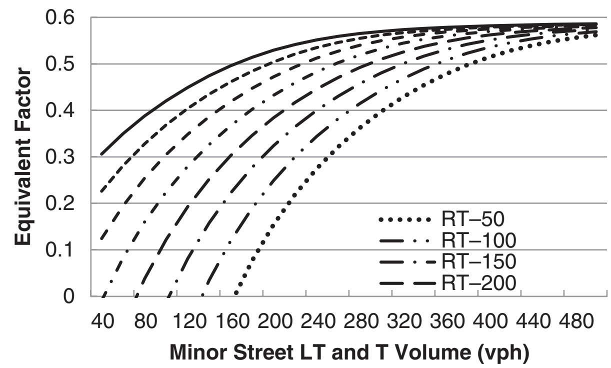

FIGURE 3 Equivalent factor graph for Configuration 1: main-street volume = 500 vph, VR = 1:1.

(a total of 192 scenarios). From the graph, it is observed that when right-turn volumes increase, equivalent factors increase accordingly. Under the same right-turn volume (such as a right-turn volume of 300 vph), when there are more left-turn and through vehicles in the minor street, the equivalent factors will increase and more right-turn traffic will be used for the warrant check. In general, when the minor-street traffic increases, the equivalent factor tends to converge to a fixed value (0.59 in this case). This value is the largest number of the entire equivalent factors in this study condition and defined as the situation equivalent factor for this study situation.

Table 3 shows situation equivalent factors under different main-street volumes and volume ratios. When the main-line volume increases, the equivalent factor decreases. This result can be explained by the fact that the main-street volume affects through vehicles more than right turns; therefore, delay increases more for minor-street through vehicles than for right turns. When the main-line volume is higher than 1,200 vph, the same equivalent factors for the 1,200 vph level will apply. In reality, the main-street volume may not be exactly in the same value in the table; thus, lower bound values are recommended. For example, the main-street volume is 625 vph; so checking the table for 600 vph in main-street volume is preferred.

Configuration 2

Configuration 2 is a shared right-through lane with an exclusive left-turn lane. With the same traffic volume scenarios, almost the same equivalent factors are obtained as those in Configuration 1. So, it is reasonable to treat Configurations 1 and 2 as one category. Also, the assumed left-turn percentage does not significantly affect the equivalent relation. The reason is that the left-turn traffic has the same effect on the through and right-turn vehicles.

Configuration 3

The geometry of Configuration 3 is a shared left-through lane with an exclusive right-turn lane, and different traffic volume scenarios are applied. For the minor-street left and through movements, 20 left turns are assumed. Delay of the right-turn movement is irrelevant to through movement, so it is assumed that the through movement is zero before reduction and the right-turn movement is from 50 vph to 510 vph with a 20 vph increment. A total of 24 scenarios are considered in each study situation.

TABLE 3 Situation Equivalent Factors for Configuration 1

Volume Ratio	Main-Street Volume[a]								
	400	500	600	700	800	900	1,000	1,100	1,200
1:1	0.64	0.59	0.55	0.52	0.48	0.45	0.42	0.39	0.36
1:2	0.69	0.66	0.63	0.60	0.57	0.54	0.52	0.49	0.47
1:3	0.72	0.70	0.68	0.64	0.62	0.60	0.58	0.56	0.54
1:4	0.74	0.72	0.70	0.68	0.66	0.64	0.62	0.60	0.58
2:1	0.57	0.52	0.47	0.43	0.39	0.37	0.33	0.29	0.26
3:1	0.55	0.49	0.44	0.40	0.36	0.32	0.29	0.26	0.23
4:1	0.53	0.47	0.42	0.38	0.34	0.30	0.27	0.24	0.21

[a]When the main-street volume is beyond 1,200 vph, equivalent factors of 1,200 vph are applied.

Situation equivalent factors for these 63 situations are shown in Table 4. It is easy to see that the volume ratio has a large influence. If the volume distribution is not considered, it may highly reduce right turns with exclusive right-turn lanes. Most institutes are inclined to exclude all the right-turn traffic in this geometry. From Table 4, equivalent factors vary from 0.09 to 0.60 for different volume ratios when the main-street volume is 400 vph. This phenomenon indicates that it is not proper to reduce all the right-turn volume when there is more main-street traffic on the near side of the subject minor street compared with the far side.

Because right-turn vehicles have a separate lane, their movement may not be affected by the through and left-turn vehicles when signal warrant analysis is conducted. There are two ways to consider the minor-street volume and the lane number as introduced in the *Manual on Uniform Traffic Control Devices* 3C.01.13. For the first, the minor street is considered to have two lanes (shared through lane and right-turn lane). The minor-street volume is the sum of adjusted right-turn and through and left-turn traffic volumes. For the other, the minor street has one lane. Under this condition, the minor-street volume is the maximum volume of adjusted right-turn and through and left-turn traffic.

Configuration 4

The lane geometry in Configuration 4 consists of two lanes with shared right turn and left turn as shown in Table 1. Traffic volume scenarios are the same as those in Configuration 1 except that minor-street left-turn and through volume is from 40 vph to 700 vph with a 20 vph increment. For the minor-street left and through movements, 20% of left turns are assumed. Figure 4 depicts the equivalent factors when the main-line volume is 500 vph. From the figure, the maximum equivalent factor is not in the highest minor-street left-turn and through volume, but is located in a medium level. In the low-volume situation, right turn and through are easy but right turn is easier, while in the high-volume situation, they are both difficult but through is more difficult because of the existence of a queue. For completeness, situation equivalent factors are shown in Table 5.

REGRESSION EQUATIONS FOR EQUIVALENT FACTORS

As mentioned, the situation equivalent factor is the maximum value of the entire volume scenarios, and the volume range is usually wide so as to consider various conditions. For a specific case, the equivalent factor may not be exact but tends to be conservative. Even though the equivalent factor graphs give the reduction results for the covered volume conditions, equivalent factors are not continuous and it is not straightforward to extract other scenarios. Therefore, the statistical method is used to build regression models for all four configurations.

Configurations 1 and 2

The equivalent factor is calculated primarily on the basis of delay, so the regression equations for Configurations 1 through 5 are inspired

TABLE 4 Situation Equivalent Factors for Configuration 3

Volume Ratio	Main-Street Volume								
	400	500	600	700	800	900	1,000	1,100	1,200
1:1	0.36	0.33	0.30	0.29	0.28	0.27	0.26	0.25	0.24
1:2	0.49	0.48	0.48	0.47	0.46	0.45	0.44	0.42	0.40
1:3	0.55	0.55	0.55	0.55	0.54	0.53	0.52	0.50	0.48
1:4	0.60	0.60	0.60	0.60	0.59	0.58	0.56	0.55	0.53
2:1	0.21	0.20	0.11	0.07	0.03	0.00	0.00	0.00	0.00
3:1	0.14	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4:1	0.09	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00

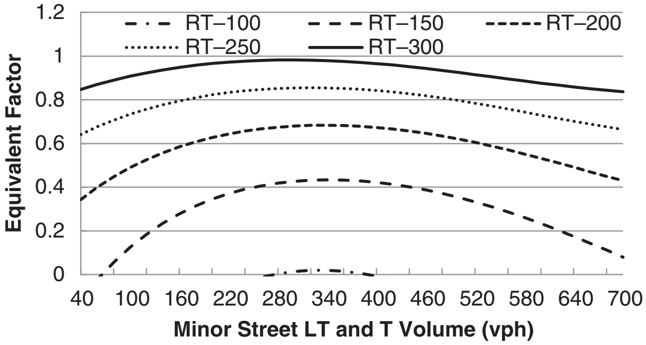

FIGURE 4 Equivalent factor graph for Configuration 4: main-street volume = 500 vph, VR = 1:4.

by the two-way stop-control delay function. The regression equation for Configurations 1 and 2 has the following form:

$$\mathrm{EF} = a\left(1 - \frac{1}{(bV_{T+L} + cV_R)^d}\right) \tag{4}$$

where

V_{T+L} = volume of through and left-turn traffic,
V_R = volume of right-turn traffic, and
a, b, c, d = regression coefficients.

MATLAB software is used to calculate the regression factors (*11*).

From Figure 5, it can be seen that all points scatter around the fitting surface. The coefficient of determination R^2 reaches up to .9964, and the sum of square error is only 0.01273. Therefore, the proposed regression model could describe the equivalent factors almost perfectly for this scenario. If the volume of through and left-turn traffic V_{T+L} and the volume of right-turn traffic V_R are smaller than certain values, the equivalent factor will be negative, which is meaningless. In this condition, the equivalent factor should be reset to zero. Because of the limited space, the regression coefficients for 63 study situations cannot be listed here [see Zhou and Tian (*12*)].

Configuration 3

The regression model for Configuration 3 is shown in Equation 5. Because there is an exclusive right-turn lane, left-turn and through volumes are not considered. The same procedures are applied to calculate the regression coefficients as for Configurations 1 and 2.

$$\mathrm{EF} = a\left(1 - \frac{1}{bV_R^c}\right) \tag{5}$$

Configuration 4

The regression models for Configuration 4 are shown in Equation 6.

$$\mathrm{EF} = a\left(1 - \frac{V_{T+L}^{0.558}}{\left(bV_{T+L}^{-0.227} + cV_R^{0.062}\right)^{4.65}}\right) \tag{6}$$

For Configuration 4, the exponents are optimized through calculation, and good regression results for 63 study situations can be obtained with these definite coefficients. In all conditions, the coefficients of determination can reach 0.9.

CASE STUDY

Blue Diamond Road (BDR) and South El Capitan Way (SELCW) are located in the Las Vegas area. BDR is the main street (east- and westbound), and SELCW is the minor street (south- and northbound). The busier leg of the minor street is the south leg. The minor-street lane configuration belongs to Configuration 3 with an exclusive right-turn lane. The main street has two lanes in each direction.

Right-Turn Adjustment

The directional volume distribution at the intersection of BDR and SELCW is not available, but there are Traffic Records Information Access data at Site 0031094 collected downstream of the intersection on BDR. Traffic volumes and the suggested volume ratios at Site 0031094 at different hours are listed in Table 6. Although the main-street volume of the street was high, the westbound traffic volume of BDR was much higher so that the high volume of right-turn traffic in the subject minor street could enter the intersection easily. After reduction, none of Condition A, Condition B, and Condition A and B at the 56% level was warranted. Warrant 2 (4-h vehicular volume) and Warrant 3 (peak hour) were also checked, and neither warrant was met.

TABLE 5 Situation Equivalent Factors for Configuration 4

Volume Ratio	Main-Street Volume								
	400	500	600	700	800	900	1,000	1,100	1,200
1:1	0.60	0.55	0.51	0.48	0.46	0.44	0.42	0.40	0.38
1:2	0.80	0.78	0.76	0.75	0.74	0.73	0.73	0.71	0.70
1:3	0.91	0.90	0.90	0.90	0.91	0.91	0.91	0.90	0.90
1:4	0.98	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00
2:1	0.42	0.35	0.29	0.25	0.22	0.20	0.17	0.15	0.13
3:1	0.34	0.25	0.19	0.15	0.12	0.10	0.07	0.05	0.03
4:1	0.29	0.20	0.14	0.09	0.06	0.04	0.02	0.00	0.00

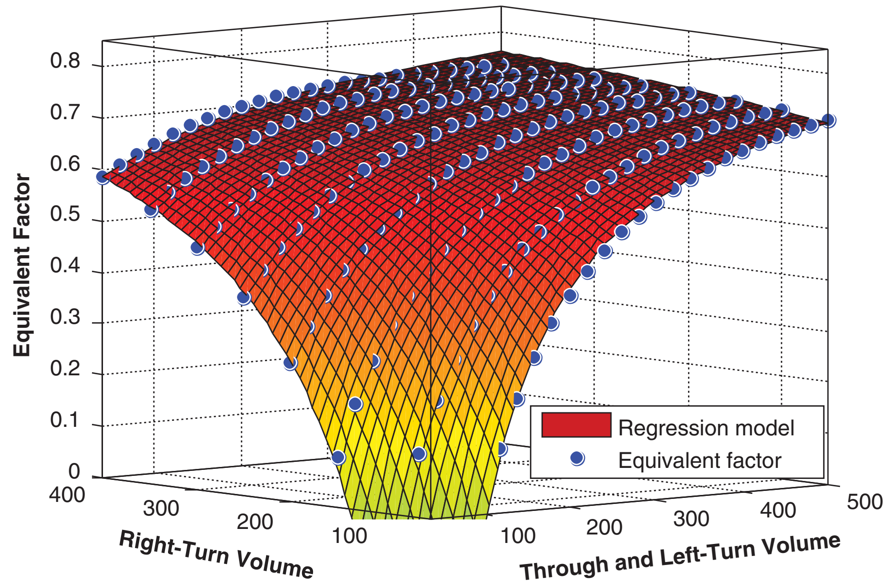

FIGURE 5 Regression model example for Configuration 1: main-street volume = 400 vph, VR = 1:1.

HCM Delay

For the purpose of assessing whether the intersection operates at acceptable levels of service, delay was calculated at the studied intersection for the 8 peak hours. The result showed that the average LOSs of left-turn, through, and right-turn in SELCW at the peak hours were C, D, and B, respectively. The minor-street through traffic might have difficulties crossing the intersection because of the high volume on the main street, while the right-turn traffic could enter the intersection easily even though the right-turn volume was very high at peak hours. Overall, the intersection operated at acceptable levels: the worst LOS was Level E, but the majority were Level C or better.

Other Reduction Methods

The Pagones theorem and NCHRP Report 457 methods were implemented for comparison. In the Pagones theorem, the lane configuration was with an exclusive right-turn lane. The minor-street adjustment factor was 0.75, and the main-line congestion factors are shown in Table 7. There were two lanes in each direction of the main street. From the

TABLE 6 Signal Warrant Analysis

Parameter	Start Time 6:00	7:00	8:00	9:00	10:00	13:00	14:00	15:00
Major volume	787	988	1,060	946	983	1,157	1,192	1,390
Volume ratio	2:1	2:1	2:1	2:1	1:1	1:1	1:1	1:1
Minor volume	353	586	519	375	296	295	318	302
Minor through and left turns	56	128	101	60	47	47	51	48
Minor right turns	297	458	418	315	249	248	267	254
Configuration 3								
Volume ratio	2:1	2:1	2:1	2:1	1:1	1:1	1:1	1:1
Equivalent factor	0.07	0	0	0	0.27	0.25	0.25	0.24
Equivalent right turns	21	0	0	0	67	62	67	61
Adjusted minor volume	77	128	101	60	114	109	118	109
Warrant 1[a]								
Condition A (70%)	F	F	F	F	F	F	F	F
Condition B (70%)	T	T	T	F	T	T	T	T
Condition A and Condition B (56%)	F	T	F	F	T	F	T	F
Warrant 2[a]	F	F	F	F	F	F	F	F
Warrant 3[a]	F	F	F	F	F	F	F	F

[a]In Warrants 1, 2, and 3, F represents that the volume is not warranted and T represents that the volume is warranted.

TABLE 7 Signal Warrant Analysis Based on Pagones Theorem

Parameter	Start Time 6:00	7:00	8:00	9:00	10:00	13:00	14:00	15:00
Major volume	787	988	1,060	946	983	1,157	1,192	1,390
Minor volume	353	586	519	375	296	295	318	302
Minor through and left turns	56	128	101	60	47	47	51	48
Minor right turns	297	458	418	315	249	248	267	254
Case 3								
Main-line volume per lane	197	247	265	237	246	289	298	348
Main-line congestion factor	0	0	0	0	0	0	0	0
Minor adjustment factor	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Reduction factor	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Reduced right turn	74	115	105	79	62	62	67	64
Adjusted minor volume	130	243	206	139	109	109	118	112
Warrant 1								
Condition A (70%)	F	T	T	F	F	F	F	F
Condition B (70%)	T	T	T	T	T	T	T	T
Condition A (56%) and Condition B (56%)	T	T	T	T	T	T	T	T
Warrant 2	F	T	T	F	F	F	F	F
Warrant 3	F	F	F	F	F	F	F	F

reduction procedure, this intersection signal was warranted on the basis of Warrant 1 Condition B and Warrant 1 Conditions A and B.

As for the NCHRP Report 457 method, the volume proportion of the main street was unavailable. Therefore, 10% of the major volume was assumed to be right turn and no left turn was presumed. It was reasonable and conservative because most people drive straight to Las Vegas. The reduction calculation is shown in Table 8, and it is found that the assumption is unimportant because the right-turn reduction is high enough to cover the total right-turn volume. After the calculation, the signal was not warranted.

For this specific case, the signal was not warranted from the proposed method and the NCHRP Report 457 method, while it was warranted from the Pagones theorem. From the intersection operation perspective, this intersection is on the edge of installing a signal. In the NCHRP Report 457 method, all right turns are assumed to operate freely, resulting in the extreme high right-turn reduction in Table 8. The Pagones theorem does not consider the uneven volume distribution on the main street, so the results tend to be conservative in that case.

SUMMARY AND CONCLUSIONS

The proposed method is based essentially on the delay equivalence method, that is, to equal the right-turn volume to through vehicles, which would produce the same control delay on the minor street. The estimation of minor-street control delay was based on the HCM 2010 method for two-way stop-controlled intersections. According to minor-street geometry, five conditions were categorized. Under each condition, a variety of volume distributions were considered. Tables were produced to indicate the volume

TABLE 8 Signal Warrant Analysis Based on NCHRP Report 457 Method

Parameter	Start Time 6:00	7:00	8:00	9:00	10:00	13:00	14:00	15:00
Major volume	787	988	1,060	946	983	1,157	1,192	1,390
Minor volume	353	586	519	375	296	295	318	302
Minor through and left turns	56	128	101	60	47	47	51	48
Minor right turns	297	458	418	315	249	248	267	254
Conflicting major road	131	165	177	158	246	289	298	348
Right-turn reduction	821	801	794	806	753	727	721	692
Reduced right turn	297	458	418	315	249	248	267	254
Adjusted minor volume	56	128	101	60	47	47	51	48
Warrant 1								
Condition A (70%)	F	T	T	F	F	F	F	F
Condition B (70%)	F	T	T	F	F	F	F	F
Condition A (56%) and Condition B (56%)	F	T	F	F	F	F	F	F
Warrant 2	F	F	F	F	F	F	F	F
Warrant 3	F	F	F	F	F	F	F	F

equivalent levels based on various volume conditions. Further, regression models for these four conditions were built to provide a more accurate reduction factor. The method was illustrated through a case study. The results show that the proposed method could help engineers make decisions on determining right-turn volume reduction levels.

Although the proposed method provides a theoretical justification for right-turn volume reduction, it has its own drawbacks. When the main-street volume increases, the minor-street through traffic suffers from more conflicting volume than the right turns. So, the delay of through traffic increases much more than the right turns in the minor street, which explains why the equivalent factors decrease when the main-street volume increases. For 8-h vehicular volume, the threshold volumes are fixed. The relationship between main-street and minor-street traffic is not considered. Therefore, to amend the proposed method, the recommendation is to apply the equivalent factors for a main-street volume of 400 vph for all main-street volume conditions. For four vehicular volume and peak hour warrants, the required minor-street volumes decrease with the increase of the main-street volumes. The relationship between main-street and minor-street volumes is considered. So it is proper to converge the right turns to through traffic.

ACKNOWLEDGMENTS

The authors thank the Nevada Department of Transportation for the sponsorship of this study. The authors particularly thank Ning Wu from Ruhr University Bochum, Germany, for providing help in the equivalent factor regression.

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The Standing Committee on Traffic Control Devices peer-reviewed this paper.