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Right-Turn Traffic Volume Adjustments in Traffic Signal Warrant Analysis

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Disclaimer

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EXECUTIVE SUMMARY

This is the final report for research project, **Right-Turn Traffic Volume Adjustment in Traffic Signal Warrants**, which was sponsored by the Nevada Department of Transportation (NDOT). To accomplish this research, a comprehensive literature review of existing guidelines and findings based on national and local studies was conducted. Ultimately, guidelines for consistent application for adjusting right-turn traffic volumes were developed for the state of Nevada.

The comprehensive literature review focused on the state-of-the-practice on handling minor-street right-turn volumes while conducting signal warrant studies. Further, a comprehensive agency survey was conducted through the Institute of Transportation Engineers (ITE) community discussion to acquire valuable information from practicing engineers. It was found that the limited guidance in the Manual on Uniform Traffic Control Devises (MUTCD) is not sufficient to provide clear directions on determining whether or how much right turns impact the signal warrant analysis. In reality, most traffic engineers have done the reduction based on engineering judgment incorporating key factors such as geometry and main street volumes. The Pagones Theorem and the method proposed by the National Cooperative Highway Research Program (NCHRP) have been adopted by some states and local agencies. However, there is no literature found to document the detailed methodologies of the Pagones Theorem and the NCHRP method. Additionally, these methods do not consider the main-street volume distribution which affects the intersection operations. It is common that some agencies adopt internal procedures but they do not necessarily publish them.

Our approach for developing the new right-turn volume adjustment guidelines is based on traffic operations measures, i.e. delay or level-of-service (LOS). This LOS-based approach has been successfully applied to determining intersection control types [1,2]. The proposed guideline is based on the delay equivalent relationship between right-turn and through traffic. The right-turn volume equals to an equivalent number of through vehicles, which would produce the same control delay on the minor street. The equivalent factor is applied to determine level of right-turn reduction. Because equivalent factors are calculated based on delay, it incorporates major influencing factors of the right-turn and through traffic inherently, such as conflicting flow rates, capacity, critical headways, and follow-up headways. Especially, the volume ratio in the two directions of the main street is considered. From the analysis, the uneven volume distribution has a greater impact on the right-turn movement of the minor street. Therefore, only considering the main street volume can cause over or under estimation of the influence of the main street traffic to the minor street.

Further, regression equations were developed based for all the configurations. The advantage of these equations is to yield a precise equivalent factor given a specific volume scenario. At last,

the proposed guidelines were tested at three intersections. The case studies revealed that the guidelines are easy to use and can yield more reasonable results than previous guidelines.

1 INTRODUCTION

1.1 Background

Traffic signals are signaling devices positioned at roadway intersections, pedestrian crossings and other locations to control conflicting flows of vehicles and pedestrians. Installation of traffic signals usually does not have a detrimental effect on both operations and safety. But unwarranted signals might cause some problems. Listed below are advantages and disadvantages of traffic signals:

Traffic control signals that are properly located, operated and maintained typically have one or more of the following advantages:

- Signals provide for the orderly movement of traffic by assigning right-of-way to conflicting traffic movements.
- Signals can increase intersection capacity by permitting conflicting traffic movements to share the same intersection.
- Signals usually reduce the frequency right-angle (broadside) collisions.
- Signals can provide progression of traffic through a series of intersections by coordinating adjacent traffic signals.
- Signals will interrupt heavy traffic to allow both lighter vehicular and pedestrian traffic to cross the heavy traffic movement.

Traffic control signals may have one or more of the following disadvantages:

- Signals can increase delay, both for the overall intersection delay and/or delay of specific movement.
- To avoid signals, drivers sometimes use alternate routes that are less adequate.
- Signals might increase traffic on minor street approaches when drivers wish to use the signal that will interrupt heavy main street traffic.
- Signals might encourage disregard of traffic control devices. When drivers on the minor street approaches have excessive wait times with very little main street traffic, they might ‘run’ the red display.
- Signals tend increase in the frequency of rear-end collisions.

Traffic signals are the most restrictive type of control at intersections that require conflicting movements to take turns using the intersection. However, traffic signals are the most expensive intersection control, costing between $250,000 and $500,000, depending on the complexity of the intersection and the characteristics of the traffic using it. Besides, signals tend to increase accidents, delay, congestion and disobedience of signals. Therefore, traffic signals should be only installed when they will alleviate more problems than they will create. The decision for traffic signals should be based on competent engineering studies and field observations to ensure that the signal is warranted and will enhance the safety and efficiency of the intersection. Before installation, less restrictive, and less expensive control measures should be considered, such as widening the approach, removing roadside parking, adding turn lanes, and roundabout.

Signal warrant analysis is the first and most important step in the signal installation process to avoid the unnecessary use of signals. There are three vehicle volume related signal warrants in the MUTCD: Warrant 1-Eight-hour vehicular volume, Warrant 2-Four-hour vehicular volume, and Warrant 3-Peak hour vehicular volume. It is customary to adjust minor street right-turn volumes to allow for the fact that a certain percentage of vehicles can make right turn without the aid of a traffic signal when a signal is being considered for capacity reasons. High volumes of right-turn vehicles from the minor street can skew a signal warrant analysis and indicate an incorrect need for a signal; consequently, how right-turn volumes are utilized can be important in signal warrant analysis. MUTCD as a guideline clearly states that the study should consider the effects of the right-turn vehicles from the minor-street approaches and engineering judgment should be used. This provides justification for reducing right-turn traffic volumes. However, MUTCD does not offer any clear direction on this matter. Pure "engineering judgment" is subjective in nature and will likely vary from engineer to engineer. Specific guidelines would be helpful when considering the right-turn traffic during signal warrant studies.

The current practice in Nevada involves two different approaches applied in two broad areas. Area 1 encompasses Clark County and its cities and there is a letter of agreement between NDOT and Clark County that, when conducting Traffic signal warrant studies, 25% of minor-street right-turn vehicles may be included in the minor-street volume. There is no supporting documentation that identifies how this percentage was developed. Area 2 covers all the remaining areas in the state. Within this broad area, right-turn volumes are entirely removed from the minor-street volume with an underlying assumption that right-turn vehicles can make turns without affecting the intersection performance. Again, no supporting documentation justifies this methodology.

As can be seen from the above discussions, limited information tends to focus on using "Engineering Judgment" when applying right-turn volume reductions. Limited research on this subject has not led to any identifiable method in developing a standard procedure to deal with minor-street right-turn traffic volumes. In this report, a standard practice for right-turn traffic reduction in signal warrant analysis will be developed for Nevada.

1.2 Objective and Scope

Currently, the specific guidelines are based on engineering judgment in NDOT and local agencies regarding right-turn volume reductions in signal warrant studies. No documentation could be found to support the current practice and limited research on this subject has not identified a method to deal with minor-street right-turn traffic volumes.

The primary objectives of this research are:

- To develop guidelines when right-turn traffic volumes should be reduced during traffic signal warrant analysis in both urban and rural settings in two-way stop control intersection;
- To develop software tool(s) or tables that can assist agencies for conducting signal warrant analysis.

To achieve these two objectives, there are three tasks:

- A working paper will be prepared to summarize the major findings from the literature review and the agency survey;
- Examine the existing methodologies and practices, and develop new models to count for the right-turn effect and to recommend adequate right-turn volume reduction amounts;
- Data collection and case study will be performed to confirm that the recommendations from the warrant analysis procedure match the existing control types.

2 LITERATURE REVIEW

Over the years, studies conducted in the United States have advanced several guidelines helping governments decide under what conditions right-turn traffic could be reduced. Basically, the literature on right-turn reduction methods can be organized as: engineering judgment, field observation, and an accepted right-turn adjustment methodology.

2.1 Existing Guidelines

The portion of the right turning traffic is able to make movement without experiencing significant delays should be reduced during signal warrant studies. However, if queued vehicles prevent right turning traffic from flowing freely or if mainline volumes are high enough that even right turning vehicles experience significant delay, the reduction should be used carefully and full right-turn volumes might be used in the warrant analysis.

Manual on Uniform Traffic Control Devices Section 4C.01 [3] serves as the general guideline and indicates as follow:

"The study should consider the effects of the right-turn vehicles from the minor-street approaches. Engineering judgment should be used to determine want, if any, portion of the right-turn traffic is subtracted from the minor-street traffic count when evaluating the count against the signal warrants listed in Paragraph 2."

Even though MUTCD states that the right-turn traffic should be subtracted from the minor street, it fails to provide clear guidance. Due to the lack of specific unified guidance for the entire country regarding this matter, several individual states have been developing of their own guidelines as seems appropriate according to their situation.

Mozdba et al. [4] indicated that including the appropriate portion of the right-turn volume in the signal warrant study was critical, as it could make the difference in whether a signal is deemed warranted or not. The City of Austin, TX had developed the guideline that considered the right-turn volume adjustment based on the application of one of the 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 carry on signal warrant analysis. These guidelines are only based on engineering experience and practice in signal warrant studies, but not developed through theoretical studies. However, this guideline is able to provide a frame of reference for including the appropriate portion of the right-turn volume.

Mcdonald [5] examined methods of DOTs' in two states. The State of Illinois DOT was divided into nine districts. Districts One, Two and Four used a process called the "Pagones Theorem", to be discussed below, to reduce the number of right turns on the minor street; District Seven just leaved the right-turn reduction to the judgment of engineers; Districts Three, Five, Six, Eight and Nine did not reduce any right turns from the minor street when performing signal warrant analysis. The State of Tennessee DOT was divided into four regions and all of them used engineering judgment to perform right-turn reduction. If the approach had one lane or no right-turn lane, the approach volume was generally not reduced. Reductions were based on traffic volume, storage capacity and geometrics. In many cases, the assumption was made that the geometry of the approach could be modified to handle an exclusive right-turn lane if the lane would help reduce the need for a signalized intersection. The author also concluded that the engineer should be aware that inter-state and intra-state variations in determining right-turn reduction.

Manual of Traffic Signal Design (MTSD) published by the ITE suggested that all right turns might be excluded in the analysis if the approach had a separate right-turn lane and a large-radius curb return. This exclusion could also apply when the right turns were made from a through lane and only a small-radius curb return was available.

A formal right-turn adjustment methodology has been developed by the IIIinois DOT and also been used by the Alabama DOT [6]. It is a two-step methodology called Pagones Theorem that uses a minor street equivalent factor and a mainline congestion factor to estimate the portion of right turn volumes. The adjusted right-turn volume is calculated as following,

$$R_{adj} = R \times \left[1 - \left(f_{minor} - f_{main}\right)\right] \quad (1)$$

where:
R_{adj}=adjusted right turn volume;
R= original right turn volume;
f_{minor}= minor street adjustment factor;
f_{main}= mainline congestion factor.

Note: if $f_{minor} - f_{main} < 0$, then $R_{adj} = R$.
The minor street adjustment factor reflects whether minor street geometry and traffic volumes permit the free movement of right turns and reduce right-turn volumes accordingly. The mainline congestion factor adjusts to account for the amount of congestion on the mainline. In essence, f_{minor} considers what portion of vehicles could get to the intersection to make a right-turn without delay while f_{main} determines whether there are enough gaps in mainline traffic to permit them to actually make that right-turn. The suggested values for f_{minor} and f_{main} are listed in Table 1 and 2 according to lane configuration and volume condition. For the mainline right-turn reduction, if there is no mainline right-turn lane, mainline right-turn volumes are added to the through volumes

for the lane volume calculations; if a right-turn lane is present, mainline right turn volumes are excluded from the calculation.

Table 1 Pagones Theorem Right-turn Adjustment Factors

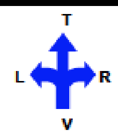
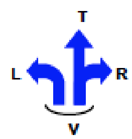
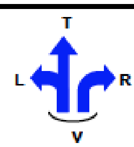
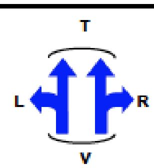
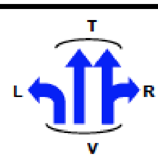
Minor Street Adjustment Factor (f_{minor})			
Case	**Lane Configuration**	**Volume Condition**	**f_{minor}**
1		R > 0.7V	0.60
		0.7V ≥ R > 0.35V	0.40
		R ≤ 0.35V	0.20
2		R > 3T	0.60
		3T ≥ R > T/3	0.40
		R ≤ T/3	0.20
3		Any configuration with an exclusive right turn lane ≥ 500 ft. long. (See note* for shorter right turn lanes)	0.75
4		R > (T+L)	0.65
		L > (T+R)	Use Case 2
		L ≈ T ≈ R (±10 veh)	0.40
		L ≈ T > 3R	0.20
		R ≈ T > 3L	0.50
		all other conditions	0.30
5		R > T	0.75
		T ≥ R > T/2	0.50
		T/2 ≥ R > T/4	0.30
		R < T/4	0.15

Table 2 Pagones Theorem Mainline Congestion Factors

Mainline Congestion Factor (f_{main})			
Mainline volume per lane (veh/hr/lane)	**f_{main}**	**Mainline volume per lane (veh/hr/lane)**	**f_{main}**
0 - 399	0.0	1100 – 1199	0.40
400 – 499	0.05	1200 – 1299	0.45
500 – 599	0.10	1300 – 1399	0.50
600 – 699	0.15	1400 – 1499	0.55
700 – 799	0.20	1500 – 1599	0.60
800 – 899	0.25	1600 – 1699	0.65
900 – 999	0.30	1700 – 1799	0.70
1000 – 1099	0.35	1800 - 1899	0.75

NCHRP report 457 [7] uses the following method to determine right-turn volume in signal warrant analysis, which is originally developed by Utah DOT. In this method, the actual right-turn volume is reduced on the basis of consideration of the major-road volume that conflicts with the right-turn movement, the number of traffic lanes serving the conflicting volume, and the geometry of the subject minor-road approach. The relationship between these factors was illustrated in Figure 1.

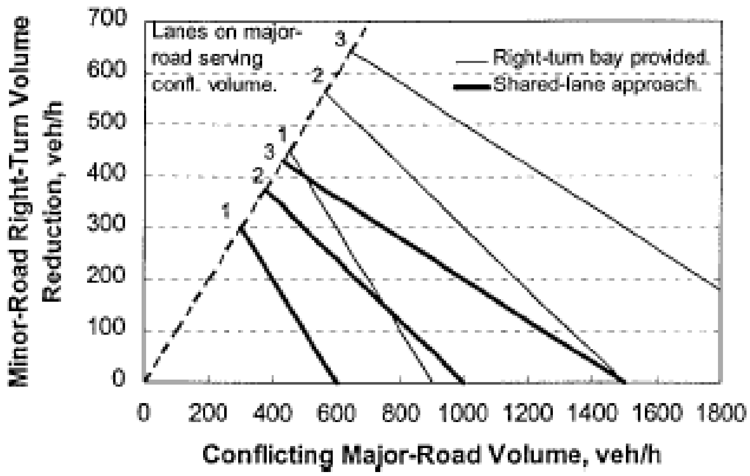


Figure 1 Minor Street Right-turn Volume Reduction in NCHRP method

To determine if a heavy right-turn volume might mislead the signal warrant analysis, the following adjusted minor street volume would be performed. The adjusted volume is computed as follows:

$$\text{Adjusted minor street volume= Max}\begin{bmatrix} V_7 + V_8 + V_9 - V_{r9} \\ V_{10} + V_{11} + V_{12} - V_{r12} \end{bmatrix} \tag{1}$$

$$V_{c9} = 0.5V_3 + \frac{V_2}{N_2}$$

$$V_{c12} = 0.5V_6 + \frac{V_5}{N_5}$$

$$V_9 - V_{r9} \geq 0$$

$$V_{12} - V_{r12} \geq 0$$

where,

V_i= volume for movement *i* (movement numbers are shown in Figure 2);

N_i=number of approach lanes serving through movement *i*;

V_{r9} (V_{r12}) = right-turn volume reduction for movement 9(12), obtained from Figure 2 using conflicting major street volume;

V_{c9}(V_{c12}) = conflicting major street volume for movement 9(12).

Also, the "Right-turn bay provided" case in Figure 1 could be used for shared-lane approaches when the shared lane functions as de facto right-turn lane. If this warrant check yields different conclusions than original warrant check (i.e., with unadjusted volumes), then right-turns volumes might be enough to affect the accuracy of the warrant check. In this situation, it is recommended that the effect of right-turns be fully examined during the warrant study.

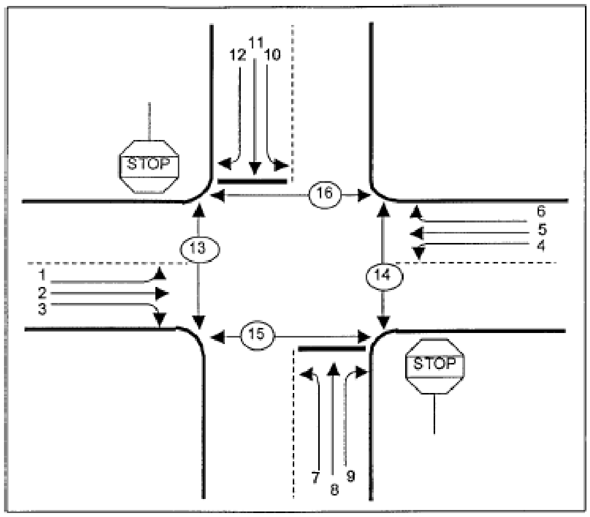


Figure 2 Movement Numbers for Right-turn Volume Adjustment

State of Wisconsin DOT [8] suggested that before evaluating traffic volumes against the warrant criteria, inclusions of right-turn vehicles shall be considered. The number of right-turn vehicles included in the intersection analysis played an important role in the overall operation of the intersection. The traffic control for the right turning vehicles should be known prior to determining the percentage of volume inclusion. The department used three right turn inclusion percentages based on the impact of the right turns on the operation of the intersection. Figure 3 shows lane configurations and the corresponding percentages.

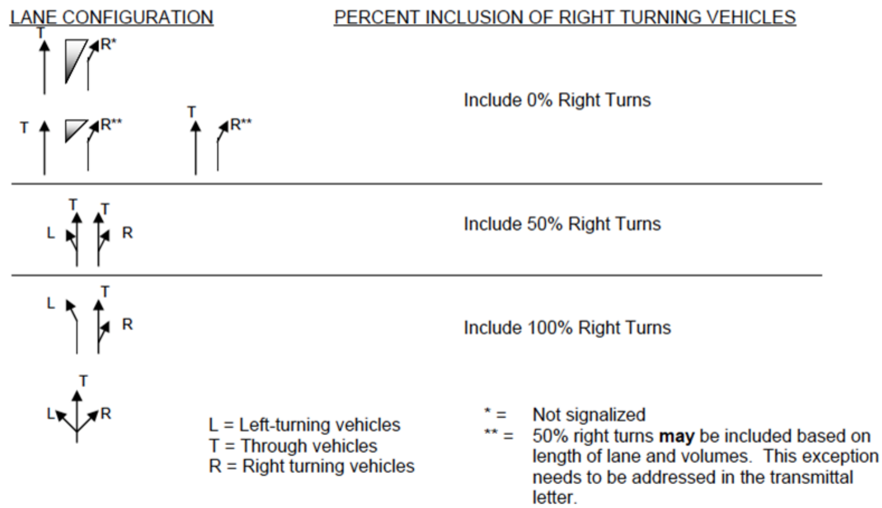


Figure 3 Right-turn Inclusion Percentages (WDOT)

Los Angeles DOT [9]indicated that if the right turning traffic was delayed less than 45 seconds under stop sign control, the right turning volume shall be subtracted from the side-street volume. The rationale for this subtraction was that side-street traffic that waits less than 45 seconds likely would turn right on red thus would not benefit from traffic signal control. Therefore, for Warrants 1, 2, and 3, if right turning vehicles were delayed less than 45 seconds under stop control and there were no more than two right-turn collisions in the most recent 12-month period, then those vehicles shall be subtracted from the side street volume.

Oregon DOT [10,11] suggested that 85% of the right-turn lane or shared lane capacity was subtracted from the right-turn volume. If the value of 85% of the lane capacity (measured in vph) exceeded the right-turn volume, no right-turn volumes were included in the analysis. If the right-turn volumes were greater, they were reduced by 0.85% of the lane capacity. This method takes into account not only traffic volumes on the minor street, but also traffic condition on the main street which affect the ability of vehicles to turn right from the minor street.

In existing signal warrant report [12], they advised that when there was exclusive right turn, the right-turn volume could be subtracted from the total volume of the approach. When the road consisted of a single approach lane for all movements, there was no reduction in volume for right-turn vehicles.

From the available literature, we found that most states simply follow the MUTCD recommendation for adjusting right-turn volumes and roughly based on engineering experience.

2.2 ITE Community Discussion

To collect more information regarding the reduction of right-turn vehicles in signal warrant analysis in current practice, we posted our project in the ITE community discussion section in October 2013. Eight responses were received in this survey. The corresponding responses are presented and summarized below:

Traffic engineers from Wisconsin DOT and Illinois DOT mentioned that their states had written policies about right-turn reduction and provided their states' methods. A transportation planner from a consulting firm said their office used the recommendations based on NCHRP 457, which attributed its methodology to the Utah DOT. Detailed introduction of all these three methods is presented in the former sections.

For DOTs that have no written policy on this matter, traffic engineers have their own consideration procedures. A traffic engineer from the City of Federal Way said, "I don't include right-turn volume at all if the LOS for that movement is A, but otherwise include all of it". A senior engineer from Lee County DOT mentioned that if there was a right-turn only lane, he would deduct the number of left turns from the right turn volume using 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 didn't consider the effect of a small right turn channel. Particularly, if there were a lot of U-turns that conflict with the right turns, then he might want to consider a greater percentage of the right-turning traffic in the count. An area traffic engineer working at Virginia DOT said that when he was researching the same question, he discovered the Pagone's Theorem used by Illinois DOT District 1 and found it useful in reduction calculations.

Especially, President of Yarger Engineering, Inc posted a long feeling about the right-turn inclusion in the signal warrant analysis. His original poster is attached as follow:

"*This area is a real gray area and I would hate to see any hard and fast rules, but more guidance would be very helpful at least for some consistency and reasonableness. The all or none call seems to be unreasonable and there should be some guidance that says under x conditions, reduce #%, and under y conditions, reduce #+1%... Why should an extra second of delay on a right turn from 9.5 second of delay to 10.5 seconds flip from reducing all to none? If LOS A is all, shouldn't LOS be more like 80% to 90%, with LOS C being 60% to 70% and so on?I have seen numerous approaches. Indiana DOT has a procedure, but they won't share it with the rest of us, so in the absence of something better, I run the question backwards. I calculate what percentage can be excluded and still warrant the signal, and then see if that looks reasonable given the unsignalized levels of services for the right turn and also compare it with Synchro's RTOR flow rate from the signalized analysis. The issue is that in most cases, we are not talking about reducing the right* *turns in the peak hours, but in the eighth highest hour in order to satisfy the 8 hour warrants. The right turn during the 8th hour typically is LOS A or B if in an exclusive lane.*

I believe if there is an exclusive right turn and RTOR would be permitted if there was a signal, then some of them need to be reduced. I have been overruled on this where the reviewer included 100%. I have also been on the other side where the reviewer didn't want the signal, and said to exclude all of the right turns. Recently when in a TIS report I said that in 10 years with an assumed development and most of the vehicles being right turners, which it was too close to call, the reviewer said I had to make a decision now and send that portion of the study back for revision."

2.3 Problems in Existing Guidelines

All these methods 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 and there are no theoretical supports behind them. Los Angeles DOT's guideline is based on field observation. It seems reasonable, but is hard to use in reality. 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 Pagones Theorem has considered the main street volume, it fails to take into account the uneven volume distribution in two directions. The NCHRP method works out the reduced right-turn volume purely based on the conflicting major-road volume and whether right-turn bay is provided. It does not consider the through traffic in the minor street at all, but in the reality, the through traffic and right turn traffic often disturb each other. Further, this method does not provide the inherit relationship between minor-street right-turn volume reduction and conflicting major-street volume except for a graph. From the case study in later chapter, this method tends to reduce right turns too much

2.4 Section Summary

Unwarranted traffic signals are detrimental for several reasons not only to the flow of traffic but may also increase overall delay. Including all right-turn traffic volumes or an inappropriate portion of the right-turn traffic volume, could result in an erroneous traffic study and possible installation of an unwarranted traffic signal. In existing reports and guidelines, engineers and scholars generally agree on reducing right-turn volumes in signal warrant analysis, but as to right-turn traffic reduction percentages, there are no mature theoretical methodologies and the reduction factors are basically based on engineering judgment.

For the present, nearly all right-turn reductions are implemented on minor streets, and only Pagones Theorem has provided quantitative reduction guidance on main streets. Minor streets reduction factors normally relate to lane configuration, capacity, minor and main streets traffic volumes, right-turn traffic percentage, delay, crash experience and sight distance.

A specific and detailed right-turn volume reduction model, which considering important aspects of right-turn traffic is important for signal warrant analysis. Proper right-turn traffic reduction is beneficial for evaluating the justification of signals.

3 PROPOSED METHODOLOGY

The approach proposed in this report is based on the principle of delay equivalence, i.e., to find the delay equivalent relationship between right-turn and through traffic under different conditions. The control delay estimation is based on Highway Capacity Manual 2010 (HCM 2010) [13] procedure for two-way stop-controlled intersections. To expedite the data analysis process, the HCM analysis procedure is implemented in Excel using Visual Basic, which allows quick analysis of multiple scenarios.

An isolated intersection shown in Figure 4 is used. The subject movements are northbound through and right turn. Both movements have a direct crossing or merging conflict with all of the major street movements, except the right turn into the subject approach. We assume that all the traffic on the main street is through movement from both directions. In the analysis, the volume distribution in the two directions of the main street is considered and defined in Equation 3.

$$VR = \frac{V_1}{V_2} \quad (3)$$

where,
VR is the volume ratio of the main street;
V_1 is the farther side of main-street to the subject minor street;
V_2 is the nearer side of main-street to the subject minor street.

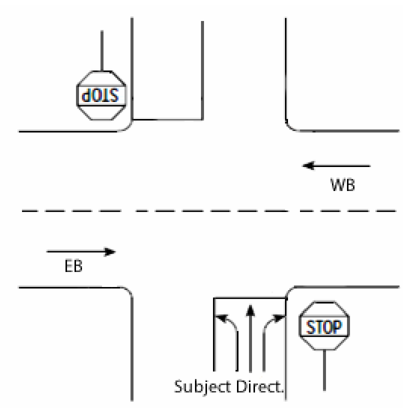
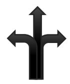
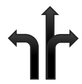
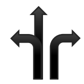
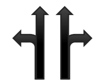


Figure 4 Study Intersection

For Figure 4, the volume ratio is the volume of the westbound divided by that of the eastbound. Furthermore, according to the minor-street lane configurations, four configurations are discussed as shown in Table 3.

Table 3 Minor Street Lane Configuration

Condition	1	2	3	4
Lane Configuration				

3.1 Configuration 1

Configuration 1 depicts shared lane geometry on the minor street. The volume ranges covered in the analysis are listed in Table 4. These volume combinations yield a total of 12,096 (9×7×8×24) cases. Each main-street volume and a volume ratio work together as one study situation. There are 63 (9×7) study situations in total for Configuration 1 and so are for other configurations.

In each study situation, there are 192 (8×24) combinations of minor-street volume scenarios. For the minor-street left and through movements, 20 percent left turns are assumed.

Table 4 Scenarios Evaluated in Configuration 1

Item	Range
Major Street (9)	400, 500, 600, 700, 800, 900, 1000, 1100, 1200 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

Under one volume scenario shown in Table 4, for example, major street volume is 400 vph; volume ratio is 1:3 (i.e. the westbound is 100 vph and the eastbound is 300 vph); minor street right turn is 400 vph and minor street left turn and through is 500 vph (i.e. left turn= 500×20%=100 vph and through volume is 500-100=400 vph). The information lists in Table 5.

In this condition, the shared lane delay is 232.1 sec/veh. Then eliminate all the right turn traffic, increase the through traffic volume until the control delay arrives at 232.7 sec/veh, which is illustrated in Figure 5.

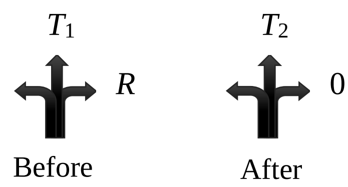


Figure 5 Right-turn Conversion

For the analysis, the right-turn equivalent factor (equivalent factor for short) is defined in Equation 4. By means of "equivalence", it is to find out the amount of right-turn traffic that is equivalent to the amount of through traffic in order to yield the same control delay.

$$EF = \frac{T_2 - T_1}{R} \qquad (4)$$

where,
EF is the right-turn equivalent factor;
$T_1$is through volume before equivalence;
T_2 is through volume after equivalence without right-turn traffic;
R is right-turn volume before equivalence.

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

$$R_{adj} = R \times EF \qquad (2)$$

For example, before reduction, the right-turn volume is 100 vph and the equivalent factor is 0.8, so the adjusted right-turn volume used for signal warrant should be 80 vph. It is obvious that the larger the equivalent factor, the more right-turn volume would be used for warrant check.

Table 5 Equivalent factor Calculation Example for Configuration 1

Configuration 1		Major Volume		400	
		Volume Ratio		1/3	
Before Equivalence					
Major Street		Subject Minor Street			Delay
EB	WB	LT	T	RT	
300	100	100	400	400	232.1
After Equivalence					
Major Street		Subject Minor Street			Delay
EB	WB	LT	T	RT	
300	100	100	688	0	232.7

Equivalent factor	*EF*= (688-400)/400 = 0.72

Figure 6 shows equivalent factors for one specific study situation where the mainline volume is 500 vph with a 1:1 volume ratio (a total of 192 scenarios). From the graph, we can see that when right-turn volumes increase, equivalent factors increase accordingly. Under the same right-turn volume (such as right turn volume of 300 vph, green line), when there are more left-turn and through vehicles in the minor street, equivalent factors would increase and it would use more right-turn traffic for 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 situation and defined as the situation equivalent factor.

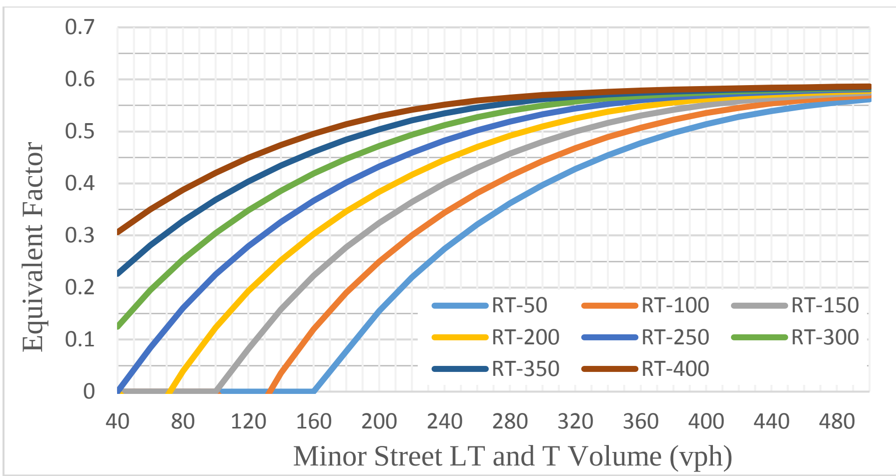


Figure 6 Equivalent Factor Graph for One Study Situation: main street volume= 500 vph; *VR*= 1:1

Table 6 and Figure 7 show equivalent factors under different main-street volumes and volume ratios. When mainline volume increases, the equivalent factor decreases. It can be explained by the fact that the main street volume affect more on through vehicles than right turns; therefore, delay increases more for minor-street through vehicles than that of right turns. When the mainline volume is higher than 1200 vph, the same equivalent factors for the 1200 vph level will apply. In reality, the main-street volume may not fall exactly in the same values in the table; it is recommended using lower bound values.

Table 6 Situation Equivalent Factors for Configuration 1

Main Street Volume / Volume Ratio	400	500	600	700	800	900	1000	1100	1200
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

*When the main street volume is beyond 1200 vph, equivalent factors of 1200 vph are applied.

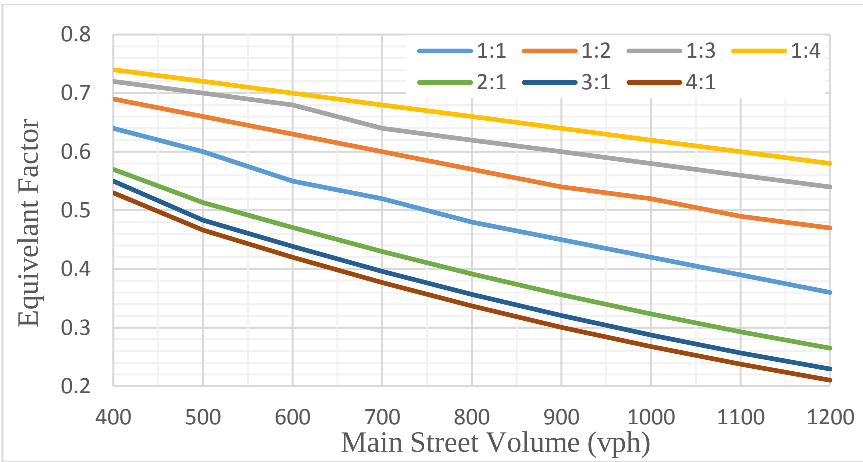


Figure 7 Situation Equivalent factor Graph for Configuration 1

3.2 Configuration 2

Configuration 2 is a shared right-through lane with an exclusive left-turn lane. Using the same traffic volume scenarios, almost the same equivalent factors are obtained. So it is reasonable to treat Configurations 1 and 2 as one category. It also shows that the assumed left-turn percentage does not significantly affect the equivalent relation. This phenomenon could be explained by that the left-turn traffic have the same impact on the through and right-turn vehicles.

3.3 Configuration 3

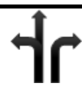
The geometry of Configuration 3 is a shared left-through lane with exclusive right-turn lane shown in Table 3. Because there is right-turn lane, the delay of the right-turn movement is irrelevant to the through movement, so it is assumed that the through movement is zero before equivalent. Different traffic volume scenarios are applied listed in Table 7. Before reduction, the right-turn movement is from 50 vph to 510 vph with a 20 vph increment. After reduction, 20 left turns are assumed for the minor-street left movements. A total 24 scenarios are considered in each study situation.

Table 7 Scenarios Evaluated in Configuration 3

Item	Range
Major Street (9)	400, 500, 600, 700, 800, 900, 1000, 1100, 1200 vph
Volume ratio (7)	1:1, 1:2, 1:3, 1:4, 2:1, 3:1, 4:1
Minor Street Right Turn (24)	50, 70, 90, 110, 130, 150, 170, 190, 210, 230, 250, 270, 290, 310, 330, 350, 370, 390, 410, 430, 450, 470, 490, 510 vph
Minor Street Left turn and Through (0)	0

Under one volume scenario shown in Table 7, for example (listed in Table 8), major street volume is 400 vph; volume ratio is 1:3 (i.e. the westbound is 100 vph and the eastbound is 300 vph); minor street right turn is 510 vph and minor street left turn 20 vph. Under this condition, the right-turn lane delay is 19.7 sec/veh. Then eliminate all the right turn traffic, increase the through traffic volume until the left and through lane control delay arrives at 19.7 sec/veh. Using Equation 4, the equivalent factor is 0.55.

Table 8 Equivalent factor Calculation Example for Configuration 3

Configuration 3 		Major Volume		400	
		Volume Ratio		1/3	
Before Equivalence					
Major Street		Subject Minor Street			Right-turn lane Delay
EB	WB	LT	T	RT	
300	100	20	0	510	19.7
After Equivalence					
Major Street		Subject Minor Street			Left and through lane Delay
EB	WB	LT	T	RT	
300	100	20	283	0	19.7
Equivalent factor	*EF*= 283/510 = 0.55				

Equivalent factors for these 63 study situations are shown in Table 9. It is easy to observe that the effect of volume ratio is obvious. If we don't consider the volume distribution in the two direction of the main street, it may often reduce too much right turns with exclusive right-turn lanes. Most institutes are inclined to exclude all the right-turn traffic in this geometry. But from Table 9, equivalent factors vary from 0.09 to 0.60 with different volume ratios when the main street volume is 400 vph. This phenomenon tells us that it is not proper to reduce all the right-turn volume when there is more traffic near the subject minor street in the main street.

Because right-turn vehicles have a separate lane, their movement may not be affected by the through and left-turn conducting signal warrant analysis traffic. There are two ways to consider the minor street volume and the lane number, which is introduced in MUTCD 3C.01. 13. For the first one, we consider the minor street has two lanes (shared through lane and right-turn lane). The minor street volume is sum of adjusted right-turn, and through and left-turn traffic volumes. For the other one, the minor street has one lane. Under this configuration, the minor street volume is the maximum volume of adjusted right-turn traffic, and through and left-turn traffic, which is defined as the critical volume.

Table 9 Situation Equivalent factors for Configuration 3

Main Street Volume / Volume Ratio	400	500	600	700	800	900	1000	1100	1200
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	0	0	0
3:1	0.14	0.07	0	0	0	0	0	0	0
4:1	0.09	0.02	0	0	0	0	0	0	0

*When the main street volume is beyond 1200 vph, equivalent factors of 1200 vph are applied.

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3.4 Configuration 4

The lane geometry in Configuration 4 is two lanes with shared right-turn and left-turn as shown in Table 3. Traffic volume scenarios are listed in Table 10. For the minor-street left and through movements, still 20 percent left turns are assumed. In each 63 study situation, 204 (34×6) cases are evaluated.

Table 10 Scenarios Evaluated in Configuration 4

Item	Range
Major Street (9)	400, 500, 600, 700, 800, 900, 1000, 1100, 1200 vph
Volume ratio (7)	1:1, 1:2, 1:3, 1:4, 2:1, 3:1, 4:1
Minor Street Right Turn (6)	50, 100, 150, 200, 250, 300 vph
Minor Street Left turn and Through (34)	40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 500, 520, 540, 560, 580, 600, 620, 640, 660, 680, 700vph

Under one volume scenario shown in Table 10, for example, major street volume is 400 vph; volume ratio is 1:1 (i.e. the westbound is 200 vph and the eastbound is 200 vph); minor street right turn is 300 vph and minor street left-turn and through volume 520 vph (i.e. left turn= 520×20%= 104 vph and through volume is 520 - 104=416 vph). Under this condition, the right-turn lane delay is 23.5 sec/veh. Then eliminate all the right turn traffic, increase the through traffic volume until the left and through lane control delay arrives at 23.5 sec/veh. The equivalent factor calculated by Equation 4 is 0.60. Detail information is listed in the Table 11.

Table 11 Equivalent factor Calculation Example for Configuration 4

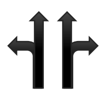
Configuration 4		Major Volume		400	
		Volume Ratio		1/1	
Before Equivalence					
Major Street		Subject Minor Street			Right-turn Delay
EB	WB	LT	T	RT	
200	200	104	416	300	23.5
After Equivalence					
Major Street		Subject Minor Street			Through Delay
EB	WB	LT	T	RT	
200	200	104	595	0	23.5
Equivalent factor	*EF*= (595-416)/300 = 0.60				

Figure 8 depicts the equivalent factor when the mainline volume is 500 vph and the right-turn volume is 400 vph. From the picture, the maximum equivalent factor is not in the highest minor-street left-turn and through volume, but corresponds to a certain middle level. It is mainly because the capacity of through traffic is relatively large in this geometry.

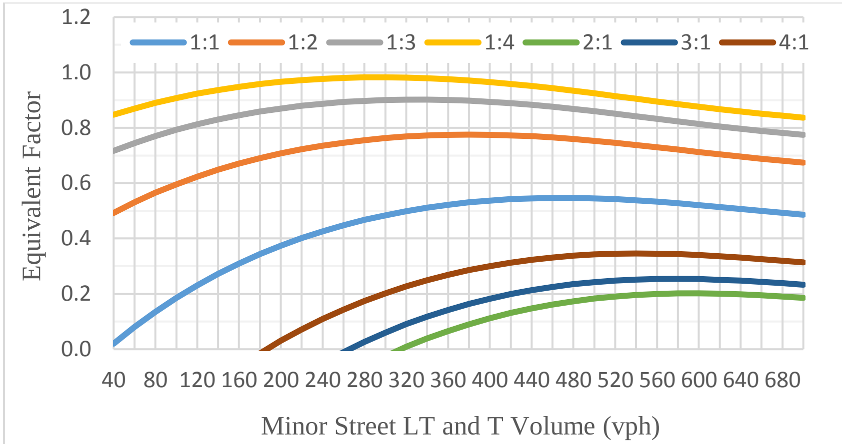


Figure 8 Equivalent factor Graph for Mainline Volume 500 vph

Table 12 Situation Equivalent factors for Configuration 4

Main Street Volume / Volume Ratio	400	500	600	700	800	900	1000	1100	1200
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	1	1	1	1
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	0

*When the main street volume is beyond 1200 vph, equivalent factors of 1200 vph are applied.

3.6 Discussion of Proposed Method

The proposed method is based on the relative delay relationship between through and right-turn traffic. When the main street volume increases, the minor street through traffic suffer 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 volumes increase. However, this phenomenon is not fit for the reality. In reality, the right-turn traffic is more difficult to enter the intersection when the main street traffic volume increases.

For Warrant 1 eight-hour vehicular volume, the threshold volumes are fixed. It does not consider the relationship between main-street and minor-street traffic. It is not proper just to converge right turns to through traffic. Therefore, to amend the proposed method, it is recommended to apply the equivalent factors for main street volume of 400 vph for all main street volume conditions.

For Warrant 2 four vehicular volume and Warrant 3 peak hour, the required minor street volume decrease with the increase of the main street volume. It considers the relationship between main street and minor street volumes. So in the reality, it is proper to converge the right turns to through traffic.

4 REGRESSION EQUATIONS FOREQUIVALENT FACTORS

In section 3, the proposed reduction method was introduced in detail. The equivalent factor is the maximum value of the entire volume scenario and the volume range is relatively wide to consider different conditions. For specific case, the equivalent factor may be not exact but tend to conservation. Even though the equivalent factor graphs (such as Figure 6) can give the reduction results for the covered volume conditions, the equivalent factors are not continuous and it is not easy to extract other conditions. Therefore, in this section, regression models are developed by statistical method. Equations and regression coefficients for all these four configurations and are provided.

4.1 Configuration 1 and 2

The equivalent factors are calculated based on delay primarily. The regression models are inspired by two-way stop-control delay function. Thus, the equations for Configuration 1 and 2, 3, 4 and 5 basically keep the similar form. The regression equation for Configuration 1 and 2 is shown as following:

$$f = a\left(1 - \frac{1}{(bV_{T+L} + cV_R)^d}\right) \tag{6}$$

where,
f is the equivalent factor;
V_{T+L} is the volume of through and left-turn traffic;
V_R is the right-turn traffic volume;
a, b, c, d are the regression coefficients.

To calculate the regression factors, MATLAB R2013a curve fitting toolbox is used.

Figure 9 is the toolbox interface. There are four steps to complete the fitting:

(1) Input fitting data: through and left-turn volume (X data); right-turn volume (Y data); equivalent factor (Z data);
(2) Choose Custom Equation and input Equation 2.
(3) Change setting in Fit Option (Figure 10),
 Robust: off;
 Algorithm: Trust Region;
 Specify starting conditions and define lower and upper bounds
(4) Read results: coefficients and goodness of fit.

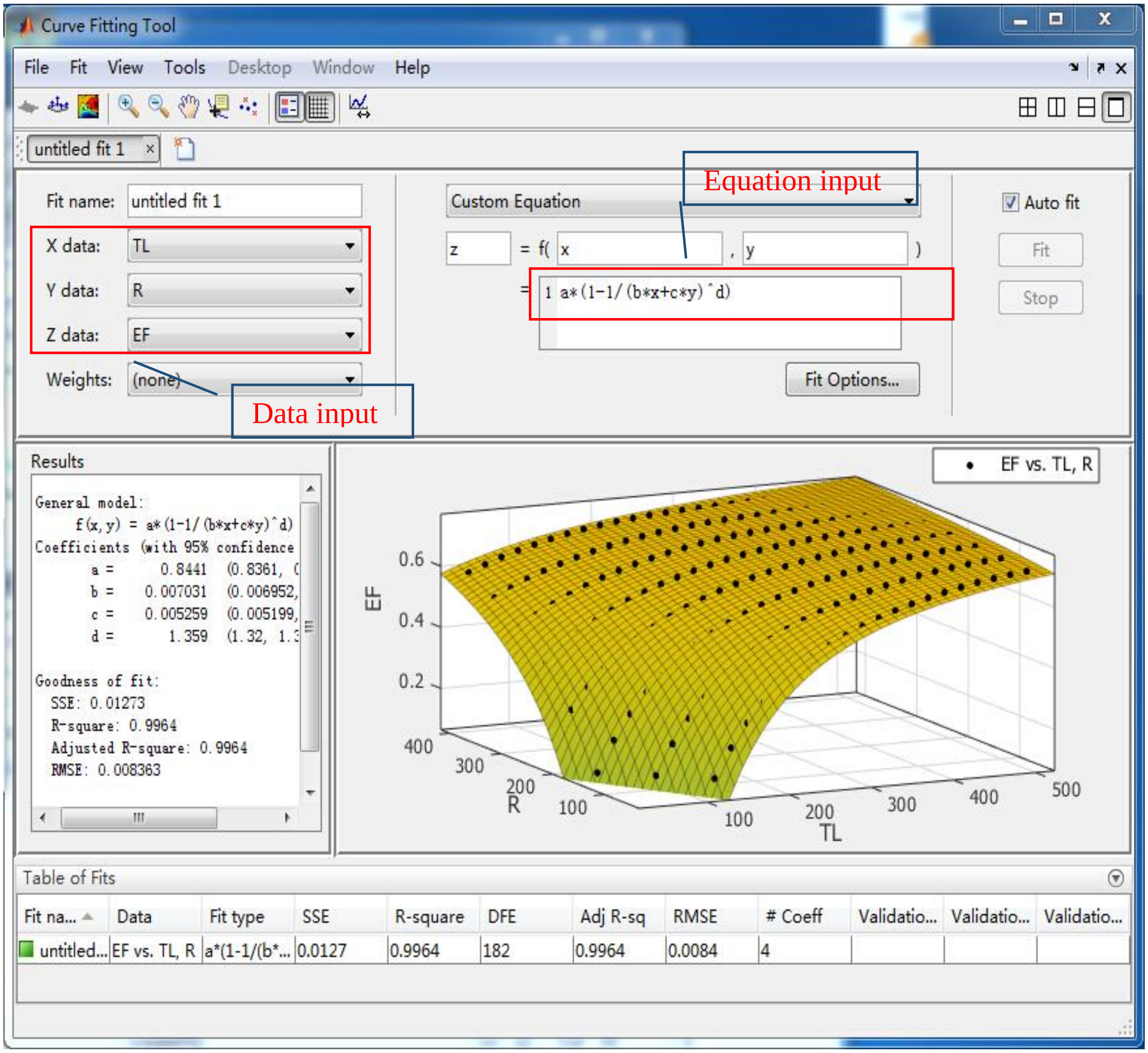


Figure 9 MATLAB Curve Fitting Interface: main street volume =400 vph; *VR*=1:4

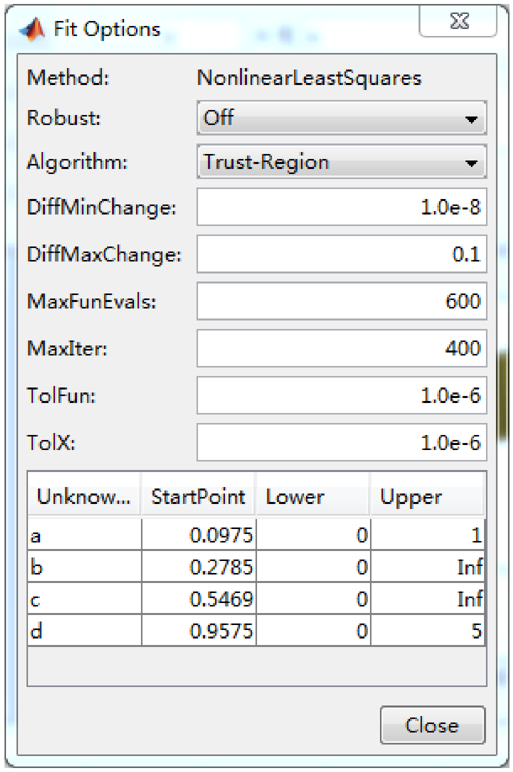


Figure 10 Fit Option Setting: main street volume =400 vph; VR=1:4

From Figure 10, we can see that all points scatter around the fitting surface. The coefficient of determination R^2 reaches up to 0.9964 and the sum of square error (SSE) is only 0.01273. Therefore, the proposed regression model could describe the equivalent factors almost perfectly for this scenario. It should be noticed that if the volume of through and left-turn traffic V_{T+L} and the right-turn traffic volume V_R are smaller than certain values, the equivalent factor will fall below zero, which is meaningless. In this condition, the equivalent factor should be reset to zero. Table 13 lists 63 study situations' regression coefficients and R^2 for Configuration 1 and 2. Three significant figures are reserved and it is also applicable to all other configurations.

Table 13 Regression Coefficients and R^2 for Configuration 1 and 2

	400						500				
	a	b	c	d	R^2		a	b	c	d	R^2
1:1	0.754	0.00498	0.00321	1.52	0.997	1:1	0.671	0.00503	0.00304	1.83	0.995
1:2	0.806	0.00593	0.00413	1.42	0.997	1:2	0.741	0.00605	0.00404	1.65	0.995
1:3	0.829	0.00660	0.00483	1.37	0.988	1:3	0.780	0.00680	0.00483	1.54	0.994
1:4	0.844	0.00703	0.00526	1.36	0.996	1:4	0.803	0.00742	0.00540	1.48	0.994
2:1	0.706	0.00436	0.00259	1.61	0.997	2:1	0.607	0.00437	0.00239	2.01	0.996
3:1	0.678	0.00410	0.00234	1.69	0.997	3:1	0.574	0.00411	0.00215	2.13	0.996

4:1	0.661	0.00396	0.00222	1.74	0.998	4:1	0.555	0.00397	0.00202	2.21	0.996
	600						700				
	a	b	c	d	R^2		a	b	c	d	R^2
1:1	0.602	0.00516	0.00294	2.16	0.994	1:1	0.543	0.00539	0.00288	2.49	0.993
1:2	0.687	0.00625	0.00405	1.86	0.993	1:2	0.636	0.00655	0.00403	2.15	0.991
1:3	0.730	0.00703	0.00487	1.77	0.992	1:3	0.687	0.00743	0.00497	1.98	0.989
1:4	0.758	0.00772	0.00550	1.68	0.992	1:4	0.713	0.00791	0.00554	2.00	0.989
2:1	0.527	0.00449	0.00227	2.43	0.995	2:1	0.462	0.00465	0.00220	2.87	0.995
3:1	0.491	0.00421	0.00202	2.61	0.996	3:1	0.426	0.00439	0.00194	3.03	0.995
4:1	0.472	0.00409	0.00189	2.68	0.996	4:1	0.403	0.00425	0.00179	3.24	0.996
	800						900				
	a	b	c	d	R^2		a	b	c	d	R^2
1:1	0.495	0.00566	0.00288	2.78	0.994	1:1	0.454	0.00607	0.00293	2.95	0.994
1:2	0.593	0.00683	0.00407	2.44	0.991	1:2	0.559	0.00722	0.00435	2.56	0.991
1:3	0.650	0.00777	0.00508	2.22	0.989	1:3	0.617	0.00815	0.00522	2.47	0.990
1:4	0.689	0.00864	0.00604	2.01	0.987	1:4	0.659	0.00910	0.00630	2.22	0.988
2:1	0.412	0.00496	0.00215	3.13	0.995	2:1	0.366	0.00521	0.00213	3.52	0.996
3:1	0.373	0.00465	0.00188	3.41	0.996	3:1	0.328	0.00489	0.00186	3.81	0.996
4:1	0.350	0.00444	0.00174	3.74	0.996	4:1	0.309	0.00479	0.00173	3.78	0.995
	1000						1100				
	a	b	c	d	R^2		a	b	c	d	R^2
1:1	0.417	0.00719	0.00296	3.11	0.995	1:1	0.384	0.00758	0.00308	3.29	0.995
1:2	0.524	0.00850	0.00432	2.84	0.994	1:2	0.499	0.00942	0.00471	2.68	0.993
1:3	0.590	0.00976	0.00551	2.54	0.992	1:3	0.564	0.0103	0.00577	2.70	0.995
1:4	0.635	0.01096	0.00676	2.25	0.988	1:4	0.611	0.01162	0.00714	2.40	0.991
2:1	0.328	0.00613	0.00215	3.68	0.995	2:1	0.297	0.00661	0.00227	3.52	0.992
3:1	0.292	0.00586	0.00185	3.77	0.994	3:1	0.260	0.00620	0.00195	3.70	0.991
4:1	0.272	0.00561	0.00174	3.92	0.992	4:1	0.241	0.00603	0.00179	3.73	0.988
	1200										
	a	b	c	d	R^2						
1:1	0.355	0.00833	0.00316	3.19	0.992						
1:2	0.471	0.01007	0.00480	2.84	0.995						
1:3	0.543	0.01168	0.00626	2.53	0.994						
1:4	0.589	0.01253	0.00723	2.54	0.995						
2:1	0.266	0.00716	0.00221	3.58	0.987						
3:1	0.231	0.00674	0.00195	3.56	0.985						
4:1	0.212	0.00645	0.00181	3.62	0.978						

*When the main street volume is beyond 1200 vph, equivalent factors of 1200 vph are applied.

4.2 Configuration 3

The regression equation for Configuration 3 is shown in Equation 8. Because there is exclusive right-turn lane, left-turn and through volumes are not considered. The same procedures are applied to calculate the regression coefficients as Configuration 1 and 2.

Figure 11 is an example for the regression model. The equation is good enough to explain the original data. Table 17 lists the regression coefficients and coefficients of determination for 63 study situations in Configuration 3.

$$f = a\left(1 - \frac{1}{bV_R^c}\right) \quad (3)$$

where,
f is the equivalent factor;
V_R is the right-turn traffic volume;
a, b, c are the regression coefficients.

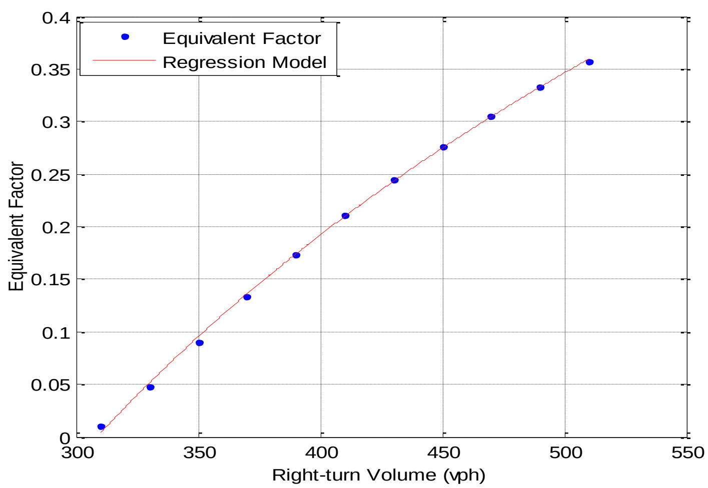


Figure 11 Regression Model Example for Configuration 3: main street volume =400 vph; *VR*=1:1

Table 14 Regression Coefficients and R^2 for Configuration 3

	400					500			
	a	b	c	R^2		a	b	c	R^2
1:1	2.79	0.208	0.274	0.999	1:1	2.92	0.200	0.278	0.999
1:2	1.54	0.058	0.518	1.000	1:2	1.13	0.0124	0.794	1.000
1:3	1.37	0.045	0.582	0.999	1:3	1.02	0.00746	0.911	1.000
1:4	1.31	0.042	0.606	0.999	1:4	1.01	0.00758	0.926	1.000
2:1	3.38	0.254	0.230	0.999	2:1	3.08	0.188	0.277	1.000

3:1	2.77	0.188	0.276	0.998	3:1	-	-	-	-
4:1	-	-	-	-	4:1	-	-	-	-
	600					700			
	a	b	c	R^2		a	b	c	R^2
1:1	3.006	0.197	0.278	0.998	1:1	3.14	0.194	0.279	0.996
1:2	1.010	0.00521	0.946	1.000	1:2	1.02	0.00540	0.939	0.998
1:3	0.940	0.00338	1.06	1.000	1:3	0.899	0.00223	1.13	0.999
1:4	0.915	0.00283	1.11	1.000	1:4	0.837	0.00102	1.31	1.000
2:1	-	-	-	-	2:1	-	-	-	-
3:1	-	-	-	-	3:1	-	-	-	-
4:1	-	-	-	-	4:1	-	-	-	-
	800					900			
	a	b	c	R^2		a	b	c	R^2
1:1	3.05	0.193	0.279	0.997	1:1	3.05	0.194	0.278	0.995
1:2	0.967	0.00371	1.01	0.996	1:2	0.769	0.0004981	1.37	0.997
1:3	0.754	0.000272	1.53	1.000	1:3	0.721	0.0002067	1.58	0.999
1:4	0.826	0.00108	1.30	0.999	1:4	0.738	0.000269	1.58	0.999
2:1	-	-	-	-	2:1	-	-	-	-
3:1	-	-	-	-	3:1	-	-	-	-
4:1	-	-	-	-	4:1	-	-	-	-
	1000				1100				
	a	b	c	R^2		a	b	c	R^2
1:1	2.93	0.192	0.280	0.992	1:1	1.53	0.0440	0.531	0.992
1:2	0.802	0.00150	1.18	0.991	1:2	0.665	0.000357	1.45	0.990
1:3	0.710	0.00036	1.49	0.995	1:3	0.612	2.94E-05	1.96	0.995
1:4	0.656	3.00E-05	2.00	0.999	1:4	0.642	5.74E-05	1.89	0.997
2:1	-	-	-	-	2:1	-	-	-	-
3:1	-	-	-	-	3:1	-	-	-	-
4:1	-	-	-	-	4:1	-	-	-	-
	1200								
	a	b	c	R^2					
1:1	1.32	0.0367	0.563	0.989					
1:2	0.530	1.93E-05	1.93	0.992					
1:3	0.573	2.73E-05	2.00	0.994					
1:4	0.624	0.000116	1.78	0.991					
2:1	-	-	-	-					
3:1	-	-	-	-					
4:1	-	-	-	-					

*When the main street volume is beyond 1200 vph, equivalent factors of 1200 vph are applied.

4.3 Configuration 4

The regression equation for Configuration 4 is shown in Equation 9. The same procedures are applied to calculate the regression coefficients as Configuration 1 and 2.

$$f = \left(1 - \frac{V_{T+L}^{0.558}}{(bV_{T+L}^{-0.227} + cV_R^{0.062})^{4.65}}\right) \quad (4)$$

where,
f is the equivalent factor;
V_{T+L} is the volume of through and left-turn traffic;
V_R is the right-turn traffic volume;
a, b, c, d are the regression coefficients.

Figure 13 is an example for the regression model. Equivalent factors scatter around the surface closely. Table 18 lists the regression coefficients and coefficients of determination for 63 study situations in Configuration 4.

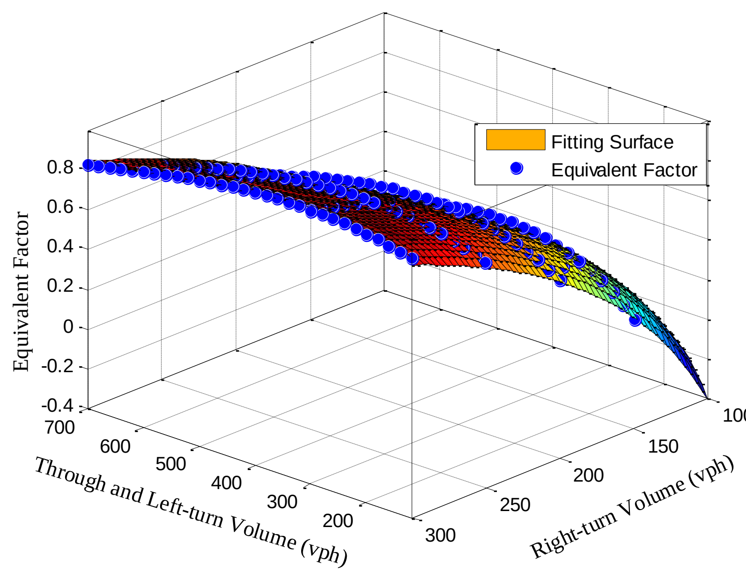


Figure 12 Regression Model Example for Configuration 4: main street volume =400 vph; *VR*=1:4

Table 15 Regression Coefficients and R^2 for Configuration 4

	400					500			
	a	b	c	R^2		a	b	c	R^2
1:1	0.754	0.00498	0.00321	0.997	1:1	0.671	0.00503	0.00304	0.995
1:2	0.806	0.00593	0.00413	0.997	1:2	0.741	0.00605	0.00404	0.995

1:3	0.829	0.00660	0.00483	0.988	1:3	0.780	0.00680	0.00483	0.994
1:4	0.844	0.00703	0.00526	0.996	1:4	0.803	0.00742	0.00540	0.994
2:1	0.706	0.00436	0.00259	0.997	2:1	0.607	0.00437	0.00239	0.996
3:1	0.678	0.00410	0.00234	0.997	3:1	0.574	0.00411	0.00215	0.996
4:1	0.661	0.00396	0.00222	0.998	4:1	0.555	0.00397	0.00202	0.996
	600					700			
	a	b	c	R^2		a	b	c	R^2
1:1	0.754	0.00498	0.00321	0.997	1:1	0.671	0.00503	0.00304	0.995
1:2	0.806	0.00593	0.00413	0.997	1:2	0.741	0.00605	0.00404	0.995
1:3	0.829	0.00660	0.00483	0.988	1:3	0.780	0.00680	0.00483	0.994
1:4	0.844	0.00703	0.00526	0.996	1:4	0.803	0.00742	0.00540	0.994
2:1	0.706	0.00436	0.00259	0.997	2:1	0.607	0.00437	0.00239	0.996
3:1	0.678	0.00410	0.00234	0.997	3:1	0.574	0.00411	0.00215	0.996
4:1	0.661	0.00396	0.00222	0.998	4:1	0.555	0.00397	0.00202	0.996
	800					900			
	a	b	c	R^2		a	b	c	R^2
1:1	0.495	0.00566	0.00288	0.994	1:1	0.454	0.00607	0.00293	0.994
1:2	0.593	0.00683	0.00407	0.991	1:2	0.559	0.00722	0.00435	0.991
1:3	0.650	0.00777	0.00508	0.989	1:3	0.617	0.00815	0.00522	0.990
1:4	0.689	0.00864	0.00604	0.987	1:4	0.659	0.00910	0.00630	0.988
2:1	0.412	0.00496	0.00215	0.995	2:1	0.366	0.00521	0.00213	0.996
3:1	0.373	0.00465	0.00188	0.996	3:1	0.328	0.00489	0.00186	0.996
4:1	0.350	0.00444	0.00174	0.996	4:1	0.309	0.00479	0.00173	0.995
	1000				1100				
	a	b	c	R^2		a	b	c	R^2
1:1	0.417	0.00719	0.00296	0.995	1:1	0.384	0.00758	0.00308	0.995
1:2	0.524	0.00850	0.00432	0.994	1:2	0.499	0.00942	0.00471	0.993
1:3	0.590	0.00976	0.00551	0.992	1:3	0.564	0.01033	0.00577	0.995
1:4	0.635	0.01096	0.00676	0.988	1:4	0.611	0.01162	0.00714	0.991
2:1	0.328	0.00613	0.00215	0.995	2:1	0.297	0.00661	0.00227	0.992
3:1	0.292	0.00586	0.00185	0.994	3:1	0.260	0.00620	0.00195	0.991
4:1	0.272	0.00561	0.00174	0.992	4:1	0.241	0.00603	0.00179	0.988
	1200								
	a	b	c	R^2					
1:1	0.355	0.00833	0.00316	0.992					
1:2	0.471	0.01007	0.00480	0.995					
1:3	0.543	0.01168	0.00626	0.994					
1:4	0.589	0.01253	0.00723	0.995					
2:1	0.266	0.00716	0.00221	0.987					
3:1	0.231	0.00674	0.00195	0.985					

4:1	0.212	0.00645	0.00181	0.978					

*When the main street volume is beyond 1200 vph, equivalent factors of 1200 vph are applied.

5 CASE STUDIES

Three intersections were selected as case studies to introduce how to apply the proposed procedures. The first two cases were from the NDOT previous signal warrant analysis data. The third one at Blue Diamond Road and South EI Capitan Way was a detailed case to apply the proposed method.

The first two intersections were chosen among twenty-six intersections with data provided by Nevada Department of Transportation. At first, according to the eight-hour warrant in MUTCD, these intersections were divided into three categories:

(1) the minor-street through and left-turn volumes met eight-hour warrant without right turning movement , which included 7 cases;
(2) all minor-street turning volumes did not meet the warrant, which included 12 cases;
(3) when considering all turning movementsthe warrant was met, which included 7 cases.

Among these three categories, the first two could be easily determined for warrants being met without considering the proper portion of right-turn volume reduction. The third category is the study focus, in which how much percentage of right-turn traffic utilized in the signal warrant influences the justified result. From the seven cases in the third category, two intersections are demonstrated here.

5.1 Lamoille Highway and Spring Creek Parkway

The first intersection located at Lamoille Highwayand Spring Creek Parkway in the rural area is shown in Figure 13. Lamoille Highway is the main street (east and west bounds) with three lanes and Spring Creek Parkway is the minor street with shared through and left-turn lane and an exclusive right-turn lane. For the eight hour warrant verification, with all turning volume, Condition A was justified and the vehicular data is shown in Table 16. It is obvious that this intersection has very high right-turn traffic, which would skew the warrant study results. By means of the proposed method, the equivalent factor and adjusted right-turn volume are listed in Table 17.

In each time period, there were two ways to consider the number of lanes and minor-street volume, which was introduced in Section 3.3. For the first one, the minor street with two lanes was considered. The minor street volume was sum of adjusted right-turn, through and left-turn traffic volumes. The required eight-hour vehicular volumes (Warrant 1 Condition A, MUTCD Table 4C-1) for main and minor streets were 420 vph and 105 vph. For the other one, consider the minor street had one lane. Under this condition, the minor street volume was the maximum volume of adjusted right-turn volume, and through and left-turn traffic. The eight-hour vehicular volumes for main and minor streets were 420 vph and 140 vph. By usinhg the adjustment methodology, Warrant 1 Condition A was not justified.

Warrant Condition B and the combination of Warrant Condition A and B were calculated because warrant Condition A was not satisfied. And these two were also not warranted. In the sum, this intersection was not justified for the Warrant 1.

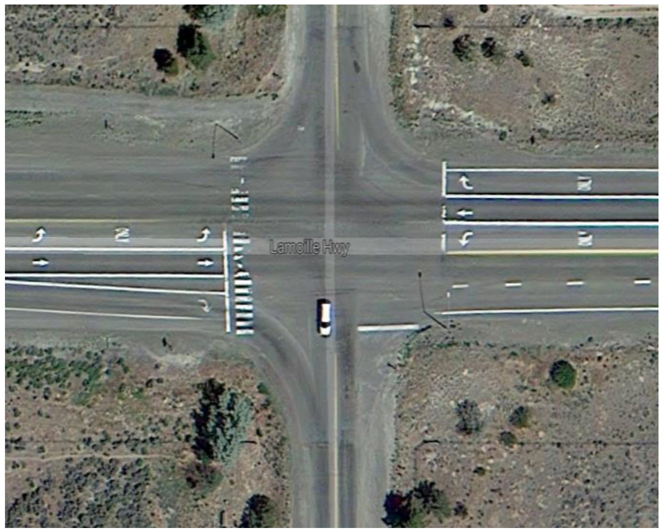


Figure 13 Intersection Picture at Lamoille Highway and Spring Creek Parkway

Table 16 Analysis Vehicular Volulme Before Adjustment (Lamoille Highway and Spring Creek Parkway)

Start Time	6:00	7:00	8:00	14:00	15:00	16:00	17:00	18:00	Requirements
Major Volume Total	454	556	480	572	582	880	1111	699	420
Minor Volume Total	290	280	268	181	178	186	202	152	105/140
Minor Through and Left Turns	38	37	62	57	56	59	63	38	N/A
Minor Right Turns	252	243	206	124	122	127	139	114	N/A

Table 17 Analysis Vehicular Volulme After Adjustment (Lamoille Highway and Spring Creek Parkway)

Start Time	6:00	7:00	8:00	14:00	15:00	16:00	17:00	18:00	Requirements
Equivalent factor	0.36	0.30	0.36	0.30	0.30	0.27	0.25	0.30	N/A
Minor Through and Left Turns	38	37	62	57	56	59	63	38	N/A
Equivalent Minor Right Turns	91	73	75	38	37	35	35	35	N/A
Critical Volume	91	73	75	57	56	59	63	38	105

(one lane)									
Minor Volume Total (two lane)	129	110	137	95	93	94	98	73	140

*The volume ratio was not availabe, so assume the factor as 1:1.

5.2 US395 and Airport Road

Another intersection is located at US395 and Airport Road as shown in Figure 14. US395 is the main street (northwest and southeast bounds) with two lanes and Airport Road is the minor street with shared lane. The flared shared lane at the intersection was not considered for the proposed method. For the eight hour warrant verification, with all the turning traffic, warrant Condition B was justified and the vehicular data is shown in Table 18. After reduction, the total minor-street volume still met the minimum requirement for warrant Condition B and detailed results are illustrated in Table 19.

Figure 14 Intersection Picture US 395 and Airport Rd

Table 18 Analysis Vehicular Volumes Before Adjustment (US395 and Airport Rd)

Start Time	9:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	Requirements
Major Volume Total	1562	1627	1671	1695	1934	1983	2053	2115	630
Minor Volume Total	74	110	100	78	106	207	171	154	53
Minor Through and Left Turns	43	65	59	46	63	123	100	91	N/A
Minor Right Turns	31	45	41	32	43	84	71	63	N/A

Table 19 Analysis Vehicular Volume After Adjustment (US395 and Airport Rd)

Start Time	9:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	Requirements
Equivalent factor	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	N/A

Minor Through and Left Turns	43	65	59	46	63	123	100	91	N/A
Reduced Minor Right Turns	12	17	15	12	16	31	26	23	N/A
Adjusted Minor Volume Total	55	82	74	58	79	154	126	114	53

*The volume ratio was not availabe, so assume the factor as 1:1.

5.3 Blue Diamond Road and South EI Capitan Way

Blue Diamond Road and South EI Capitan Way is the study intersection and the geometry picture is shown in Figure 15. The Blue Diamond Road is the main street (east and west bounds), and the South EI Capitan Way is the minor street (south and north bounds). The busier approach of the minor street is the south one. The minor street lane configuration is Configuration 3 with exclusive right-turn lane. The sketch of the study intersection is shown in Figure 16.

Figure 15 Intersection Picture at Blue Diamond Road and South EI Capitan Way

5.3.1 Right-turn Adjustment

The volume directional distribution at the intersection of Blue Diamond Road and South EI Capitan Way was not available, but there was TRINA data at Site 0031094 collected downstream of the intersection on Blue Diamond Road. The locations of these two sites are shown in Figure 17. Traffic volume and the volume ratio at Site 0031094 from Monday to Sunday are shown in Table 20. From these data, the volume ratios in each peak hour could be derived and are listed in Table 21.

From Table 20, we can see the westbound direction of Blue Diamond Road is busier which does not directly affect the northbound approach, which is the subject minor street approach to be analyzed. This explains why the high volume of right-turn traffic can enter the intersection easily. Table 22 provides detail information about the reduction process. After the reduction, warrants

Condition A, Condition B and the combination of Condition A and B at the 56% level were all not warranted.

Warrant 2 (Four-hour vehicular volume) and Warrant 3 (Peak hour) were also checked and neither warrant is met. The warrant volume requirement is shown in Figure 18.

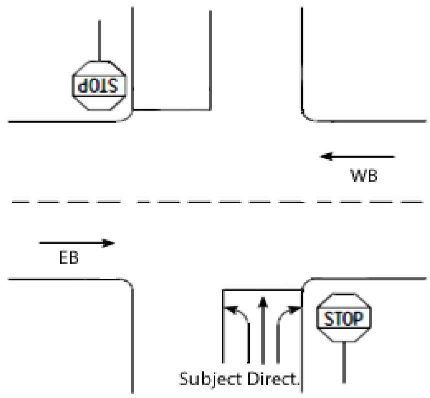


Figure 16 Intersection Sketch at Blue Diamond Road and South EI Capitan Way

Figure 17 Relative Locations between Study Site and Site 0031094

Table 20 Traffic Volume and Volume Ratios at Site 0031094

		6:00	Ratio	7:00	Ratio	8:00	Ratio	9:00	Ratio	10:00	Ratio	1:00	Ratio	2:00	Ratio	3:00	Ratio
Sun	W	359	1.5	550	1.8	760	1.7	990	1.7	1001	1.5	1137	1.2	1032	1.1	1058	1.0
	E	232		301		460		572		670		966		920		1010	
Mon	W	1171	1.9	1954	2.7	1557	2.0	1250	1.8	1069	1.5	1109	1.2	1099	1.0	1164	0.9
	E	626		735		797		690		720		933		1079		1248	
Sat	W	1209	1.9	1934	2.5	1578	2.0	1234	1.7	1065	1.4	1099	1.2	1097	1.1	1178	1.0
	E	647		770		772		719		742		921		1041		1193	
Wed	W	1159	1.6	1883	2.5	1585	2.0	1221	1.8	1059	1.4	1043	1.1	1029	1.0	1118	0.9
	E	704		747		795		691		738		919		1033		1216	
Thu	W	1271	2.5	1972	2.6	1982	2.7	1426	2.0	1106	1.6	1067	1.2	1089	1.0	1176	1.0
	E	500		755		734		723		693		923		1082		1234	
Fri	W	1043	1.9	1883	3.0	1642	2.2	1339	1.9	1234	1.7	1153	1.1	1307	1.2	1278	1.0
	E	536		623		732		720		715		1096		1130		1231	

Sat	W	516	1.1	858	1.6	1035	1.8	1139	1.7	1227	1.5	1265	1.3	1240	1.1	1257	1.1
	E	469		541		583		690		836		975		1118		1126	

Table 21 Suggested Volume Ratios at Each Peak Hour

Start Time	6:00	7:00	8:00	9:00	10:00	1:00	2:00	3:00
Volume Ratio	2:1	2:1	2:1	2:1	1:1	1:1	1:1	1:1

Table 22 Signal Warrant Analysis Based on Proposed Method

START TIME	6:00	7:00	8:00	9:00	10:00	1:00	2:00	3:00
MAJOR VOLUME	787	988	1060	946	983	1157	1192	1390
MINOR VOLUME	353	586	519	375	296	295	318	302
MINOR THROUGH & 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
Reduced Right turns	21	0	0	0	67	62	67	61
Adjusted Minor volume	77	128	101	60	114	109	118	109
Warrant 1								
Condition A (70%)	0	0	0	0	0	0	0	0
Condition B (70%)	1	1	1	0	1	1	1	1
Condition A (56%) & Condition B (56%)	0	1	0	0	1	0	1	0
Warrant 2	0	0	0	0	0	0	0	0
Warrant 3	0	0	0	0	0	0	0	0

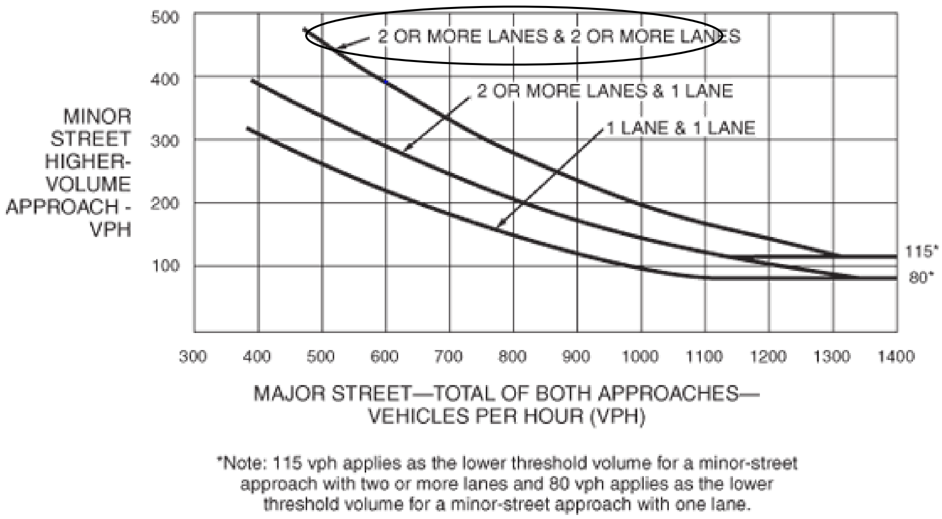
*In Warrant 1, 2 and 3, 0 represents that the volume is not warranted and 1 represents that the volume is warranted

Warrant 1: Eight-Hour Vehicular Volume

Condition		Main Street	Minor Street
A	70%	420	140
	56%	336	112
B	70%	630	70
	56%	504	56

*The number of lanes for major street are 2 or more; the number of lanes for minor street are 2 or more

Warrant 2: Four-Hour Vehicular Volume



Warrant 3: Peak Hour

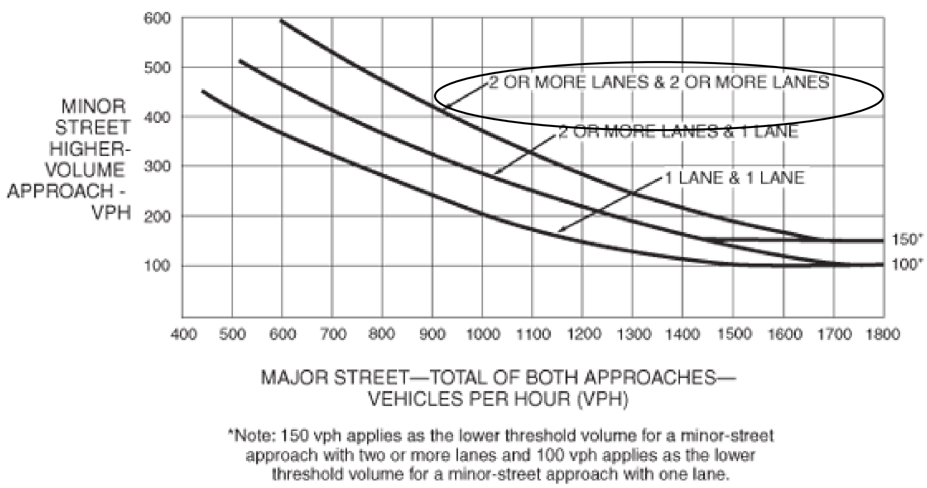


Figure 18 Signal Warrants 1, 2 and 3 Volume Requirements

5.3.2 HCM Delay

Synchro is used to calculate the delay at the study intersection for the eight peak hours. The purpose of this analysis is to access if the intersection operates at acceptable levels of service. The LOSs of each movement at the pick hour periods are shown in Table 23. From the delay, we can see the minor street through traffic may have difficulties to cross the intersection due to the high volume on the main street. The right-turn traffic can enter the intersection easily, even though the right-turn volume is very high at peak hours. Overall, the intersection operates at acceptable levels. The worst LOS is E, but the majority are C or better.

Table 23 Intersection LOS at Blue Diamond Road and South EI Capitan Way

LOS	Minor Street		
	Left turn	Through	Right turn
6:00	B	C	B
7:00	C	D	C
8:00	C	D	B
9:00	C	C	B
10:00	C	C	B
13:00	C	D	B
14:00	C	D	B
15:00	D	E	B

5.3.3 Other Reduction Methods

Pagones Theorem and NCHRP 475 methods were conducted for this case and further were compared with the proposed method.

5.3.3.1 Pagones Theorem

For Pagones Theorem, the lane configuration was with exclusive right-turn lane. Based on Table 1, minor street adjustment factor was 0.75. And the mainline congestion factors was extracted from Table 2 shown in Table 24. There were two lanes in each direction of the main street.

From the reduction procedure, this intersection signal was warranted based on Warrant 1 Condition B, and Condition A and B.

Table 24 Signal Warrant Analysis Based on Pagones Theorem

START TIME	6:00	7:00	8:00	9:00	10:00	1:00	2:00	3:00

MAJOR VOLUME	787	988	1060	946	983	1157	1192	1390
MINOR VOLUME	353	586	519	375	296	295	318	302
MINOR THROUGH & LEFT TURNS	56	128	101	60	47	47	51	48
MINOR RIGHT TURNS	297	458	418	315	249	248	267	254
CASE 3								
MALINE VOLUME PER LANE	197	247	265	237	246	289	298	348
MAINLINE 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%)	0	1	1	0	0	0	0	0
Condition B (70%)	1	1	1	1	1	1	1	1
Condition A (56%) & Condition B (56%)	1	1	1	1	1	1	1	1
Warrant 2	0	1	1	0	0	0	0	0
Warrant 3	0	0	0	0	0	0	0	0

5.3.3.2 NCHRP 475 Method

The volume proportion of Main Street was unavailable. So 10% of major volume was assumed as right turns and no left turns was assumed. It was reasonable and conservative. Most people drove to Las Vegas and went straight. After calculation, it was found that the assumption was not important. Because the right-turn reduction was high enough to cover the total right-turn volume. After calculation, the signal was not warranted.

Table 25 Signal Warrant Analysis Based on NCHRP 475 Method

START TIME	6:00	7:00	8:00	9:00	10:00	1:00	2:00	3:00
MAJOR VOLUME	787	988	1060	946	983	1157	1192	1390
MINOR VOLUME	353	586	519	375	296	295	318	302
MINOR THROUGH & 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%)	0	1	1	0	0	0	0	0
Condition B (70%)	0	1	1	0	0	0	0	0
Condition A (56%) & Condition B (56%)	0	1	0	0	0	0	0	0
Warrant 2	0	0	0	0	0	0	0	0
Warrant 3	0	0	0	0	0	0	0	0

5.3.3.3 Comparisons

For this specific case, signal was not warranted from the proposed method and NCHRP 475 method. And signal was warranted from the Pagones theorem. In the intersection operation perspective, this intersection was at the edge of installing a signal.

In NCHRP 475 method, from conflicting major-road volume, minor-road right-turn volume reduction was calculated. From Table 24, the right-turn reduction volume was too high. It assumed all these right turns operated freely, but in reality, the right lane may be blocked by through traffic.

6 GUIDELINE APPLICATION STEPS

This chapter provides the key steps for applying the proposed righ-turn volume reduction guideline described in the previous chapter.

The major methodology based on the delay equivalent principle which associates right-turn volume to an equivalent number of through vehicles that would produce the same amount of control delay on the minor street. The amount of right-turn volume reduction is obtained by the equivalent factor. The key steps for applying the guideline are provided next.

Step 1: Identify the study intersection geometry according to Table 3 and confirm the Configuration number (there are five Configurations);

Step 2: Define the subject minor street approach and obtain the main street volumes of V_1 (far side) and V_2 (near side);

Step 3: Calculate the volume ratio using Equation 3:

$$VR = \frac{V_1}{V_2}$$

Obtain the equivalent factor from the corresponding table based on the geometric configuration;

Step 4: The adjusted right-turn volume is estimated by the equivalent factor as follow: $R_{adj} = R \times EF$.

7 SUMMARY AND CONCLUSIONS

Unwarranted traffic signals are detrimental not only to the flow of traffic but also to the overall delay. Including all right-turn traffic volume or an inappropriate portion could result in an erroneous traffic study and hence possible installation of an unwarranted traffic signal. A review of previous studies and existing guidelines revealed that, engineers and scholars generally agree on reducing right-turn volumes in signal warrant analysis. However, determining the reduction percentage has primarily done based on engineering judgments. Although limited guidelines exist on right-turn volume reduction, no detailed documentations were found to back up the methodologies. This project serves the purpose of filling out such methodological gaps by developing new right-turn volume reduction guidelines.

The guidelines are essentially based on what is so-called the delay equivalence methodology, i.e. to equal the right-turn volume to an equivalent number of through vehicles, which would produce the same control delay on the minor street. Equivalent factor is defined as the measurement of reducing level. The estimation of minor street control delay was based on the HCM 2010 methodology for two-way stop-controlled intersections. To expedite the data analysis process, the HCM procedure was implemented in EXCEL VBA, which allowed generating and analyzing multiple scenarios at the same time. According to the geometry of the minor street, five configuration are classified, which cover the most common geometry. Under each configuration, a variety of volume distributions are considered which yield a total of 63 study scenarios. Configuration 1 and Configuration 2 use the same equivalent factors based on calculation. Tables and figures are produced to indicate the right-turn traffic volume equivalent levels based on various combinations of volume values.

Major findings and conclusions from this research can be summarized below:

- The volume ratio in the two directions of the main street has a major impact on the right-turn volume reduction. This factor is specifically considered in developing the new guidelines.
- Application of the guidelines at three intersection sites revealed that the proposed guideline could easily help engineers determine appropriate right-turn volume reductions.
- Field studies are crucial to adjusting right-turn traffic in signal warrant analysis, because every intersection's situation is usually unique due to its location, traffic volume and geometry. Engineering judgment still plays an important role even with the new guidelines. The final right-turn reduction should be verified through field studies.

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