An Empirical Analysis of Critical Headway for Drivers Turning Right-On-Red at Signalized Intersections

by

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ABSTRACT
Right-turn-on-red (RTOR) movements can significantly affect the capacity of right-turn lanes at signalized intersections. Vehicles turning right-on-red must wait for an adequate opening in conflicting vehicle traffic (and/or pedestrian traffic if present) in order to complete the turn and, consequently, there exists a RTOR critical headway. The Highway Capacity Manual (HCM) recommends field measurements of RTOR vehicles in calculating capacity at signalized intersections, but this is not always possible. In these cases, the RTOR must either be assumed to be zero, which may lead to significantly inflated right-turn delay calculations, or estimated based on intersection geometry and traffic patterns. Previous research on the effects of RTOR on capacity and delay has assumed a RTOR critical headway equal to that of the HCM base critical headway values for two-way stop-controlled (TWSC) intersection minor street right turns. To assess this assumption, an empirical analysis of the critical headway for RTOR maneuvers was conducted using observational data obtained from five signalized intersection approaches in different regions of the United States. Headway acceptance and rejection data were extracted manually from high-definition videos taken at the intersection approaches and the RTOR critical headway was determined. It was found the RTOR critical headway is generally less than the HCM base critical headway values for TWSC intersection minor street right-turns, indicating drivers are more aggressive at traffic signals. Implications of RTOR critical headway on capacity and delay calculations for signalized intersections are discussed.
INTRODUCTION

Right-turn-on-red (RTOR) occurs when a vehicle completes a right turn at a signalized intersection during the phase in which their approach is faced with a red traffic signal. RTOR is allowed at most signalized intersections in the United States after a vehicle has come to a complete stop at the stop bar, unless prohibited for reasons such as limited sight distance. Vehicles turning right-on-red must wait for an adequate opening in conflicting vehicle traffic (and/or pedestrian traffic if present) in order to complete the turn. Accordingly, there exists a critical headway for every RTOR driver in which that driver would reject any headway less than their critical headway, and would accept any headway larger.

RTOR can significantly increase the capacity of right turn movements at signalized intersections, particularly at approaches with exclusive right turn lanes. Consequently, the overall capacity and delay of an intersection can be significantly affected by the behavior of RTOR vehicles. The *Highway Capacity Manual (HCM)* (1) states that RTOR flow rates should be collected in the field when possible because RTOR is difficult to predict as it depends on many different factors. However, field measurement is not possible for new intersections or intersections undergoing significant reconstruction or alignment changes. In these cases or other situations where field measurement is not possible, the *HCM* recommends assuming zero RTOR vehicles, which can result in significantly inflated delay predictions for right turn movements. If estimated right turn delays are inflated, unneeded capacity may be added or unnecessary green time may be provided to approaches with the RTOR movements. It may be more beneficial for the analyst to assume a reasonable prediction for RTOR movements based on expected (or existing) conditions at the intersection.

RTOR can occur during the phase in which cross street through traffic has a green signal indication, or during protected left turn phases. In the case of cross street protected left turn phases, RTOR vehicles in an exclusive right turn lane do not encounter any conflicting vehicle traffic and the *HCM* recommends reducing the number of right turns by the number of ‘shadowed’ left-turning vehicles. This paper, however, focuses solely on the regime where cross street through traffic has a green indication and RTOR vehicles must select a headway in cross street traffic to complete the RTOR. In this situation, the RTOR volume is much more difficult to predict. This scenario has been likened to the case of a minor street vehicle turning right at a two-way stop-controlled (TWSC) intersection and this comparison is known as the ‘stop sign analogy’. The *HCM* (1) provides default critical headway values for right-turning vehicles at TWSC intersections as 6.2 seconds, 6.9 seconds, and 7.1 seconds for two-lane, four-lane, and six-lane major roadways, respectively. These critical headway values have been applied in calculating predicted RTOR flow rates in traffic simulation software such as *Synchro/SimTraffic* (2) (although in the case of *Synchro/SimTraffic*, the critical headway is set at 6.2 seconds regardless of the number of lanes on the cross street has). However, the critical headway for drivers at a signalized intersection turning right-on-red may in fact differ from that of drivers at TWSC intersections. For example, signalized intersections would generally be located in more urbanized areas and would tend to experience higher traffic volumes than TWSC intersections which could affect driver behavior.

This paper presents an empirical analysis of the critical headways for drivers turning right-on-red using observational data obtained from five signalized intersection approaches in different regions of the United States. All study intersection approaches have flat grades and intersect at 90 degree angles. The headway acceptance and rejection data for vehicles turning right-on-red during the phase in which conflicting through traffic has a green signal indication
are extracted from field videos. The RTOR critical headway is then calculated and compared to the default values in the HCM under the ‘stop sign analogy’, as well as default values used in some traffic simulation software, and the implications on capacity and delay calculations are discussed.

LITERATURE REVIEW

The HCM (1) suggests simply reducing the number of right turns by the field observed number of RTOR vehicles in calculating capacity at signalized intersections (in the absence of a shadowed left turn phase). There are two problems with this: the first is that field observations are not always possible, and the second is that by subtracting vehicles from the approach volume, their effect on signal delay is ignored (3). Ignoring these vehicles can ultimately affect the level of service (LOS) of the intersection. Despite this shortcoming, there is only a limited body of research analyzing the effects of RTOR on capacity and delay at signalized intersections. Most studies have focused on developing predictive models based on a number of traffic and driver related factors, while only a few have investigated the critical headway characteristics of RTOR drivers.

Tarko (4) developed a model to predict RTOR volumes at isolated and coordinated signals based on several parameters such as intersection geometry, patterns of arriving vehicles (both right-turning vehicles and conflicting vehicles), and signal timing parameters. However, in the development of the model, a critical headway time for RTOR vehicles was assumed to be 6.9 seconds. This assumption follows the HCM suggestion for TWSC intersections with 4-lane major roads (1). Qureshi and Han (5) developed a delay model for right turn lanes with RTOR traffic based on queuing theory. They also assumed the HCM default critical headway value for right turns at TWSC intersections, which was 5.5 seconds at that time. Creasey et al. (6) developed RTOR volume estimation models and incremental capacity models for shared right turn lanes, which also utilized the HCM default critical headway values for right turns at TWSC intersections.

Virkler and Maddela (7) tested both the left turn shadowing method and the stop sign analogy of accounting for RTOR vehicles to determine the effects on intersection capacity with data from 40 intersections. It was found that both methods improve intersection capacity, indicating that if RTOR vehicles are ignored, the HCM method for signalized intersections may over-estimate delay. Again, the critical headway for RTOR vehicles was assumed to follow HCM default values for right-turning vehicles at TWSC intersections. Virkler and Krishna (3) provide another analysis of the stop sign analogy and assess SIDRA software. The SIDRA software uses a default RTOR critical headway of 6.0 seconds which is slightly lower than the current HCM default values for TWSC intersections in the United States. An observational RTOR headway acceptance study was conducted at three intersections and the critical headway for RTOR was found to be 4.05 seconds, 4.47 seconds, and 5.54 seconds at for each of the three intersections. This is one of the first field-observed RTOR critical headway analyses on record; however, the conditions at the three intersections are not applicable to all scenarios. One of the intersections had a yield-controlled right turn lane which allowed for ‘free right-turns’ (and is really not necessarily applicable to an RTOR scenario). As for the other two intersections, one included a one-way street with two conflicting through traffic lanes and the other had only one conflicting through lane.

Chen et al. (8) estimated RTOR capacity for dual right turn lanes at signalized intersections considering both left turn shadowing situations and the stop sign analogy. Of
greater relevance to the current study, Chen et al. (9) performed an empirical assessment of headway-acceptance behavior of RTOR drivers at dual right-turn lanes. Using data from six intersections (all either interchange ramps or frontage roads), the critical headway for RTOR drivers was found to be 5.6 seconds for drivers in the curb lane and 6.7 seconds for drivers in the inside right-turn lane. These findings are useful for analyses of dual right-turn situations, but may not be applicable to single right-turn lanes. Overall, it is clear that research on the critical headway for RTOR drivers is limited, as almost all analyses of RTOR impacts on capacity and delay assume the critical headway is equal to that of right-turning vehicles at TWSC intersections. This study provides important empirical data to address this gap in the research literature.

DATA DESCRIPTION
The data for this study were extracted from an existing database of video taken at numerous intersection approaches across the United States. This database contains four to six hours of video at 87 different intersection approaches from California, Maryland, Michigan, and Virginia. The video at each site generally started after the AM peak hour (around 11 AM) and continued for 4 to 6 hours into the PM peak hour. The sites were originally chosen at random from intersections with at least two through lanes and where municipalities granted permission for video recording. It is important to note that many of these sites were not viable candidates for an RTOR headway acceptance analysis. To identify appropriate sites, one hour of video was reviewed for each site to record the number of usable RTOR headway acceptances observed. Several sites were eliminated immediately due to their geometry (e.g., t-intersections, yield-controlled free right-turns, etc.) as well as in cases of low right-turn or conflicting through traffic volumes (i.e. no useable RTOR headway acceptances). Ultimately, five intersection approaches were chosen as good candidates for an RTOR headway acceptance study based on their geometry and traffic patterns. Summary statistics for the five study sites are shown in Table 1.

TABLE 1 Summary of Study Sites Selected for RTOR Headway Acceptance Analysis

<table>
<thead>
<tr>
<th>Study Approach</th>
<th>Location</th>
<th>Cross Street Speed Limit</th>
<th>Number of Through Lanes on Cross Street</th>
<th>Hours of Video Reviewed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. WB Westminster Ave at Harbor Blvd</td>
<td>Santa Ana, CA</td>
<td>40 mph</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>2. NWB Waters Road at Ann Arbor Saline Road</td>
<td>Ann Arbor, MI</td>
<td>40 mph</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3. WB Lee Jackson Memorial Hwy at Walney Road</td>
<td>Chantilly, VA</td>
<td>45 mph</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>4. WB Six Mile Road at Newburgh Road</td>
<td>Livonia, MI</td>
<td>45 mph</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>5. NB Newburgh Road at Six Mile Road</td>
<td>Livonia, MI</td>
<td>45 mph</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>
The videos are shot from high-definition video cameras, which are mounted on telescoping poles approximately 20 feet above the pavement surface. The cameras are attached to street signs, allowing for covert monitoring of driver behavior. The elevated view provides an excellent vantage point for conducting a headway study. Figure 1 shows a screen shot of the video taken at Westminster Avenue and Harbor Boulevard in Santa Ana, California in which a vehicle in the right turn lane is waiting to accept a headway in the cross street through traffic.

FIGURE 1  Screen shot of video at Westminster Ave. and Harbor Blvd. in Santa Ana, CA.

To analyze the critical headway of RTOR drivers, both headway acceptances and rejections were recorded for all RTOR vehicles. This was done manually with a stopwatch while watching the videos in real-time (although videos were frequently rewound to confirm accuracy of a measured headway or to capture a headway that the observer had initially missed). For the purpose of this study, only headways (and not lags) were recorded because a driver’s reaction to a lag may not be the same as to a headway and the inclusion of lags may bias the results of the study (10). It should be noted that not all the observed RTOR vehicles had a usable observed accepted headway. In cases where an RTOR driver rejected several headways but did not find an adequate one to accept during the red phase, their rejected headways were recorded as usable data but there was no observed accepted headways for those drivers. Similarly, in cases where an RTOR driver turned right after all cross street traffic had already passed, those drivers’ rejected headways were recorded as usable data, but there was no observed accepted headway (because the accepted headway size in these cases is not measurable). It should be noted that no RTOR headway data were collected during protected left turn phases; as this study focused solely on the traffic regime in which cross street through traffic had a green signal indication. The headway sizes were recorded to the tenth of a second and the data were later compiled into bins.
RTOR CRITICAL HEADWAY ANALYSIS RESULTS
After headway data collection was complete, the Ramsey and Routledge (11) method of determining critical headway was utilized to determine the RTOR critical headway. The Ramsey and Routledge method is recommended in the Manual of Transportation Engineering Studies (12) and has advantages over other methods of critical headway calculation. The main advantage of this method is that it does not require any assumption of the distribution of critical headways in the driver population. The method efficiently estimates the entire distribution of critical headways using all headway data (accepted and rejected headways) (12). Additionally, this method is relatively simple to use and has been shown to provide good precision and accuracy when compared with other methods (10). One requirement when using this technique, however, is that the proportions of accepted headways must increase with headway size. This is usually not an issue (and was not in the case of this study) because drivers would tend to reject smaller headways and accept larger headways. Table 2 presents the results of the RTOR critical headway analysis including a summary of the RTOR headway acceptance and rejection data and the calculated critical headway for all five locations, as well as for the aggregated dataset.

TABLE 2 Summary of RTOR Critical Headway Analysis

<table>
<thead>
<tr>
<th>Study Approach</th>
<th>Headway Sizes (mean of bins)</th>
<th>RTOR Mean Critical Headway</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 sec</td>
<td>5 sec</td>
</tr>
<tr>
<td>1. WB Westminster Ave at Harbor Blvd</td>
<td># Acceptances 1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td># Rejections 125</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>% Accepting 0.8</td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td># Acceptances 5</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td># Rejections 190</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>% Accepting 2.6</td>
<td>17.5</td>
</tr>
<tr>
<td>2. NWB Waters Road at Ann Arbor Saline Road</td>
<td># Acceptances 2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td># Rejections 87</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>% Accepting 2.2</td>
<td>27.3</td>
</tr>
<tr>
<td>3. WB Lee Jackson Memorial Hwy at Walney Road</td>
<td># Acceptances 1</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td># Rejections 123</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>% Accepting 0.8</td>
<td>27.3</td>
</tr>
<tr>
<td>4. WB Six Mile Road at Newburgh Road</td>
<td># Acceptances 12</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td># Rejections 349</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>% Accepting 3.3</td>
<td>19.2</td>
</tr>
<tr>
<td>5. NB Newburgh Road at Six Mile Road</td>
<td># Acceptances 21</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td># Rejections 874</td>
<td>205</td>
</tr>
<tr>
<td></td>
<td>% Accepting 2.3</td>
<td>21.5</td>
</tr>
</tbody>
</table>
The final sample size of RTOR headway acceptances was 259. To obtain accurate critical headway calculations, Ramsey and Routledge suggest a minimum of 200 acceptances for 2-second bins and a minimum of 500 acceptances for 1-second bins (11). Therefore, a bin size of 2 seconds was selected for this study, which is considered adequate for most headway acceptance studies (12). The proportions of accepted headways increased with headway size for all five study locations, as well as for the overall analysis. It should be noted that data for headways less than 2 seconds are not included in Table 2 because no RTOR drivers were observed to accept a headway of less than 2 seconds and such data do not influence the determination of critical headway in the Ramsey and Routledge method.

The RTOR critical headways were found to be 5.01 seconds, 5.21 seconds, 5.00 seconds, 4.92 seconds, and 4.56 seconds for the five study locations. These RTOR critical headway results for the individual study sites, however, are based on a relatively low sample size of RTOR headway acceptances at each individual site. Of most importance is the overall (aggregate) RTOR critical headway analysis, which showed a mean critical headway of 4.88 seconds. This is significantly less than the HCM assumed values for TWSC intersections (6.2 seconds, 6.9 seconds, and 7.1 seconds for two-lane, four-lane, and six-lane major roadways, respectively). This indicates RTOR drivers tend to be more aggressive than drivers turning right at TWSC intersections, possibly due to differences in drivers and traffic conditions between rural TWSC and urban/suburban signalized intersections. The distributions of the RTOR critical headways estimated by the Ramsey and Routledge method were approximately normal for each site individually, as well as for the aggregate data for the five locations. The distribution of RTOR critical headways is shown graphically in Figure 2. The potential impacts of the RTOR critical headway on the calculation of capacity and delay for right turns at signalized intersections are discussed in the next section.

![Figure 2](image-url)
IMPACT OF RTOR CRITICAL HEADWAY ON CAPACITY AND DELAY ESTIMATES

The RTOR mean critical headway for this empirical study was found to be 4.88 seconds. This critical headway time is significantly less than the default value for the right-turn critical headway at TWSC intersections found in the *HCM*. As discussed previously, nearly all prior research on the impact of RTOR on capacity and delay at signalized intersections has assumed that the RTOR critical headway is equal to that of right-turning minor street traffic at TWSC intersections (i.e. the stop sign analogy). Similarly, the *Synchro/Simtraffic* traffic simulation software assumes an RTOR critical headway of 6.2 seconds for all intersection geometries (2). Since the critical headway for RTOR drivers in this study is found to be less than the commonly used default values, it seems delay calculations for right turns may be frequently over-estimated. *Synchro/Simtraffic* fully models RTOR movements by calculating a saturation flow rate for RTOR and applying that flow rate to right-turn movements when they are red (2). The formula used to calculate RTOR saturation flow, which is very similar to Equation 19-32 in the *HCM* used to calculate capacity at TWSC intersections, is as follows:

\[
s_{RTORi} = \frac{v_{xi} e^{-\frac{v_{xi} \times 6.2}{3600}}}{1 - e^{-\frac{3.3}{3600}}}
\]

where:

- \( s_{RTORi} \): RTOR saturation flow rate in veh/hr (1091 veh/he if zero conflicting traffic)
- \( v_{xi} \): Merging volume during time interval \( i \)
- 6.2: Assumed RTOR critical headway time in seconds
- 3.3: Assumed follow up time in seconds

In assuming the RTOR critical headway time is 6.2 seconds, this formula may be underpredicting the actual RTOR saturation flow rate. For example, for conflicting traffic of 900 veh/hr, the \( s_{RTORi} \) is calculated to be 340 veh/hr (intermediate calculations involving cycle and phase lengths are left out here for simplicity). However, if the assumed 6.2 seconds RTOR critical headway is replaced with the 4.88 sec RTOR critical headway found empirically in this study, the resulting \( s_{RTORi} \) is 473 veh/hr. Using the 4.88 seconds RTOR critical headway found in this study, the resulting \( s_{RTOR} \) was 133 veh/hr higher representing a 39.1% increase. This potential increase could significantly affect the capacity and delay estimates for right-turns, as well as for the overall intersection.

Most of the existing literature that attempts to estimate RTOR effects on capacity or delay use the default critical headway values for TWSC intersections from the *HCM* (4,5,6,7). The results from this study, however, suggest using an RTOR critical headway of 4.88 seconds may provide greater accuracy, and would yield higher RTOR capacities. It should be noted that this RTOR critical headway can be applied to exclusive or shared right-turn lanes, but the method for determining capacities would differ as shared lanes have the added restriction of possible blockages by through vehicles.

CONCLUSIONS

RTOR movements can significantly affect the capacity of right-turn lanes at signalized intersections. Vehicles turning right-on-red must wait for an adequate opening in conflicting
traffic in order to complete the turn and, therefore there exists a RTOR critical headway. This paper presented an empirical analysis of the critical headway for drivers turning right-on-red using observed data obtained from five signalized intersection approaches in different regions of the United States. Headway acceptance and rejection data were extracted manually from high-definition videos collected at these approaches. Using the Ramsey and Routledge method, it was found that the RTOR critical headway is 4.88 seconds.

The results of this study indicate that RTOR drivers are more aggressive than right-turning drivers at TWSC intersections, and previous research on RTOR using the ‘stop sign analogy’ may have under-estimated RTOR effects on capacity and delay. An example of RTOR saturation flow showed that using RTOR critical headway of 4.88 seconds resulted in a 39.1% increase in RTOR saturation flow as compared to the default value of 6.2 seconds. This example demonstrates the importance of accurately accounting for RTOR, as failure to do so could result in analysts adding unneeded capacity to intersections or providing unneeded green time.

RTOR is a topic which could benefit from further detailed research as traffic congestion in urban areas continues to be a major concern and transportation engineers are always seeking to improve efficiency, even incrementally. Future research could examine RTOR critical headway at intersections with differing geometry and traffic patterns to determine if the value found in this study is consistent with different scenarios. The effect of differing cross-street speed limits could also be investigated as this study was limited to sites with 40 mph or 45 mph cross-street speed limits. Additionally, RTOR follow up headways could be analyzed with observational data and compared to values found in the HCM for base follow-up headways at TWSC intersections. Left-turn-on-red (LTOR) critical headway at one-way streets could also be examined with observational data, as this movement is allowed at intersections with one-way streets in most states in the U.S.

REFERENCES