A STUDY OF LOCAL GAP ACCEPTANCE BEHAVIOR USING DRONE VIDEOGRAPHY

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Introduction and Problem Statement

The engineering design of an intersection sometimes is a balance between the conflicted relationship of intersection sight distance (ISD) and the on-street parking often relied upon by local business owners and residents. The City of Laramie in the State of Wyoming, in particular, is feeling pressure to maintain on-street parking when evaluating existing intersections. Typical procedure for the City when evaluating sight triangles is to use the methodologies found in *A Policy on Geometric Design of Highways and Streets 7th Edition* (Green Book) developed by the American Association of State Highway Transportation Officials (AASHTO). The typical design parameters from the Green Book for a sight triangle at a two-way stop-controlled intersection (Case B) states that drivers typically stop their vehicles 6.5 ft from the edge of the traveled way. The driver's eye location is also typically 8.0 ft behind the front bumper of the vehicle. Therefore, the driver's eye location should be, at a minimum, 14.5 ft behind the edge of the nearest traveled-way. Figure 1 shows a typical sight triangle evaluation for a major two-way stop-controlled intersection in Laramie with a design speed of 30 mile per hour. The "nearest traveled-way" in the case of Figure 1 is the bicycle lane. Approximately five on-street parking spaces need to be removed at the intersection shown in Figure 1 when using the 30 mph ISD value from the Green Book (290 ft), and setting the driver's eye 14.5 feet behind the bike lane.

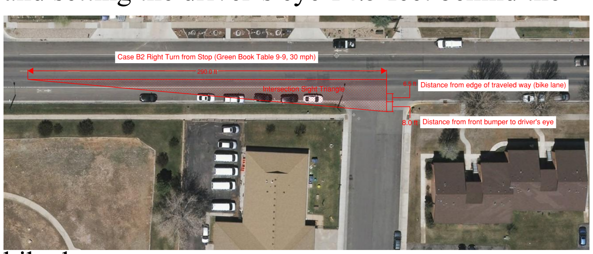

Figure 1 Intersection in Laramie, WY Evaluated with Typical Sight Triangle Dimensions, as per the Green Book

Residents and business owners who operate in the City of Laramie have expressed concern about the loss of on-street parking due to increased enforcement of sight triangles at major existing intersections. This has prompted the City's engineering staff to reevaluate the sight triangle process and to determine alternative solutions within the bounds of the Green Book. There are a few variables of a sight triangle evaluation that can be changed to reduce the impact to on-street parking:

- Reduce the assumed vehicle speed of the vehicle traveling on the major leg (major vehicle);
- Reduce the distance the vehicle on the minor leg (minor vehicle) is located when stopped; or
- Reduce the typical gap acceptance for the minor vehicle.

The purpose of this project was to evaluate local gap acceptance behavior at two-way stop-controlled intersections. If typical gap acceptance around the City of Laramie is less than Green Book recommendations, sight triangles could be reduced to provide more on-street parking while also maintaining a safe and efficient intersection.

NCHRP Report 383 Intersection Sight Distance

The Green Book gap acceptance recommendations for intersections are based on the National Cooperative Highway Research Program (NCHRP) Report 383, Intersection Sight Distance published in 1996. The report evaluates the previous policy for safe sight distance at intersections and recommends the method that is used today. Although the NCHRP report makes recommendations for all types of intersection control, this City of Laramie study will focus on the ISD policies and recommendations for the gap acceptance model at two-way stop-controlled (TWSC) intersections.

Gap Acceptance Model

The gap acceptance model relies on a simple equation for sight distance calculations based on gaps available to vehicles on the minor road at a TWSC, shown in Equation 1.

Equation 1 Gap-Acceptance Equation

$$ISD = 1.47 * V * G$$

where:

ISD = Sight Distance (ft)
V = Major-Road Design Speed (mph)
G = Specified critical gap (sec)

The critical gap in the equation needs to be observed in the field for the most accurate results. In previous research, this had been done by surveying a group of people at stop-controlled intersection, asking them which gaps they would accept and which gaps they would reject. Using this methodology, previous studies have shown that critical gaps range between 6 and 7 seconds (Harwood, Mason, Brydia, Pietrucha, & Gittings, 1996).

Field Study Results

Data collection for was done at thirteen TWSC in three different states: Illinois, Missouri, and Pennsylvania.

The study evaluated two methods to determine the appropriate critical gap time from these observations: the Raff method and the logistic regression method.

The Raff method involves determining the cumulative distribution percentages of both the rejected gaps and the accepted gaps. When the cumulative distribution graph of the rejected gaps and accepted gaps are superimposed, the intersection point is considered the critical gap, t_c (Figure 2).

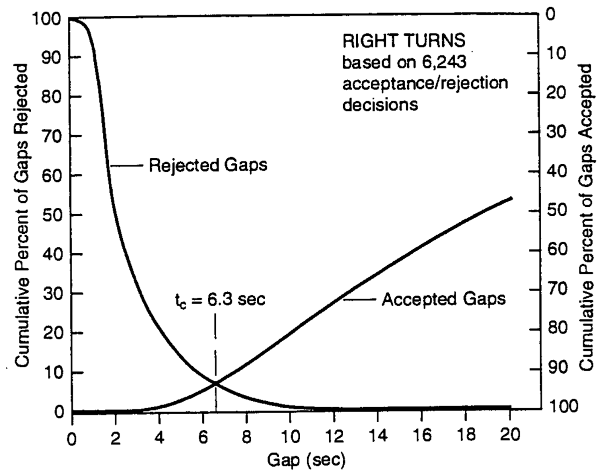

Figure 2 The Raff Method for Right Turning Vehicles (Harwood, Mason, Brydia, Pietrucha, & Gittings, 1996)

The Raff method states that the critical gap for gap acceptance is at the point where the percentage of gaps larger than the critical gap is equal to the percentage of accepted gaps smaller than the critical gap. In the case of Figure 2, approximately 8% of vehicles from the study rejected a gap larger than 6.3 seconds, and 8% of vehicles accepted a gap smaller than 6.3 seconds.

The next method used in determining the critical gap from field data was the logistic regression method. A logistic regression is a statistical method used to determine the probability that an event will or will not occur. In this case, the probability that a gap will be accepted by a minor vehicle at a stop sign. When logistic regression is applied to the data, a predictive equation (Equation 2) was produced for vehicles turning right. The critical gap is calculated by determining the gap acceptance P=0.5. In Equation 2, inputting P=0.5 gives a critical gap (t_{50}) of 6.5 seconds. Figure 4 shows the graph produced from Equation 2.

Equation 2 Gap Logistic Regression Equation for Right Turning Vehicles (Harwood, Mason, Brydia, Pietrucha, & Gittings, 1996)

$$\ln\left(\frac{P}{1-P}\right) = -4.75 + 0.730X$$

Where:

P = probability that a gap of length X will be accepted

X = gap (sec)

Final Recommendations

The NCHRP report concluded that the gap acceptance model results provided an easy to understand method for ISD calculations, and the final ISD values from this method are conservative for design. The final recommendations from the report for gap acceptance at a TWSC intersection is 7.5 seconds for vehicles turning left and vehicles turning right. This is in line with observed driver behavior for left turn vehicles, and it provides a 1.0 to 1.8 second margin of safety for right turn vehicles.

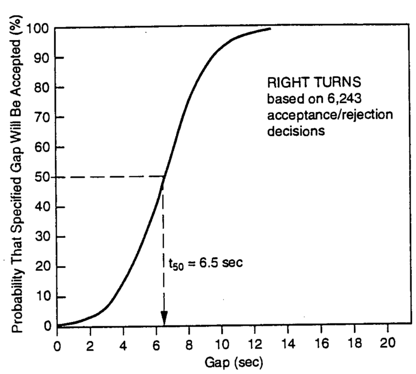

Figure 3 Logistic Regression for Right Turning Vehicles (Harwood, Mason, Brydia, Pietrucha, & Gittings, 1996)

Study Methodology

The methods used in this study closely resemble the methods used in NCHRP Report 383, with the exception of using a drone hovering above the intersection to capture video instead of cameras on the ground.

Study Intersections

The TWSC intersections for this study were selected based on the following criteria:

- Two of the legs must have a functional classification of "collector" or "arterial";
- The major movement on the major legs of the intersection must be the crossing movement;
- All legs must be two-lane streets; and
- Pavement type must be asphalt

Five intersections were selected across the City of Laramie which met all these criteria:

- 4th Street & Clark Street
- 9th Street & Spring Creek Drive
- 17th Street & Spring Creek Drive
- 22nd Street & Reynolds Street
- 22nd Street & Sheridan Street

Video Collection

The intersection observation at each intersection was recorded during the AM and PM peak periods using a DJI Phantom 4 Pro drone. Using a drone is an inconspicuous way to observe and record driver behavior at intersections. Collection by drone is similar to the practice of hiding a radar device when conducting a speed study. The drone's maximum video recording capabilities are at 1080p resolution and 60 frames per second (FPS). This is ideal for the video analysis later in the process. The higher FPS allows for fine tuning of the time stamp when major vehicles enter the intersection and when minor vehicles start to leave their stopped position. For each collection period, the drone was flown directly above the center of the intersection, usually between 150 ft and 200 ft above ground level (AGL). Weather conditions needed to be ideal for flying over intersections, which meant the wind had to be relatively calm, and snow could not be accumulated on the ground.

There are disadvantages to using a drone for data collection as opposed to cameras on the ground, like in NCHRP 383. When a drone is in the air, there needs be a pilot observing it at all times which increases the number of hours required to collect data by a person. The drone's battery life is also a limiting factor in video collection. The drone used for this study could only record high quality video for 10 to 15 minutes per battery depending on conditions. Also, the battery change could take 5 to 10 minutes depending on the distance between the intersection and the landing area. This means that the entirety of peak period intervals were not collected as a whole, but instead peak period intervals were sampled for 10-15 minutes with 5-10 minute omissions for maintenance.

In total, 6.5 hours of video was recorded over all study intersections. The intersections were recorded during their AM and PM peak periods when the weather conditions were optimum. Table 1 shows the break down on when each intersection was flown and recorded.

Table 1 Video Recording Summary

Intersection	Dates	Recording Time
4th Street and Clark Street	4/16/2019; 10/21/2019	1 Hour 16 Minutes
9th Street and Spring Creek Drive	10/24/2019	1 Hour 8 Minutes
17th Street and Spring Creek Drive	11/13/2019; 11/15/2019	1 Hour 7 Minutes
22nd Street and Reynolds Street	10/25/2019	1 Hour 26 Minutes
22nd Street and Sheridan Street	11/4/2019; 11/5/2019	1 Hour 36 Minutes
	Total=	**6 Hours 33 Minutes**

Video Analysis

The analysis was completed using the same method outlined in NCHRP 383. VLC Media Player was used with the Time v3.2 extension to record specific times in each video, called time stamps. The extension is important because it displays the time stamp of the video with millisecond precision. Going frame-by-frame in a 60 FPS video equates to 0.017 seconds for each frame advance. For each minor vehicle that approaches the intersection, the following time stamps are recorded:

1. Time when the minor vehicle stops
2. Time when the first major vehicle crosses in front of minor vehicle
3. Time when next major vehicle crosses in front of minor vehicle
4. Repeat step three if minor vehicle does not enter the intersection
5. Time when the minor vehicle starts to accelerate away from their stopped position

There are four types of gap acceptance times that were recorded: lag accept, lag reject, gap accept, and gap reject. "Lag" is the time measured between the timestamp of the minor vehicle's stop and the timestamp of when the first major vehicle intersects the front of the stopped minor vehicle across the intersection. If the driver stops at the intersection and decides to enter the intersection, without waiting for a major vehicle, that would be recorded as a "lag accept". If the driver decides to wait for a gap, the time it takes for a major vehicle to cross in front of the minor vehicle is recorded as a "lag reject". "Gap" is measured between the rear bumper of the first major vehicle and front bumper of the next major vehicle. Similar to NCHRP 383, lag and gap values were not recorded if the major vehicle turned left or right at the intersection.

Once all intersections were collected, and all four types of gap acceptance were recorded, the Raff method and logistic regression method from NCHRP 383 were applied to determine the final recommended ISD values for each type of movement.

Results

All intersection data were combined into one data set to determine recommended ISD values for the City as a whole. The results for the study are split into two parts: the Raff method and the logistic regression method.

Raff Method Results

The data was separated by turning movement, and a cumulative distribution of accepted gaps/lags and rejected gaps/lags were overlaid. Figure 4 shows the Raff method results for left turning vehicles, Figure 5 shows the results for crossing vehicles, and Figure 6 shows the results for right turning vehicles.

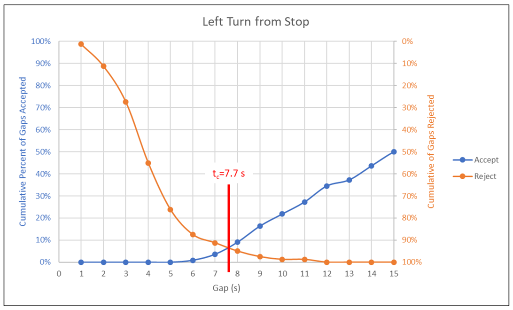

Figure 4 Raff Method Results Left Turn from Stop

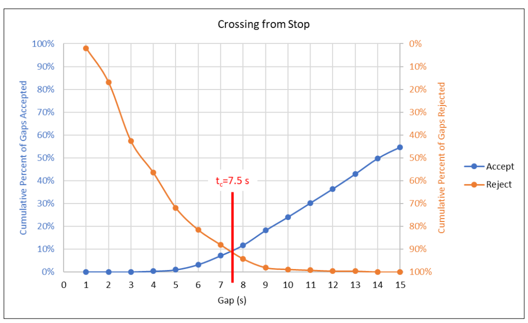

Figure 5 Raff Method Results Crossing from Stop

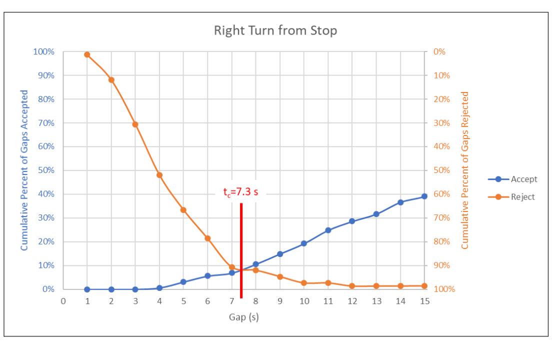

Figure 6 Raff Method Results Right Turn from Stop

The Raff method states that the critical gap acceptance is at the point where the two cumulative distributions meet. Similar to the results from NCHRP 383, the "left turn from stop" critical gap is the longest gap of the three movements, and the "right turn from stop" critical gap is the shortest. However, all three recommended gaps were within 0.4 seconds of each other, which is not in line with NCHRP 383, which states that the observed "right turn from stop" critical gap should be 1.0 to 1.8 seconds shorter than the "left turn from stop" gap.

Logistic Regression Results

All intersection data was separated by movement direction, and each gap/lag was given a value of "1" if it was accepted, and "0" if it was rejected. These table of values were used in the statistical program "R" to determine a logistic regression equation for each movement. The resulting equations are shown below. Figure 7 shows the three logistic equations plotted next to each other.

Equation 3 Logistic Regression Equation Left Turn from Stop

$$\ln\left(\frac{P}{1-P}\right) = -5.9590 + 0.8537X$$

Equation 4 Logistic Regression Equation Crossing from Stop

$$\ln\left(\frac{P}{1-P}\right) = -6.3969 + 0.8645X$$

Equation 5 Logistic Regression Equation Right Turn from Stop

$$\ln\left(\frac{P}{1-P}\right) = -4.4070 + 0.62484X$$

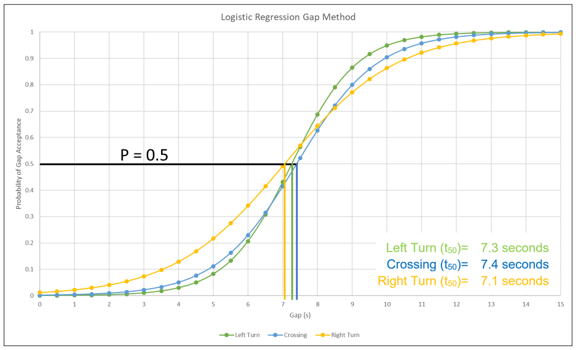

Figure 7 Logistic Regression Results

Results from this gap acceptance study show that left-turn and crossing match very closely to Green Book recommendations, within 0.2 seconds. The critical gap acceptance that was measured for right-turn vehicles around the City of Laramie was between 0.6 and 0.8 seconds longer than Green Book recommendations.

Conclusion

The purpose of this study was to determine what methods are available to reduce sight distance requirement around TWSC intersections. Sight distance at intersections severely reduces on-street parking around the intersection, which is relied upon by residents and local businesses. Similar to previous studies on gap acceptance, the right-turn critical gap was the shortest out of all three measured. Table 2 shows a summary of the results from the Raff method and the Logistic Regression method compared to the current Green Book recommendations.

Table 2 Gap Acceptance Result Summary

	Green Book 8th Edition (s)	Raff Method Laramie (s)	Logistic Regression Laramie (s)
Left Turn	7.5	7.7	7.3
Crossing	7.5	7.5	7.4
Right Turn	6.5	7.3	7.1

Overall, the drone methodology used in this study was very effective in discretely recording driver behavior, and the results from this study closely match the recommendations from the Green Book. The City will continue to use drones to monitor and analyze sensitive intersections that rely on on-street parking in the future. By following Green Book recommendations for

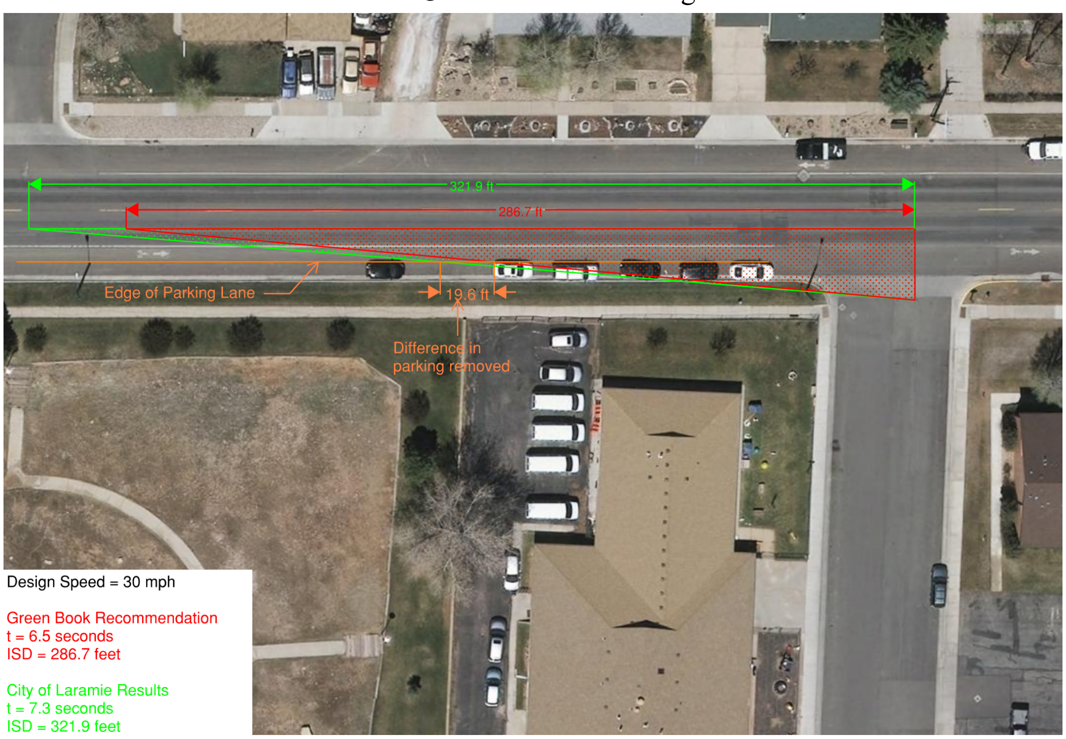

Figure 8 Laramie Gap Acceptance Results and Green Book Recommendation

most intersections, the City of Laramie may be saving some of parallel parking on the left side of intersections compared to the observed gap acceptance behavior. The 0.8 second difference between observed minor vehicle right turn driver behavior and Green Book recommendations equates to approximately 20 ft of parking saved on the left side of a typical intersection in the City of Laramie. Figure 8 shows the difference between Green Book recommendations and the results from the City of Laramie study. The City engineering division will continue to use the Green Book with added confidence that the amount of parking removed is at a minimum while still maintaining safe and efficient two-way stop-controlled intersections.

References

American Association of State Highway and Transportation Officials. (2018). *A Policy on Geometric Design of Highways and Streets.*

Harwood, D. W., Mason, J. M., Brydia, R. E., Pietrucha, M. T., & Gittings, G. L. (1996). *NCHRP Report 383 Intersection Sight Distance.* Washington, D.C.: National Academy Press.