Evaluation of Left-Turn Lane Offset Using the Naturalistic Driving Study Data

Jessica M. Hutton (Corresponding Author)
Senior Traffic Engineer
MRIGlobal
425 Volker Boulevard
Kansas City, MO 64110
Telephone: (816) 360-5482
Fax: (816) 753-8420
e-mail: jhutton@mriglobal.org

Karin M. Bauer
Principal Statistician
MRIGlobal
425 Volker Boulevard
Kansas City, MO 64110
Telephone: (816) 360-5287
Fax: (816) 753-8420
e-mail: kbauer@mriglobal.org

Chris A. Fees
Staff Traffic Engineer
MRIGlobal
425 Volker Boulevard
Kansas City, MO 64110
Telephone: 816-326-5435
Fax: (816) 753-8420
e-mail: cfees@mriglobal.org

Dr. Alison Smiley
President
Human Factors North, Inc.
174 Spadina Ave
Suite 202
Toronto ON
M5T 2C2
Telephone: (416) 596-1252
Fax: (416) 596-6946
e-mail: asmiley@hfn.ca

Word Count: 4,600 words + 12 tables and figures = 7,600 words
Submitted to the Transportation Research Board for Presentation and Publication
November 14, 2014
ABSTRACT

The SHRP 2 Naturalistic Driving Study (NDS) data were used to evaluate the gap acceptance behavior of drivers at left-turn lanes with offsets ranging from −29 ft to 6 ft. The study included 3,350 gaps evaluated (accepted or rejected) by 145 NDS drivers and 275 non-NDS drivers (whose turns were visible from the in-vehicle camera of an NDS driver) at 14 two-way stop-controlled intersections and 44 signalized opposing left-turn pairs. Logistic regression was used to model the critical gap length for drivers as a function of offset, under conditions when their view was either blocked by an opposing left-turning driver or not. The analysis found that the critical gap was longer for negative offsets than for zero or positive offsets, and also longer when sight distance was blocked by an opposing left-turning driver than when it was not. These longer gap lengths can result in decreased operational efficiency of an intersection. Sight distance was much more likely to be restricted by an opposing left-turning driver at negative-offset intersections than at zero- or positive-offset intersections, and drivers at negative-offset intersections were less likely to accept a gap when an opposing left-turn driver was present. An analysis of the shortest post-encroachment times showed that while drivers making left-turns at negative-offset left-turn lanes wait to accept longer gaps, they are, on average, also more likely to leave the shortest amount of time between their turn and the arrival of the next opposing through vehicle, which may present a potential safety concern.
INTRODUCTION

Objective
The objective of this research was to evaluate the safety effect of left-turn lane offset on gap-acceptance behavior using in-vehicle video data from the Naturalistic Driving Study (NDS) recently collected by the Strategic Highway Research Program 2 (SHRP 2). The video data were used to measure the time length of accepted and rejected gaps by study drivers (NDS) and non-study drivers (non-NDS) visible in the video making left turns through intersections with varying left-turn offsets. The video data were also used to collect several other variables related to left-turn behavior.

The specific research questions addressed were:

1. Do intersection approaches with negative offsets, zero offsets, and positive offsets for opposing left-turn vehicles differ from one another in the gap acceptance behavior of left-turning drivers considering the following measures: critical gap ($t_c$ or $t_{50}$), percentage of drivers accepting lags of specific durations less than $t_c$ or $t_{50}$, and rate of occurrence for erratic maneuvers during left turns?

2. Do intersection approaches with negative offsets, zero offset, and positive offsets for opposing left-turn vehicles differ in gap-acceptance behavior (using the same measures as for Question 1) between times when opposing left-turn vehicles are present (and potentially block the view of oncoming through traffic for both left-turning drivers) and times when no opposing left-turn vehicle is present (so that the driver’s view of oncoming through traffic is not blocked)?

Figure 1 provides an illustration of negative-, zero-, and positive-offset left turn lanes. Red arrows indicate the extent of offset.

![Figure 1. Illustration of Intersection Left-Turn Lanes With Negative Offset, Zero Offset, and Positive Offset](image-url)
Background

Approximately 20 percent of all traffic fatalities occur at intersections (1). While only about 10 percent of intersections are signalized, one-third of the intersection fatalities occur at signalized intersections. Angle collisions involving vehicles crossing each other’s paths tend to be some of the most severe crashes at intersections; they make up over 40 percent of fatal crashes at signalized intersections. About half of these crashes are left-turn crashes. FARS data for 2009 show that left-turn collisions constitute 8.5 percent of all traffic fatalities (1). A substantial proportion of these fatalities occur when a turning driver’s view of oncoming opposing through traffic is limited by the presence of another left-turning vehicle in the opposing left-turn lane, as shown in Figure 2.

Figure 2. Illustration of Sight Obstruction Caused by an Opposing Left-turning Vehicle

Left-turn lanes are used at intersections to provide a safe location for storing left-turning vehicles, out of the through traffic lanes, while their drivers wait for a suitable gap in opposing traffic to turn left. The provision of a left-turn lane minimizes the potential for rear-end collisions with through vehicles approaching from behind the left-turning vehicle.

Highway medians, especially wider medians, are desirable in part because they generally have a positive effect on road safety by providing greater separation between traffic traveling in opposite directions. However, wider medians may create safety concerns at intersections with conventional left-turn lanes, as vehicles in the opposing left-turn lanes may block one another’s views of oncoming through traffic.

The AASHTO Green Book (2), as well as the two NCHRP 500 Series Guides focused on intersections (3, 4), recommend using offset left-turn lanes but provide no guidance on the desirable amount of offset or the effectiveness of implementing such a strategy. Several studies have provided guidance on desirable offset, but these have used physical models to estimate driver behavior rather than empirical measurements of behavior (5,6,7).
A more recent Empirical Bayes before-after study evaluating the safety effect of left-turn lane offset improvements at 117 signalized intersections in Florida, Nebraska, and Wisconsin showed mixed results between states. While in Wisconsin the treatment included major reconstruction to provide a positive offset, the implementations in Florida and Nebraska typically used striping treatments to narrow or shift the left-turn lane to provide offsets that were slightly less negative. The treatments in Wisconsin were found to reduce all crashes by 34 percent, injury crashes by 36 percent, and left-turn crashes by 38 percent, while the treatments in Florida and Nebraska showed no crash reduction. The study did not provide offset measurements at each intersection before and after the improvement, and no analysis was performed to evaluate the degree of offset that would result in improved safety (8).

Application of the NDS Data to the Evaluation of Offset Left-Turn Lanes

Safety studies have traditionally used historical crash data to evaluate the effect of a given countermeasure by comparing crashes before and after its implementation. However, a desire to provide countermeasures proactively, rather than only after a crash pattern develops, requires that designers anticipate the likelihood of crashes before they happen. Previous studies that have used various measures of left-turn behavior as safety surrogates in place of a crash analysis have used either fixed cameras at a limited number of locations (often only one intersection), driving simulators, or fixed driving courses with an evaluator in the car with the study participant. In the first case, the study is limited in the range of offsets that can be evaluated, and in the second and third cases, it is unlikely that the driver’s behavior is truly naturalistic.

The NDS data provide not only data from truly naturalistic driving maneuvers, but also an opportunity for researchers to bypass field data acquisition and go straight to data reduction and analysis. Because study drivers traveled through so many intersections, data are available for a very large number of potential study sites. The NDS data also provide the opportunity to see the traffic conditions from the driver’s perspective. Other studies that have evaluated sight obstructions related to opposing left-turn lanes have simply used the presence of an opposing left-turn vehicle as a surrogate for sight distance restrictions, or used physical models to calculate sight distance based on assumptions about each driver’s position. In contrast, the NDS data (including video recorded through the windshield of the vehicle to show the driver’s view) allowed the video data analyst to record whether an individual driver’s view was obstructed by an opposing driver during each accepted or rejected gap.

DATA COLLECTION

Data used for the study included intersection characteristics from the Roadway Inventory Database (RID), visual inspection of aerial and street-view images from Google Earth and ArcGIS maps; environmental characteristics during turning maneuvers of interest observed in NDS video files; NDS driver demographic data; and time-series data related to the trip from the in-vehicle data recorders.

Intersection Selection

Figure 3 illustrates the procedure used to select intersections for inclusion in the study. The figure shows six action steps, each describing a data request or filter. The figure also shows the number of signalized and stop-controlled intersections remaining in the database after each step. The Center for Transportation Research and Education (CTRE) at Iowa State developed and maintained the roadway inventory database (RID) associated with heavily traveled routes in the
Hutton et al.

NDS for SHRP 2. They provided us with an extensive list of intersections that met basic criteria (four intersection approaches, at least two approaches with a single left-turn lane, and no more than two through lanes, with either two-way stop control or signal control). The list was substantially reduced as we began filtering for other desirable characteristics, such as no sight restrictions due to intersection geometry, a broad distribution of left-turn offset values, and, most importantly, a sufficient number of NDS drivers making left-turn maneuvers from approaches of interest. In the end, the research team identified 44 left-turn pairs at 33 signalized intersections and 14 stop controlled intersections for inclusion in the analysis.

Figure 3. Flow Chart of Intersection Selection Procedure

Video Data Reduction
The NDS data requested included video clips from NDS drivers making left turns at the intersection approaches chosen for the study. The video was taken from a forward-facing camera attached to the rear-view mirror and facing out of the windshield, and from a rear-facing camera facing out of the rear windshield, showing what the driver might see. (While the video showed the available view, there was no indicator of exactly where the driver was looking at the time.) A
user interface was designed using LabVIEW software to synchronize the viewing of forward- and rear-facing videos, provide the video analysts with a more efficient method of data collection, standardize the input for the variables we collected, and automate database population. A screen shot of this tool is shown in Figure 4.

![Figure 4. Video Data Reduction User Interface](image)

Three video analysts from the research team reviewed and recorded data for over 1,000 videos of turns made by NDS drivers. The variables recorded from the videos included some that were specific to the turning event and had only one value for the entire video, such as the NDS vehicle arrived in the queue, the number of vehicles in the queue, the time the signal turned green, and the time that the intersection could no longer be seen in the rear video. The event-level variables were those recorded for every gap that was visible in the video, whether rejected or accepted, by either an NDS study driver, or a non-NDS vehicle whose behavior could be observed from the study vehicle. Variables included information about the gap length, whether the gap was accepted, when the turn was initiated if the gap was accepted, which vehicle accepted the gap, if there was a driver behind the vehicle judging the gaps, and if the driver’s view was obstructed by an opposing left-turning vehicle.

**Safety Surrogates**

The surrogates that were used for this study were measured from the video data, and included:

- Gap length—the end gap time minus the start gap time. A gap ended when either the next opposing through vehicle arrived at the intersection (crossed the stop bar) or the left-turn signal turned red.
Post-encroachment time (PET)—the time between the start of left turn and the time the next opposing vehicle reached the stop bar on its approach to the intersection. Note that the post-encroachment time measurements in this study are slightly different than those described in the literature due to limitations of what can be viewed in the NDS videos. The measure is designed to closely approximate that described in the literature.

These variables are illustrated in Figure 5. The frequency of near crashes and crash avoidance maneuvers were also included as safety surrogates.

The research team also requested demographic information for each video of the NDS driver making the left turn. The difference in gap acceptance behavior between men and women, and among age groups, was evaluated for NDS drivers.

- **Time $T_0$:** First opposing through vehicle reaches the stop bar after the study vehicle arrives
- **Time $T_1$:** Next opposing through vehicle reaches the stop bar
- **Time $T_2$:** Turn is initiated by study driver
- **Time $T_3$:** First opposing through vehicle reaches the stop bar after the study vehicle makes the left turn

$T_0$, $T_1$, and $T_2$ are viewed in the forward-facing camera

$T_3$ is estimated from forward camera or viewed in rear camera

Rejected gap length = $T_1 - T_0$

Accepted gap length = $T_3 - T_1$

Post-encroachment time (PET) = $T_3 - T_2$

**Figure 5. Illustration of the Measurement of Surrogate Safety Variables**

**Descriptive Statistics**

Number of trips, events, and accepted gaps for NDS and non-NDS drivers are shown, separately for each offset category, in Table 1.
Table 1. Trip and Event Statistics by Intersection Type and Offset Category

<table>
<thead>
<tr>
<th>Offset Category</th>
<th>Total Events</th>
<th>Number of Drivers</th>
<th>Number of Trips</th>
<th>Number of Measured Accepted Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NDS</td>
<td>Non-NDS</td>
<td>NDS</td>
</tr>
<tr>
<td><strong>Signalized Intersections</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) –16 ft or less</td>
<td>196</td>
<td>5</td>
<td>8</td>
<td>19</td>
</tr>
<tr>
<td>(b) –11 to –15 ft</td>
<td>100</td>
<td>15</td>
<td>20</td>
<td>54</td>
</tr>
<tr>
<td>(c) –6 to –10 ft</td>
<td>225</td>
<td>24</td>
<td>19</td>
<td>46</td>
</tr>
<tr>
<td>(d) –1 to –5 ft</td>
<td>594</td>
<td>35</td>
<td>30</td>
<td>79</td>
</tr>
<tr>
<td>(e) 0 ft</td>
<td>618</td>
<td>39</td>
<td>62</td>
<td>149</td>
</tr>
<tr>
<td>(f) 1 to 3 ft</td>
<td>234</td>
<td>21</td>
<td>50</td>
<td>76</td>
</tr>
<tr>
<td>(g) 4 to 6 ft</td>
<td>98</td>
<td>21</td>
<td>20</td>
<td>29</td>
</tr>
<tr>
<td>All signalized</td>
<td>2,065</td>
<td>160</td>
<td>209</td>
<td>452</td>
</tr>
<tr>
<td><strong>Two-way Stop-Controlled Intersections</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) –16 ft or less</td>
<td>45</td>
<td>4</td>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>(b) –11 to –15 ft</td>
<td>932</td>
<td>21</td>
<td>53</td>
<td>194</td>
</tr>
<tr>
<td>(c) –6 to –10 ft</td>
<td>201</td>
<td>9</td>
<td>8</td>
<td>66</td>
</tr>
<tr>
<td>(e) 0 ft</td>
<td>107</td>
<td>10</td>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>All two-way stop-</td>
<td>1,285</td>
<td>44</td>
<td>66</td>
<td>306</td>
</tr>
<tr>
<td>controlled</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>All Intersections</strong></td>
<td>3,350</td>
<td>204</td>
<td>275</td>
<td>758</td>
</tr>
</tbody>
</table>

Prior to analysis, the distribution of available and accepted gap lengths was assessed across the various offset categories for each intersection type. This evaluation found that available gap length is relatively evenly distributed across offset categories. It was a concern of the research team that the magnitude of available gap lengths might be confounded with offset category; this would have made the study of the effect of offset on gap acceptance behavior difficult. However, this concern did not arise.

In all cases where gap length could be recorded in the videos (1,669 events across both intersection types), a vehicle in the opposing left-turn lane was blocking the NDS driver’s view in 326 cases (approximately 20 percent of all cases studied). Table 2 shows the percentage of events for which an opposing left-turning vehicle was present; the percent of events for which the NDS driver’s view was blocked by the opposing vehicle; and the percent of cases in which an opposing vehicle was present and it actually obstructed the NDS driver’s view of oncoming traffic.
is defined as the and rejected gap durations of accepted and an indication of its acceptance or rejection by the left view was blocked or the left driver’s view was blocked. The table also shows that the percent of evaluated gaps at signalized intersections with an offset of −16 ft or less, this percentage dropped to only 7 percent when considering only accepted gaps. This indicates that drivers tended to wait until their view was no longer obstructed before accepting a gap.

### STATISTICAL METHODOLOGY

This research sought to answer two main questions: (1) does the amount of left-turn lane offset affect gap-acceptance behavior (specifically the critical gap length)? and (2) does the presence of an opposing left-turn driver affect driver behavior when turning left at an intersection?

The primary statistical analysis approach chosen in this study is driven by the two main measurements recorded from the videos: the duration (recorded in seconds) of each available gap and an indication of its acceptance or rejection by the left-turning driver. The durations of accepted gaps represent crash risks judged acceptable by the left-turning driver while the durations of rejected gaps represent crash risks judged unacceptable by the left-turning driver.

The analysis of choice was logistic regression analysis in which the distributions of the accepted and rejected gap durations are analyzed to establish the critical gap duration ($t_c$). The critical gap is defined as the gap that is equally likely to be accepted or rejected.

### Table 2. Sight Obstruction Statistics

<table>
<thead>
<tr>
<th>Offset Category</th>
<th>Available Gaps</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percentage of Events When an Opposing Vehicle is Present</td>
<td>Percentage of Events When Driver’s View is Blocked</td>
<td>Ratio of Driver’s View Blocked to Opposing Vehicle Present</td>
<td>Percentage of Events When an Opposing Vehicle is Present</td>
<td>Percentage of Events When Driver’s View is Blocked</td>
<td>Ratio of Driver’s View Blocked to Opposing Vehicle Present</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signalized Intersections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) −16 ft or less</td>
<td>34.7</td>
<td>30.1</td>
<td>86.8</td>
<td>7.4</td>
<td>7.4</td>
<td>100.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) −11 to −15 ft</td>
<td>25.0</td>
<td>12.0</td>
<td>48.0</td>
<td>23.0</td>
<td>8.1</td>
<td>35.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c) −6 to −10 ft</td>
<td>48.0</td>
<td>44.9</td>
<td>93.5</td>
<td>32.8</td>
<td>25.0</td>
<td>76.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d) −1 to −5 ft</td>
<td>26.1</td>
<td>23.6</td>
<td>90.3</td>
<td>24.1</td>
<td>18.5</td>
<td>76.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e) 0 ft</td>
<td>26.5</td>
<td>3.9</td>
<td>14.6</td>
<td>21.3</td>
<td>4.7</td>
<td>22.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(f) 1 to 3 ft</td>
<td>35.5</td>
<td>3.0</td>
<td>8.4</td>
<td>34.9</td>
<td>3.2</td>
<td>9.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(g) 4 to 6 ft</td>
<td>21.4</td>
<td>3.1</td>
<td>14.3</td>
<td>30.6</td>
<td>4.1</td>
<td>13.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-Way Stop-Controlled Intersections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) −16 ft or less</td>
<td>4.4</td>
<td>0.0</td>
<td>0.0</td>
<td>9.5</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) −11 to −15 ft</td>
<td>7.8</td>
<td>6.4</td>
<td>82.2</td>
<td>8.7</td>
<td>7.5</td>
<td>85.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c) −6 to −10 ft</td>
<td>23.9</td>
<td>18.9</td>
<td>79.2</td>
<td>9.6</td>
<td>8.2</td>
<td>85.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e) 0 ft</td>
<td>9.3</td>
<td>0.0</td>
<td>0.0</td>
<td>3.3</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All Intersections Combined</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative offset</td>
<td>20.9</td>
<td>17.9</td>
<td>85.6</td>
<td>15.8</td>
<td>11.2</td>
<td>70.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero offset</td>
<td>24.0</td>
<td>3.3</td>
<td>13.8</td>
<td>19.1</td>
<td>4.1</td>
<td>21.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive offset</td>
<td>31.3</td>
<td>3.0</td>
<td>9.6</td>
<td>33.7</td>
<td>3.4</td>
<td>10.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Columns 2 and 5 in Table 2 show that the percent of events in which the driver’s view of opposing through traffic is obstructed is substantially higher at negative-offset left-turn lanes than at zero or positive offsets. The table also shows that the percentage of accepted gaps where the driver’s view is blocked (Column 6) was, in general, much lower than the same percent of all available gaps (Column 3), especially at left-turn lanes with negative offsets at signalized intersections. For example, while a driver’s view was blocked during 30 percent of evaluated gaps at signalized intersections with an offset of −16 ft or less, this percentage dropped to only 7 percent when considering only accepted gaps. This indicates that drivers tended to wait until their view was no longer obstructed before accepting a gap.
The logistic regression analysis consists of modeling the relationship between the probability of accepting or rejecting a gap of a given length and the length of the gap and the left-turn offset distance. The basic relationship can be expressed in the form of a logistic function as follows:

\[ P(Y = 1|X) = \frac{1}{1+e^{-(\beta_0 + \beta_1 X + \beta_i I_i)}} \]  

(1)

where:

\[ P(Y=1|X) = \text{probability of accepting a gap of given length X} \]

\[ X = \text{gap length (sec)} \]

\[ I_i = \text{indicator variable for the categorical offset parameter (covariate)} \]

\[ \beta_0 = \text{overall intercept} \]

\[ \beta_1 = \text{common slope on } X \]

\[ \beta_i = \text{parameter representing the deviation of offset category } I_i \text{ intercept from the overall intercept, } i=1 \text{ to } k, \text{ where } k \text{ is the number of offset categories in the model} \]

\[ \beta_0, \beta_1, \beta_i = \text{regression coefficients estimated by maximum likelihood method} \]

By calculating the logit of P [i.e., the (natural) log odds of the outcome] and modeling it as a linear function of the gap length, Equation (1) is then linearized to read:

\[ logit(P) = ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 X + \beta_i I_i \]  

(2)

The model in Equation (2) assumes that the regression lines in the groups defined by offset categories are parallel. This assumption of parallel slopes was first tested by including an interaction term between offset category and gap length into the model in Equation (2) as follows:

\[ logit(P) = ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 X + \beta_i I_i + \delta_i X \]  

(3)

where:

\[ \delta_i = \text{parameter representing the deviation of offset category } I_i \text{ slope from the common slope, } \beta_1 \]

Either model then allows for estimating a number of gap lengths of interest, in particular, the gap length corresponding to a probability of 0.5, i.e., the critical gap length, t_{50}.

The overall offset effect is estimated by the significance level associated with the offset factor in the model, in other words, the significance of the coefficients \( \beta_i \) associated with the indicator variable \( I_i \). From the logit regression models, the critical gaps, t_{50}, and their 95-percent confidence intervals are estimated at each level of offset. These confidence intervals are then compared in a pairwise fashion to assess which offset category differs statistically from which other offset category with respect to critical gap. This final comparison is performed using a visual hypothesis testing method modified to take into account sample sizes and variability of the
data modeled in each group (Smith, 1997). In general, a 10-percent significance level was used to test for the significance of the regression coefficients. However, all confidence intervals were calculated as two-sided 95-percent confidence intervals.

RESULTS

Effect of Left-Turn Lane Offset on Critical Gap Length

Based on 1,671 events (269 accepted and 1,402 rejected gaps), the following results were obtained for signalized intersections:

- The interaction term between gap length and offset category is significant at the 10-percent level (p-value = 0.06)
- Offset is significant at the 10-percent level (p-value = 0.09)
- The slopes of the 7 regression curves are not parallel

Figure 6 shows the predicted probability that a gap is accepted for each offset category as a function of gap length.

![Figure 6. Predicted Probability of Accepting a Gap as a Function of Gap Length and Offset Category for Signalized Intersections](image)

Based on 1,126 events (207 accepted and 919 rejected gaps), the following results were obtained for two-way stop-controlled intersections:

- The interaction term between gap length and offset category was not significant at the 10-percent level thus a parallel lines logit model was assumed
- Offset is not significant (p-value = 0.94)
The results for both signalized and two-way stop-controlled intersections, along with the number of accepted and rejected gaps in each offset category, are shown in Table 3.

**Table 3. Critical Gap Estimates by Intersection Type and Offset Category**

<table>
<thead>
<tr>
<th>Traffic Control Type</th>
<th>Offset Category</th>
<th>Critical Gap Estimate (sec)</th>
<th>95% Confidence Limits (sec)</th>
<th>Number of Accepted Gaps</th>
<th>Number of Rejected Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signalized</td>
<td>(a) -16 ft or less</td>
<td>7.5</td>
<td>6.0</td>
<td>10.2</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>(b) -15 to -11 ft</td>
<td>6.1</td>
<td>4.4</td>
<td>12.0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>(c) -10 to -6 ft</td>
<td>6.5</td>
<td>5.6</td>
<td>8.0</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>(d) -5 to -1 ft</td>
<td>7.0</td>
<td>6.2</td>
<td>8.1</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>(e) 0 ft</td>
<td>6.2</td>
<td>5.7</td>
<td>6.9</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>(f) 1 to 3 ft</td>
<td>5.0</td>
<td>4.5</td>
<td>5.7</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>(g) 4 to 6 ft</td>
<td>4.7</td>
<td>3.8</td>
<td>6.3</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>All Signalized</td>
<td></td>
<td></td>
<td>269</td>
<td>1,402</td>
</tr>
<tr>
<td>Two-way stop</td>
<td>(a) -16 ft or less</td>
<td>4.8</td>
<td>3.4</td>
<td>6.2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(b) -15 to -11 ft</td>
<td>5.2</td>
<td>4.9</td>
<td>5.5</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>(c) -10 to -6 ft</td>
<td>5.2</td>
<td>4.7</td>
<td>5.9</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>(e) 0 ft</td>
<td>5.3</td>
<td>4.4</td>
<td>6.2</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>All two-way stop controlled</td>
<td></td>
<td></td>
<td>207</td>
<td>919</td>
</tr>
</tbody>
</table>

From each model, the critical gap length, $t_{50}$, and its 95%-confidence interval were estimated, separately for each offset category. The critical gap estimates were then compared between pairs of offset categories at signalized intersections only. The following pairs of offset categories are statistically significantly different with respect to $t_{50}$:

- -16 ft or less (7.5 sec) from 1 ft to 3 ft (5.0 sec) and from 4 ft to 6 ft (4.7 sec)
- -10 ft to -6 ft (6.5 sec) from 1 ft to 3 ft (5.0 sec)
- -5 ft to -1 ft (7.0 sec) from 1 ft to 3 ft (5.0 sec) and from 4 ft to 6 ft (4.7 sec)
- 0 ft (6.2 sec) from 1 ft to 3 ft (5.0 sec)

The analysis of critical gap by offset category for signalized intersections shows that, in general, the critical gap is longest for intersections with negative offset left-turn lanes and shortest for those with positive offset left-turn lanes. This is to be expected given that the intersection geometry of a left-turn lane with negative offset requires the turning vehicle to travel farther during the turning maneuver to clear the intersection. Positive offset left-turn lanes bring the turning vehicle closer to the opposing through lanes of traffic and, therefore, shorten the travel distance (and time) required to clear the intersection. In addition, it should be noted that the provision of positive offset reduces or eliminates the potential for opposing left-turn vehicles to block their respective driver’s view of opposing through vehicles, which allows drivers to more comfortably accept shorter gaps.

Since offset was not statistically significant for stop-controlled intersections, the critical gap estimates were not compared between pairs of offset categories. The number of observations available for two-way stop-controlled intersections was substantially lower than that for signalized intersections. In general, all offset categories showed similar critical gaps at two-way stop-controlled intersections. Larger sample sizes would be needed to better distinguish the gap acceptance behavior between offset categories at two-way stop-controlled intersections.
The effect of sight obstruction on the probability of gap acceptance at signalized intersections (all seven offset categories combined) and at two-way stop-controlled intersections (all four offset categories combined) was estimated as a function of gap length. The following results were obtained:

- The interaction term between gap length and sight obstruction was not significant at the 10-percent level in either of the two analyses thus parallel lines logit models were assumed.
- Sight obstruction had a significant effect on gap length for both intersection types:
  - Signalized intersections: $p$-value = 0.02
  - Two-way stop-controlled intersections: ($p$-value = 0.03)

The two pairs of regression curves are plotted in Figure 7.

**Figure 7. Predicted Probability of Accepting a Gap as a Function of Gap Length and Presence of Sight Obstruction for a) Signalized Intersections—All Offsets Combined and b) Two-Way Stop Controlled Intersections—All Offsets Combined**

The critical gap length, $t_{50}$, and its 95-confidence interval were estimated, separately for sight obstruction (present/absent) and intersection type. The results, along with the number of accepted and rejected gaps for each combination, are shown in Table 4. Although sight obstruction has an overall significant effect on the probability of gap acceptance over the range of available gaps in the study, the comparisons of the critical gaps between sight obstruction and no sight obstruction are inconclusive (i.e., there is not enough evidence to prove statistical significance of the difference between the two estimates.) This might seem contradictory at first but it should be noted that the logistic regression predicts probability of acceptance ($Y$-axis) as a function of gap length ($X$-axis). When comparing critical gaps, one uses inverse regression. Estimates and their confidence limits corresponding to a 0.5 probability ($Y$-axis) are computed on the gap length axis ($X$-axis). The steeper the curves, the more difficult it becomes to prove statistically significant differences on the $X$-axis by reverse regression.
Table 4. Critical Gap Estimates by Intersection Type and Presence of Sight Obstruction—All Offsets Combined

<table>
<thead>
<tr>
<th>Traffic Control Type</th>
<th>Is Sight Distance Obstructed?</th>
<th>Critical Gap Estimate (sec)</th>
<th>95% Confidence Limits (sec)</th>
<th>Significant Difference Between Obstruction and No Obstruction?</th>
<th>Number of Accepted Gaps</th>
<th>Number of Rejected Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signalized</td>
<td>Yes</td>
<td>7.5</td>
<td>6.6</td>
<td>8.5</td>
<td>No</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>6.4</td>
<td>6.0</td>
<td>6.9</td>
<td>No</td>
<td>243</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td></td>
<td></td>
<td></td>
<td>269</td>
<td>1,402</td>
</tr>
<tr>
<td>Two-Way Stop</td>
<td>Yes</td>
<td>6.4</td>
<td>5.3</td>
<td>7.6</td>
<td>No</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>5.1</td>
<td>4.8</td>
<td>5.4</td>
<td>192</td>
<td>853</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td></td>
<td></td>
<td></td>
<td>207</td>
<td>919</td>
</tr>
</tbody>
</table>

Although this analysis showed that the critical gaps for the two sight obstruction conditions are not statistically significantly different, in both cases, the critical gap when view is obstructed is longer than when view is unobstructed, by 1.1 sec at signalized intersections and by 1.3 sec at two-way stop-controlled intersections. These differences are somewhat smaller than those found by Yan and Radwan (2007). Their research showed a critical gap of 5.6 sec for drivers with unobstructed view vs. 7.7 sec for drivers with an obstructed view due to the presence of a left-turning driver (difference of 2.1 sec.)

Analysis of Short Gap Lengths and Post-Encroachment Times

The analyses presented thus far show that, on average, drivers wait to accept longer gaps where left-turn lanes are negatively offset, and when their view of opposing vehicles is obstructed. However, it is possible that the shortest accepted gaps are also taken in these conditions. That is, while many drivers wait for longer gaps when they don’t have a good view of the available gaps, a few drivers may accept gaps that are shorter than they would have otherwise chosen because they could not see how short the gap was. The research team investigated this possibility in two ways:

1. For each of the six combinations of offset (negative, zero, and positive) and sight obstruction (present/absent), the 1st, 5th-, 10th-, and 15th-percentile accepted gap lengths were estimated for comparison
2. The percentage of accepted gaps with a post-encroachment time less than 4, 3, 2, or 1 sec were calculated for each of the six offset and sight obstruction combinations

Table 5 shows that the 1st-, 10th-, and 15th-percentile accepted gaps were shorter at negative-offset left-turn lanes than at zero- or positive-offset left-turn lanes at both signalized and stop-controlled intersections. It also shows that a higher percentage of accepted gaps had post-encroachment times less than 2, 3, and 4 seconds at signalized intersections with negative offsets than at zero or positive offsets. These findings suggest that while the 50th percentile accepted gap length is generally longer at negative-offset left-turn lanes than at zero- or positive-offset left-turn lanes, there is also a higher likelihood that drivers will accept shorter gaps at negative-offset intersections. It appears that while on average, drivers at negative-offset left-turn lanes are more cautious and wait for longer gaps than drivers at other intersections, they are also more likely to leave a very short amount of clearance time between their turn and the arrival of the next opposing through vehicle than drivers at other intersections. Two possible explanations for
this are that 1) some drivers take short, risky gaps when their view is obstructed because they cannot properly assess the risk, and 2) that drivers may hesitate before initiating a left turn when their view is obstructed, resulting in less time between the turn and the arrival of the next opposing through vehicle.

<table>
<thead>
<tr>
<th>Offset Category</th>
<th>Number of Obs</th>
<th>Percentile</th>
<th>Percent of Observations with Post-encroachment Time Less Than:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1st</td>
<td>5th</td>
</tr>
<tr>
<td>Signalized Intersections</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative</td>
<td>114</td>
<td>-1.33</td>
<td>0.34</td>
</tr>
<tr>
<td>Zero</td>
<td>95</td>
<td>0.02</td>
<td>2.15</td>
</tr>
<tr>
<td>Positive</td>
<td>60</td>
<td>-1.50</td>
<td>1.17</td>
</tr>
<tr>
<td>Two-Way Stop-Controlled Intersections</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative</td>
<td>196</td>
<td>2.14</td>
<td>2.42</td>
</tr>
<tr>
<td>Zero</td>
<td>13</td>
<td>1.76</td>
<td>1.76</td>
</tr>
</tbody>
</table>

**RECOMMENDATIONS**

- Update Green Book text to indicate that any amount of negative offset can allow a left-turning vehicle to restrict the view of oncoming traffic for the opposing left-turning vehicle and that zero or positive-offset left-turn lanes are desirable to minimize this possibility and allowing turning drivers to adequately judge available gaps.
- New intersection designs should consider positively offsetting left-turn lanes, especially at signalized intersections with permissive left-turns. Retrofitting negative offset left-turn lanes to positive or zero offset should be considered where feasible.
- Where negative-offset left-turn lanes create potential sight restrictions, protected-only left-turn signal phasing should be considered.

**ACKNOWLEDGEMENTS**

This research was performed as part of SHRP 2 Project S08B, *Analysis of the SHRP 2 Naturalistic Driving Study Data: Evaluation of Offset Left-Turn Lanes*. More details are available in the final report of the research (9). The findings and recommendations presented here are those of the authors and do not necessarily reflect the views of SHRP 2 or its sponsors. The authors acknowledge the contribution of Mr. John J. Ronchetto and Ms. Jessica Brucker in reducing video data and managing the databases developed for this research.

**REFERENCES**

456 Transportation Research Board of the National Academies, Washington, D.C.

460 the AASHTO Strategic Highway Safety Plan, Volume 5: A Guide for Addressing
461 Unsignalized Intersection Collisions. Transportation Research Board of the National
462 Academies, Washington, D.C.

465 Unprotected Left-Turning Traffic at Intersections. In Transportation Research Record:
466 Journal of the Transportation Research Board, No. 1356, Transportation Research Board
467 of the National Academies, Washington, D.C., pp. 73-79.

470 Opposing Left-Turn Lanes. In Transportation Frontiers for the Next Millennium: 69th
471 Annual Meeting of the Institute of Transportation Engineers. CD-ROM. Washington,
472 D.C.

475 Left-Turn Lanes on Four-Lane Divided Roadways. In Transportation Research Record:
476 Journal of the Transportation Research Board, No. 1356, Transportation Research Board
477 of the National Academies, Washington, D.C., pp. 28-36.

480 of Offset Improvements for Left-Turn Lanes. Publication FHWA-HRT-09-035. FHWA,
481 U.S. Department of Transportation.

484 Naturalistic Driving Study Data: Evaluation of Offset Left-Turn Lanes. SHRP 2. Final