Empirical Evaluation of J-turn Intersection Performance – Analysis of Conflict Measures and Crashes

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ABSTRACT

A high percentage of crashes occurring on high-speed rural expressways occur at intersections with minor roads. This is especially true of the through and left turn movements on the minor roads. One low-cost alternative design for improving the safety of at-grade intersections on such expressways is the J-turn. This study evaluated the effectiveness of the unsignalized J-turn intersection design in Missouri utilizing field studies, crash analysis, and traffic conflict analysis. The field studies utilized detailed video-derived data at a J-turn site and a control site. The crash analysis included an Empirical Bayes (EB) before-after safety evaluation of five J-turn sites. The EB analysis found that J-turn produced a 31.2% reduction in crash frequency for all crashes and a 63.8% reduction in crash frequency for injury and fatal crashes. Annual disabling injury crashes and minor injury crashes decreased by 91.6% and 67.9%, respectively. The annual right angle crashes decreased from 8.6 to 0.8, a 90.2% reduction. No left turn right angle crashes were reported after the installation of J-turn at any of the study sites. The average time to collision conflict measure was four times higher at the J-turn site as compared to the two-way stop control (TWSC) site among minor road turning vehicles, indicating greater safety at the J-turn site. The average wait time at the J-turn site (5 seconds) was half the wait time at the control site (11 seconds), while the average travel time at the J-turn site was approximately one minute greater than at the TWSC site. Although the study was conducted using Missouri data, several study findings are transferable to J-turn installations in other states.

INTRODUCTION

The majority of crashes occurring at unsignalized intersections on high-speed rural expressways are right-angle crashes resulting from turning movements (1). For example, the proportion of right-angle crashes at rural high-speed expressways in the states of Minnesota, Utah, and Iowa are 57%, 69%, and 52%, respectively (1). The issue of right-angle crashes is of concern to many states, since this crash type exhibits an elevated percentage of fatal and serious injuries. As a result, state departments of transportation (DOTs) are looking for ways to improve safety at at-grade intersections on rural expressway corridors. NCHRP 650 report (1) presents three treatment strategies for DOTs to consider for eliminating or reducing right-angle crashes on rural expressways. These strategies are: 1) the use of alternative designs, such as J-turns and offset T-intersections, that have fewer conflict points and less severe conflicts as a replacement for conventional two-way stop control (TWSC) intersections, 2) improving intersection sight distance and providing advice on gap selection for minor road traffic, and 3) cautioning traffic on both minor and major roads of an upcoming intersection.

At a TWSC intersection on a four-lane divided highway, vehicles accessing the major highway from the minor road can make a left turn or through movement at the intersection by crossing major road movements. Highways with high volumes or high speeds may make these minor road movements difficult to execute, and cause long delays. In contrast, in a J-turn design, vehicles accessing the major highway from the minor road make a right turning movement and then use a U-turn at a downstream location. The major road vehicles accessing the minor road via a left turning movement may or may not have to use the U-turn for their movements. One variation of the J-turn design allows for major road turning movements to occur at the intersection, but still requires the minor road movements to use the U-turn. Conceptual schematics of the TWSC and the J-turn intersections are shown in Figure 1. Figure 1a depicts the left-turning movement from the minor road at the TWSC intersection. Figure 1b depicts the left-turning movement from the minor road at the J-turn intersection.

The safety of the J-turn design stems from the elimination of severe high-risk conflict points. A conflict point occurs whenever there is the possibility for two vehicles to occupy the same position. According to NCHRP 650 (1), on a four-lane divided highway, a TWSC intersection has 42 conflict points, while a J-turn intersection has 24 conflict points. Not only does the J-turn have fewer total conflict
points, but it eliminates the most severe forms of conflict, i.e., crossing conflicts that result in right-angle crashes.

FIGURE 1 Conceptual Schematic of TWSC and J-turn Intersections (Not to Scale)

Empirical research documenting the safety effectiveness of J-turn design is limited. An evaluation was conducted of a restricted crossing U-turn (RCUT) design in Maryland (2); the RCUT and Superstreet
designs are alternative names for the J-turn design. The authors conducted field observations of an RCUT intersection on a rural, four-lane divided highway. Both mobility and safety performance measures were extracted from the field data. A control site was used for comparison. They reported using lag as a conflict measure in lieu of the time to collision measure. Lag is the time difference between the arrival of a merging vehicle and the arrival of the following vehicle on the mainline at the same crossing point. If the following vehicle does not change speed, i.e., neither accelerates nor decelerates, lag is the same as the time to collision (2). Time to collision (TTC) is another conflict measure used to study intersection safety (3). TTC is defined as the time it takes for a collision between two vehicles to occur if the vehicles do not take an evasive action. Higher TTC values indicate safer conditions (3).

Some studies reported the results of Empirical Bayes (EB) crash analysis of J-turns (2, 4). The EB method for assessing the safety effectiveness of a treatment is documented in chapter nine of the Highway Safety Manual (5). Crash analysis using the EB method revealed a 44% reduction in total crash frequency for J-turns in Maryland (2) and a 27.2% reduction in North Carolina (4). In terms of reduction in crash severity, Maryland J-turns witnessed 70% and 42% reductions in fatalities and injury crashes, respectively (2). In North Carolina, J-turns resulted in a 51% reduction in fatal and injury crashes (4).

Over the past few years, the Missouri Department of Transportation (MoDOT) has converted some TWSC intersections on high-speed, four-lane divided highways into unsignalized J-turns. Despite their increased use in Missouri, the safety and mobility effects of J-turns have not been investigated and documented. This research attempted to address the effectiveness of the unsignalized J-turn designs. Specifically, the following two objectives were accomplished in this research:

1) **Field studies using detailed video data of traffic movements and the analysis of safety and mobility performance measures were conducted.** The analysis focused on several safety and operational performance measures, including conflicts, time to collision, travel times, and wait times.

2) **Crash analysis was conducted using all J-turn sites in Missouri for which sufficient after-installation period crash data were available.** Two crash analysis methods were utilized: a simple before-and-after comparison of crash data based on severity and an Empirical Bayes (EB) analysis to account for regression to the mean. The EB analysis produced crash modification factors for total crashes and fatal and injury crashes for an unsignalized J-turn intersection on a four-lane divided high-speed rural highway.

While the current study uses techniques similar to those used in Maryland and North Carolina studies (2, 4), this study makes a few new contributions to the field of alternative geometric designs. First, this study is unique in that it applies a project-level EB analysis to study the safety effectiveness of the entire footprint of the J-turn treatment. The footprint includes the main intersection, the two U-turns, and the road segments between. Thus, this study contrasts with safety studies that focus on the intersection only. The correlations among the facilities within the footprint were also accounted for. Second, this study presented a comprehensive safety analysis including both operational conflict analysis and crash analysis. The time to collision measure is new and has not been used in previous J-turn research. The conflict measures were derived from video data of vehicle trajectories. Previous research on J-turns primarily used simulation-based conflict analysis (6). Third, the crash reduction percentages obtained using the EB method can be used as guidance for future J-turn installations. The crash reductions are in agreement with those witnessed in the Maryland and North Carolina studies. Finally, as pointed out earlier, the literature on J-turn safety effectiveness is very limited. Thus this research complements the limited existing research and further validates the safety effectiveness of J-turns. Collectively, the current Missouri study along with Maryland and North Carolina studies can help provide guidance on the crash modification factor for J-turn treatments, nationally.

**METHODOLOGY**

*Field Studies*

Field studies were conducted at a J-turn site and a control TWSC site. The J-turn site was located at US 63 and Deer Park Road in central Missouri. The control site, which operated as a traditional TWSC
intersection, was also on US 63, further north of the J-turn site at Calvert Hill Road/Hinton Road. The approach of using a control site for operational measures is similar to previous studies (2). The control site was chosen due to its similarity to the treatment site in terms of geometry, land-use, and driving population, and was also recommended by MoDOT personnel. Both sites were located on a four lane divided highway with a speed limit of 70 mph. The J-turn site also operated as a two-way stop control prior to the J-turn treatment. The AADT for the J-turn site was 27,321, and 17,217 for the control site. The J-turn intersection was opened to traffic in October of 2012. Video data were collected at the treatment and control sites in November 2012 and May 2013. A description of the video data used for each performance measure is shown in Table 1. As illustrated in the table, data collection occurred at peak hour periods. More details of the data collection setup, such as the locations of cameras, speed radars, and delineators at the J-turn site can be found in the project final report (7).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Location</th>
<th>Time Collected</th>
<th>Date Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time</td>
<td>J-turn and Control</td>
<td>AM peak (7 am-9 am), PM peak (4 pm-6 pm)</td>
<td>November 2012</td>
</tr>
<tr>
<td>Wait time</td>
<td>J-turn and Control</td>
<td>AM peak (7 am-9 am)</td>
<td>November 2012</td>
</tr>
<tr>
<td>TTC</td>
<td>J-turn and Control</td>
<td>AM peak (7 am-9 am)</td>
<td>May 2013</td>
</tr>
<tr>
<td>Gap Acceptance</td>
<td>J-turn and Control</td>
<td>AM peak (7 am-9 am), PM peak (5 pm-7 pm)</td>
<td>November 2012, May 2013</td>
</tr>
</tbody>
</table>

**Operational Measures**

Data were collected for two operational measures: travel times and wait times. The computations of these measures from video data are discussed next. One additional measure, acceleration lane use, was also evaluated but not reported in this paper due to space limitations. The acceleration lane use findings can be found in the project final report (7).

**Travel Time**

The travel times of vehicles turning left from the major road to the minor road were measured for the J-turn and TWSC. For TWSC, travel time included the wait time at the intersection and the time taken to cross two lanes on the mainline. For the J-turn, travel time included the time taken to traverse the distance between the intersection and the U-turn, and the time taken to traverse the distance between the U-turn and the minor road. Due to the additional distance traversed in the J-turn, travel times were expected to be longer than at the TWSC. Travel times were also measured for vehicles turning left from the minor road to the major road at both the J-turn and TWSC sites.

Collecting video data of the entire J-turn footprint required a large viewing area and multiple camera fields-of-view to obtain the necessary coverage. Travel times were collected for the left turn movements from the major and minor roads. The travel time values collected for both maneuvers differed from the control due to the geometry of the alternative J-turn design. For the left turning maneuver from the minor road to the major road, vehicles must turn right then access a U-turn downstream to complete the movement. Similarly, the left turning movement from the major road must continue past the intersection and utilize the downstream U-turn, travel in the opposite direction, then turn right into the minor road.

**Wait Time**

Wait time (WT) represents the amount of time a vehicle must wait before initiating a turning movement. The J-turn site had an acceleration lane for minor road turning movements, thus reducing vehicle wait times. Even though the minor road acceleration lane is not a requirement for the J-turn design, it was implemented for this particular J-turn. Wait times were obtained for the left turning movements from the
minor road. Unlike the analysis for the travel time measure, the wait time measure required only one camera recording the minor road movements.

**Safety Measures**

Video monitoring was also used to obtain safety measures. The approaches used to extract the time to collision and gap acceptance measures are presented next.

**Time to Collision**

Time to collision, or TTC, is a surrogate safety measure that was developed and used originally by Hayward (8, 9) to evaluate the interactions between vehicles. The TTC is a conflict measure defined as the time after which a vehicle will collide with another vehicle if both vehicles were to maintain their current speed and path. The smaller the TTC value, the higher the likelihood of a collision occurring if no evasive action were to be taken. In this study, the TTC value was computed using a through moving vehicle on the major road and a left turning vehicle from the minor road. The TTC value is a function of the traffic flow on the major road, so higher flows will lead to smaller TTC values. The equation developed by Hayward to relate the difference in speed between nearby vehicles with collision risk (3) is:

\[
TTC = \frac{(x_{i-1} - x_i - l_{i-1})}{(v_i - v_{i-1})}, \quad v_i > v_{i-1}
\]

Where,

- \(x_{i-1}\) = the position of the lead or merging vehicle;
- \(x_i\) = the position of the trailing or mainline vehicle;
- \(l_{i-1}\) = length of the trailing vehicle (20 ft. was used as the average vehicle length);
- \(v_{i-1}\) = velocity of the lead or merging vehicle;
- \(v_i\) = velocity of the trailing or mainline vehicle.

The location of the left turn from the minor road to the major road differs between the traditional TWSC and J-turn design. In the TWSC design, minor road vehicles turning left onto the major road cross through traffic then merge into the opposing lanes; whereas in a J-turn, minor road vehicles make a right turn into an acceleration lane and then use the downstream U-turn to complete the turn. Thus, the potential conflict in a J-turn design occurs downstream of the intersection, unlike the TWSC, where it occurs at the intersection. Theoretically, the additional distance to the conflict in a J-turn should result in higher TTC values.

**Gap Acceptance**

Gap acceptance is a conflict measure defined as the gap accepted by a merging vehicle. For through and left turn movements originating from the minor road, the J-turn replaced the crossing conflicts across the major road with merging conflicts. The crossing gap at the control site involved a vehicle crossing both lanes of the major roadway in the same direction at one time, while the merging conflict occurred sequentially as a vehicle traveled from the minor road to the major right lane, from the major right lane to the left lane, and finally to the U-turn. Even though merging and crossing gaps are different types of gaps, they both reflect the willingness of a driver to make a maneuver in light of a potential conflict.

The minor road through and left turn movements at the control TWSC intersection cut across the major road through movements. The gaps accepted for crossing the major road traffic were also calculated using the time stamps recorded in the video data. However, the gap acceptance values obtained for the J-turn site could not be compared with those obtained for the control TWSC site since the type of conflicts were entirely different. The conflicts assessed for the J-turn were merging conflicts, whereas the conflicts assessed for the TWSC intersection were crossing conflicts.
Crash Analysis

A safety evaluation was performed by analyzing the crashes occurring before and after the implementation of the J-turn design. The safety evaluation was performed using two methods. The first method compared the crash frequency for different severity levels and types for the before and after period. Nine intersections in Missouri were implemented with J-turns, but only five have adequate data after implementation to be included in the safety evaluation. Table 2 shows the characteristics of each J-turn used in the study. All sites had high speed limits of 65 or 70 mph (105 or 113 kph).

<table>
<thead>
<tr>
<th>J-Turn Location</th>
<th>Average AADT After (Before)</th>
<th>Type</th>
<th>Speed Limit</th>
<th>Before period</th>
<th>After period</th>
</tr>
</thead>
<tbody>
<tr>
<td>US 63 and Deer Park Rd.</td>
<td>26470 (25807)</td>
<td>4-leg</td>
<td>70</td>
<td>2.50</td>
<td>1.25</td>
</tr>
<tr>
<td>Columbia, Boone County, MO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US 54 and Honey Creek Rd.</td>
<td>18922 (18848)</td>
<td>4-leg</td>
<td>65</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>Jefferson City, Cole, MO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US 54 and Route E Henley, Cole, MO</td>
<td>15591 (15541)</td>
<td>4-leg</td>
<td>65</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>MO 13 and NE 364 Rd. Osceola, St. Clair, MO</td>
<td>10630 (10630)</td>
<td>4-leg</td>
<td>65</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Route M and Old Lemay Ferry Rd. Imperial, Jefferson, MO</td>
<td>10326 (10326)</td>
<td>3-leg</td>
<td>65</td>
<td>3.50</td>
<td>3.50</td>
</tr>
</tbody>
</table>

The annual crash frequency was computed for each site by dividing the total number of crashes by the duration. Crash frequencies were computed for four severity levels: 1) Property Damage Only (PDO), 2) Minor Injury (MI), 3) Disabling Injury (DI), and 4) Fatality (F). The effects of the J-turn on specific crash types were also analyzed. Specifically, the following intersection-related crash types were analyzed: 1) Right Angle, 2) Right Turn, 3) Right Turn Right Angle, 4) Left Turn, 5) Left Turn Right Angle, 6) Rear End, 7) Side Swipe, and 8) Passing. The aforementioned eight crash types were the most relevant to J-turn and TWSC intersections. The angle crash types were included since they are common occurrences at at-grade intersections and are typically of high severity. The J-turn design introduces new weaving maneuvers between the minor road and the U-turn. Thus, rear end, sideswipe, and passing types of crashes were also analyzed.

The second method, Empirical Bayes (EB), is more statistically rigorous and has been used in previous studies to evaluate the safety effectiveness of alternative intersection designs (2, 4, 10). The EB method is also recommended by the Highway Safety Manual (HSM 2010) for conducting safety evaluations. The EB method was used to compute the safety effectiveness of the J-turn design replacing a TWSC intersection. The method uses Safety Performance Functions (SPF) to predict crashes with specified base conditions for a facility type. Crash Modification Factors (CMF) are used to adjust the base SPF predictions to the site geometric, signal, and traffic conditions. The analysis was conducted at the project level, meaning that the entire footprint of the treatment was covered. The project-level EB used in this research is different from the site-specific analysis performed by Hummer et al (4). In the site-specific analysis conducted by Hummer et al (4), only intersection-related crashes occurring at the main intersection were included in the safety evaluation. However, a project-level analysis considered the entire footprint including the main intersection, the two U-turns, and the segments between them. Since multiple facilities (intersections and segments) are included in the analysis, a correlation among the facilities was incorporated. According to Hauer et al (11), there are two bounds of correlation: perfectly correlated and independent facilities. The weight adjustment factors for the two bounds of correlation.
were computed. For partial correlation conditions, Bonneson et al. (12) recommend averaging the expected crash estimate of the perfect correlation and independent conditions.

The analysis period was adjusted by removing the actual construction period for each J-turn and by matching the seasons (months) exactly in the before and after periods. The durations of before and after periods are reported in Table 2. The predictions for each site were performed for fatal and injury (FI) and total (TOT) crashes, as those were the only two currently available SPFs in the HSM. To accurately predict crashes using HSM functions, the functions were calibrated for Missouri conditions. Calibration factors for FI and TOT crashes were developed for rural multilane intersections and rural multilane divided segments. The sampling criteria recommended by the HSM were followed to randomly generate samples of intersections and segments for calibration. Additional information on calibration of different facilities for Missouri can be found in Sun et al (13). The calibration factors for rural multilane four-leg intersection with minor road stop control were (sample size of 66 intersections): 0.64 for FI, 0.73 for TOT crashes, rural multilane three-leg intersection with minor road stop control were (sample size of 71 intersections): 0.85 for FI, 1.08 for TOT crashes, and rural multilane divided segments were (sample size of 37 segments): 0.59 for FI, 0.98 for TOT crashes.

RESULTS

Operational Measures

Travel Times and Wait Times

In contrast to the TWSC design, all minor road movements and major road turning movements of the J-turn require travel of some additional distance to complete the movements. The increases in travel times for these movements were measured in the field. Travel time statistics are shown in Table 3. The mean travel time of major road left turns at the J-turn site was approximately one minute (58 seconds) greater than at the TWSC site. The travel times of vehicles turning left from the minor road to the major road were also measured for the J-turn and TWSC and reported in Table 3. For the TWSC, travel time included wait times at the intersection and the time it took to cross two lanes of traffic to the median then access the major road on the opposite side. For the J-turn, travel time included wait time, the time it took for the vehicle to drive from the minor road to the U-turn, and the time taken to travel the distance from the U-turn to the intersection to complete the turning movement. The mean travel time for the J-turn site was also about one minute (56 seconds) greater than the TWSC site.

The wait times of vehicles wanting to turn left from the minor road onto the major road were measured at the TWSC and J-turn sites. The mean wait times were 5 seconds for the J-turn and 11 seconds for the TWSC site. This difference in wait times was significant, especially since the major road AADT at the J-turn site was higher (27,321) than at the control site (17,217). As major road AADT increases, the wait times at the TWSC were expected to increase.

<table>
<thead>
<tr>
<th>TABLE 3 Travel Time Statistics for Left Turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistic</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Mean (seconds)</td>
</tr>
<tr>
<td>Median (seconds)</td>
</tr>
<tr>
<td>Mode (seconds)</td>
</tr>
<tr>
<td>Std. Dev. (seconds)</td>
</tr>
<tr>
<td>Sample Size (vehicles)</td>
</tr>
</tbody>
</table>
**Safety Measures**

**Time to Collision**

The differences in TTC values at the J-turn site and the TWSC site were analyzed and reported in Table 4. A majority of TTC values (74%) for the J-turn design were greater than 20 seconds. On the other hand, the TWSC design experienced lower TTC values, with 62% of those values being less than 10 seconds. The mean TTC value for the J-turn design was 41 seconds versus 10 seconds for the TWSC design—a 300% difference. Higher TTC values indicate safer traffic conditions.

<table>
<thead>
<tr>
<th>Measure</th>
<th>J-Turn Time (sec)</th>
<th>TWSC Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>41.28</td>
<td>10.40</td>
</tr>
<tr>
<td>Median</td>
<td>34.59</td>
<td>9.10</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>30.34</td>
<td>6.80</td>
</tr>
<tr>
<td>Minimum</td>
<td>3.14</td>
<td>3.80</td>
</tr>
<tr>
<td>Maximum</td>
<td>114.48</td>
<td>36.90</td>
</tr>
<tr>
<td>Count</td>
<td>39</td>
<td>45</td>
</tr>
</tbody>
</table>

**Gap Acceptance**

At the J-turn site, a vehicle intending to turn left from the minor road onto the major road turns right into the acceleration lane, then change two lanes—driving lane (right) and passing lane (left)—followed by another lane change into the deceleration lane. The vehicle then uses the acceleration lane after making the U-turn and merges into the passing lane of the major road. The time gaps accepted by turning movements from the minor road at the J-turn site were computed from video data. Time gaps were computed for two lane changes: 1) from the right turn acceleration lane to the right lane, and 2) from the right lane to the left lane. Vehicles accepted shorter gaps for the first lane change, from the acceleration lane to the right lane, than for the second lane change, from the right lane to left lane. This could mean that drivers were more cautious when changing to the passing lane, possibly due to higher operating speeds in the passing lane and due to the impending deceleration into the U-turn lane. The mean accepted time gap for entering the right lane was 8.3 seconds, compared to 11.6 seconds for entering the passing lane.

Unlike the J-turn design, left turn vehicles in the TWSC design face a crossing conflict with the major road through movement. This is an important difference between the two designs; the J-turn design eliminates the crossing conflict and replaces it with lane change or merging conflicts. In terms of safety, a crossing conflict possesses a higher risk involving a severe angle crash. In contrast, the potential rear-end or sideswipe crashes that could result from a lane change are less severe than those observed in an angle crash. Thus, in the J-turn design, a severe crash type is traded for a less severe crash type. The mean accepted time gap for the minor road vehicle to enter the median in the TWSC intersection was 21 seconds. This time gap value for a TWSC, though higher than the J-turn, should not be directly compared to the values obtained at the J-turn site, since the two designs consist of different conflict types, i.e., crossing versus diverging.

**Crash Analysis**

Two methods were used to compare before and after crash frequency and severity: a graphical comparison by severity and crash type and EB analysis. Figure 2 presents the graphical comparison by severity and by crash type for all five J-turn sites combined.
Figure 2 shows that the total number of crashes per year, combined across all sites and all severities, decreased from 32.0 to 14.6 (54.4% reduction) after the J-turn treatment. There were no fatal crashes at any of the sites in the after period. Disabling injury crashes per year decreased from 3.9 to 0.3 (91.6% reduction). The elimination of fatal crashes and a significant reduction in disabling injury crashes are substantial safety improvements offered by the J-turn treatment. Minor injury crashes per year also decreased from 7.5 to 2.4 (67.9% reduction). Property damage only crashes per year decreased from 19.1 to 11.9 (37.8% reduction). Figure 2 shows the goal of decreasing angle crashes was accomplished: right angle crashes per year decreased from 8.6 to 0.8. One of the most severe crash types, left turn right angle crashes, was totally eliminated by the J-turn. Rear-end and passing crashes also decreased post J-turn implementation.

The project-level EB method compared the predicted crash frequency without the J-turn to the actual crash frequency with the J-turn. Calibration factors and correlations discussed previously were used in the predictions. The safety effectiveness values for the three correlation conditions were found to be: 1) independent – 60.4% reduction in FI crashes, 28% reduction in TOT crashes, 2) fully correlated – 66.7% reduction in FI crashes, 34.2% reduction in TOT crashes, and 3) partially correlated – 63.8% reduction in FI crashes, 31.2% reduction in TOT crashes. All reductions were significant at the 95% confidence level. These safety effectiveness values are comparable to, but higher than, the site-specific effectiveness values reported by Hummer et al. (4) – a reduction of 51% in FI crashes and a 27.2% reduction in TOT crashes.

The safety effectiveness results for individual sites are presented in Table 5. The safety effectiveness values for FI and TOT crashes are shown in the far right columns. For each site, the expected crash frequency obtained from the EB method (assuming partial correlation) for the after period, the observed crash frequency for the after period, and the safety effectiveness value are reported. The standard error values are also reported in parenthesis next to each safety effectiveness value. The overall safety effectiveness for all sites combined is shown in the last row of Table 5.

<table>
<thead>
<tr>
<th>J-turn site</th>
<th>Location</th>
<th>Crash measure</th>
<th>FI</th>
<th>TOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>US 63 and Deer Park Rd.</td>
<td>EB Expected Crashes</td>
<td>6.6</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>Columbia, Boone County, MO</td>
<td>Observed Crashes</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SE % (Std. Error %)</td>
<td>100.0 (0.0)</td>
<td>65.8 (12.5)</td>
</tr>
</tbody>
</table>
The EB results for individual sites showed that the J-turn was effective at decreasing the FI crashes at all five sites. The reductions in FI crashes were statistically significant, at the 95% confidence level, only for the first three sites; reductions in FI crashes witnessed at sites 4 and 5 were not statistically significant. The TOT crashes decreased at four out of the five sites, although only two of those sites (sites 1 and 3) witnessed a statistically significant decrease. One site, site 4, witnessed an increase in TOT crashes but the increase was not statistically significant. The results of site 4 were further investigated. The observed numbers of crashes during the 3-year before period were: 13 TOT with 5 PDO and 8 FI, while the observed numbers of crashes during the 3-year after period were: 15 TOT with 12 PDO and 3 FI. Based on the observed crash frequency at site 4 it appears that the J-turn traded higher severity FI crashes with lower severity PDO crashes.

### CONCLUSIONS

This paper addressed the effectiveness of the J-turn intersection design using field studies, crash analysis, and traffic conflict analysis. The study used both existing and new evaluation methods and measures for the safety evaluation. The project-level EB analysis considered the entire footprint of the J-turn treatment, including the U-turns, the main intersection, and the segments in between. The crash modification factor (CMF) for the J-turn treatment based on this study was 0.31 for total crashes, and 0.64 for fatal and injury crashes, assuming the segments and then intersection are partially correlated. Comparatively, Inman and Haas (2) reported a 44% reduction in total crashes in Maryland (a CMF of 0.44) and Hummer et al (4) reported a 27.2% reduction in total crashes in North Carolina (a CMF of 0.27) after J-turn implementation. The EB results for individual sites showed that the FI crashes decreased due to J-turn installations at all five sites. The total number of crashes decreased at four out of the five sites.

The time to collision measure for the J-turn was evaluated empirically for the first time in this research. The average time to collision for minor road turning vehicles at the J-turn site was found to be four times higher than the value observed at a control TWSC intersection. This higher time to collision value implies that the J-turn intersection allowed for significantly safer interactions between the minor road vehicles and the major road vehicles, as compared to the TWSC intersection.

The graphical examination of the crash data showed the annual disabling injury crashes decreased by 91.6% and minor injury crashes decreased by 67.9%. None of the five sites exhibited a fatal crash following J-turn implementation. The elimination of fatal crashes and a significant reduction in disabling
injury crashes are substantial safety improvements offered by the J-turn design. The main goal of the J-turn design is to decrease the frequency of angle crashes. This analysis showed that annual right angle crashes decreased from 8.6 to 0.8, a 90.2% reduction. No left-turn crashes were reported after implementation of J-turns at the study sites. Rear-end and passing crashes also decreased post J-turn implementation.

Wait times at the J-turn site were lower than those at the TWSC site. The average wait time at the J-turn site was five seconds, compared to 11 seconds at the control TWSC site. These findings are consistent with the literature. As drivers become used to the J-turn intersection, and especially with the use of acceleration lanes, it is anticipated that wait times will decrease even further. In contrast, the average travel times at the J-turn site were about one minute longer than at the TWSC site for minor road and major road turning movements.

The average gap acceptance value for minor road vehicles merging from the acceleration lane into the right lane was 8.3 seconds, and 11.6 seconds for merging from the right lane to the left lane. The higher accepted value for the merge into the left passing lane was presumably due to higher traffic speeds in the passing lane.

In summary, all the safety performance measures analyzed in this study pointed to the superior safety performance of J-turn over TWSC for high-speed rural expressway crossings. These safety measures included EB estimates of crash frequency by severity, crash frequencies by severity and crash type, and TTC. Even though travel times were lengthened by approximately one minute for several movements, wait times were reduced due to the addition of acceleration lanes. While this study focused on the safety aspects of J-turns, there are many other trade-offs that are involved in design selection including mobility, access, right-of-way, geometrics, and cost.

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