DRIVING SIMULATOR STUDY OF J-TURN ACCELERATION/DECELERATION LANE AND U-TURN SPACING CONFIGURATIONS

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Word count: 5,284 words text + 3 tables, 4 figures x 250 words (each) = 7,034 words

ABSTRACT
The J-turn, also known as RCUT (Restricted Crossing U-Turn) and Superstreet, is an innovative geometric design that can improve intersection safety. Even though this design has been in use in several states for many years, there is very little research-based guidance for several design parameters. A driving simulator study was conducted to analyze the parameters of lane configuration, U-turn spacing, and signage. Two lane configurations were examined: 1) acceleration/deceleration configuration where acceleration and deceleration lanes are provided and 2) deceleration only configuration where only deceleration lanes are provided. Lane configuration was found to be the most important parameter affecting J-turn safety based on speed-differentials. The only significant interaction effect among parameters was between lane configuration and U-turn spacing. The acceleration/deceleration configuration performed better than the deceleration only configuration with 66.3% fewer safety critical events. Vehicle trajectories and average lane change locations showed that U-turn spacing impacted significantly the acceleration/deceleration configuration (e.g. average merge locations changed by 96% to 101%) but not the deceleration only configuration. No strong preference was demonstrated for either the directional or the diagrammatic signage style. This paper presented one of the first human factors studies of the J-turn focused on developing design guidance. This human factors approach complements other traditional approaches such as crash analysis and micro-simulation.

Keywords: superstreet, J-turn, driving simulator
INTRODUCTION

J-turn intersections, also known as restricted crossing U-turn (RCUT) intersections, serve as an alternative to a two-way stop controlled intersection on high-speed roadways. This design has been in operation in Maryland and North Carolina for many years (1). J-turns force the through and left turn movements from the minor street to turn right and make a U-turn at a downstream location. Figure 1a and 1b are schematic diagrams of the J-turn design. These figures contain a large X in the center of the intersection representing the prohibition of the through and left-turn movements from the minor approach. Figure 1 does not show the alternative J-turn configuration that allows left-turn movements from the major road to the minor road. The J-turn design improves safety due to fewer conflict points and less severe conflict types. The number of crossing conflicts can be completely eliminated if the major road left turns are not allowed at a J-turn. Several empirical safety studies (e.g., (2), (3)) document the safety effectiveness of the J-turn design, such as a fatal and injury crash reduction of around 64%. Studies have also examined J-turn’s operational performance. These studies (2, 4, 5, and 6) found that the overall intersection performance is improved even though minor road movements can have a slight increase in travel time.

FIGURE 1a Acceleration and deceleration lanes.

FIGURE 1b Full deceleration lanes only (AD).

FIGURE 1 J-turn turn design considerations (DF).
There are many considerations involved in the design of a J-turn intersection. These considerations can include intersection elements, median U-turn crossover elements, medians, auxiliary lanes, and shoulders. Despite the increasing interest in the J-turn design, there are certain design considerations that require additional empirical research. One consideration involves the implementation of the acceleration and deceleration lanes. An acceleration lane onto the major highway allows for easier entry for the minor road vehicles, but adds cost and additional right-of-way. Figure 1 shows two possible options that have been implemented in Missouri. Figure 1a includes both deceleration and acceleration lanes at half the length (AD), while Figure 1b only includes deceleration lanes, but at full length (DF). Other states, such as Mississippi, also make mainline deceleration lanes mandatory before the U-turn but make acceleration lanes optional after the U-turn (7). The Green Book (8) recommends that deceleration lane lengths be based on the design volume at the median U-turn. A simulator study that tracks the lane changing locations of the with and without right-turn acceleration lane configurations will help to test the conclusions presented in Inman and Haas (5) and Zhang and Kronprasert (9) that the U-turn spacing affects the two lane configurations differently.

The dimension shown as L in Figure 1 illustrates the issue of appropriate spacing between the crossroad and the U-turn. A longer spacing offers a greater distance over which a vehicle can maneuver from the minor road to the U-turn and reduces the possibility of spillback. But the longer spacing increases travel time delay. In the example of a two-lane major highway, a vehicle from the minor road will need at least two lane changes to reach the deceleration lane leading to a U-turn. Some sources of guidance related to the design of J-turn spacing include state DOT guidelines, the AASHTO Green Book, and the TRB Access Management Manual. J-turns spacing recommendations from several DOTs (e.g., North Carolina, Michigan, Oregon, Mississippi, and Missouri) range from 400 feet to 1,320 feet (7, 10, 11). In Missouri, actual spacings range from 630 feet to 3,000 feet. The Green Book (8), citing a FHWA guide on signalized intersections (12), recommends an optimum spacing of 660 feet. However, this recommendation is oriented towards signalized intersections and not un-signalized high-speed facilities. TRB’s Access Management Manual (13) recommends a distance of 400 to 1,000 feet. The FHWA RCUT Informational Guide (14) states that the spacing can vary from 400 feet for a stop or signal-controlled intersection to 2,640 feet (1/2 mile) for a merge-controlled intersection. The literature presents several recommendations for the U-turn spacing, but none of them appear to be based on research; many are based on convenient distances such as 1/8 mile (660 feet), 1/4 mile (1,320 feet) or 1/2 mile (2,640 feet).

A third consideration involves J-turn signage. Currently, the Manual on Uniform Traffic Control Devices (MUTCD) (15) does not contain specific guidance for the signing of J-turns. A driver on the minor road desiring to make a left or through movement requires signage to guide the driver to the U-turn. Two options for minor road signage used by the Missouri DOT (MoDOT), diagrammatic versus directional, are shown in Figure 2, circled in red. The diagrammatic signage shows the bird’s eye view, including the U-turn movement, while the directional signage only directs the minor road traffic to the major road where other signage continues to guide the traffic. Some DOTs, such as Mississippi DOT, recommends the use of the diagrammatic signage in their
J-turn design guide (7). WISDOT (16), on the other hand, uses neither signage at the minor road approach but use extensive signage on the major road to guide drivers. There is no existing guidance on the effectiveness of the three approaches, i.e., diagrammatic, directional, or none. The guidelines developed in this paper for the acceleration/deceleration configuration, length of spacing, and signage help to address knowledge gap in the existing literature.

FIGURE 2a Diagrammatic-style signage on minor road.
Some options for investigating the aforementioned design considerations include field, driving simulator, and micro-simulation studies. These options are complementary and have different tradeoffs. This paper describes the driving simulator study only; the authors were also involved with field and micro-simulation studies of J-turn design considerations. One benefit of the simulator study is the ability to examine multiple design considerations via a factorial experiment design that assesses relative contributions and interactions among different variables of interest (17). Also, a driving simulator provides human perspectives and perceptions that are not directly measurable by other existing approaches. A post-simulator survey provides human participants the opportunity to express their opinions on the J-turn design, providing additional data.

LITERATURE ON DRIVING SIMULATORS

Driving simulator research has expanded greatly in the past decade and beyond. Van Leeuwen (18) found 2752 papers that included the words “driving simulator” in the title, abstract, or keywords between 2000 and 2013. Undoubtedly, the increase in popularity of driving simulator research is due to the usefulness of the driving simulator for a variety of fields, the affordability of such systems, and improvements in graphical, software, and computing technologies. There is a diverse range of disciplines that utilize driving simulators and a large number of resultant studies. It is evident that driving simulators have become an accepted and oft-used experimental
One main advantage in the use of a driving simulator is the ability to conduct studies that would otherwise be risky or even unethical if it were conducted in the field (20) (21). Another advantage is the ability to control the experiment and to eliminate extraneous events that would negatively impact experimental consistency (22). In safety research, a major difficulty in the use of crash statistics is accounting for confounding factors; a simulator allows a level of optimal control that is nearly impossible to achieve using real world experiments and data. Driving simulators can investigate nonexistent designs such as road elements that are not currently employed (22). A further advantage is the relative affordability of such experiments when compared to costly field experiments that were sometimes infeasible due to safety risks.

In contrast to traffic parameter studies, where sample sizes could be upwards of over 100,000 using 30-second detector data as a single sample, driving simulator studies typically involve small sample sizes of around 30 subjects (18, 23, 24). One main reason for the disparity in sample size between these two types of experiments is that simulator studies collect and utilize much more information (e.g., monitoring acceleration, speed, clutch depression, accelerator depression, brake pedal load, and electromyography readings (25). Another reason is the labor-intensive nature of simulator studies, which require hosting, briefing, observing, de-briefing, and analyzing each human subject.

Despite the many benefits of a driving simulator, a major disadvantage is the possibility of simulator sickness. Simulator sickness refers to the range of symptoms experience by participants of simulator studies, including driving simulators (26). Such symptoms can include disorientation, dizziness, eye strain headache, dry mouth, drowsiness, nausea, and vomiting (27, 28).

**ZOUSIM DRIVING SIMULATOR EXPERIMENT DESIGN**

ZouSim, the University of Missouri Driving Simulator, is a medium fidelity simulator that is built around the half cab of an actual sedan. For the J-turn experiment, a triple LED monitor setup was used because it provides greater clarity and brightness than the other options, leading to a lower probability of sickness. Minimizing sickness was a major concern since the experiment involved extreme turns (i.e., U-turns), and frequent weaving and acceleration/deceleration. Figure 3 shows a picture of ZouSim from the inside of the sedan. The active instrumentation in the vehicle includes a force-feedback steering wheel, brake and acceleration pedals, turn signals, and engine vibration generator.
FIGURE 3 Picture of ZouSim driving simulator.

ZouSim software was developed using the Unity simulation engine which contains a realistic physics engine, 3D capabilities, animation tools, and compatibility with popular 3D CAD (computer-aided design) software which allows accurate modeling of the road design. A scene in a driving simulator is a specific scenario that a human participant is asked to drive. In the J-turn experiment, a scene is a fully loaded J-turn network which a human participant has to navigate. Surfaces were textured or painted with the appropriate colors, striping, and markings that conform to the MUTCD (15). The static objects modeled in scenes include road signs, trees, and grass. Even though specific street names were used in scenes, the scenes were not modeled after existing roads to avoid participants introducing their memories into the experiment. Moving vehicles were introduced on the major highway at a constant headway; the flow rate was kept constant so that each participant experienced the same scenario. These vehicles were intentionally designed without colliders so that any contact with the subject vehicle would not result in a crash, though contacts were logged. The primary virtual camera was the forward windshield view. Three additional virtual cameras presented the left, right, and rearview mirror perspectives.

The ZouSim J-turn experiment was calibrated in four main ways: acceleration/deceleration data, field videos, flow rates, and speed distributions. The first two were for the subject vehicle and the last two were for the background traffic. Since the physical cab used was a sedan, the vehicle performance was modeled after the manufacturer’s data on maximum acceleration and braking.
rates (e.g. 190 feet stopping distance from 70 mph). Drive videos were recorded for the J-turn on US-63/AB. Multiple iterations of evaluation and refinement with test drivers improved the experiential congruence with corresponding real-world driving conditions. These refinements included improvements in representation of physical environment as well as the human-machine-simulation interaction between the test subject, hardware configuration involving steering wheel, pedals, turn indicators and the resulting response in the simulation.

Flow rates were collected from both major and minor approaches at the US-63/AB J-turn for both morning and evening peak hours. Vehicle speeds of the major road traffic were collected using radar guns. The mainline traffic in ZouSim was then modeled after the field traffic characteristics from US-63/AB. The details of the field data collection were documented in Edara et al. (29).

The three design considerations investigated, acceleration/deceleration lane configuration, U-turn spacing, and signage, were restricted to certain values in order to make the experiments feasible in terms of duration. As shown previously, the half-length acceleration/deceleration lane configuration (AD) and the full length deceleration lane configuration (DF) were the only two designs tested. For the U-turn spacing only two values were used: 1,000 and 2,000 feet. As discussed previously, the diagrammatic and the directional minor road signage were the only two signage options tested. In addition, the effect of the major road traffic was investigated. For the major road, the following two flow rates were used in each of the two lanes per direction: 545 vphpl (medium) and 720 vphpl (high). The values for spacing and flow rate were selected by the project technical advisory panel as the most relevant for J-turn design in rural Missouri.

Each experiment run was designed with a unique set of lane configuration, U-turn spacing, signage, and traffic flow rate. Table 1 shows the different combinations of runs from the possible design values. For example, Run 2 in Table 1 represents a J-turn design with the half-length acceleration/deceleration lane configuration (AD), a U-turn spacing of 2,000 feet (2K), medium major road traffic (ME), and directional minor road signage (DR). In order to further reduce the number of experiment combinations, the signage consideration was separated from the other design considerations. The reason for this separation was twofold. First, if the U-turn movement was missed due to signage confusion, then important data related to the U-turn would be absent from that particular run. Second, signage is assumed to be somewhat independent from the other considerations of lane configuration, spacing, and traffic flow. Therefore, in terms of the order of experimentation, the signage runs were always conducted first, i.e. Runs 1 and 2. For these first two runs, participants were only told to start from the minor road and drive across the major road, and they were not told that a J-turn was involved. Thus, there was the potential for participants to miss the U-turn, and some did. After Runs 1 and 2 were completed, then the participants were told about the J-turn so has to not miss the U-turns.
TABLE 1 ZouSim J-turn Experiment Runs

<table>
<thead>
<tr>
<th>Run</th>
<th>Pattern Code</th>
<th>Lane Configuration</th>
<th>Spacing (feet)</th>
<th>Major Road Traffic</th>
<th>Signage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AD2KMEDA</td>
<td>Accel./Decel.</td>
<td>2,000</td>
<td>Medium</td>
<td>Diagrammatic</td>
</tr>
<tr>
<td>2</td>
<td>AD2KMEDR</td>
<td>Accel./Decel.</td>
<td>2,000</td>
<td>Medium</td>
<td>Directional</td>
</tr>
<tr>
<td>3</td>
<td>AD1KHIDR</td>
<td>Accel./Decel.</td>
<td>1,000</td>
<td>High</td>
<td>Directional</td>
</tr>
<tr>
<td>4</td>
<td>AD1KMEDR</td>
<td>Accel./Decel.</td>
<td>1,000</td>
<td>Medium</td>
<td>Directional</td>
</tr>
<tr>
<td>5</td>
<td>AD2KHIDR</td>
<td>Accel./Decel.</td>
<td>2,000</td>
<td>High</td>
<td>Directional</td>
</tr>
<tr>
<td>6</td>
<td>DF1KHIDR</td>
<td>Full Decel.</td>
<td>1,000</td>
<td>High</td>
<td>Directional</td>
</tr>
<tr>
<td>7</td>
<td>DF1KMEDR</td>
<td>Full Decel.</td>
<td>1,000</td>
<td>Medium</td>
<td>Directional</td>
</tr>
<tr>
<td>8</td>
<td>DF2KHIDR</td>
<td>Full Decel.</td>
<td>2,000</td>
<td>High</td>
<td>Directional</td>
</tr>
<tr>
<td>9</td>
<td>DF2KMEDR</td>
<td>Full Decel.</td>
<td>2,000</td>
<td>Medium</td>
<td>Directional</td>
</tr>
</tbody>
</table>

Sequence bias or order effect is the influence of the order in which the runs are conducted in a human participant study. This is because early runs can act as an “anchor” affecting subsequent runs (30). One way of controlling for this bias is to randomize the runs. The signage runs and the non-signage runs were randomized separately.

Two post-simulator surveys were administered after a participant completed the nine simulator runs. The first survey is a 17-question survey on a participant’s view on J-turn lane configuration, U-turn spacing, minor road signage, J-turn knowledge, safety, simulator realism, and demographics. For questions involving the preference between two alternatives, such as between the acceleration/deceleration configuration versus the full deceleration configuration, a five point Likert scale was used as a response. The second survey is the well-known Simulator Sickness Questionnaire (SSQ) (31). The SSQ asks 16 questions, each one related to a symptom, such as eye strain, nausea, or dizziness.

SIMULATOR AND SURVEY RESULTS

Simulator Results

The study protocols and measurement tools were evaluated and approved by the campus institutional review board (IRB). Each participant was briefed about study procedures and potential risks, and the informed consent was obtained. Of the 34 participants, 30 completed all the runs. Three participants were unable to continue after experiencing symptoms during the warm up scenario. The participants who completed the runs reflected a wide range of demographics and they were all licensed Missouri drivers. The participants were divided equally in gender between male and female. Even though the age distribution was skewed slightly towards younger drivers, the majority were older than 26 years old, with 10% older than 56 years old. The participants were all from the metropolitan Columbia, Missouri, area and reflected a wide range of professions.
Several measures of performance (MOEs) were recorded automatically from the simulator experiments. Some of the safety MOEs, such as speed differential and Time-To-Collision (TTC), were used because actual collisions are rare in real life and in simulator experiments. Previous research (e.g. 9) indicated that the location where vehicles change lanes to reach the U-turn vary between the AD and DF configurations. Thus the average locations of lane changes were measured along with full trajectories of subject vehicles. Travel times and wait times were measured to compare the efficiency among different designs. The record of a driver missing the U-turn on a run was used to assess driver comprehension of signage. In other words, a participant who did not understand the J-turn signage would continue past the U-turn.

MOEs derived from vehicle speeds can be helpful for assessing both safety and operations. Speed differential is defined here as the difference in speeds between the subject vehicle and the speed of a vehicle approaching the subject vehicle at the instance the subject vehicle crosses a lane for a lane change maneuver. Even though the relationship between speed measures and safety is complicated (32), the speed differential measure adds to the safety information provided by other measures. Speed measures also help to assess J-turn operations. A large speed differential that causes merging turbulence can lead to the deterioration of mainline traffic flow.

Analysis of variance (ANOVA) (17) was used for modeling and residual assessment of the dependent variable, speed differential (SD). The requirements of normality, independence, and homoscedasticity were verified before modeling. The speed differential was recorded for four separate lane change movements: 1) from the minor road to the outside lane, 2) from the outside lane to the inside lane, 3) from the U-turn to the inside lane in the opposite direction, and 4) from the inside lane to the outside lane. Similar analysis was performed for all four movements, and the results were similar. The independent variables were lane configuration (AD or DF), U-turn spacing (1000 or 2000 feet), and traffic volume (545 vphpl or 720 vphpl). The variable names were M for lane configuration/movement, L for U-turn spacing/length, and V for traffic volume. L and V were standardized since the variables have different units of measurement. By considering interaction effects, the following seven possible variables resulted: M, V, L, MV, VL, ML, and VML. Thus there were 7! or 5040 possible variable combinations for modeling.

Table 2 shows the results of ANOVA modeling of the post-turn speed differentials that included all possible variables. Note that it is common in social science cross-sectional studies for the magnitude of ANOVA sum of squares values to be lower than other studies; the estimate of the relationship between the independent and dependent variables are still valid (33). Table 2 shows the variables M, L, and M*L were the only significant ones. Thus a final model was developed using M, L, and M*L variables; equation 1 represents this model. Equation 1 implies that the lane configuration is the most important design factor with the largest coefficient of 0.7141. The U-turn spacing was also significant although with the much smaller coefficient of 0.0938. The only interaction effect was between lane configuration and spacing. This means that lane configuration and spacing are related. This interaction will be examined further with other performance measures such as lane change distances and vehicle trajectories.
TABLE 2 ANOVA Modeling Results for Post U-turn Speed Differentials

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F Value</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>127.797</td>
<td>7</td>
<td>18.257</td>
<td>35.04</td>
<td>0.000</td>
</tr>
<tr>
<td>M</td>
<td>122.464</td>
<td>1</td>
<td>122.464</td>
<td>235.03</td>
<td>0.000</td>
</tr>
<tr>
<td>L</td>
<td>2.101</td>
<td>1</td>
<td>2.101</td>
<td>4.03</td>
<td>0.046</td>
</tr>
<tr>
<td>V</td>
<td>0.228</td>
<td>1</td>
<td>0.228</td>
<td>0.44</td>
<td>0.509</td>
</tr>
<tr>
<td>M*L</td>
<td>2.607</td>
<td>1</td>
<td>2.607</td>
<td>5.00</td>
<td>0.026</td>
</tr>
<tr>
<td>M*V</td>
<td>0.007</td>
<td>1</td>
<td>0.007</td>
<td>0.01</td>
<td>0.908</td>
</tr>
<tr>
<td>L*V</td>
<td>0.024</td>
<td>1</td>
<td>0.024</td>
<td>0.05</td>
<td>0.829</td>
</tr>
<tr>
<td>M<em>L</em>V</td>
<td>0.007</td>
<td>1</td>
<td>0.007</td>
<td>0.01</td>
<td>0.905</td>
</tr>
<tr>
<td>Error</td>
<td>112.549</td>
<td>216</td>
<td>0.521</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>240.346</td>
<td>223</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ SD = -0.0509 + 0.7141M + 0.0938L + 0.1043M \times L \]  (1)

TTC is defined as the time until a collision if two vehicles were to continue on the same course without changing speeds \((34)\). In other words, it is the time that is needed to travel the space separating the lead and the following vehicle at the relative speed between the lead and following vehicles. The equation for TTC is

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

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 leading 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.

In analyzing TTC values, large TTC values were not included since they are not safety critical. A value of 6 seconds was the threshold applied following Vogel’s research \((35)\) that vehicles with a headway of more than 6 seconds chose their speed independent of the leading vehicle. Furthermore, there does not exist any research that point to a TTC larger than 6 seconds as impacting safety \((34)\), instead some studies have suggested an even smaller TTC threshold of 4 seconds \((36)\).

The TTC results show that there is a statistical significant difference \((p=0.0243)\) of 106 (66.3%) more total safety-critical TTC values with the DF configuration as compared to the AD. This is consistent with the speed differential results that indicate M as a significant variable. When examining each lane configuration individually, the U-turn spacing affected the number of TTC conflicts in the AD design \((p=0.326)\) but not the DF design. AD1K had 22 (31.9%) more total safety-critical TTC events than AD2K, but the DF1K and DF2K designs had the same number.
Where a vehicle makes lane changes while traveling through a J-turn has both safety and practical implications. A safety issue arises if a vehicle is forced to either make a lane change into a small gap or miss the U-turn or minor road. Unnecessary extra travel time results if the U-turn spacing is never fully utilized and a shorter spacing could have been just as effective. Lane change behavior is analyzed in two complementary ways. A vehicle trajectory plot overlays each individual vehicle maneuvers on top of each other. When trajectories overlap it appears darker and thicker. Thus, the vehicle trajectory plot shows the locations and patterns of lane changes, qualitatively. Figure 4 shows the vehicle trajectory plots for the aggregated DF1K, AD1K, DF2K, and AD2K runs. These subfigures show a visual difference between the DF and AD trajectories in that the AD lane changes are distributed across a longer spacing. The DF trajectories, for both 1K and 2K, show more concentrated maneuvers near the beginning, either at the minor road or at the U-turn. The implication is that a shorter spacing is adequate for the DF design as compared to the AD.

FIGURE 4a DF1K (top) AD1K (bottom).
FIGURE 4b DF2K (top) AD2K (bottom).

FIGURE 4 Vehicle trajectory plots.

The average lane change distance represents a single quantitative measure where a lane change occurs for a particular lane change maneuver. The following four lane changes are of particular importance:

- LC1: from the minor road (DF) or acceleration lane (AD) to the outside lane
- LC2: from the inside lane to the deceleration lane towards the U-turn
- LC3: from the U-turn (DF) or acceleration lane (AD) to the inside lane in the opposite direction
- LC4: from the outside lane to the deceleration lane towards the minor road in the opposite direction

Table 3 shows the average lane change distance for LC1-LC4. For LC1 and LC2, the distance is measured from the intersection of the minor road with the major highway. For LC3 and LC3, the distance is measured from the U-turn. The average lane change distances are consistent with the vehicle trajectory plots. For AD, Table 3 shows that LC1 and LC3 do not differ much in magnitude as this is the first lane change in each direction. However, LC2 and LC4 show a large magnitude difference between AD1K and AD2K, both statistically significant (p<0.000). In contrast to AD, the DF LC2 and LC4 magnitudes do not differ by much. Furthermore, the DF LC2 and LC4 values are both less than 1000 feet. For DF, LC1 and LC4 values are always 0.000 since there is no acceleration lane at the minor road or U-turn.
TABLE 3 Lane Change Locations

<table>
<thead>
<tr>
<th></th>
<th>AD1K</th>
<th>AD2K</th>
<th>difference</th>
<th>T-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC1</td>
<td>312.67</td>
<td>420.32</td>
<td>34.4%</td>
<td>&lt;0.000</td>
</tr>
<tr>
<td>LC2</td>
<td>628.04</td>
<td>1106.90</td>
<td>76.3%</td>
<td>&lt;0.000</td>
</tr>
<tr>
<td>LC3</td>
<td>136.26</td>
<td>274.27</td>
<td>101.3%</td>
<td>&lt;0.000</td>
</tr>
<tr>
<td>LC4</td>
<td>494.99</td>
<td>971.77</td>
<td>96.3%</td>
<td>&lt;0.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>DF1K</th>
<th>DF2K</th>
<th>difference</th>
<th>T-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC1</td>
<td>0.00</td>
<td>0.00</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>LC2</td>
<td>517.11</td>
<td>575.83</td>
<td>11.4%</td>
<td>&lt;0.138</td>
</tr>
<tr>
<td>LC3</td>
<td>0.00</td>
<td>0.00</td>
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<td>NA</td>
</tr>
<tr>
<td>LC4</td>
<td>348.67</td>
<td>418.81</td>
<td>20.1%</td>
<td>&lt;0.000</td>
</tr>
</tbody>
</table>

The results of the lane change analysis show that the lane changing patterns different significantly between the AD and DF designs. For the AD design, lane changes are distributed across a longer spacing, whereas the 2K spacing is underutilized in the DF design. These results validate the hypothesis raised in existing literature about the differing AD and DF lane change behavior (e.g. 9).

Average wait times were measured at the minor road and at the U-turn. There was not a significant difference in wait times at the minor road (p=0.381), but there was a significant difference of 4 seconds at the U-turn (p=0.001) between AD (11.69 sec) and DF (15.69 sec). And, as expected, wait times increased by 4.53 seconds with the higher mainline flows scenario (p=0.002). In terms of operations, AD was more efficient than DF.

The performance of signage was measured by recording any vehicles that missed the U-turn. In other words, if the J-turn signage was unclear, then a driver would not comprehend the need to make a U-turn. The number of missed U-turns were exactly the same for DR and DA, being 10 each.

Survey Results

Responses from the post-simulator survey complemented the data obtained through the simulator experiments. The majority of the respondents have driven through actual J-turns (77%), believe they are easy to navigate (73%), know about the safety benefits (70%), and feel safer driving through J-turns (76%). In regards to the auxiliary lane configuration, 73% of the respondents preferred the acceleration/deceleration configuration over the full deceleration configuration. The top reasons given for the preference are safety and ease of maneuvering. For the U-turn spacing, 83% of the respondents preferred the 2,000 foot over the 1,000 ft spacing. In terms of signage,
there was not a majority preference with 37% preferring diagrammatic, 47% preferring direction, and 16% neutral.

There were several questions related to simulator realism. A large majority of respondents agreed that the simulator was realistic which was consistent with researcher observations of the participant driving behavior; drivers appear to exhibit natural care while turning and lane changing. A majority of respondents answered that the experience was natural (80%), they felt they were actually there (67%), and they could drive around freely (73%). However, there is potential for refining the movement of the simulator (e.g., steering, accelerator and brake pedals) as a minority expressed that the movement was not natural (23%).

The responses to the SSQ revealed that a significant number of participants experienced one or more symptoms of simulator sickness. The most frequent symptoms experienced were general discomfort (57%), eye strain (40%), nausea (53%), and stomach awareness (50%). These results were unsurprising due to the length and nature of the study. Even though each design consideration was limited to two values, the combination of several considerations required nine runs. On average, each participant spent approximately 30 minutes with the simulator, including the breaks between runs. This duration did not include the pre-simulator orientation or the post-simulator survey. The long duration of the simulator study was one contributing factor for the symptoms. Another contributing factor was the sudden maneuvering involved in traveling the through movement from the minor road. Sudden acceleration, braking, and turning were all involves in weaving multiple lanes and making the U-turn; these are the very scenarios that researchers recommend to minimize in order to avoid simulator sickness (37). Despite the frequency of symptoms, the dropout rate of 10% was comparable to the rate of other studies (e.g., 14% for (37)). In hindsight, it would have been more preferable to shorten the study and to use multiple groups to cover the required sample size.

CONCLUSION

The simulator results were consistent with survey results. Both the simulator and survey results favored the acceleration/deceleration lane (AD) design due to smaller speed differentials, safer TTCs, and higher survey ratings. Vehicle trajectory plots generated from the trials also showed that drivers traveled differently on the AD versus the deceleration lane (DF) configurations. The 1K versus 2K U-turn spacing results were similar for DF, while results improved with the longer spacing for AD. The practical design guidance is to use the AD configuration over the DF. With the AD design, increasing the U-turn spacing will increase safety. Locations with high traffic demand should especially consider longer lengths such as 2,000 feet. U-turn spacing did not impact the DF design, thus the 1,000 foot spacing was adequate for DF.

Even though survey results showed a slight preference for the directional (DR) style over the diagrammatic (DA), the simulator results did not vary between the two signage styles. Therefore both signage styles performed similarly. There were a significant number of drivers that missed the U-turn. This study suggests that strong media and public information campaign be employed
when J-turns are implemented in communities unfamiliar with their operation. An agency can
consider using additional signage to guide left-turn and through traffic on the minor road to
reinforce the single signage on the minor road.

The results from this study add to the knowledge of this innovative geometric design and
presents guidance for the design of the lane configuration, U-turn spacing, and signage. These
findings can be incorporated into a national design guide to assist agencies in the deployment of
this low-cost safety countermeasure for intersections.

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