Field Observations of Path and Speed of Motorists at Double-Lane Roundabouts

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ABSTRACT

Roundabouts generally have fewer crashes and less severe crashes compared to signalized intersections. Reduced speed and low speed differences between entering and circulating traffic are thought to be important contributors to roundabout safety. The geometric design of modern roundabouts has many attributes that may influence drivers' selection of path and speed. Deflection at entry is one of the attributes that contributes to both the reduced speeds and low speed differences. The FHWA publication *Roundabouts: and Informational Guide* suggests a method for evaluating geometric designs for adequacy in controlling speed and speed differences. This study evaluated that method against observations of path and speed at two double-lane roundabouts. The results suggest that the method given in the FHWA publication predicts actual operational speed fairly well. A method is described for recording speed and path through approach, circulatory roadway, and departure. This method provides for economical recording of lane position at five locations along a through path, and spot speed at three locations.

INTRODUCTION

The goal of this study was to systematically observe path and speed at two existing double-lane roundabouts, and to relate the observations to geometric design and markings. One of the roundabouts is a relatively small urban roundabout. The other is a relatively large rural interchange roundabout. Because of its exploratory nature, the study was not intended to establish causal relations between roundabout design elements and drivers' selection of speed and path. The study was intended to generate data that can be used to evaluate the adequacy of existing roundabout design guidelines and to suggest directions for additional research. Specific questions addressed are:

- Do the observed paths and speeds through the roundabouts conform to those that would be predicted using the techniques described in the FHWA roundabout informational guidelines?
- Can groups of drivers be identified that respond differently, but in a predictable manner, to the same geometric and marking configuration?

METHOD

Individual vehicles were observed and recorded on video as they traveled through the roundabouts. Only through traffic traveling along the major roadway was recorded, and only for one direction of travel. This report examines path and speed of vehicles that arrived when no other vehicles were present that might influence path or speed. Video analysis yielded speed and path at locations on approach, within, and on exit from each roundabout.

Field Sites

The urban double-lane roundabout was at the intersection of a collector roadway and a shopping access road. In 2001 the Annual Average Daily Traffic (AADT) at that roundabout was 12,025. The interchange roundabout was located on a rural two-lane arterial highway adjacent to the overpass of a major 4-lane highway. Although the highway on which this roundabout is located is two lanes, it expands to four lanes on both sides of the interchange. The most recent AADT for this intersection, which was obtained before it was converted to an interchange roundabout, was 9175.

Small Urban Roundabout

The radius of the central island, with truck apron, is 14 m (47 ft). The radius of the inscribed circle is 24 m (78 ft). Lane width at the entry and within the circular roadway is approximately 5 m (16ft). However, at the exit used in the study, the roadway narrows to 8 m (27 ft), or approximately 4 m (13 ft) per lane. The speed limit is 48 km/h (30 mi/h). Speed advisory placards on the roundabout warning signs are for 24 km/h (15 mi/h).

Interchange Roundabout

All four legs or the roundabout can accommodate 2 lanes of traffic. The radius of the central island, with truck apron, is 22 m (72 ft). The radius of the inscribed circle is 32 m (106 ft). Roadway width at the entry and exits for the main through pathway was 10 m (32 ft), or approximately 5 m (16 ft) per lane. However, roadway width within the circular roadway is considerably greater, 12 m (40 ft). There are no posted speed limits or speed advisory placards in proximity to the roundabout. The nearest posted speed limit prior to the roundabout, 72 km/h (45 mi/h), is more than 3 km (2 mi) upstream. Although a speed study was not done upstream of the roundabout, it is likely that the 85^{th} percentile free flow speed on this portion of the state highway is between 80 and 89 km/h (50 and 55 mi/h).

Video Data Collection Method

Two color CCD “lipstick” video cameras (Panasonic model GP-KS1000) were used at each roundabout. The camera bodies are approximately 1.3 cm (0.5 in) in diameter, and about 7.5 cm (3 in) in length. The cameras are rated by the manufacturer at 560 lines of resolution. One camera was equipped with a 7.5 mm lens, the other with a 3 mm (wide-angle) lens. The cameras were mounted approximately 10 m (33 ft) above the roadway surface. Thirty-three foot leads were used between the camera bodies and the camera control units. Coaxial cables from the camera control units were fed first into Hi-8 recording units, one for each camera. Each image was also fed into a video multiplexer from which the two images were recorded side-by-side onto a third Hi-8 tape. The recording and multiplexing equipment were concealed within a vehicle that was parked out of the view of motorists.

Recording at the small urban roundabout

At the small urban site, both cameras were mounted on a single pole that was attached to a lighting standard located on the splitter island on the eastern leg of the roundabout. One camera imaged the southern entrance. The other camera imaged the central part of the east side of the circular roadway and the northern exit, with sufficient overlap between images to ensure vehicle identification during data analysis.

Recording at the Interchange Roundabout

The interchange roundabout was considerably larger than the urban roundabout, and required three cameras for complete coverage. One camera was mounted on a utility pole that was proximal to the roundabout entrance. A second camera was mounted on a light pole that was approximately midway through the roundabout. A third camera was mounted on a lane-drop warning sign downstream of the exit. The first two cameras were each mounted approximately 10 m (33 ft) above the roadway surface. The third camera was only about 3 m (10 ft) above the roadway surface; a height that proved inadequate for accurate speed estimation. All three camera outputs were first fed into individual Hi-8 recorders and then through a multiplexer to a fourth Hi-8 recorder.

Video Analysis Method

The video analysis began with the identification of vehicles that passed through the intersection one at a time. The multiplexed view was scanned to identify vehicles that traversed the intersection in the absence of other vehicles that might reasonably be expected to have influenced either the driver's speed or path. This criterion required: (1) at least a 4 s time-gap to any preceding vehicles traveling in the same direction, (2) no vehicles approaching from the minor road (i.e., the East leg at small urban roundabout or the South leg at interchange roundabout), and (3) no vehicles within the circular roadway to the driver's left when the subject vehicle reached the edge of the inscribed circle.

Next, the analyst prepared templates for scoring speed and path for each camera view. To measure speed from the video, "speed boxes" were marked on a video monitor. The monitor used for this analysis was a 96 cm (38 in) direct-view CRT. The speed boxes were created by placing white tape on the monitor screen at points on the image that had been established in the field during recording.

The key to estimating speed was the assumption that the video was recorded and played at 30 frames per second. In the laboratory, research team members counted the number of frames required for a part of each vehicle (preferably a tire) to pass through the speed box. The accuracy of this method varies with vehicle speed and the length of the speed box. In general, the speed of each vehicle was estimated to within 1.24 km/h (2 mi/h).

Lane position was assessed at five locations along the subject path: 25 m (84 ft) upstream of the inscribed circle, at the inscribed circle at the entrance, midway through the circular path, at the inscribed circle at the exit, and 25 m (84 ft) downstream of the inscribed circle. Lane position was quantified on a 0 to 8 ordinal scale as follows:

0 Some part of vehicle was beyond the left roadway edge.
1 The left side of the vehicle was within about 10 cm (4 in) of the left lane edge.
2 The vehicle was in the left lane.
3 The right side of the vehicle was within about 10 cm (4 in) of the lane divide.
4 The lane divide was between the right and left wheels.
5 The left side of the vehicle was within about 10 cm (4 in) of the lane divide.
6 The vehicle was in the right lane.

7 The right side of the vehicle was within about 10 cm (4 in) of the right edge of the right lane.
8 Some part of the vehicle was beyond the right roadway edge.

RESULTS

Small Urban Roundabout

At the small urban, 212 vehicles were observed that traveled through the roundabout from South to North. The observations were made between 8 AM and 11 AM on a weekday in the spring of 2002.

To assist in identifying meaningful groups of vehicles that had speed and path profiles similar to each other, but were distinct from other groups, the speed and lane position data for the 212 drivers was submitted to a Ward's method cluster analysis.(*1*) For this analysis, the three speed and five position measures were standardized and submitted to analysis. Although cluster analysis is a numerical procedure, determination of the appropriate number of clusters is subjective. The procedure itself could generate from 1 to n – 1 (i.e., 211) clusters. A five cluster solution was judged to best represent the driving behavior of the small urban sample. This judgment was based on two factors: (1) low within group variability, and (2) distinct differences between groups.

Table 1 shows the 85th percentile speeds for each of the five groups. The predicted speed shown in the table is addressed in the Discussion and Conclusions. In Figure 1, which shows a scale drawing of the small urban roundabout, the speed box at the entrance extended 6 m (20 ft) along the travel path upstream from the crosswalk. The box at the center of the circle was 5.8 m (19 ft) across. The box at the exit had to be moved close to the inscribed circle and extended only 3 m (10 ft) because a tree occluded the camera's view of the planned speed box location. As can be seen in Table 1, entry speeds were relatively high, and there was an approximately 1.4 to 1 ratio between speed at the entrance and speed at mid-circle.

In Figure 1, vehicle icons are used to depict the lane position of each group at each of five locations. The path of all groups was measured perpendicular to the travel way on the same 5 axes, which are indicated by large black arrows in the figure. However, the vehicle icons are displaced longitudinally along the direction of travel to reduce icon overlap. For example, at the center of the circle, Group 5 is depicted following Group 1, which is depicted as following Group 4 even though the positions of all three groups were assessed at the location where Group 3 is depicted. The vehicle icons accurately reflect the lateral lane position at a spot perpendicular to the large arrows in Figure 1. It can be seen that the largest group (Group 1, n = 73) approached the roundabout in the left lane, shifted to right side of that lane at the entrance, hugged the left road edge line at mid-circle, straddled the lanes on exiting, then departed in the extreme right portion of the left lane. The next largest group (Group 2, n = 71) remained in the right lane except through the middle of the circle where it straddled the lanes. The third largest group (Group 3, n = 38) approached at a relatively high speed 53 km/h (33 mi/h) in the right lane, shifted to the left lane through mid-circle, and exited in the right lane. Group 4 was the smallest (n = 14) and was distinguished by approaching in the left lane, but changing to the right lane between mid-circle and the exit. Group 5 had the highest entry and exit speeds. Drivers in this group approached in left lane, straddled the two lanes at the entrance, hugged the truck apron at mid-circle, again straddled the two lanes at the exit, and departed in the left lane.

Groups 3 and 5 are the most problematic from a safety perspective because of their relatively high speed, and lane shifting. Lane shifting presents increased opportunities for conflicts with other vehicles, should drivers try to follow the same paths when other vehicles are present. Therefore, further analysis was conducted of the paths taken by these groups. This analysis included documenting lane position at four additional locations, and more closely examining variation in lane position within these groups.

Group three was identified as the most critical group for evaluation of geometric design because of its size (18 percent of the sample) and speed, which in the overall sample approximated a 92nd percentile speed. Among individual members of this group, any variation in lane position from that shown in Figure 1, was to the left, with the greatest variation upstream of the entrance and downstream of the exit. At the entry, no vehicle in this group was further to the left than straddling the lane division marking. At no point was any Group 3 vehicle further left than the center of the left lane, except that at mid-circle a few of these vehicles hugged the left edge of the roadway.

Among the vehicles in Group 5, most of the lane position variation occurred from the approach through mid-circle; past mid-circle there was no more than 1 m (3 ft) variance in lane position from that shown in Figure 1.

Interchange Roundabout

At the interchange roundabout, 206 vehicles were observed that traveled through the roundabout from West to East. The observations were made between 8 AM and 11 AM on a weekday in the spring of 2002.

Table 2 shows the 85th percentile speeds for five groups identified by cluster analysis. As with the small urban roundabout, entry speed were high, and drivers slowed between the entrance and mid-circle, where speed was still relatively high. However, unlike at the urban roundabout, drivers here accelerated between mid-circle and the exit such that exit speeds were approximately equal to entry speeds.

The exit camera that was mounted about 3 m (10 ft) above the ground, atop a lane drop warning sign. That camera proved inaccurate for speed estimation because the view angle was too acute relative to the roadway surface, and not sufficiently perpendicular to the traveled path. Tests with a radar gun that were completed after the video was recorded yielded nearly identical average speed at the entrance and mid-circle. However mean video speed estimates at the exit were 13 km/h (8 mi/h) higher than mean radar readings. In Table 2, the 85th percentile speeds for the exit were computed by subtracting 13 km/h from the "observed" video estimates. Although the exit speeds as a whole are probably an accurate reflection of actual exit speeds, the individual group speeds at the exit should not be considered to be as accurate as the group speeds at entry and mid-circle. The exit speeds were not used in the interchange roundabout cluster analysis.

The paths of the five groups identified at the interchange roundabout are indicated on the scale drawing in Figure 2. Group 1, the largest group (*n* = 67), approached the intersection from the left lane, straddled the lane at the entrance, moved to the left edge of the travel way at mid-circle, and then exited in the left lane. Group 2, the smallest group (*n* = 16) followed a speed and path profile similar to Group 1, but exited in the right lane. The right lane exit is curious, in that 300 feet downstream of the exit there is a right lane drop. Group 3, the second largest group (*n* = 61), was similar to the small urban Group 3, in that it approached from the right lane, but moved to the center of the left lane at mid-circle. Unlike the Small Urban Group 3, the interchange Group 3 did not depart in the right lane, but rather straddled the lanes on departure. Group 4 was the fastest group, and the third largest group (*n* = 33) drivers. This group came closest to following the "fastest" path as described by Robinson et al.(*2*) That is, Group 4 drivers started in the right lane but moved further right as they entered, then cut all the way to the left by mid-circle, swung back to the right lane as they approached the exit, then began shifting back to the left lane as they departed the intersection.

Group 4 was identified as most problematic from a safety perspective, and therefore most critical for evaluation of geometric design. This group made up 16 percent of the sample, and drove as fast or faster than all the other drivers. Not only did this group have the highest 85th percentile speed of any group, it also exhibited the largest amount of lane shifting, going from right to extreme left and back to the right lane. These lane changes were within the circular part of the roadway. The majority of drivers, those in groups 1, 3, and 5, which constituted 76 percent of the sample tended to stay in or close to one of the two lanes, and thus presented little lane excursion threat of conflict with other vehicles. Although Group 2 drove somewhat slower than Group 4, it also showed a great deal of lane shifting.

DISCUSSION AND CONCLUSIONS

Roundabouts are generally considered safer than conventional at-grade intersections because: (1) there is a reduction in the number of potential conflict points, (2) all traffic travels in the same direction, (3) speed is lower, (4) speed differences between vehicles are reduced, and (5) pedestrians can use the splitter islands for refuge. (*2*) A key feature for controlling speed in modern roundabouts is deflection at the entries. Theoretically, adequate entry deflection at will slow vehicles – before entering the circulatory roadway – to a speed that approximates the speed of vehicles within the circulatory roadway. Thus, deflection contributes to two of the modern roundabout safety advantages: lower speeds and reduced speed differences.

The majority of motorists observed in this study did not slow to a speed that approximated that of circulating vehicles before they enter the circulatory roadway. The speed differentials between the entrance and circular path were 1.4:1 and 1.3:1, respectively, at the small urban and interchange sites. The observed intersections fall slightly outside the maximum recommended speed differential, based on Australian accident data of Arndt and Troutbeck, who recommend limiting entering to circulating speed ratios to 1.25:1.(*3*) Had the speed of vehicles making opposing-direction left-turn movements been considered, the speed differentials probably would have been higher.

In the FHWA publication *Roundabouts: an Informational Guide,* a method is suggested for predicting operating speed from the geometric design for a roundabout.(*2*) It is suggested that designers use that method to verify the adequacy of their design. A variation on that method was applied to the as-built design of the roundabouts observed in this study.

Figure 3 illustrates an approach to estimating the fastest path through the small urban roundabout. This approach is similar to that recommended in the FHWA guide, but was not based on hand drawn curves, and does not use short tangents between the curves. The method employed consisted of the following steps:

1. Draw the fastest through path as described in the FHWA guide. This path puts the centerline of the design vehicle 1.5 m (5 ft) from concrete curbs, and 1 m (3 ft) from painted edge lines. Thus, the right side of a 1.8 m (6 ft) wide design vehicle passes 0.6 m (2 ft) of concrete curbs, and passes flush with painted edge lines.
2. Place three tangent circles over this path such that they overlay this path to the greatest extent feasible and such that the circles maintain the minimum distances between concrete curbs and painted edge lines. Alternatively, the three circles may not be tangential, but rather connected by short tangent sections.
3. Use Equation 1to compute the predicted speed for the radius of each circle, where V is velocity, R is radius in meters, e is superelevation, and f is side friction. The FHWA guide recommends assuming +0.02 superelevation for the entrance and exit radii, and -0.02 superelevation for the circular roadway in the absence of actual values. The US customary unit equivalent equation is provided in the FHWA guide.

$$V = \sqrt{127R(e+f)} \qquad \text{Equation 1}$$

4. This step is not given in the FHWA guide, but is necessary when the radius suggests a substantial difference in speed between the curves. If the change in speed between curves is greater than approximately 1.25:1, determine whether there are constraints that would prevent drivers from accelerating or decelerating to the speeds suggested by the radii.

In Figure 3, the thickness of the circles represents the 2 m assumed for vehicle width. Based on the radii the path shown in Figure 3 would result in a predicted entry speed of 57 km/h (35 mi/h). The side friction was value was estimated using the assumed design for intersections curve from exhibit 3-11 of the AASHTO publication *A Policy on Geometric Design of Highways and Streets 2001*.(*4*)

Predicting speed at the mid-circle location is a bit more complicated, because two factors may govern this speed: (1) the curve radius, and (2) the rate of comfortable deceleration. The higher of these two factors will govern speed at mid-circle. By Equation 1, with 58 m for the radius, -0.02 for the super elevation, and 0.23 for side friction, the speed would be 39 km/h (24 mi/h). To estimate speed based on available deceleration, it is necessary to posit where the driver would begin decelerating. In this case we assumed deceleration began slightly before the inflection point between the first and second curves. In this instance we used a point where the theoretical path entered the circulatory roadway. Further, if we assume that the driver might enter the central curvature a bit fast and reach minimum speed at mid-circle, then the deceleration distance is about 27 m (89 ft). Comfortable deceleration, estimated from exhibit 2-25 of the AASHTO policy book, assuming an initial speed of 57 km/h, speed could reduce to 40 km/h (25 mi/h). Because the speed based on the deceleration is greater than the speed based radius, we used the deceleration based estimate.

Because the radius of the exit is larger than the radius of the central path, we would expect vehicles to accelerate from mid-circle to the exit. Thus exit speed would be the lesser of either (1) speed predicted by the exit curve radius, or (2) the maximum comfortable acceleration over the distance between mid-circle and the location where exit speed was measured. We assumed that the driver would not begin accelerating before the transition to the larger curve. Thus, we measured the acceleration distance from the inflection point at the tangent between the second and third circles, and the location where the third speed measurement was made. That distance was approximately 7 m (21 ft). The estimate based on equation 2, with 77 m (252 ft) radius, 0.02 super elevation, and 0.21 side friction is 47 km/h (29 mi/h). According to exhibit 2-24 of the AASHTO policy, in the 7 m available for acceleration with an initial speed of 40 km/h a speed of about 42 km/h (26 mi/h) could be reached. Thus, the speed based on available acceleration is less than the speed based on the exit radius. So comfortable acceleration governs.

These fastest path speed predictions are very close to the observed speed of small urban Group 3 drivers, and are reasonably close to the observed speed for groups 1 through 4.

The same process was used for predicting speed based on the interchange roundabout design. This resulted in predicted fastest path speeds of 67 km/h (42 mi/h), 45 km/h (28 mi/h), and 55 km/h (34 mi/h) at entrance, mid-circle, and exit respectively. As with the urban roundabout, the predicted speeds are reasonably close to the observed speeds. Because the predicted speeds were for the "fastest path," and because the observed speeds were often equal to or slightly greater than the predicted path, "fastest path" is probably a misnomer. Nonetheless the method does correctly suggest that additional entry deflection is needed to slow entering vehicles to the recommended speed.

The method suggested here for predicting operational speeds is not precise. It is probably accurate to plus or minus 5 km/h (3 mi/h). Additional research would be needed to identify where drivers begin their acceleration or deceleration relative to the inflection points on the fastest path curves. Also, the location of the actual inflection points, and the extent to which tangents be used to join the reversing curves could be further refined. Nonetheless, the method suggested here, if employed during roundabout design, could result in greater speed consistency than might otherwise be the case.

This analysis suggests that, with the addition of checks for available deceleration and acceleration, the current FHWA guidelines for predicting speed and speed differences are adequate. The high predicted entry speeds that resulted from the small deflection at the entries were reflected in the observed speeds at the roundabouts.

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List of Tables and Figures

Table 1. Small Urban Roundabout 85th Percentile Speeds in km/h (mi/h).

Group	Number of Vehicles	Percent of Vehicles	Entrance		Mid-circle		Exit	
1	73	34%	43	(27)	32	(20)	35	(22)
2	71	33%	48	(30)	34	(21)	34	(21)
3	38	18%	53	(33)	39	(24)	37	(23)
4	14	7%	47	(29)	35	(22)	32	(20)
5	16	8%	60	(37)	39	(24)	39	(24)
Predicted Speed			57	(35)	40	(25)	42	(26)
Total	212							

Table 2. Interchange Roundabout 85th Percentile Speed in km/h (mi/h).

Group	Number of Vehicles	Percent of Vehicles	Entrance		Mid-circle		Exit	
1	67	33%	55	(34)	43	(27)	60	(37)
2	16	8%	53	(33)	43	(27)	64	(40)
3	61	30%	55	(34)	43	(27)	56	(35)
4	33	16%	71	(44)	55	(34)	64	(40)
5	29	14%	55	(34)	43	(27)	56	(35)
Predicted Speed			67	(42)	45	(28)	55	(34)
Total	206							

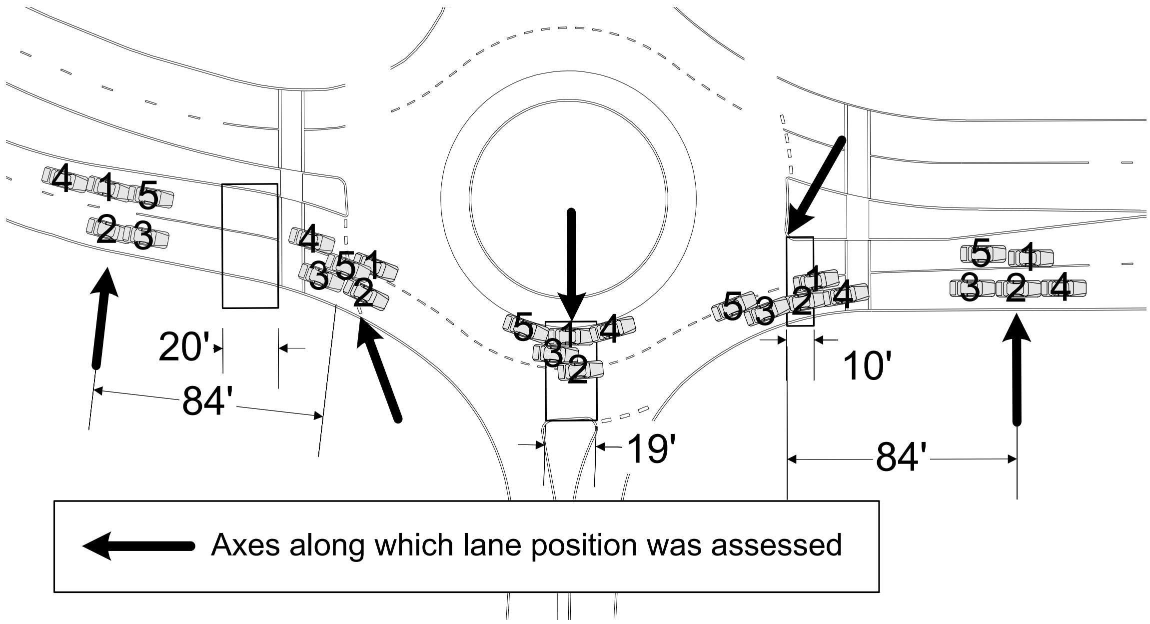

Figure 1. This Scale Drawing of the Small Urban Roundabout Depicts the Mean Lane Position for Each of the Five Identified Groups.

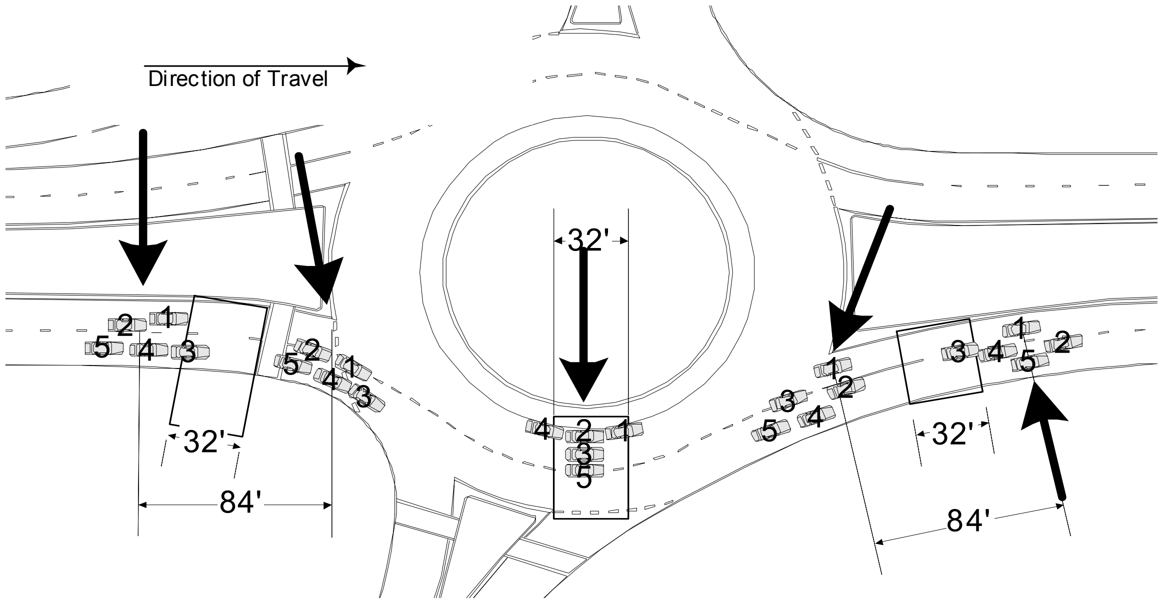

Figure 2. This Scale Drawing of the Interchange Roundabout Depicts the Mean Lane Position for Each of the Five Identified Groups.

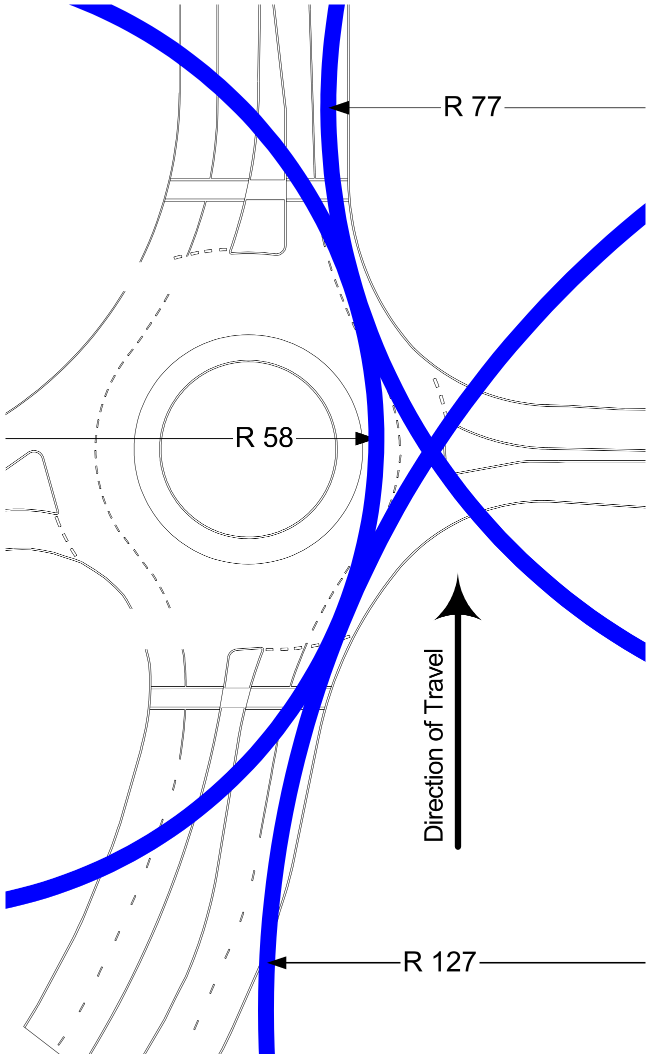

Figure 3. Fastest Path Approximation for Small Urban Roundabout.