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Density Models and Safety Analysis for Rural Unsignalised Restricted Crossing U-turn Intersections

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Abstract

The first objective of this study was to provide designers with a model that would help them assess the suitability of implementing an unsignalized restricted crossing U-turn (RCUT) based on the traffic volume arriving to a given rural intersection. Specifically, this study identified the zones that were most susceptible to bottlenecks and provided regression models that calculate the traffic density as a function of the traffic volume. In addition, the second objective of this study was to look at how the number of traffic conflicts varied with the traffic volume. Two geometric design cases were studied: four-lane and six-lane arterials using 1000 foot long (305 m long) weaving sections. VISSIM traffic simulations were used to identify the critical zones, and calculate the traffic density for different traffic flows. Volumes and densities allowed the development of regression models. Two critical zones were identified: where vehicles coming from the minor road merge to enter the U-turn and where vehicles exiting the U-turn merge to the multilane arterial. Also, based on the classification given by this study to the traffic volumes, a sensitivity analysis determined which of them had the greatest impact on the level of service. For the number of traffic conflicts from simulation, the Surrogate Safety Analysis Model was applied to measure them. This study found that at certain traffic volumes, traffic conflicts rise sharply.

Keywords: J-turn ; RCUT; restricted crossing u-turn ; superstreet

1. Introduction

The restricted crossing U-turn (RCUT), also known as super street or J-turn, is a design typically used when a minor road intersects a major arterial road. This study focuses on applications of the RCUT to stop controlled rural multilane arterial intersections. The RCUT restricts direct through and direct left-turns from the minor road by requiring them to (1) turn right, (2) travel to a median intersection, and (3) make a U-turn through the median. Figure 1 depicts these three steps. After making the median U-turn, the equivalent of making a left-turn is made by continuing through the main intersection, and the equivalent of a through movement is made by a redirected right turn at the main intersection.

The main intersection can be designed to allow direct left-turns from the major road (as the case shown in figure 1), or they can be restricted when opposing through traffic combined with left-turns are heavy. This study focuses on RCUTs which are rural, unsignalized, and with this latter restriction.

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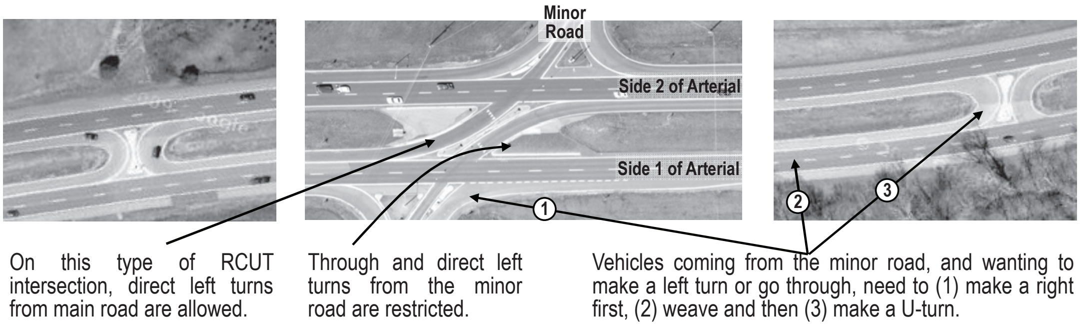

Figure 1 Main features of an unsignalized RCUT intersection in a rural area in Maryland (Google Maps, 2009)

1.1. Objective and Importance of the Research

Implementing an unsignalized RCUT instead of having an at-grade signalized intersection reduces operational costs. And it has been shown through several studies that unsignalized RCUTs diminish the number of accidents (Hummer, & Jagannathan, 2008; Hochstein, Maze, Welch, Preston & Storm, 2009; Hugues, Jagannathan, Sengupta, & Hummer, 2010). Given these benefits, it would be of interest for designers to have a tool that would allow them to assess the viability of implementing an unsignalized RCUT. Such a tool would require having a model that calculates the level of service as a function of, not only the traffic volume, but the geometry of the design. Also, it would require validating the model with several existing RCUTs. This study is just a first step in obtaining such a model. This study does answer the question of how the level of service is affected by the levels of traffic volume arriving to the intersection but it is limited to two specific simulated unsignalized RCUTs. To some extent, this study also takes into account the geometry of the design by providing a model for a four-lane arterial and another model for a six-lane arterial. As the reader will observe, answering the above question through the development of a statistical model, required answering two simpler questions. First, which zones within the RCUT are more prone to present bottlenecks? Second, how should the level of traffic volume be segregated in order to analyze its impact over the level of service? For example, this study found out that attention should be put on where the volume originates and where it ends. The resulting statistical models were used to determine how sensible the level of service is to each of the segregated levels of traffic volumes.

Finally, this study also analyzed some safety features of RCUTs. Specifically, this study provided some graphical insight and argumentation on how the number of "traffic conflicts" from simulation varies with the traffic volumes served by the RCUT. The concept of traffic conflict used in this study is the same as the one used by Amundsen and Hyden (as cited in Gettman, G., Pu, L., Sayed, T., & S. Shelby, p. 4): "an observable situation in which two or more road users approach each other in time and space to such an extent that there is risk of collision if their movements remain unchanged". Traffic conflicts and traffic crashes are two different representations. But it is the assumption that an increase of the former increases the probability of occurrence of the latter. Traffic conflicts were recorded for this study using the same simulation data generated for the density models. Although a statistical model could also be developed as with the traffic density, this study found out that a better understanding of the traffic conflicts needs to be addressed before suggesting a credible statistical model.

1.2. Organization of the Paper

This paper is organized as follows. First, a section called "PREVIOUS WORK" shows that although similar studies have been conducted, they have not really addressed the concept of the rural unsignalized RCUT. Second, a section called "METHODOLOGY" presents how an RCUT was simulated using the VISSIM software (PTV AG, 2008) and the assumptions that were made. Also, this section presents how the application of a software package was implemented for counting the number of traffic conflicts. Third, a section called "RESULTS" presents the statistical models that explain, as it is the main objective of this study, how traffic volume affects the level of service. Not only this section provides the estimation of statistical coefficients but it provides the critical areas that are more susceptible to bottlenecks and that in consequence should be part of the model. This section also presents, in a more specific case, how the number of traffic conflicts varies with the traffic volume. Fourth, a section called "DISCUSSION" analyses the implications of the density models and analyses the sensitivity of the level of service to traffic volumes depending on where they originate and end. This section also gives a qualitative explanation to the results obtained in terms of surrogate safety. Finally, conclusions and recommendations for further research are presented.

2. Previous work

The RCUT derives from the original concept introduced by Kramer (1987). His goal was to develop an innovative intersection that would reduce congestion on suburban arterials. The intersection would also have provisions for accommodating pedestrians and transit. Currently, there seems to be no full implementation of Kramer's design. This study utilizes his ideas of (*a*) replacing direct left crossings from the minor road with a U-turn in the median (*b*) allowing high through traffic volumes on the major street and (*c*) having a design which would accommodate the operation of large size vehicles. Intersections with the above three characteristics, implemented in the states of Maryland (Google Maps, 2009a; Google Maps, 2009b) and North Carolina (Google Maps, 2009c), are now known as RCUTs, super streets, or J-turns. As an option (*d*), as in Maryland (Google Maps, 2009a; Google Maps, 2009b) and as in the design used for this study, some RCUTs have an acceleration lane on the major road for right turning traffic from the minor road, and have a deceleration lane at the entrance to the U-turn on the major road.

The research literature on RCUTs is somewhat limited. However, other intersection designs that incorporate some, but not all, of the four characteristics (identified above as *a*, *b*, *c* and *d*) have been the subject of more study (Koepke & Levinson, 1993; Stover, 1994; Maki, 1996; Gluck, Levinson, & Stover, 1999; Al-Masaeid, 1999; Bared, & Kaisar, 2002; Zou, Lu, Yang, Dissanayake, & Williams, 2007). These other designs are suitable for urban settings where speeds range from 45 to 55 mi/h, acceleration and deceleration lanes are absent, medians are narrow (less than 45 ft) and traffic lights are sometimes present.

Regarding RCUTs with the four characteristics mentioned above, the Highway Capacity Manual (National Research Council, 2000) seems to serve as a guideline. Nevertheless, these guidelines fall short. For example, the Highway Capacity Manual (hereafter HCM) does not provide recommendations for freeway segments in which merging, weaving and diverging occur simultaneously such is the case of the RCUT considered in this study (see for example, National Research Council, 2000, exhibit 13-21). In addition, in an example of a freeway that the HCM provides which resembles an RCUT (see National Research Council, 2000, exhibit 13-10b), vehicles enter the weaving segment at one point and exit at another point. But in the RCUT of this study, vehicles do not enter at one point but they merge along the acceleration lane. Also, when vehicles merge, they immediately start weaving. Thus, in the segment previous to the weaving section, merging and weaving happen simultaneously. At the end of the weaving section, vehicles do not exit at one point (as depicted in National Research Council, 2000, exhibit 13-10b) but they exit by diverging along the deceleration lane. Also, weaving and diverging happen simultaneously because many vehicles that need to exit the arterial are not able to finish their weaving along the weaving section. Therefore, the methodology recommended by the HCM for weaving segments and merging or diverging segments does not apply directly to the RCUT.

Two other documents relevant to this study are the work conducted by Hochstein et al. (2009) and the work conducted by Hugues et al. (2010). They both indicate that three are the aspects that dominate the design of an RCUT: the width of the median, the need for adding loons or jughandles, and the offset or distance between the intersection and the U-turn. They state that the first two aspects depend on the longitude of the vehicles that need to use the median and therefore, the guidelines of AASTHO's *Green Book* (American Association of State Highway and Transportation Officials [AASHTO], 2004) should be followed. For the length of the offset, they also recommend following te AASTHO's *Green Book*. Nevertheless, this latter recommendation, as well as other lengths recommended by several State Departments of Transportation of the United States, assume that the RCUT is signalized. For example, the length of 400 ft to 600 ft that AASTHO's *Green Book* suggests is not based on capacity or density limitations but in order to achieve signal coordination. Both studies also state that for unsignalized RCUTS, there is still not a criterion for calculating the length of the offset (Hochstein et al., 2009, p. 4, and Hugues et al., 2010, p. 126).

From the point of view of safety, three studies have reported reduction in the number of collisions after the RCUT was implemented. These reports (Hummer et al., 2008; Hochstein et al., 2009; Hugues et al., 2010) include RCUTs in Maryland which have the four characteristics (*a*, *b*, *c*, and *d*) mentioned above. Nevertheless, no study has generated a model that estimates the number of accidents as a function of the traffic volume that is served by an RCUT.

In 2008, Gettman, Pu, Sayed, and Shelby (2008) implemented and validated a model for identifying traffic conflicts assuming that the trajectories are simulated. This model, called the "Surrogate Safety Assessment Model" (SSAM), was used to develop a software application now available online for free (Siemmens, 2008). Gettman et al. (2008) showed that SSAM is a promising tool in relating simulated conflicts to crashes. For this reason, this study used SSAM to generate a model that could estimate the number of traffic conflicts as a function of the traffic volume that is served.

3. Methodology

This section explains how the simulation of the traffic volume of a typical unsignalized RCUT was made, how the density models were established, and how the traffic conflicts were obtained. First, this section presents the assumptions made in terms of general characteristics, traffic composition, traffic behavior, and specific geometrical features. Then, in the subsection "Traffic Flow Scenarios and Density Measurements", specific traffic scenarios are defined. This subsection also establishes how the RCUT was segmented for its analysis and how traffic volumes were segregated according to their origins and destinations.

The geometry of one of the two RCUTs used for the present study is shown in figure 2. The multilane arterial in this RCUT has four lanes. The minor road in the RCUTs consists of two lanes, one lane in each direction. Vehicles exiting the minor road and entering the major arterial must merge with through traffic on the arterial. If these vehicles need to use the U-turn (for the equivalent of a left or a through movement from the minor road), they must weave across the through traffic on the major arterial.

The second RCUT used for this study presents the same geometry shown in figure 2 except for the fact that the multilane arterial has six lanes. For each RCUT, two sides of the intersection were analyzed separately as depicted in figure 2. The two sides and the two RCUTs led to the definition of four different cases. These will be referred to as: "1st Side-Two Lanes", "1st Side-Three lanes", "2nd Side-Two lanes" and "2nd Side-Three lanes". From each case, one regression model was developed.

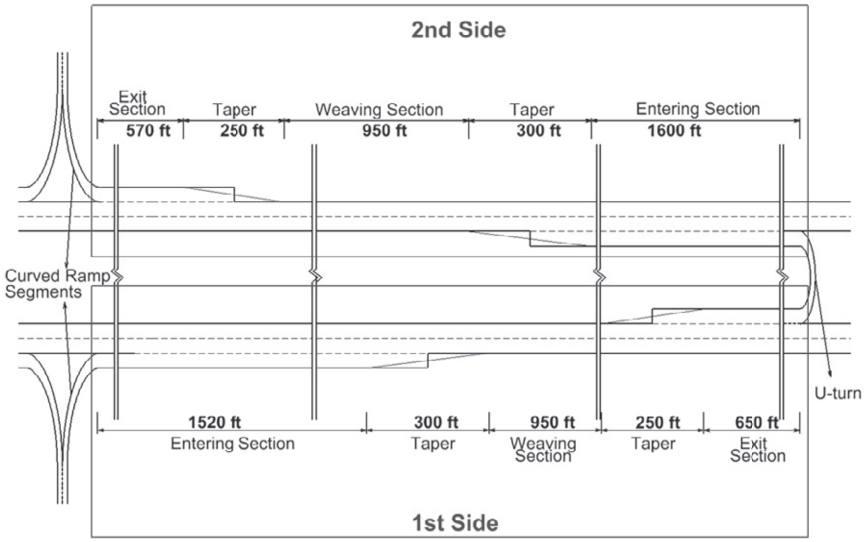

Figure 2 Geometry of the RCUT intersection for this study and its different parts (dimensions on the vertical axis are three times dimensions on the horizontal axis).

In order to simulate the traffic volumes in VISSIM, the following parameters were input. Using the "desired speed" feature within VISSIM, a free flow speed of 60 miles per hour (97 km/h) was used on all arterial segments. A maximum speed of 12 mi/h (19 km/h) was set for the "U-turn" and a 15 mi/h (24 km/h) speed was set for the "free right-turn ramps". The traffic composition was specified as 95 percent cars and 5 percent trucks ("heavy goods vehicles" as identified in VISSIM). The "Freeway" option default from VISSIM was chosen to represent the traffic behavior. This "Freeway" option differs from the alternative "Right-Side rule" option in that it establishes conditions in which merging is more difficult when entering the major road from the U-turn than it is from the minor road.

3.1. Justification for the Dimensions Used in the Simulated RCUT

The dimensions of the RCUT shown in figure 3 were derived from AASHTO's recommendations (AASHTO, 2004) for freeway segments when merging and diverging maneuvers are involved.

On the first side, the acceleration lane of the entrance terminal (at the entering section) requires a length of 1520 ft (463 m) so that, according to AASHTO (2008, p. 847), this distance would allow enough time for vehicles to accelerate from an initial speed of 18 mi/h (29 km/h) to an entering speed of 53 mi/h (85 km/h). The deceleration lane of the exit terminal has a length of 650 ft (198 m) allowing a decrease in speed from 61 mi/h (98 km/h) to 5 mi/h (8 km/h) according to AASHTO (2008, p. 851). These two lengths are conservative considering that AASHTO recommends them for highway design speeds of 70 mi/h (113 km/h) and 75mi/h (121 km/h) respectively, and not 60 mi/h (97 km/h) as was adopted in this study.

On the second side, the acceleration lane is 1600 foot long (488 m long) and the deceleration lane is 570 foot long (174 m long). These values are also recommended by AASHTO (2008, p. 847, 851). The lane width is 12 feet (3,7 m) for all lanes. Figure 3 also presents the simplification made for the modeling of the taper in VISSIM. Instead of modeling a triangular form (which would have implied adding "rules of priority"), the taper is simply split in two halves of regular highway segment where one of them would have one additional lane. The same simplification was made for the flares.

3.2. Traffic Flow Combinations and Density Measurements

Simple observation revealed that the traffic densities in the entering, weaving and exit sections are not only affected by the volume of vehicles passing through them but also by the distribution of that volume among the different paths. For this reason, it is important to identify the paths that pass through the sections. These paths as well as their origins and destinations are presented in figure 3.

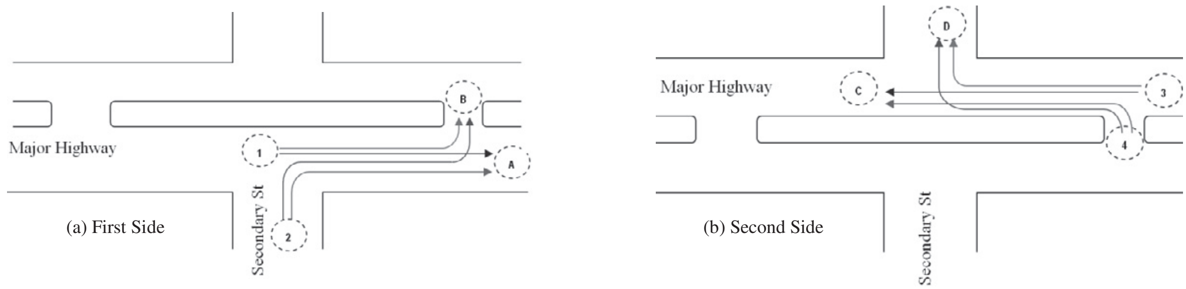

Figure 3 Origins, destinations and paths for each side of the RCUT.

The ranges in the traffic volumes selected for the simulation were such that the resulting densities would be in the neighborhood of 45 passenger-cars per mile per lane (28 passenger-cars per kilometer per lane; this is the limit between Level of Service E and Level of Service F, as defined by the National Research Council, 2000, p. 23-3; the term “passenger-cars” is defined by the National Research Council, 2000, p. 23-9). Hereafter, the abbreviation “pc” will refer to “passenger-cars” and “ln” to lane. The free right-turns from the minor road and the U-turns on the major arterial should not be saturated during the simulation. Otherwise, this saturation can trigger congestion along the weaving section. For this purpose, and according to the HCM (National Research Council, 2000, Exhibit 25-3), the volume of a single-lane ramp with speeds less than 20 mi/h (32 km/h) should not be greater than 1800 pc/h. This limit was multiplied by a factor of 0,3 in order to guarantee free flow on the ramps. Specifically, the volumes chosen for the paths (as defined in figure 3) were such that they complied with the following four constraints (the notation V_{od} will be used hereafter to refer to a volume that starts at origin *o* and ends at destination *d*):

$$V_{2A} + V_{2B} \leq 540\ pc/h \qquad (1a)$$

$$V_{1B} + V_{2B} \leq 540\ pc/h \qquad (1b)$$

$$V_{4C} + V_{4D} \leq 540\ pc/h \qquad (1c)$$

$$V_{3D} + V_{4D} \leq 540\ pc/h \qquad (1d)$$

Preliminary results indicated that the density varies significantly from lane to lane and from segment to segment. Figure 4 shows how the road segments were divided into zones before measuring their corresponding densities. Figure 4 also presents the “critical zones”. The critical zones are those for which the density tends to be the highest. The identification of the critical zones was achieved after observing the density on the ranges of input volumes presented in Table 1. For each combination of traffic volumes, two random seeds were used. Then, shorter ranges (where the density was closer to the neighborhood of 45 pc/mi or 28 pc/km) were used for estimating the density models. Density models were fitted as functions of the four directional volumes presented in table 1. SAS statistical software (SAS Institute, Inc., 2004) was used to estimate the values of the parameters with the best fit (using the procedure “NLIN”).

Table 1 Input Volumes and Number of Simulation Runs used to Identify the Critical Zones and used to Estimate the Density Models (to convert veh/h to pc/h, multiply by 1.025)

Case	Path	Volumes used for Identifying the Critical Zones [veh/h]	Total Number of Simulation Runs for Identifying the Critical Zones	Volumes used for Estimating the Models [veh/h]	Total Number of Simulation Runs for Estimating the Models
1st Side - 2 Lanes	1A	2900 to 6400	552	2900 to 4100	274
	1B, 2A, 2B	100 to 400		100 to 400	
1st Side - 3 Lanes	1A	4000 to 6400	674	4000 to 6400	674
	1B, 2A, 2B	100 to 400		100 to 400	
2nd Side - 2 Lanes	3C,	3100 to 6200	586	3100 to 4200	440
	3D, 4C, 4D	100 to 400		100 to 400	
2nd Side - 3 Lanes	3C,	4800 to 6200	534	4800 to 5800	400
	3D, 4C, 4D	100 to 400		100 to 400	

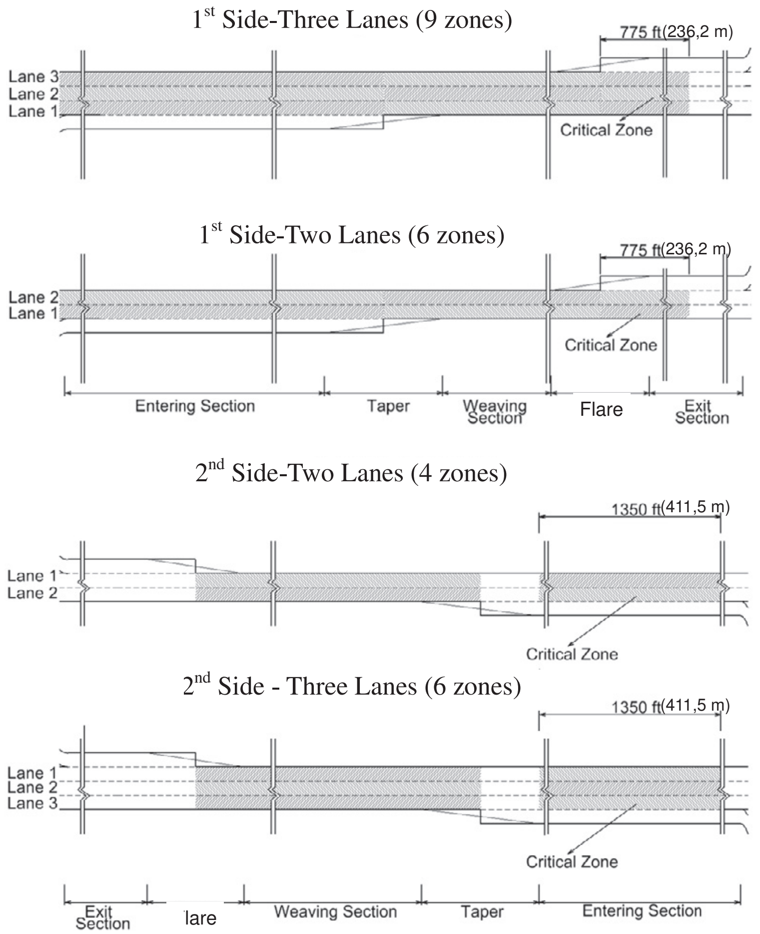

Figure 4 Zones at which the density was measured and zones that were critical (Notice that zones that are contiguous have their hatchings in opposite directions).

3.3. Implementation of the SSAM Software Application

For this study, the case "1st Side - Three Lanes" was used to observe the number of traffic conflicts. The SSAM software application, which is available online for free (Siemmens, 2008), was used to count the number of simulated traffic conflicts. The SSAM application is fed with the trajectory files that the VISSIM generates. In addition to the trajectory files, the SSAM application requires as input several parameters. These parameters are shown in Table 2. For each parameter, a minimum and a maximum value were required in order to determine a range of values at which two trajectories of two vehicles should be considered as a traffic conflict. The precise definitions of these parameters appear in the report that validated the SSAM application (Siemmens, 2008).

Table 2 Ranges used for the Parameters in the SSAM Application for the case "1st Side-Three Lanes"

Parameter	Description	Minimum	Maximum
TTC	Minimum time to collision	0.01 s	1.5 s
PET	Minimum post-encroachment	0.01 s	5 s
MaxS	Maximum speed	5 ft/s (1,52 m/s)	30 ft/s (9,14 m/s)
DeltaS	Maximum speed differential	1,748 ft/s (0,53 m/s)	10,778 ft/s (3,29 m/s)
DR	Initial deceleration rate	-7.834 ft/s^2 (2,38 m/s^2)	0,36 ft/s^2 (0,11 m/s^2)
MaxD	Maximum deceleration rate	-8 ft/s^2 (-2,43 m/s^2)	0,36 ft/s^2 (0,11 m/s^2)
DeltaV	Vehicle velocity change had the event proceeded to a crash	1,119 ft/s (1,34 m/s)	6,977 ft/s (2,12 m/s)

Once the SSAM application is executed, one obtains the number of conflicts for the whole area considered. For this reason, the observations obtained in this study do not correspond to a street segment but to a wide area. For the case "1st Side - Three Lanes", this area is delimited by the corresponding box shown in figure 2.

4. Results

This section presents the results obtained in the following order. First, the zones most susceptible to high levels of congestion are identified. Second, for these critical zones, this section presents the estimation of the regression models that predict the level of congestion. Finally, the distribution of traffic conflicts is shown as well as the distribution of traffic speeds.

4.1. Zones most susceptible to high levels of congestion (critical zones)

The simulation runs showed that in the first side, the highest density occurs at the "Exit Section" on the second lane adjacent to the U-turn. In this zone, some vehicles have to stop in order to change lanes and enter the U-turn. As a consequence, queues are sometimes generated during high volumes (this situation will be later depicted in figure 7). On the second side, the congestion appears on the inside lane (lane adjacent to the median) of the "Entering Section". In this zone, the lane is already congested and the traffic flow is impacted by the vehicles trying to merge into it. Figure 4 shows the exact location of these critical zones.

4.2. Density models

Having identified the critical zones, a statistical model was fitted for each of the four cases. Each model estimates the density on the critical zone based on input volumes with the constraints shown in expressions 1a to 1d. These volumes generate densities between 30 pc/mi/ln (18 pc/km/ln) to 70 pc/mi/ln (44 pc/km/ln) approximately. Below are the selected density models for each of the four cases. For a 95 percent confidence level, all the coefficients presented below are statistically significant.

4.2.1. 1st side-two lanes

Equation (2) presents the regression model with the best fit found. The coefficient of determination (R^2) is equal to 0.69.

$$\rho = exp(0.9263 \cdot V_1 + 0.7770 \cdot V_{2A} + 2.4816 \cdot V_{2B}) \quad (2)$$

where, following the convention established in figure 4a,
ρ is the density in pc/mi/ln in the critical zone,
V_1 is the total input volume in thousands of pc/h coming from origin 1,
V_{2A} is the input volume in thousands of pc/h coming from origin 2 to destination A, and
V_{2B} is the input volume in thousands of pc/h coming from origin 2 to destination B.

4.2.2. 1st side-three lanes

Equation (3) presents the model with the best fit. Its R^2 is equal to 0.81.

$$\rho = exp(0.5955 \cdot V_1 + 1.1406 \cdot V_{2A} + 1.4239 \cdot V_{2B}) \quad (3)$$

where the variables are defined as for equation (2).

4.2.3. 2nd side-two lanes

Equation (4) presents the model with the best fit. Its R^2 is equal to 0.89.

$$\rho = exp(0.8535 \cdot V_3 + 2.1926 \cdot V_{4C} + 2.0040 \cdot V_{4D}) \quad (4)$$

where, following the convention established in figure 4b,
ρ is the density in pc/mi/ln in the critical zone,
V_3 is the total input volume in thousands of pc/h coming from origin 3,
V_{4C} is the input volume in thousands of pc/h coming from origin 4 to destination C, and
V_{4D} is the input volume in thousands of pc/h coming from origin 4 to destination.

4.2.4. 2nd side-threelLanes

Equation (5) presents the model with the best fit. Its R^2 is equal to 0.82.

$$\rho = exp(0.5923 \cdot V_3 + 1.7582 \cdot V_{4C} + 1.5648 \cdot V_{4D}) \quad (5)$$

where the variables are defined as for equation (4).

Other combination of input variables were tried without generating improved models. The above models are four-dimensional. In consequence, they do not have a straightforward graphical representation. Nonetheless, it is worth observing how the density varies according to only two variables. For the case "1st SideThree-Lanes", Figure 5a presents how the density varies as a function of volume V_1 and volume V_2 (volume V_2 is all the volume that originates at Origin 2 or equivalently, it is the sum of volume V_{2A} and volume V_{2B}).

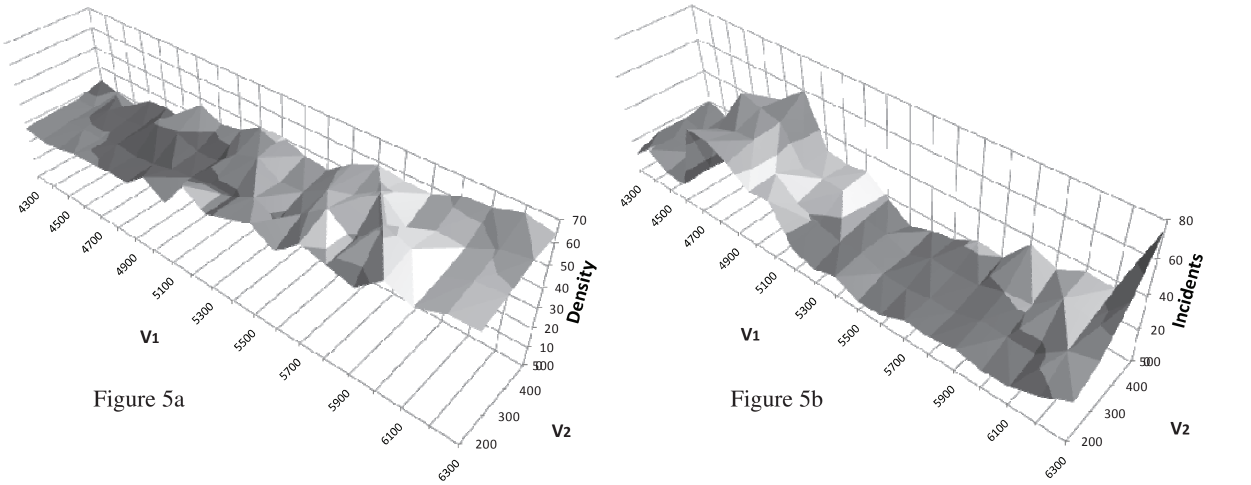

Figure 5 (a) Density values observed in the critical zone for the 1st Side-Three Lanes as a function of V_1 and V_2. Volumes are in veh/h and densities are in veh/mi. (b) Traffic conflicts observed in all lanes and segments of the case 1st Side-Three Lanes as a function of V_1 and V_2. Volumes are in veh/h.

4.3. Traffic conflicts

Figure 5b presents the distribution of the traffic conflicts obtained from the SSAM application as a function of the traffic volume. Figure 5b uses the same input volumes used in figure 5a and also only focuses on the case "1st Side-Three Lanes". The traffic conflicts shown in figure 5b are not limited to those found in the critical zones but include all the street segments within the box shown in figure 2.

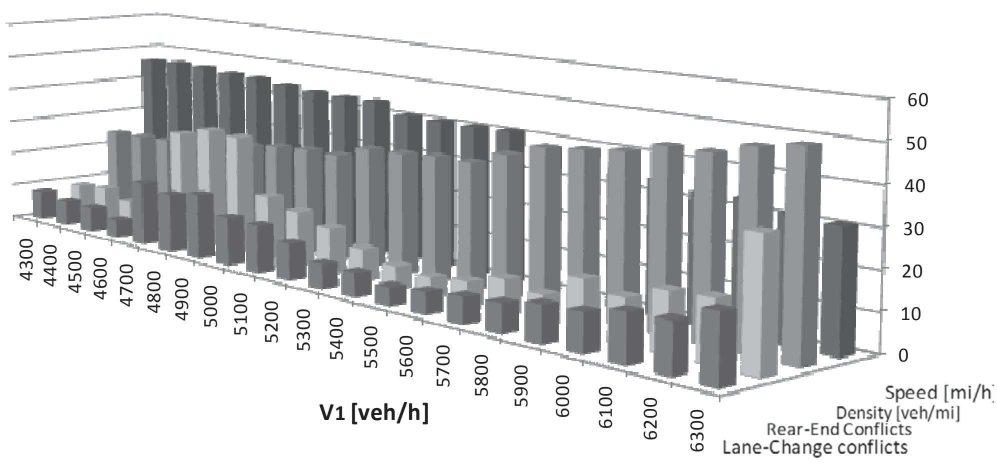

Figure 6 Number of lane change conflicts, number of rear end conflicts, and average speed and traffic density as a function of V_1. Values correspond to the case "1st Side-Three Lanes". Average Speed was measured on all the zones. Traffic density was measured on the critical zone. These zones were depicted previously in figure 4.

The SSAM application discriminates conflicts according to the driving maneuver that causes them. Therefore, conflicts are classified as lane-change events, rear-end events, crossing events or unclassified events. All conflicts obtained in this study and presented in figure 5b are due only to either rear-end events or lane-change events. Figure 6 shows the number of these two types as a function of volume V_1.

On the same axis where the conflicts are presented, figure 6 also shows the average speed on all the zones depicted in figure 4. As it will be explained in the next section, some relation between the traffic conflicts and the average speed can be observed from putting these two measures on the same axis. For consistency, figure 6 also shows the traffic density measured only on the critical zone depicted in figure 4. Figure 7 presents a steady increase in the density and a steady decrease in the speed as volume V_1 ranges from 4300 veh/h (1433 pc/h/ln) to 6300 veh/h (2100 pc/h/ln).

5. Discussion

Equations (2) and (3) present the density in the critical zone as a function of the total volume coming from the major arterial (V_1), and separately the volumes V_{2A} and V_{2B} which come from the minor road. In both equations, volume V_1 has more influence on the density since through volume is much higher than entering volumes. The volume of traffic weaving to make the U-turn (V_{2B}) has a higher coefficient than the traffic merging and continuing (V_{2A}).

Equations (4) and (5) are in some sense analogous to equations (1) and (2). Again, volume coming from the major arterial (V_3) has the greatest influence. All volumes starting from the U-turn (V_{4C} and V_{4D}) have a comparable impact; however, when considering volumes V_{3C} and V_{3D} separately, this separation does not generate satisfactory models.

For more insight on the models obtained above, the following sensitivity analysis was conducted. This analysis allowed assessing how the traffic density is affected by changes in the weaving volumes.

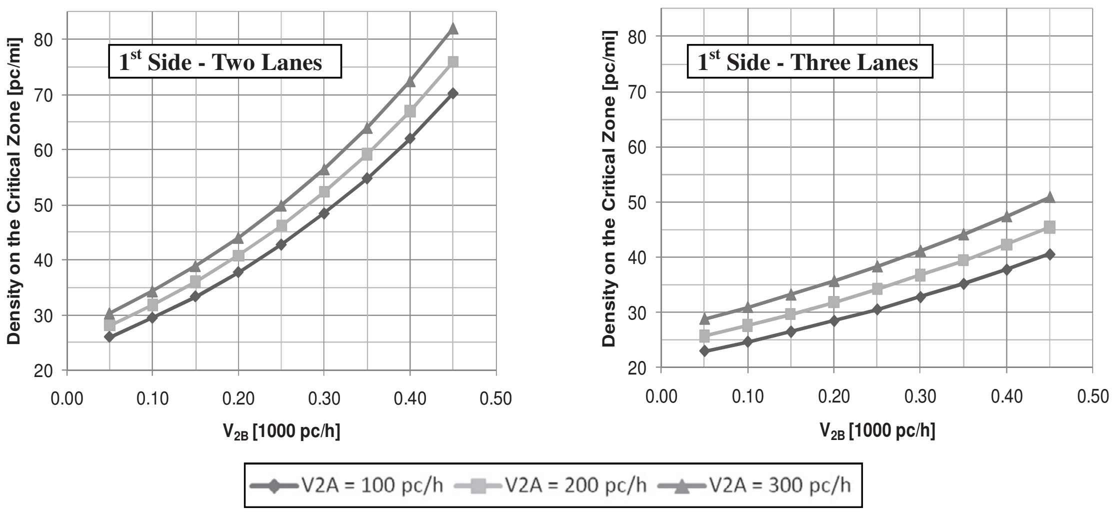

Figure 7 Sensitivity of the density (on Exit Section-Lane 1) to the volume of vehicles that weave (V_{2B}). Volume coming from major arterial (V_1) is 1650 pc/h/ln.

For the “1st Side Two Lanes” case and the “1st Side Three Lanes” case, figure 7 presents how the density on the critical zone varied with the weaving volume V_{2B}. Input volumes of 1650 pc/h/ln on the major arterial and three levels of merging volumes V_{2A} were used to estimate densities around 45 pc/mi/ln (28 pc/km/ln). According to the HCM, the level of service passes from E to F at a threshold density of 45 pc/mi/ln (28 pc/km/ln). For two-lanes the density increases substantially as a function of the weaving volume when compared with the three-lanes. In the case of three-lanes, Level of Service F is not reached as long as the weaving volume V_{2B} is less than 350 pc/h.

Figure 8 presents sensitivity of the density for the two cases corresponding to the second side. As with the first side, the density increases with the weaving volume (in this case, the weaving volume is V_{4D} instead of V_{2B}). Another observation to note is that the vertical offset between the curves of the same case is wider on the second side than on the first side. This wider offset indicates that the influence of merging through volumes at the U-turn (V_{4C}) have greater impact than volumes that start at the minor road (V_{2A}). Finally, when comparing the three-lane alternative between figure 7 and figure 8, it can be observed that the densities of the second side are higher for the same combination of traffic volumes.

Now, from a safety point of view, figures 5 to 6 present the following findings. In the case analyzed, “1st Side-Three Lanes”, it is natural to expect an increase of traffic conflicts as traffic density increases. Figure 5a and figure 5b confirm this expectation but raise the following question: Why does the number of conflicts also increase in the range 4700 veh/h (or 4818 pc/h or 1605 pc/h/ln) to 4900 veh/h (or 5023 pc/h or 1674 pc/h/ln), that is, when the density is not particularly high? Figure 6 suggests that while the average speed is above 40 mi/h (64 km/h), the number of conflicts increases steadily as the density increases. But, once the density is high enough that the speed falls below 40 mi/h (64 km/h), the conditions for increased safety are triggered: As the speed falls below 40 mi/h, the number of conflicts drops dramatically. Perhaps this drop in the number of conflicts is explained when comparing the number of rear-end conflicts vis-à-vis the number of lane-change conflicts. Conflicts emerge, not so much from the weaving maneuvers, but from the formation of queues due to vehicles that fail to weave on time to exit the major road into the U-turn. This observation is depicted in figure 9. Once the average speed falls below 40 mi/h (64 km/h), vehicles have more time to make the necessary lane changes to enter the U-turn.

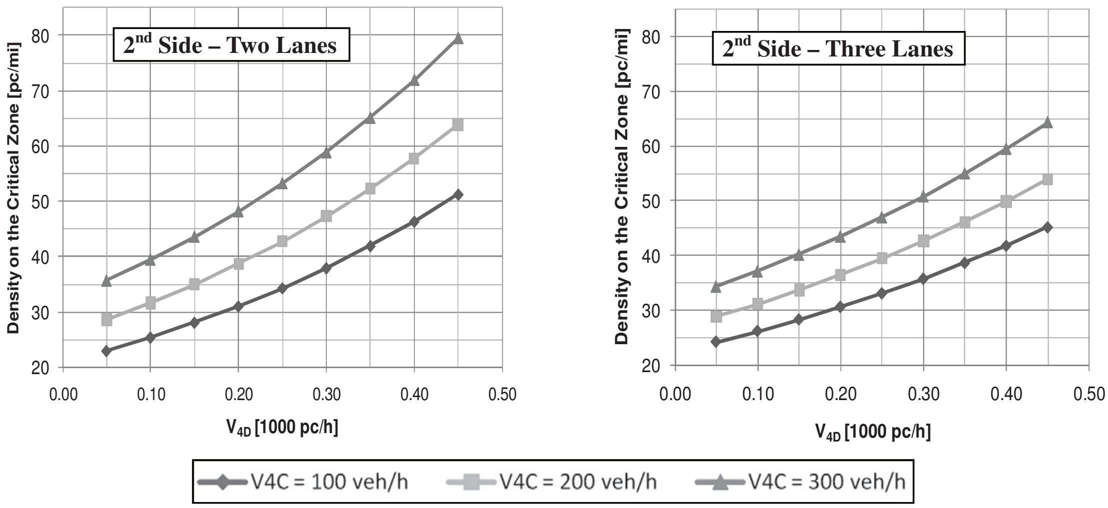

Figure 8 Sensitivity of the density (on Entering Section-Lane 2) to the volume of vehicles that weave (V_{4D}). Volume coming from major arterial (V_3) is 1650 pc/h/ln.

Stating that 40mi/h (64 km/h) is the threshold where the number of conflicts drops comes with two caveats. First, the speed (shown in figure 6) is an average of all the speeds on the zones depicted in figure 4. Therefore, the threshold of 40 mi/h (64 km/h) varies depending on which zones are used to measure the average speed. Second, it is not known the probability with which vehicles would dare to stop like the one depicted in figure 9.

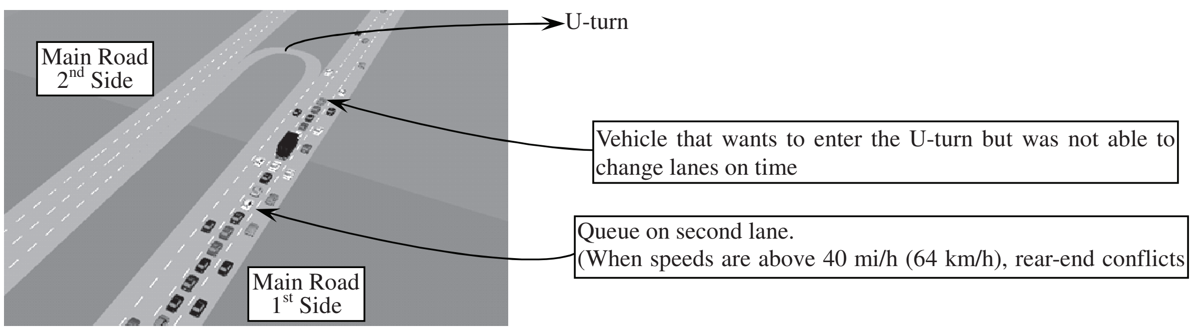

Figure 9 Sensitivity of the density (on Entering Section-Lane 2) to the volume of vehicles that weave (V_{4D}). Volume coming from major arterial (V_3) is 1,650 pc/h/ln.

In conclusion, in terms of safety, when deciding whether to implement or not implement an RCUT, the designer's decision should be based on what the density models indicate but adopting two of the following measures. One such measure is to put in place speed-reduction signalization. Probably, vehicles should not be allowed to go at speeds higher than 40 mi/h (64 km/h). The second measure would be to put in place signing that tells drivers not to stop on the weaving or exit sections.

6. Conclusions and further research

In this study, planning density models were developed for two and three-through-lanes RCUTs. For each configuration, one model was developed for one side of the arterial and another one for the other side. These four models will allow planners to avoid recommending an RCUT that would lead to an unacceptable level of service, when the capacity of the RCUT is surpassed.

The four models presented here, from equation (2) to equation (5), calculate the density on the most critical zone (as indentified in figure 4) as functions of traffic volumes that go through the weaving section of the RCUT. Coefficients of these volumes are generally different from each other and all coefficients are statistically significant.

This study made the following findings. First, the coefficients on the models indicate that the density is obviously most influenced by the total traffic volume that comes from the major arterial (specifically V_1 on the first side and V_3 on the second side). Entering volumes from the minor road that are merging and weaving are also significant variables. On the first side, weaving volume has a higher impact on density than merging, especially more for the two through lanes than the three through lanes. On the second side, equation (4) and equation (5) revealed that impacts of merging and weaving volumes from the U-turn are comparable. This is a consequence of the difficulty that vehicles have when merging from the U-turn to the inside or median lane of the arterial. On the first side where the same volumes are used per lane, the addition of a third lane does reduce the density considerably. On the second side, with the addition of a third lane, the reduction in density is smaller.

When analyzing the safety aspects of the RCUT, the results in this study suggest that careful attention should be given when volume V_1 ranges between 1605 pc/h/ln to 1708 pc/h/ln. Since the number of conflicts increase in this range, especially lane change conflicts, any or both of the following measures should be adopted: Signing advisory speed reductions of, probably, 40 mi/h (64 km/h), and other signs that tell drivers not to stop on the weaving or exit sections.

As mentioned in the subsection “Objective and Importance of the Research”, this study is just the first step in building a density model that also takes into account more variables such as the length of the acceleration and deceleration lanes as well as the length of the weaving section. Besides validating the four models of this study, further research could focus on including input volumes that generate densities not only in the neighborhood of 45 pc/mi (28 pc/km, limit between Level of Service E and Level of Service F), but also densities much closer to free flow conditions. A comparison can also be made between the equations obtained in this paper (2 to 5) and those proposed by the HCM when considering the RCUT as a chain of separate merging, weaving and diverging phenomena. In respect to traffic safety, causes of the rise of conflicts for low volumes should be studied (specifically, as shown in figure 7, when V_1 is between 4700 veh/h or 1605 pc/h/ln and 4900 veh/h or 1674 pc/h/ln). Results on whether signing would reduce these levels of conflicts should also be studied in more detail.

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