RELATIONSHIP BETWEEN ROUNDABOUT GEOMETRY AND ACCIDENT RATES

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ABSTRACT

This paper describes relationships between roundabout geometry and accident rates for one hundred roundabouts from throughout Queensland, Australia. Regression analyses are undertaken on 'single vehicle', 'approaching rear end', and 'entering/circulating' accident categories. After various trials, it was found to be most important that accident models incorporate appropriate explanatory variables. The models described here were based on the concept of exposure and propensity, and on observed driver behavior. The driver behavior model developed in this study uses the 85th percentile speeds on each geometric element and the location of vehicle paths through the roundabout. The single-vehicle accident model included traffic flow, length of driver path on the geometric element, 85th percentile speed on the previous geometric element, and radius of the geometric element. This model demonstrated the importance of limiting the difference between the expected drivers' speeds through successive geometric elements. The approaching rear-end vehicle accident model included approaching and circulating traffic flow, and approach speed. This model demonstrated the importance of limiting the approach speed. Similarly, the entering/circulating vehicle accident model included approaching and circulating traffic flow, and relative speed between entering and circulating vehicles. This model demonstrated the need to minimize the relative speed between entering and circulating vehicles. A brief discussion on the application of this research to other intersection types and roadways is given.

INTRODUCTION

The design of any type of roadway including intersections is a compromise between the following factors:

- *Capacity or Delay*
- *Safety*
- *Cost*

A good balance between these factors is required to obtain optimum intersection performance. To achieve a good balance, it is necessary to understand how the geometric design affects each of these factors. A geometric parameter which increases capacity and reduces delay may have an adverse effect on safety. Another geometric parameter may increase both capacity and safety but substantially increase construction costs.

A substantial amount of research on the effect of roundabout geometry on capacity and delay has already been completed. For instance, Troutbeck (*1*) has shown how several geometric parameters affect roundabout capacity and queuing delay. This paper reviews the results of a study to relate roundabout geometry to safety.

Numerous studies have been undertaken to compare the safety of roundabouts to other intersection types e.g. Lalani (*2*); Jordan (*3*); and The Country Roads Board of Victoria (*4*). These studies show that roundabouts are a safer intersection type for vehicle occupants and pedestrians, but may be more dangerous for cyclists. This safety record has been found to apply in Australia, the United Kingdom, and several other European countries.

MAYCOCK AND HALL'S RELATIONSHIP OF GEOMETRY TO SAFETY OF ROUNDABOUTS

Maycock and Hall (*5*) analyzed accidents at 84 roundabouts in the United Kingdom and this is regarded as a benchmark paper on the subject. Maycock and Hall found that entry path curvature, entry widths and the proportion of motorcyclists had a substantial effect on accident rates at roundabouts. The angle between entry arms and the gradient had only a small effect on accident rates. Finally, visibility, approach curvature and approach width affected accident rates but the mechanism giving rise to this could not be identified.

It is expected that the results from Maycock and Hall's study cannot necessarily be applied to Australian conditions for the following reasons:

- *Driver behavior in Australia may be different to that encountered in the United Kingdom.*
- *Roundabout geometry in Australia is not identical to that in the U.K.*
- *Different traffic conditions occur in Australia than in the U.K.*
- *A number of other parameters expected to influence safety at roundabouts either were not considered by Maycock and Hall or were not found to be statistically significant.*

DATA COLLECTION AND REVIEW

One hundred roundabouts on urban and rural arterial roads throughout Queensland, Australia, were selected at random. Geometric data, traffic volume data, and accident data were then collected from the relevant authorities and from on-site surveys. A total of 492 major accidents, each accident with over $1000 property damage and/or personal injury, were recorded over a five year period from 1/1/86 to 31/12/90 at these 100 roundabouts. Data for minor accidents could not be obtained. Figure 1 shows the various geometric elements of a roundabout. 'Give way' signs are placed on each roundabout approach leg so that the approaching traffic gives way to the circulating traffic. This is the Australian equivalent of the American 'entering-traffic-yield modern rotary'.

Figure 1 also shows the accident types that were recorded. The major accidents are categorized in Figure 2.

SINGLE-VEHICLE ACCIDENT PATTERNS

Most single-vehicle accidents occur as drivers lose control of their vehicle and collide with part of the roundabout (e.g. curbing or traffic sign) or overturn. The majority of single-vehicle accidents are caused by a driver traveling too fast to adequately negotiate the particular geometric element for the particular conditions. Slippery road conditions are significantly overrepresented in the data.

Motorcyclists are also overrepresented. Accidents involving motorcyclists are generally more severe and therefore are more likely to be reported. Articulated vehicles are overrepresented in the single-vehicle accident data because they are more prone to overturning.

The single-vehicle accident rate is significantly higher when visibility is reduced for drivers to view the features of the roadway - in wet weather, in fog and at night. In wet weather conditions, the roadway provides less available friction, making it easier to skid.

The single-vehicle accident rate appeared to be higher at sites with the following geometry:

- *High absolute speed on the particular geometric element*
- *Large decrease in speed between geometric elements*
- *Curves where motorists use high values of side friction*
- *Long curves*

MULTIPLE-VEHICLE ACCIDENT PATTERNS

Multiple-vehicle accidents consist of the accident types given in Figure 2. It appears that the major driver error in multiple-vehicle accidents is generally the result of a driver not seeing another vehicle in enough time (or at all) to adjust the speed and position of his/her vehicle to avoid an accident with the other vehicle.

Motorcycles and bicycles are often overrepresented as vehicles that were hit by the vehicle at fault because they are harder to see. Articulated vehicles and trucks are under-represented as vehicles that were hit by the vehicle at fault because they are easier to see. Generally, no particular weather condition or lighting condition is significantly over-represented in multiple-vehicle accidents.

The multiple-vehicle accident rate appeared to be higher in areas consisting of the following geometry:

- *High relative speeds between vehicles*
- *Limited visibility to other vehicles*

For the best practical models, the explanatory variables should be chosen carefully. It was found important to incorporate the following features when developing the accident models.

- *The explanatory variables chosen should not have strong correlation to each other.*
- *The accident equation developed should be logically sound.*
- *Exposure and propensity concepts as explained by Hughes (6) should be used. Hughes explained that accident occurrence equals exposure multiplied by propensity. Exposure equals the number of opportunities for accidents of a given type to occur in a given time in a given area. Propensity equals the conditional probability that an accident occurs, given the opportunity for one.*
- *The propensity is strongly related to driver behavior, and explanatory variables should be based on a driver behavior model.*

As drivers travel along a roadway, they perceive the visual information of the roadway geometry to control the speed and position of their vehicle on the roadway as described in Chapter 16 of Lay (*7*). Two of the major parameters that determine the average speed of drivers on a particular geometric element are the speed environment of the particular section of roadway and the radius of the particular horizontal geometric element the drivers are negotiating.

The speed environment is predominantly related to the average size of horizontal curves used on the section of roadway and the general topography of the area as discussed in Austroads (*8*). The speed environment is the 'mental' speed that an 85th percentile driver will assume that he could travel at on straight, level sections of the road. A means of determining drivers' speed will be described further below.

Drivers use the visual information supplied from the edge line and center line of the roadway to determine a path of travel. Generally, drivers will reduce their workload by using larger radii than the geometric radii. Drivers use the visual information to calculate their planned transitional path and their chosen speed is based on this radius of this path. A method of identifying drivers' paths is also discussed below.

SPEED ENVIRONMENT AND DRIVERS' SPEEDS ON CURVES

The accident models developed in this study require driver speeds on each geometric element to be estimated. This study has adopted the speed environment concepts given in Chapter 2 of Austroads (*8*) to estimate speeds on horizontal curves and straights. The speed environment concepts were originally developed by McLean (*9*) from data measurements on rural roads.

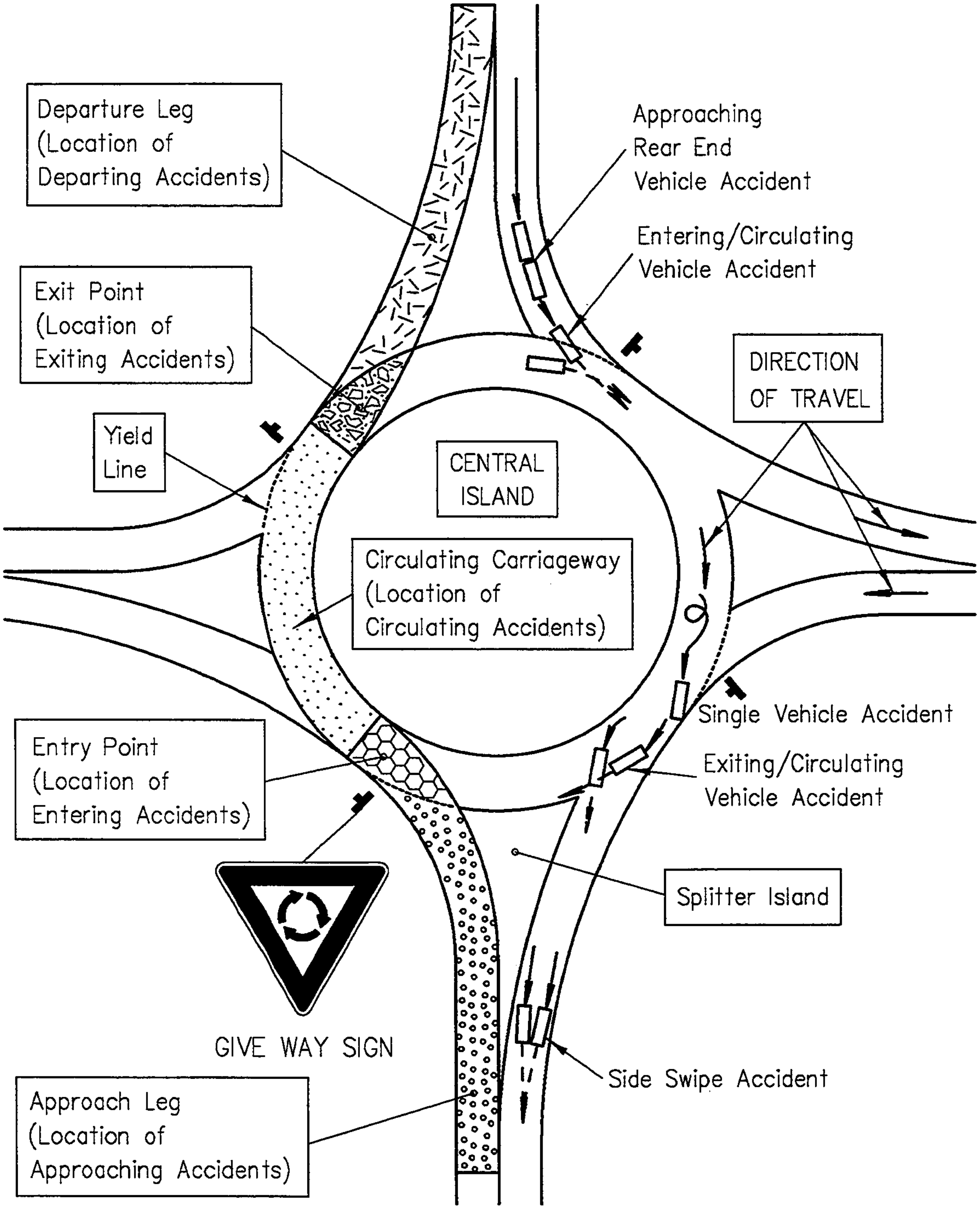


FIGURE 1 **Geometric Elements of a Typical Roundabout and Recorded Accident Types**

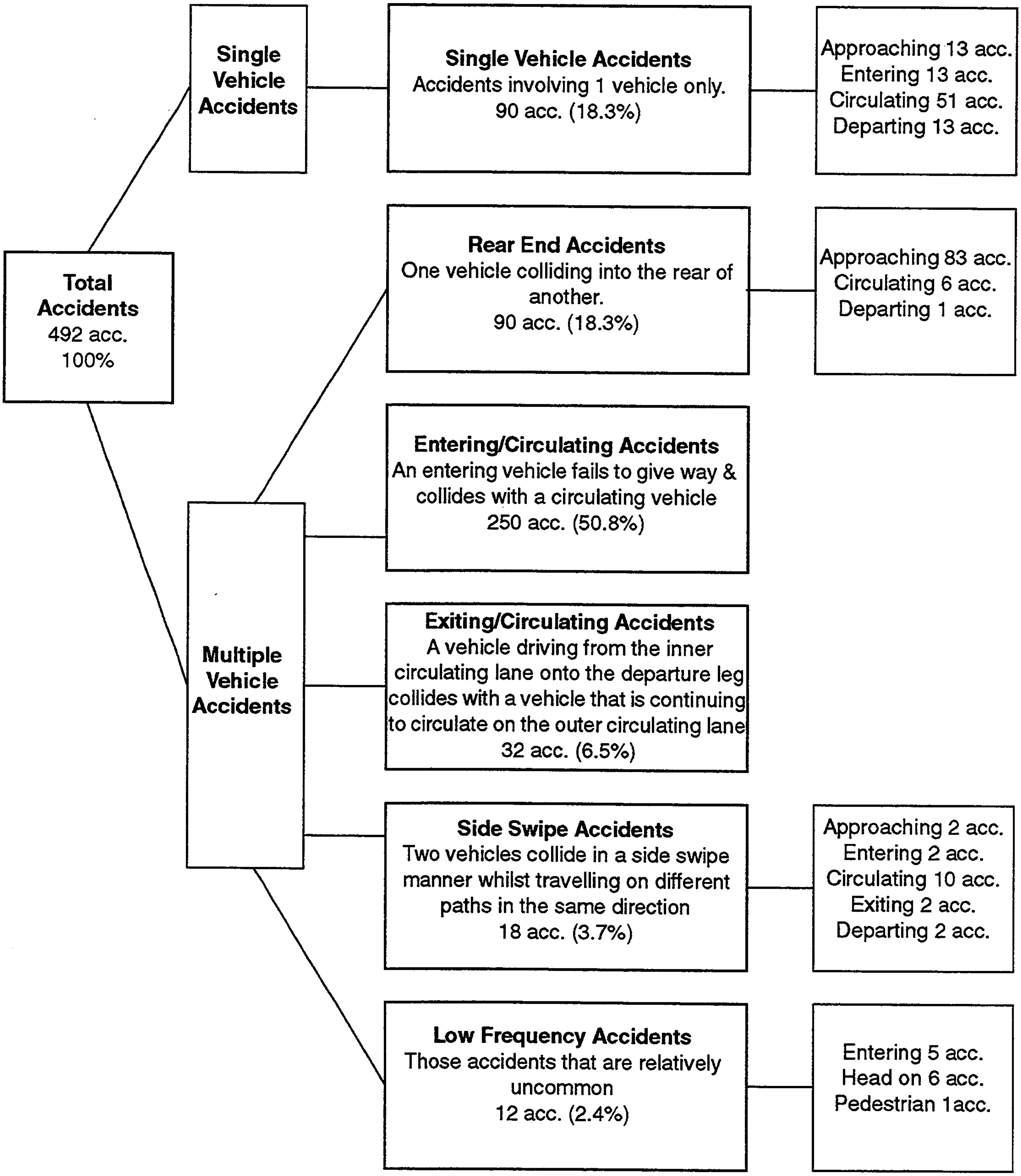


FIGURE 2 Accident Categories Development of Accident Models

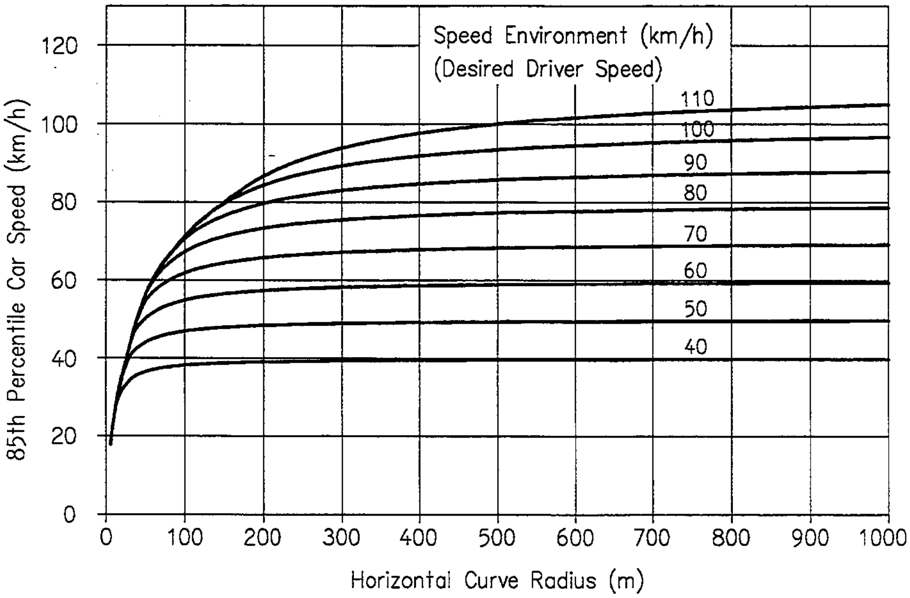


FIGURE 3 85th Percentile Car Speed Versus Horizontal Curve Radius

The original work by McLean (*9*) was required to be modified for the following reasons:

1. By definition of speed environment concepts, it is believed that each desired driver speed curve should reach an 85th percentile speed equal to the speed environment at large values of horizontal curve radii.
2. The curves shown on the graph by McLean do not predict speeds for very small radii or speed environments less than 60 km/h (the curves were not intended to do so!). Some of the roundabouts comprised very small curve radii so prediction of speeds on these elements was required.

To achieve the first requirement above, the original desired driver speed equations were modified so that each desired speed curve would reach an 85th percentile speed equal to the speed environment at large values of horizontal curve radii. The forms of the original desired driver speed equations were changed and were placed through the center of each set of data and through a point equal to the speed environment at zero curvature.

To achieve the second requirement above, an equation was developed to predict 85th percentile speeds in the range of the lower curve radii. This equation was set at a coefficient of side friction of 0.5, which appeared as a general maximum recorded by McLean. This equation therefore limited the coefficient of side friction to 0.5 in the range of the lower horizontal curve radii. The speed prediction models developed are applied to roundabouts by assuming that there was no acceleration between curves. The resultant graph of the developed desired speed curves is shown in Figure 3.

VEHICLE PATHS THROUGH ROUNDABOUTS

On-site inspections at roundabouts revealed that vehicles do not necessarily follow the center line or edge line of the roadway. Drivers transition their paths to obtain the largest possible radii. This reduces the amount of driver workload required and minimizes reductions in their speed.

Actual vehicle paths comprise a series of straights, circular curves and spirals. Spirals are used as drivers cannot instantaneously turn the steering wheel from one position to another. However, it is unnecessarily too complex to model vehicle paths using spirals. A model that predicted vehicle paths through roundabouts based on on-site inspections was developed as discussed below.

For single-lane roundabouts, drivers transition their paths on each geometric element allowing for minimum observed distances from vehicle centerlines to roadway edges/lane lines.

On-site inspections at dual-lane roundabouts revealed that drivers may cut across lanes. The degree to which this occurred appeared to depend on the following factors:

- *The ratio of the speed attainable if the driver completely cuts into the adjacent lane to the speed attainable if the driver stays within his own lane. Most drivers will stay within their correct lane if this ratio is limited to 1.25. It is recommended that, where possible, roundabout geometry be designed to limit this ratio to 1.25.*
- *The presence of lane lines. If lane lines are present, drivers have a lesser tendency to cross them because they can see the edge of their lane.*
- *The proportion of vehicles in bunches. The percentage*

of vehicles that cut across lanes appears to decrease as the percentage of bunched vehicles increases.

However, it was found that generally the majority of drivers stay in their correct lane. This was assumed for the vehicle path model in addition to the observed minimum distances to the roadway edge/lane lines

EQUATION FOR THE SINGLE-VEHILCE ACCIDENT MODEL

The form of the equation of the single-vehicle accident model developed is shown in Equation 1. This model has been based on the concepts given, except that this equation has the additional constant 'C_3'. This term was added so that the equation could be analyzed using a stepwise multiple linear regression analysis program.

$$A_s = C_2 x Q^a x L^b x (S + \Delta S)^c C_1 x Q^a x L^b x (S + \Delta S)^c x f_l^d + C_3 \quad (1)$$

where

A_s = number of single-vehicle accidents per year
C_2, C_1, C_3 = constants
a, b, c, d = constants
Q = average annual daily traffic in the direction considered, i.e., one-way traffic only (veh/d)
L = length of the driver path on the geometric element (m)
S = 85th percentile speed on the geometric element (km/h)
ΔS = decrease in 85th percentile speed at the start of the geometric element (km/h)
f_l = potential coefficient of side friction

The term headed by the C_2 coefficient explains accidents which occur at random locations and generally do not result from a driver traveling too fast for the particular section of roadway. Most single-vehicle accidents that occur on straights and large radii curves are random-event accidents.

The term headed by the C_1 coefficient explains site-specific accidents. Vehicles negotiating curves require side or lateral friction to provide centrifugal acceleration and it is expected that the probability of losing control would be related to the amount of side friction required. It is expected that the use of higher values of potential side friction will result in a greater probability of an accident occurring because greater driving skills are required at higher values of side friction.

A workable solution would be to set the exponent constants 'a' and 'b' in Equation 1 to one. This would mean that single-vehicle accident rates are directly proportional to the traffic flow and the length of the particular element. Zegeer et al. (*10*) found that the single-vehicle accident rate on rural roads was directly proportional to the traffic flow and the roadway length. Maycock and Hall's results gave an exponent for traffic flow of 0.82. A value of 1 is not substantially different from 0.82 especially when considering the nature of accident data. Values of a and b of 0.5, 2, and 3 were tried but the linear relationships were found to give the best results.

A stepwise multiple linear regression analysis found that the exponents c and d are best set at 2 and 1.5, respectively. Accident rates can be expected to be related to the amount of kinetic energy lost, which is a function of the square of the speed, and consequently c was expected to be 2.

The constant C_3 equaled 0.001, which is a small value, as expected. This equation gave an F-test value of 215 and explained 18.1% of the variance in the data. The F-test value at 95% significance for 2 terms entered is 3.0 and the degrees of freedom for this data is 1947. Çompared to studies in other fields, accident studies usually contain a low number of accidents for any particular location and the total number of parameters that have some effect on the result are very large. The proportion of variance explained is usually small.

The single-vehicle accident model does not include every possible parameter that has an influence on single-vehicle accident rates. For example, the crossfall of the circulating carriageway probably has an influence on circulating single- truck accidents. However, the statistical analysis is only reasonably accurate in identifying the major parameters.

If C_3 was forced to be zero and the driver path radius 'R' was used, then equation 1 becomes:

$$A_s = 3.63 x 10^{-14} x Q x L x (S + \Delta S)^2 x (((S + \Delta S)^3 / R^{1.5}) + 47.4) \quad (2)$$

Discussion

The effect of each of the selected parameters from the single-vehicle accident model on single-vehicle accident rates is described here. This is a simplistic look into the effect of these parameters because often the value of one parameter cannot be changed without affecting the value of another parameter/s. An example of this is using a larger radius approach curve. If the approach curve radius is increased 50%, the driver path radius on the approach curve is increased, and the length of the driver path on the approach curve will usually also be increased. This also changes the 85th percentile speed on the geometric element, which affects the decrease in 85th percentile speed at the start of the geometric element.

The single-vehicle accident rate is directly proportional to the traffic flow and the length of the driver path on the geometric element. Figure 4 shows the effect of driver path radius on the single-vehicle accident rate for the example shown in this graph. It shows that for a driver path length of 60m, for a traffic flow of 15000 veh/d and an 85th percentile speed on the previous geometric element of 100 km/h, the accident rate increases substantially as the driver path radius decreases below about 60m.

This graph shows that it is preferable to use the largest curves possible to minimize single-vehicle accident rates. This is usually never possible at roundabouts due to the relatively small radii of the circulating carriageway. Also large radii curves promote high speed at roundabouts which substantially increases multiple-vehicle accident rates as discussed in the sections "Equation for the Approaching Rear-End Vehicle Accident Model" and "Equation for Entering/Circulating Vehicle Accidents". This makes it very important for roundabout approaches in high speed environments to gradually slow drivers. This is best achieved by designing the approach to consist of a number of back to back horizontal curves, each of a smaller radius than the previous horizontal curve, to limit the maximum decrease in speed between successive geometric elements.

Figure 5 shows the effect of the 85th percentile speed on the previous geometric element 'S + ΔS' on the single-vehicle accident rate for the example shown in this graph. It shows that for a driver path radius of 50m, a driver path length of 60m, and a traffic flow of 15000 veh/d, the accident rate increases substantially with an increase in 85th percentile speed on the previous geometric element.

Figure 6 shows the effect of the decrease in 85th percentile speed at the start of the geometric element 'ΔS' on the single-vehicle accident rate for the example shown in this graph. It shows that for a driver path radius of 50m, a driver path length of 60m, and a traffic flow of 15000 veh/d, the accident rate increases substantially as the decrease in speed at the start of the geometric element increases. For this reason, it is important to limit the maximum decrease in speed between any successive geometric elements. A reasonable estimation at the maximum allowable decrease in speed between successive geometric elements at a roundabout to achieve a balance between safety and construction costs would be 20km/h.

Application of the Single-Vehicle Accident Model

Figure 7 shows a typical roundabout in a rural environment which has a 60m central island diameter. The southern approach has a approaching traffic flow of 15,000 vehicles per day and is in a 100km/h speed environment. The driver path on the approach curve is radius 55m for a length of 51m. Applying the single-vehicle accident model (Equation 2) to this example, the southern leg (which includes a 123m straight) has a predicted single-vehicle accident rate of 0.73 accidents/year. The cost for each single-vehicle accident calculates to be approximately $63,300.

Figure 8 shows the same roundabout with the southern approach consisting of three back-to-back horizontal curves, each of a smaller radius than the previous horizontal curve. These curves minimize the decrease in speeds between successive geometric elements. The total accident rate for these three curves is 0.41 accidents per year. This is a 44 percent reduction in the accident rate over the approach given in Figure 7 or a saving of 0.32 accidents per year.

This is a saving to the community of approximately $20,200/year for this approach alone. It is believed that this type of geometry should always be provided on roundabout approaches in high speed rural environments to minimize accident rates.

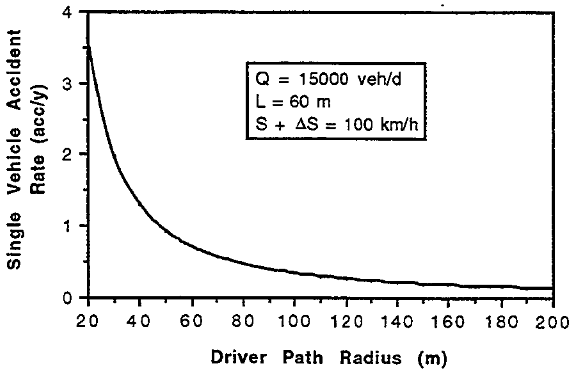


FIGURE 4 Single-Vehicle Accident Rate Versus Driver Path Radius

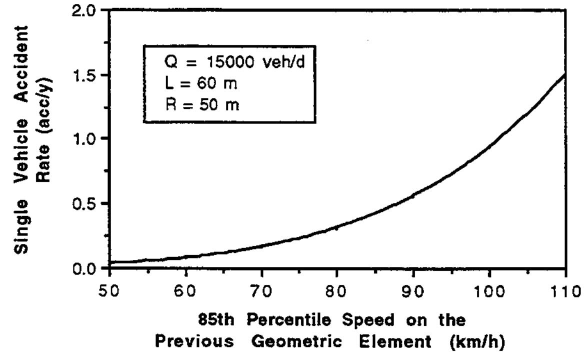


FIGURE 5 Single-Vehicle Accident Rate Versus 85th Percentile Speed on the Previous Geometric Element

These curves should not be excessively long as single-vehicle accident rates are directly proportional to the length of the driver path on each geometric element. Shifting the approach roadway laterally by 7m (as shown on Figure 8) usually enables an adequate layout to be obtained with keeping the lengths to a minimum. If this lateral shift is too small, vehicles may cut into the adjacent lane. The ratio of the speed attainable if drivers cut fully into the adjacent lane divided by the speed attainable if drivers stay in their own lane (on the approach leg) for this example is 19%. This value is small enough that very few drivers will cut into the adjacent lane.

EQUATION FOR THE APPROACHING REAR-END VEHICLE ACCIDENT MODEL

Approaching rear-end vehicle accidents are rear-end accidents occurring on the approach legs. The form of the equation of the approaching rear-end vehicle accident model developed is shown in Equation 3.

$$A_r = C_1 x Q_a^x x Q_c^y x S_a^z + C_2 \qquad (3)$$

where

A_r = number of rear-end accidents per year on the approach curve

C_1, C_2 = constants

x,y,z = constants

Q_a = average annual daily traffic on the approach, i.e., one-way traffic only (veh/d)

Q_c = average annual daily traffic on the circulating carriageway adjacent to the approach, i.e., one-way traffic only (veh/d)

S_a = 85th percentile speed on the approach curve (km/h) - (the potential relative speed between approaching vehicles)

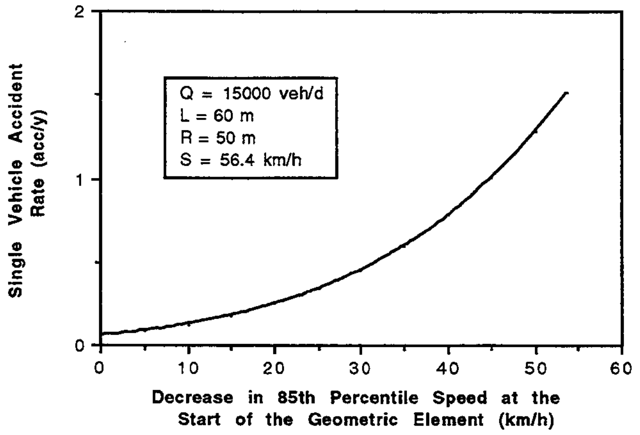


FIGURE 6 Single-Vehicle Accident Rate Versus Decrease in 85th Percentile Speed at the Start of the Geometric Element

A stepwise multiple linear regression analysis found that the exponents x, y and z are best set at 1, 0.5, and 2, respectively. The constant C_2 equaled -0.07 and is a small value as expected. This equation gave an F-test value of 168 and explained 30.6% of the variance in the data. The F-test value at 95% significance for 1 term entered is 3.84 and the degrees of freedom for the data is 381.

Using a regression technique without the intercept term, the analysis gave the following equation:

$$A_r = 9.62 x 10^{-11} x Q x Q^{0.5} x_a S^2 \qquad (4)$$

Equation 4 is an initial equation developed to predict rear-end vehicle accidents on the approach curve. Further refinement of this model is currently being undertaken.

Discussion

The approaching rear-end vehicle accident rate is directly proportional to the traffic flow on the approach. The square root of the traffic flow on the circulating carriageway parameter 'Q_c' in the approaching rear-end vehicle accident model is a function of the accident rate. This means that a doubling of the traffic flow on the circulating carriageway will result in an increase in the approaching rear-end vehicle accident rate of 41%.

Figure 9 shows the effect of the driver path approach radius on approaching rear-end vehicle accident rate for the example shown in this graph. It shows that for an approach leg with a traffic flow of 10000 veh/d, a speed prior to the approach leg of 100 km/h, and a circulating flow of 6000 veh/d, the accident rate increases as the driver path radius on the approach increases.

For this reason, it is important to limit the maximum radius of the driver path on the approach leg. This will limit the 85th percentile speed on the approach, which will minimize the approaching rear-end vehicle accident rate. A reasonable estimation of the maximum allowable 85th percentile approach speed to achieve a balance between safety, practical construction and ease of driver workload would be about 60km/h. In higher speed environments, this will mean limiting the driver path radius on the approach curve to around 60m.

The Application of Hughes' Model to this Data

Hughes (*6*) found the following equation to predict rear-end and side-swipe accident rates at roundabouts:

$$A = 1.61 x Q_a \qquad (5)$$

where:

Q_a = traffic flow on the approach (million vehicles/annum)

This equation explained 33% of the variance in the Hughes' data. Applying the form of this equation to the rear-end accident data on the approach curve in this study, the equation was found to be significant. An F-test value of 63 was recorded and the equation explained 13.8% of the variance in this group of data. The F-test value at 95% significance for 1 term entered is 3.84.

Therefore, Hughes' equation form is significant to this data; however, it is not as significant as Equation 4. It is interesting to note that the approach flow alone explained

33% of the variance in Hughes' data but only 13.8% of the variance in the data in this study. This shows that the data in this study contains more variance. This is possibly because of the wide range of roundabouts chosen, i.e., those with high and low traffic volumes, those with low and high accident rates, and those with various forms of geometry.

EQUATION FOR ENTERING/CIRCULATING VEHICLE ACCIDENTS

The form of the equation of the entering/circulating vehicle accident model developed is shown in Equation 6.

$$A_e = C_1 \; x \; Q_a^x \; x \sum(Q_{ci}^y \; x \; S_{ri}^z) + C_2$$
(6)

where:

A_e = number of entering/circulating vehicle accidents per year
C_1, C_2 = constants
x,y,z = constants
Q_a = average annual daily traffic on the approach, i.e., one way traffic only (veh/d)
Q_{ci} = the various average annual daily traffic flows on the circulating carriageway adjacent the approach from each direction according to Figure 10 (veh/d)
S_{ri} = the various relative 85th percentile speeds between vehicles on the approach curve and vehicles on the circulating carriageway from each direction according to Figure 10 (veh/d)

A stepwise multiple linear regression analysis found that the exponents x, y, and z are best set at 1, 1, and 2, respectively. The constant C_2 equaled 0.067 which is a small value as expected.

This equation gave an F-test value of 46 and explained 10.7% of the variance in the data. The F-test value at 95% significance for 1 term entered is 3.84 and the degrees of freedom for the data is 381.

Using a regression technique without the intercept term and applying the formulae for relative speeds, the analysis gave the following equation:

$$A_e = 3.45 \; x \; 10^{-12} \; x \; Q_a \; x \sum(Q_{ci} \; x \; S_{ri}^2) \qquad (7)$$

Equation 7 is an initial equation developed to predict entering/circulating vehicle accidents. Further refinement of this model is currently being undertaken.

Discussion

The entering/circulating vehicle accident rate is directly proportional to the traffic flow on the approach. The entering/circulating vehicle accident rate is directly proportional to the traffic flow on the circulating carriageway adjacent the approach providing that the directional split of traffic from the first and second preceding leg remains the same.

The square of the relative speed between entering and circulating vehicles is a function of the entering/circulating vehicle accident rate. To minimize entering/circulating vehicle accident rates on a particular approach of a roundabout, the relative speed between entering and circulating vehicles must be limited. A reasonable estimation of the maximum allowable relative speed between entering and circulating vehicles to achieve a balance between safety, practical construction, and cost would be 35km/h.

The relative speed between entering and circulating vehicles can be reduced by any of the following methods:

1. Reducing the 85th percentile speed on the approach curve by providing a smaller radius approach curve and minimizing the entry widths
2. Reducing the 85th percentile speed on the circulating carriageway by any of the following design procedures:
    - Providing tighter deflection through the roundabout by the better positioning of the first preceding approach leg and the next departure leg and minimizing of the entry and exit widths
    - Providing a smaller radius approach curve on the first preceding approach leg
3. Reducing the angle between the two vehicle paths by any of the following design procedures:
    - Increasing of the central island diameter
    - Further separation of the approach and next departure leg
    - Redesigning of the approach curve to be more tangential to the roundabout circulating carriageway.

APPLICATION OF THE ENTERING/CIRCULATING VEHICLE ACCIDENT MODEL

Figure 11 shows a typical two-lane roundabout in an urban environment which has an 18m central island diameter. The southern approach has an approaching traffic flow of 10,000 vehicles per day and is in a 70km/h speed environment. The driver path on the approach curve is radius 110m and the driver path radius on the circulating-through maneuver is 40m. The circulating traffic flows and driver paths are as shown.

Applying the entering/circulating vehicle accident model (Equation 7) to this example, the southern leg has a predicted entering/circulating accident rate of 0.61 accidents/year. The cost for each entering/circulating vehicle accident calculates to be approximately $26,400.

Figure 12 shows the same roundabout with each approach modified to decrease the radius of the driver path on the approach and departure curves and the circulating carriageway. This is undertaken by narrowing of the median and the addition of 'blisters'. Blisters are traffic islands placed on the pavement to slow vehicle paths by decreasing the driver path radius.

The modifications to the roundabout have decreased the entering/circulating vehicle accident rate on the southern leg to 0.32 accidents/year which is a 48% reduction in these accidents. This calculates to be a saving to the community of approximately $8,000/year for this approach alone.

The ratio of the speed attainable if drivers cut fully into the adjacent lane divided by the speed attainable if drivers stay in their own lane (for the circulating carriageway) for both layouts (Figures 11 and 12) is 45%. This means that a significant number of drivers will cut into the adjacent lane if no other vehicles are present. The only way to reduce the number of drivers cutting lanes in this example is to increase the roundabout diameter.

APPLICATION OF THIS RESEARCH TO OTHER INTERSECTION TYPES AND ROADWAYS

The results from this study enable roundabouts to be designed to minimize accidents for a similar construction cost. It is believed that these results may also be immediately applied to all intersection and roadway types to minimize accidents. The parameters that were found to be important in the single-vehicle accident model are expected to correlate with single-vehicle accidents at all roadway and intersection types. These parameters include traffic flow, length of the geometric element, radius, 85th percentile speed, and decrease in 85th percentile speed between successive geometric elements. The decrease in 85th percentile speeds between successive geometric elements is an important parameter when designing rural roads, off ramps of interchanges and approaches to intersections in high speed environments. The decrease in 85th percentile speeds between successive geometric elements should be minimized for optimum safety.

For intersections, drivers should have sufficient warning to slow down before entering the intersection. This is best achieved by using a number of back-to-back horizontal curves, each of a smaller radius than the previous horizontal curve, to limit the maximum decrease in speed between successive geometric elements. The length of each curve should not be excessive as this will actually increase accident rates. Alternatively, they should not be too short as drivers will tend to cut lanes.

When designing rural roads, a larger radius curve may be required at a particular location to ensure that the decrease in 85th percentile speed at the start of the geometric element is not too excessive. If this is not possible, use of a number of back-to-back horizontal curves each of a smaller radius than the previous horizontal curve may be provided prior to the particular curve so that driver speed is reduced gradually. The off-ramps of interchanges and the approaches to intersections may also require such a layout so that driver speed is reduced gradually instead of abruptly at the intersection.

The parameters that were found to be important in the approaching rear-end accident model and the entering/circulating vehicle accident model are expected to correlate with accidents at all roadway and intersection types. These parameters include the traffic flows on the legs, the 85th percentile speeds approaching the intersection, and the relative speeds between vehicles.

The relative speed between vehicles is an important parameter at merge and diverge points of interchanges and at intersections controlled by traffic lights, stop signs or give way signs. The relative speed between any conflicting stream of vehicles should be minimized for optimum safety.

When designing any type of intersection, use of curvature on or near the approaches may be necessary to decrease the relative speeds between vehicles on both traffic streams. If it is possible, reduction of the angle that the two roads meet will lower this relative speed. The use of curves on the approach will lower vehicle speeds, therefore reducing the rear-end accident rate for vehicles in the same traffic stream.

Providing adequate lengths of acceleration and deceleration lanes at interchanges will ensure the 85th percentile speed of drivers on these lanes will be similar to those on the through lanes. This reduces the relative speed between these vehicles, which minimizes the accident rates.

CONCLUDING REMARKS

The accident rate is a function of the propensity of an accident. This is in turn related to the driver behavior. The path drivers take was found to be important and, in general, drivers transition each geometric element within their own lane. However, if the speed attainable by drivers cutting completely into the adjacent lane is significantly higher than the speed attainable by staying in their own lane, a majority of drivers will cut into the adjacent lane. To minimize the number of drivers cutting into adjacent lanes at roundabouts, the ratio of the speed attainable if the driver completely cuts into the adjacent lane to the speed attainable if the driver stays within his own lane should be limited to around 1.25.

Single-vehicle accident rates at roundabouts are dependent upon the speed drivers chose on the previous geometric element and the decrease in speed at the start of the geometric element under consideration. This becomes an important design consideration. The design speed of successive geometric elements at roundabouts should not differ by more than 20 km/h. This means that a number of back-to-back horizontal curves, each of a smaller radius than the previous horizontal curve, may be needed to slow drivers down to a reasonable approach or negotiation speed.

Each curve should not be excessively long as single-vehicle accidents are directly proportional to the length of the geometric element. Alternatively, these curves should not be excessively short as drivers will tend to cut into the adjacent lane. Shifting the approach roadway laterally by 7m usually enables an adequate layout to be obtained with keeping the lengths to a minimum.

To minimize approaching rear-end vehicle accident rates on roundabouts, it is important to limit the 85th

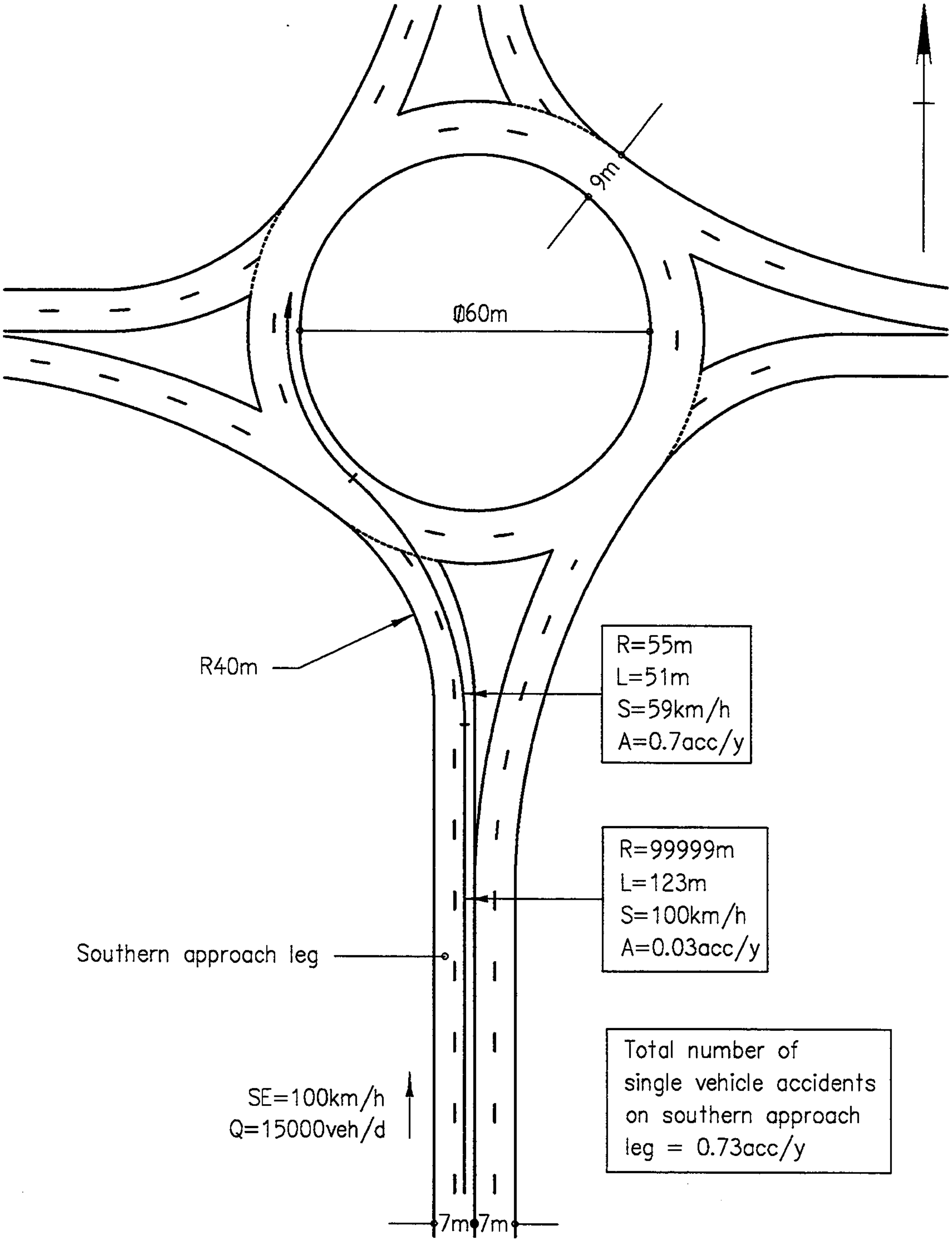


FIGURE 7 Typical Rural Roundabout with One Approach Curve

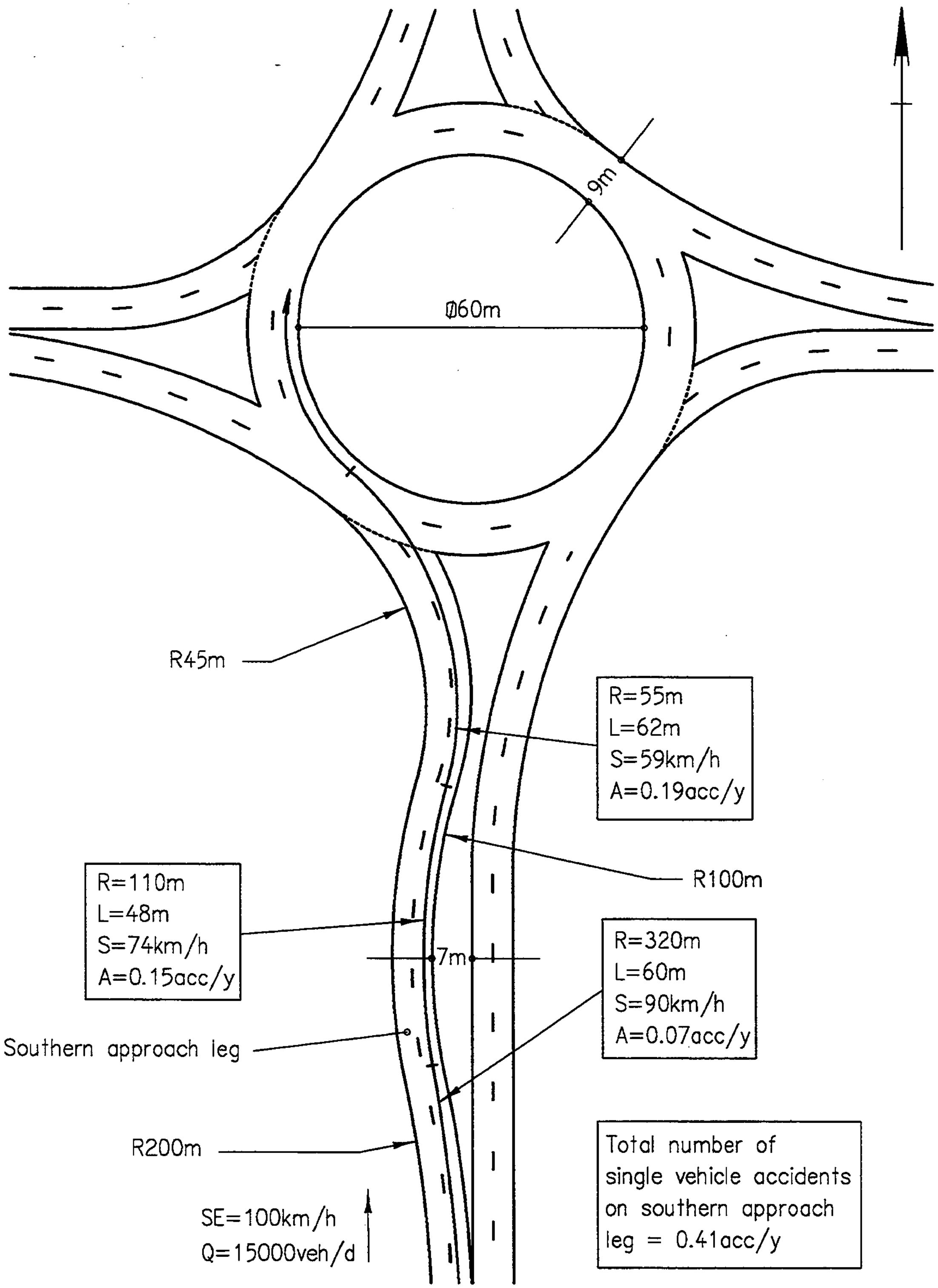


FIGURE 8 Typical Rural Roundabout with Approach Consisting of Three Horizontal Curves

percentile speed on the approach leg to around 60km/h. In higher speed environments, this will require limiting the driver path radius on the approach curve to around 60m.

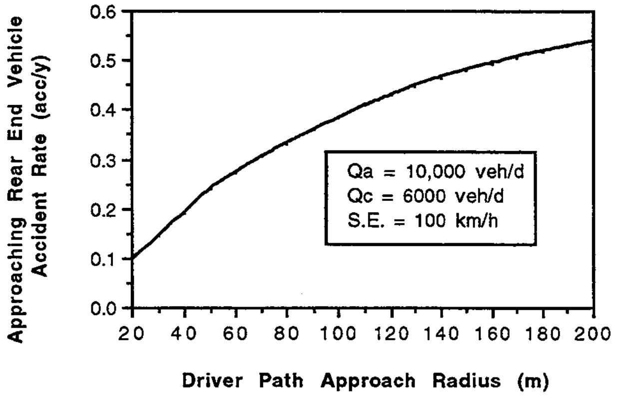


FIGURE 9 Approaching Rear-End Vehicle Accident Rate Versus Driver Path Approach Radius

To minimize entering/circulating vehicle accident rates on roundabouts, it is important to limit the relative speed between entering and circulating vehicles to around 35 km/h. Reducing the radius of the approach curve, minimizing of the entry, exit and circulating lane widths, better positioning of the entry and departure legs, and increasing the central island diameter will decrease relative speeds between entering and circulating vehicles.

The design principles given above for minimizing single-vehicle, approaching rear-end, and entering/circulating vehicle accidents need to be combined and applied to roundabout design to enable total accident rates at roundabouts to be minimized. Each design principle of a particular accident type can be applied without compromising the effect of a design principle of another accident type.

It is believed that the concepts developed in this study can be immediately applied to all intersection and roadway types. The decrease in 85th percentile speed between successive geometric elements is an important parameter when designing rural roads, off-ramps of interchanges, and approaches to intersections in high speed environments.

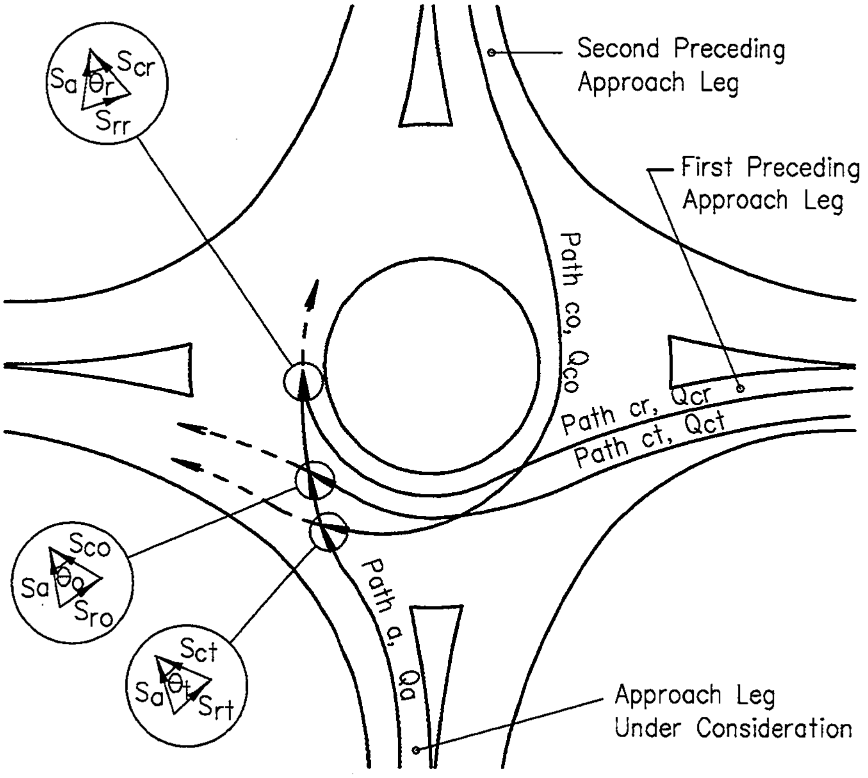
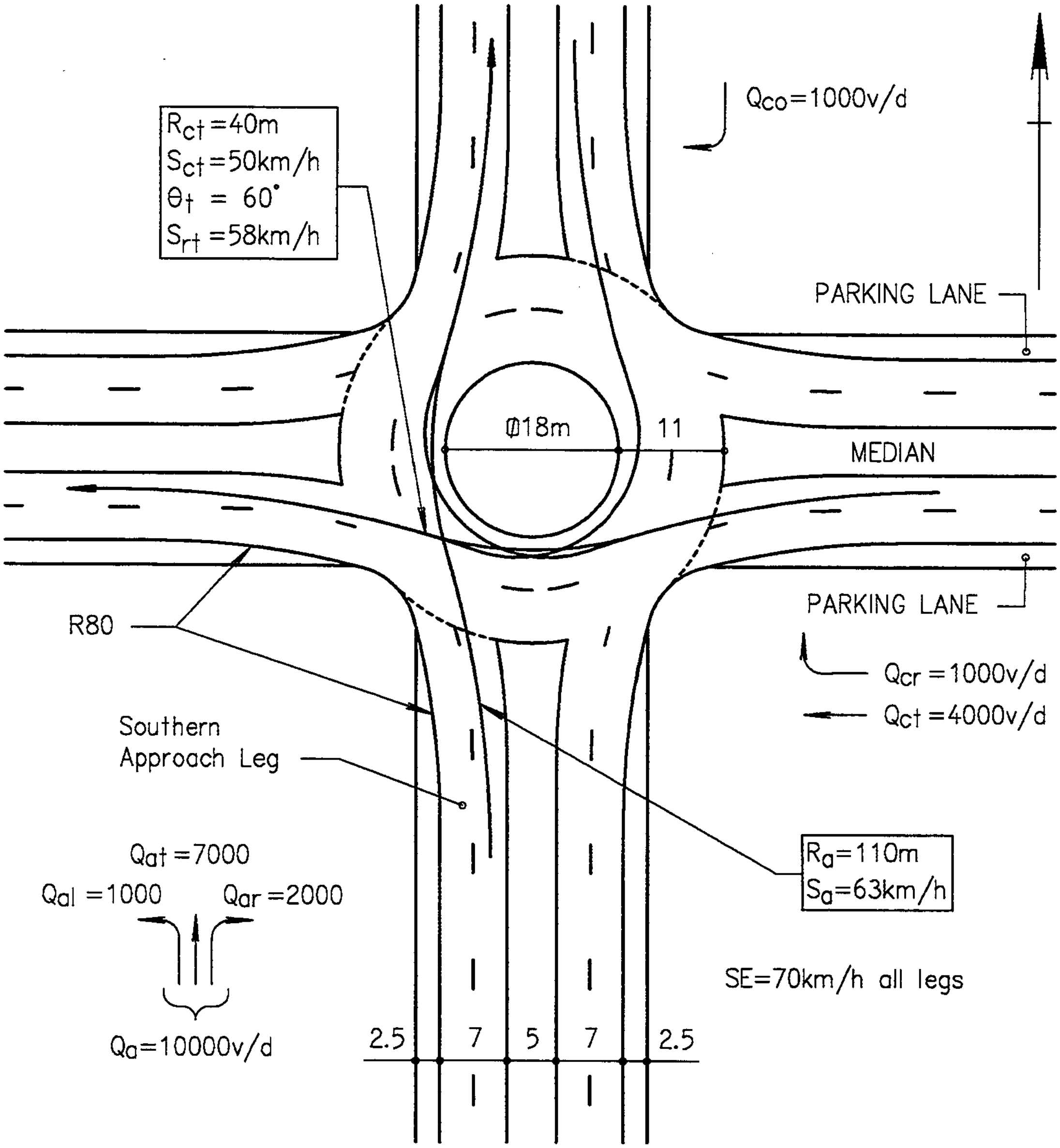


FIGURE 10 Various Traffic Flows on the Circulating Carriageway and Various Relative Speeds Between Approaching and Circulating Vehicles

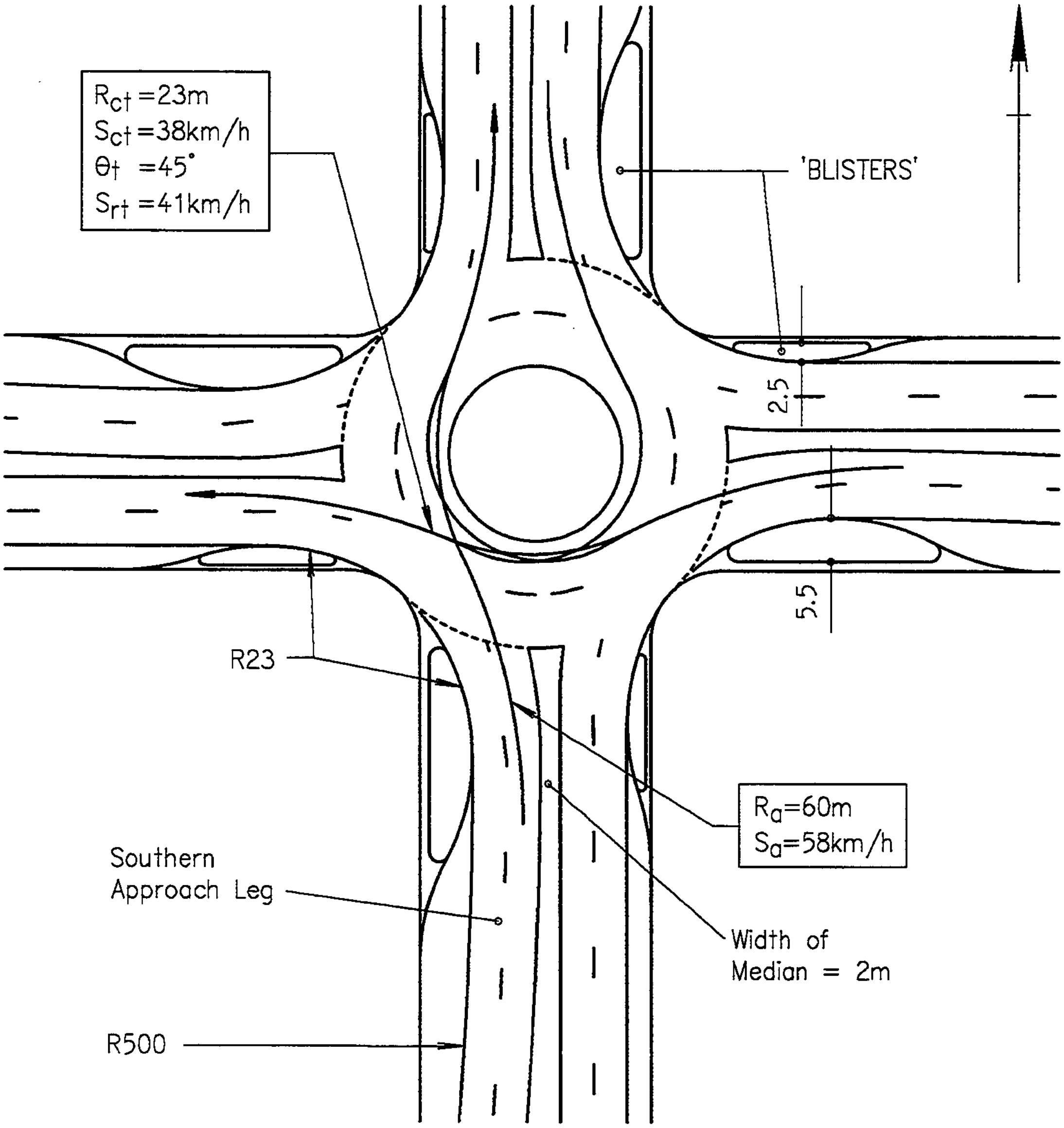


Predicted Accidents for Vehicles Approaching on the Southern Leg

Accident Type	Accidents/Year/Leg	Cost/Acc	Cost/Year/Leg
Entering/Circulating	0.61	$26400	$16100
Approaching Rear End	0.29	$15600	$ 4500
Single Vehicle	0.092	$63300	$ 5800

Total Cost/Leg/Year $26400

FIGURE 11 Typical Dual-Lane Roundabout in an Urban Environment



Predicted Accidents for Vehicles Approaching on the Southern Leg

Accident Type	Accidents/Year/Leg	Cost/Acc	Cost/Year/Leg
Entering/Circulating	0.32	\$26400	\$8400
Approaching Rear End	0.25	\$15600	\$3900
Single Vehicle	0.10	\$63300	\$6300

Total Cost/Leg/Year \$18600

Cost Saving/Leg/Year \$7800

FIGURE 12 Typical Dual Lane Roundabout in an Urban Environment with the Addition of 'Blisters'

The decrease in 85th percentile speed between successive geometric elements should be minimized for optimum safety.

The relative speed between vehicles is expected to be an important parameter at merge and diverge points of interchanges and at intersections controlled by traffic lights, stop signs or give way signs. The relative speed between any stream of vehicles should be minimized for optimum safety.

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