GEOMETRIC DESIGN OF ROUNDABOUTS FOR OPTIMUM SAFETY – USE OF THE SOFTWARE PROGRAM ‘ARNDT’

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ABSTRACT

This paper summarises the work undertaken in a study titled ‘Relationship Between Roundabout Geometry and Accident Rates’, in which data on geometry, traffic volumes and accidents were collected and analysed for one hundred Queensland roundabouts.

From this data, five major accident types were identified, with predictive equations developed for each using a generalised linear model with a Poisson error distribution.

During the analysis of this data, it was found that the most significant equations were developed by selecting parameters for trial, based on the known or expected behaviour of drivers involved in accidents.

The predictive equations are given in the paper, together with design considerations to minimise rates of each accident type. The most important geometric parameters found were approach curvature, central island diameter, decrease in speeds between successive horizontal geometric elements, separation between legs and length of horizontal geometric elements.

Following this summary, the paper then discusses the program ARNDT – ‘A Roundabout Numerical Design Tool’. This tool enables designers to predict accident rates and costs for new or exiting roundabouts, by utilising the results of the roundabout study.

The ARNDT program was developed to avoid the many tedious manual calculations that would otherwise be required to determine some of the input parameters. It is a useful tool for determining the potential safety performance of a roundabout, by identifying potentially hazardous geometry. It can be used to determine the likely saving in accident costs by the adoption of particular geometric treatments.
Section 1 - Introduction

The purpose of this paper is twofold. Firstly it summarises the work undertaken in a study titled ‘Relationship Between Roundabout Geometry and Accident Rates’ - Arndt (1998), to determine the effect of geometric and traffic volume parameters on accident rates at roundabouts. This summary is given in Section 2.

Secondly, the paper discusses the development and use of the roundabout safety program ARNDT ‘A Roundabout Numerical Design Tool’. The program, based on the results of the roundabout study Arndt (1998), was developed to enable road designers to identify the likely safety performance of new or existing roundabouts. This discussion is given in Section 3.

Section 2 - Arndt (1998), Relationship Between Roundabout Geometry and Accident Rates

2.1 Background

Arndt (1998) was an analysis of one hundred Queensland roundabouts, where 492 major accidents were recorded, generally over a five-year analysis period. Relevant authorities provided data on geometry, traffic volume and major accidents.

Figure 1 illustrates the various geometric elements of a roundabout and the accident types recorded. Major accidents are categorised in Figure 2.

The equations for each major accident type were developed using a generalised linear model with a Poisson error distribution. This method of analysis is appropriate for accident data (which is not normally distributed) where the dispersion of the dependent variable (ratio of variance to mean of the observed accident rates) is approximately equal. Each parameter of each developed accident model was significant to at least the 5% level.

2.2 Driver Behaviour

During the initial phase of this study, when selecting geometric parameters for trial in the accident equations, no consideration was given to the driver behaviour that gave rise to the accidents. The resulting equations explained little of the variance in the data and few parameters were found significant. However, by selecting parameters for trial based on the known or expected behaviour of drivers involved in accidents, it was found that much more significant equations could be developed. Sub-section 2.3 describes one example where the selected speed parameters are based on measured speeds adopted by drivers under a number of conditions. In other words, they are based on driver behaviour.

2.3 Speed Parameters

As stated in Sub-section 2.2, the accident models developed in this study were based on vehicle speeds on each geometric element. To estimate speeds on horizontal curves and straights, the study adopted the speed environment concepts given in Chapter 2 of Austroads (1989).

These speed environment concepts were originally developed by McLean (1978) from data measurements on rural roads.

The speeds predicted by this method will not necessarily be the same as the actual 85th percentile speeds at roundabouts. However, on-site inspections revealed that there is potential for drivers to travel at these predicted speeds. The statistical significance of the developed accident equations show that there is a strong correlation between accident rates and these predicted speeds. This suggests that the speed of drivers involved in roundabout accidents may be closer to the 85th percentile speeds predicted by this method, rather than the actual 85th percentile speeds.
Speed parameters were incorporated in each accident model developed. These parameters included ‘absolute speed’, ‘decrease in speed between successive horizontal geometric elements’ and ‘relative speed between vehicles’. In general, speed parameters were found to considerably more significant than traffic flow parameters.

The geometry of roundabouts is more complex than for other intersection types. Roundabouts generally comprise a circulating carriageway with approach and departure legs comprising horizontal curves. In contrast, at-grade intersections generally comprise a straight or large radius curve on the major road, intersecting a horizontal straight on the minor road. By comparison, there is greater scope for designers to control vehicle speeds at roundabouts than at-grade intersections, by the appropriate selection of the radii of the horizontal curves.

2.4 Vehicle-Path Models

On-site roundabout inspections revealed that drivers do not necessarily follow the centre line or edge line of the roadway. A vehicle-path model, based on this behaviour, was created to determine vehicle path radii for calculation of 85th percentile vehicle speeds.

A vehicle-path model for single-lane roundabouts was developed and consisted of drivers transitioning their paths to obtain the largest possible radii within their lane. At multi-lane roundabouts, drivers may cut across lanes. Three vehicle-path models were developed for multi-lane roundabouts based on the following:

1. Vehicles remaining in the inner lane
2. Vehicles remaining in the outer lane
3. Vehicles cutting across all lanes

Each developed vehicle-path model was based on observed minimum distances to the roadway edge/lane lines.

2.5 Single-Vehicle Accidents

Single-vehicle accidents occur when a driver of a vehicle loses control and either collides with part of the roundabout, or overturns. They predominantly occur due to excessive speed on a particular geometric element. They occur on all geometric elements of the roundabout but mainly on the approach curve and the circulating carriageway.

The single-vehicle accident model is based on vehicle paths in the inner lane (for multi-lane roundabouts) and is shown as Equations 1 and 2. The cost per single-vehicle accident prior to the give way line ‘$A_{sp}$’ and after the give way line ‘$A_{sa}$’ was calculated at $74,200 and $50,000 respectively.

\[
A_{sp} = 1.64 \times 10^{-12} \times Q^{1.17} \times L \times (S + \Delta S)^{4.12} / R^{1.91} - (1)
\]

\[
A_{sa} = 1.79 \times 10^{-9} \times Q^{0.91} \times L \times (S + \Delta S)^{1.93} / R^{0.65} - (2)
\]

Where:

- $A_{sp}$ = number of single-vehicle accidents per year per leg for vehicle path segments prior to the give way line
- $A_{sa}$ = number of single-vehicle accidents per year per leg for vehicle path segments after the give way line
- $Q$ = average annual daily traffic in the direction considered i.e. one way traffic only (veh/d)
- $L$ = length of the driver path on the horizontal geometric element (m)
- $S$ = 85th percentile speed on the horizontal geometric element (km/h)
- $\Delta S$ = decrease in 85th percentile speed at the start of the horizontal geometric element (km/h)
- $R$ = vehicle path radius on the horizontal geometric element (m)

Design Considerations

Based on the results of the single-vehicle accident model, the following parameter limits were set:
To minimise single-vehicle accidents at roundabouts, the decrease in 85th percentile speed between successive geometric horizontal elements should be limited to 20km/h. Exceptions to the above limit are as follows:

- For low-volume circulating movements that can be considered as a 'right-turn', a maximum decrease in 85th percentile speed of 30 km/h is deemed to be acceptable if the 85th percentile speed on the approach curve is less than 60 km/h.
- For compound curves, the maximum decrease in 85th percentile speed between successive geometric elements should be limited to 10 km/h.

Design considerations to obtain the above criteria are as follows:

- Appropriate approach curvature will ensure that the decrease in speed between the approach curve and the circulating curve is kept to a minimum.
- For roundabouts where no pedestrians are present, the use of maximum radii departure curves will usually ensure that the decrease in speed between the circulating curve and the departure curve is zero. However, where pedestrians are present, it is desirable to have smaller radius departure curves.
- In higher speed environments (80km/h or greater), use of horizontal reverse curves before the approach curve (each successive curve of smaller radii than the preceding curve) will enable the decrease in speed between successive elements to be minimised. If this is not possible, consideration should be given to alternative treatments to slow drivers before the approach curve.

### 2.6 Approaching-Rear-End-Vehicle Accidents

Approaching-rear-end-vehicle accident are the result of two vehicles colliding in a rear-end type accident on the approach curve. Before the accident, the vehicles were travelling on the same path in the same direction. They generally occur on larger radii approach legs in high-speed environments.

The approaching-rear-end-vehicle accident model is based on vehicle paths in the inner lane (for multi-lane roundabouts) and is shown as Equation 3. The cost per each approaching-rear-end-vehicle accident was calculated at $14,500.

\[
A_r = 1.81 \times 10^{-18} \times Q_a^{1.39} \times (\sum Q_{ci})^{0.65} \times S_a^{4.77} \times N_a^{2.31} \quad - (3)
\]

Where:

- \(A_r\) = number of approaching-rear-end-vehicle accident accidents per year per approach leg
- \(Q_a\) = average annual daily traffic (AADT) flow on the approach ie. one way traffic only (veh/d)
- \(Q_{ci}\) = the various AADT flows on the circulating carriageway adjacent the approach (veh/d)
- \(S_a\) = 85th percentile speed on the approach curve (km/h)
- \(N_a\) = the number of lanes on the particular roundabout approach

**Design Considerations**

To minimise approaching-rear-end-vehicle accidents at roundabouts, the 85th percentile speed on the approach curve should be limited to 60km/h. In higher speed environments (80 km/h or greater), the driver path radius ‘R’ on the approach curve should be limited to around 60m.

The 85th percentile speed prior to the approach curve should be limited to 80 km/h. In high-speed environments (greater than 80 km/h), this can be achieved by the introduction of a reverse curve before the approach curve, which must limit the driver path radius to around 150m. Where this is not possible, consideration should be given to alternative treatments to slow drivers prior to the approach curve.

Minimising the number of approach lanes ‘\(N_a\)’ will also minimise approaching-rear-end-vehicle accident. This will obviously be subject to capacity limitations and cannot often be achieved.

### 2.7 Entering/Circulating-Vehicle Accidents

Entering/circulating-vehicle accidents are the result of an entering driver failing to give way and
colliding with a vehicle on the circulating carriageway. They predominantly occur on smaller diameter roundabouts and roundabouts with inadequate approach curvature and deflection.

The entering/circulating-vehicle accident model is based on vehicle paths in the inner lane (for multi-lane roundabouts) and is shown as Equation 4. The cost per each entering/circulating-vehicle accident was calculated at $26,700.

\[
A_e=7.31 \times 10^{-7} \times Q_a^{0.47} \times N_c^{0.9} \times \left( \frac{Q_{ci}}{G53} \right)^{0.41} \times S_{ra}^{1.38} / t_{Ga}^{0.21} \quad - (4)
\]

Where:
- \(A_e\) = number of entering/circulating-vehicle accidents per year per approach leg
- \(Q_a\) = average annual daily traffic flow (AADT) on the approach ie. one way traffic only (veh/d)
- \(N_c\) = the number of circulating lanes of the roundabout
- \(Q_{ci}\) = the various AADT flows on the circulating carriageway adjacent the approach from each direction
- \(S_{ra}\) = the average relative 85th percentile speed between vehicles on the approach curve and vehicles on the circulating carriageway from each direction
- \(t_{Ga}\) = the average travel time taken from the give way lines of preceding approaches to the intersection point between the entering and circulating vehicles

\[
P_e=N_c^{0.9} \times S_{ri}^{1.38} / t_{Gi}^{0.21} \quad - (5)
\]

Where:
- \(P_e\) = Entering/circulating-vehicle accident parameter combination
- \(N_c\) = the number of circulating lanes of the roundabout
- \(S_{ri}\) = the various relative 85th percentile speeds between vehicles on the approach curve and vehicles on the circulating carriageway from each direction
- \(t_{Gi}\) = the various travel times taken from the give way lines of preceding approaches to the intersection point between the entering and circulating vehicles

**Design Considerations**

To minimise entering/circulating-vehicle accidents at roundabouts, the 85th percentile relative speeds between entering and circulating vehicles \(S_{ri}\) should be limited to 50km/h and the entering/circulating-vehicle accident parameter combination \(P_e\) to 300.

The following design considerations will reduce \(S_{ri}\) and \(P_e\):

1. Reducing the 85th percentile speed on the approach curve by the provision of a smaller radius approach curve and minimising the entry widths.
2. Reducing the 85th percentile speed on the circulating carriageway by either of the following design procedures:
   - Providing tighter deflection through the roundabout by better positioning the first preceding approach leg and the next departure leg and minimising the entry and exit widths of these legs
   - Provide a smaller radius curve on the first preceding approach leg
3. Reducing the angle between the two vehicle paths by any of the following design procedures:
   - An increase in the central island diameter
   - A further separation of the approach and next departure legs

\(P_e\) may also be reduced by decreasing the number of circulating lanes. Obviously, this will be subject to capacity limitations and cannot often be achieved.

**2.8 Exiting/Circulating-Vehicle Accidents**

Exiting/circulating-vehicle accidents occur as an exiting vehicle, driving from the inner circulating lane (or close to the central island), attempts to cross to a departure leg. This vehicle collides with a circulating vehicle on the outer circulating lane (or a vehicle close to the outside of the circulating carriageway), which is continuing to circulate around the roundabout. These accidents predominantly occur on multi-lane roundabouts only ie. not single lane.

The exiting/circulating-vehicle accident model applies to multi-lane roundabouts only, based on vehicle paths in the inner and outer lanes and is shown as Equation 6.
The cost per each exiting/circulating-vehicle accident was calculated at $27,100.

\[
A_d = 1.33 \times 10^{-11} \times (Q_{ci})^{0.32} \times (Q_{ei})^{0.68} \times S_{ra}^{4.13} \quad - (6)
\]

Where:
- \(A_d\) = number of exiting/circulating-vehicle accidents per year per departure leg
- \(Q_{ci}\) = the various AADT flows at the exit point of a departure leg that are continuing to circulate around the roundabout (veh/d)
- \(Q_{ei}\) = the various AADT flows exiting the roundabout at the exit point of a departure leg (veh/d)
- \(S_{ra}\) = the average relative 85th percentile speed between vehicles exiting the roundabout and vehicles continuing to circulate around the roundabout at the particular departure leg (km/h)

**Design Considerations**

To minimise exiting/circulating-vehicle accidents, the 85th percentile relative speeds between exiting and circulating vehicles ‘\(S_{ri}\)’ should be limited to 35km/h. Adopting most of the above design considerations given for entering/circulating-vehicle accidents will reduce the 85th percentile relative speed between exiting and circulating vehicles.

### 2.9 Sideswipe-Vehicle Accidents

Sideswipe-vehicle accidents are the result of a collision between two vehicles travelling on a different path but in the same direction. These accidents are the fault of one, or both drivers, who collide whilst travelling side by side. These accidents generally occur on multi-lane geometric elements, where drivers can travel at significantly higher speeds and have a lower workload level by cutting across lanes, rather than remaining in their correct lane.

The sideswipe-vehicle accident model applies to multi-lane geometric elements only, based on vehicle paths in the inner lane and cutting lanes and is shown as Equation 7. The cost per each sideswipe-vehicle accident was calculated at $23,800.

\[
A_{ss} = 6.49 \times 10^{-8} \times (Q \times Q_t)^{0.72} \times \Delta f_1^{0.59} \quad - (7)
\]

Where:
- \(A_{ss}\) = number of sideswipe-vehicle accidents per year per vehicle path segment per leg
- \(Q\) = the average annual daily traffic for the particular movement on the particular geometric element (veh/d)
- \(Q_t\) = the total average annual daily traffic flow on the particular geometric element (veh/d)
- \(\Delta f_1\) = difference in potential side friction according to Equation 8 (km/h²/m)

\[
\Delta f_1 = \text{ABS}((S_c + \Delta S_c)^2 / (127 \times R) - (S_c + \Delta S_c)^2 / (127 \times R_c)) \quad - (8)
\]

Where:
- \(\Delta f_1\) = difference in potential side friction (km/h²/m)
- \(S_c\) = 85th percentile speed on the horizontal geometric element for the particular movement for vehicles cutting lanes (km/h)
- \(\Delta S_c\) = decrease in 85th percentile speed at the start of the horizontal geometric element for vehicles cutting lanes (km/h)
- \(R\) = radius of the vehicle path for vehicles not cutting lanes (m)
- \(R_c\) = radius of the vehicle path for vehicles cutting lanes (m)

**Design Considerations**

To minimise sideswipe-vehicle accidents at roundabouts, the difference in potential side friction (‘\(\Delta f_1\)’ as given by Equation 8) should be limited to 0.7. This can be achieved by selecting appropriate radius and length of successive geometric elements, to minimise the number of drivers cutting lanes as follows:
- Avoiding the design of short length curves
- Limiting the decrease in 85th percentile speeds between successive geometric elements to 20 km/h.

### 2.10 ‘Other’ Accidents

Approximately 5% of the accidents recorded were placed into a category labelled ‘Other Accidents’, as they could not be classified under one of the five major accident categories. These accidents were related to the total approaching traffic flow as given by Equation 9.
The cost per each ‘Other Accident’ was calculated at $45,000.

\[
A_0 = 4.29 \times 10^{-6} \times Q_a
\]

Where:
- \( A_0 \) = number of ‘other’ accidents per year per roundabout
- \( Q_a \) = average annual daily traffic flow on the approach ie. one-way traffic only (veh/d)

### 2.11 Important Parameters Influencing Roundabout Safety

The accident models in Sub-sections 2.5 to 2.9 have shown that the following four parameters have a major impact on accident rates:

1. **Approach curvature**
2. **Max decrease in speeds between successive geometric elements**
3. **Separation between legs**
4. **Length of horizontal geometric element**

These parameters are discussed below.

#### 2.11.1 Approach curvature

One of the most important geometric parameters is the approach curvature. For optimum safety, a left approach curve should be designed with the appropriate radius to slow vehicles before reaching the roundabout. Figure 3 shows desirable and undesirable approach leg geometry.

Appropriate approach curvature can only be obtained with the provision of adequate roundabout diameter. Based on the limits of parameters given in Sub-sections 2.5 to 2.9, a guide to the minimum initial roundabout central island diameters have been developed and are shown in Tables 1 and 2. These diameters are based on the following:

- Four-legged roundabout
- Each leg being in the same speed environment
- Each leg being at 90 degrees to adjacent legs
- The provision of good geometry on each leg
- The existence of kerbs on both sides of all carriageways
- There being no medians on any of the approaches

Should any of the above not apply (which is usual), an adjustment to the roundabout diameter will be required. Generally, an increase in the roundabout diameter will be required if:

- The roundabout has more than four legs
- The angle between any adjacent roundabout legs is considerably less than, or greater than 90 degrees.
- There are shoulders and no kerb on some, or all of the carriageways
- There are medians on some, or all of the approaches
- Other considerations apply eg. roundabout will form an overpass, or underpass, with a highway or motorway.
- Circulating carriageway is of greater width than that shown in Tables 1 and 2.

#### 2.11.2 Max decrease in speeds between successive geometric elements

It is particularly important in higher speed environments to limit the maximum decrease in speeds between successive horizontal geometric elements by introducing treatments to slow vehicles prior to the approach curve. One method of achieving this is by the use of successive reverse curves as shown in Figure 3.

#### 2.11.3 Separation between legs

It is important to minimise the relative speeds between entering and circulating vehicles by the provision of adequate separation between legs as shown in Figure 4.
Table 1 - Initial Selection of Minimum Central Island Diameters of Single-Lane Roundabouts

<table>
<thead>
<tr>
<th>Speed Environment (km/h)</th>
<th>Minimum Central Island Diameter of Single Lane Roundabout (m)</th>
<th>Circulating Carriageway Width (m)</th>
<th>Treatments Required Prior to the Approach Curve to Reduce Vehicle Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>10</td>
<td>7.6</td>
<td>No</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>7.6</td>
<td>No</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
<td>7.1</td>
<td>No</td>
</tr>
<tr>
<td>70</td>
<td>20</td>
<td>6.7</td>
<td>No</td>
</tr>
<tr>
<td>80</td>
<td>25</td>
<td>6.5</td>
<td>Desirably</td>
</tr>
<tr>
<td>90</td>
<td>25</td>
<td>6.5</td>
<td>Yes</td>
</tr>
<tr>
<td>100</td>
<td>25</td>
<td>6.5</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2 - Initial Selection of Minimum Central Island Diameters of Two-Lane Roundabouts

<table>
<thead>
<tr>
<th>Speed Environment (km/h)</th>
<th>Minimum Central Island Diameter of Two Lane Carriageway Roundabout (m)</th>
<th>Circulating Carriageway Width (m)</th>
<th>Treatments Required Prior to the Approach Curve to Reduce Vehicle Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>15</td>
<td>11.1</td>
<td>No</td>
</tr>
<tr>
<td>50</td>
<td>15</td>
<td>11.1</td>
<td>No</td>
</tr>
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<td>60</td>
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<td>10</td>
<td>No</td>
</tr>
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<td>Desirably</td>
</tr>
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</tr>
<tr>
<td>110</td>
<td>40</td>
<td>9.6</td>
<td>Yes</td>
</tr>
</tbody>
</table>

2.11.4 Length of each horizontal geometric element

Adequate lengths of each horizontal element need to be provided to minimise the number of drivers cutting across adjacent lanes. Where possible, these lengths should not be excessively long either, as the rate of single-vehicle accidents increases as the lengths of horizontal elements is increased.

2.12 Modifying Roundabout Geometry

It is important to note that modifying the value of a particular geometric element to reduce the rate of a certain accident type may increase the rate/s of other accident type/s. Examples of this are as follows:

1. Decreasing the radius of an approach curve will decrease the approaching-rear-end-vehicle accident rate and will usually decrease the entering/circulating and exiting/circulating-vehicle accident rates. The single-vehicle accident rate on the approach curve and possibly the sideswipe-vehicle accident rate, however, will increase. A similar situation exists when increasing the amount of deflection.

2. Decreasing the length of horizontal geometric elements reduces single-vehicle accident rates, however, increases sideswipe-vehicle accident rates.

When modifying the value of a geometric element to improve the safety of a particular accident type, it is important to check that a significant increase in the rates of other accident types does not occur. This can readily be checked when using the program ARNDT as discussed in the next section.

Section 3 - Roundabout Program ‘ARNDT’

The program ARNDT - A Roundabout Numerical Design Tool’ enables designers to predict accident rates and costs for new, or existing roundabouts, by utilising the results of the roundabout study in Section 2. This program was developed to avoid the many tedious manual calculations that would otherwise be required to determine the various vehicle path and speed parameters.
Users of the program are required to input geometric, speed environment and traffic flow data for the required roundabout. From the geometric data, the program displays a plan view of the roundabout for the user to determine that all input parameters are correct. The user may then choose to generate an output report that details the safety performance of the roundabout.

This program identifies several major parameters affecting accidents at roundabouts and enables a designer to form the basis of a good roundabout design. However, the program does not consider all factors that can influence accident rates at roundabouts. Designers should refer to guidelines such as DMR (2000) - Chapter 14 ‘Roundabouts’ of the draft Queensland Department of Main Roads ‘Interim Road Planning and Design Manual’ or Austroads (1993) - Guide to Traffic Engineering Practice - Part 6 - Roundabouts.

3.1 Benefits of Program

1. When the various limits of parameters given in Section 2 are exceeded, the program will identify potentially hazardous geometry. This enables designers to modify the geometry to improve safety.

2. The program predicts accident costs in addition to accident rates. Therefore, it can be used to determine if the additional construction costs of a particular roundabout warrant the saving in accident costs. This is especially helpful when:
   - Determining the benefits of changing the roundabout diameter
   - Determining whether the reconstruction of parts of an existing roundabout produces benefits eg. the incorporation of ‘blisters’

3. Comparing the accident rates of an existing roundabout, with those predicted by the program, will identify if other major factors are influencing accident rates. Examples of factors not considered by the program are driver recognition of the roundabout, number of roadside hazards etc.

3.2 Current Release and Limitations

The May 2000 release of this program is referred to as ‘Beta Version Number 1’. This version analyses circular roundabouts only. It does not analyse elliptical roundabouts, nor does it analyse varying number of lanes on the circulating carriageway. The program is windows based and runs on Windows 95/98 or Windows NT.

3.3 Input of Data into the Program

When running the program, each roundabout input is placed into a separate data file. The various geometric elements of the roundabout are coded into the data-entry forms ‘Centre Area Parameters’ and ‘Leg Parameters’. These data-entry forms are shown in Figure 5. Some of the required geometric parameters are shown on the diagram in Figure 6. A leg may comprise a combined entry and exit roadway, or a roadway that is an exit or an entry only. Horizontal curves prior to approach curves can be input.

The various traffic flows and speed environment of each roundabout leg are input using the data-entry form ‘Traffic Flow and Speed Environment Parameters’. This data-entry form is shown in Figure 7.

3.4 Program Output Data

Following the input of geometric data, the screen will display a layout of each leg, the centre island and the circulating carriageway. An example is shown in Figure 8. Should any of the geometric details displayed be incorrect, the data-entry forms can be reselected to allow modification of the input data.

An output report is selected using the ‘Generate Report’ data-entry form shown in Figure 7. The user can select the output details required. The major purpose of this report is to list the results of the safety analysis, detailing the values of each calculated parameter obtained using the accident equations in Section 2 for each accident type.
The output report identifies where various parameter limits are exceeded. These are the primary identifiers of poor roundabout geometry. Where limits are exceeded, the designer should modify the geometry (using the procedures discussed in Sub-section 3.3) in order to achieve improved safety. The output report can then be regenerated to identify these improvements.

**Figure 9** shows a section of the output report for the roundabout shown in Figure 6. The entering/circulating-vehicle accident rates for legs 3 and 4 are given. Several ‘$S_0$’ values and ‘$P_e$’ values have been flagged. This indicates that these legs will have potentially high entering/circulating-vehicle accident rates. This has occurred because inappropriate approach curvature has been provided on approach legs 3 and 4 for the given speed environments.

As with other roadway analysis programs eg ‘SIDRA’, engineering judgement should be used to obtain useful results when interpreting the output report.

### 3.5 Other Features

The scale of the displayed roundabout can be changed before being printed. By using one of the ‘Select Vehicle Paths’ data-entry forms, the vehicle paths used to calculate the various accident parameters can be displayed. The on-line ‘Help’ function gives the user an overview of the program, including the process of inputting the various parameters, and the interpretation of the output results.

### 3.6 Future Work

It is anticipated that the next version of the ARNDT program will allow the importation of the displayed roundabout into AutoCAD. This will streamline the design process by allowing practitioners to input the original design data into one program rather than two.

The Queensland Department of Main Roads and the Queensland University of Technology are currently undertaking a study titled ‘Relationship between Unsignalised Geometry and Accident Rates’. The purpose is to determine the effect of unsignalised at-grade intersection geometry (excluding roundabouts) on crash rates. This is a similar study to that undertaken at roundabouts as discussed in Section 2.

It is planned to add the results of this study to the current program ‘ARNDT’. The purpose being to alert practitioners to potentially hazardous at-grade intersection geometry, and allow practitioners to compare the safety performance of a designed roundabout with that of an unsignalised at-grade intersection.

### 4.0 Concluding Remarks

The roundabout program ‘ARNDT’ is a useful tool in determining the potential safety performance of a roundabout by identifying potentially hazardous geometry. It can be used to determine the likely savings in accident costs by the adoption of particular geometric treatments. It is based on the work undertaken in a study titled ‘Relationship Between Roundabout Geometry and Accident Rates’ - Arndt (1998).

Widespread usage of this program is desired in order to obtain a greater amount of feedback which can then lead to improvements in the current version.
REFERENCES


DMR (2000), *Interim Road Planning and Design Manual*, Queensland Department of Main Roads, Brisbane, Chapter 14, Roundabouts.

Owen Arndt holds the position of Senior Engineer (Traffic) in the Queensland Department of Main Roads. His experience covers the planning and design of many urban and rural roadways and intersections, together with the management of several road and noise barrier construction projects.

Current responsibilities include developing and updating road design standards, undertaking of research projects, and providing specialist advice and reports on road design standards and projects. He has completed a major research project into the relationship between roundabout geometry and accident rates.

Owen is currently undertaking a similar study at unsignalised intersections as a PhD.

For enquires or information on the roundabout program ‘ARNDT’, please contact Owen Arndt:
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Postal Address:
Queensland Department of Main Roads
GPO Box 1412, Brisbane, Q 4001
Figure 1 - Geometric Elements of a Typical Roundabout and Recorded Accident Types
Single Vehicle Accidents
(excluding left turning vehicles)
Accidents involving 1 vehicle only.
87 acc. (17.7%)

Approaching Rear-End Accidents
One vehicle colliding into the rear
of another on the approach.
83 acc. (16.9%)

Entering/Circulating Accidents
An entering vehicle fails to give way
& collides with a circulating vehicle.
250 acc. (50.8%)

Exiting/Circulating Accidents
An vehicle driving from the inner
circulating lane onto the departure
leg collides with a vehicle that is
continuing to circulate on the outer
circulating lane.
31 acc. (6.3%)

Sideswipe Accidents
Two vehicles collide in a side swipe
manner whilst travelling in adjacent
lanes in the same direction.
16 acc. (3.2%)

Other Accidents
Those accidents that are not one
of the five major accident types.
25 acc. (5.1%)

Figure 2 - Accident Categories
Figure 3 - Desirable and Undesirable Roundabout Approach Geometry

Left curve approach to minimise entry speed and relative speed between entering and circulating vehicles

Provision of 'blisters' on wide carriageways to minimise entry speed and relative speed between entering and circulating vehicles

Successive reverse curves to limit decrease in speed between successive horizontal elements in high speed environments

EXAMPLES OF GOOD APPROACH GEOMETRY

Straight approach (High entry speed)

Right curve approach

Large radius left curve approach (High entry speed)

EXAMPLES OF UNDESIRABLE APPROACH GEOMETRY
Figure 4 - Desirable and Undesirable Separation between Roundabout Legs

**Examples of Good Separation Between Legs**

- Use of corner kerb radius increases relative speed between entering and circulating vehicles
- No kerbed splitter island between approach and departure legs
- Approach legs too close

**Examples of Undesirable Separation Between Legs**

Low speed exit (Suitable where pedestrian crossings are required)

High speed exit (Suitable where pedestrian crossings are not required)
Figure 5 – Data Entry Forms
Figure 6 – Centre Area and Leg Parameter Details
Speed Environments and Traffic Flow Parameters

Figure 7 – Data Entry form Parameter Details
### Crossing Paths

<table>
<thead>
<tr>
<th>From Leg</th>
<th>To Leg</th>
<th>Traffic Flow (veh/d)</th>
<th>Speed Environment ('VE')</th>
<th>Circulating Traffic Flow (veh/d)</th>
<th>Speed Environment ('VE')</th>
<th>Radius of Circulating Path (m)</th>
<th>Angle at Crossing Point (degrees)</th>
<th>Distance To Giveaway Line (m)</th>
<th>Relative Speed (km/h)</th>
<th>Travel Time (seconds)</th>
<th>Accident Parameter 'Pe'</th>
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Average relative 85th percentile speed : 44.825 km/h
Average travel time from giveawy line : 5.721 seconds

### Leg Number : 4

Traffic Flow Entering : 4000 veh/d
Radius of entering vehicle path : 124.696 m
85th Percentile Speed \ Entry speed : 70.277 km/h
Number of Circulating Lanes : 2

### Crossing Paths

<table>
<thead>
<tr>
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Average relative 85th percentile speed : 49.939 km/h
Average travel time from giveawy line : 3.808 seconds

Accident Rate for leg : 0.48946 acc/yr
Accident Cost for leg : 130.899 $/yr

Total Roundabout Entering/Circulating Vehicle Accident Rate : 1.51214 acc/yr
Total Roundabout Entering/Circulating Vehicle Accident Cost : 40374 $/yr