ROUNDABOUT SAFETY – INFLUENCE OF SPEED, VISIBILITY AND DESIGN

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ABSTRACT

Roundabout design in New Zealand generally follows the Austroad guideline for intersection design (Austroads, 2005), which recommends long approach sight distances and provision of relatively high design speeds. This is in contrast to European based design philosophy where visibility is normally restricted and the geometric design encourages slow approach and negotiation speeds. This paper reports on the results of a study that used crash prediction models to investigate how the characteristics of roundabouts influences safety at 104 roundabouts in three centres. Using a dataset that contains pedestrian, cyclist and motor vehicle flows, approach and circulating speeds and sight distances an analysis was carried out for a number of crash types and new crash relationships established. It will be shown that safety benefits can be achieved by a more European based design philosophy.

Introduction

New Zealand has a large number of roundabouts, which have been installed over a number of decades. Over the decades roundabout design standards have evolved considerably, and later designs are generally of higher standard. Many older roundabouts were installed prior to the widespread introduction of safety audits and therefore a number of deficiencies, which would be identified in more recent times, were not picked-up. There are a number of roundabouts still in operation that have fundamental deficiencies including inadequate deflection, two approach lanes but only one circulating lane, inconsistent visibility on different approaches, which leads to differential negotiation speeds, and poor camber/superelevation, which can cause problems for trucks.

Despite their many faults, the majority of roundabouts have relatively good safety records, compared with other intersection control types (signals, priority controlled and uncontrolled), particularly in high-speed environments. In many parts of the country roundabouts are a preferred intersection treatment, as up to relatively high traffic volumes they have the benefit of keeping the traffic flowing, particularly outside peak periods, when compared with signalised intersection control, with the lost-time such intersection experience. They are however unpopular, particularly larger roundabouts, with cyclists and pedestrians, with crash occurrence for the former being a higher proportion of all intersection accidents when compared with other forms of control.

While there has been a lot of research/discussion on the safety of roundabouts, which has resulted in changes to the design standards and a list of matters to consider in safety audits, there have been few studies that have tried to quantify the effect of deficiencies on roundabouts safety and in particular the safety of cyclists and pedestrians. The paper contains research that quantifies, through the use of accident prediction models the effect of a number of variables on roundabout safety. This research can be used by safety auditors, and other transport professionals, to estimate the impact on safety of a particular deficiency and prioritise intersections for treatment.

The research presented in this paper focuses on the relationship between accidents, speed, traffic volume and sight distance for various approach and circulating movements at roundabouts. The 'flow-only models previously developed by Turner (2000) have been extended to include observed speed, sight distance and intersection layout variables in various forms. Given the different impact vehicle speed is expected to have on the 'active' modes (walking and cycling), separate models have been developed for the major accident type for each mode.

Selected Sites

In total a sample set of 104 roundabouts were selected in Auckland, Christchurch and Palmerston North. The sites were selected so that a variety of different layouts and sizes were included in the sample from around the country. Table 1 shows a breakdown of the sites by location and roundabout type.

Table 1: Roundabout Locations and Types

Type	Location			
	Christchurch	Auckland	Palmerston North	Total
Single Lane Circulating				
3-arm	0	2	2	**4**
4-arm	35	22	8	**65**
Two Lane Circulating				
3-arm	0	4	0	**4**
4-arm	4	21	3	**28**
5-arm	0	3	0	**3**
TOTAL	**39**	**52**	**13**	**104**

A smaller sample set of 17 high-speed roundabouts was also selected from around the country. This included sites in Christchurch, Auckland, Hamilton and Tauranga. A high-speed roundabout must have one road that has a speed limit of 80km/h or more. Given the limited number of sites that meet these criteria, all high-speed roundabouts for which data was readily available were included in the sample set.

Predictor variables

A list of key roundabout variables was specified following the outcomes of a workshop with experts in roundabout design, a review of overseas studies on roundabouts and a review of the publication 'Ins and Outs of Roundabouts' (Transfund 2000). This process identified the following variables: sight distance, approach and negotiation speed, traffic and cyclist volume, deflection, approach and exit curve design, approach and circulating road width.

Traffic, Pedestrian and Cycle Volume Data

The flow variables used in the urban roundabout intersection models are versions of those defined in Turner (1995), where each movement is numbered in a clockwise direction starting at the northern-most approach. Approaches are also numbered using the same technique and are numbered in a clockwise direction (see **Figure 1**).

Individual movements are denoted as a lower case character for the user type (e.g. q_i). Totals of various movements are denoted with an upper case character (e.g. Q_i). Models are developed for each approach and are defined using the totals of various movements. These are:

Q_e Entering volume for each approach.
Q_c Circulating flow perpendicular to the entering flow.
Q_a Approach flow (two-way flow on intersection leg).

Three one-hour manual turning volume counts were collected at each site, in the morning, evening and at mid-day. Weekly, daily and hourly correction factors from the "*Guide to Estimation and Monitoring of Traffic Counting and Traffic Growth*" (TDG, 2001) were used to estimate the AADT.

Visibility and Speed

Speeds measured in this study are the free speeds of vehicles travelling through the roundabouts and not of vehicles turning left, right or having to give way. The visibility and speed variables used in the models are shown in Table 2. Diagrams of vehicle speeds and the measurement of visibility variable can be found in **Figure 2** and **Figure 3** respectively.

Table 2: Visibility and Speed Variables

Variable	Description
V_{LL}	visibility from the limit line to vehicles turning right or traveling through the roundabout from the approach to the right;
V_{10}	visibility from 10 metres back from the limit line to vehicles turning right or traveling through the roundabout from the approach to the right;
V_{40}	visibility from 40 metres back from the limit line to vehicles turning right or traveling through the roundabout from the approach to the right;
S_{LL}	free mean speed of entering vehicles traveling through the roundabout at the limit line;
S_C	free mean speed of circulating vehicles traveling through the roundabout as they pass the approach being modeled;
SSD_{LL}	standard deviation of free speeds of entering vehicles at the limit line;
SSD_C	standard deviation of free speeds of circulating vehicles as they pass the approach being modeled;

Intersection Layout

Data on the layout of each roundabout were collected on site. From this data, variables were developed to represent different situations; these variables were not of the continuous type such as vehicle flows and mean speeds; and were incorporated into the accident prediction models as covariates. The covariates are represented by multiplicative factors that are used to adjust the prediction if the feature is present. The covariates used in the modelling process and their definitions are shown in Table 3.

Table 3: Intersection Layout Covariates

Variable	Description
Φ_{MEL}	Multiple entering lanes
Φ_{MCL}	Multiple circulating lanes
Φ_{3ARM}	Intersections with three arms
Φ_{GRADD}	Downhill gradient on approach to intersection

Research is currently underway to consider other layout variables; continuous variables; including approach, circulating and exiting curve radius, distance to upstream approach, total width of approach and deflection. These variables are to be incorporated into future accident prediction models and negotiation speed models.

Accident Data

Accident data for roundabouts nationally was extracted from the Ministry of Transport's Crash Analysis System (CAS) for the period 1January 2001 to 31 December 2005. During this period there were 1202 reported injury accidents at urban roundabouts in New Zealand, including 7 fatal and 154 serious accidents. This compares to the 365 reported injury accidents, including 2 fatal and 44 serious accidents, that occurred at the 104 urban roundabouts included in the sample set.

Modelling results

The models were developed using generalised linear modelling methods. Generalised linear models were first introduced into road safety by Maycock and Hall (1984), and extensively developed in Hauer et al. (1988). These models were further developed and fitted using accident data and traffic counts in the New Zealand context for motor vehicles only accidents by Turner (1995).

The aim of the models is to develop relationships between flows, non-flow contributing variables (the independent variables) and the mean number of accidents (the dependant variable).

The typical mean-annual numbers of reported injury accidents for urban roundabouts can be calculated using turning movement counts, non-flow data and the accident prediction models in Table 4. The total number of accidents can be predicted by summing the individual predictions for each accident group on each approach.

The flow variables used in these models are for daily average flows and are shown graphically in Figure 1. Table 2, Figure 2 and Figure 3 define the visibility and speed variables.

Table 4: Urban roundabout accident prediction models

Accident Type	Equation (accidents per approach)	Error Structure	GOF**
Entering-vs-Circulating (Motor-vehicle only)	$A_{UMAR\,1} = 6.12 \times 10^{-8} \times Q_e^{0.47} \times Q_c^{0.26} \times S_C^{2.13}$	NB (k=1.3)*	0.26
Rear-end (Motor-vehicle only)	$A_{UMAR\,2} = 9.63 \times 10^{-2} \times Q_e^{-0.38} \times e^{2.42 Q_e}$	NB (k=0.7)*	0.25
Loss-of-control (Motor-vehicle only)	$A_{UMAR\,3} = 6.36 \times 10^{-6} \times Q_a^{0.59} \times V_{10}^{0.68}$	NB (k=3.9)*	0.25
Other (Motor-vehicle only)	$A_{UMAR\,4} = 1.34 \times 10^{-5} \times Q_a^{0.71} \times \phi_{MEL}$ $\phi_{MEL} = 2.66$	Poisson	0.17
Pedestrian	$A_{UPAR\,1} = 3.45 \times 10^{-4} \times P^{0.60} \times e^{0.67 Q_a}$	NB (k=1.0)*	0.17
Entering-vs-Circulating (Cyclist circulating)	$A_{UCAR\,1} = 3.88 \times 10^{-5} \times Q_e^{0.43} \times C_c^{0.38} \times S_{LL}^{0.49}$	NB (k=1.2)*	0.61
Other (Cyclist)	$A_{UCAR\,2} = 2.07 \times 10^{-7} \times Q_a^{1.04} \times C_a^{0.23}$	Poisson	0.50

Accident Type	Equation (accidents per approach)	Error Structure	GOF**
All Accidents	$A_{UAAR\,0} = 6.11 \times 10^{-4} \times Q_a^{0.58} \times \phi_{MEL}$ $\phi_{MEL} = 1.66$	NB (k=2.2)*	0.28

*k is the gamma distribution shape parameter for the negative binomial (NB) distribution.
**GOF (Goodness Of Fit statistic) indicates the fit of the model to the data. A value of less than 0.05 indicates a poor fit whereas a high value indicates a very good fit.

Effect of Higher Speed Limits

Using the link data collected from the high-speed roundabouts with speed limits greater than 70km/h, a covariate analysis of the effect of higher speed limits on accidents was carried out. The following model was developed using a data set that contains approach flows, accidents on each approach and the respective speed limit grouping:

$$A_{RAXR} = 3.21 \times 10^{-4} \times Q_a^{0.66} \times \phi_{HS} \qquad \phi_{HS} = 1.35$$

The model is a good fit and has a negative binomial dispersion parameter (k) of 1.9. The covariate for the higher speed sites indicates that at speed limits of 80 km/hr or greater there are 35% more reported injury accidents than at a roundabout with an urban speed limit, for a given traffic volume.

Discussion

The majority of the preferred models for motor-vehicle and pedestrians accidents include non-flow variables. This justifies the extension of previous ‘flow-only’ models to include the non-flow variables

For the motor-vehicle entering versus circulating accidents, the non-flow variable is the mean speed of circulating vehicles (Sc). The exponent on this variable indicates that as circulating speeds increase so does the number of accidents. For example, the model suggests that if mean circulating speeds of 26 km/hr were reduced by 20% then the resulting reduction in accidents of this type would be 38%. Figure 4 shows the change in accident numbers as the speed increases (for entering volume of 5000 vpd and circulating of 6000 vpd). The accident rate for a circulating speed of 60km/h is almost 10 times that of a circulating speed of 20km/h.

The ‘total accident’ model for high-speed roundabouts also shows that as the speed limit increases the number of accidents increase. Roundabout with a speed limit above 70km/h have on average 35% more reported injury accidents than those below 70km/h.

The research implies that the European approach to the design of roundabouts, of lower speed, has merit from a safety perspective.

Examination of the correlation matrix indicates that the speed of circulating vehicles is correlated to the flow of circulating vehicles. This may be a result of roundabouts at higher volumes being designed for faster speeds, for capacity reasons. There is therefore a clear capacity-safety trade-off.

The ‘loss-of-control’ model was the only preferred model to include a visibility variable. In developing models for other accident types the only other model where it featured as a stronger predictor variable than speed was for ‘other cyclist’ accidents. The exponents of the visibility variables were consistent, however, taking positive values ranging from 0.08 to 0.8 for most accident types except both ‘other’ accident types (other cyclist, and other motor-vehicle) where they were generally in the range -0.3 to -0.4. The reason for most accident types showing an increase in accidents with increased visibility is likely to be the result of associated speed increases. It is unclear why this would be different for ‘other’ accidents.

For the ‘other motor-vehicle’ and ‘all accident’ models the preferred models included the covariate for number of entering lanes. Both these models indicate that the accident rate is higher if the roundabout has multiple entry lanes for a given traffic flow. No matter which accident type was being modelled, every time this variable was included the covariate was always greater than 1.0. This strong result indicates the reduced safety of multi-lane roundabouts when compared to single lane roundabouts.

The models developed can be compared with those of previous studies, as illustrated here by comparing models developed for ‘entering-versus-circulating’ accidents developed in Turner (2000) and Turner et al. (2006b). To allow for this comparison, the ‘flow only’ models developed for this study are shown in Table 5 along with the model for cyclist circulating accidents from Turner et al. (2006b) and the model for accidents involving all wheeled road users (eg. includes motor-vehicles accidents only and those with cyclists) in Turner (2000).

Table 5 shows that the relationships between the flow variables and motor-vehicle accidents are similar for the current study and the Turner (2000) study. The higher coefficient for the earlier study is likely to be the result of a downward trend in accidents in New Zealand and the inclusion of cyclist accidents. It is interesting that the models for cyclist accidents have similar exponents on the circulating flow variable to the models for motor-vehicle only accidents. This indicates that similar relationships between flows and accidents may exist for both road user groups.

Table 5: Entering-versus-circulating accident prediction models

Model	Study	Equation (accidents per approach)
Motor Vehicle Only Accidents	Current Study	$A_{UMAR\ 1} = 2.49 \times 10^{-5} \times Q_e^{0.48} \times Q_c^{0.37}$
Motor Vehicle (only and with cyclists) Accidents	Turner 2000	$A_{UWXR\ 1} = 1.14 \times 10^{-4} \times Q_e^{0.42} \times Q_c^{0.41}$
Cyclist Circulating Accidents	Current Study	$A_{UCAR\ 1} = 1.51 \times 10^{-4} \times Q_e^{0.46} \times C_c^{0.38}$
Cyclist Circulating Accidents	Turner et al. (2006b)	$A_{UCXR\ 1} = 2.40 \times 10^{-5} \times Q_e^{0.79} \times C_c^{0.32}$

Summary

This paper presents a number of accident prediction models that have been developed for roundabouts in urban and rural road networks. Models have been developed for the major accident types for motor vehicles only, motor vehicles versus cyclists and pedestrians versus motor vehicle classifications. The models include the principal flow variables and a number of non-flow variables. Multiplicative factors have been produced to show the difference in accident rate for low speed (70 km/hr and less) and high speed (80 km/hr and more) at roundabouts.

The preferred ‘non-flow’ models include a number of the variables that were collected in addition to the flow variables, including visibility, speed and multiple entry lanes. While not in all preferred models, there were strong relationships observed between visibility and number of entry lanes with accident occurrence.

The models indicate that there would be benefits in a move to European design standards that reduce both circulating and entry speeds. For example, the models indicate that reduction of mean circulating free speeds of 26km/hr by 20% would result in a 38% accident reduction in entering-versus circulating accidents. The models also predict that the 'entering versus circulating' accident rate is 10 times worse at a circulating speed of 60km/h, compared with a circulating speed of 20km/h.
There are also benefits possible through reduction of visibilities. Further research, however, is required to explain why the models indicate that 'other' motor-vehicle accidents may increase with reduced visibilities. Research is currently underway to look at the effects on safety of more geometric features, continuous features, including deflection, entering an exiting radius and approach width.

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Figures

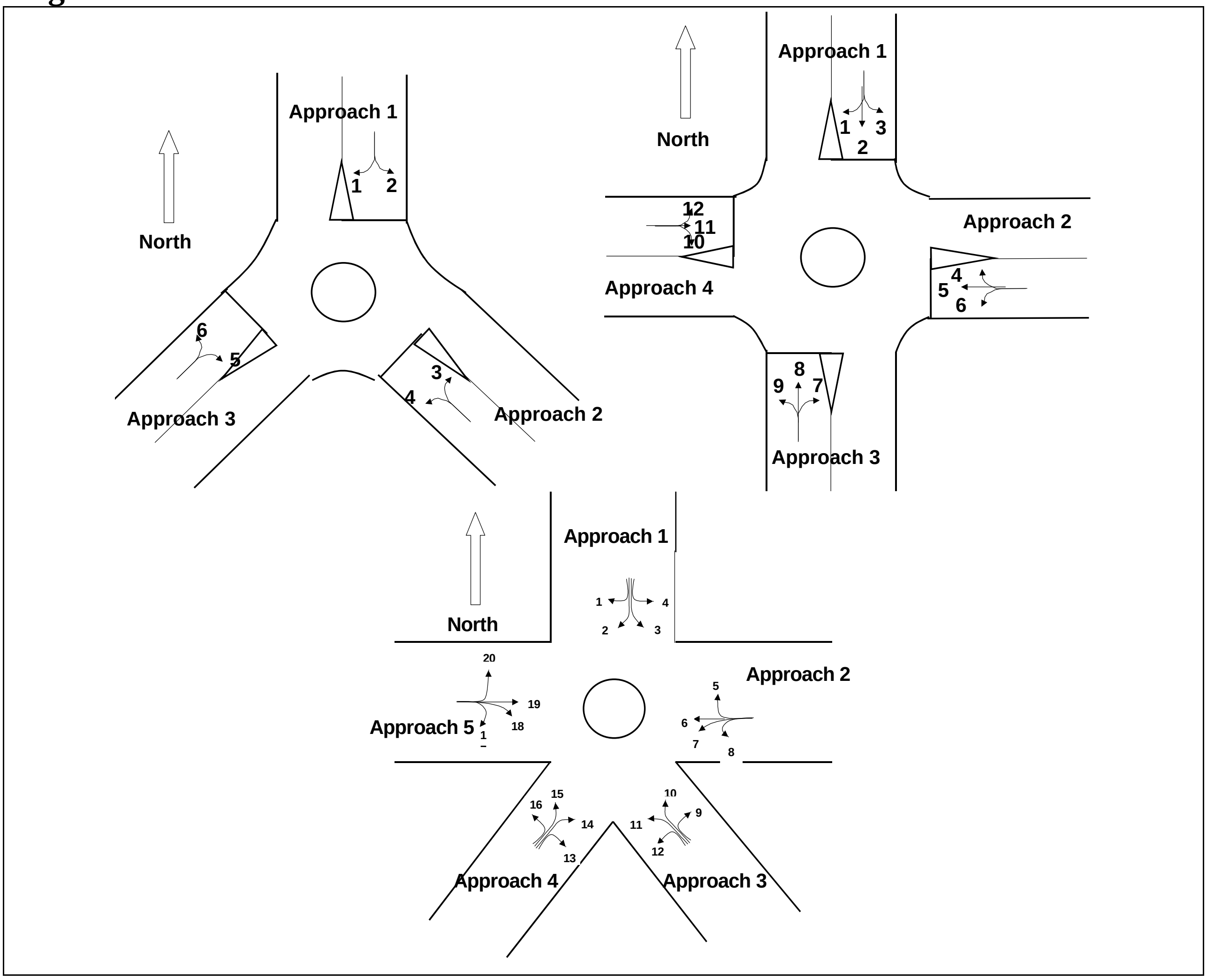

Figure 1: Numbering convention for movements and approaches

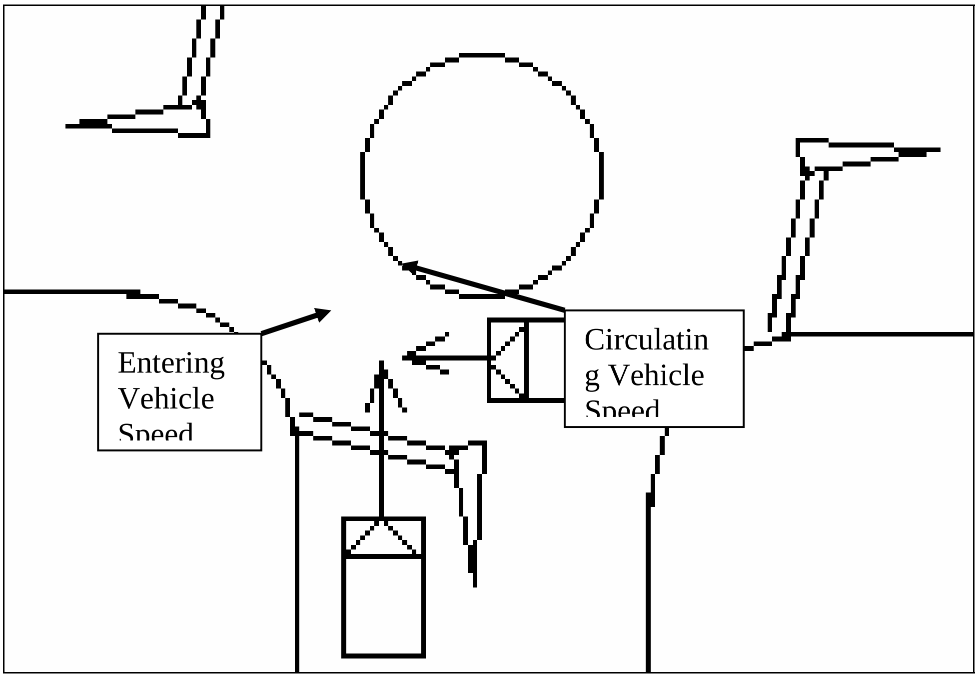

Figure 2: Measuring points for entering and circulating vehicle speeds

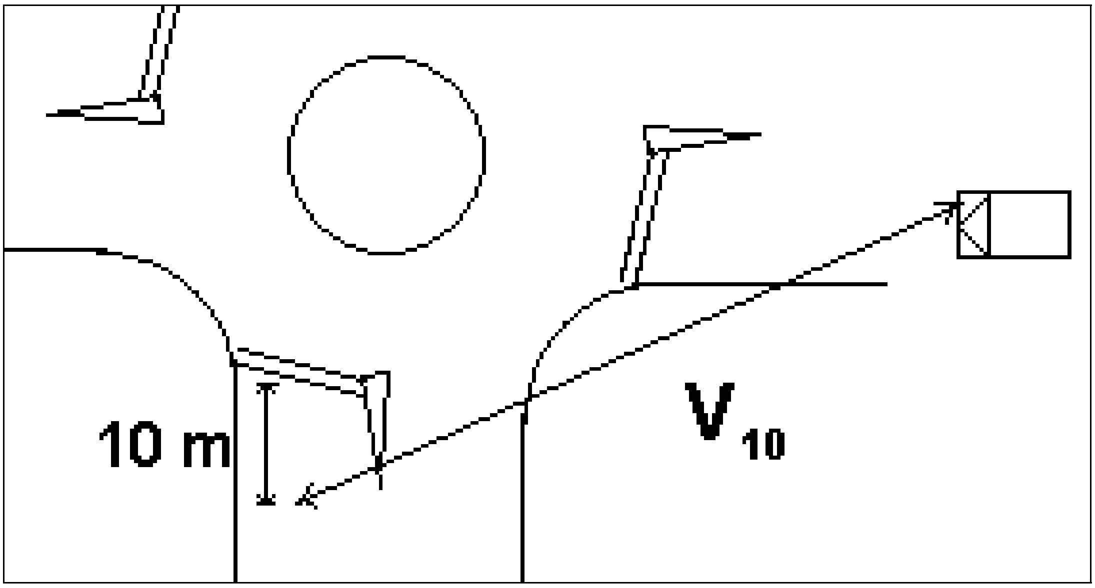

Figure 3: Measurement of V_{10}

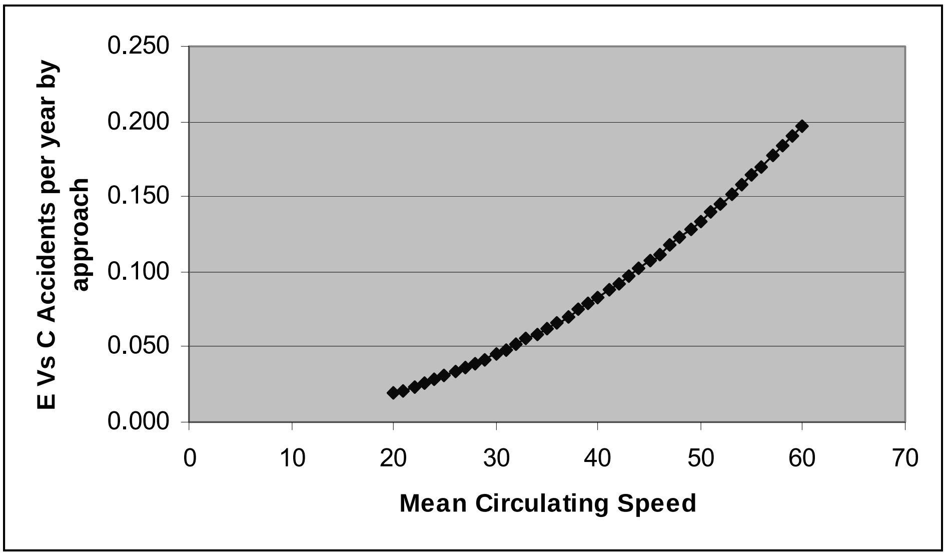

Figure 4: Effect of Circulating Speed on Entering Versus Circulating Accidents (Qe of 5000 and Qc of 6000)