TRANSPORT and ROAD
RESEARCH LABORATORY

Department of the Environment
Department of Transport

TRRL LABORATORY REPORT 1120

ACCIDENTS AT 4-ARM ROUNDABOUTS

by

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Crowthorne, Berkshire
1984

ISSN 0305 - 1293

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ABSTRACT

The report gives the findings of a study of personal injury accidents at a sample of 84 four-arm roundabouts on main roads in the UK. The study includes small roundabouts and roundabouts of conventional design, in both 30–40 and 50–70 mile/h speed limit zones. Tabulations are given showing accident frequencies, severities, and rates by roundabout type. The accidents are further analysed by type (entering-circulating, approaching, single-vehicle, etc) and by road-user involvement (cyclist, motorcyclist, pedestrian, etc). The accident frequencies by type are related to traffic flow and roundabout geometry using regression methods. Equations are developed to enable roundabout accidents to be predicted for use in design and appraisal. The report illustrates the features of the prediction model, and includes a discussion of prediction errors.

1. INTRODUCTION

In the late 1960's and early 1970's the design of single-level roundabouts was revolutionised by the introduction of the offside priority rule (give way to traffic from the right) and the re-appraisal of geometric design principles which followed. In particular, it was found that roundabout capacity could be substantially increased within an existing junction area, by reducing the size of the central island and by making use of the extra space this created to provide widened entries with flared approaches.

It soon became clear however, that the safety record of some of the new designs was unacceptable. The problem was particularly evident in cases where the reduction of the central island size of a large roundabout had resulted in inadequate deflection of through traffic. Accordingly, the official design guidance for such roundabouts was modified to include adequate deflection (Department of the Environment, 1975). The deflection criterion specified that vehicle paths (assumed 2m wide) through the roundabout should be constrained to follow a radius of 100 metres or less – a degree of curvature corresponding to a sideways force of 0.2 g at about 50 Km/h.

The greater accident potential of the new 'small island' roundabouts was confirmed in a before and after study conducted by the Transport and Road Research Laboratory (Green, 1977). This study examined accidents at 150 junctions where 'small island' roundabouts or 'mini-roundabouts' had been installed during 1970–73. Of these, a total of 39 junctions had been converted from 'conventional' (large island) to 'small island' designs (3, 4 and 5-arm single-island designs and some multiple roundabouts). Although the analysis of before/after accident data showed that the samples used were not homogeneous, inasmuch as the before/after accident change varied from site to site, it showed that at sites with 4 or more approach arms, personal injury accidents had almost doubled. The report commented that many of the small-island designs included in the survey were early designs and may have had inadequate deflection. There was however, clearly a need to establish in much greater detail, the characteristics of the accidents occurring at the newer designs, to compare accident rates at small roundabouts with those at more conventional designs, and if possible, to determine how accidents were related to geometric layout.

Accordingly, the Transport and Road Research Laboratory invited the Transportation Research Group at Southampton University to undertake, under contract, a study of accidents at major 4-arm roundabouts in the UK. This report summarises the main findings of the study. The study of roundabouts reported here forms part of a larger investigation including also major junctions on dual carriageways (roundabouts, signals and major-minors), the preliminary findings of which have been reported elsewhere (Hall and Surl, 1981). The two parts of this work (roundabouts and dual carriageway junctions), whilst overlapping, are sufficiently extensive to justify separate reporting.

2. STUDY APPROACH

The specific study objectives were three fold:

(a) to produce accident tabulations for both 'small' roundabouts and roundabouts of conventional design, which would give insights into the main accident problems and lead to design improvements and remedial measures;

(b) to derive relationships between accident frequency, traffic flow and geometry which could be used to optimise designs, and,

(c) to provide methods for predicting mean accident frequencies (personal-injury accidents per year) for use in junction appraisal.

In order to fulfil these objectives, a representative sample of the target group (4-arm single-level roundabouts) with a wide range of potential explanatory variables – notably traffic flows and geometric variables –was needed. The sample needed to cover both the semi-urban situation (30–40 mile/h speed limit) and the rural situation (50–70 mile/h), and the sample size would have to be large enough to give a good chance of yielding statistically significant relationships.

The target group of junctions for the study was defined as follows:

(i) it was to include 'small' roundabouts (ie with kerbed central islands greater than 4 metres diameter) with a relatively large ratio of inscribed circle diameter to central island size, and often with widened entries and flared approaches. One of the roads passing through the junction would be a Class A road.

(ii) it would include roundabouts of conventional design – ie those with relatively large central islands and usually with parallel (unflared) entries. These roundabouts would be at the junction of 2 Class A roads. Separate samples would be taken to be representative of roundabouts on all types of road (mainly single carriageways) and of roundabouts on sections of dual carriageway at least 5 Km in length.

(iii) all junctions would be on one level, with the 4-arms intersecting approximately at right angles. Central islands would be approximately circular.

(iv) roundabouts with unusual features – eg exits and entrances to premises opening onto the roundabout (with a few exceptions), yellow-bar markings on an approach, construction on the central island, etc – were excluded.

(v) separate samples of roundabouts with 30–40 mile/h and 50–70 mile/h speed limits would be taken.

Mini-roundabouts (with central islands less than 4 m in diameter) were excluded from the study.

3. SAMPLE SELECTION

The first step in selecting the study sample was to compile a list of roundabouts in England and Wales from which the sample could be drawn . This list was compiled from the following sources:

(i) Stats 19 listings of all reported injury accidents at junctions on Class A roads for 1974–1976. (Note: this source was not used to select junctions with high accident frequencies, but simply to locate major junctions; most major junctions will appear in the accident lists over a period of three years);

(ii) information from Local Authorities;

(iii) inspection of 1:50,000 Ordnance Survey maps; and,

(iv) TRRL Report LR 774 (Green, 1977).

All the sites in this list were visited and photographed, and traffic flow data (usually limited only to major road flows) were obtained where it was available. The final selection of junctions for analysis was made according to the target specification given in section 2 above, to provide a wide range of flows within the various roundabout categories. No specific note was taken of accident data during this selection stage. The final number of roundabouts in each of six categories is given in Table 1.

TABLE 1

Numbers of roundabouts in the sample by junction category

Junction Category	Speed Limit Group	
	30–40 mile/h	50–70 mile/h
Small Roundabouts	25 (17)	11 (8)
Conventional Roundabouts *	11 (10)	11 (10)
Dual-carriageway Roundabouts *	14 (11)	12 (11)
TOTAL	84 (67)	

( ) The numbers in brackets are the numbers of roundabouts which either remained unchanged in design throughout the accident sampling period, or if changed were included in only one form.

* Terminology: for convenience, the terms "conventional" and "dual-carriageway" roundabouts are used throughout this report to distinguish the two sub-samples. Dual carriageway roundabouts are also conventional in design, and where reference to both categories is intended, the phrase "conventional designs" will be used.

During the course of the accident sampling period (mainly 1974–1979), some of the roundabouts were changed in design (eg from a conventional design to a small-island design, or by increasing the entry widths etc); one junction was converted to traffic signal operation. The figures in Table 1 refer to the total numbers of different designs in the sample (ie a conversion from one roundabout to another, is regarded as 2 different designs). In some of the later analyses (relating to geometric data) some of the sites which were changed prior to the survey date (Winter 1977–78), have had to be omitted where geometric information on superseded layouts was not available. The total numbers of roundabouts (or arms) included in each analysis is quoted where a sub-set of the total data base is being used.

Referring to the distribution of sites in Table 1, it will be noted that the small roundabout, 30–40 mile/h category, has a relatively high number of sites. This is to represent adequately the wide range of geometry found at these sites. In fact, the small roundabouts selected for study form a high proportion of all such junctions on major roads. The sample of conventional roundabouts was chosen to complement the small roundabouts so as to cover the range of designs on all-purpose roads. The dual-carriageway roundabouts had at least two dual-carriageway approaches on opposite arms, and a few had three or four. It should also be remembered that the small and conventional roundabout categories will include some dual-carriageway approaches, and that quite a high proportion of the approaches to dual-carriageway roundabouts are single carriageways (the side roads). A complete list of the sample of roundabouts classified by the three categories of roundabout (small, conventional and dual-carriageway) and the two speed limit groups (30–40 and 50–70 mile/h) is given in Appendix 1. Included also in this Appendix are some basic geometric and traffic features of the roundabouts, together with aggregate 'observed' accident data, and the corresponding numbers of accidents calculated using the final predictive formula (section 7 of this report).

An attempt has been made to check that the sample resulting from the above procedure is reasonably representative (Faulkner, 1980). Ordnance Survey maps were scanned to find roundabouts at four-arm junctions of two A-roads. A total of 212 were found in England (excluding roundabouts in Dorset and Lancashire for which locational cross-referencing to Stats 19 was inadequate). All but 9 of these roundabouts were represented in the Stats 19 accident records for 1974–77. The absence of accidents at the 9 'missing' roundabouts was confirmed with the local highway authority, and it was estimated that the flows at these sites ranged from 7,000 – 13,000 per day (ie they were comparatively low flow sites). The distribution of accidents (personal injury accidents per 4 years) among these sites is shown in Fig. 1. The mean of this distribution (the target population) is 9.6 accidents per roundabout in the four years.

It is probable that although the map searching procedure covered all areas (urban and rural) and all types of road (single and dual-carriageway), the small-island roundabouts will be under-represented due to their being recent innovations compared with the date of map revision. The 212 roundabouts should therefore be compared with the sample of 42 conventional designs in the present study (ie excluding sites which changed during the study period). It is worth noting, firstly that they represent very roughly a 20 per cent sample (possibly rather less if Scotland and Wales are taken into account); secondly, the mean 4-year accident frequency at the 42 sample sites for the years 1974–77 is 11.8 accidents per roundabout, with a 95 per cent confidence limit of ±1.3. It would appear therefore, that whilst the sample reported on in the present study might be slightly biassed towards the higher accident frequency sites (probably the busier sites), the difference is sufficiently small to give confidence that the analyses of accident rates (ie with flow effects taken into account), severities, proportions of different types of accident and geometric effects, given in this report, are representative of all roundabouts in current operation.

4. DATA

4.1 Accident data

Records of all personal-injury accidents occurring at or within 20 metres of each site were provided by the relevant local highway authority for the years 1974–1979. These data included the date and time of each accident, the road and weather conditions prevailing at the time, number and type of each road user involved and the severity (fatal, serious or slight) of each casualty. For each vehicle or pedestrian involved in an accident, information was generally available on the location of the accident within the junction and the movement prior to the accident. All these data were carefully checked against Stats 19 listings.

4.2 Traffic flow data

At most of the sites a 16 hour (0600 h – 2200 h) classified turning count was carried out. The classification used was pedal cycles, motor cycles (ie powered two wheelers), cars, light goods, heavy goods, buses and coaches. At nearly all sites in the 30–40 mile/h speed limit categories, flows of pedestrians crossing each arm of the junction were also counted. Flows were recorded by hour during the off-peak periods, and in quarter-hour periods during the peaks. The counts were taken on a weekday during April, May, June, September or October 1978. For the seven sites in the Greater London area, classified turning counts were carried out for 7 sample hours during the 16-hour day in conjunction with 16 hour automatic counts of the in-flows on each arm. At one site (site number 190) no flow counting was possible, and historical flow data have been used.

The measured flows have been scaled up to total flows during the whole period for which accident data were available on each design (mostly 1974 to 1979) or to an average 24-hour equivalent. For flows of all vehicles except two-wheelers the scaling was achieved by using the monthly M-factors designed for use with COBA, and data from the 50-point traffic census for 1974–1979. For flows of two-wheelers, however, this method was felt to be inadequate, since the seasonal variation in the flows of such vehicles, particularly pedal cycles, is rather different from that of other motor vehicles. Thus a separate procedure was used for scaling the pedal cycle and motor cycle counts, which makes use of detailed 1980 pedal cycle and motor cycle traffic census data and the annual variation indices for each mode (Department of Transport, 1981). Thus account was taken of the vehicle type, day of the week, month and year of the traffic count, the speed limit group of the junction, and traffic growth over the 6-year period. For the analysis of accident rates by year, month, day of week and time of day, the relevant flow factors were derived from census data from comparable sites.

4.3 Site and geometric data

Detailed layout data were recorded for all the roundabouts in the sample (with the exception of some details relating to junctions converted prior to the survey of sites). General site data includes junction type and speed limit category at the junction (ie 30–40 or 50–70 mile/h), and some category factors relating to each approach – road class, carriageway type, approach speed limit etc. Geometric data includes overall dimensions such as inscribed circle diameter and central island diameter, as well as a number of arm-specific dimensions – eg entry path curvature, entry width, flare dimensions and so on. A list of the main variables and factors with their ranges (excluding the main junction type/speed limit categories) is given in Appendix 2. The mean deviance ratios given in this Appendix will be referred to in Section 6.3.5 (vi) of the report. Those geometric parameters which proved to be significant in the accident analysis are defined in Appendix 3, and are referred to at the appropriate point in the report.

5. ACCIDENT TABULATIONS

5.1 Introduction

This section presents the basic accident data by means of a series of summary tabulations. In addition to presenting accident numbers, the tabulations have been drawn up in terms of two accident measures: average accident frequency (ie the average number of accidents per junction per year over the period 1974–1979), and basic accident rate (ie accidents per 100 million vehicles passing through the junction, calculated over the same period).

For ease of assimilation, the data have been averaged to provide answers to questions which may be conveniently grouped as follows:

(1) How many accidents are there overall, of what severity, and what are the basic accident rates?

(2) What types of conflict occur at roundabouts of the different types, and to what extent are the different road users involved?

(3) How many vehicles or pedestrians are involved in each accident, and how many casualties?

(4) How are accidents distributed by hour of day, day of week, month and year?

5.2 Accident frequencies, severities and rates

Table 2 shows for each roundabout category, the number of sites, the total number of junction years, and the numbers of accidents classified as fatal, serious and slight. The table also shows the average accident frequency (per junction per year) and the severity, defined as the percentage of accidents which are fatal or serious.

TABLE 2

Number, frequency and severity of accidents by roundabout category

Roundabout Category	Number of		Accidents				Accident frequency (per junction per year)	Severity* (per cent)
	Sites	Junction years	Fatal	Serious	Slight	Total		
Small:								
30–40 mile/h	25	113.4	2	86	409	497	4.38 (0.48)	18 (2.3)
50–70 mile/h	11	53.0	1	20	129	150	2.83 (0.65)	14 (3.4)
Total	36	166.4	3	106	538	647	3.89 (0.40)	17 (1.9)
Conventional:								
30–40 mile/h	11	61.9	3	37	106	146	2.36 (0.20)	27 (5.7)
50–70 mile/h	11	62.2	0	30	163	193	3.10 (1.01)	16 (2.4)
Dual-carriageway:								
30–40 mile/h	14	72.5	1	30	213	244	3.37 (0.57)	13 (2.2)
50–70 mile/h	12	68.3	0	22	175	197	2.88 (0.67)	11 (2.7)
Total	48	264.9	4	119	657	780	2.94 (0.33)	16 (1.7)
All Categories	84	431.4	7	225	1,195	1,427	3.31 (0.26)	16 (1.3)

* Severity is the percentage of accidents which are classified fatal or serious.

( ) Figures in brackets are the standard errors of the mean values calculated from the site to site variation of the observed frequencies.

The accident frequencies in the table suggest that the small roundabouts (30–40 mile/h) are generating more accidents than average whilst the conventional (30–40 mile/h) are generating rather fewer. The remaining categories appear much the same. However, comparisons of accident frequencies are not of themselves particularly meaningful, and conclusions regarding the relative safety of the different roundabout categories cannot properly be drawn until exposure to risk (traffic flows) has been taken into account.

The proportion of fatal and serious accidents in the present sample averages 16 per cent; there would appear to be little practical or statistical significance in the variation between the categories. The high figure for conventional (30–40 mile/h) sites if anything reflects not a higher incidence of fatal and serious accidents compared with the rest, but a lower incidence of slight accidents.

Table 3 shows the basic accident rates for the different accident severities (fatal, serious and slight) and for total accidents.

The table shows that the use of total vehicle inflow as a measure of exposure to risk, has brought the conventional (30–40 mile/h) roundabouts into line with the dual-carriageway roundabouts. The small roundabout (30–40 mile/h) accident rate remains notably higher than that of the conventional designs, although in statistical terms any differences between the remaining categories would be difficult to sustain.

TABLE 3

Basic accident rates by roundabout category

Roundabout Category	Number of sites	Total vehicle flow x 10^8	Accidents per 100 million vehicles			
			Fatal	Serious	Slight	Total
Small:						
30–40 mile/h	25	13.39	0.15	6.4	30.5	37.1 (3.1)
50–70 mile/h	11	5.22	0.19	3.8	24.7	28.7 (3.3)
Total	36	18.61	0.16	5.7	28.9	34.8 (2.5)
Conventional:						
30–40 mile/h	11	6.89	0.44	5.4	15.4	21.2 (2.0)
50–70 mile/h	11	6.72	0	4.5	24.2	28.7 (6.3)
Dual-carriageway:						
30–40 mile/h	14	10.86	0.09	2.8	19.6	22.5 (2.5)
50–70 mile/h	12	8.78	0	2.5	19.9	22.4 (3.1)
Total	48	33.26	0.12	3.6	19.8	23.5 (1.8)
All Categories	84	51.87	0.13	4.3	23.1	27.5 (1.6)

( ) Figures in brackets are the standard errors of the mean values calculated from the site to site variation of the observed values.

5.3 Accident types and road user involvement

Roundabout accidents may be classified in a number of ways, some of which are mutually exclusive and some of which are not. This distinction will be pointed out where it arises, but needs always to be borne in mind when interpreting the information presented in the following tables.

Results will first be presented of an analysis of accidents by type of conflict. Since this particular disaggregation of accidents (which is mutually exclusive) forms the basis of later regression analyses, the various categories are defined as follows:

(i) *Entering-circulating accidents.* These are accidents involving collisions between an entering vehicle and a circulating vehicle. (Note: in this context, pedal cycles are included in the term 'vehicles'). By far the majority are 2 vehicle accidents although there are a few in which more than two vehicles were involved.

(ii) *Approaching accidents.* Accidents between vehicles on the approach to the junction; mostly rear-end shunts when one vehicle runs into the back of another, but also including accidents where a vehicle is changing lanes. Again, these will be mainly 2-vehicle accidents.

(iii) *Single-vehicle accidents.* Accidents involving a vehicle colliding with some part of the junction layout or with street furniture, lighting columns, etc.

(iv) *Other accidents.* This category includes a variety of vehicular accidents which occur relatively infrequently. It includes, circulating vehicles colliding with each other, circulating vehicles colliding with vehicles exiting from the junction, exiting vehicles colliding with entering vehicles and with other exiting vehicles. There are also a small number of miscellaneous accidents in this category which it has not been possible to classify into one of the other categories.

(v) *Pedestrian accidents.* Accidents involving pedestrians and vehicles.

Table 4 presents the percentages of accidents in the five mutually exclusive types defined above, by roundabout category. The total number of accidents and the average basic accident rate are given for reference, so that the numbers or rates in each conflict category can be obtained by direct multiplication.

TABLE 4

Accidents by accident type and roundabout category

Roundabout category	Total number of accidents	Average accident rate (per 10^8 vehicles)	Percentage by accident type				
			Entering-circulating	Approaching	Single-vehicle	Other	Pedestrian
Small:							
30–40 mile/h	497	37.1	72.2	6.6	7.5	9.7	4.0
50–70 mile/h	150	28.7	67.3	8.0	10.7	12.0	2.0
Total	647	34.8	71.1	7.0	8.2	10.2	3.5
Conventional:							
30–40 mile/h	146	21.2	16.4	18.6	37.6	19.2	8.2
50–70 mile/h	193	28.7	24.9	26.9	29.0	17.1	2.1
Dual-carriageway:							
30–40 mile/h	244	22.5	21.7	24.2	24.2	18.4	11.5
50–70 mile/h	197	22.4	16.8	29.9	32.5	17.8	3.0
Total	780	23.5	20.3	25.3	30.0	18.0	6.4

This table reveals the basic difference between the accident characteristics of the small-island roundabouts and the conventional designs. In the former, about 70 per cent of all accidents are conflicts between entering and circulating vehicles. The remaining categories each represent 12 per cent or less of all accidents. There are no real differences between the speed limit sub-groups. In the conventional and dual-carriageway categories however, the accidents are distributed between three main types: entering-circulating accidents, approaching accidents and single-vehicle accidents. With the exception of pedestrian accidents, there are no outstanding differences between the four categories of conventional designs. As expected, the proportion of pedestrian accidents is significantly higher at the 30–40 mile/h junctions than at those with 50–70 mile/h speed limits. In all probability, this is due to higher pedestrian flows at the former, although this point cannot be verified since pedestrian flows were not obtained at the 50–70 mile/h sites. The differences illustrated by Table 4 clearly arise from the basic differences in the geometry and operation of small roundabouts as compared with those of conventional design. These geometric effects will be examined further in section 6. An analysis of accidents in terms of the 'movement before accident' (MBA) as coded on Stats 19 has been undertaken. The results, which are not given in detail here, reproduce the effects shown in Table 4 in that MBA 4 (two moving vehicles – different roads) dominates at the small roundabouts, whereas at conventional designs, accidents are divided between MBA 1 (one moving vehicle), MBA 2 (two moving vehicles, same direction) and MBA 4 (two moving vehicles, different roads) in that order.

Table 5 shows the proportion of accidents at small roundabouts and the conventional designs (including dual carriageway) which involve pedal cycles, motor cycles and heavy goods vehicles. These categories are not mutually exclusive. Table 5 shows also how the accidents involving these particular road user categories are distributed among the 5 accident types. It will be seen that for all roundabouts, pedal cycles are involved in about 13–16 per cent of all accidents, motor cycles in 30–40 per cent and heavy goods vehicles in about 6–8 per cent. Bearing in mind the fact that some of the percentage figures given in columns 3–7 of the table are based on small numbers of accidents, it would appear that the pattern of accidents characteristic of the two basic types of roundabout (noted in connection with Table 4) is reproduced within the individual road-user groups. The exceptions to this would seem to be that pedal cycles are not apparently involved in either single-vehicle accidents or in accidents with pedestrians. It is known that many cycle accidents are not reported, and it may well be that under-reporting particularly affects the categories of accidents mentioned in the previous sentence.

TABLE 5

Accidents by conflict type and road user category

Roundabout and road-user category	Number of accidents (percent of total)	Percentage of accidents in each road-user category, by accident type *				
		Entering-circulating	Approaching	Single-vehicle	Other	Pedestrian
Small (30–40 and 50–70):						
All accidents	647	71	7	8	10	4
Pedal cycle accidents	86 (13.3)	78	5	0	17	0
Motor cycle accidents	252 (38.9)	78	3	8	9	2
HGV accidents	51 (7.9)	71	8	2	17	2
Conventional and Dual-carriageway (30–40 and 50–70):						
All accidents	780	20	26	30	18	6
Pedal cycle accidents	124 (15.9)	41	21	3	35	0
Motor cycle accidents	240 (30.8)	27	19	36	15	3
HGV accidents	48 (6.2)	10	33	17	34	6

* In many cases the figures in this table are based on only a few accidents. They are to be regarded therefore as a very general indication of the way the accidents involving specific road user types are distributed between the different accident types.

Table 6 shows the distribution of accidents among the vehicle/road-user classes, and the accident involvement rate of the different classes related to the total flow of the particular class in the accident period. These tabulations are not mutually exclusive. With the exception of single-vehicle accidents, each accident may be attributed to more than one category according to the vehicles involved. Thus a collision between a car and a pedal cycle will be attributed to both categories; a car-car conflict will contribute 2 entries to the car involvement category, whilst multi-vehicle accidents may be assigned to more than 2 categories. The resulting numbers of accidents are then divided by the appropriate flows (eg pedal cycle accidents are divided by pedal cycle flows etc) to give accident involvement rates per 100 million traverses of the junction by that particular class. The table is headed by the total number of vehicle/road-user involvements in each road-user category for all roundabout types taken together, and the percentage of the total involvements attributed to each road-user category. With regard to these percentage figures, it was considered appropriate to report only the overall results, because with the exception of pedestrians and pedal cyclists there is no evidence that the proportion of the different road-user categories differed from one roundabout type to another. There is some evidence (as previously noted) that there are fewer pedestrian accidents at the 50–70 mile/h sites, and the same may be true of accidents involving pedal cyclists.

Standard errors of the involvement rates are given in the Table as a guide to the variability of the site to site variation. No rigorous statistical testing of differences had been attempted.

TABLE 6

Vehicle/road-users involved in accidents at roundabouts, and involvement rates per 100 million of road-user class

	Roundabout Category	Vehicle/road-user class *						
		Pedal cycle	Motor cycle	Car	L.G.V.	H.G.V.	Bus/ coach	Pedestrian
Number of involvements	All Roundabouts	210	497	1,569	110	104	37	78
Percentage	All Roundabouts	8.0	18.8	59.4	4.2	3.9	1.4	3.0
Involvement rate per 10^8 of road-user class	Small:							
	30–40 mile/h	785 (90)	663 (49)	56 (2)	31 (5)	43 (6)	62 (16)	33 (8)
	50–70 mile/h	629 (209)	757 (89)	43 (3)	45 (10)	10 (4)	0	–
	Total	765 (83)	687 (43)	53 (2)	35 (5)	31 (4)	49 (13)	
	Conventional:							
	30–40 mile/h	291 (50)	267 (39)	23 (2)	11 (4)	18 (6)	45 (23)	45 (12)
	50–70 mile/h	605 (119)	407 (52)	43 (3)	29 (7)	19 (4)	69 (31)	–
	Dual-carriageway:							
	30–40 mile/h	811 (116)	326 (36)	29 (2)	14 (4)	9 (3)	60 (21)	72 (15)
	50–70 mile/h	522 (135)	331 (47)	35 (2)	15 (4)	13 (4)	49 (22)	–
	Total	498 (45)	329 (21)	32 (1)	17 (3)	14 (2)	55 (12)	

* In addition to those included in the table, there was a total of 35 involvements not allocated to specific categories.

( ) Figures in brackets are the standard errors of the mean values, obtained by regressing the site specific numbers of involvements against the relevent inflows through the origin.

The main feature of the table is the very high accident involvement rates of two-wheeled vehicles, which are 10–15 times those of cars. This figure highlights the vulnerability of the riders of two-wheeled vehicles, and in combination with the high proportion of accidents involving two-wheelers at roundabouts, justifies further study of possible accident causation and remedial treatment. It is not easy to identify consistent differences between the involvement rates of the various roundabout categories given in Table 6, except to note that the higher accident rates at small roundabouts as compared with the conventional designs can again be detected.

5.4 Distribution of accidents by number of vehicles/pedestrians involved per accident, and number of casualties per accident

Table 7 shows the percentage of accidents which involved N vehicles or pedestrians (N = 1 to 5) for the two main types of roundabout.

TABLE 7

Distribution of accidents by number of vehicles or pedestrians involved

Junction category	Total number of accidents	Percentage of accidents with N vehicles/pedestrians per accident				
		N = 1	N = 2	N = 3	N = 4	N = 5
Small roundabouts	647	8.2	88.9	2.9	0	0
Conventional and Dual-carriageway roundabouts	780	30.0	64.5	4.5	0.6	0.4

These distributions clearly reflect the differences between the two types of roundabout already noted in connection with accident type in Table 4. The average number of vehicles or pedestrians per accident for all roundabouts is 1.85.

Table 8 shows the percentage of accidents with N casualties (N = 1 to 6) per accident. Since there are no discernible differences between any of the roundabout sub-groups (small, conventional or speed limit groups) an average for all roundabouts is given.

TABLE 8

Distribution of accidents by number of casualties

	Total number of accidents	Percentage of accidents with N casualties per accident					
		N = 1	N = 2	N = 3	N = 4	N = 5	N = 6
All roundabouts	1,427	83.7	12.5	2.1	1.0	0.5	0.2

The average number of casualties per accident at this sample of roundabouts is 1.23. The national average figure for 1974–1979 has remained consistently at about 1.32.

5.5 Distribution of accidents in time

The date and time of each accident has been recorded in the data base. It is therefore possible to look at the distribution of accidents by year (1974–1979) by month of year, by day of week, and by hour of day (or by selected groups of hours). If estimates of traffic flow can be obtained for the relevant periods, then the basic accident rates (accidents per 10^8 vehicles) can also be calculated. In the present study, since traffic counts were undertaken on a single day, it was not considered appropriate to attempt to estimate flows by year, month or day of week. Accident rates for these periods have not therefore been calculated. The traffic flow information obtained by hour during the day of observation has however been scaled up and used to provide estimates of average accident rates for specific periods within the day.

The distributions of accidents by year, month and day of week have been calculated on the basis of average frequencies (to allow for the fact that some junctions were not operating for the whole of the 6 year period (1974–1979)). When the differences between the average accident frequencies for the six roundabout sub-groups have been allowed for (by calculating ratios or percentages) there remains no consistent differences in the way the accidents are distributed in time between the various roundabout sub-groups. The average distributions for all roundabouts in the sample (small, conventional and dual carriageway) are therefore presented in this section.

Tables 9–12 show respectively, the distribution of accidents by year, by month (averaged over the years 1974–1979), by day of week and by time period within the day. In the latter case, estimates of the ratios of the accident rate (per 100 million vehicles) in a specific time period to the corresponding figure for 24 hours is also given. The figures for the roundabout sample are compared in each case with appropriate national statistics (Department of Transport, Road Accidents in Great Britain, 1974–1979). The national 'accident' ratios given in Tables 10, 11 and 12 have been calculated from published casualty data relating to all roads and junctions, since the relevant accident data are not readily available.

TABLE 9

Average accident distribution for all roundabouts in the sample, by year 1974–1979

	Ratio: $\frac{\text{Accident frequency for a specific year}}{\text{Average for 1974–1979}}$					
	1974	1975	1976	1977	1978	1979
All Roundabouts in sample	0.87	1.05	1.08	1.17	0.99	0.82
National statistics						
All junction accidents*	0.94	0.95	1.02	1.06	1.05	0.99
All accidents on 'A' roads	0.97	0.95	0.99	1.04	1.05	1.00

* These figures are derived from 'all accidents' minus those designated 'not at or within 20 yards of junction'. Accidents at all roundabouts could have been used here, but all junction accidents are preferred, since the total number of junctions is likely to have remained reasonably stable over the years.

TABLE 10

Accident distribution for all roundabouts in the sample, by month, averaged over the years 1974–1979

		All Roundabouts in sample	National statistics
Ratio: $\frac{\text{Accident frequency for a specific month}}{\text{Average for all months}}$	January	1.00	0.90
	February	0.82	0.80
	March	0.82	0.91
	April	0.70	0.88
	May	1.04	1.00
	June	0.91	0.99
	July	0.98	1.06
	August	1.08	1.06
	September	0.91	1.07
	October	1.29	1.09
	November	1.25	1.13
	December	1.11	1.12

TABLE 11

Accident distribution for all roundabouts in the sample, by day of week, averaged over the years 1974–1979

		All roundabouts in sample	National statistics
Ratio: Accident frequency for a specific day of the week / Average for all days	Monday	1.00	0.91
	Tuesday	0.99	0.90
	Wednesday	1.02	0.93
	Thursday	1.00	1.00
	Friday	1.03	1.19
	Saturday	1.01	1.16
	Sunday	0.97	0.91

TABLE 12

Accident distribution for the average day for all roundabouts in the sample, by period of day, averaged over the years 1974–1979

	00.00–06.00	06.00–10.00	10.00–14.00	14.00–18.00	18.00–22.00	22.00–24.00
	Percentage in the specific time period					
All Roundabouts in sample	9.4	17.4	14.8	28.7	19.2	11.5
National statistics (Traffic Flow)	8 (2.3)	13 (21.8)	19 (23.8)	30 (29.6)	18 (18)	12 (4.5)
	Accident rates for specific time period / Accident rate for 24 hours					
All Roundabouts in sample	2.87*	0.75	0.68	0.99	1.04	2.41*

( ) The figures in brackets represent the percentage of vehicle travel (vehicle-kilometres) occurring in each time period, calculated from 1979 50-point census data, for all roads in Great Britain. The ratio of the two figures in the row designated 'National Statistics' gives a figure which can be compared with the corresponding roundabout ratios in the row below.

* The ratios in the period 22.00–06.00 should be treated with caution since no flow counts were undertaken during this period, and flows have been estimated using factors derived from national data.

It will be seen from the above tables, that the distribution of accidents in time at the sample of roundabouts included in the present study, generally reflects the national pattern.

6. REGRESSION ANALYSIS

6.1 Introduction

The objective of the analysis presented in this section is to relate the accident frequency (the average number of accidents per year) to a range of 'explanatory variables', and hence to determine a relationship which could be used to predict site-specific mean accident frequencies from such variables.

The technique used was multiple regression analysis, and the explanatory variables were traffic flow and a range of geometric variables. Since however, numbers of accidents in a given period are not Normally distributed, standard least squares regression could not be used, and a generalised linear model formulation available in the GENSTAT and GLIM (Baker and Nelder, 1978) computer statistical packages have been employed. These packages allow the dependent variable in the regression analysis to be drawn from distributions other than the Normal distribution (the Poisson distribution for example), and allow non-linear models to be fitted by means of suitable data transformations. Appendix 4 gives an outline of the principles of generalised linear models as applied to the analysis of accidents.

The analysis proceeded in two stages; the first an analysis of accidents relating to the roundabout as a whole, and the second in which arm-specific accidents are analysed. In the latter accidents are sub-divided by type (as previously defined), so that entering-circulating accidents, approaching accidents, single-vehicle accidents, 'other' accidents and pedestrian accidents are treated separately.

6.2 Regressions relating to roundabouts as a whole

The first stage in this analysis was to attempt to fit a simple linear model, of the form:

$$A = b_0 + b_1 V$$

where A = average accident frequency (accidents per year) at individual roundabouts,*
V = annual average 24-hour vehicle inflows (in thousands of vehicles), and b_0, b_1 are coefficients to be estimated.

These analyses were carried out at an early stage of the project, when the only accident data available were those for 1974–1977. Significant relationships were obtained using these data, for all roundabout types except the conventional 30–40 mile/h category. This group did not produce significant relationships because the range of the flow data was too small. The remaining categories however yielded values of b_0 ranging from -2.49 to -0.55 (all negative) and values of b_1 ranging from 0.13 to 0.19. (The range of the dependent variable (accidents per year) was 0 to 10.) Clearly negative mean accident frequencies are unacceptable, and although it would have been possible to force the relationships through the origin, the resulting model would have shed little light on the dependence of accidents on traffic flow, merely reproducing the results given in section 5 under 'basic accident rates'. It was felt preferable therefore, to explore flow dependency using a more flexible non-linear model, which would automatically be constrained to pass through the origin but which could reproduce the very simplest linear model if it proved to be adequate. The model was of the form:

$$A = k\,(Q)^{\alpha}$$

where A = accidents per year (as before),
Q, the flow function, is an algebraic combination of the various elements of flow within the junction (All 24-hour averages expressed in thousands of vehicles), and
k, α are parameters to be estimated

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* In carrying out all the regressions presented in this report, the dependent variable used is not the accident frequency but the total number of accidents within the sampled period. The regression process allows the results to be expressed in the above form (see Appendix 4).

Three basic flow functions (Q) were tried:

- Total inflow; simply the sum of the four entering flows.
- Cross product; the product of the total entering flows on one pair of opposite arms with the total entering flows on the other pair of opposite arms.
- Entering-circulating; the product of the entering and circulating flows at each entry, summed over the four arms.

With the exception of the conventional roundabouts (30–40 mile/h) all categories yielded highly significant relationships (1 per cent level or better) relating total accidents to flows for all flow functions. There was little to choose between these alternatives as models of accidents for the roundabouts as a whole. However, for comparisons between the accident rates of roundabouts and junctions with other forms of control, the total inflow function proved to be entirely unsuitable. This was particularly the case where the comparisons included major-minor junctions, since there was virtually no correlation between accidents and total inflow at such junctions, but a very significant correlation when the cross-product flow function was used. Since the cross-product function (for whole junctions) proved as good as the more complex entering-circulating function, the former was selected as the most appropriate for the initial analysis of accidents for the roundabouts as a whole.

Table 13 shows the results of an analysis of total accidents for the six roundabout categories for accident data from 1974–79, using the cross-product flow function. Since there were no significant differences in the exponent (α) between any of the roundabout categories, a common value has been fitted and the variation in the data reflected in the different k values. This table is analogous to the basic accident rate table (Table 3) and the differences between the roundabout categories noted there can be seen in the values of k in Table 13.

TABLE 13

Parameters in the relationship $A = kQ^{\alpha}$ for 1974–79 accident frequencies by roundabout category (Q = cross-product flow function)

Roundabout category	Number of sites	k	α
Small:			
30–40 mile/h	25	0.101	
50–70 mile/h	11	0.081	
Total	36	0.095	
Conventional:			
30–40 mile/h	11	0.057	0.68
50–70 mile/h	11	0.080	
Dual-carriageway:			
30–40 mile/h	14	0.057	
50–70 mile/h	12	0.061	
Total	48	0.062	

The standard errors of the values of k were about 22 per cent, and of α about 0.04. (See footnote (5), Table 16).

6.3 Arm-specific accident analysis

One of the objectives of the present study was to relate roundabout accidents to geometry. Up to the present point in this report, differences in junction geometry have been reflected only in the roundabout categories (mainly the difference between small and conventional designs). The present section describes a more detailed geometric analysis. Since however, each arm of a roundabout will have a different geometric layout, it becomes necessary to consider the arm and its approach as the basic element rather than the junction as a whole. In the subsequent sections therefore, the analyses will relate accident frequencies per arm to traffic and geometric variables. The analyses are based on 78 roundabouts (312 arms) for which full geometric data was available. The first stage in this process is to consider the flow dependency.

6.3.1 Arm-specific flow relationships. Common sense suggests that different types of accidents (eg entering-circulating, approaching, etc) might well correlate with different combinations of flow. Accordingly, the set of arm-specific accidents were disaggregated into the five accident type categories defined in section 5.3, and for each sub-set equations of the form:

$$A = kQ^{\alpha} \quad \text{or,} \quad A = kQ_1^{\alpha}\ Q_2^{\beta}$$

were fitted, where

A is accidents per year
<u>per arm</u>,

Q, Q_1 and Q_2 are flow functions (ie flow elements or combinations of flow elements within the junction), and,
k, α and β are parameters to be determined.

A number of intuitively reasonable flow functions were tried for each conflict category. With the exception of pedestrian accidents, all flow functions for all accident types gave relationships which were statistically significant (judged by the reduction in deviance – see Appendix 4) at the 1 per cent level or better. As in the case of the data for roundabouts as a whole, there was often little to choose between the flow functions and a choice was made largely on the basis of simplicity and functional appropriateness. Regarding pedestrian accidents, pedestrian flows were available only for sites in 30–40 mile/h groups. Analyses of all roundabout categories using flow functions including vehicular flows only, showed that the relationships between pedestrian accidents and vehicular flows barely reached the 5 per cent significance level; moreover they showed clearly (as pointed out in section 5.3) that relating pedestrian accidents to vehicular flows only, did not remove the difference between the 30–40 mile/h group and the 50–70 mile/h group – presumably because the main difference arises from the different levels of pedestrian flow. When the 30–40 mile/h group (where pedestrian flow data were available) was analysed separately, the flow functions involving only vehicular flows, failed to reach significance, whereas the flow functions involving pedestrian and vehicular flows were highly significant.

Table 14 presents the results of those models which were selected as being the most useful. In all cases, roundabout categories have been pooled and equation parameters combined where there was no statistical justification for preserving separate sub-groups. This means that the two small-roundabout categories and the four conventional categories have been combined in most cases, and a common exponent has been used within each accident type, for all roundabouts. For 'other' accidents and 'pedestrian' accidents, a single relationship for all roundabouts has proved adequate.

TABLE 14

Best accident-flow regression models for the five accident types by roundabout category

Accident type	Model	Flow function*	Model parameters: Small roundabouts	Model parameters: Conventional designs
Entering-circulating	$A = kQ^{\alpha}$	Q = entering x circulating flow	$\alpha = 0.52$ (0.06) k = 0.090 (0.020)	k = 0.017 (0.004)
	$A = kQ_1^{\alpha} Q_2^{\beta}$	Q_1 = entering flow Q_2 = circulating flow	$\alpha = 0.68$ (0.08) $\beta = 0.36$ (0.08) k = 0.088 (0.020)	k = 0.017 (0.004)
Approaching	$A = kQ^{\alpha}$	Q = entering flow	$\alpha = 1.58$ (0.14) k = 0.0025 (0.0009)	k = 0.0055 (0.0019)
Single-vehicle	$A = kQ^{\alpha}$	Q = entering flow	$\alpha = 1.20$ (0.13) k = 0.0068 (0.0021)	k = 0.0164 (0.0049)
Other	$A = kQ^{\alpha}$	Q = entering x circulating flow	$\alpha = 0.75$ (0.10) k (all sites) = 0.0052 (0.0022)	
Pedestrian (30–40 mile/h sites only)	$A = kQ^{\alpha}$	Q = (entering + exiting vehicular flow) x pedestrian crossing flow	$\alpha = 0.53$ (0.13) k (all sites) = 0.028 (0.007)	

* All flows are 24-hour flows averaged over the accident study period, expressed in thousands of vehicles.

( ) The standard errors of the model parameters given in this and subsequent tables are based on an assumption of Poisson errors (see Appendix 4).

Table 14 shows that entering-circulating accidents and pedestrian accidents follow a law which is very close to the 'square root' law determined in early work at major/minor junctions (Colgate and Tanner, 1967). It might be expected that accidents between crossing flows would be directly proportional to the product of the flows, and some have indeed suggested cross-product as the most appropriate measure of exposure. However, in practice, due no doubt to a number of behavioural factors, accidents tend to increase with total traffic in a more linear fashion – a fact reflected in the square root law. The 'other' accidents increase more rapidly than this law would suggest. Approaching accidents and single-vehicle accidents, which are both related to entering flow, also increase more rapidly than a linear relationship would predict.

In all cases, the alternative model $A = kQ_1^{\alpha} Q_2^{\beta}$ was tried wherever a cross-product (mainly entering x circulating flow) flow function had been fitted. It proved to be useful only in the case of entering-circulating accidents, where both α and β were significantly different from zero and from each other. Although this more complex model reduced the residual deviance within the entering-circulating data base, the reduction was not quite statistically significant at the 5 per cent level. However, the separate flow exponents are themselves determined robustly, increasing the model complexity makes little difference to the values of k, and the result is practically sensible; it is considered worthwhile therefore, to retain the more complex model for this accident category.

One reservation about the model parameters in Table 14 should be made at this point. If there are significant correlations in the data base between the flow values and the geometric variables (as for obvious reasons there is between flow and entry or approach width), there will be a trade-off between the α values (Table 14) and the coefficients of the correlated geometric variables, when the geometric variables are introduced into the model. In fact, this effect only proved significant for single-vehicle accidents but is taken into account in all accident categories when choosing a suitably rounded value of the exponents (see Section 7).

The values of k in Table 14 are a kind of flow-related accident rate. The previously noted differences between small and conventional roundabouts (see Section 5.3, Table 4) are reflected here. Entering-circulating k-values are more than 4 times greater at small roundabouts than at those of conventional design. Approaching accident and single-vehicle accident k-values at conventional designs are rather more than double those at small roundabouts. It is the object of the following sections to relate these differences to roundabout geometry.

6.3.2 Geometric factors – the form of the model. In order to take account of the geometric variables, the model relating average accident frequency to traffic flows needs to be extended to include the geometric variables. The simplest form of this extended model (given that the regression analysis involves a logarithmic transformation) is:

$$\begin{aligned} A &= kQ^{\alpha} \exp\,[b_1 G_1 + b_2 G_2 + b_3 G_3 + \ldots \\ &= kQ^{\alpha} \exp \Sigma\,[b_i G_i] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1) \end{aligned}$$

where A is accidents per year per arm,
Q is the relevant flow function,
G_i are the geometric variables, and
k, α and the b_i are coefficients to be estimated.

An equation of this form was fitted to approaching accidents, single-vehicle accidents, 'other' accidents and pedestrian accidents using the flow functions (Q) previously determined (Table 14).

The alternative form used for entering-circulating accidents is:

$$A = kQ_e^{\alpha}\, Q_c^{\beta} \exp \Sigma\,[b_i G_i] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where Q_e and Q_c are entering and circulating flows respectively, and
α and β are separate exponents.

Each accident type has its own set of geometric variables (G_i).

Although equations (1) and (2) above represent the form of expression best suited to performing calculations, for presentational purposes it is useful to express these relationships in a multiplicative form in which the geometric variables are related to the mean values of the variables over all sites. Thus if $\overline{G_i}$ represents the mean value of the ith variable, equations (1) and (2) can be rewritten:

$$A = KQ^{\alpha}\, \Pi \exp\,[b_i(G_i - \overline{G_i})] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$A = KQ_e^{\alpha}\, Q_c^{\beta}\, \Pi \exp\,[b_i\,(G_i - \overline{G_i})] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where all the symbols are as previously, except that:

$$K = k\, \Pi \exp\,[b_i \overline{G_i}\,]$$

K now has a specific meaning. Since when all the geometric variables are at their mean values (ie $G_i = \overline{G_i}$) the exponential terms become unity, K is the annual average number of accidents for the arm in question when the flow terms are also unity (ie when the average 24-hour daily entering and circulating flow is 1000 vehicles). At values of the G_i different form the mean value, the terms exp $[b_i(G_i - \overline{G_i})]$ are factors which modify the mean accident frequency.

This principle will be used to illustrate the variation in the effects of the geometric variables. The maximum range of the multiplying factors will be from exp $b_i\ [G_i(\text{min}) - \overline{G_i}]$ at one extreme of the observed data base to exp $b_i\ [G_i(\text{max}) - \overline{G_i}]$ at the other, and this range of factors gives a good indication of the sensitivity of each factor over the observed data range. These multiplying factor ranges are quoted in subsequent tables.

6.3.3 Geometric factors – the analysis. As part of the data collection phase of the study, a large number of geometric parameters associated with each junction were recorded (as indicated in Appendix 2). It was expected that only a few of these would prove useful in accident prediction. Moreover, since the geometric variables would be necessarily correlated with each other to varying degrees, there would be alternative 'models' which could be derived for predictive purposes. The procedure adopted for selecting the most appropriate model representation (for each accident type separately) was as follows. The flow functions used in the analyses were those shown in column 3 of Table 14 and the exponent (α) was fixed at the values given in columns 4 and 5. Thus in this stage of the analysis, only the coefficients (b_i) of the geometric variables remained to be determined. The most useful explanatory variables were identified by calculating (using GENSTAT) the value of the coefficient b_i and the reduction in total deviance* achieved by introducing the variable, for each geometric variable taken singly. Because of correlations between the independent variables, there were in some cases alternative geometric variables with similar explanatory power, and a selection of the most suitable alternative had to be made. These choices were made on the grounds of plausibility (ie whether the variable was sensible or not), of practical design usefulness (whether the variable was acceptable in a design sense) and statistical validity. For example, a prime geometric determinant of entering-circulating accidents is related to deflection of entering traffic. Three geometric measures of deflection gave highly statistically significant results: central island diameter, conflict angle (the estimated angle between the paths of entering and circulating traffic at the point of crossing) and the maximum entry curvature (1/minimum radius) on the straight-ahead vehicle path (see Appendix 3 for geometric definition) – henceforth called simply the 'entry path curvature'. The first, although closely reflecting the 'small' – 'conventional' distinction for roundabouts as a whole, is not approach arm specific – and was thus rejected. Conflict angle was quite effective in statistical terms, but is not particularly easy to define or to use in a design sense. The entry path curvature was therefore chosen to represent deflection, because it is a usable design parameter, similar to the deflection criterion in current use, and is highly statistically significant.

Having chosen the best single geometric variable in each accident type category (where there was one) subsequent variables were chosen on the grounds of plausibility, design usefulness and statistical significance, with the additional proviso that coefficients of variables already included should remain reasonably stable as the extra terms are added.

6.3.4 The proportion of two-wheelers as an explanatory variable. Table 5 shows that two-wheeler accidents represent nearly 50 per cent of accidents at roundabouts. Notwithstanding the fact that the traffic flow functions have taken the 'first order' flow effects into account, it was felt that the proportion of two-wheelers might provide further explanatory power if introduced in the same form as described above for geometric variables – ie as an exponential factor. Accordingly the proportion of pedal cycles, the proportion of motor cycles and the proportion of two-wheelers (cycles and motorcycles) – all expressed as percentages – were tried as explanatory variables alongside the geometric variables.

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* The statistical usefulness of adding single terms in this way may be tested by means of the change in deviance at each step – see Appendix 4 – 14.2.4 for a discussion of significance testing in this case.

The only significant two-wheeler variable was the proportion of motorcycles used as a predictor of entering-circulating accidents and 'other' accidents. The actual value used (P_m) was the average of the proportion of motorcycles entering and the proportion circulating. However, the proportion entering was almost as good as a predictive variable and is probably the only figure likely to be available in practice. The proportion of two-wheelers (motorcycles and pedal cycles combined) was significant also, mainly because of the motorcycle component. Thus only the proportion of motorcycles (P_m) is included in the tables of results discussed in the following section.

6.3.5 Geometric factors — the results. Table 15 lists the geometric variables which were considered to provide the most acceptable combinations of explanatory variables for roundabout accidents disaggregated by accident type. The geometric definitions of these variables are given in Appendix 3. After the 'best' set of geometric variables had been selected in the way described in 6.3.3 (with fixed flow exponents) the models were re-run with the constraints on the flow exponents removed. This was done in order to reveal any instability of the coefficients due to correlations between traffic flows and geometric variables. Table 16 gives the results with the re-calculated flow exponent values. The main features of the results shown in Table 16 will be reviewed in the following paragraphs with some explanatory comment on the predictive variables.

(i) *Variables relating to entry geometry*

The prime determinants of the three main accident types (ie entering-circulating, approaching, and single-vehicle accidents) are variables associated with the geometry of the roundabout approach or entry — maximum curvature of the straight-ahead vehicle path (C_e), entry width (e) and approach road half-width (v). The entry path curvature (C_e) proved to be a much better explanatory variable than entry radius, and was chosen rather than other measures of deflection for reasons given in 6.3.3 above. Other radii of curvature on the straight-ahead vehicle path were measured (eg the radius of the path at the point where it touched the central island and the exit radius), and the corresponding curvatures tried as predictive variables. The vehicle path curvature on entry was always the most effective variable statistically. The other path curvatures were correlated with entry curvature (especially the exit curvature with a correlation coefficient of 0.5) and could provide a degree of explanatory power provided the entry path curvature (C_e) was excluded. However, they did not give any improvement in the model fit once C_e was included. A subsidiary analysis of the geometric effects at 49 roundabouts which had no entry deflection was carried out as a check on any possible correlations with circulating curvature (or radius) or exiting curvature (or radius) independent of entry curvature effects. Although the analysis gave coefficients for entering flow (Q_e), circulating flow (Q_c) and entry width (e), which were entirely consistent with the analysis of the data base as a whole, circulating or exiting curvature (or the corresponding radii) were far from statistically significant. The result should not necessarily be interpreted as implying that exit geometry is always unimportant. There may well be some cases where the entry curvature is determined not only by the entry geometry, but also by the alignment or geometry of the exit.

The magnitude of the effect of entry path curvature on entering-circulating accidents is considerable. Zero curvature (ie no deflection) gives an accident rate which is about 8.5 times that achieved with maximum deflection. Of course, this result cannot in practice be considered in isolation from the other two main accident types — approaching and single-vehicle accidents, where entry path curvature is also a moderately important determinant of accidents. In these latter accident types the sense of the effect of variations in C_e is the opposite of that observed in the case of entering-circulating accidents. These results are intuitively reasonable, and the combined influence of entry path deflection on total accidents will be illustrated in section 7.2.

Entry width is also a significant correlate of both entering-circulating accidents and approaching accidents. The effects are opposite in sign for the two accident types so that in the entering-circulating category large entry widths correlate with high accident frequencies, whereas in the case of approaching accidents the reverse is true.

TABLE 15

The explanatory 'geometric' variables for the five accident types

Accident type	'Geometric' variable (1)	Symbol (units)	Observed values (2)		
			Minimum	Mean	Maximum
Entering-circulating	1. Entry path curvature	C_e (m^{-1})	−0.010	0.013	0.053
	2. Entry width	e (m)	4.6	8.71	18.8
	3. Approach half-width correlation	ev (m^2)	16.9	47.4	147.8
	4. Ratio of Inscribed Circle Diameter (ICD) to Central Island Diameter (CID) –	R	(1.07)	(2.17)	(5.69)
	used in the Ratio Factor (RF)	RF	0	0.49	0.94
	5. Proportion of motorcycles	P_m (per cent)	0.65	2.24	5.91
	6. Angle between approach arm and the next arm clockwise	θ (deg.)	44	90	152
	7. Approach gradient (4) (category: −3, −2, −1, 0,1,2,3)	g	−3	−0.11	+3
Approaching	1. Entry path curvature	C_e (m^{-1})	−0.010	0.013	0.053
	2. Reciprocal of the sight distance to the right, from 15m back from the give-way line	$1/V_r$ (m^{-1})	0.0025	0.015	0.051
	3. Entry width	e (m)	4.6	8.71	18.8
	4. Approach gradient (4) (category: −3, −2, −1, 0,1,2,3)	g	−3	−0.11	+3
Single-vehicle	1. Approach half-width	v (m)	2.6	5.3	11.0
	2. Entry path curvature	C_e (m^{-1})	−0.010	0.013	0.053
	3. (a) Approach curvature (5) (category: −3, −2, −1,0,1,2,3)	C_{ac}	−3	0.05	+3
	(b) Approach curvature (sampled)	C_a (m^{-1})	−0.025	0 (3)	+0.033
	4. Reciprocal of the sight distance to the right, from 15m back from the give-way line	$1/V_r$ (m^{-1})	0.0025	0.015	0.051
'Other'	1. Proportion of motorcycles	P_m (per cent)	0.65	2.24	5.91
Pedestrian	NONE				

(1) Detailed geometric definitions of these variables is given in Appendix 3. The proportion of motorcycles (average for entering and circulating traffic) is included where significant, as explained in 6.3.4.

(2) Ranges appropriate to those junctions used in the geometric analyses (78 roundabouts in all).

(3) This value is a nominal mid-point value, since approach curvature values were not measured at all sites (see 6.3.5 (iv)).

(4) Negative values represent gradients which are downhill and positive values represent gradients which are uphill when travelling towards the roundabout.

(5) Negative values represent left-hand bends and positive values represent right-hand bends on approaching the roundabout.

TABLE 16

The results of the 'geometric' regression analyses by accident type

Accident type	Regression variables (including the flow function)		Constants (1) and flow exponents: Value (SE) (5)	'Geometric' coefficients: b_i (SE) (5)	Initial and residual deviances/ DOF (2)	Mean deviance ratios (3)	Multiplying factor range (4): Minimum	Maximum
Entering-circulating	Constant	k	ln k = −3.09 (0.38)		1002/311			
	Entering flow	Q_e	α = 0.65 (0.10)			42		
	Circulating flow	Q_c	β = 0.36 (0.09)			7.6		
	Entry path curvature	C_e		−40.3 (7.7)		182	2.5	0.2
	Entry width	e		0.16 (0.02)		44	0.5	4.9
	Approach width correction	ev		−0.009 (0.003)		4.8	1.3	0.4
	Ratio factor (6)	RF		−1.0 (0.18)		35	1.6	0.6
(Equations 2 and 4)	Percentage of motorcycles	P_m		0.21 (0.05)		12	0.7	2.2
	Angle between arms	θ		−0.008 (0.002)		7	1.4	0.6
	Gradient category	g		0.09 (0.03)		4.4	0.8	1.3
	'Corrected' constant	K	0.033		472/302			
Approaching	Constant	k	ln k = −4.79 (0.51)		512/311			
	Entering flow	Q	α = 1.76 (0.15)			135		
	Entry path curvature	C_e		20.7 (7.4)		24	0.6	2.3
	Reciprocal sight distance	$1/V_r$		−43.9 (13.0)		7.7	1.7	0.2
(Equations 1 and 3)	Entry width	e		−0.093 (0.037)		7.8	1.5	0.3
	Gradient category	g		−0.13 (0.06)		4.6	1.5	0.7
	'Corrected' constant	K	0.0025		323/306			
Single-vehicle	Constant	k	ln k = −4.71 (0.36)		551/311			
	Entering flow	Q	α = 0.82 (0.15)			88		
	Approach width	v		0.21 (0.04)		24	0.6	3.3
	Entry path curvature	C_e		23.7 (5.8)		12	0.6	2.6
	Approach curvature category	C_{ac}		−0.17 (0.05)		9.9	1.7	0.6
(Equations 1 and 3)	Approach curvature (sampled)	C_a		− 45 (17)		–	3.1	0.2
	Reciprocal sight distance	$1/V_r$		− 33 (11.8)		6.5	1.5	0.3
	'Corrected' constant	K	0.023		377/306			
'Other' (Equations 1 and 3)	Constant	k	ln k = −5.69 (0.45)		450/311			
	Entering x Circulating flows	Q	α = 0.73 (0.09)			53		
	Percentage of motorcycles	P_m		0.21 (0.07)		6.6	0.7	2.2
	'Corrected' constant	K	0.0054		377/309			
Pedestrian (7) (Equations 1 and 3)	Constant	k	ln k = −3.59 (0.27)		156/174			
	(Entering + exiting vehicle flow) x Pedestrian flow	Q	α = 0.53 (0.13)			20		
	'Corrected' constant	K	0.028		137/173			

(1) The constants are given in two forms. k is the constant in equations 1 and 2 (see 6.3.2); the regression procedure calculates the value of ln k and its standard error. K is the 'corrected' value for use in equations 3 and 4.

(2) The deviances given here are the Poisson scaled deviances (see Appendix 4 – 14.2.4). DOF is the corresponding degrees of freedom and equals n-p-1 where n is the number of data points (roundabout arms) and p is the number of parameters (including the flow terms) fitted in the model.

(3) Mean deviance ratio (MDR) is the reduction in scaled deviance produced by the addition of a term to the model, divided by the residual mean deviance (see Appendix 4 – 14.2.4). The statistical significance of the added term can be judged by comparing MDR with the critical points of the F-distribution. 5 per cent significance requires MDR to be 3.87 whilst for 1 per cent its value should be 6.73.

(4) The multiplying factor is that factor by which the overall average accident frequency is multiplied as the geometric variable deviates from its mean value (where the factor is 1). 'Minimum' and 'maximum' refer to the value of the factor at the minimum and maximum values of the relevant geometric variable.

(5) The standard errors given in Tables 13, 14, 16 and 17 are based on Poisson errors only. In the above table, between site variation would increase the SE's somewhat. In the case of entering-circulating accidents SE's would be increased by a factor equal to the square root of the residual mean deviance, ie 472/302 = 1.25 (compare with Table 24, Appendix 5).

(6) Ratio Factor (RF) is 1/(1 + exp (4R-7)), where R = Inscribed circle diameter/Central island diameter (see 6.3.5 (iii)).

(7) The Pedestrian results have been obtained from the analysis of the 30–40 mile/h roundabouts only.

These results are again intuitively reasonable. The magnitude of the effect in the case of entering-circulating accidents is slightly larger than that of entry curvature; predicted accident frequencies increase by a factor of 10 as the entry width increases from the narrowest (4.6 m) to the widest (18.8 m). Equally important is the interaction between entry width and entry curvature generated by the multiplicative model of equation (2) (or (4)). These effects are easier to illustrate graphically than to describe, and will be considered further in section 7.2 and Appendix 5.

The data were analysed to see whether the geometry of entry flare (as distinct from entry width alone) could provide some added explanation of data variability. For entering-circulating accidents approach width (v) proved to be a significant variable only when it was included as a 'correction' term to the coefficient of entry width itself. Thus Table 16 shows a term called 'approach width correction', the explanatory variable for which is the product of entry and approach width (ev). This variable taken together with entry width (e) gives a combined entry-approach width term of the form $0.16\ (1-v/18)e$. As v can take values from 2.6 to 11 m, the coefficient of e (ie the sensitivity of entering-circulating accidents to a unit change in entry width) falls from about 0.14 at v = 2.6 m to about 0.06 at v = 11 m.

Once the basic widths (e and v) had been incorporated into the model, the 'sharpness of flare' parameter S (where $S = \frac{e-v}{l}$, and l is the length over which the flare is developed), a parameter essential to capacity calculations (Kimber, 1980), did not improve accident prediction.

(ii) *Angle, gradient and visibility*

The angle (θ) between an arm and the next arm round in a clockwise direction is a relatively minor variable (a factor range of 2.3 for entering-circulating accidents) which nevertheless proved to be very robust. It is hardly a design variable since it is unlikely to be under the designers control. However, the effect is intuitively reasonable, since as θ increases, so the entering-circulating interaction becomes less of a crossing conflict and more of a merge, and so reinforces the merge behaviour imposed by entry deflection. It is worth noting that the effect of θ does not cancel out when the four arms of a roundabout are averaged, since the model is multiplicative. A minimisation of accidents results when those arms which carry the highest flows are arranged to have the largest θ. Obviously this would not always be practical nor desirable.

Gradient appears as only marginally significant in entering-circulating accidents and approaching accidents. The gradient variable used is in fact a category variable determined subjectively since accurate measures of approach gradient were not available for all sites. The variable ranges from −3 (a 'severe' downhill towards the junction), to +3 (a 'severe' uphill towards the junction), through 0 (level) in integer steps. From the information available on actual gradients at the steeper sites, the indications are that category 2 covers the range 1.5 per cent to 4 per cent and category 3, above 4 per cent. From Table 16 it will be seen that gradient does not have a large effect (a factor range of 1.6 for entering-circulating, and 2.1 for approaching accidents), and that the effects on the two types of accident are opposite in sense. Thus, entering-circulating accidents are lowest on downhill gradients, whereas approaching accidents are lowest on uphill grades. In total accident terms, these effects will tend to cancel one another out, and unsuccessful attempts to determine a gradient effect for total accidents from the whole data base have confirmed this conclusion. For this reason, gradient will not be included in a final predictive formula for roundabout accidents. It should however be remembered that the gradient range is limited.

Measurements of sight distance to the right were taken from a series of points 0, 2, 9, 15, 25 and 50 m back from the give-way line to object heights of both 0.6 and 1.05 m (see Appendix 2, note 6). In the analysis, sight distances were tried directly and in reciprocal form. In all cases, the reciprocal form gave noticeably better statistical results and the form of the reciprocal relationship accords better with the intuitive feeling that the sensitivity of the variable should fall as the sight distance increases. There was no evidence that one object height was statistically better for predictive purposes than the other, so the more normal value of 1.05 m was chosen.

In the reciprocal form, sight distance was a significant explanatory variable in both approaching accidents and single-vehicle accidents. In the former, sight distances from 15 m back from the give-way line appeared to provide the best correlation, whereas in the latter, the 25 m sight distances seemed better. The differences between the various sight distance measures used as explanatory variables in the model, were not particularly large or consistent, so the 15 m value was arbitrarily selected for both accident types.

The magnitude of the sight distance effects for approaching accidents and single-vehicle accidents are appreciable (about a factor of 5–8 between the best and the worst) but the sense of these effects is unexpected; accidents increase as sight distance increases. The mechanism giving rise to this result is not known. It is not reasonable on this evidence to suggest that sight distances should deliberately be limited. It would not be possible to predict confidently the effects of such a policy on entering-circulating accidents even though sight distance did not prove to be a statistically significant correlate in the present analysis for that accident type.

Accordingly, sight distance as a design variable, will be omitted from the final predictive formula (section 7).

(iii) *Ratio Factor*

The geometric variables discussed in (i) and (ii) above are continuous 'co-variables'. GENSTAT and GLIM both allow categories within the data to enter the analysis as factors. Thus for example the three roundabout types – small island, conventional and dual-carriageway, could be represented in the analysis by a 3-level factor; speed limit (30–40 mile/h and 50–70 mile/h) could enter as a 2-level factor. These factors can be used in the analysis either singly or in combination (with themselves or with any or all of the 'co-variables') to become in effect extra terms in the linear predictor (see Appendix 4). The statistical usefulness of these extra terms (and therefore of the usefulness of making distinctions between the categories described by the various factors), can be judged by the resulting reduction in deviance in just the same way that the usefulness of including an extra co-variable can be judged. This technique can be used to examine the way the constant and coefficients of the 'best fit' equation given for the full data base in Table 16 vary from one sub-set of the data base to another, and to decide whether these variations are statistically significant.

For none of the accident types was there the slightest indication that distinctions made on the basis of speed limit categories had any effect whatsoever. However, some significant distinctions emerged between the roundabout type sub-groups (small, conventional, dual-carriageway) in relation to entering-circulating accidents and single-vehicle accidents. In the latter case, the results were inconsistent and are not considered further here. On the other hand the results for entering-circulating accidents required further evaluation. Table 17 shows the effect of adding a 2-level factor representing small roundabouts (as a group) and conventional together with dual-carriageway roundabouts (as a second group) to the linear predictor.

The change in deviance (22) for the loss of only one degree of freedom, shows that the addition of the factor was statistically very significant. The effect of the factor is to create separate constants for the small roundabout sub-group ($\ln k = -3.0$) and for the conventional designs ($\ln k = -3.76$). This difference means that small roundabouts have a constant which is 2.1 (exp 0.76) times that of the conventional designs. The same factor can be used to allow the geometric variables to have different coefficients for the two sub-sets of data. This failed however, to produce a significant reduction in overall deviance, and the coefficients in the two sub-sets were not significantly different. The coefficients given in column 4 of Table 17 can thus be regarded as representing the common 'within sub-group' geometric effects.

Table 17 shows that the main consequence of adding the small/conventional factor, is to reduce the coefficients of entry curvature (C_e) and to a lesser degree entry width (e). This suggests that these variables are acting as proxies for the small/conventional distinction. It would be desirable to attempt to avoid this happening, since the 'within design' sensitivity of accidents to entry geometry could well be important in the design process. Accordingly, a geometric 'co-variable' was sought which could take the place of this category distinction. Inscribed circle diameter (ICD) or central island diameter (CID) are obvious candidates, the former having been used for just this purpose in the analysis of roundabout capacities (Kimber R M, 1980). In the present case, ICD alone was found to be relatively ineffective, but the ratio of ICD/CID (denoted henceforth by R) used in the form devised for the capacity work proved to be a very effective substitute for the small/conventional category factor.

TABLE 17

Illustrating the effect of including a category distinction between small and conventional roundabout designs on the regression results for entering-circulating accidents

Variable		Without category factor		With category factor	
		Coefficient	S.E.	Coefficient	S.E.
Constant (ln k – equation 2)		−3.28	0.39	−3.00	0.39
Change in ln k due to level 2 of the factor (ie on going from small to conventional roundabouts)		–	–	−0.76	0.16
Flow exponents		0.65	0.10	0.65	0.10
		0.36	0.09	0.35	0.09
'Geometric' parameters					
Entry curvature	C_e	−67	6.1	−41	8
Entry width	e	0.20	0.02	0.13	0.03
Approach width correction	ev	−0.012	0.003	−0.007	0.003
Proportion of motorcycles	P_m	0.23	0.05	0.24	0.05
Angle between arms	θ	−0.010	0.002	−0.008	0.002
Gradient category	g	0.077	0.034	0.071	0.033
Residual Scaled Deviance		503		481	

A new geometric variable, termed the ratio factor (RF) is thus defined as:

$$RF = 1/(1 + \exp(4R - 7)), \text{ where R is ICD/CID.}$$

The constants 4 and 7 in the above expression were determined by trial and error so as to minimise the best fit model deviance. The ratio factor and its exponentiated form are illustrated in Figure 2.

Table 16 shows that the ratio factor (RF) has a range of 2.5 (similar to the magnitude of the small/conventional factor) and is highly statistically significant. Comparison of the coeffients of the other geometric variables in Tables 16 and 17 show how effective the ratio factor has proved in reproducing the small/conventional category distinction.

(iv) *Approach geometry*

The remaining geometric variables affect single-vehicle accidents only; they are approach width (v) and approach curvature (C_a). It is not clear why approach width should be so effective as a predictor of single-vehicle accidents, but the magnitude of this term is relatively large, giving a multiplying range of 6 or so, in the sense that accident frequencies are higher for the wider roads. There is a fairly strong interaction in this category of accidents between approach width and entry flow. Comparison between Tables 14 and 16 will show that whereas for all accident types except single-vehicle accidents the flow exponent remained fairly stable, in the case of single-vehicle accidents the exponent fell from 1.20 to 0.82 due to correlation between flow and width. This exponent change produced a significant reduction in the deviance of the model, and the form given in Table 16 is therefore preferred.

In the original surveys of the roundabouts included in this study, the curvature of the approach road (as distinct from the entry curvature) was classified subjectively on a seven point scale as were gradients. The categories were −3 for severe left-hand bends (approaching the roundabout) through −2, −1, 0 (straight), 1, 2 to +3 for severe right-hand bends. Table 16 shows that this approach curvature category (C_{ac}) was highly significant statistically as a predictor of single-vehicle accidents. In view of this, it seemed desirable to establish the magnitude of this effect more precisely. Accordingly, Local Authorities were asked to provide estimates of the actual radii of curvature of all those roundabout approaches classified in categories 2 and 3 (positive and negative). There were 75 approaches in all. Analysis of this sub-set of data provided the estimate of the coefficient of C_a (styled 'approach curvature (sampled)') given in Table 16. The range of this factor (about 13) is far greater than the range of the corresponding factor for approach curvature category (about 3), because the range of the variable itself is inevitably greater.

Neither approach road width nor approach curvature can really be regarded as design variables, since the former is dependent upon the basic approach road type (single or dual) and the latter on overall alignment.

(v) *'Other' accidents and pedestrian accidents*

The proportion of motorcycles (P_m) was the only variable (other than flow) found to be a significant predictor of 'other' accidents.

No geometric variables have been found to correlate with pedestrian accidents. Road width was the most likely contender, but it failed to prove significant.

(vi) *Non-significant layout variables*

It is of some interest to note which of the layout variables observed during the survey of roundabouts did not correlate with accidents. Accordingly Appendix 2 which lists all the 'observed' layout variables, includes the change in deviance which resulted from adding each variable singly to the 'best' predictive model (Table 18) with the model parameters 'fixed'. In this case the mean deviance ratio reflects the degree of correlation between the layout variable and the residuals from the 'best fit' model (see Appendix 4 – 14.2.4).

6.3.6 Geometric factors – observed versus predicted. Because of the nature and extent of scatter in the accident data, it is not helpful to present the geometric accident models in the form of observed versus predicted graphs, without a considerable degree of averaging of observed data, particularly when arm-specific accidents of a specific conflict type are being considered. Accordingly a method has been devised to examine these effects graphically by grouping the sites and averaging within groups. For illustrative purposes only the effect of entry curvature (C_e) on entering-circulating accidents will be presented in this report. The averaging has been done in the following manner.

Let A_o represent the observed accident frequency for a particular arm (one of 312 junction arms in the total data base) which has a particular set of flow and geometric variables each of which, in general, will be different from the mean value of the variables averaged over all sites. It is possible, using the regression model given in Table 16, to correct each observed value A_o to the value it would have had if the flow variables and all the geometric variables except the one under review (C_e in the present case) were at the mean value. So for each arm, the 'corrected' value of A_o (A'_o) is calculated as:

$$A'_o = A_o\left(\frac{\overline{Q}_e}{Q_e}\right)^{\alpha}\left(\frac{\overline{Q}_c}{Q_c}\right)^{\beta}\Pi\exp\left\{b_j(\overline{G}_j - G_j)\right\}$$

where b_j and G_j refer to all geometric variables excluding the one under review. $\overline{Q}_e$, $\overline{Q}_c$ and $\overline{G}_j$ are the mean values for entering flow, circulating flow and geometric variable j, over all sites in the sample. For convenience the corrected observed accident frequency A'_o is normalised by dividing by the overall mean accident frequency $\overline{A}$.

These normalised and corrected values ($A'_o/\overline{A}$) can then be ordered in increasing values of the geometric parameter of interest (in this example, C_e), arranged in groups of suitable size (usually the group sizes used were between 30 and 60), and the group average values plotted against the mean value for each group of exp (b ($C_e-\overline{C}_e$)). The resulting plot which should be a straight line at 45° through the origin, is shown in Figure 3. It will be seen that the exponential factor model represents the data quite well. In particular there are no obvious discontinuities in the results, so that as far as accidents are concerned the entry curvature can be regarded as continuous in its effect, with no detectable threshold at any particular standard value. Thus in the case of entering-circulating accidents, the traditional figure of 100 m radius for acceptable deflection in the design of roundabouts is shown by this study to be a reasonable guideline (it represents an accident frequency multiplier of 1.13 for entering-circulating accidents – i.e. only 13 per cent above the mean accident frequency for all roundabouts in the present sample and rather closer to the mean if the other accident categories are allowed for). Nevertheless, considerable further accident reductions can be achieved by imposing greater deflection.

Plots of the other geometric parameters for entering-circulating accidents and similar plots for other accidents types show that the continuous nature of the geometric variables illustrated in Figure 3 for entry curvature, applies to all cases.

7. ACCIDENT PREDICTION

7.1 Accident prediction

The previous section reports the detailed geometric analyses of accident frequencies. The present section proposes a model for accident prediction which simplifies the results presented in Table 16. The simplification has two aspects – (a) the omission of some minor variables, and (b) the rounding of the coefficients.

It has already been pointed out that gradient is not a particularly important variable. Moreover, since gradient affects entering-circulating accidents and approaching accidents in opposite senses, the net effect is very small. Accordingly gradient will be omitted from the predictive formula. Visibility to the right will also be omitted for reasons given in section 6.3.5 (ii).

The proposed formulae are given in Table 18. All coefficients have been recalculated (in the absence of gradient and visibility as explanatory variables). The constants have then been recalculated with rounded values of the coefficients and flow exponents 'fixed'.

It will be seen that in general the traffic flow exponents have been rounded to values intermediate between those given in Tables 14 and 16 with the exception of the single-vehicle accident flow exponent which has been rounded to 0.8 for reasons given earlier. However, in choosing rounded values, the results obtained from an analysis of the data in which the data errors were assumed to be negative binomially distributed (see Appendix 5, Table 20) has also been taken into account.

TABLE 18

Equations for the prediction of accident frequencies at roundabouts
(personal injury accidents per year per roundabout arm (A))

$A = kQ^{\alpha}$ (or $Q_e^{\alpha} Q_c^{\beta}$) $\exp \Sigma b_i G_i$ – Equations (1) and (2) see Section 6.3.2

Accident type	k (ln k)	Flow function (1)	α, β	'Geometric variable' (G_i) (2)	b_i
Entering-circulating	0.052	Entering Flow (Q_e)	0.7	Entry curvature C_e (m^{-1})	–40
				Entry width e (m)	0.14
				Approach width correction (3) ev (m^2)	–0.007
	(–2.957)	Circulating Flow (Q_c)	0.4	Ratio Factor RF (4)	–1
				Proportion of motorcycles P_m(%)	0.2
				Angle between arms θ (deg)	–0.01
Approaching	0.0057 (–5.174)	Q = Entering Flow	1.7	Entry curvature C_e (m^{-1})	20
				Entry width e (m)	–0.1
Single-vehicle	0.0064 (–5.046)	Q = Entering Flow	0.8	Entry curvature C_e (m^{-1})	25
				Approach width v (m)	0.2
				Approach curvature C_a (m^{-1})	–45
'Other'	0.0026 (–5.958)	Q = Entering x Circulating flow	0.8	Proportion motorcycles P_m (%)	0.2
Pedestrian	0.029 (–3.528)	Q = (Entering + Exiting vehicular flow) x Pedestrian Crossing Flow	0.5		

The total predicted accident frequency (accidents per year) for the roundabout as a whole is obtained by summing the values calculated using the above equations over all accident types and over all arms of the roundabout.

(1) All traffic flows are total flows (all classes combined) expressed in units of 000's of vehicles per 24-hour day averaged over the relevant period.

(2) Definitions of the geometric variables are given in Appendix 3 of the report. Proportion of motorcyclists is not strictly a geometric variable, but is incorporated into the predictive model in a similar way.

(3) This correction has the effect of modifying the entry width effect. The combined entry/approach width term is 0.14 (1-v/20)e.

(4) RF is the Ratio Factor 1/(1 + exp (4R – 7)), where R = Inscribed circle diameter (m)/Central island diameter (m).

The 'two exponent' model is proposed for entering-circulating accidents; if however turning movements are not available and the value of the circulating flow (Q_c) cannot be obtained, the default option should be to set $Q_e = Q_c$.

7.2 Model output

The most noteworthy features of the accident prediction model given in the previous section (excluding pedestrians) are shown in Figures 4–8. Figure 4 shows the predicted effects of traffic flow. It will be seen that these effects are almost linear; different combinations of geometry and of the balance of entering and circulating flow, simply alter the proportions of the four main accident types. Figure 4 represents a dual carriageway approach with a moderately flared entry, loaded so that the entry and circulating flows are equal. The vertical 'bars' on the right-hand side of the diagram show what happens to the accident predictions (at maximum entering flow) if the circulating flow is reduced. This unbalanced flow situation corresponds to a roundabout with turning movements – 20 per cent left, 60 per cent straight and 20 per cent right, in which the 'main' road carries 4 times the traffic flow of the side road.

Figure 5 illustrates for a parallel entry 5 m wide and an entry flaring from 5 m to 15 m wide, how accidents may be expected to vary with entry curvature (C_e). Because entering-circulating accidents decrease, whilst approaching accidents and single-vehicle accidents increase with C_e, total accidents show a minimum value. The value of C_e for minimum accident frequency depends on entry geometry; it is about 0.015 m^{-1} for parallel entries and increases to the maximum observed values (0.05 m^{-1}) for heavily flared entries.

The same interactive effect is also illustrated in Figure 6. Here predicted accident frequencies are plotted against entry width (approach half-width being fixed at 5 m) at two values of entry curvature (C_e). It will be seen that the combination of wide entry and small deflection (Fig. 6(a)) results in very high accident predictions, whereas with maximum deflection (Fig. 6(b)), total accidents are relatively insensitive to entry width.

The interaction of entry width (and flare) and entry curvature is clearly important. These results suggest that for safety, wide (or flared) entries should only be used in conjunction with substantial deflection (ie on conventional roundabouts) rather than as has been more usually the case, on small roundabouts with little deflection. It must however be said, that the effect arises from the multiplicative structure of the model used (ie Equation (3) or (4), section 6.3.2). This aspect of model structure is discussed in Appendix 5. Suffice it to say here, that alternative non-interactive models were tried, and found to be statistically inferior to the multiplicative model finally adopted. It follows therefore, that the interactive effects illustrated in Figures 5 and 6 are supported by the data. However, extreme combinations of wide entries with large values of entry curvature are not represented in the data, possibly because of physical constraints of layout.

A further cautionary note: the geometric effects shown in Figures 5 and 6 have been calculated on the basis that entering and circulating flows are both 7,500 vehicles per day (a figure close to the mean 'observed' values for all sites). In fact, this flow is probably too high to be carried on roundabouts with approach and entry widths at the lower end of the range, and too low to be appropriate to the higher end. However, this lack of realism does not invalidate the features of the results presented.

Figures 7 and 8 illustrate the magnitude of the effects of the proportion of motorcycles (P_m) and approach curvature (C_a) respectively. Presumably the greater accident frequency resulting from an increase in P_m, largely involves accidents to motorcyclists. This conclusion has not yet been checked by a separate analysis of motorcycling accidents. Such an analysis will be the subject of the study of two-wheeler accidents mentioned in section 5.3.

7.3 Model errors

The basic accident data used to determine the predictive model given in this section consists of the numbers of accidents occurring at a range of geometrically dissimilar sites during a specific period (mainly the 6 years 1974—1979). The standard errors of the coefficients given in Table 16, calculated by the regression program, are derived from the residual data scatter about the 'best' fit relationship. They are a measure of the accuracy with which the predicted relationships are determined. However, this data scatter is composed of two elements — a within site element, due to the fact that the generation of accidents is a Poisson process, and a between site element which reflects the fact that the mean rate of generation of accidents at nominally identical sites will vary from site to site due to unexplained effects. (There is a third element of error associated with the 'lack of fit' of the assumed model form; the unsuccessful attempts to find better models described in Appendix 5, suggests this element is relatively small.) Appendix 5 discusses model errors and their consequences.

Although it can be argued that in economic terms what is required of an accident prediction model is that it should produce unbiassed estimates of accident frequencies averaged over many sites, there is considerable practical interest in estimating the mean accident frequency at an individual site together with its associated error. In order to do this, it is necessary to extract from the data estimates, the between-site variation of mean accident frequencies free from within-site Poisson error.

Appendix 5 assumes an error model for this unexplained between site variation, of Gamma form, and attempts to determine the parameter of the appropriate Gamma distribution from the accident data. The result suggests that if A_1, A_2, A_3 and A_4 are the numbers of accidents predicted by the model for entering-circulating accidents, approaching accidents, single-vehicle accidents and 'other' accidents respectively, the standard error of the total number of accidents at a roundabout (excluding pedestrian accidents) is:

$$\text{S.E.} = \left[\Sigma\left\{\frac{A_1^2}{2.75} + \frac{A_2^2}{2.5} + \frac{A_3^2}{2.5} + \frac{A_4^2}{1.25}\right\}\right]^{1/2}$$

where the summation is over the four arms of the roundabout.

Appendix 1 which contains values of the observed and predicted number of accidents in the relevant junction period at the individual roundabouts included in the sample, gives also the standard errors of these estimates based upon the above calculation. It will be seen that the percentage error ranges from 20—25 per cent. Thus for an average roundabout generating 3 accidents per year, the between site error is of the same order as the error arising from the within site Poisson process after 16—25 accidents or 5—8 years-worth of accident data have accumulated. Also included in Appendix 1 are the aggregated numbers of observed and predicted accidents for the six main roundabout categories, for each accident type (entering-circulating, approaching, single-vehicle, 'other' and pedestrian).

7.4 Other factors relevant to accident prediction

The model set out in Table 18 and illustrated in section 7.2 above predicts a site specific mean accident frequency of reported personal injury accidents (a high proportion of cycle accidents are not reported). It also reflects the national accident situation during the years 1974—1979, and relates specifically to the target group of roundabouts defined in section 2.

Accident frequencies in the future will obviously depend upon national accident trends as they are affected for better or worse by a large variety of influences (for example, the recent seat belt legislation). It is unlikely that the functional form of the accident-flow or accident-geometry relationships will change significantly over the years, although different road user groups may well be affected by national trends to differing degrees. However, it is suggested that these trends be corrected for using as a control the published figures for non-link accidents in the UK. Table 19 gives the average number of such accidents for the years 1974–79 together with the individual years figures for 1980–82, and the resulting correction factors.

TABLE 19

Time trend correction factors based on all non-link accidents in UK

	1974–1979 (Average)	1980	1981	1982
Number of non-link accidents (all areas, all severities)	147,264	146,386	144,328	150,529
Correction Factor	–	0.994	0.980	1.022

The 'target group' specification deliberately excluded roundabouts with unusual features. Although the effect of features such as premises opening onto the roundabout, or construction on the central island cannot be predicted, the presence of approaches with yellow bar markings can. The results of a study of accidents at 42 sites where the markings were installed (Helliar-Symons, 1981) showed that the average reduction in all accidents on those arms with markings was about 50 per cent. At present such markings are only authorised for use on high speed dual-carriageway approaches. It is suggested that for approaches marked in this way, the accident frequency predicted by the model be halved.

Although the accident model does not cover grade separated roundabouts or 3-arm at-grade roundabouts, it might nevertheless be useful in comparing alternative designs in these cases; the absolute predictions may be unreliable, but the relative effects due to changes in flow and geometry are likely to be fairly robust.

8. SUMMARY

1. This report gives the findings of a study of personal injury accidents at a sample of 84 four-arm roundabouts on main roads in the UK. The roundabout types included small roundabouts, conventional roundabouts and roundabouts on dual-carriageways – in both 30–40 and 50–70 mile/h speed limit zones. The objectives of the study were to provide some insights into the character of roundabout accidents, and to derive relationships between accident frequencies, traffic flows and geometric design, which could be used in design and appraisal.

2. The average accident frequency (averaged over all roundabouts in the sample) was 3.31 personal injury accidents per year, 16 per cent of which were classed as fatal or serious. The average accident rate per 100 million vehicles passing through the junction was 27.5. Small roundabouts in 30–40 mile/h speed limit zones had both higher accident frequencies and higher accident rates than other roundabout types.

3. Analysis of accidents by accident type (entering-circulating accidents, approaching accidents, single-vehicle accidents and 'other' accidents) showed that the pattern of accidents is different at small roundabouts as compared with roundabouts of conventional design. Rather more than two-thirds of accidents at the former were of the entering-circulating type, by contrast, accidents at the latter were relatively evenly divided between entering-circulating accidents, approaching accidents and single-vehicle accidents.

4. A disaggregation of accidents by road user, showed that pedal cyclists are involved in 13–16 per cent of all accidents and motorcyclists in 30–40 per cent. The accident involvement rates (per 100 million of road-user class) of two-wheeler riders were about 10–15 times those of car occupants. Pedestrian accidents represented about 4–6 per cent of all accidents at this sample of roundabouts.

5. Analysis of the roundabout accidents by year, by month of year, by day of week and by period within the day showed that the temporal distribution of accidents at these sites reflected the national pattern.

6. An analysis of accidents by arm using a generalised linear modelling methodology was successful in relating the accident frequencies (accidents per year per arm) of the four accident types mentioned in 3 above, to traffic flow and roundabout geometry. Pedestrian accidents were related to vehicular and pedestrian flows only. The significant geometric variables for the various accident types are listed in Table 15 and 16, and discussed in section 6.3.5.

7. Some simplification of the regression results was undertaken to produce the predictive formula for roundabout accidents, shown in Table 18. Some of the noteworthy features of the predictions of this accident model are illustrated in Figures 4–8 and discussed in section 7.2. In particular, the model suggests that for safety, roundabouts with heavily flared entries should have as much entry path deflection as possible.

8. The question of errors of prediction are discussed in section 7.3 and Appendix 5. Overall, the percentage error in the prediction of the mean accident frequency for a whole roundabout is about 20–25 per cent. This error is of the same order as the error arising from the within site Poisson process after 5–8 years-worth of accident data has accumulated.

9. Finally, suggestions are made in section 7.4, for updating the model predictions over time, and for allowing for roundabouts with yellow bar markings. It is suggested that although the study was concerned solely with 4-arm at-grade roundabouts, the results could provide guidance in the design of other roundabout types.

9. ACKNOWLEDGEMENTS

The work described in this report forms part of the research programme of the Traffic Systems Division of the Traffic Engineering and Control Department of TRRL. The data collection and preliminary analysis was carried out by the Transportation Research Group, Department of Civil Engineering, University of Southampton (Prof. T E H Williams).

The authors would like to thank the Local Authorities for providing the accident data, and for their help in traffic counting and in supplying some of the geometric data. They would also like to record their indebtedness to Mr R A J Surl and Mr P Smith who assisted in the earlier analysis and to Dr C R Faulkner and members of Engineering Intelligence Division DTp for valuable discussions during the course of the work.

The accident data was checked using the national accident statistics (Stats 19) available at TRRL. The authors are grateful to the members of the Road Safety Division for providing accident tabulations.

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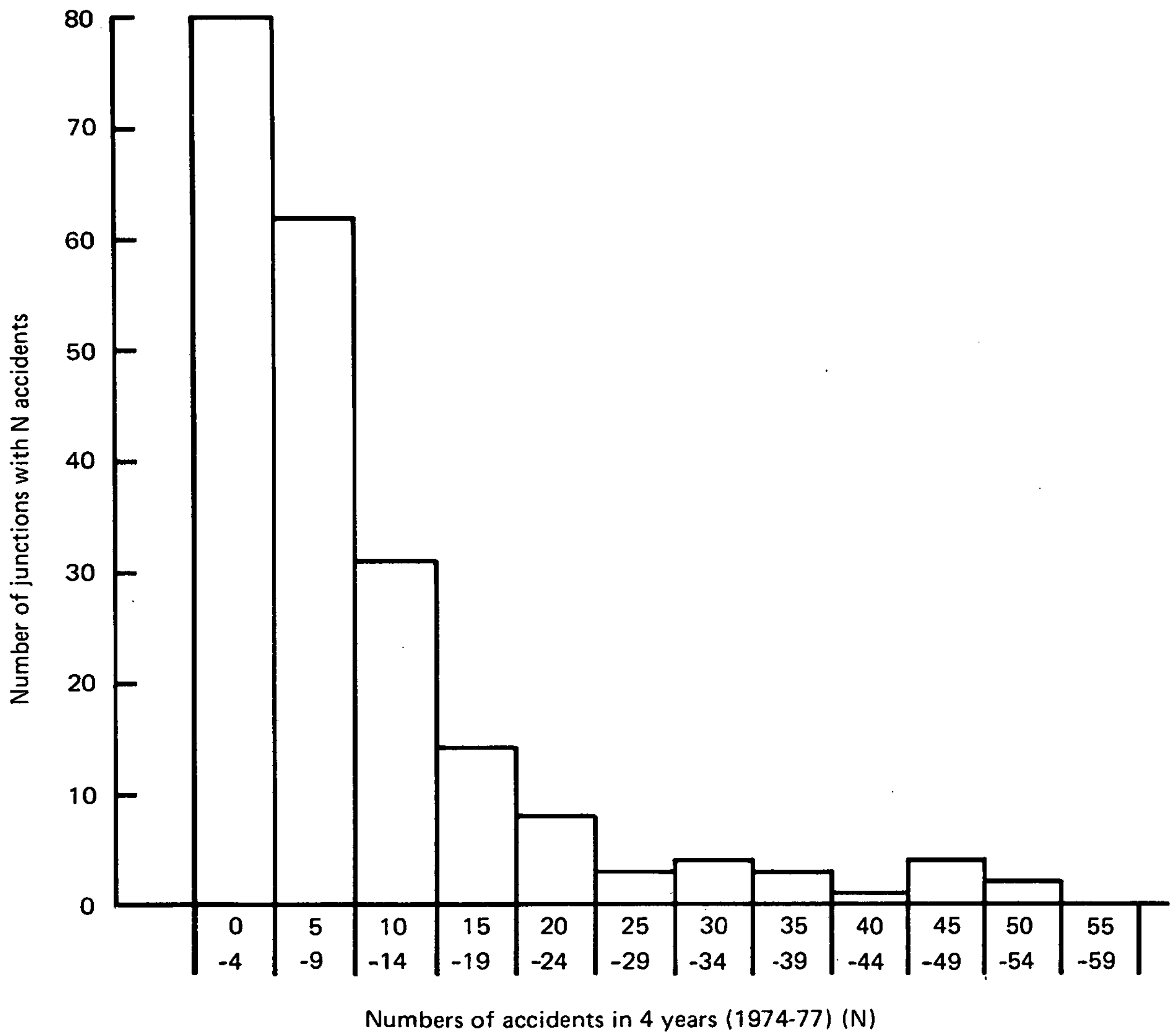


Fig. 1 Frequency distribution of reported injury accidents at 212 roundabouts at intersections of class 'A' roads

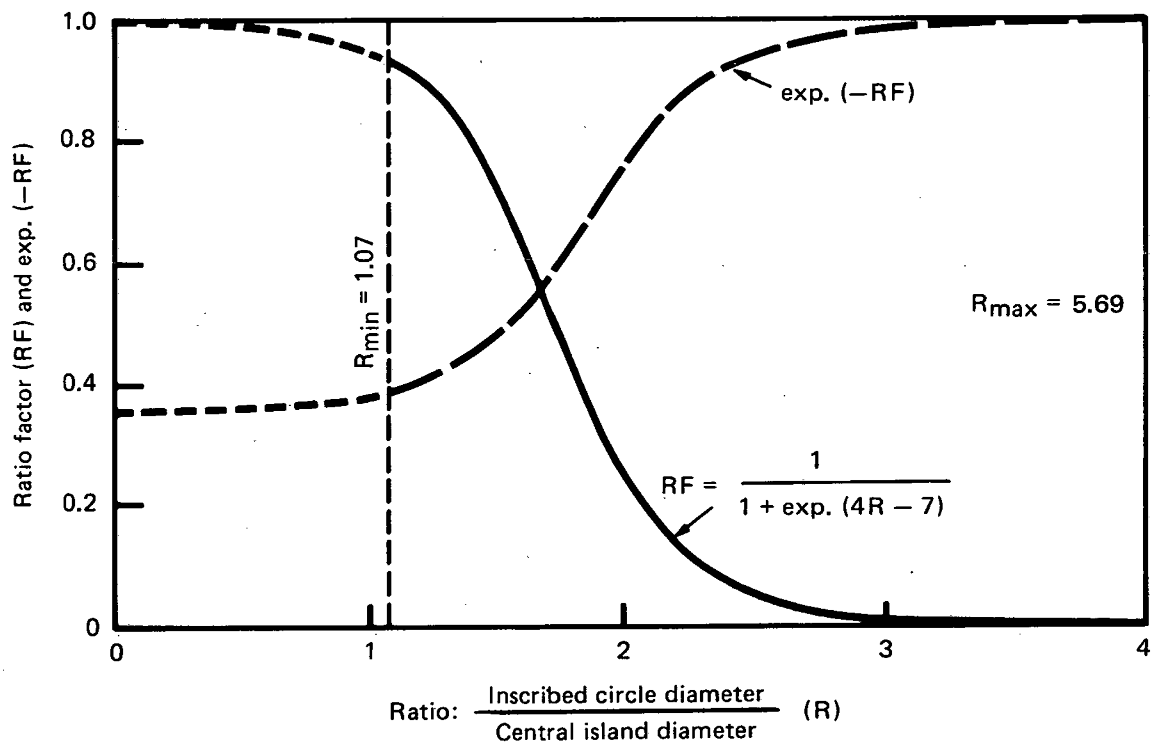


Fig. 2 Illustrating the ratio factor and its exponentiated form

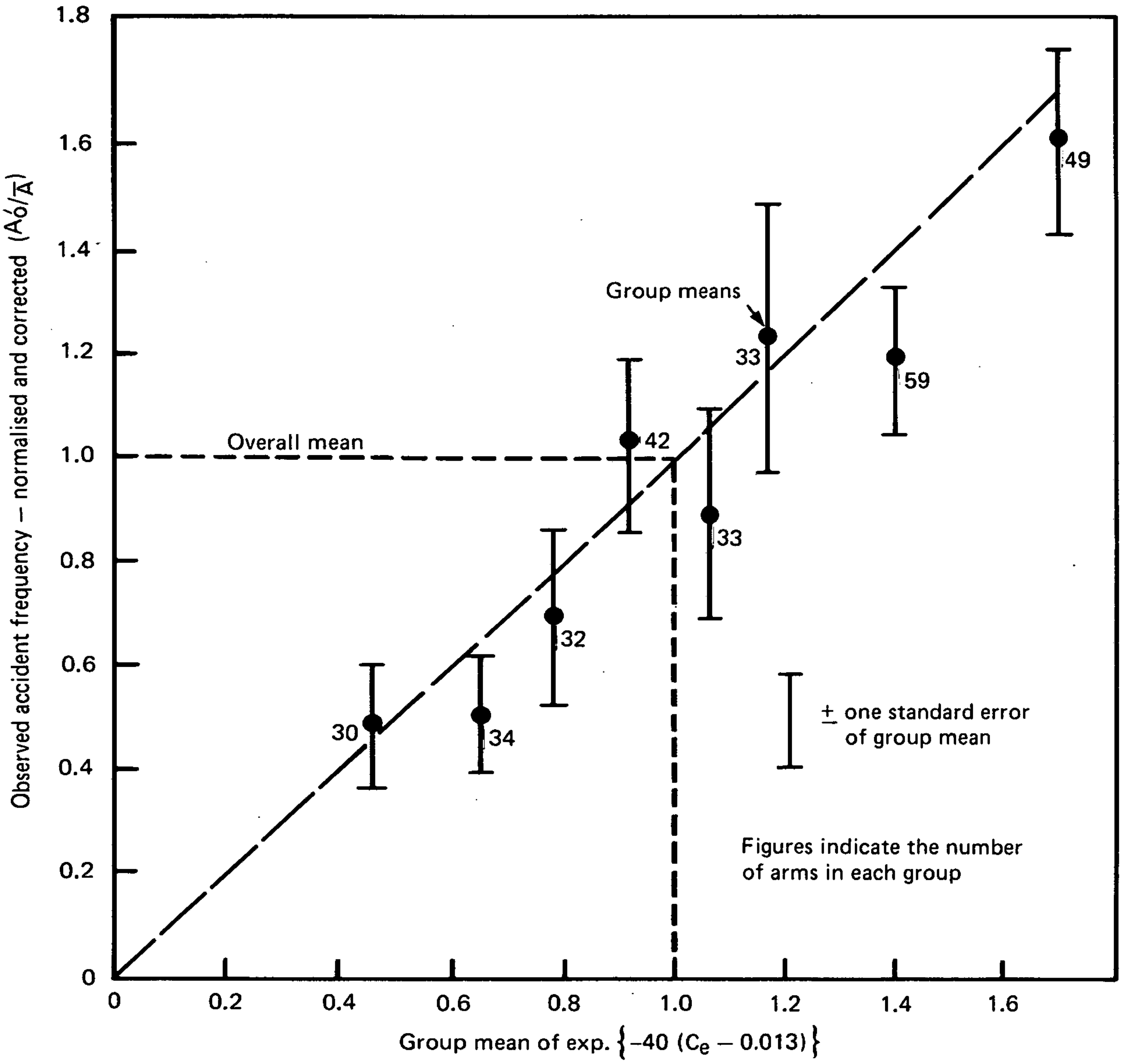


Fig. 3 Observed entering—circulating accident frequency (corrected and normalised) plotted against the predictive function Exp. $\{b(C_e - \overline{C}_e)\}$

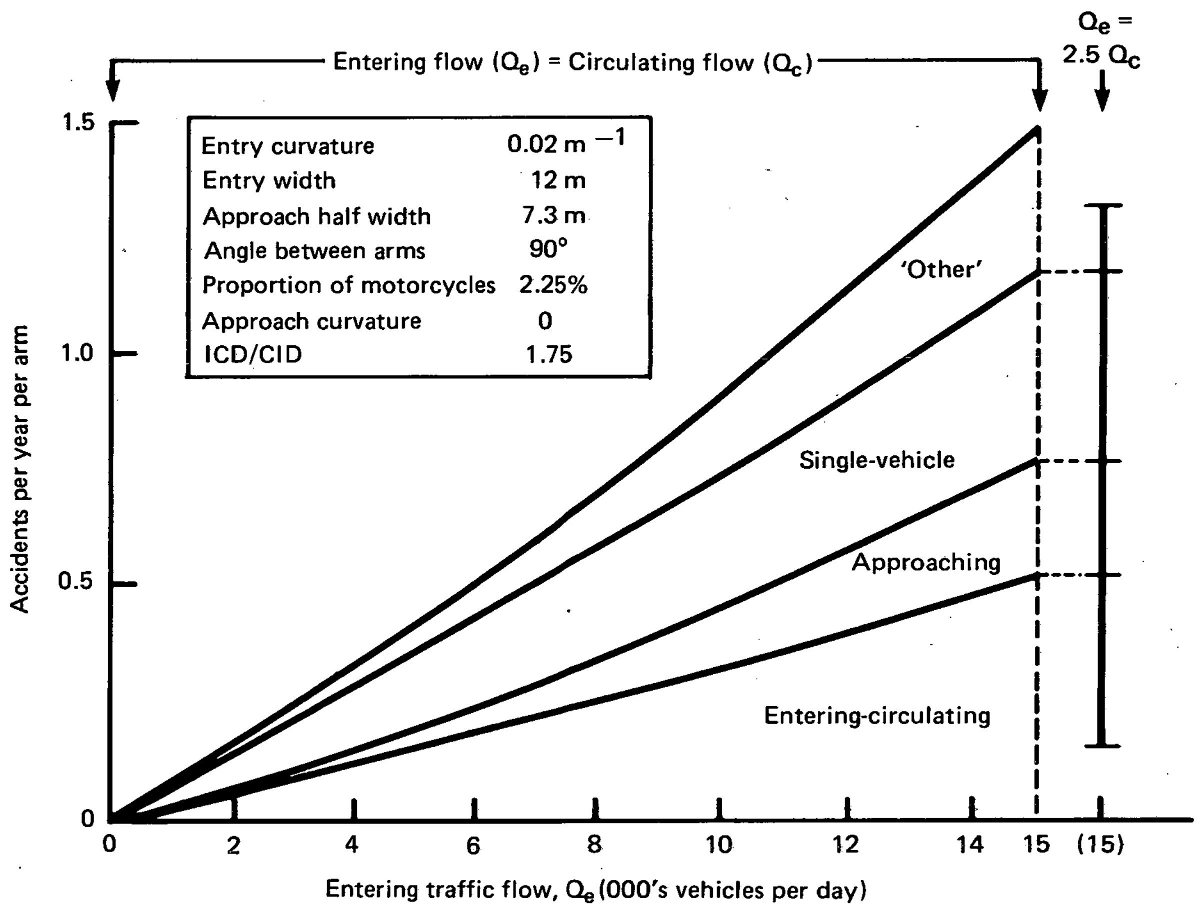
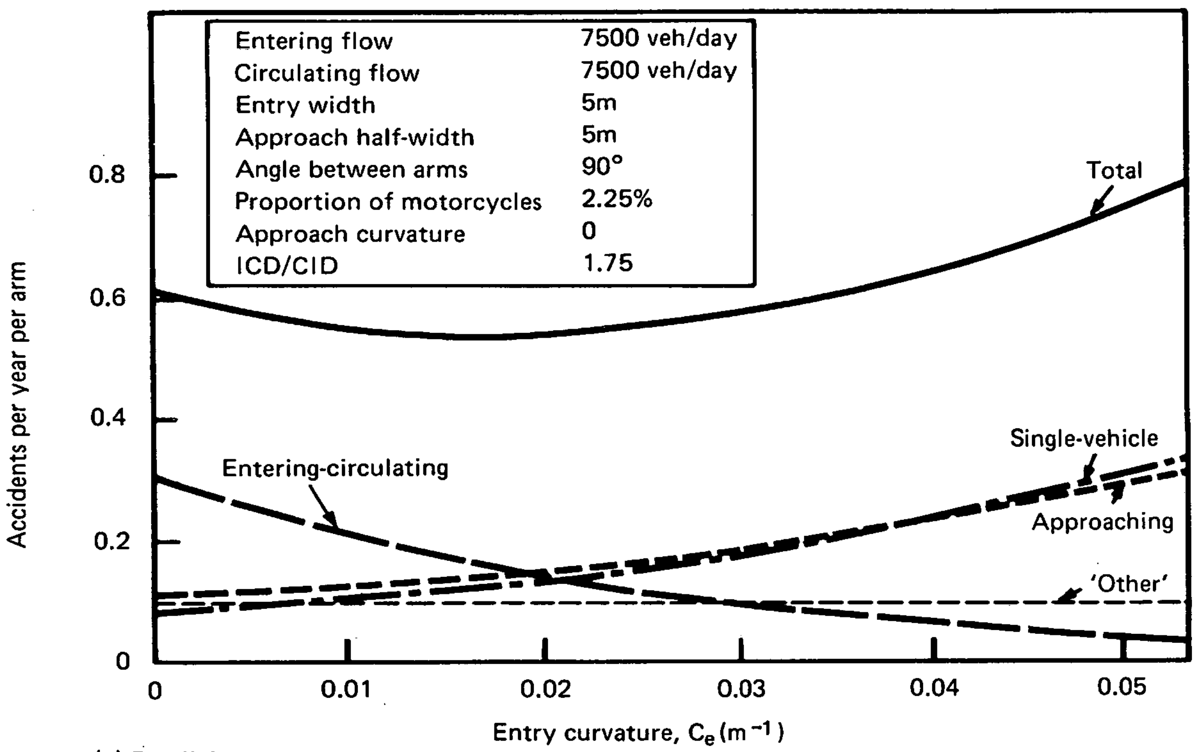
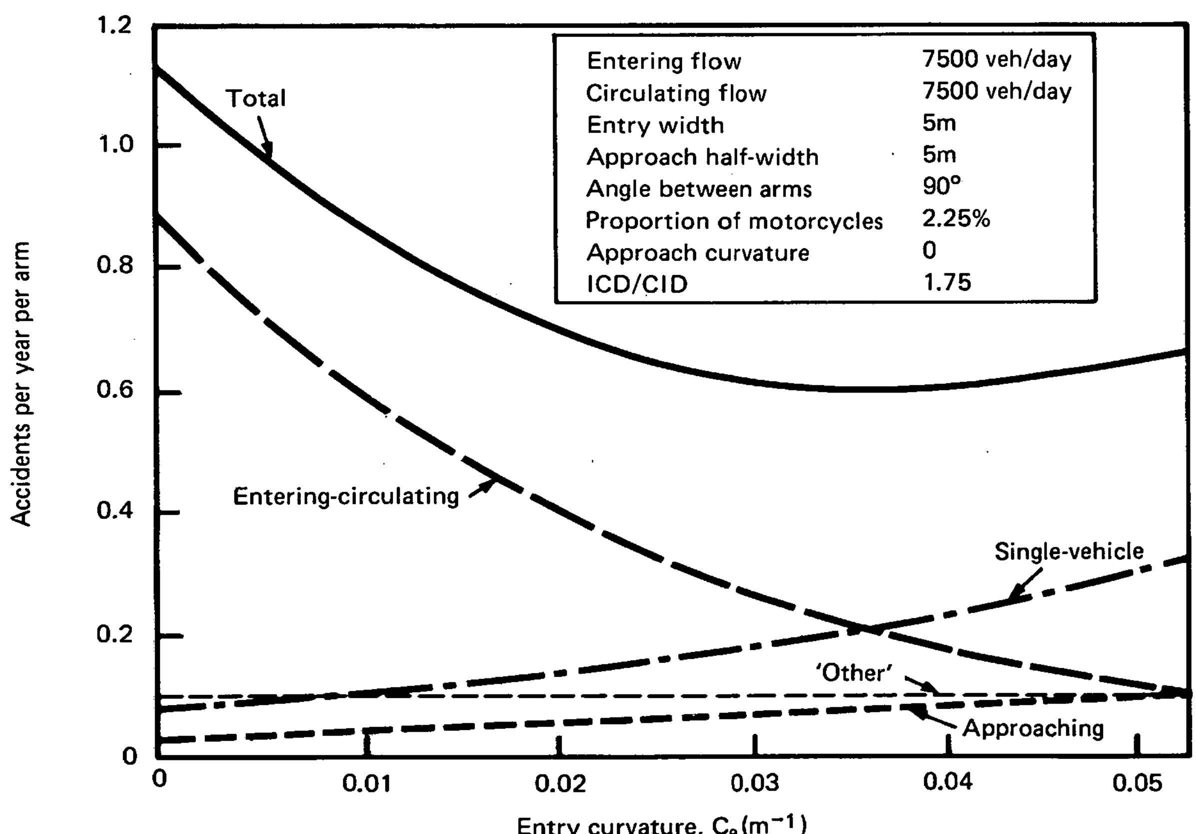


Fig. 4 The predicted effect of traffic flow on accidents at a 'dual carriageway' approach with mid-range deflection and some entry flare

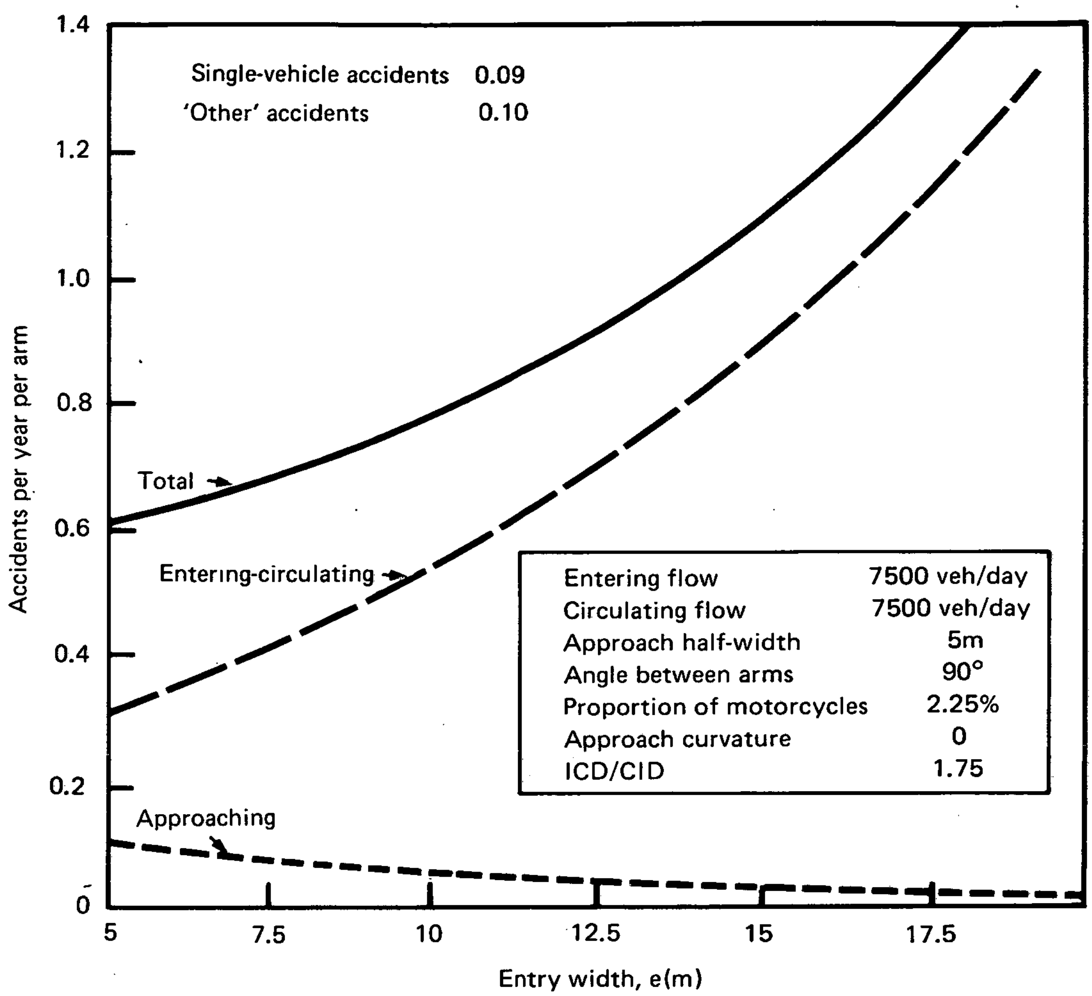


(a) Parallel entry

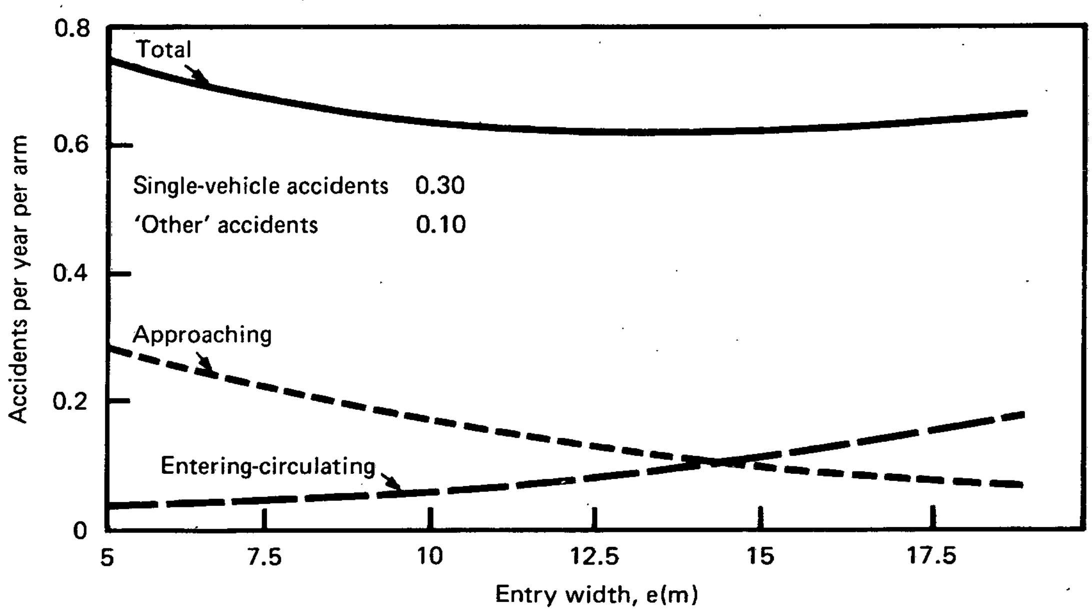


(b) Flared entry

Fig. 5 The predicted effect of entry curvature on roundabout accidents



(a) Undeflected entry ($C_e = 0$)



(b) An entry with maximum deflection ($C_e = 0.05m^{-1}$)

Fig. 6 The predicted effect of entry width on roundabout accidents

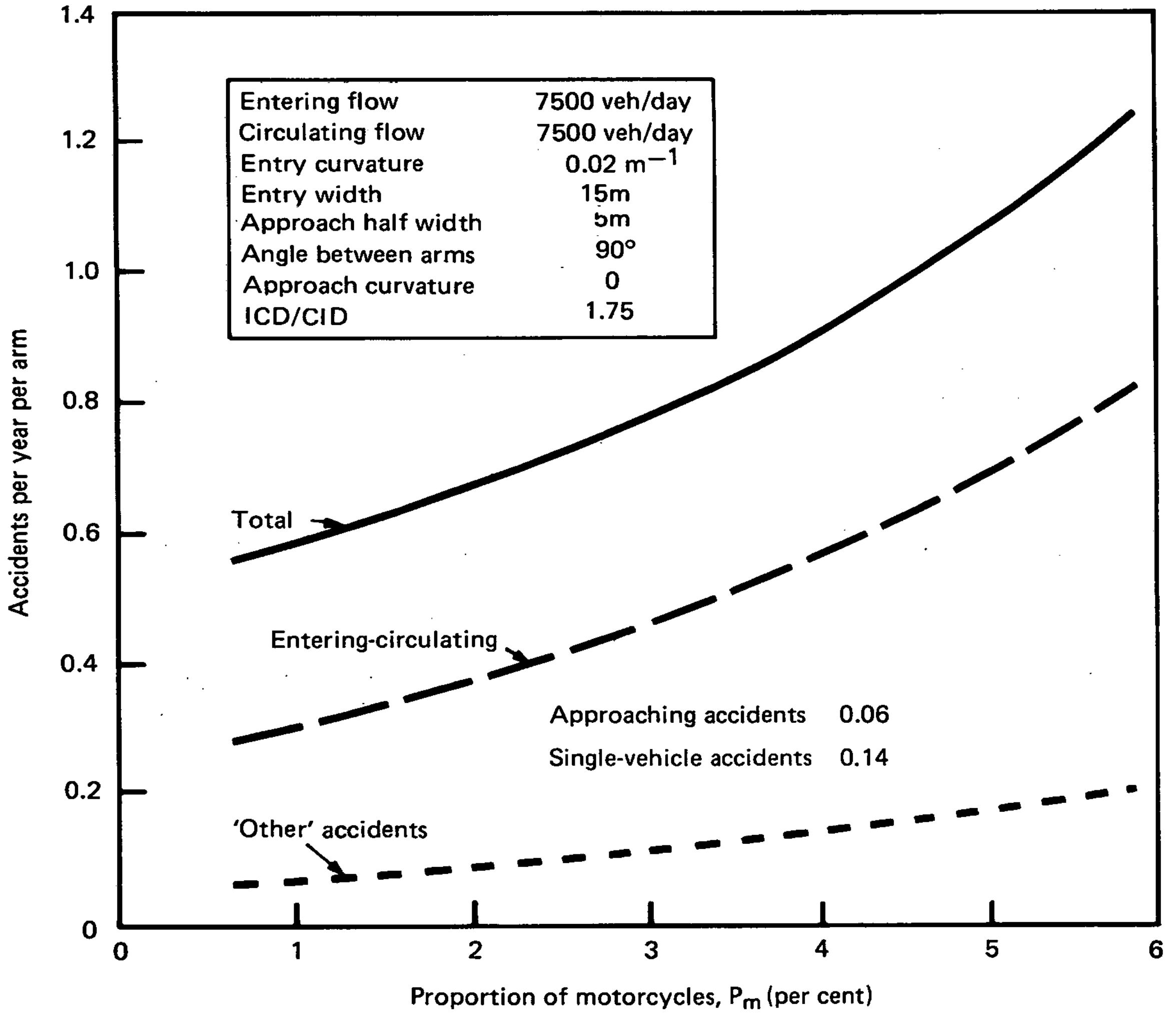


Fig. 7 The predicted effect of the proportion of motorcycles on roundabout accidents (flared entry)

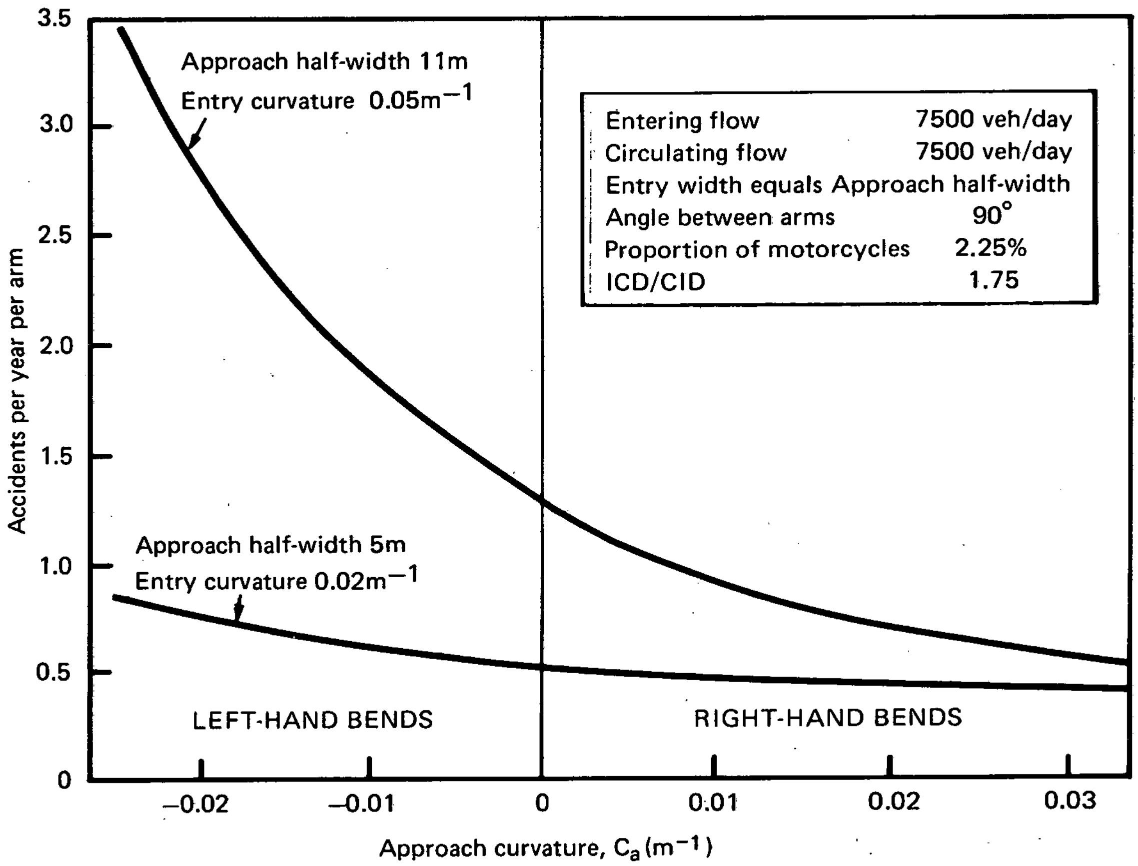


Fig. 8 The predicted effect of approach curvature on total accident frequency for two values of approach half-width and entry path curvature

11. APPENDIX 1

ROUNDABOUTS INCLUDED IN THE STUDY

TABLE 20

Basic data including observed and predicted accidents site by site

Junction Reference Number	Location	Grid Reference	ICD/CID (metres)	Number of dual carriageway arms	Junction period (months)	Total daily traffic flow (000's vehicles)	Observed number of accidents (3)		Predicted average number of accidents (3)		
							Vehicular	Pedestrian	Vehicular	SE (%)	Pedestrian
A. SMALL ROUNDABOUTS 30–40 mile/h											
21	Norwich	207 110	45/11	0	60	34.1	36	0	28.4	25	0.3
46	Bournemouth	058 968	36/14	1	44	31.8	15	0	13.5	21	0.7
133	Derby	339 376	38/14	0	72	30.9	25	0	25.1	23	1.2
161	Leeds	268 380	54/24	4	72	40.6	38	3	35.7	22	1.7
173	Newcastle	203 654	40/10	0	59	35.0	16	3	24.3	25	1.3
175	Newcastle	246 669	39/9	2	72	45.8	49	3	42.7	28	1.0
181	Teesside	433 205	44/20	0	72	25.2	35	3	22.2	25	1.0
183	Teesside	531 175	32/17	0	72	27.6	25	1	22.6	24	2.0
190 (2)	Guildford	998 508	58/18	0	47	55.0	30	0	35.3	24	–
219	Halesowen	982 848	30/6	1	67	33.9	20	1	20.1	21	2.1
258	Sunderland	366 557	35/9	1	46	25.8	14	0	10.2	22	1.4
262	Teesside	430 187	48/12	0	72	21.7	27	0	21.4	25	1.3
263	Stockton on Tees	449 194	43/14	1	48	21.7	4	0	8.6	21	0.9
292 (2)	Slough	964 798	74/42	2	52	49.9	30	1	23.4	22	–
293	Hemel Hempstead	053 076	56/29	0	52	32.2	4	1	13.4	20	1.1
313	Hitchin	204 304	26/5	0	72	21.3	9	1	11.2	23	0.6
322	Wigston	609 992	61/27	2	24	30.6	12	0	11.6	28	0.1
328	Llanishen	167 814	37/7	0	72	28.5	13	1	20.8	24	2.1
331	Cardiff	191 764	28/6	1	72	27.4	18	1	18.5	23	1.2
333	Gloucester	835 197	42/12	2	72	31.4	12	0	27.3	23	0.9
346 (2)	Emsworth	749 058	28/12	0	65	26.6	11	0	12.8	22	1.7
386	Wigston	609 992	60/20	2	24	29.1	11	0	14.2	30	0.1
389	Bournemouth	058 968	36/14	0	24	29.2	6	1	6.6	22	0.4
392	Norwich	207 110	45/11	0	12	37.3	8	0	6.2	24	0.1
393	Cranford	109 766	70/42	4	17	71.0	9	0	11.1	19	0.5
B. SMALL ROUNDABOUTS 50–70 mile/h (2)											
76	Halesowen	970 829	44/20	3	67	48.9	21	1	31.3	21	–
113	Ellesmere Port	394 737	54/31	0	66	26.5	15	0	13.7	22	–
114	Ellesmere Port	388 734	54/31	0	45	33.9	15	0	13.0	22	–
115	Chester	366 718	60/33	2	36	25.8	20	0	7.4	21	–
180	Newcastle	287 620	32/10	2	36	43.1	10	0	19.4	24	–
228	Brockworth	897 159	34/17	0	72	20.3	10	1	11.4	21	–
265	Teesside	445 228	42/18	4	72	48.6	35	0	37.0	23	–
336	Churchstow	706 457	32/6	0	72	5.0	0	0	2.1	26	–
345	Stony Stratford	795 407	42/10	0	68	22.5	16	1	12.9	20	–
350	Longwick	794 046	30/9	0	72	7.3	3	0	3.8	25	–
383 (1)	Chester	366 718	56/33	0	30	24.1	2	0	–	–	–

(1) These roundabouts were not included in the geometric analyses because complete layout data was not available.

(2) Pedestrian flow data was not available for some or all arms of these roundabouts; the relevant arms have not therefore been included in the pedestrian accident model.

(3) These figures are the total number of accidents in the junction period.

(4) These values refer to the standard errors of the mean predicted number of accidents expressed as a percentage (see 7.3 and Appendix 5). The same percentage error applies to the predicted mean accident frequency.

TABLE 20 (Continued)

Junction Reference Number	Location	Grid Reference	ICD/CID (metres)	Number of dual carriageway arms	Junction period (months)	Total daily traffic flow (000's vehicles)	Observed number of accidents (3)		Predicted average number of accidents (3)		
							Vehicular	Pedestrian	Vehicular	SE (%)	Pedestrian
C. CONVENTIONAL ROUNDABOUTS 30–40 mile/h											
20	Norwich	206 094	42/24	0	72	38.9	9	1	18.7	18	1.3
22	Norwich	240 111	50/31	0	72	40.0	16	2	19.6	17	1.6
26	Norwich	217 071	56/37	0	72	39.8	17	0	17.5	18	1.4
32	Cockfosters	284 957	70/55	0	72	34.9	19	2	13.2	18	2.1
139	Lincoln	977 730	36/20	0	72	19.0	11	1	9.7	19	1.5
166	Leeds	359 282	62/45	2	72	20.9	13	1	9.9	21	0.9
178	Tynemouth	350 699	60/42	1	72	31.9	7	2	12.8	17	2.1
185	Crawley	273 365	34/22	1	72	28.6	10	1	12.5	17	1.9
295	Luton	087 232	58/37	0	72	33.8	16	1	14.1	18	1.2
321	Corby	900 888	76/59	3	72	20.4	12	1	10.2	19	0.7
380 (1)	Stockton	449 194	43/24	1	23	20.0	4	0	–	–	–
D. CONVENTIONAL ROUNDABOUTS 50–70 mile/h (2)											
29	Tilbury	653 812	72/55	0	72	45.1	18	1	19.7	20	–
31	Elstree	175 945	79/55	1	72	25.2	36	0	12.7	19	–
63	Woodstock	459 156	79/62	1	72	23.8	7	0	8.1	20	–
81	Cannock	968 091	55/51	0	72	28.7	8	0	10.0	18	–
85	Telford	785 109	76/58	0	72	14.4	5	0	4.1	21	–
138	Lowdham	670 461	45/31	2	72	21.0	3	0	8.6	18	–
147	Foots Cray	470 704	64/44	1	72	61.0	67	0	34.7	19	–
279	Scunthorpe	892 100	57/40	2	72	37.4	22	3	22.1	18	–
308	Abington	523 500	74/60	1	72	24.9	14	0	8.1	18	–
309	Caxton Gibbet	297 607	72/56	0	72	13.3	4	0	3.6	18	–
382 (1)	Ellesmere Port	388 734	49/33	0	27	31.9	5	0	–	–	–
E. DUAL-CARRIAGEWAY ROUNDABOUTS 30–40 mile/h											
2	Chichester	857 038	74/68	2	72	32.7	14	0	14.5	19	0.6
42	Cranford	109 766	70/52	4	54	66.3	40	2	27.4	18	1.4
148	Lee	411 743	60/45	4	48	63.2	24	3	32.1	19	1.6
158	Leeds	307 392	70/55	4	72	36.8	11	5	14.2	18	2.4
163 (2)	Bradford	157 306	80/66	3	72	51.7	17	5	25.4	18	–
201	Oxford	537 032	72/56	2	72	34.6	11	1	20.7	19	0.6
205	Coventry	306 772	52/37	2	67	30.3	11	0	12.1	18	0.9
208	Sutton Coldfield	132 917	46/32	4	67	35.9	14	6	15.0	18	2.8
210	Kingstanding	078 964	52/33	2	67	21.3	3	0	7.1	18	0.7
270	Hessle	033 273	45/26	2	72	32.0	10	1	14.4	18	1.1
283	Nottingham	565 436	43/39	2	72	36.9	24	5	15.7	17	2.3
311 (2)	Hertford	326 124	56/43	2	63	47.0	13	0	20.0	20	–
395 (2)	Hertford	326 124	56/43	2	9	50.7	0	0	3.1	19	0.1
316 (1)	Waltham Cross	348 998	76/63	2	63	57.3	24	0	–	–	–
F. DUAL-CARRIAGEWAY ROUNDABOUTS 50–70 mile/h (2)											
7	Washington	120 134	84/78	2	72	19.3	8	0	6.4	19	–
19	Basildon	681 900	65/46	2	72	49.9	34	1	23.9	22	–
41	Uxbridge	062 855	82/62	2	72	71.5	38	0	38.5	19	–
59	Crawley	258 357	64/46	3	72	36.8	16	0	15.7	20	–
78	Wombourne	881 936	57/39	2	72	28.6	6	0	11.2	20	–
82	Cannock	912 106	49/34	2	72	28.5	5	0	10.4	18	–
89	Golbourne	603 971	58/40	2	72	24.7	9	1	9.4	19	–
159	Leeds	298 389	64/46	2	72	28.4	15	1	11.0	18	–
176	Newcastle	265 702	110/90	3	72	26.8	11	1	11.5	20	–
179	South Shields	361 638	60/42	2	72	26.3	11	1	12.2	17	–
100 (1)	Liverpool	366 995	49/31	2	72	34.0	7	1	–	–	–
381 (1)	Chadwell Heath	484 891	78/53	2	28	66.9	31	0	–	–	–

Notes to table – see previous page

TABLE 21

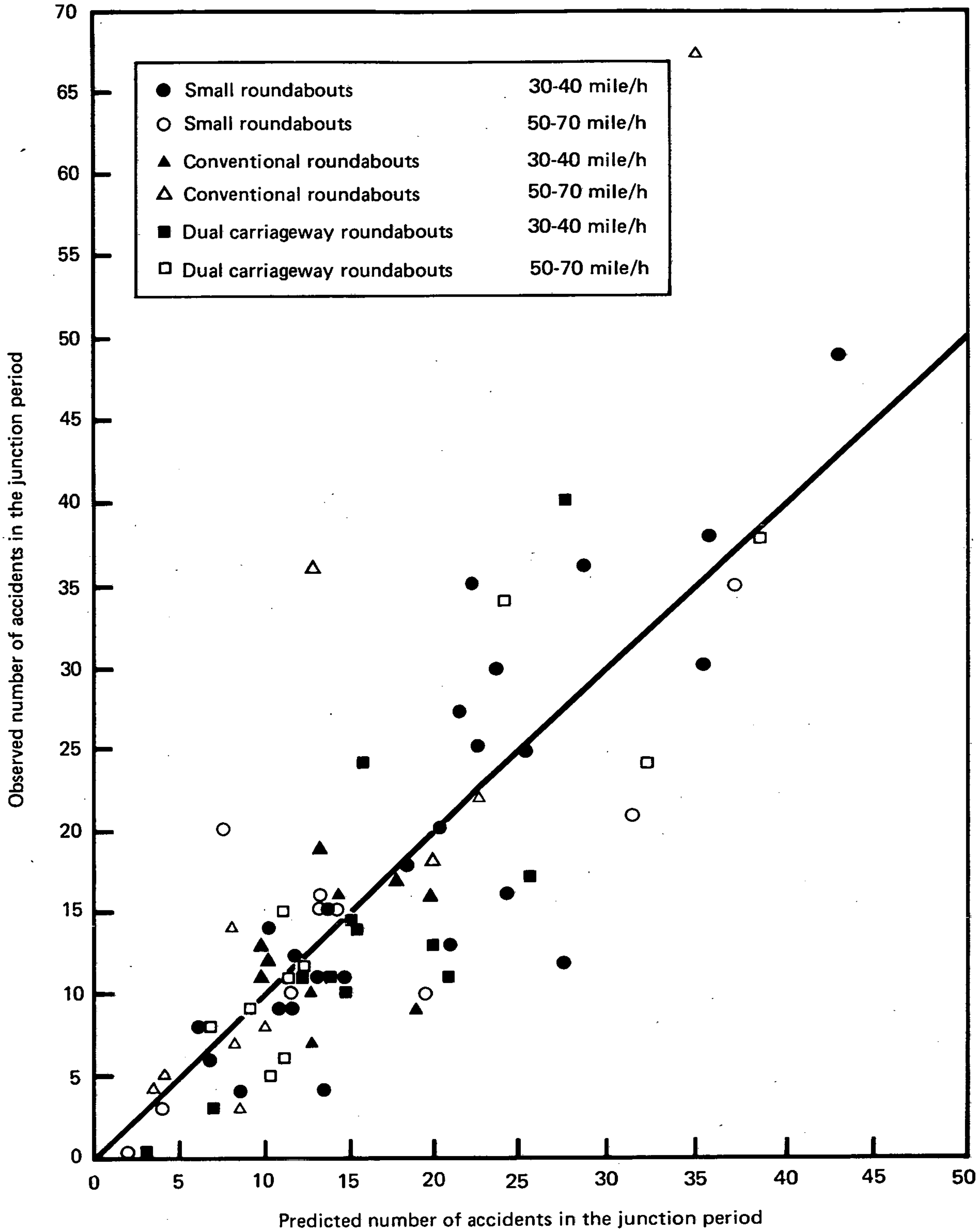
Observed and predicted number of accidents by roundabout category and accident type (1)

Roundabout category		Accident type					
		Entering-circulating	Approaching	Single-vehicle	'Other'	Total (2) vehicular	Pedestrian
Small:							
30–40 mile/h	Observed	359	33	37	48	477	19
	Predicted	349	37	52	49	487	24
50–70 mile/h	Observed	99	12	16	18	145	3
	Predicted	101	14	20	17	152	–
Conventional:							
30–40 mile/h	Observed	22	26	55	27	130	12
	Predicted	40	35	37	27	138	15
50–70 mile/h	Observed	46	51	54	33	184	4
	Predicted	32	35	39	25	132	–
Dual-carriageway:							
30–40 mile/h	Observed	49	51	54	38	192	23
	Predicted	50	57	69	46	222	15
50–70 mile/h	Observed	28	46	53	26	153	5
	Predicted	30	41	53	26	150	–
All Roundabouts	Observed	603	219	269	190	1,281	54(3)
	Predicted	602	219	270	190	1,281	54

(1) The figures given in this table do not correspond to the totals given in Table 2 of the main report because accident predictions were made only for those roundabouts included in the geometric analysis (see Table 20, footnote (1)).

(2) Including 2-wheeler accidents.

(3) These figures relate to those sites in 30–40 mile/h areas where pedestrian flow data was available (see Table 1 of this Appendix, footnote (2)).



Appendix 1 Fig. 9 Comparison of observed and predicted vehicular accidents at individual roundabouts

12. APPENDIX 2

VARIABLES AND FACTORS USED IN THE ANALYSIS

This appendix lists those variables and factors which are regarded as having some relevance to roundabout accidents and which have been tried as explanatory variables in the analysis. The table is followed by brief notes describing the parameters – the note number corresponding to the number of the parameter in the list. The distinction between variables and factors, is that the former have been handled in the analysis as taking any numerical value, whereas the latter are categories restricted to integer values or levels (up to 5).

The mean deviance ratios (an 'F' statistic) in the table have been obtained by taking the predictive model given in Table 18 as fixed, and regressing the resulting residuals against each parameter in turn. In the case of the variables, the mean deviance ratio would have to reach about 3.9 for the relationship to be regarded as significant at the 5 per cent level. The 5 per cent significance level for 2 level factors is 3.9, for the 3-level factors 3.0 and for the 5-level factor 2.4. In some cases a variable was tried in alternative forms – for example, distance of first sight of the roundabout was tried as measured, as a reciprocal and in log form. The mean deviance ratio is the highest value obtained in such trials.

TABLE 23

Variables and factors used in the analysis

	Parameter	Range	Mean Deviance Ratio				
			Entering-circulating	Approaching	Single-vehicle	'Other'	Pedestrian*
VARIABLES (arm specific)							
1	Entry Path Curvature	−0.01 – 0.053 m	–	–	–	0.1	1.3
2	Entry width	4.6 – 18.8 m	–	–	0.1	0.4	0.8
3	Approach half-width	2.6 – 11.0 m	–	0.5	–	0.2	2.4
4	Angle between arms	44 – 152 degrees	–	0.8	1.1	0.6	0
5	Gradient category	−3 – +3	4.1	3.1	2.6	0.2	0.3
6	Sight distance to the right	20 – 400 m	0.3	10	7.3	2.1	1.0
7	Approach curvature category	−3 – +3	3.7	0.5	–	0.4	1.6
8	Distance of first sight of the roundabout	40 – 650 m	1.3	0.4	2.1	0.2	5.9
9	Number of signs on the approach	0 – 10	0	0	0	0.2	0.4
10	Width of central reserve	0 – 16.7 m	0.3	0.9	0.2	0	1.9
11	Weaving length	7 – 77 m	0.1	5.2	2.2	0.4	4.8
12	Circulating width	6.5 – 19 m	1.6	0.2	2.8	0.1	0.1
13	Weaving width	7 – 25 m	0.5	0.2	1.7	0.8	0.4
14	Number of chevrons on central island	0 – 12	15	0.1	3.4	2.8	0.5
15	Entry angle	0 – 74 degrees	0	0.6	6.3	3.0	2.9
16	Average flare length	0 – 99 m	3.6	6	1.0	0.1	0
17	Sharpness of flare	0 – 2.8	1.6	1.9	1.5	0.6	0
18	Visibility round central island	8 – 90 m	6	12	4.8	0	1.1
19	Entry path curvature from opposite arm	−0.01 – 0.053 m	2.3	3.6	1.0	0.8	0.9
20	Entry path curvature from previous arm	−0.01 – 0.053 m	1.0	0.9	2.9	0.2	4.2

TABLE 23 (Continued)

Parameter	Range	Mean Deviance Ratio				
		Entering-circulating	Approaching	Single-vehicle	'Other'	Pedestrian*
FACTORS (arm specific)						
21 Road class	3 levels	0.3	0.2	2.5	2.3	1.7
22 Carriageway type	2 levels	0.1	0.3	1.4	0.1	1.3
23 Approach speed limit category	5 levels	0.4	1.5	2.4	0.7	3.7
24 Approach lighting category	2 levels	0.6	1.0	0.2	0.7	–
GENERAL VARIABLES						
25 Inscribed circle diameter	25 – 110 m	0.3	9.7	5.8	0.1	2.5
26 Central island diameter	5 – 90 m	0	6.3	6.4	0.1	3.7

* These figures refer to 30–40 mile/h roundabouts only.

NOTES:

1–4 See Appendix 3 for definitions

5 See 6.3.5 (ii)

6 The sight distance to the right is the value appropriate to a point 15 m back from the give-way line (see 6.3.5 (ii)). The actual distances recorded for all sight distance measurements are not 'crow fly' distance, but were measured from the give-way line to the farthest point visible along the approach road to the right.

7 See 6.3.5 (iv)

8 This is the distance in metres from the give-way line to the point on the approach from which the roundabout itself is first visible (ignoring advanced direction or other signs).

9 The total number of signs on the approach, including advanced direction signs, reduce speed signs (on both sides) etc.

10 Central reserve width (metres) measured on the approach.

11 Weaving length (metres) measured from splitter island to splitter island.

12 Circulating width (metres) measured from splitter island circulating carriageway kerbline to central island.

13 Weaving width (metres) measured from central island to roundabout outer kerbline mid-way along the weaving section.

14 Included because of the obvious relevance of such warning signs to accidents. This parameter appears significant for entering-circulating accidents. Its coefficient is however positive; it may be that more chevrons are put on dangerous entries. Similar results were obtained with chevrons on the splitter island.

15 A parameter used in capacity calculations as a proxy for the conflict angle between entering and circulating streams (Kimber, 1980).

16, 17 Parameters used in capacity calculations (Kimber, 1980). See also 6.3.5 (i).

18 Visibility round central island was included as it was thought relevant to detecting the presence of right turning traffic. It appears significant for the main three accident types, but its coefficient is positive in all cases (ie the better the visibility, the more accidents). Its value is limited by the size of the central island.

19, 20 As for variable 1. Thought to be possibly relevant to circulating traffic entering from previous entries.

21 Three road class types: Trunk and Principal, as separate types, with Class A, Class B, Class C and unclassified grouped together.

22 Two carriageway types: Single and Dual. This and the previous factor were tried to check that there were no road characteristics which had not been taken into account by the geometric variables.

23 Approach road speed limits (as distinct from the categories 30–40, 50–70 mile/h in the main report which were speed limits at the junction). Five categories: 30, 40, 50, 60 and 70 mile/h. The significant result for pedestrian accidents arose mainly from a rather lower accident rate on 30 mile/h approaches than on the remainder.

24 Approaches with or without lighting.

25, 26 See Appendix 3 for definitions. There is a significant but modest correlation in the case of approaching and single-vehicle accidents. It is not included in the predictive formulae since these variables are not arm specific. For entering-circulating accidents, they are incorporated into the Ratio Factor for reasons given in 6.3.5 (iii).

13. APPENDIX 3

DEFINITIONS OF THE GEOMETRIC PARAMETERS IN THE PREDICTIVE RELATIONSHIP

The geometric parameters included in the final predictive relationship (Table 18) are defined as follows:

(i) The *entry path curvature* (C_e) in metres^{-1} is defined in terms of the 'shortest' straight-ahead vehicle path. Consider a vehicle making a straight through movement at the roundabout in the absence of other traffic. Construct a path 2m wide with flowing curves representing the shortest path the vehicle could take through the roundabout keeping on its own side of the road but otherwise ignoring lane markings. The heavy line in Diagram A represents the locus of such a path. (Note: it is assumed that the path would start adjacent to the nearside kerb). Now measure as C_e the maximum value of the curvature of this path occurring in the region of the entry (ie the reciprocal of the minimum value of R in metres – Diagram A). The sign convention is that the curvature is *positive* if deflection is to the left, and *negative* if the path deflects to the right. (Note: a more comprehensive definition of entry path curvature is contained in the Department of Transport's Departmental Standard – The geometric design of roundabouts.)

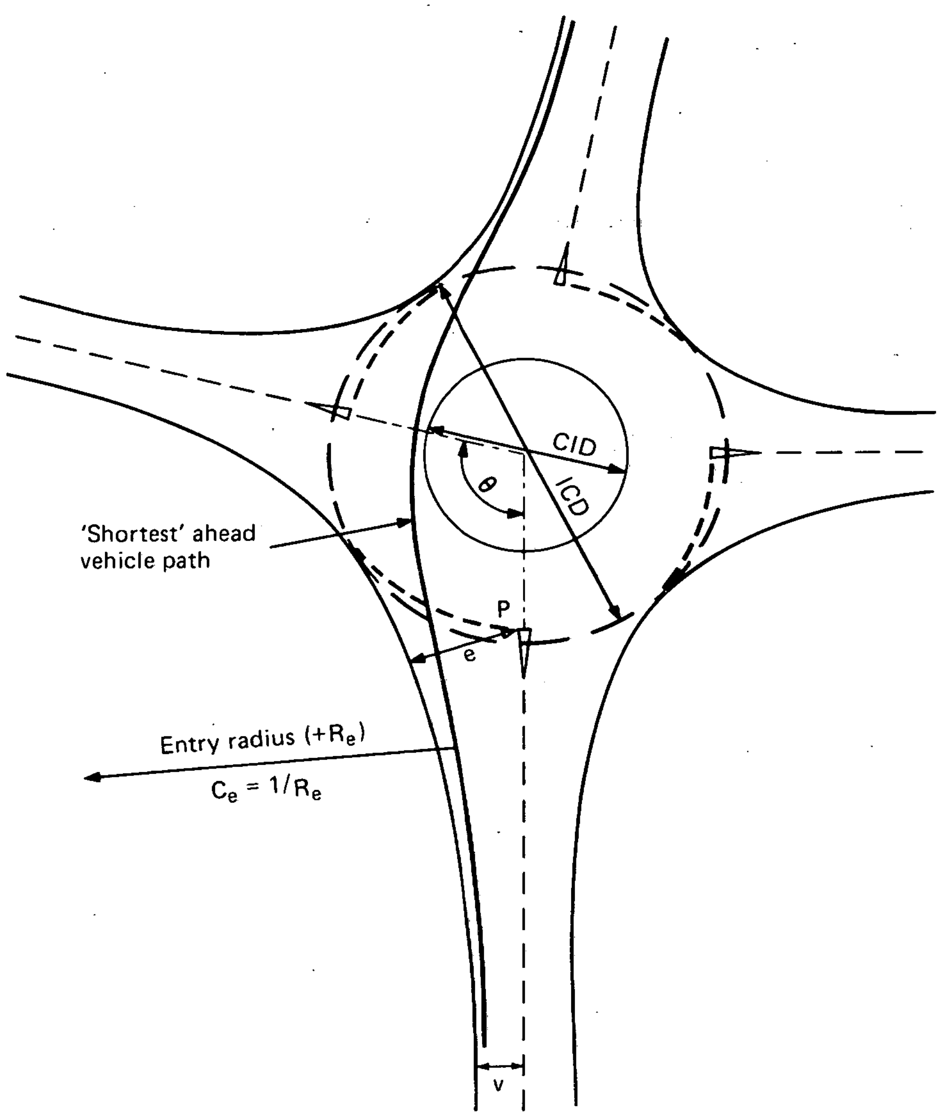


Diagram A Illustrating, entry path curvature (C_e), entry width (e), approach half-width (v), angle between arms θ Inscribed circle diameter (ICD) and Central Island Diameter (CID)

(ii) The *entry width* (e) in metres is measured from the poin P (Diagram A) along a line normal to the nearside kerb.

(iii) The approach half-width (v) in metres, is measured at a point in the approach upstream from any entry flare, from the road centre marking to the nearside kerb along a normal (Diagram A).

(iv) The *angle* (θ) between the approach arm and the next arm clockwise (in degrees), is the angle subtended by projections of the relevant approach centre lines as shown in Diagram A. If the approaches are curved then the tangents to the centre lines at the entry point (P) are used for this construction.

(v) *Inscribed circle diameter* (ICD) in metres is the diameter of the largest circle that can be inscribed within the junction outline (Diagram A). In cases of asymmetric junction outlines (where a circle cannot conveniently be fitted within the design) a compromise value for ICD should be adequate.

(vi) *Central island diameter* (CID) in metres is in cases of non-circular islands the maximum value. Asymmetry in the sample included in the study rarely exceeded 20 per cent.

(vii) *Approach curvature* (C_a) in metres^{-1} is defined in terms of that section of the junction approach road within the range of about 50 m (to be clear of the immediate entry geometry) to 500 m from the roundabout give-way line. C_a is the maximum curvature (the reciprocal of the minimum radius in metres) of the bend nearest to the junction within this section of the approach. Diagram B illustrates this parameter in two cases. The sign convention is that right hand bends (approaching the roundabout) are *positive* and left hand bends are *negative.* A straight approach has $C_a = 0$.

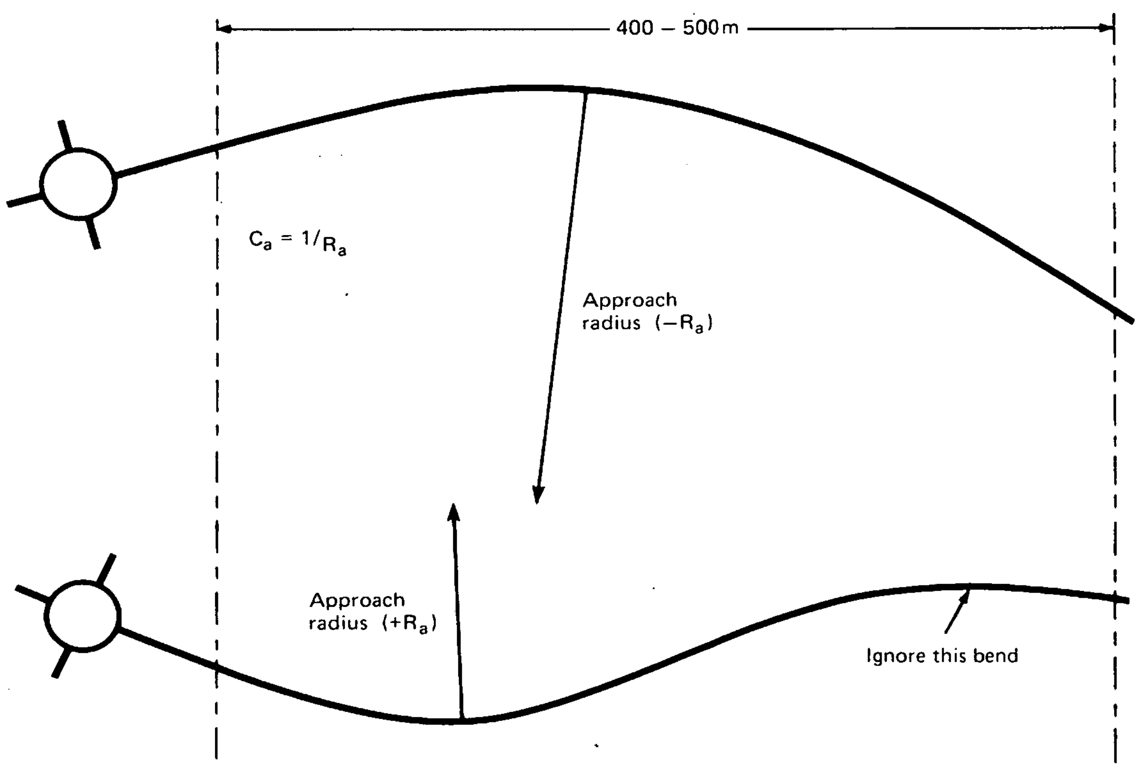


Diagram B Illustrating approach curvature (C_a)

14. APPENDIX 4

GENERALISED LINEAR MODELS

14.1 Introduction

The objective of the regression analysis described in section 6 of the main report, was to relate the accident frequency (the number of accidents per year) at roundabout 'sites' (either the roundabout as a whole or the individual approaches to the roundabout), to a range of explanatory variables. The technique used was Generalised Linear Modelling detailed in the paper by Nelder and Wedderburn (1972) and implemented in the computer programs GENSTAT and GLIM. The principles of the method and its particular application to the accident analysis problem are described briefly here.

14.2 Model components

A statistical model of a particular set of observations may generally be regarded as consisting of two elements – the systematic component and the random component.

14.2.1 The Systematic component. The systematic component describes the way that the expected (or predicted) values of the dependent variable relate to a set of independent 'explanatory' variables. Thus in ordinary least squares regression the fitted equation would have the form:

$$\mu = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + \ldots$$

where μ is the value of the dependent variable predicted by the regression line (the fitted value) for a particular set of the x's – the independent variables, and the a's are the regression coeffients. The generalised linear methodology preserves the linear form of the right-hand side of the above equation, but generalises the relationship between the value of this 'linear predictor' (usually denoted by η) and the fitted value μ. Thus,

$$\eta = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + \ldots \text{ as before,}$$

$$\text{but,} \quad \eta = f(\mu).$$

The latter relationship is known as the link function, and a number of standard link functions (including of course the identity link $\eta = \mu$) are available in GLIM and GENSTAT.

In the accident context, the dependent variable would be the accident frequency (or more usually the number of accidents occurring at a particular site within a given time period – since this is normally regarded as having a Poisson error structure, see 14.2.2 below), and the independent variables are those associated with traffic flow and junction geometry.

Since as was explained in section 6.2, the simple linear model was not regarded as acceptable (yielding negative predicted accident frequencies), it was decided to fit a multiplicative model. This can be achieved by using a log link such that:

$$\eta = \ln(\mu) \qquad (\ln = \text{log to the base e})$$

The linear equation then becomes:

$$\ln(\mu) = \eta = \ln(J) + b_0 + b_1 \ln(Q) + b_2 g_1 + b_3 g_2 + \ldots$$

Here μ is the number of accidents occurring at a given site in J years, ln(Q) is a transformed flow variable, $g_1, g_2 \ldots$ are geometric variables, and $b_0, b_1, b_2 \ldots$ are coefficients to be determined. Ln(J) is termed an 'offset' variable and is included in the way shown above so that the dependent variable remains simply the number of accidents occurring during J years. The above equation has the form of equation (1) section 6.3.2 when exponentiated.

In order to obtain maximum likelihood estimates of the coefficients (the b's) the transformation of the dependent variable requires that the data points are appropriately weighted as described in 14.2.3 below.

14.2.2 The random component. The other component of the statistical model is the random element. In least squares regressions it is required that the observations should be regarded as having been drawn from a population with a mean equal to the value given by the regression 'line' – and with a variance which is constant throughout the range of the data. If the data are drawn from a normal population standard significance tests can be applied (eg F-tests) and the least squares estimates of the regression parameters are also maximum likelihood estimates. If it is known that the observations are drawn from a non-normal population (as is the case with accident 'counts' where the error distribution can be regarded as Poisson) then the constant variance assumption is violated, since the variance of a Poisson distribution equals its mean. Although it is possible to allow for non-constant variance by suitable weighting of the data, the generalised linear model formulation allows a known (or assumed) error distribution of the dependent variable to be specified explicitly for the exponential family of distributions (see 14.2.4 below). Thus in GENSTAT and GLIM, Normal, Poisson, Binomial or Gamma errors can be simply selected as appropriate. The procedure then calculates an appropriate weighting factor for each data point which allows for the way the variance of the distribution changes as the mean changes. The relationship between the mean and the variance is called the variance function and is automatically taken into account if one of the standard error distributions is specified. GLIM also allows the user to perform 'fits' using his own error distribution, provided its variance function can be specified. This feature has been used to explore both the model and the error structure as described in Appendix 5.

14.2.3 Fitting the models. Having specified the link function and the error structure, the fitting procedure calculates the maximum likelihood estimates of the coefficients. The 'normal' equations (which are solved to give the coefficient estimates) are similar to those for ordinary weighted least squares regression, except that the dependent variable is replaced by a modified variate equal to:

$$\eta + \delta\ (y - \mu)$$

Here η is the linear predictor, y is the 'observed' dependent variable, μ is the fitted (or predicted) value and δ is $\frac{d\eta}{d\mu}$ – the derivative of the link function. The weights used in the weighted regression are equal to $\frac{1}{\sigma^2\,\delta^2}$ where $\sigma^2 = F(\mu)$ is the variance function. Clearly, both the weights and the modified variate depend on the fitted values μ which in turn depend upon the calculated coefficients. The procedure is thus iterative, each cycle of the fit using estimates of the various parameters from the previous cycle until convergence is obtained (usually in 3 or 4 cycles).

14.2.4 Significance testing. When alternative forms are possible for the systematic component of a statistical model it is necessary to be able to decide whether one model is significantly better or worse than another.

In particular, if alternative explanatory variables exist, it is necessary to be able to choose the variable that contributes most to 'explaining' the variation in the data; if additional variables are being added to a model, it is important to be able to decide whether any improvement in 'fit' is statistically significant.

The statistic calculated in GENSTAT and GLIM which has been used in this study for significance testing is the Scaled Deviance. Deviance is a likelihood ratio statistic equal to $-2 \ln \lambda$, where:

$$\lambda = \frac{\max L}{\max L_f}$$

Hence, Scaled Deviance = $-2 [\ln (\max L) - \ln (\max L_f)]$, where:

$\ln (\max L)$ is the maximised log-likelihood for the model under review (the current model) and,

$\ln (\max L_f)$ is the corresponding value for the full model, ie that model which exactly fits all the data points ($\mu = y$).

These likelihood ratios (log-likelihood differences) are effectively calculated for each point in the data set and summed over all points, to give the total deviance.

The error distributions for which the generalised model methodology has been developed belong to an exponential class which includes (among others) the Binomial, Poisson, Normal and Gamma distributions. Theoretically the type of significance test (based on scaled deviance) which can be used depends upon the 'scale factor' of the distribution. Binomial and Poisson distributions (and their derivatives – see Appendix 5) being single parameter distributions have a scale factor of 1. In this case, providing μ (the predicted value) is greater than about 0.5 (see Appendix 5 – 15.3.3) scaled deviance is assymptotically distributed like χ^2 with the number of degrees of freedom equal to n-p-1, where n is the number of data points and p is the number of parameters fitted in the model. Thus for a well fitting model with appropriate link function, error distribution and functional form the expectation value of the scaled deviance will approximately equal the number of degrees of freedom. Moreover the difference in scaled deviances between two nested models with degrees of freedom df_1 and df_2 will be distributed like χ^2 with degrees of freedom equal to $df_1 - df_2$. Thus theoretically, the significance of adding a single term to a Poisson model can be assessed by comparing the difference in scaled deviance with 3.84 (the 95 per cent point of the χ^2 distribution with 1 degree of freedom). For error distributions with scale factors not equal to 1 (eg Normal and Gamma) significance testing is based on mean deviance ratios and the F-distribution.

In the present study two arguments suggest that significance testing based on differences in scaled deviance is inappropriate:

(a) The error structure is not 'pure Poisson' since there is likely to be a significantly large element of 'between site' error in addition to the 'within site' Poisson process. As a consequence the effective 'scale factor' does not equal 1, and,

(b) The data set implies values of mean accident frequency (μ) less than 0.5 in many cases. This has the effect of reducing the values of scaled deviance below that expected for χ^2.

Both aspects of the error structure are discussed in greater detail in Appendix 5. In the present context it is sufficient to state that in most of the analysis reported earlier the Poisson scaled deviance has been calculated:

$$\text{Scaled Deviance} = 2 \sum_i \left\{ y_i \log \frac{y_i}{\mu_i} \right\}$$

but that significance tests have been based on the mean deviance ratio:

$$\text{Mean deviance ratio (MDR)} = \frac{\text{Deviance difference}/(df_1 - df_2)}{\text{Residual deviance}/df}$$

The residual deviance is the scaled deviance corresponding to the best fit model. By calculating the mean deviance ratio, the scaling effects (a) and (b) mentioned above cancel, and the resulting MDR can be compared with the critical points of the F distribution in the usual way.

15. APPENDIX 5

TESTING THE MODEL STRUCTURE

15.1 Introduction

For error distributions with a scale factor of 1, the expectation value of the residual unexplained scaled deviance of a well fitting model should be approximately equal to the number of degrees of freedom. (This statement will be elaborated in 15.3.2 below, and qualified for small values of the predicted accident rate, μ). For the moment it is sufficient to note that few of the analyses reported in the main report succeeded in reducing the residual deviance to a value close to its expectation value. That is with the 'best' model fitted to the data, there was generally a significant amount of unexplained variation. The failure of a model deviance to match its expectation value can arise in two ways:

(a) the systematic component of the model may be incorrect,

or

(b) the error structure is inappropriate.

In the former case, either the link function or the linear predictor may be wrong; even if the linear predictor contains all the relevant terms, they may not be included in the most appropriate functional form or they may not be combined in the right way. This aspect of the model structure will be examined in section 2 below. As far as the error structure is concerned, it is usually assumed that accidents occur randomly, and that therefore the total number of accidents occurring at a specific site in a particular junction period is a Poisson variate. However, the present analysis is based mainly on between-site variations in accident rates, and although the within site 'counting' errors may be Poisson, the overall error structure of the model will be a combination of within and between-site variability and will not therefore be Poisson. This aspect will be considered in section 3.

15.2.1 The structure of the systematic component. The use of a log link function and additive geometric variables results in the model form given in the main report (equation 3) viz:

$$A \text{ (accidents per year) } = kQ^{\alpha} \Pi \exp [b_i (G_i - \overline{G}_i)] \qquad \ldots\ldots\ldots\ldots\ (1)$$

As far as the geometric variables are concerned this model is partially interactive – the degree of interaction depending on the range of values taken by the exponential factors. Thus if this range is small (say up to ± 20 per cent) the above expression can approximate to:

$$A = kQ^{\alpha} \Pi [1 + b_i (G_i - \overline{G}_i)]$$

and since the cross product terms are not large this in turn approximates to:

$$A = kQ^{\alpha} [1 + \Sigma b_i (G_i - \overline{G}_i)]$$

It is therefore virtually non-interactive; that is to say, changes in one geometric variable have the same additive effect on accident frequency (A) irrespective of the values of the other geometric variables. If on the other hand, the range of one (or more) of the exponential factors is large, particularly if the factor approaches zero, the model becomes heavily interactive. The point is well illustrated by the interactions between the variables describing the entry geometry (ie entry curvature and entry width) noted in section 7.2 of the main report. There it was pointed out that the effect of entry width on entering-circulating accidents depends critically on the value of entry curvature; if entry curvature is zero (and exp $(-b\,(C_e-\bar{C}_e))$ about 1.7) the effect of the entry width term is large (Fig. 6(a)), whereas at maximum deflection, where the exponential factor falls to 0.2, the entry width term has little effect (Fig 6(b)) in additive terms. This feature of the results reflects the model structure. Clearly, it is necessary to determine whether the data supports this interactive model structure and the conclusions discussed in Section 7.2 which flow from it.

An alternative non-interative model structure for the entry geometry variables might be:

$$A = (a_0 + a_1\, C_e + a_2\, e + a_3\, v)\, Q^{\alpha}\, \Pi \exp\,[b_j\,(G_j-\bar{G}_j)] \qquad \ldots\ldots\ldots\ldots\ (2)$$

where G_j are the useful geometric variables excluding C_e, e and v, and the a's and the b_j's are coefficients to be determined. As far as the entry variables are concerned, this model would be non-interactive. The effect of e or v on A would be the same irrespective of the value of C_e. There are of course a large number of models in between those represented by equations (1) and (2) above, which include terms in simple or exponentiated form (eg exp (C_e)), and which introduce interactive elements by means of a variety of product terms.

Statistically, it is necessary to devise a method for fitting these alternative model forms and for allowing the effectiveness of the models to be assessed using residual deviance. The following section describes such a method and its results.

15.2.2 The factored Poisson fit. GENSTAT and GLIM allow Poisson variate models to be fitted as a standard procedure. If however it is required to fit directly a variate which is a Poisson variable divided by a constant (for example Accidents per year), the standard fitting routine cannot be used, since the new variate does not conform to a Poisson distribution; it is termed here a 'factored Poisson' distribution. Such a distribution has the following characteristics:

(a) The probability density function:

$$P\,(y) = \frac{(\mu f)^n\, e^{-\mu f}}{n!}\ ; \ n = 0, 1, 2, 3, \ldots\ldots \text{ and } y = n/f$$

where μ is the mean value and f the 'factor'.

(b) The variance function:

$$\text{Var}\,(y) = \mu/f$$

(c) The scale factor is 1, and the scaled deviance is $2\,\Sigma\, y\, f \ln \left\{ y/\mu \right\}$

GLIM allows 'own' models to be fitted, provided the program is supplied with the means of calculating the derivative of the link function (1 for the identity link used in the present analysis), the variance of the distribution (which is calculated from the mean ('fitted') values), and the scaled deviance. This facility was used to fit a variety of non-interactive models to the entering-circulating accident data, using as the dependent variable A (accidents per year) or A divided by a function of those parameters which it was desired to exclude from the right-hand side of the predictor equation. The functions used for this purpose were derived from the more conventional Poisson analyses, that is to say they were usually of the form $Q^{\alpha}\, \Pi \exp\,[b_j G_j]$, where and the b_j's were regarded as fixed.

This procedure allowed the following conclusions to be drawn about the model structure.

(a) A simple linear relationship between accident frequency and the main flow and geometric variables (Q_e, Q_c, P_m, C_e, e, v, and θ) though reducing the scaled deviance very significantly, did not perform as well as the 'best' exponential multiplicative model. In particular the flow variables were significantly more effective in multiplicative than in additive form.

(b) The entry curvature term (C_e) – the only geometric variable with a large negative effect – was statistically a much better fit in negative exponential form (which avoids negative predicted accident frequencies) than in linear form.

(c) A model which includes the entry width variables in an interactive form proved to be statistically far better than one in which these terms were included additively.

It was accordingly concluded that the straightforward multiplicative exponential model presented in the main report could be supported by the data in preference to alternative models. Even so, some care has to be exercised in applying these models to heavily flared and deflection entries, since such entry geometries are not strongly represented in the database used for this analysis.

In the case of the other accident types, the interactions between geometric variables are neither as strong nor do they raise important practical issues as in the case of entering-circulating accidents. The 'simple' exponential multiplicative models are accordingly acceptable in these cases.

Since during the course of experimenting with alternative model forms the residual deviances of the best fit models were not reduced significantly, it would not seem unreasonable to conclude that the contribution to the unexplained variation from model 'lack of fit' is small compared with the random errors discussed below.

15.3.1 The error structures. It was earlier suggested that the accident data used for the purposes of the present analysis should be regarded as having an error structure arising from two components: the within site errors (which can be regarded as a Poisson process), and an unspecified between site error distribution. The latter is of course 'unexplained' variation, because if the systematic component of the model had succeeded in 'explaining' all the between site variation in the accident data, then only the within site Poisson errors would have remained and the residual mean deviance would have reflected this fact.

Consideration of the basic error structure of the model is of value for two reasons:

(a) if an inappropriate error structure is assumed during the analysis, the calculated coefficients could also be in error because during the fitting procedures incorrect data weightings have been used (see Appendix 4);

(b) accident predictions are mainly calculated for individual sites, and although in overall economic terms it could be argued that it is the mean value over many sites which matters, it is of considerable interest to attempt to estimate the individual between site 'unexplained' variation free from the within site Poisson errors.

15.3.2 A possible error model. It is well known eg (Abbess, Jarrett and Wright, 1981) that if the within site error structure is Poisson, and the between site errors are distributed according to a Gamma distribution, the resulting combined sampling distribution is Negative Binomial.

The combined distribution can be derived as follows:

If P(x) is the probability density function of Gamma form for the distribution of mean accident frequencies between sites (x being a continuous positive random variable), then

$$P(x) = \frac{S^S x^{S-1} e^{-(s/\mu)x}}{\mu^S \Gamma(S)}$$

where μ is the mean of the distribution, and S is its other parameter.

The variance of this distribution is $\frac{\mu^2}{S}$, so that its coefficient of variation ($\sqrt{\text{variance}}$/mean) is $1/\sqrt{S}$, and independent of μ. As a representation of between site errors, this distribution presupposes therefore, that the 'spread' of mean accident frequencies between sites is proportional to the mean value – that is, it is small for low accident sites and proportionately larger for the higher accident sites. This seems reasonable. When S>8–10, the distribution is practically very close to being normal. Below this value the distribution is skewed; the mode being at $\frac{(S-1)}{S}\mu$.

The sampling distribution (ie the probability of y accidents in a given period) at any site with a mean accident frequency x will be Poisson:

$$P(y|x) = \frac{x^y e^{-x}}{y!}, \quad y = 0, 1, 2 \ldots$$

So the sampling distribution over all sites will be:

$$P(y) = \int_0^\infty P(x)\; P(y|x)\, dx$$

(regarding y as a constant whilst integrating over x) which gives:

$$P(y) = \frac{S^S}{\mu^S \Gamma(S)\, y!} \int_0^\infty x^{S+y-1} \exp\left\{-\left(1 + \frac{S}{\mu}\right) x\right\} dx$$

Substituting $z = x(1 + S/\mu)$ and integrating gives:

$$P(y) = \frac{\Gamma(S+y)}{\Gamma(S)\, y!} \left(\frac{S}{\mu + S}\right)^S \left(\frac{\mu}{\mu + S}\right)^y \quad \text{The Negative Binomial Distribution}$$

This distribution becomes the Poisson distribution as $S \to \infty$, and the between site variation disappears.

The mean value of the distribution is μ, and the variance $\frac{\mu(\mu + S)}{S}$.

This error distribution can be fitted using the 'own' fit facility in GLIM. In this case the log link is used (as with the Poisson model), so that GLIM has to be supplied with the derivative of the link function ($1/\mu$ for the log link), the variance function as given above, and the deviance. For the negative binomial error model, the scale factor is again 1, and

$$\text{Scaled Deviance} = 2\Sigma\left\{y \ln\left(\frac{y}{\mu}\right) - (y + S) \ln\left(\frac{y + S}{\mu + S}\right)\right\}$$

Again, when $S \to \infty$, this expression becomes equal to the scaled deviance of the Poisson error model. In terms of the accident analysis, the question is, how can the parameter S of the underlying distribution of the mean site-to-site values be determined? For this, it is necessary to consider the expectation values of the scaled deviance.

15.3.3 The expectation value of Scaled Deviance. The Poisson Scaled Deviance equals the Negative Binomial when $S = \infty$, but as S decreases, so does the Negative Binomial Deviance. The value of S which corresponds to the between site distribution of errors can thus be estimated as that value for which the sample scaled deviance equals its expectation value. In order to do this calculation it is therefore necessary to estimate the sample expectation values of scaled deviance as a function of the mean value and the parameter S.

This was done numerically, for population values, by summing the relevant series, for integer values of S. Figure 10 shows the results of these calculations.

For convenience in calculating the population expectation values of a particular data set, the curves of Figure 10 were approximated by algebraic functions. The sample expectation value was taken to be the population value multiplied by the ratio: degrees of freedom/number of observations.

A point of some practical significance about the results of Figure 10 is that whereas expectation values for Negative Binomial and Poisson distributions are approximately 1 when $\mu > 0.5$, below this value the expectation values fall rapidly to zero. Data sets with very low mean values (and a high proportion of zeros in the set) will accordingly have scaled deviances which are considerably lower than the number of degrees of freedom. The fact needs to be borne in mind therefore when using scaled deviance as a measure of overall goodness of fit, and is one of the reasons for preferring mean deviance ratio for significance testing purposes (Appendix 4).

15.3.4 Results. The value of S obtained in the way described in the previous section was about 2.75 for entering-circulating accidents and 2.5 for approaching accidents and single-vehicle accidents. For 'other' accidents it was nearer 1.25. The value 2.5 (to choose a middle value for illustrative purposes), implies that the distribution of 'unexplained' between site (individual arms) variation of mean values had the distribution shown in Figure 11. The coefficient of variation for this distribution is 0.63 independent of the mean. This is a rather disappointingly high value, but of course applies to one type of accident only on one arm of a roundabout. Since it is the predicted accident frequency for the roundabout as a whole which is usually the figure of interest, there will be a degree of averaging when the accident types are summed over the four arms.

Ignoring for the moment pedestrian accidents, if the predicted number of accidents of the remaining four types are A_1, A_2, A_3, and A_4, each having Gamma distributions as outlined above (Variance $= \frac{A^2}{S}$), the variance of the sum of all types of accidents on a particular arm (assuming each type to be statistically independent) will be:

$$\text{Var}\,(A_{\text{Total}})_{\text{Arm i}} = \frac{A_1^2}{2.75} + \frac{A_2^2}{2.5} + \frac{A_3^2}{2.5} + \frac{A_4^2}{1.25}$$

For the roundabout as a whole, the variance of total accidents will be the sum of the variances appropriate to the individual arms.

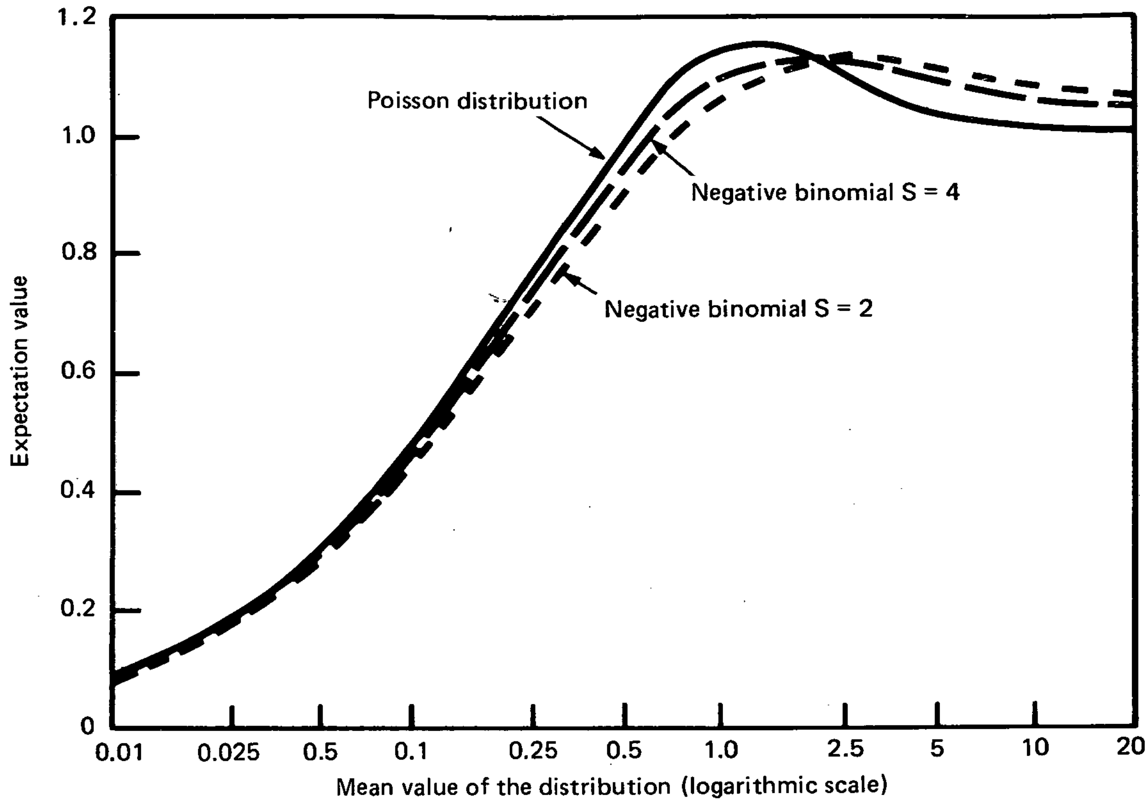
If moreover this averaging procedure has resulted in the distribution of A being approximately normal, then the square root of Var(A) can be regarded as the standard error of the predicted mean accident frequency for an individual roundabout arising from between site differences. Site specific results of these calculations are included in Appendix 1.

As far as the coefficients are concerned, the Negative Binomial analyses did not generate values which were significantly different from the Poisson analyses for any of the accident types. By way of example Table 24 gives the Negative Binomial results for entering-circulating accidents for comparison with Table 16. Since the residual deviance of this model equals its expectation value, the deviance differences given in column 7 can be treated as χ^2 variables with 1 degree of freedom. Extra terms added to the model can therefore be regarded as significant at the 5 per cent level if the deviance difference exceeds 3.84.

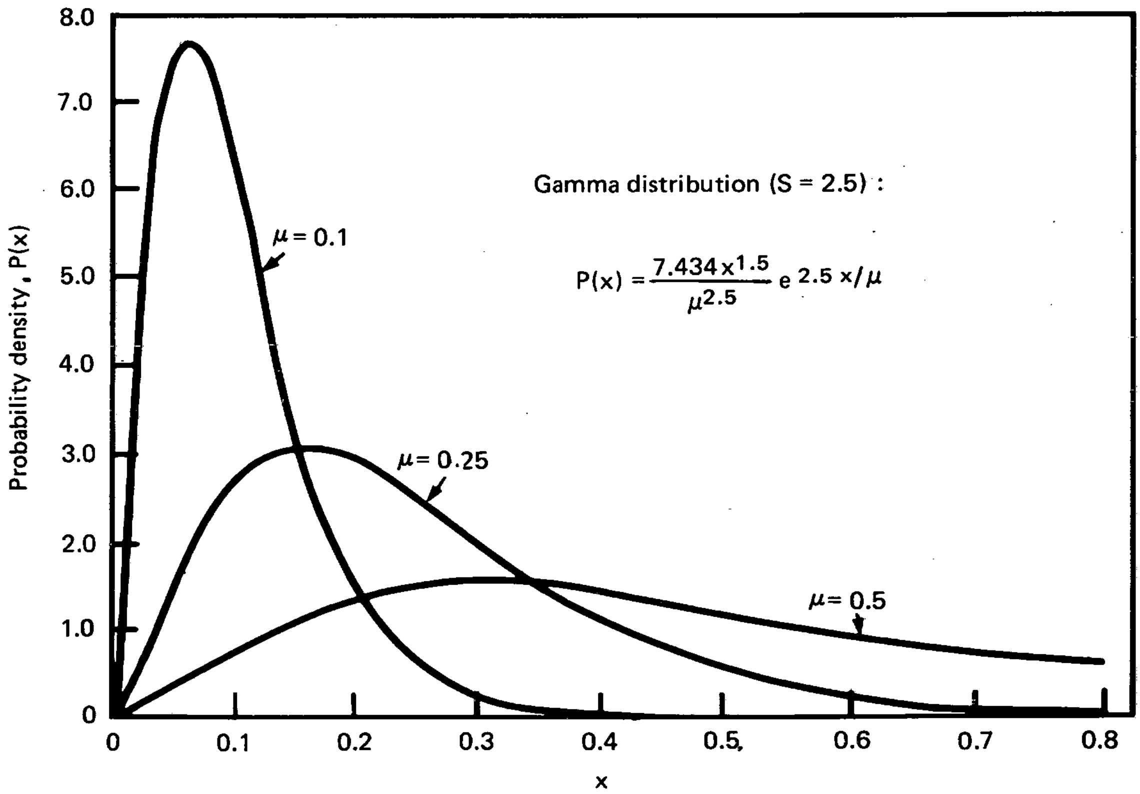
TABLE 24

Results of the regression analysis for entering-circulating accidents using a Negative Binomial error model (S = 2.85)

Constant and Flow Coefficient		'Geometric' Variables		'Geometric' Coefficients		Scaled Deviance	
Value	S.E.			b	S.E. of b	Initial & residual	Reduction
						622	
		Entry curvature	C_e	−42	10		166
ln k = −2.97	0.52	Entry width	e	0.15	0.04		38
		Approach width correction	ev	−0.008	0.004		2.8
α = 0.65	0.14	Ratio Factor	RF	−1	0.25		32
		Proportion of Motorcycles	P_m	0.21	0.07		9.5
β = 0.42	0.12	Angle between arms	θ	−0.01	0.003		8.0
		Gradient category	g	0.086	0.047		3.5
						313	



Appendix 5 Fig. 10 Expectation values of scaled deviance for Poisson and negative binomial distribution as a function of the mean value



Appendix 5 Fig. 11 Illustrating the gamma distribution used to represent between site variation

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ABSTRACT

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ISSN 0305 - 1293

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