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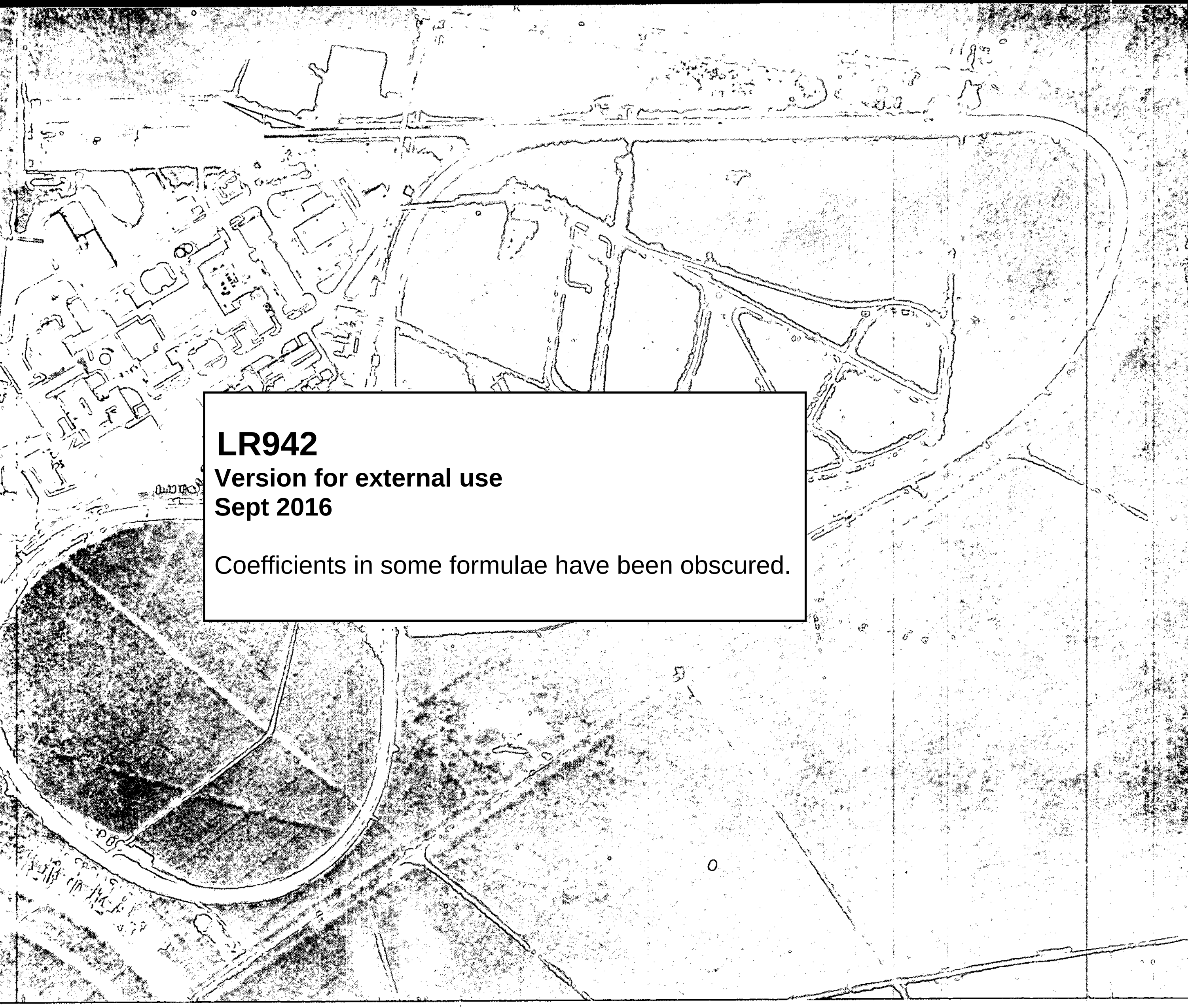

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Coefficients in some formulae have been obscured.

Alterations

① P.17, line 2, Appendix 2

~~② Fig. 3, vertical axis~~
~~$b_0(1)/b_0(1)$~~

① P.39, line 7, Calculated in (ii)

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THE TRAFFIC CAPACITY OF ROUNDABOUTS

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CONTENTS

THE TRAFFIC CAPACITY OF ROUNDABOUTS

ABSTRACT

A study has been made of the entry capacities of conventional and offside priority roundabouts at eighty-six public road sites, and a unified formula for capacity prediction developed. The traffic flow entering a roundabout from a saturated approach was found to be linearly dependent on the circulating flow crossing the entry. The most important factors influencing the capacity are the entry width and flare. The entry angle and radius have small but significant effects. The inscribed circle diameter, used as a simple measure of overall size, is more effective as a predictive variable for the capacity than the category distinction between conventional and offside priority roundabouts, and for capacity prediction there is no need to retain this distinction. In addition to normal capacity prediction, methods have been developed which allow: (i) the predictive equation to be corrected to take account of local operating conditions at overloaded existing sites; and (ii) the equation to be used specifically to predict the effects of changes in the entry geometry of existing sites.

1. INTRODUCTION

The design of roundabouts has changed considerably in recent years. Before the 1970s most roundabouts were designed with large central islands and parallel-sided weaving sections and entries. Newer designs have smaller central islands with wide circulation widths and flared entries, and offer considerable advantages in efficiency of land use and construction cost. Both types are used widely.

The prediction of roundabout capacity is a crucial element in design, and the traffic engineer has to steer a careful course between, on the one hand, inadequate provision, with the resulting costs in traffic delays, and, on the other, over-elaborate designs for which the excessive costs of construction outweigh the potential traffic benefits. Until recently, the methods of capacity prediction had a number of fundamental shortcomings, the most important of which were, firstly, that the older traditional roundabouts with large central islands (now generally known as *conventional* roundabouts) were designed according to formulae developed before the introduction of the offside priority rule, and, secondly, that for *offside priority* roundabouts (mini- and small-island designs) it was not possible to evaluate the capacities of individual entries. The recent development of entry capacity prediction formulae for both conventional[1] and offside priority roundabouts[2,3] has improved the situation considerably. However, the unsatisfactory distinction between conventional and offside priority roundabouts remains, and the present study was undertaken to remove this distinction – at least from capacity calculations.

Several earlier studies have presented analyses of data obtained at conventional[1,4] and offside priority[3] roundabouts on the public roads. In 1978 the consultants Halcrow Fox and Associates were appointed to analyse the combined data from these earlier studies together with some additional offside priority roundabout data[5]. This report describes the analysis of the total data base and formulates a general capacity prediction procedure for all at-grade roundabouts.

The structure of the report is as follows. Section 2 outlines the historical reasons for the present status of capacity calculations. Section 3 describes the principles on which the capacity procedure developed here is based. Section 4 gives details of the data base. Section 5 describes the analytical framework, and Section 6 the results of the analysis. Finally, Section 7 gives what are seen as the main applications of the capacity formula.

2. BACKGROUND

2.1 History

Prior to 1966 there were no rules defining the priority of one traffic stream over another at roundabouts, and early designs suffered from a tendency to 'lock' under heavy traffic load, when vehicles already on the roundabout were prevented from leaving by entering vehicles. In order to reduce the probability of locking, long 'weaving sections' between successive entries were increasingly used by designers so as to absorb temporary queueing which occurred in the roundabout itself. This often resulted in extremely large designs.

The offside priority rule, introduced in November 1966, specified that entering drivers should give way to vehicles approaching from their right, which were already on the roundabout. As a result traffic could always exit from the roundabout, and the phenomenon of locking disappeared. It was subsequently possible to develop much smaller designs offering relatively high traffic capacities and much greater efficiency of land-utilisation; these are the *offside priority* designs, so-named because their mode of operation depends intrinsically on the offside priority rule. They comprise both mini- and small-island designs and cover a wide range of traffic capacities.

2.2 Capacity prediction

Before the introduction of the priority rule, capacity prediction was based on the 'weaving section' – the area into which entering and circulating traffic merged. In 1957 Wardrop[6] developed a formula giving the capacity of a weaving section in terms of the geometric parameters defining its size and shape, and one traffic parameter, the proportion p of traffic which had to 'weave'. With the introduction of the priority rule the traffic interaction changed fundamentally, and it has since been demonstrated by Ashworth and Field[7], Ashworth and Laurence[4], and Philbrick[1] that the proportion weaving, p, is no longer a satisfactory predictor of the capacity. Moreover, since entering traffic now has to give way to circulating traffic, the operational basis for the weaving section formula no longer exists, and it is necessary to deal in terms of the capacities of *entries,* rather than of weaving sections. This concept is explained fully in Section 3.

Capacity prediction for offside priority roundabouts was developed originally along completely different lines. Blackmore developed a formula[8] which allowed the total capacity of offside priority roundabouts (the junction throughput with queueing on all approaches) to be calculated from a knowledge of the basic road widths and the area of widening at the junction. This offered an indication of the overall traffic performance of the roundabout, but did not permit the capacity of individual entries to be calculated, nor did it enable the effects of imbalanced demand, with queueing on one or two entries only, to be assessed. Recently, predictive formulae have been developed for the capacity of individual entries to offside priority roundabouts[2,3].

In the last year or two, capacity prediction for both 'conventional' and 'offside priority' roundabouts has thus been brought together into a common framework in which the capacity is predicted entry by entry. However, the two types are designed according to geometric principles evolved as a result of differently perceived operational mechanisms – weaving for conventional designs and gap-acceptance for offside priority designs. Consequently their characteristic geometric features and sizes are different: conventional roundabouts have large and often irregularly shaped central islands, parallel sided weaving sections and unflared entries (usually two-lane), whereas offside priority designs have smaller, usually circular, central islands and flared approaches.

Two main issues need to be resolved. Firstly, is there any fundamental difference between the factors determining the capacity of conventional and offside priority roundabouts? Secondly, if there is not, what is the best single procedure for predicting the capacity of roundabouts? Because capacity prediction and overall design are intimately linked, the development of a coherent design strategy can only be achieved when these issues have been settled.

3. THE ENTRY-CIRCULATING FLOW RELATIONSHIP

The entry capacity is defined as the maximum inflow from an entry when the demand flow is sufficient to cause steady queueing in the approach. Since the introduction of the priority rule traffic waiting to enter a roundabout on one arm has had to give way to traffic already on the circulating carriageway crossing the entry. Consequently, the entry capacity decreases if the circulating flow increases, since there are then fewer opportunities for waiting drivers to enter the circulation. It is therefore necessary to specify the entry capacity at each level of circulating flow. The dependence of entry capacity on circulating flow is known as the *entry/circulating flow relationship,* and itself depends on the roundabout geometry. The basic task of capacity estimation is to define how this relationship may be predicted from a knowledge of the geometric layout.

In principle, two strategies are possible. The first is to establish a theoretical 'model' of the vehicle-vehicle interactions which are taking place at a roundabout entry, to calculate the entry/circulating flow relationship from this model, and then to calibrate the parameters of this relationship in terms of roundabout geometry. The second is to determine the dependence of the entry/circulating flow relationship on the geometric parameters directly, without recourse to models of vehicle-vehicle interactions.

3.1 Vehicle-vehicle interactions

The entry/circulating flow relationship describes the average effect of the vehicle-vehicle interactions that take place in the region of the entry. In the literature, the only vehicle-vehicle mechanism to have received much attention is gap-acceptance, and a considerable amount of fundamental work has been done[9], relating mainly to major/minor priority junctions, although the principles are similar for roundabouts[10].

The basic gap-acceptance model is this: the circulating flow consists of vehicles which may be subject to certain minimum headway constraints, but are otherwise randomly spaced; gaps occur between groups of one or more circulating vehicles, and vehicles waiting to enter move only into gaps exceeding a certain minimum value. The minimum gap value is often assumed to be fixed, although the more comprehensive theories[11] allow for a frequency distribution of minimum acceptable gaps. Theories of gap-acceptance are intrinsically passive in the sense that circulating traffic is assumed not to react to the presence of entering traffic. In addition the gap-acceptance parameters are assumed to be independent of the magnitude of the circulating flow.

However, at roundabouts, other mechanisms are involved, and the entry process is in reality somewhat more interactive than the gap-acceptance assumptions allow. For example, (i) 'merging' behaviour often takes place especially at high circulating flows, (ii) individual entering vehicles often cause circulating vehicles to slow down and alter their headways, and (iii) there are sometimes short periods of priority reversal in which entering vehicles 'force' their way into the junction and circulating traffic has to wait temporarily until the normal priority is regained. The boundaries between these interactive processes and the simple gap-acceptance mechanism are not very clearly defined. Vehicles always enter gaps, of course, but usually it is difficult to say whether the gaps are naturally occurring or are modified for, or by, the entering vehicle.

The entry capacity is therefore determined by a variety of mechanisms, and although the gap-acceptance mechanism as incorporated in theoretical models is a very important element in vehicle-vehicle interactions, it is unlikely to be a complete and sufficient determinant of the capacity. However, it has provided a useful basis for the development of practical entry capacity models[4,12]. Such models are discussed further in Section 6.4.

A comprehensive vehicle-by-vehicle 'model' of the entry/circulating flow relationship should include all of the various mechanisms, separately identified. But it is not feasible in practice to construct such a model, because of the complexity of (i) separating the mechanisms observationally, (ii) determining their relative importance from site to site, and (iii) relating a parametric description of each to geometric details of layout.

3.2 Empirical methods

The empirical approach is to infer the form of the entry/circulating flow relationship directly from capacity observations. Since the relationship is inverse – as the circulating flow increases, so the entry capacity decreases – the simplest empirical form, a *first order* model, is:

$$Q_e = F - f_c Q_c \qquad \ldots \qquad (1)$$

where Q_e is the entry capacity, Q_c the circulating flow across the entry (see Figure 1, a and b), and F and f_c are positive constants that depend on the geometry of the entry. Gap-acceptance theory predicts a degree of non-linearity, such that the line (see Figure 1b) becomes concave upwards. A *second order* empirical model might therefore be:

$$Q_e = F - f_c Q_c + g Q_c^2$$

where g is another positive constant, and the relationship applies only in the range CD shown in Figure 1b. In principle, a hierarchy of models could be formulated in this way, by successively including terms of higher order in Q_c. The higher powers would only be included if they could be statistically justified by the data.

In order to develop empirical models, observations are made of the entry capacity Q_e and circulating flow Q_c at a number of roundabouts of different geometry. Now, variations in Q_e are associated with variations in Q_c *for a given site (within-site variation)* and with variations in the mean value of Q_c and in the parameters describing the geometric layout *from site to site (between-site variation)*. Apparent non-linearity might in principle be inferred from either type of variation. The second has to be treated with care, however: unless geometric variation is effectively accounted for, it can easily be confused with non-linearity because of correlations which often exist between site-mean values of Q_c and the geometry. The analytic approach is therefore to derive a first order model (linear in Q_c), which includes both within- and between-site variations,in which F and f_c are expressed as functions of the junction geometry, and then to test for residual non-linearity in the data; the higher order terms in Q_c are then included only if they can be statistically justified.

This is the procedure adopted here. In fact it has not been possible to detect any significant non-linearity with respect to Q_c (see Section 6.2).

4. BASIS OF THE PRESENT WORK

There are five major data sources for the present analysis; Table 1 gives details. Four are public road studies, two of conventional and two of offside priority roundabouts, and the fifth is a Track Experiment investigation of offside priority layouts. The results of the latter have been used to guide the analysis, but the raw data have not been included because they are not directly comparable with public road data. In all, the public road studies provide about 11,000 minutes of capacity data from a total of 86 sites, of which 42 are conventional, and 44 offside priority roundabouts. Further details are given in reference 13.

4.1 Geometric characteristics of the sites

Appendix 1 defines the main geometric characteristics employed in this study. They are:

(i) the entry width, e (m),
(ii) the approach road half-width, v (m),
(iii) the equivalent measurements, e′ and v′, for the *previous* entry,
(iv) the circulation width, u (m) at the point of maximum entry deflection,
(v) the average effective length, ℓ (m) (or alternatively ℓ' (m) – see Appendix 1) over which the flare is developed,
(vi) the sharpness of flare, $S = (e-v)/\ell$, (or $S = 1.6(e-v)/\ell'$),
(vii) the entry radius, r (m),
(viii) the angle of entry, ϕ (degrees),
(ix) the inscribed circle diameter, D (m),
(x) the width of the weaving section, w (m),
(xi) the length of the weaving section, L (m).

The sites spanned a wide range of overall size; for example the range achieved in D was from 13.5m to 171.6m. Table 2 lists the ranges of the geometric parameters over all sites.

4.2 Traffic observations

The traffic flows basic to this study are the entry flow under conditions of steady queueing in the approach, Q_e, and the corresponding circulating flow across the entry, Q_c, as in Figure 1a. More detailed flow divisions were employed in some of the data subsets, but they are not relevant here. Most flow counts were measured either on a one-minute or five-minute basis, although some were for intermediate intervals of two, three, or four minutes. In the statistical analysis traffic flow values were weighted directly according to the duration of count to which they corresponded, a flow based on a five-minute count having a weight five times that based on a one-minute count, and so on.

In all counts vehicles were classified as light (3 or 4 wheels) or heavy (more than 4 wheels). Data set (3) employed a third category – two-wheeled vehicles – but this is not used here. The effects of variations in traffic composition on the entry capacity of roundabouts have been assessed previously[1,3,4] on various subsets of the data. *Passenger car units (pcu's)* derived for heavy vehicles both in the entering and circulating flow were close to 2.0 in all cases, and this is the value adopted for the present analysis. Thus in all that follows

$$Q_e = Q_e(l) + 2Q_e(h)$$

$$Q_c = Q_c(l) + 2Q_c(h)$$

where Q_e and Q_c are in pcu's per hour, and $Q_e(l)$, $Q_e(h)$ are the flows in vehicles per hour of light and heavy vehicles in the entry, and $Q_c(l)$, $Q_c(h)$ those in the circulation.

In addition to these observations, records of the number of entry lanes occupied were kept.

5. ANALYTICAL FRAMEWORK AND METHODS

The analysis was based on the linear representation of the entry capacity, equation (1) in Section 3.2:

$$Q_e = F - f_c Q_c$$

where F and f_c are positive constants determined by the geometric characteristics of the entry. The problem is to obtain predictive relationships whereby f_c and F can be calculated from a knowledge of the entry geometry. It is possible to approach the analysis in two ways[2].

The first is to determine F and f_c for each site individually by simple regression of Q_e on Q_c, and then to regress these values separately on the geometric parameters. This results in separately optimised predictive equations which link F and f_c to the site parameters, but does not necessarily correspond to an overall optimum in the final predictive equation for Q_e.

The second is to write F and f_c in equation (1) as explicit functions of geometry, and to regress Q_e on the independent variable terms of the resulting equation (see reference 2). This results in predictive relationships for F and f_c that are jointly optimised such as to produce a minimum in the unexplained variance of Q_e.

Of course, the second achieves the required result – the minimisation of the predictive error in the entry capacity – but it has the disadvantage that all regression tests have to be conducted on the whole data base, which is extensive. It is therefore rather expensive in computer time. In comparison, the first is considerably less expensive to run. In the present analysis, the approach has therefore been to employ the first method for the preliminary testing of a wide range of possible predictive equations, and to submit the more robust and logical of these to the full optimisation procedure of the second method.

6. RESULTS

6.1 The effects of geometric factors

The effects of the geometric factors fall into a distinct hierarchy. The entry width and flare have by far the most important effect; the inscribed circle diameter has a small but important effect; and the angle and radius of entry contribute minor corrections. The remaining parameters have no significant influence.

6.1.1 Entry width and flare. It has been demonstrated previously[3] that for offside priority roundabouts the entry capacity is determined primarily by the number of queues, n, at entry and that this, in turn, is determined by the entry width and flare. For such designs, n, which is an average over time, can be predicted by means of the equation

$$n = a\left\{v + \frac{e-v}{1+CS}\right\} \quad \ldots \quad (2)$$

where v, e, and S are as defined in Section 4.1, and a and C are empirically determined coefficients. The entry capacity is a linear function of n, and the general predictive equation for Q_e in terms of e, v, and S takes the form:

$$Q_e = a_0 + a_1\left\{v + \frac{e-v}{1+CS}\right\} - \left[b_0 + b_1\left\{v + \frac{e-v}{1+CS}\right\}\right]Q_c \quad \ldots \quad (3)$$

ie equation (1) with

$$F = a_0 + a_1\left\{v + \frac{e-v}{1+CS}\right\} = a_0 + a_1x_C \quad \ldots \quad (4)$$

and $$f_c = b_0 + b_1\left\{v + \frac{e-v}{1+CS}\right\} = b_0 + b_1x_C \quad \ldots \quad (5)$$

where $x_C = \left\{v + \frac{e-v}{1+CS}\right\}$.

The results of the present analysis follow the same pattern. The optimum value of C was determined by:

(i) regressing the site specific F and f_c values separately on e, v, and S using equations (4) and (5) for each of a series of trial values of C, and choosing that value of C which gave a maximum in the explained variance of F and f_c respectively;

and

(ii) regressing Q_e on x_C, Q_c, and x_CQ_c using equation (3) with the whole data base, for a series of trial values of C, and choosing that value which gave a maximum in the explained variance, V_e, of Q_e.

(i) indicated an optimum value of 2 for C, and (ii) a value of 2 or 3. In addition equation (2) was used in conjunction with the observed number of queues at entry to obtain a further estimate of the optimum value of C, with the result C = 2; this explained 64.2 per cent of the variance of n. In the region of maximum explained variance (in either Q_e or n) the sensitivity to C is slight and it is not critical which value, 2 or 3, is used. (The choice does affect the values of the coefficients a_1 and b_1, of course.) The value adopted was

C = 2. The regression (ii) above, with C = 2 gives the corresponding values of the coefficients a_0, a_1, b_0, and b_1.

The effectiveness of x_C as a predictive variable compared with either e or v alone can be seen in Figure 2, which shows the dependence of the explained variance V_e on C. The value corresponding to the use of e or v alone is obtained by setting C = 0 and C = ∞ respectively. Thus, with C = 0, 43.7 per cent of the variance of Q_e is explained, and with C = 21 (which is close to the C = ∞ limit for most practical values of S at flared entries) 60.8 per cent is explained. Both figures are significantly less than the 67.2 per cent obtained with C = 2 (ie with x_2). The corresponding results for the prediction of n are 37.1 and 49.8 per cent using respectively e and v alone, and 64.2 per cent using x_2.

The analysis was not very sensitive to changes in the ratio (b_1/b_0), which defines the relative effects of the x_C term and the constant term in the slope, f_c, of the entry/circulating flow relationship: over the range $0.1 \lesssim (b_1/b_0) \lesssim 0.25$, the correlation coefficient between observed and predicted values of Q_e remained approximately constant at 0.82. (b_1/b_0) was therefore fixed at 0.2, a value consistent with previous work[1,3].

The constant term a_0 was consistently small compared to the remaining terms of equation (3), and in terms of explained variance the penalty in applying the constraint $a_0 = 0$ was negligible. The intercept, F, is therefore to a very good approximation proportional to x_2 (= v + (e–v)/(1 + 2S)), and thus to the average number of queues at entry.

The resulting equation for this stage of the analysis was:

$$Q_e = \text{[redacted]} \left\{ v + \frac{e-v}{1+2S} \right\} - \left[\text{[redacted]} \left(1 + 0.2 \left\{ v + \frac{e-v}{1+2S} \right\} \right) \right] Q_c \quad \ldots\ldots\ldots\ldots \quad (6)$$

and this explained 67.2 per cent of the variance of Q_e.

This result may be interpreted as follows. For parallel entries (e = v, and S = 0) and for entries with very gradual flare ($e > v$, $S \simeq 0$) equation (6) reduces to

$$Q_e = \text{[redacted]}\,e - \left[\text{[redacted]} (1 + 0.2e) \right] Q_c,$$

whereas for extremely sharp flares ($e > v$, and S is large), it reduces to

$$Q_e = \text{[redacted]}\,v - \left[\text{[redacted]} (1 + 0.2v) \right] Q_c.$$

These expressions are identical except that in the second, it is the approach road half-width, and not the full entry width that determines the entry capacity. Thus if the flare is gradual, all of the available entry width, e, is used, but if the flare is extremely sharp, traffic uses only the 'basic' width v and ignores the extra width (e–v). For intermediate cases, the extra width is utilised partially, with an *efficiency factor* equal to $(1/(1+2S))$.

6.1.2 Inscribed circle diameter. The inscribed circle diameter, D, acts as a scale factor: its function is to distinguish larger roundabouts of given entry geometry from smaller ones of the same entry geometry. In this function it overlaps somewhat with the traditional distinction between *offside priority* and *conventional* roundabouts, since the former are usually smaller than the latter.

The effect on the entry capacity of increasing D is to decrease the magnitude f_c of the slope of the entry/circulating flow relationship. The effect is illustrated in Figure 3 which shows the relative variation of the slope coefficients $b_0(s)$ calculated on a site-specific basis (and corresponding to b_0 in equation (3)) with D.

Two main groups can be distinguished, corresponding roughly to $D < 50$m and $D > 50$m. These differ significantly in the ratio $b_0(s)/\overline{b_0(s)}$, the overall mean value for the first group being about 40 per cent higher than that for the second. Disaggregation within these two groups, as in Figure 3, does not show any systematic within-group variation, although slight trends within the groups might go unnoticed because of the extent of random variation.

Past work[2] has shown that for offside priority roundabouts of $D \leqslant 70$m increases in D are accompanied by slight increases in the entry capacity, although it was not possible to associate the effect unambiguously with either the slope or the intercept of the entry/circulating flow relationship. For convenience, a small D-dependence of the intercept has previously been used to represent the effect. In the present analysis, using a more extensive data base, the intercept is robustly determined by x_2 alone, and the D-dependence is confined to the slope. In practice, the overall effect of a small reduction in slope with increasing D is similar to that of a small increase in intercept at constant slope, and statistically the effects are difficult to distinguish. It is therefore reasonable to interpret the previously observed D-dependence of the entry capacity for offside priority roundabouts in terms of the slope rather than the intercept. Previous work[1] on conventional roundabouts showed no effect of scale factors: D was not considered directly, but the weaving section length, which also acts as a scale factor, had no detectable effect on the entry capacity. To an extent the division of sites into the categories *'offside priority'* and *'conventional'* implies a division into the two D-groups (although there is a substantial degree of overlap), and the lack of weaving length dependence in reference 1 must correspond in some measure at least to the lack of D-dependence in the second D-group here.

To summarise, there is direct evidence for a difference in slope coefficient between the first and second D-groups, and indirect evidence for a slight trend of reducing coefficients with increasing D in the region of the first group. The slope of the entry/circulating flow relationship for a given entry geometry reflects the degree of interaction between entering and circulating streams, and the trend towards shallower slopes at the larger roundabouts probably corresponds[2] to a greater degree of 'merging' behaviour at entry.

It would be relatively easy to represent these effects by including in the slope a simple linear dependence on D, so that equation (5) took the form

$$f_c = b_0(1 + (b_1/b_0)x_2)(c_0 + c_1 D) \qquad (7)$$

where c_0 and c_1 are coefficients to be determined. Since f_c decreases as D increases, c_1 would be negative. However, this representation retains a D-dependence at high values of D, for which there is no evidence. Moreover, it is unsafe in design terms since it implies an indefinite decrease in f_c with increasing D, and this would lead to unrealistically high predictions of the entry capacity at very large roundabouts with high circulating flows. Simple negative exponential functions are well-behaved at high values of D, but are too sensitive to changes in D for lower values.

A logistic curve of the form shown in Figure 3 has therefore been employed: in place of the multiplying factor $(c_0 + c_1 D)$ of equation (7), a factor of the form $\{d_0 + d_1/(1 + \exp(D - d_2)/d_3)\}$ has been used. d_0, d_1, d_2, and d_3 are coefficients to be determined; d_0 specifies the level, d_1 the 'amplitude' of the change in f_c from low to high values of D, d_2 the 'central' value of D, and d_3 the range of values of D over which the change takes place. A curve of this form ensures that the slope behaves correctly at the extreme values of D.

Now, Figure 3 relates to site-specific coefficients, and does not contain the appropriate statistical weighting required to optimise the entry capacity; it is used here for illustrative purposes only. The effects of D on Q_e have really to be determined from the complete data base. Accordingly, equation (3) is rewritten to incorporate the D-dependence of the logistic curve in the slope:

$$Q_e = a_0 + a_1 x_2 - \left[b_0 (1 + 0.2x_2) \{ d_0 + d_1/(1 + \exp(D - d_2)/d_3) \} \right] Q_c.$$

(The constraint $(b_0/b_1) = 0.2$ is retained.) This is equivalent to:

$$Q_e = a_0 + a_1 x_2 - \left[e_0 (1 + 0.2x_2) \{ 1 + e_1/(1 + \exp(D - d_2)/d_3) \} \right] Q_c \qquad \ldots\ldots (8)$$

where $e_0 = b_0 d_0$, and $e_1 = d_1/d_0$.

The coefficients a_0, a_1, e_0, and e_1 were determined by regressing Q_e on the independent variable terms of equation (8) for several combinations of assumed values for d_2 and d_3. The number of such combinations is in practice restricted, and the proportion of the variance of Q_e explained is not very sensitive to which combination is used. The values adopted were d_2 = 60m and d_3 = 10m, which give a curve of the same shape as that shown in Figure 3, corresponding to a smooth progression approximately from mid-point to mid-point of the two groups. As before, a_0 was close to zero and could be omitted without significant loss. The result was:

$Q_e =$ [redacted] $x_2 - [$ [redacted] $(1 + 0.2x_2)\{1 + 0.500/(1 + \exp((D - 60)/10))\}]Q_c$ . . . . (9)

This explained 70.6 per cent of the variance of Q_e, an increase of 3.4 per cent on the 67.2 per cent explained by equation (6). In this region, changes in explained variance of $\sim$ 1 per cent are significant at the 95 per cent confidence limit, and this increase is extremely significant.

Because the parameter D is loosely associated with the division of roundabouts into the categories *offside priority* and *conventional*, it is possible to arrive at an alternative description whereby the constant term b_0 of equation (5) is allowed to take a different value for each category, and D is omitted from the description. In this sense, the category distinction becomes a proxy for D. However, this approach is unsatisfactory in two respects. Firstly there is no geometric descriptor apart from D that both distinguishes between offside priority and conventional roundabouts and also accounts for a significant proportion of the variance of Q_e. Thus, although it is possible to recognise visually examples of the two categories, there is nothing to suggest that from a capacity viewpoint anything but overall size is important (for a given entry geometry). Secondly the use of a dummy variable alone to distinguish the categories results in an increase in the explained variance of Q_e of only 1.7 per cent above that achieved by equation (6), significantly less than the 3.4 per cent increase corresponding to the use of D. It is not therefore very effective to use the category distinction as a proxy for D (even if it were desirable), presumably because of the degree of overlap in D between the categories.

In view of this, the distinction between offside priority and conventional roundabouts is unnecessary for capacity purposes.

6.1.3 Entry angle and radius. The entry angle ϕ and radius r (see Appendix 1) have slight modifying effects on the entry capacity. Because the effects are relatively small, they are most conveniently represented as simple 'percentage' corrections to the capacities predicted by equation (9) above.

Observed Q_e values were therefore regressed against the product of the predicted capacities and a term of the form $(g_0 + g_1\phi + g_2(1/r))$, where g_0, g_1, and g_2 are coefficients to be determined. r was included in reciprocal form since values of $r = \infty$, corresponding to straight kerb-lines at entry, are not uncommon, whereas values of zero are never used; moreover, the sensitivity to changes in r should be greatest when r is small. The result was:

Q_e = ([redacted] – [redacted] ϕ – [redacted] (1/r)) $\{F - f_c Q_c\}$ . . . . (10)

where the intercept F and slope f_c are as in equation (9). This explained 72.9 per cent of the variance of Q_e, a significant increase of 2.3 per cent over that explained by equation (9).

Previously ϕ has not been investigated in detail, although Track Experiment results[2] have indicated an association between entry angle and capacity, in the same sense as that detected here. This association was previously described by a change in the intercept alone, whereas in the present representation changes in both slope and intercept are in the same proportion. This reflects a deliberate choice of representation since it is safer for design purposes to treat minor corrections as simple percentages of the entry capacity, and so avoid the possibility of producing what appear to be very large percentage increases in capacity at the high circulating flow end of the entry capacity line as a result of minor geometric adjustments.

Similar considerations apply to r. Significant effects associated with r were detected previously for conventional roundabouts[1], but described by changes in the intercept alone. For offside priority roundabouts[3] no effect was detected, although in view of the present sensitivity to r, that is not a surprising result: r is a very minor factor. Again the present policy has been to adopt the simple percentage description as leading to a conservative design strategy.

6.1.4 Other geometric factors. Apart from those factors dealt with in Sections 6.1.1–6.1.3 above, no other geometric factor had a significant influence on the entry capacity. The more notable of those investigated were the circulation widths (u and w), see Appendix 1. Previous work showed a slight dependence of the intercept of the entry capacity relationship on u for offside priority roundabouts, and of the slope on w for conventional roundabouts, but there is no equivalent dependence in the present more extensive data base. In practice both parameters are subject to fairly restrictive design constraints[14]. Provided that these constraints are retained, the present result indicates that u and w need not enter into capacity prediction.

6.2 Linearity

The predictive equations of Section 6.1 are linear in the circulating flow. In previous work it has not been possible to demonstrate any degree of non-linearity. For example, in the Track Experiment described in reference 2 there was no measurable deviation from linearity in any test, and straight-line fits accounted for more than 90 per cent of the variance of Q_e in most tests, with no systematic trend in the residual 10 per cent or so.

The present analysis yields similar results. The problem is slightly more complicated for public road sites, where the variability of entry capacity measurements for a given site (equivalent in a Track Experiment to a single geometric variation) is rather higher than on the Test Track. The conclusion that there is no evidence for non-linearity in the data for sites considered separately might not then be sufficient in itself, since *between-sites variation* might, after geometric differences had been accounted for, provide evidence for residual non-linearity.

The form of non-linearity sought is simple. As in Figure 1b, if non-linearity is present it should result in a curve of the form of line CD, concave upwards and with no oscillatory behaviour. It is easiest to represent such a trend by means of a parabolic correction term in the entry capacity:

$$Q_e = Q_e(p) + (A + BQ_c + CQ_c^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

where $Q_e(p)$ is the capacity predicted by the linear representation, and A, B,and C are coefficients defining the parabolic term, and are determined by regression analysis. Formally, equation (11) corresponds to a *second order* empirical model as defined in Section 3.2.

However, the inclusion of such a parabolic term does not contribute significantly to the explained variance of the entry capacity. The result obtained, that A = +[redacted]pcu/h, B = –[redacted], and C = +[redacted](pcu/h)$^{-1}$, contributes a non-significant 0.6 per cent to the explained variance of Q_e, and the parabolic term has a very low value over the range of circulating flow.

The point is further illustrated by examining the residuals left by the linear representation. Figure 4 shows the means of residuals within successive 300 pcu/h bands of circulating flow. Simple non-linearity would result in a trend from positive values of the mean residuals at low Q_c to negative values at intermediate Q_c, and to positive values again at high Q_c. But the results shown do not justify such a conclusion.

Apart from gap-acceptance considerations, non-linearity might in principle arise from the fact that in practice it is difficult to suppress the entry flow entirely, even when the circulating flow is very large. As Q_c increases the entry/circulating flow line is likely ultimately to become horizontal at some small but finite value of Q_e. The present analysis suggests that the operation of roundabouts on the public roads does not normally reach this region. From the design point of view it would be highly undesirable for roundabouts to be designed to operate in such a manner. The linear entry/circulating flow relationship will ensure that designs are conservative for abnormally high values of circulating flow.

6.3 Precision

Uncertainties of prediction arise from two sources: unexplained within-sites variation and unexplained between-sites variation. The first is a property of the sampling technique used in the capacity determination for each site. In principle, the entry/circulating flow relationship for a particular site can be determined with arbitrarily narrow confidence limits simply by making a very large number of capacity observations, but the cost in resources has to be balanced against the improved accuracy. For models based on pooled data from many sites, the effect of this type of variation on the accuracy of prediction of the mean capacity value (at a given value of Q_c) for a single site is very small (of the order of a few pcu/h).

The main uncertainties of prediction arise from unexplained between-sites variation, which does not depend on the sample size at individual sites. In the present work it gives rise to a standard error with respect to the population of at-grade roundabouts (ie the standard error of the mean) of about $25\ (1 +$ [redacted] $(Q_e(p) - 1300)^2)^{1/2}$ pcu/h, where $Q_e(p)$ is the predicted capacity value. For single-site prediction a further component of variation arises in the usual way from the distribution of individual site-mean values about the population mean. The resulting standard error of prediction for a typical site (for which Q_e = 1300 pcu/h or so) is about 200 pcu/h – about 15 per cent of the entry capacity.

6.4 Comparison with previous work

The present results apply to both conventional and offside priority roundabouts and supersede the previously separate treatments of references 1 and 3. In the present approach, there is no distinction between offside priority and conventional roundabouts except that implied by size alone. In most cases the capacity predictions agree closely with those calculated according to the previous treatments, except that there previously existed a range of sizes around $50 < D < 70$ where the need to distinguish between the categories *offside priority* and *conventional* gave rise to differences in the predicted capacities. (In this region of overlap both previous representations were near the extremes of their own ranges of applicability.) These differences are now removed.

Apart from the TRRL work described in references 1 and 3, roundabout entry capacity models have also been developed by Ashworth and Laurence[4], and by McDonald and Armitage[12]. The data base used by Ashworth and Laurence is a subset of the data used here, and concerns conventional roundabouts. McDonald and Armitage do not distinguish between roundabout types. Both models are based on the theory of gap acceptance, and direct functional comparison with the present work is not strictly possible. However, the main features of the results can be compared.

Bearing in mind the differences in model structure, there is a good measure of agreement between both gap-acceptance based models and the present work. In each, the entry width plays the predominant role. Ashworth and Laurence ascribe no variation to any other parameter, although recently[15] they have suggested a method for including the effects of entry flare in their model, in order to extend the descriptive framework to offside priority roundabouts. The sensitivity of the entry capacity to changes in the entry width is approximately the same in Ashworth and Laurence's model and the present work, and slightly greater in McDonald and Armitage's model.

Otherwise, the main differences are these. Firstly, being based on gap-acceptance theory the models of Ashworth and Laurence, and McDonald and Armitage are non-linear, although this does not in itself have a very pronounced effect on the capacity estimates. Secondly, the rate of decrease of the entry capacity with circulating flow in McDonald and Armitage's model (equivalent in the linear representation to f_c) is influenced by the geometry of the *previous* entry, whereas in Ashworth and Laurence's model it is influenced by the entry width alone, and in the present work mainly by the entry width, but also by the inscribed circle diameter, D. The question of linearity is discussed in Section 6.2; in practical terms it is unlikely to be very important. The second aspect may also be less significant than it appears at first sight. The geometry of entries in general is not independent of D – large roundabouts tend to have wider entries than small roundabouts, so large values of D are usually associated with large values of e′ and v′ (the entry width and approach half-width for the previous entry). McDonald and Armitage's model predicts a reduced sensitivity of the entry capacity to increases in the circulating flow as e′ and v′ increase, just as f_c decreases with increasing D in the present description. The two descriptions are therefore to some degree complementary, but the mechanisms proposed for the change in sensitivity are different: McDonald and Armitage attribute it to changes in the headway distribution within the circulating flow, whereas here it is believed to arise from a trend towards merging behaviour at the larger conventional roundabouts. Both mechanisms have been discussed previously in reference 2.

7. APPLICATIONS

7.1 Entry capacity prediction

Equation (10) can be rearranged somewhat for convenience of use as a design equation. It is useful to emphasise the entry width parameter $x_2 = v + (e-v)/(1+2S)$, since it is the primary determinant of the entry capacity relationship. A tabular approach is therefore suggested here to represent the effects of D, ϕ, and r, leaving x_2 as the only explicit geometric parameter in the design equation.

7.1.1 The term in D. Table 3 lists values of the term in D of equation (9),

$$t_D = 1 + 0.5/(1 + \exp((D - 60)/10))$$

In addition, Figure 5 shows a plot of the function.

7.1.2 Nominal values of the correction parameters, ϕ and r. It is convenient to rewrite equation (10) such that the correction factors are expressed in terms of deviations about *nominal* values, ϕ_n, r_n. Appropriate values are $\phi_n = 30^o$ and $r_n = 20m$ ($(1/r_n) = 0.05m^{-1}$), which are close to the average values for the present data set, and are fairly central values for public road sites in general. Using these values, equation (10) can be rewritten:

$Q_e = \{1 -$ [redacted] $(\phi - 30) -$ [redacted] $((1/r) - 0.05)\}[F - f_cQ_c]$ . . . . . . (12)

Thus, for typical sites (ie those for which $\phi \simeq 30^o$ and $r \simeq 20m$), the correction terms vanish, and it is only when ϕ or r deviate from the nominal values that correction must be applied. Such corrections are listed as percentages of the entry capacity in Table 4.

7.1.3 Predictive equation. The predictive equation for the entry capacity is now

$Q_e =$ [redacted] $x_2 -$ [redacted] $t_D(1 +$ [redacted] $x_2)Q_c$ . . . . (13)

where $x_2 = v + (e-v)/(1+2S)$ as before. This equation applies to sites which have approximately the nominal ϕ and r values. For those which do not, the corrections of Table 4 should be applied. (It should be noted that equation (13) and all other expressions for absolute capacity prediction given here apply so long as the right-hand side is positive or zero. Negative values (corresponding to $f_c Q_c > F$) indicate a capacity, Q_e, of zero. Thus in Figure 1 the capacity is on the line AB for points to the left of B and zero for those to the right.)

Figures 6, 7 and 8 illustrate the dependence of the entry capacity on the various geometric parameters according to equation (13).

7.2 Design strategy

By far the most important factors determining the capacity of an entry are the entry width e and flare S, whose effects are represented by the parameter x_2. Now, a given value of x_2 can potentially derive from entries of different shape. For example, a small value of excess width (e–v) might be associated with a gradual flare (of long ℓ and therefore small S), and lead to the same capacity as a larger excess width coupled with a more severe flare. Which is the more appropriate will depend on site constraints. The percentage efficiency of use of excess width, $100/(1+2S)$, is shown as a function of sharpness of flare, S, in Figure 9; the most effective range of S is clearly $0 \leqslant S \leqslant 1$, since for $S > 1$ the efficiency falls below about 33 per cent. However, at large values of S (sharp flares), extra width is relatively easily achieved, and in cases where more gradual flares are not possible, significant, if not large, contributions can still be made by this extra width.

Now, $S = (e-v)/\ell$ (or $1.6(e-v)/\ell'$), and v is fixed by the approach road geometry, so in design terms the value of x_2 is determined by a choice of e and ℓ, (or ℓ') which are therefore the primary design parameters. (For design purposes ℓ' is preferable to ℓ: see Appendix 1.) It would be wrong to use D, ϕ, or r, whose effects are relatively much less important, to 'adjust' the capacity of an entry.

For new roundabout designs the approach should be to select for each entry in turn a value for ℓ' to give a reasonably efficient flare consistent with land-take and other site constraints, and a value for e to provide approximately the required entry capacity. A minimum value for D should be adopted that is consistent with the resulting set of entry widths and flares. A set of ϕ and r values should then be established. ϕ will in general be affected by constraints arising from the alignment of the approach roads, although as far as possible the aim should be to achieve smaller rather than larger values. The choice of r is more a matter of detailed design; provided that all other requirements have been satisfied, it should be set at a reasonably large value if that is possible. For smaller designs, of course, low values will be unavoidable. The entry capacities can then be calculated in detail using equation (13). Some iteration in the process will be necessary. Appendix 3 sets out the procedure on a step by step basis.

This strategy will in general result in the most efficient use of land resources for a given traffic handling requirement. A computer program currently available predicts the performance of geometrically specified layouts for a range of traffic demand conditions (see Section 7.4), and can be used as an aid to the design process. In future development it is intended to incorporate routines allowing *geometric optimisation* for a given traffic requirement, so that the procedure outlined above and detailed in Appendix 3 can be performed automatically. Such optimisation routines will generate the layout giving minimum overall traffic delay within specified design constraints (for example, turning paths for heavy goods vehicles, and vehicle path deflection criteria for safety).

7.3 The appraisal of existing sites

7.3.1 Corrections for local conditions. For some purposes it is useful to complement the predictions of equation (13) by local traffic observations. The advantages of such an approach over the direct application of equation (13) consist mainly in narrowing the confidence limits of prediction by eliminating the unexplained between-site variation implicit in the equation. For example, for some traffic engineering problems (eg queue length prediction), it is clearly preferable to have a locally-corrected capacity relationship for those junctions that operate consistently at or near capacity in peak periods.

When traffic demand is sufficiently high to cause persistent queueing on one or more approaches to a roundabout, it is possible to make direct capacity measurements, and these can be used to correct the capacity calculated from equation (13) to local conditions. However, it should be emphasised that the measurements must be reliable and well-defined, and above all must correspond to periods of continuous saturation; the inclusion of periods of incomplete saturation, where queueing becomes fragmented, even if only slightly, will lead to significant errors.

It is not suggested that the full entry/circulating flow relationship is investigated: the quality of such investigations depends on a number of factors, and for statistical reasons it is not straightforward to infer the appropriate corrections to the general predictions of equation (13). Instead a simple correction should be made to the intercept; the procedure is specified in Appendix 2. It will in general only be possible to apply intercept correction if the existing site is heavily overloaded on the relevant arm.

7.3.2 Differential prediction: the effects of changes to existing layouts. The design strategy of Section 7.2 applies primarily to new sites. In cases of existing junctions, where modification is necessary to increase the capacity, similar considerations apply, although in general site constraints will be more severe. Equation (13) can be used to predict the effects of detailed changes in any of the parameters, but it is again important to recognise the relative sensitivity of the entry capacity to changes in the respective parameters: entry width and flare have by far the largest effect and it would be wrong to look for significant increases in capacity from changes in anything but e and ℓ.

Equation (13) can be used in two ways. Used as in Section 7.2 it predicts *absolute* capacity values; but with existing sites it can, if required, also be used in a differential mode. Thus if an entry has a known average circulating flow Q_c the predicted effect of an increase in entry width from e_1 to e_2 (and a corresponding change of ℓ from ℓ_1 to ℓ_2) is a change ΔQ_e in the capacity:

$$\Delta Q_e = \left\{ \left(\frac{e_2 - v}{1 + 2S_2} \right) - \left(\frac{e_1 - v}{1 + 2S_1} \right) \right\}$$ ([redacted] – [redacted] $t_D Q_c$) . . . . (14)

where S_1 and S_2 are the initial and final values of the sharpness of flare:

$$S_1 = (e_1 - v)/\ell_1 \qquad (= 1.6(e_1 - v)/\ell'_1)$$

$$S_2 = (e_2 - v)/\ell_2 \qquad (= 1.6(e_2 - v)/\ell'_2).$$

ΔQ_e is subject to the same corrections as Q_e, ie if ϕ and r deviate from the nominal values, 30^o and 20m, the percentage-corrections of Table 4 should be applied to ΔQ_e.

The change in capacity calculated by equation (14) has, of course, to be referred to some datum; for example, if the local capacity Q_e^{ℓ} has been established by means of the procedure of Appendix 2, the new capacity will be $(Q_e^{\ell} + \Delta Q_e)$. When ΔQ_e is substantially less than Q_e^{ℓ}, as is often the case, the confidence interval associated with this prediction method is likely to be narrower than that associated with the application of equation (13) in an absolute sense to the modified layout.

7.4 The balance between entry capacities at saturated roundabouts

The present capacity formula treats individual roundabout entries separately. However, since the capacity of an entry depends on the circulating flow Q_c across it and this originates from previous entries, the balance of flows in the roundabout as a whole is in some circumstances interactive. There are two extreme cases.

(i) If all entries are saturated the entry capacities become completely interactive: the magnitude of the circulating flow across one entry depends on the inflows from previous entries and these are determined entirely by their capacities. So each entry flow in turn depends on the traffic discharge from the remaining entries. Given the entry/circulating flow relationship and the turning movements for each entry, the balance of inflows for the whole roundabout can be calculated by methods first formulated by Maycock[16].

(ii) If no entry is saturated the circulating flow across each entry is compounded simply from the demand flows from previous entries in accordance with the turning movements of the traffic. Consequently changes in the demand flow at one entry are not accompanied by changes in the inflows at other entries. (Of course, such changes do cause small changes in the queueing delay at other entries[17], but the queues formed in these circumstances are very short, so that the net inflows evaluated over even relatively brief counting intervals – five minutes, for example – are virtually unaffected.) This is the usual case for new designs and lightly or moderately loaded existing roundabouts. The design strategy of Section 7.2 is based on this type of operation.

Between these extremes there is a variety of mixed cases, corresponding to saturation at one or more, but not all, entries. A computer program has been written to enable calculations to be performed automatically for any case, and is described elsewhere[18,19,20]. It employs equation (13) to calculate the entry/circulating flow relationship for each entry, given the entry geometries. Delays and queue lengths are also predicted arm by arm.

Generally, the traffic interactions in the region of a saturated entry give rise to correlated fluctuations between entry and exit flows. The topic has little practical importance, although it can give rise to confusions of interpretation. It is sometimes suggested, for example, that the relationship between exit and entry flows is causal. Appendix 4 considers the problem in detail and shows that this is not so.

7.5 Pedestrian activity

It is fairly common, particularly in urban areas, to site pedestrian crossings (usually 'Zebras') close to a roundabout entry. This influences the entry capacity to some degree. Some work has been done to determine the interactions between such a crossing and the roundabout entry, and will allow the effects of pedestrian activity to be estimated. Preliminary results will be made available shortly. If the vehicular capacity of the crossing exceeds that of the entry, it will be possible to calculate the percentage reduction in capacity caused by the crossing as a function of its distance from the give-way line. This distance can be adjusted somewhat, along with the geometric parameters determining the entry capacity, so as to provide the required overall capacity. If the vehicular capacity of the crossing is less than that of the entry, adjustments to the entry alone will have little effect, and it will be necessary to provide an improved pedestrian facility. The problem of vehicles queueing back from the crossing on the exit side of the junction, and so blocking the roundabout, has not yet been explicitly studied, but current work on delays at Zebra crossings should enable this problem to be assessed.

7.6 Other aspects of roundabout design

7.6.1 General. This report is concerned with capacity prediction. In the overall design process, however, a number of other factors have to be taken into account. Some are geometric and so interact with the capacity calculations; they act as constraints and determine which combinations of the 'capacity' parameters (e, v, ℓ', D, ϕ, and r) are acceptable. Examples are:

- standards of visibility, circulation width, and corner radius
- space requirements for turning vehicles
- deflection criteria for vehicle paths (see Section 7.6.2)
- central island design

Other, non-geometric, aspects – such as lighting provision, the use of signs, markings, and road 'furniture', and aesthetic considerations – do not enter directly into capacity calculations, but still contribute to the overall effectiveness or 'level of service' of the layout. The principles of good design with respect to these matters are set out in Departmental Standards (currently reference 14).

7.6.2 Safety. Accident rates at different types of roundabout are currently being studied. It is hoped to relate these rates to traffic flow and geometric design, possibly by accident category. An earlier study[21] of sites converted from 'conventional' roundabouts to 'small-island' designs suggested that the average accident rate (for all personal injury accidents) approximately doubled on conversion. However, many of the small-island designs included in the study did not conform to the deflection criterion now incorporated in Departmental Standards. Preliminary results from the current studies suggest that the more recent small-island designs – at least those constructed in areas where the speed limit is 50 miles per hour or more – are little different in accident terms from conventional designs. Roundabouts are probably the safest form of at-grade junction available to traffic engineers, and the accident studies now in progress should help to determine whether the modification of current design principles would lead to even safer layouts. It is perhaps worth pointing out in this connection that, whereas the capacity assessment procedures are specific to particular sites, it is extremely unlikely that it will ever be possible to predict a site-specific accident rate with any degree of confidence.

8. SUMMARY

The development of a unified formula for predicting the capacity of roundabout entries has been described. The most important factors influencing the capacity are the entry width and flare. The inscribed circle diameter, used as a simple measure of overall size, is more effective as a predictive variable than the category distinction between offside priority and conventional roundabouts, and for capacity prediction there is no need to retain this distinction. The angle of entry and the entry radius have small but significant effects on the entry capacity.

The best predictive equation was:

$$Q_e = k(F - f_c Q_c) \qquad \text{when } f_c Q_c \leqslant F$$
$$= 0 \qquad \text{when } f_c Q_c > F$$

where

k = $1 -$ [redacted] $(\phi - 30) -$ [redacted] $((^1/_r) - 0.05)$,

F = [redacted] x_2,

f_c = [redacted] $t_D(1 + 0.2x_2)$,

$t_D = 1 + 0.5/(1 + \exp((D - 60)/10))$,

$x_2 = v + (e-v)/(1 + 2S)$,

$S = (e-v)/\ell \;\; (= 1.6(e-v)/\ell')$,

and e, v, ℓ, ℓ', D, and r are in metres, ϕ in degrees, and Q_e and Q_c in pcu/h. The ranges of the geometric parameters in the data base were

e	:	3.6–16.5	(m)
v	:	1.9–12.5	(m)
ℓ, ℓ'	:	1 – ∞	(m)
S	:	0–2.9	
D	:	13.5–171.6	(m)
ϕ	:	0–77	(^{o})
r	:	3.4–∞	(m)

The primary elements of design are e and ℓ (or ℓ'). A simplified form of the predictive equation has been developed using tabulations for the effects of D, ϕ, and r.

Methods have been described which allow: (i) the predictive equation to be corrected to take account of local operating conditions at overloaded existing sites, and (ii) the equation to be used specifically to predict the effects of changes to the entry geometry of existing sites. The implications of the flow interactions arising from the operation of more than one entry at capacity have been briefly outlined.

The present results apply to all roundabout types except those at grade-separated interchanges. A further report, based on the present work but taking account of slight differences of operation, will describe capacity prediction methods for these layouts.

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TABLE 1

Data sources

Data set number	Data source	Roundabout type	Number of sites	Reference
1	Public road study: Freeman Fox and Associates/ University of Sheffield/TRRL	Conventional	21	1, 4
2	Public road study: University of Sheffield/TRRL	Conventional	21	4, 5
3	Public road study: Halcrow Fox and Associates/ TRRL	Offside priority	28	3
4	Test track study: TRRL	Offside priority	35 geometric variations	2
5	Public road study: University of Sheffield/TRRL	Offside priority	16	5

TABLE 2

Ranges of geometric variables

Variable	Range	Variable	Range
e	3.6–16.5 (m)	S	0 – 2.9
v	1.9–12.5 (m)	r	3.4– ∞ (m)
e′	3.6–15.0 (m)	ϕ	0 – 77 (°)
v′	2.9–12.5 (m)	D	13.5–171.6 (m)
u	4.9–22.7 (m)	w	7.0– 26.0 (m)
ℓ,ℓ′	1 – ∞ (m)	L	9.0– 86.0 (m)

TABLE 3

The term $t_D = 1 + 0.5/(1 + \exp((D-60)/10))$ listed for various values of D

D	t_D	D	t_D
10	1.4967	75	1.0912
15	1.4945	80	1.0596
20	1.4910	85	1.0379
25	1.4853	90	1.0237
30	1.4763	95	1.0147
35	1.4621	100	1.0090
40	1.4404	110	1.0033
45	1.4088	120	1.0012
50	1.3655	130	1.0005
55	1.3112	140	1.0002
60	1.2500	150	1.0001
65	1.1888	160	1.0000
70	1.1345		

TABLE 4

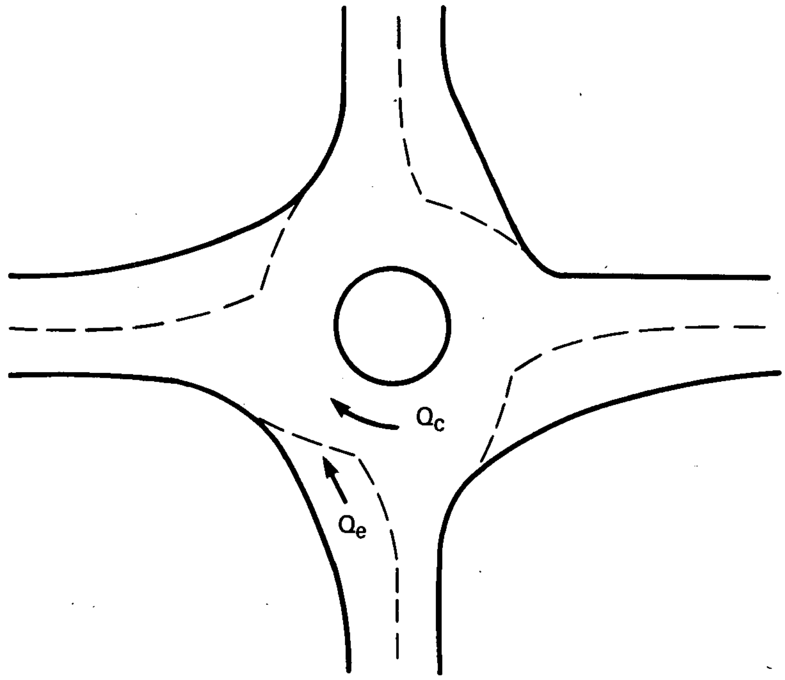
Corrections for deviations of the entry angle ϕ and radius r from their nominal values

(i) Entry angle ϕ

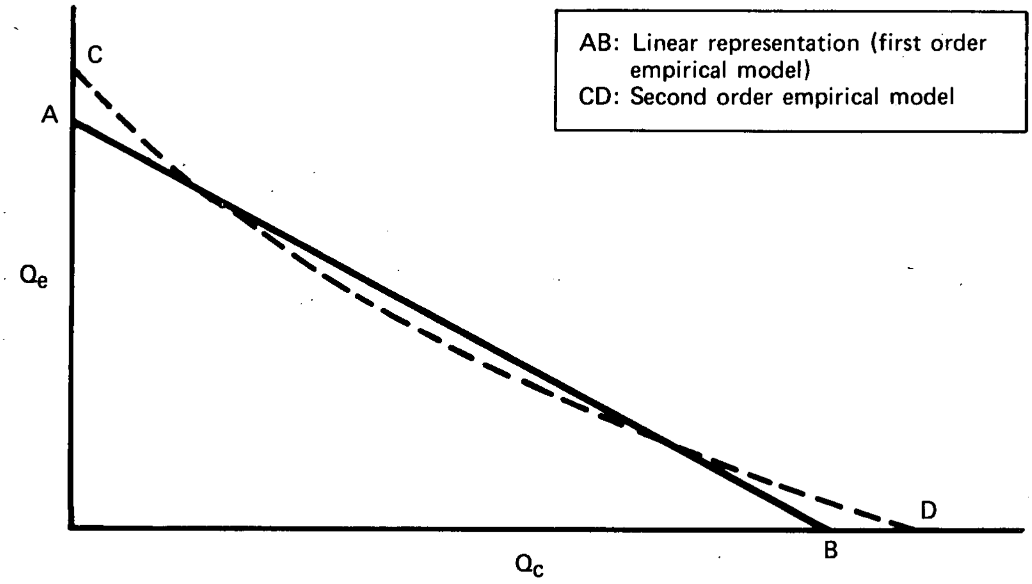
ϕ (°)	Correction (per cent of Q_e)	ϕ	Correction
0	[redacted]	40	[redacted]
5		45	
10		50	
15		55	
20		60	
25		65	
30		70	
35		75	

(ii) Entry radius, r

r (m)	Correction (per cent of Q_e)	r	Correction
4	[redacted]	20	[redacted]
5		22	
6		24	
7		26	
8		28	
9		30	
10		35	
12		40	
14		50	
16		100	
18		∞	



(a) TRAFFIC FLOWS AT ONE ENTRY



(b) ENTRY/CIRCULATING FLOW RELATIONSHIP

Fig. 1 ENTRY CAPACITY, Q_e, AND CIRCULATING FLOW, Q_c, AT A ROUNDABOUT ENTRY

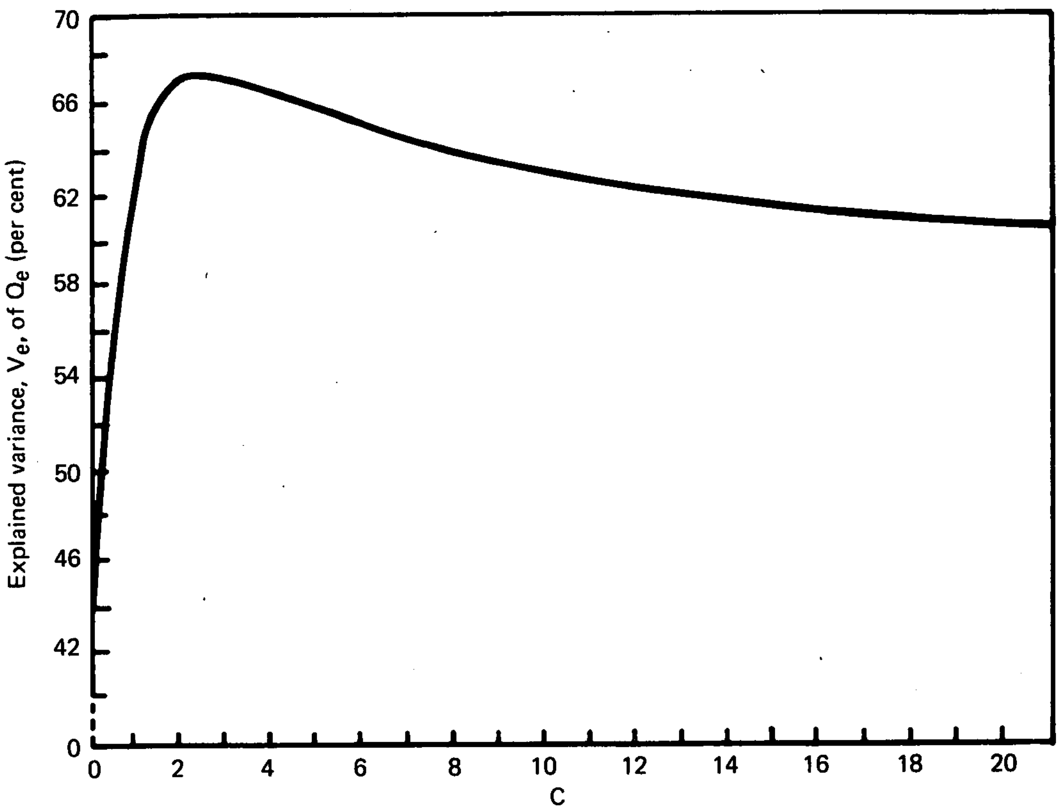


Fig. 2 THE DEPENDENCE OF THE PERCENTAGE OF TOTAL VARIANCE OF Q_e EXPLAINED BY EQUATION (3) ON THE COEFFICIENT C

$\overline{b_0(s)}$ is the mean value of $b_0(s)$ over all sites. One value of the ratio $b_0(s)/\overline{b_0(s)}$ is obtained for each site. Ratios have been banded according to the D-values of the sites: solid circles represent the means in each band and vertical bars the 95 per cent confidence limits of the means. The broken line shows the form of the logistic curve $a + b/(1 + \exp((D-60)/10))$; the coefficients a and b have to be determined against the full data base.

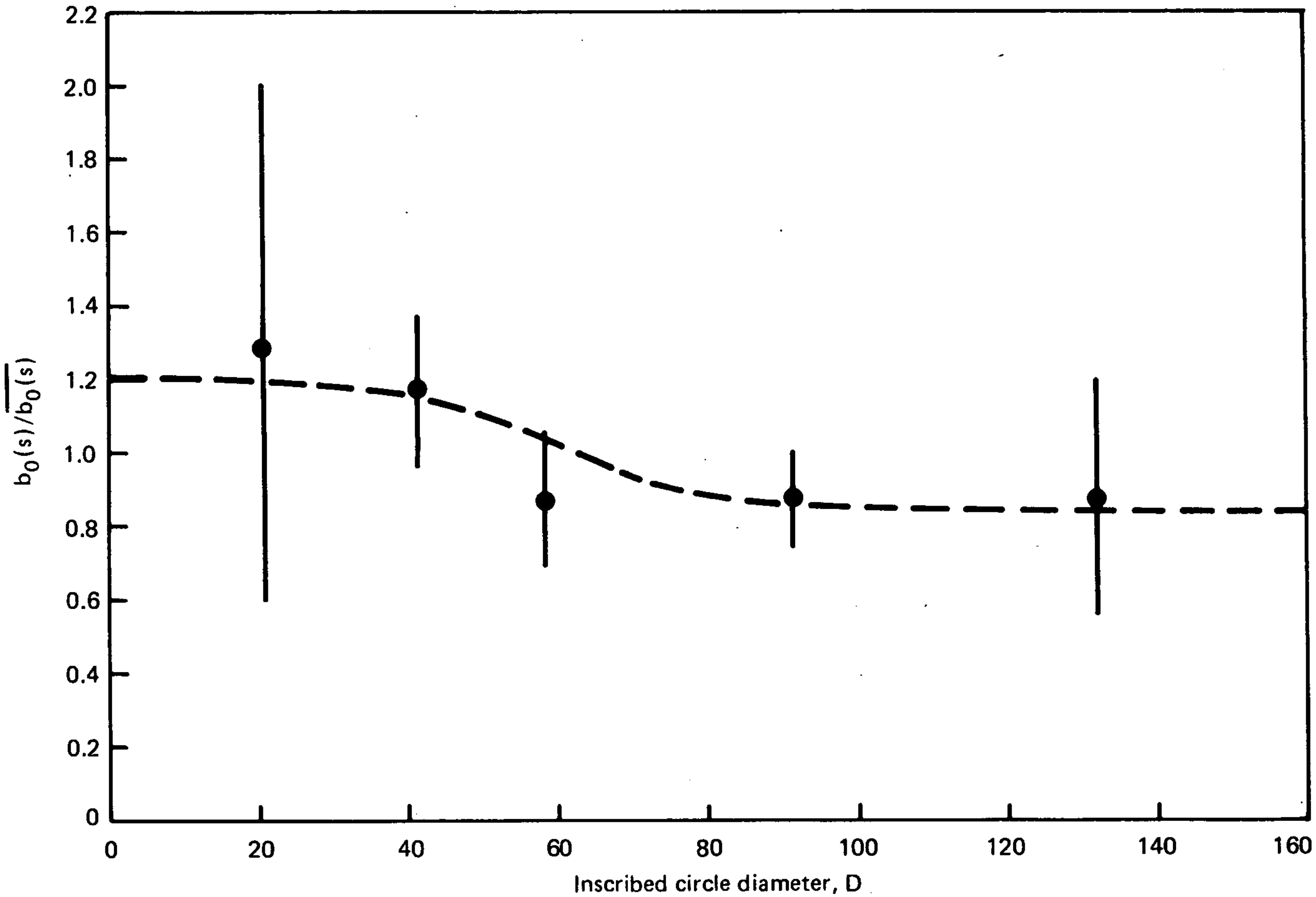


Fig. 3 RELATIVE VARIATION OF SITE–SPECIFIC SLOPE COEFFICIENTS WITH INSCRIBED CIRCLE DIAMETER

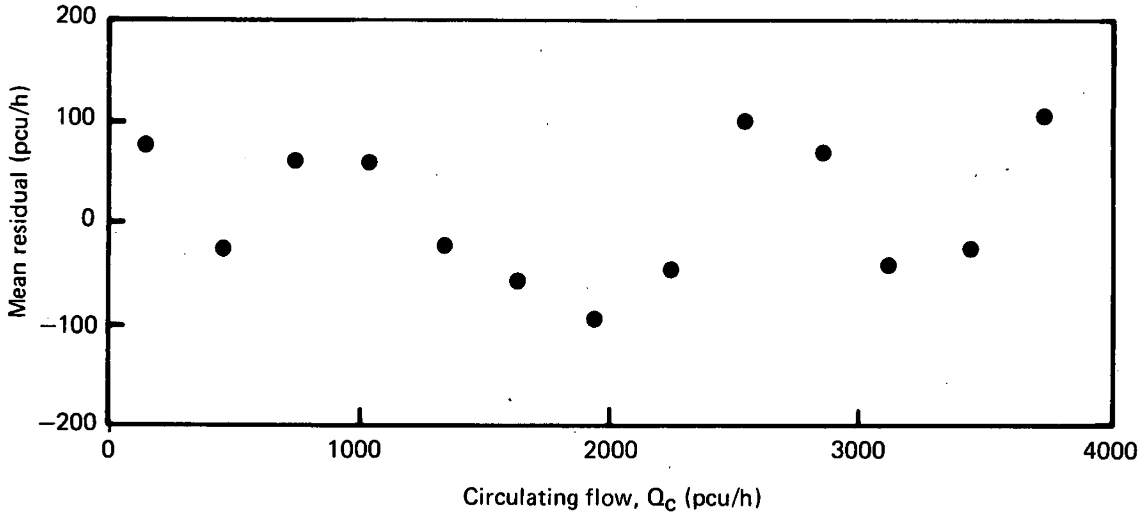


Fig. 4 MEAN VALUES OF THE RESIDUALS IN ENTRY CAPACITY Q_e LEFT BY THE LINEAR REPRESENTATION IN SUCCESSIVE 300 pcu/h BANDS OF THE CIRCULATING FLOW Q_e

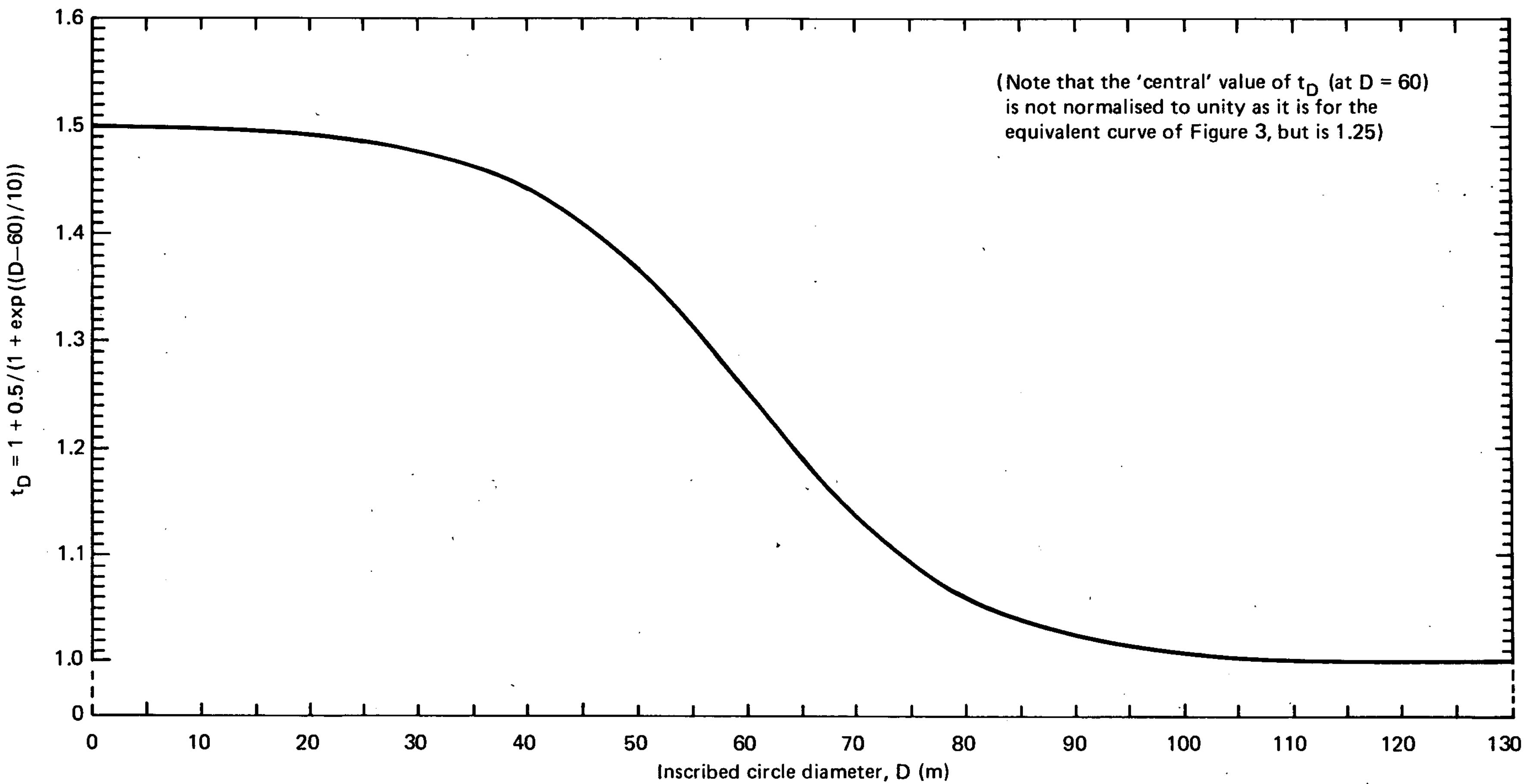


Fig. 5 THE TERM t_D AS A FUNCTION OF D

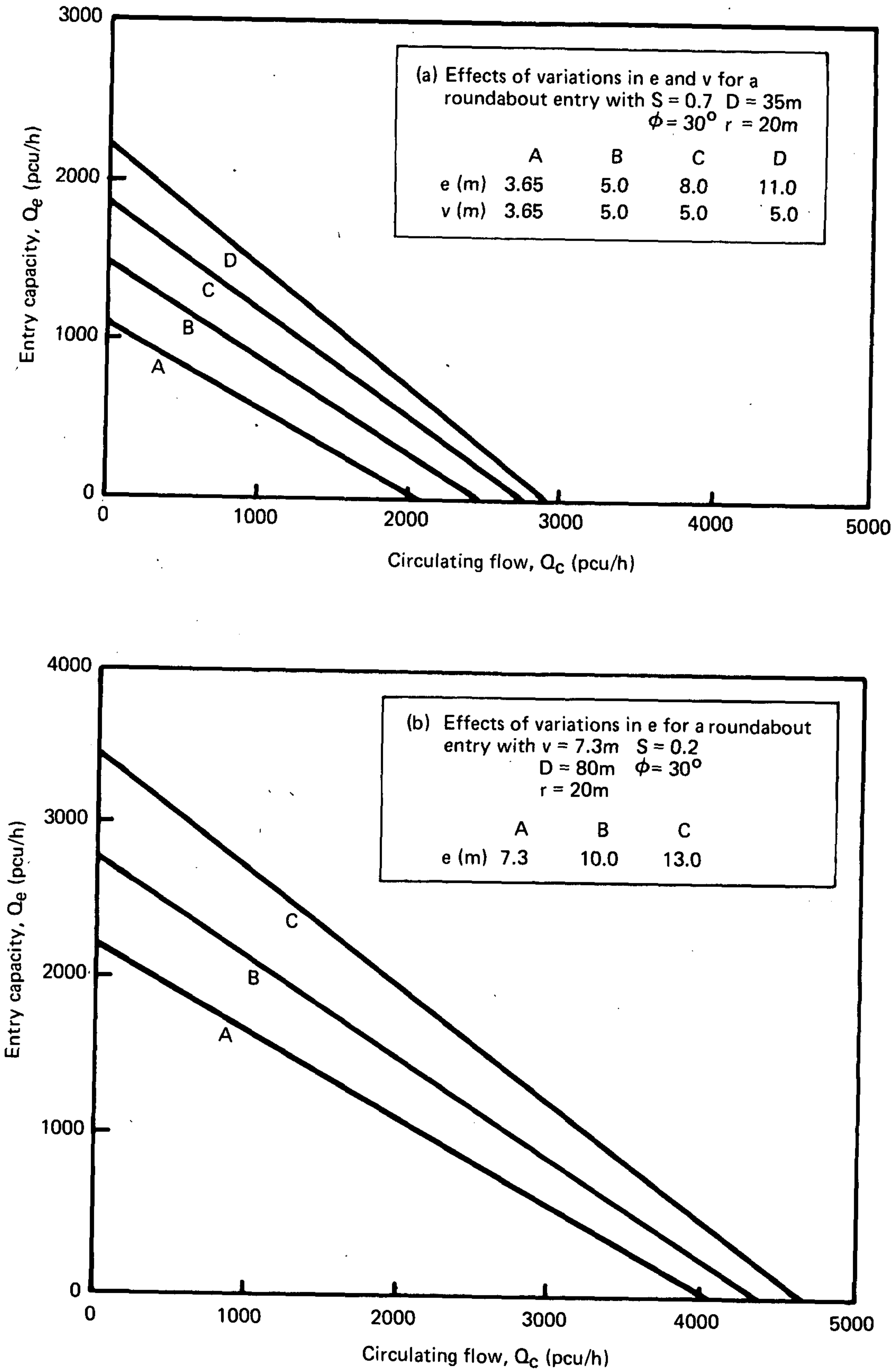


Fig. 6 DEPENDENCE OF THE ENTRY CAPACITY RELATIONSHIP ON THE ENTRY GEOMETRY ACCORDING TO EQUATION (13)

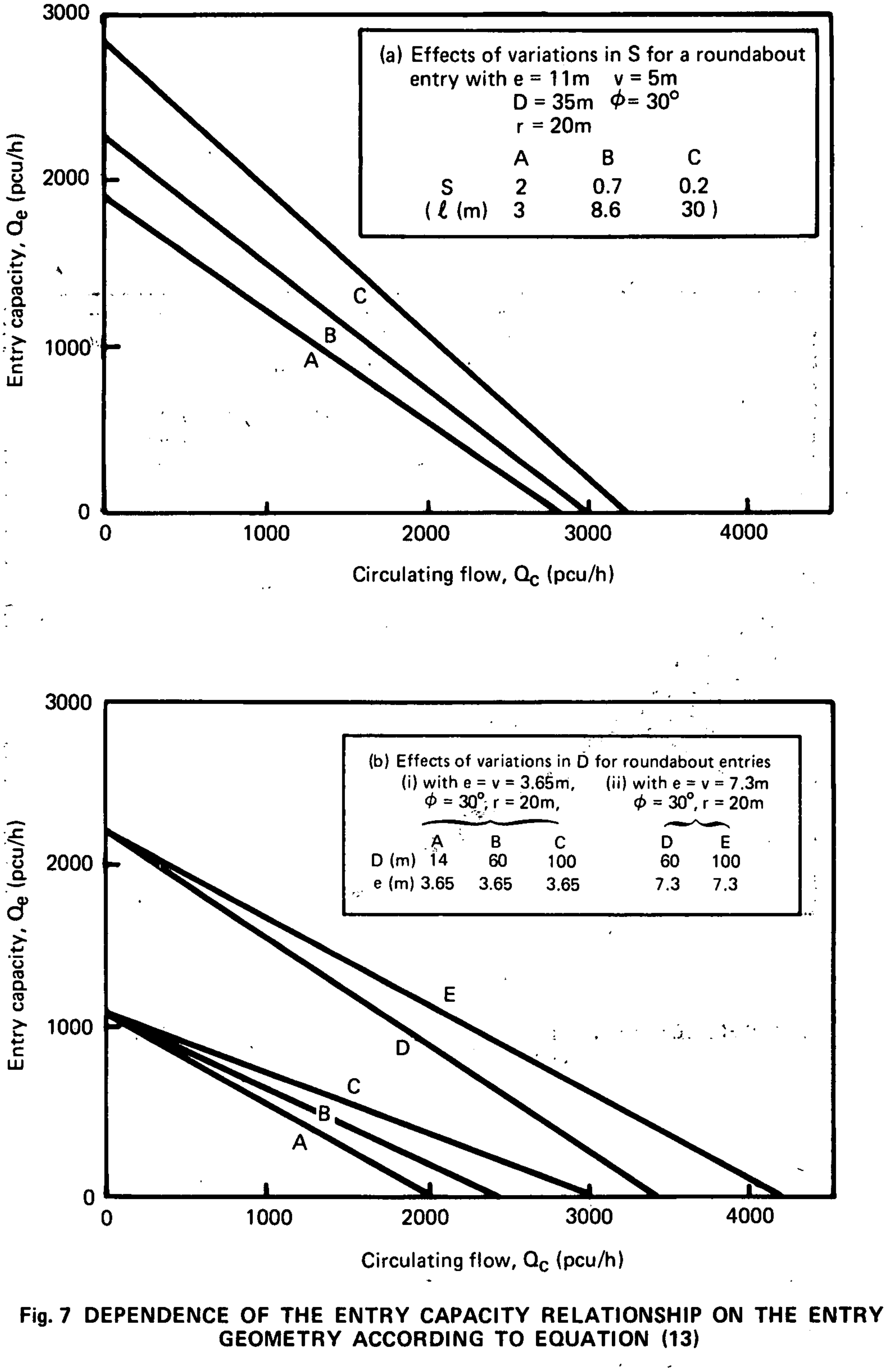


Fig. 7 DEPENDENCE OF THE ENTRY CAPACITY RELATIONSHIP ON THE ENTRY GEOMETRY ACCORDING TO EQUATION (13)

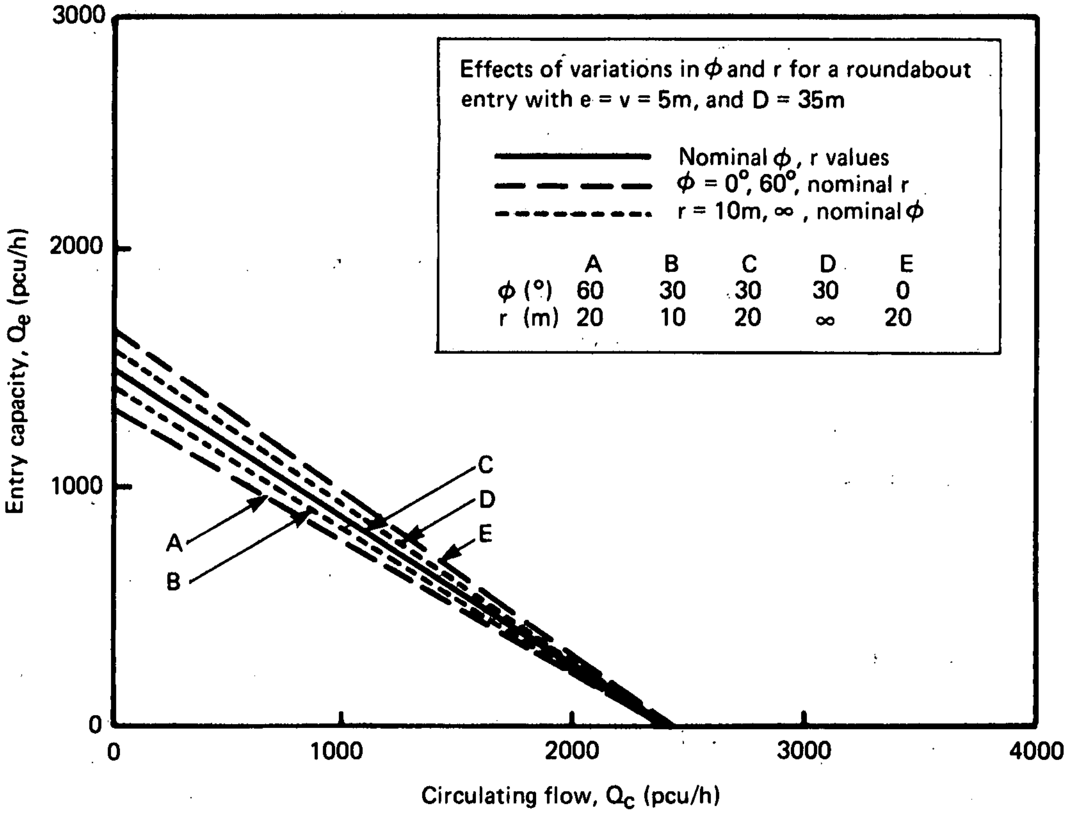


Fig. 8 DEPENDENCE OF THE ENTRY CAPACITY ON THE ENTRY GEOMETRY ACCORDING TO EQUATION (13)

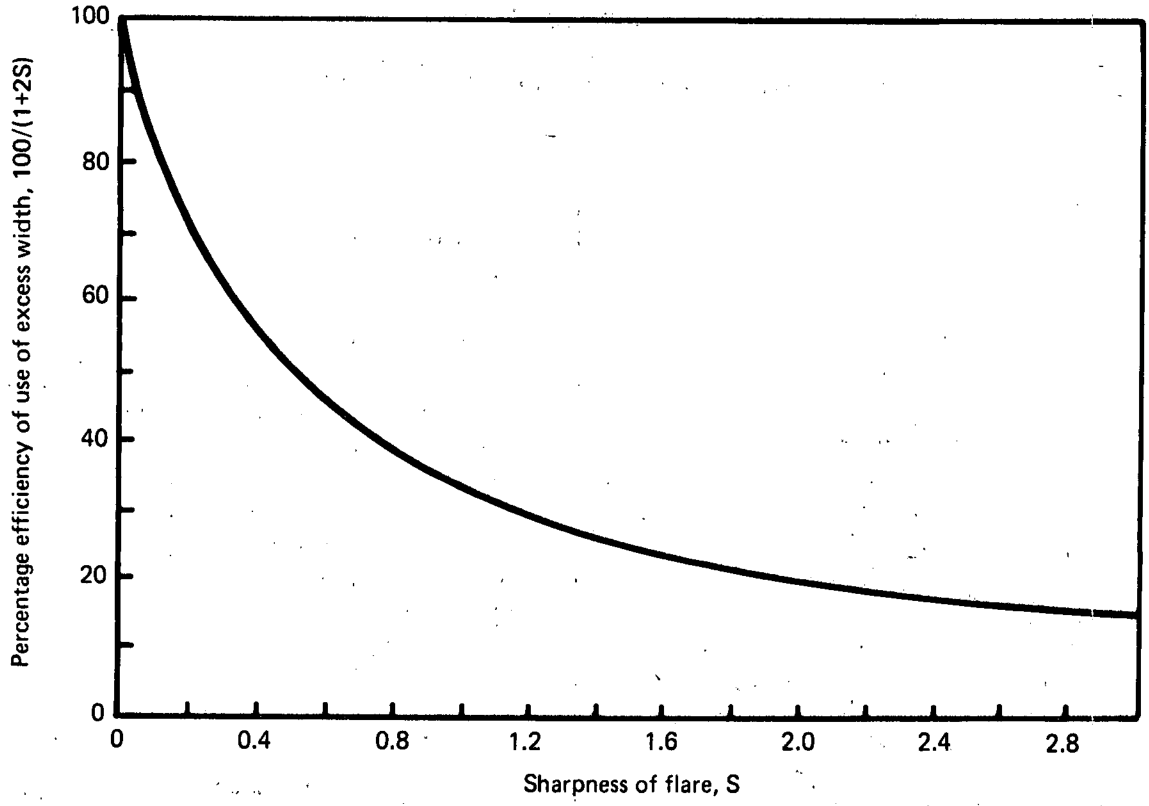


Fig. 9 THE EFFICIENCY OF USE OF EXCESS WIDTH AS A FUNCTION OF SHARPNESS OF FLARE

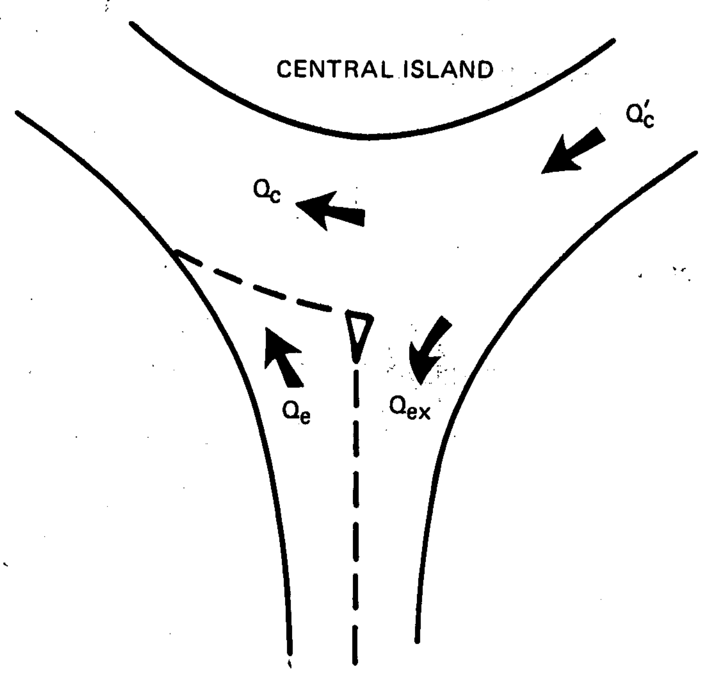


Fig. 10 TRAFFIC FLOWS IN THE REGION OF A ROUNDABOUT ENTRY

11. APPENDIX 1

DEFINITIONS OF GEOMETRIC PARAMETERS

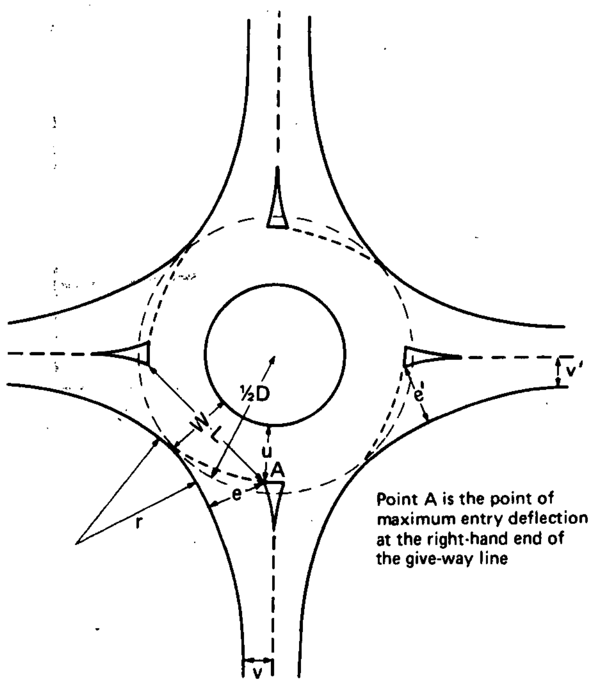


Diagram (a)

(i) The *entry width,* e, is measured from the point A along the normal to the nearside kerb, see Diagram (a).

(ii) The *approach half-width,* v, is measured at a point in the approach upstream from any entry flare, from the median line to the nearside kerb, along a normal, see Diagram (a).

(iii) The *entry width,* e′, and *approach half-width,* v′, for the *previous entry* are measured in the same way as e and v, see Diagram (a).

(iv) The *circulation width,* u, is measured as the shortest distance between point A and the central island, see Diagram (a).

(v) Two alternative constructions can be used to obtain the *average effective length over which the flare is developed.* The first (ℓ) is as used previously (see reference 3), and is shown in Diagram (b).

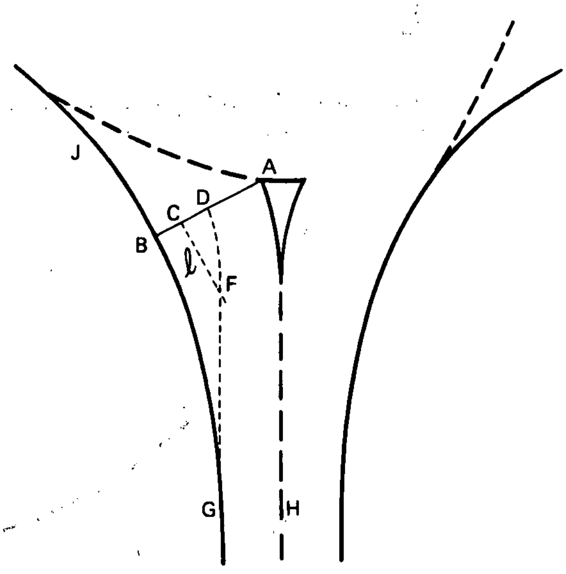


Diagram (b)

Here ℓ = distance CF, where the line CF is the perpendicular bisector of BD, and F is the point of intersection with the line GFD, which is the projection of the nearside kerb edge from the approach towards the give-way line, parallel to the median HA and distance v from it. BA is the line along which e is measured (and is therefore normal to GBJ), and D is distance (e–v) from B. The use of BG instead of CF (or CF′ as below) would be simpler, of course, and would also give an effective measure for the length of flare (although CF or CF′ give a closer measure of the *average* flare length available to vehicles using the extra width at entry: those moving to the left of the line have more available length and those to the right less). In many designs, however, the divergence of width from e to v is gradual and the point G is poorly defined. BG is therefore not in practice a very well-defined length.

Although CF gives an effective measure of ℓ, there is sometimes a tendency for the value determined in this way to be sensitive to the details of the curvature of the nearside kerb. The second construction shown in Diagram (c) avoids this difficulty.

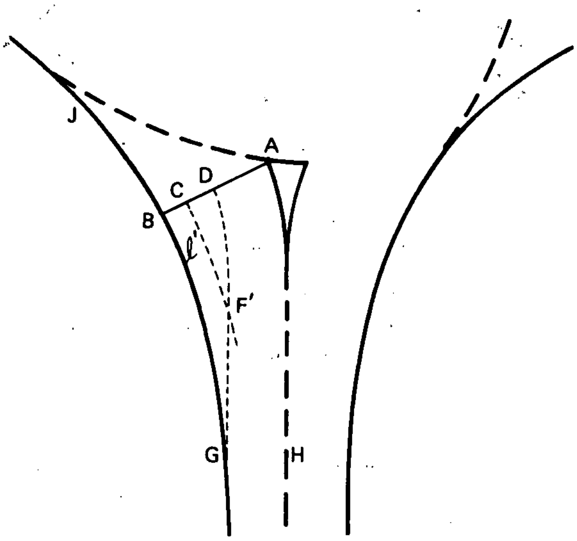


Diagram (c)

Here a slightly modified flare length ℓ' is defined by $\ell' = CF'$. The line CF′ is parallel to BG and distance ½(e–v) from it. Usually CF′ is therefore curved and its length is measured along the curve. The points B, C, D, A, G, and H are as in Diagram (b). This construction is more robust than the first: detailed changes in the kerb line affect ℓ' only slightly. It is therefore preferable to the first construction. ℓ' is related to ℓ over the practical range of designs approximately by $\ell' = 1.6\ell$. The author is grateful to Mr D J Armitage who suggested the second construction.

(vi) The *sharpness of flare*, S, is defined by the relationship:

$$S = (e-v)/\ell = 1.6(e-v)/\ell'$$

and is a measure of the rate at which extra width is developed in the flare: large values of S correspond to short severe flares, and small values to long gradual flares.

(vii) The *entry radius*, r, is measured as the *minimum* radius of curvature of the nearside kerbline at entry, see Diagram (a). For some designs the arc of minimum radius may extend into the following exit, but this is not important provided that a half or more of the arc length is within the entry region.

(viii) The *entry angle*, ϕ, serves as a geometric proxy for the conflict angle between entering and circulating streams. Three constructions are used for ϕ: the first two apply to well-defined conventional roundabouts, and the third to all other types.

For conventional roundabouts (ie those with identifiably parallel-sided weaving sections) the construction is illustrated in Diagrams (d) and (e).

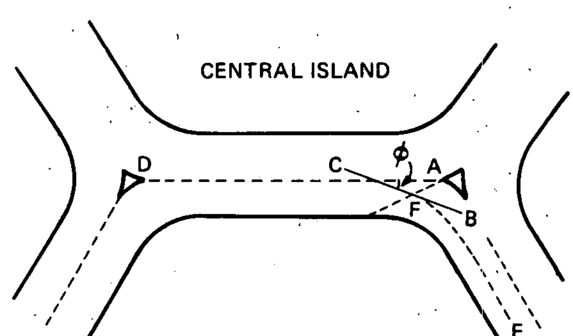


Diagram (d)

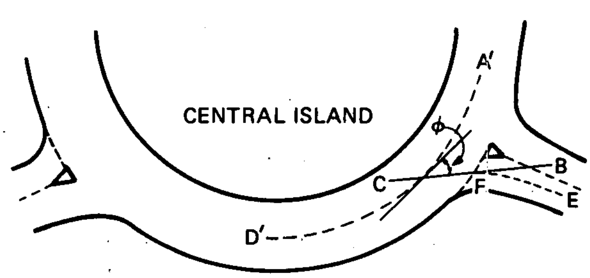


Diagram (e)

Diagram (d) refers to roundabouts with approximately straight weaving sections, in which the line parallel to the weaving section is AD, where the point A is as in the general plan, Diagram (a), and D is the point nearest to A on the median island (or marking) of the *following* entry. Diagram (e) shows the equivalent construction for roundabouts with curved weaving sections (or those for which the line AD is clearly not parallel with the weaving section). A'D' replaces AD as the line parallel to the weaving section.

In both cases the line BC is at a tangent to the line, EF, midway between the nearside kerbline and the median line and nearside edge of any median island at the point where this line intersects the give-way line. ϕ is measured as the angle between the lines BC and AD in Diagram (d), and as the angle between BC and the tangent to A'D' at the point of intersection in Diagram (e).

For all other cases the construction is as in Diagram (f).

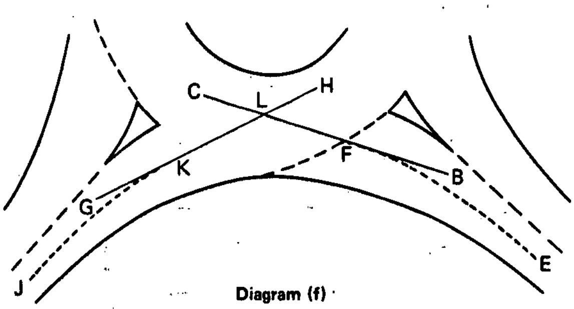


Diagram (f)

Here, the line BC is as in Diagram (d), and the line GH is the tangent to the line, JK, in the following *exit* midway between the nearside kerb and the median line and nearside edge of any median island at the point where this line joins the outer boundary of the roundabout circulation. BC and GH intersect at L. ϕ is then defined by:

$$\phi = 90 - \frac{1}{2}(\text{angle } G\hat{L}B)$$

when the right-hand side is positive, and $\phi = 0$ when the right-hand side is zero or negative (ie when $G\hat{L}B \geqslant 180^{\circ}$). $G\hat{L}B$ is the angle measured on the 'outside' of the roundabout, ie on the side facing away from the central island.

The practical difference between this and the previous constructions is that in the first two ϕ is independent of the angle at which the following exit joins the roundabout whereas in the third ϕ takes account of this angle. The reason is that for roundabouts with appreciable separation between entry and following exit (conventional roundabouts) the direction of circulating traffic depends on the alignment of the weaving section and is largely independent of the geometry of the following exit, but when the separation is smaller (as for off-side priority roundabouts) circulating traffic which leaves at the following exit traces a path determined in part by the angle at which that exit joins the roundabout. The conflict angle reflects this difference.

(ix) The *inscribed circle diameter*, D, is the diameter of the largest circle that can be inscribed within the junction outline, see Diagram (a). In cases where the outline is asymmetric, the *local* value in the region of the entry considered is taken. The extreme case arises for a 'double' offside priority roundabout at a 'scissors' cross-roads; Diagram (g) illustrates the determination of D in such cases.

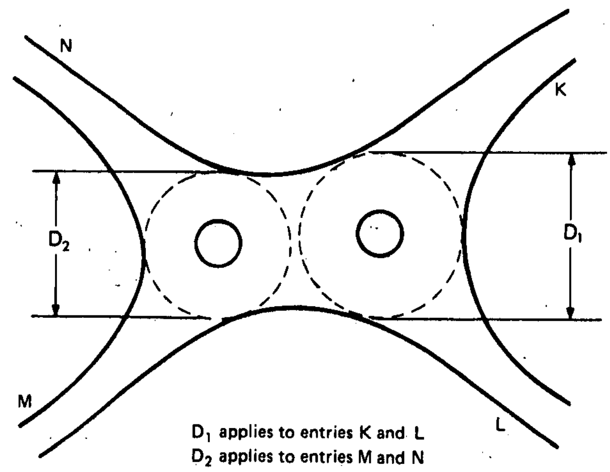


Diagram (g)

(x) The *weaving section width*, w, is a parameter originating in the Wardrop description of conventional roundabouts. The generalisation of the definition to offside priority roundabouts is difficult, since such designs have no clearly defined weaving sections. The form adopted is shown in Diagram (a), and is measured as the shortest distance from the central island to the nearside kerb between entry and exit. In the case of conventional roundabouts it corresponds to the original definition.

(xi) The *weaving section length*, L, is defined as the distance between the point A (Diagram (a)) and the nearest point of the median marking or island at the following entry.

12. APPENDIX 2

CORRECTION FOR LOCAL CONDITIONS AT EXISTING SITES

The following procedure can be used to correct the capacity formula, equation (13), for local conditions provided that the relevant entry is substantially overloaded during peak periods.

(i) Make on-site counts of the total inflow from the entry and the corresponding circulating flow across the entry during successive minutes during which there is continuous queueing in all available lanes in the *approach* to the entry. Queueing should occur continuously for periods of twenty minutes or more during peak periods. The approach queues should be stable for at least five vehicle lengths upstream of any entry widening. At minimum a total of sixty minutes of saturation should be obtained.

(ii) Calculate the mean entry flow $\bar{Q}_e$ and mean circulating flow $\bar{Q}_c$ for all of the saturated minutes together, both in pcu/h.

(iii) Calculate from the roundabout geometry the *slope* of the entry/circulating flow relationship by means of equation (13), ie

f_c = k[redacted]

(where k = [redacted]).

(iv) Then the locally corrected intercept is given by

$$F^{\ell} = \bar{Q}_e + f_c\bar{Q}_c,$$

and the entry/circulating flow line is

$$Q_e^{\ell} = F^{\ell} - f_cQ_c.$$

The confidence limits associated with equations obtained in this way depend on the conditions of operation of the entry in question, but typically the standard error of estimate near the mean will be rather less than 100 pcu/h. It can be evaluated for any given site simply by calculating the standard deviation, σ (pcu/h), of the one-minute counts of Q_e, and the correlation coefficient, R, between the Q_e and Q_c values. Then the standard error of the predicted capacity near the mean will be $\sigma\sqrt{(1-R^2)/N}$, where N is the number of one-minute counts. Both σ and R depend on the conditions of operation, and are thus site-specific.

13. APPENDIX 3

A PROCEDURE FOR DESIGN

Section 7.2 outlines the overall design strategy for the most efficient land utilisation. The process of selecting appropriate values for the parameters that determine the capacity is interactive, for two reasons. Firstly, the parameters are subject to constraints arising from the minimum land-take requirement: for example, D cannot be chosen until the values of e have been decided – it is not possible to accommodate a set of very wide entries (large e-values) at a small roundabout (small D-value). Secondly, other factors influence roundabout design (see Section 7.6) and the capacity determining parameters must be chosen with these in mind. This is not an unusual situation in junction design. The procedure for design is set out below in detail.

For new designs the problem is to choose values for the geometric parameters that will lead to a required traffic capacity, Q_e, for each entry. This capacity will usually be chosen to exceed the predicted demand flow at the entry in question for the design year by a margin (currently recommended as 15 per cent) which allows for inaccuracies in prediction (due for example to 'between-site variation' (see Section 6.3)) and for effects not explicitly taken into account by the formula (eg weather, daylight/darkness, etc). Provided the design allows such a margin of spare capacity, queueing at the peak demand flow level in the design year will only be of a short term nature (ie not over-capacity queueing). The circulating flow across each entry can therefore be calculated from the predicted *demand* flows (not the capacities) and turning proportions. In general, the peak hour flow and turning movement figures will be required, and since they will usually be different for morning and evening peaks, the calculations described below will need to be performed for both peaks and the roundabout layout based on whichever peak condition results in the largest geometric requirement.

Let us suppose that for each entry there is a required capacity, Q_e, and a circulating flow, Q_c (both in pcu/h, assuming the pcu factor for a 'heavy' is 2). Usually there will be Q_e and Q_c values for both morning and evening peak conditions separately. The geometry of the approach road to each entry will have been fixed by other considerations; suppose the half-width is v (one value for each entry). Then values of e, ℓ', ϕ, and r are required for each entry, and a value of D is required for the whole roundabout (for asymmetric designs the D-value will also be entry-specific – see Appendix 1). They should be determined as follows.

(1) For each entry in turn:

(i) Estimate roughly the maximum acceptable value of ℓ' (m).

(ii) For both morning and evening peaks (if available) calculate the required value of x_2 (m) from the appropriate values of Q_e and Q_c (both in pcu/h) using the relationship:

x_2 = [redacted] . . . . (15)

This assumes (for initial estimation) that D = 60m (the 'central' value), $\phi = 30^o$, and r = 20m. (Note: do *not* combine morning and evening peak flows.) Table 5 gives approximate values of x_2 suitable for this initial stage, for ranges of Q_e and Q_c.

(iii) Calculate the values of e (m) from the given values of v (m) and ℓ' (m), and the calculated values of x_2 (m), using the relationship:

$$e = v + \frac{(x_2 - v)\,\ell'}{\ell' - 3.2\,(x_2 - v)} \qquad \ldots\ldots\ldots\ldots \quad (16)$$

Table 6 gives values of e derived from this equation for various combinations of v and ℓ'. It is intended for use in the initial stages of design only.

Note: The parameters are subject to the constraints: $e \geqslant v$; $x_2 \geqslant v$; $\ell' > 0$.

Thus:

- If x_2 calculated in (ii) is less than v, then let e = v. The capacity requirement is then exceeded without widening.

- If ℓ' is less than $3.2(x_2 - v)$ then it is impossible to satisfy the capacity requirement without increasing ℓ'.

(2) For each entry, select the larger of the e values (obtained from the morning and evening peak calculations), and, with the associated ℓ' and v values, draw a plan of the junction, using the minimum overall size possible consistent with established geometric standards. At this stage it is necessary to take fully into account the general design principles for roundabout layout, laid down in the Departmental Technical Memorandum. In particular, visibility standards, deflection standards (for reducing vehicle speeds to an acceptable level), vehicle turning characteristics, central island design, circulation width and corner radii, and site constraints, will all have to be properly considered in arriving at the overall geometric arrangement of the roundabout. Having arrived at an acceptable layout, the values of D, ℓ', ϕ and r can be measured directly from the plan. Recalculate x_2 for each entry and for each 'peak' using the general form of equation (15), viz:

x_2 = [redacted] . . . . (17)

(where k = [redacted]

and $t_D = 1 + 0.5/(1 + \exp((D-60)/10))$).

Calculate the corresponding values of e using equation (16).

(3) Repeat (2), using the new values of e.

Steps (2) and (3) should be repeated until approximately the same values of e (within about 0.5m or so) are obtained in successive repetitions. This will involve slightly modifying the plan and reassessing the geometric design requirements for each repetition. The junction represented by the final plan should have the required entry capacities for a minimum land-take. The entry capacity values can be checked directly by means of equation (13), or can be calculated together with the expected average queue lengths by means of the computer program 'ARCADY' (reference 19). As is explained in the text, this program is not yet able to perform the *optimisation* procedure described above, but it is hoped to develop it into a more comprehensive computer-aided design package in the near future. If, because of site (or other) constraints, it is not possible to provide the full entry geometries, the implications on saturation delay and queue length can be evaluated using the program.

TABLE 5

x_2 (m) for various values of Q_e and Q_c (pcu/h) (assuming D = 60m, $\phi = 30^o$ and r = 20m)

Q_c \ Q_e	200	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400	2600	2800	3000	3200	3400	3600
200	3*	3*	3*	3	4	4	5	6	6	7	8	8	9	10	10	11	12	12
400	3*	3*	3*	3	4	5	5	6	7	7	8	9	10	10	11	12	12	–
600	3*	3*	3	4	4	5	6	6	7	8	9	9	10	11	12	12	–	–
800	3*	3*	3	4	5	5	6	7	8	8	9	10	11	12	12	–	–	–
1000	3*	3	3	4	5	6	7	7	8	9	10	11	11	12	–	–	–	–
1200	3*	3	4	5	5	6	7	8	9	10	10	11	12	–	–	–	–	–
1400	3*	3	4	5	6	7	8	9	9	10	11	12	–	–	–	–	–	–
1600	3	4	5	6	6	7	8	9	10	11	12	–	–	–	–	–	–	–
1800	3	4	5	6	7	8	9	10	11	12	–	–	–	–	–	–	–	–
2000	4	5	6	7	8	9	10	11	12	–	–	–	–	–	–	–	–	–
2200	4	5	6	7	8	10	11	12	–	–	–	–	–	–	–	–	–	–
2400	5	6	7	8	9	10	12	–	–	–	–	–	–	–	–	–	–	–
2600	5	7	8	9	10	11	–	–	–	–	–	–	–	–	–	–	–	–
2800	6	7	9	10	11	12	–	–	–	–	–	–	–	–	–	–	–	–
3000	7	8	10	11	12	–	–	–	–	–	–	–	–	–	–	–	–	–
3200	8	9	11	12	–	–	–	–	–	–	–	–	–	–	–	–	–	–
3400	9	10	12	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
3600	10	12	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Notes

(i) The range of x_2 allowed here is from 3m to 12m.
(ii) * indicates required x_2 value is less than the allowed minimum.
(iii) – indicates that more than the maximum allowed value of x_2 is required, ie that it is impossible to satisfy the capacity requirement.

TABLE 6

e (m) for various values of v, ℓ', and x_2 (all in m)

	ℓ' / x_2	2	4	6	8	10	12	14	16	18	20	30	40	∞
v = 3.65	3	set	e = v											
	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	5	–	–	8	7	6	6	6	5	5	5	5	5	5
	6	–	–	–	–	13	10	9	8	8	7	7	7	6
	7	–	–	–	–	–	–	–	14	12	11	9	8	7
	8	–	–	–	–	–	–	–	–	–	–	12	10	8
	9	–	–	–	–	–	–	–	–	–	–	–	13	9
	ℓ' / x_2	2	4	6	8	10	12	14	16	18	20	30	40	∞
v = 5	5 or less:	set	e = v											
	6	–	10	7	7	6	6	6	6	6	6	6	6	6
	7	–	–	–	15	11	9	9	8	8	8	8	7	7
	8	–	–	–	–	–	–	15	12	11	11	9	9	8
	9	–	–	–	–	–	–	–	–	–	–	12	11	9
	10	–	–	–	–	–	–	–	–	–	–	–	13	10
	ℓ' / x_2	2	4	6	8	10	12	14	16	18	20	30	40	∞
v = 7.3	7 or less:	set	e = v											
	8	–	9	8	8	8	8	8	8	8	8	8	8	8
	9	–	–	–	13	11	10	10	10	10	10	9	9	9
	10	–	–	–	–	–	–	14	13	12	12	11	11	10
	11	–	–	–	–	–	–	–	–	–	–	13	13	11
	12	–	–	–	–	–	–	–	–	–	–	–	15	12
	ℓ' / x_2	2	4	6	8	10	12	14	16	18	20	30	40	∞
v = 11	11 or less:	set	e = v											
	12	–	–	13	13	12	12	12	12	12	12	12	12	12

Notes

(i) The range of e allowed here is from 3m to 15m.
(ii) – indicates that the required x_2 value cannot be achieved for any value of e ($\leqslant$ 15m) unless ℓ' is increased.
(iii) Values omitted from the x_2 column indicate that no value of e ($\leqslant$ 15m) will provide the required x_2 value unless $\ell' = \infty$.

14. APPENDIX 4

CORRELATED FLUCTUATIONS IN ROUNDABOUT TRAFFIC STREAMS

The basic principle of capacity estimation for roundabout entries is that the inflow from a saturated entry is determined by the circulating flow according to an entry/circulating flow relationship which results from the geometric layout:

$$Q_e = F - f_c Q_c$$

No other factor has been found to influence the entry capacity. The application of this principle to successive entries of a fully or partially saturated roundabout enables the balance of inflows from the various entries to be predicted completely, as described in Section 7.4.

As a result of the flow interaction at an entry, short term correlations often occur between entry and exit flows on the same arm. Such effects are readily observable – for example a driver waiting to enter a roundabout will observe that he is able to enter because a platoon of traffic exiting into the arm from which he is entering inhibits the circulating flow from his immediate right. In view of this it is not unreasonable to ask whether the exit flow has a direct *causative* influence on the entry flow, and whether such correlations might form the basis for an alternative method for predicting the entry capacity. However, the following arguments lead to the conclusion that it is more appropriate to regard the correlations as *associated* effects, which stem from common causes.

Figure 10 shows the flow components in the region of a roundabout entry. Suppose that immediately before the exit the flow on the circulating carriageway is Q_c', and that a proportion p of this flow leaves at the exit ($Q_{ex} = pQ_c'$). It follows that the circulating flow across the entry, Q_c, is given by $Q_c = (1-p)Q_c'$. If the entry/circulating flow relationship for the entry is $Q_e = F - f_c Q_c$, and there is steady queueing in the approach, the inflow from the entry will be

$$Q_e = F - f_c(1 - p)\,Q_c'$$

Now:

(i) If Q_c' remains constant and there is an upward fluctuation in p (ie for a short time, a larger-than-average proportion of Q_c' takes the exit), Q_c (= $(1-p)Q_c'$) falls and Q_e increases. At the same time Q_{ex} increases.

(ii) If p remains constant and there is an upward fluctuation in Q_c', Q_c increases and Q_e decreases. At the same time Q_{ex} increases.

In either case downward fluctuations in p or Q_c' have the opposite effect.

Thus fluctuations in p cause positively correlated fluctuations in Q_{ex} and Q_e, and fluctuations in Q_c' cause negatively correlated fluctuations. Fluctuations in both p and Q_c' will arise from the complex interaction of inflows and turning movements from the other entries, and viewed on a short timescale (say a few seconds) can be very large.

In the sense that correlations between Q_{ex} and Q_e derive jointly from variations in Q_c' and p it is not appropriate to regard the link between Q_{ex} and Q_e as a causal one. That an increase in Q_{ex} may be associated with an increase in Q_e does not imply that Q_{ex} *determines* Q_e; in other circumstances an increase in Q_{ex} may be associated with a *decrease* in Q_e. Moreover, in view of the multiplicity of conditions that can give rise to the same type of correlation between Q_{ex} and Q_e, it would not be sound to attempt to use any associative relationship between Q_{ex} and Q_e to *predict* Q_e from Q_{ex}.

It should be noted that the fluctuations described here have nothing to do with another, secondary, mechanism which has sometimes been proposed in the past, whereby modifications of the *headway distribution* for a given flow Q_c in the circulating stream are supposed to result from exiting traffic, and to affect the entry capacity. This mechanism has been investigated in some detail, and is reported elsewhere[2,20]. It appears to have no significant influence on the entry capacity.

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