A47 DUALLING – NORTH TUDDENHAM TO EASTON

Scheme no. TR010038

APPENDICES C and D to FURTHER TRANSPORT SUBMISSIONS in response to Deadline 6 submissions

On behalf of A.C. MEYNELL of the [redacted]

IP reference 2002/8353

ACM 19

18 January 2022

Infrastructure Planning – Planning Act 2008

The Infrastructure Planning
(Examination Procedure) Rules 2010
Regulation 10

The A47 North Tuddenham to Easton Development Consent Order 202[x]

Appendices C and D to Further Transport Submissions in response to Deadline 6 submissions

On behalf of A.C. MEYNELL of the [redacted]

Application reference:	TR 010038
Interested Party reference:	2002/8353
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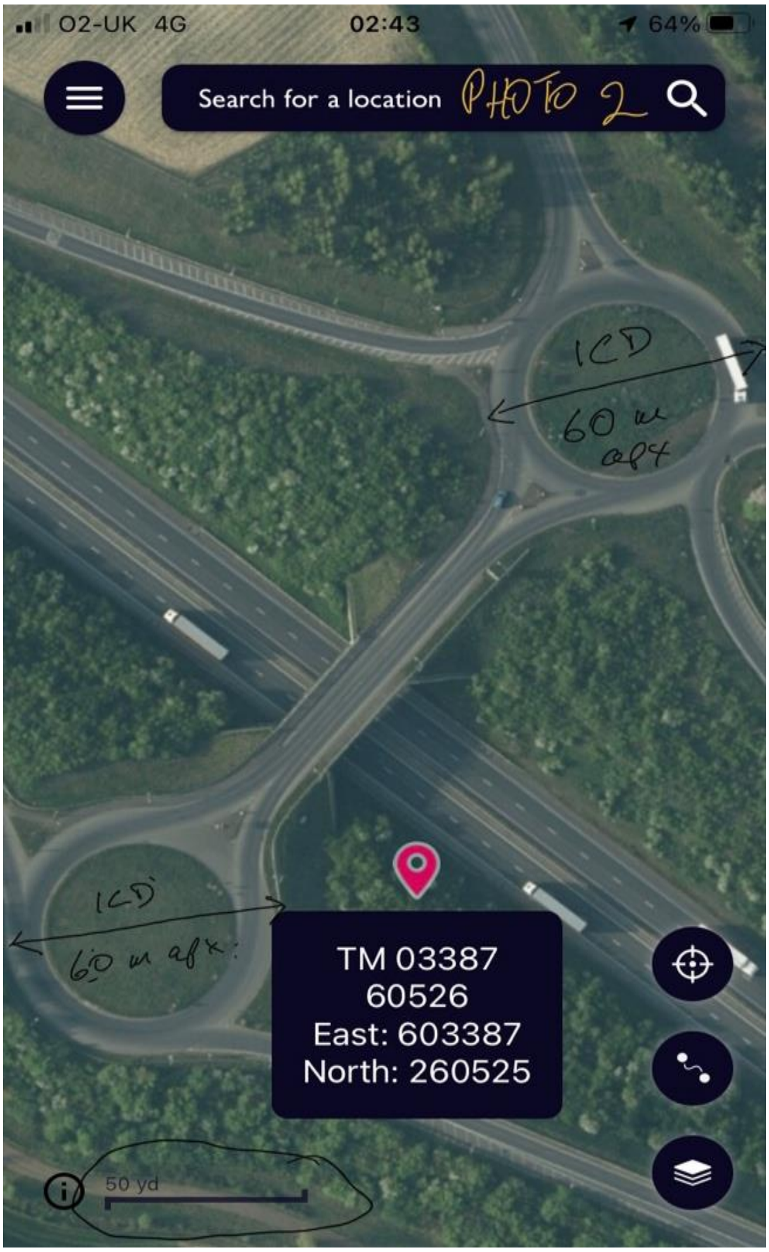
APPENDIX C

Photographs

Photo 1 - Single roundabout, two bridge, A14

Photo 2 - Twin dumbbell, est’d approx 60m ICD, near dumbbell a tear drop



TM 03387 60526
East: 603387
North: 260525

Photo 3 twin dumbbells – ICD est'd approx 65m

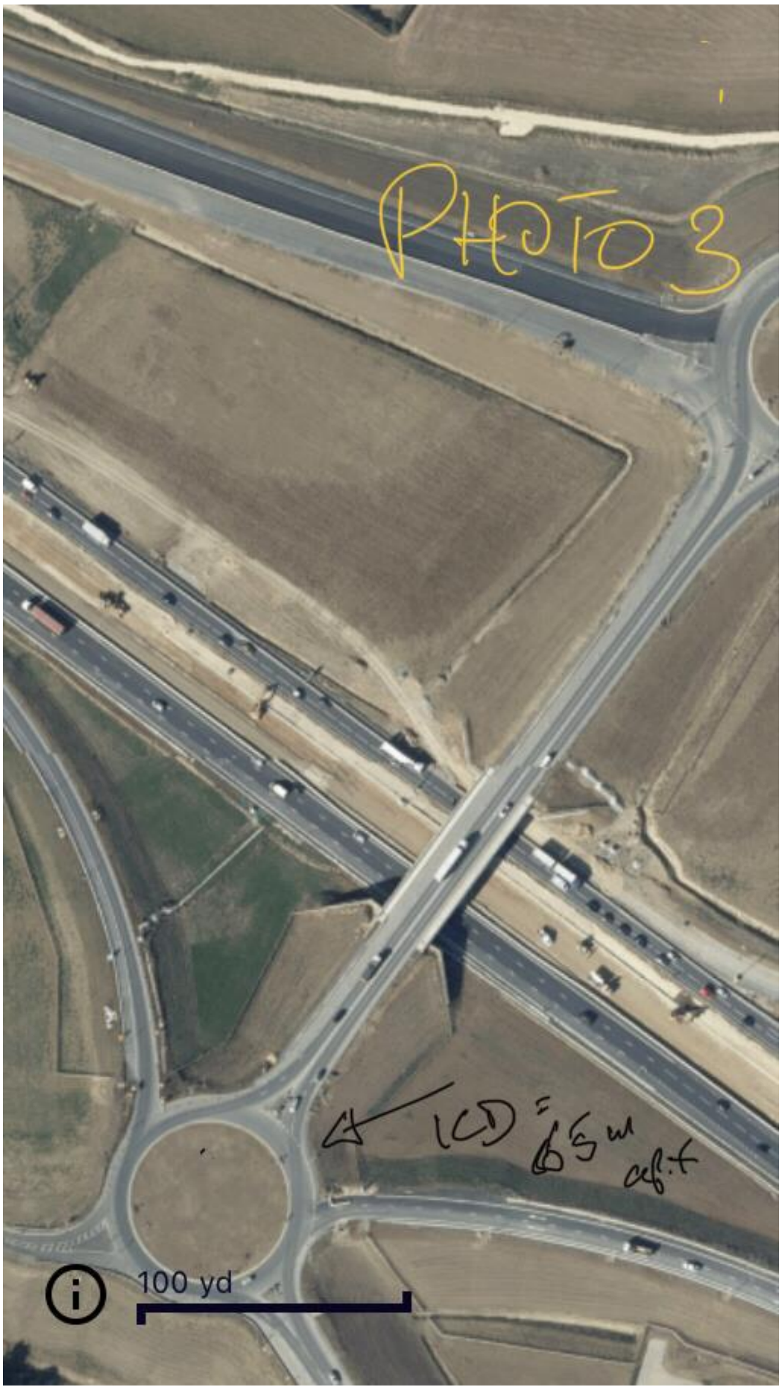


Photo 4 – Wood Lane junction south dumbbell as proposed (from REP6-018 pdf page 17/37) with 100m ICD

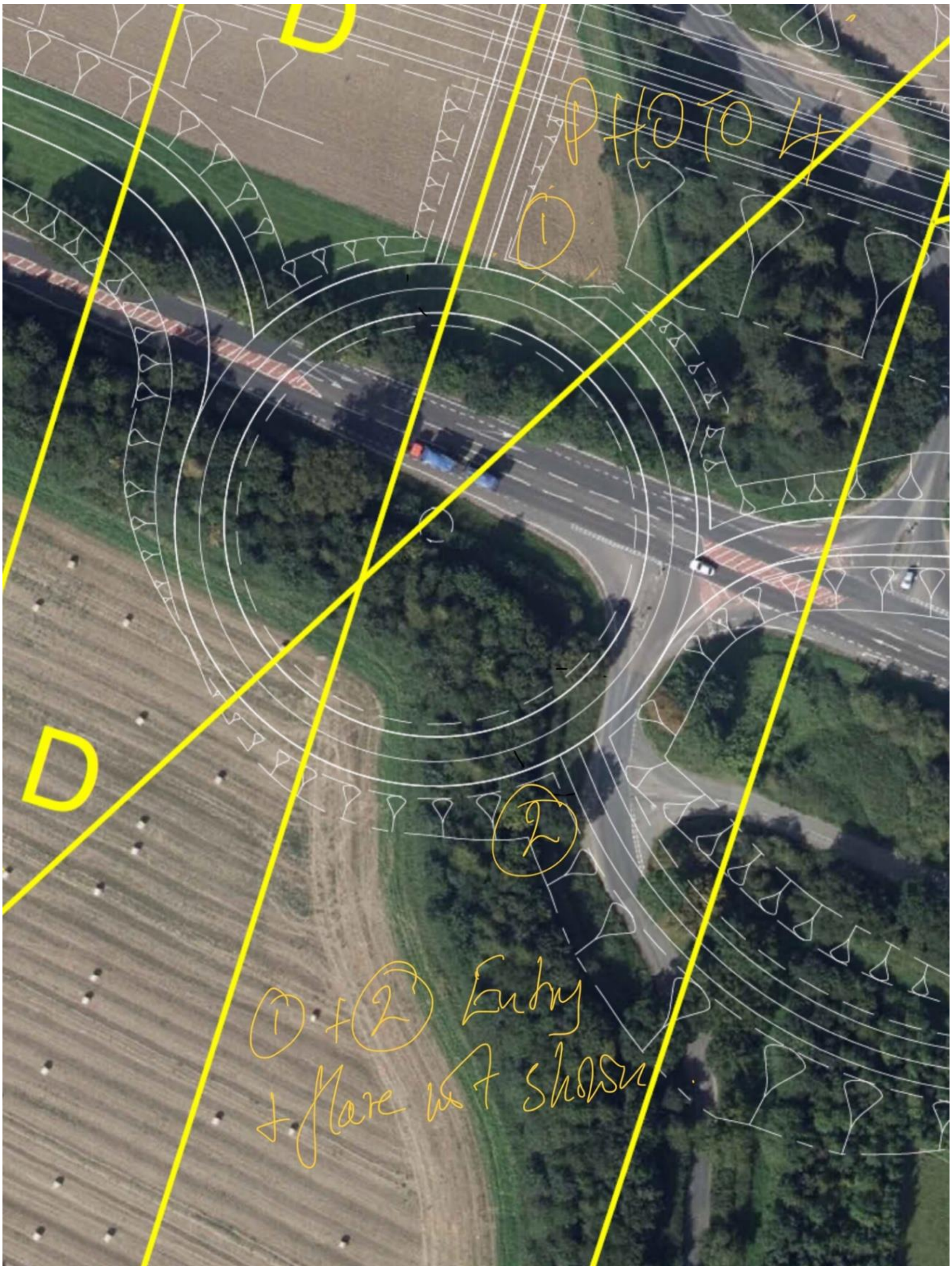


Photo 5 – Wood Lane Junction south dumbbell with 80m roundabout overdrawn as sketch, aligned with north side as existing with indicative entry and flares.

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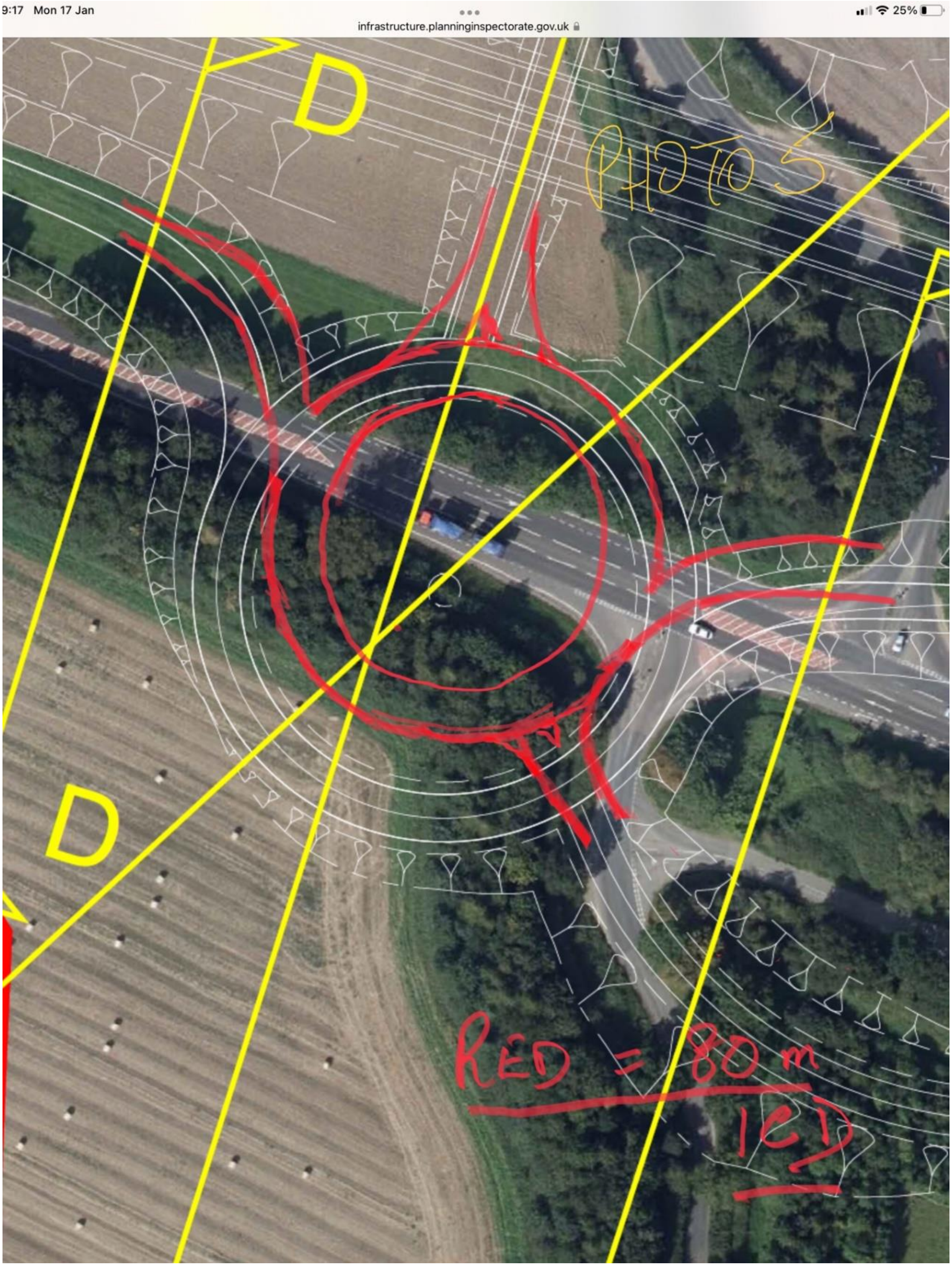
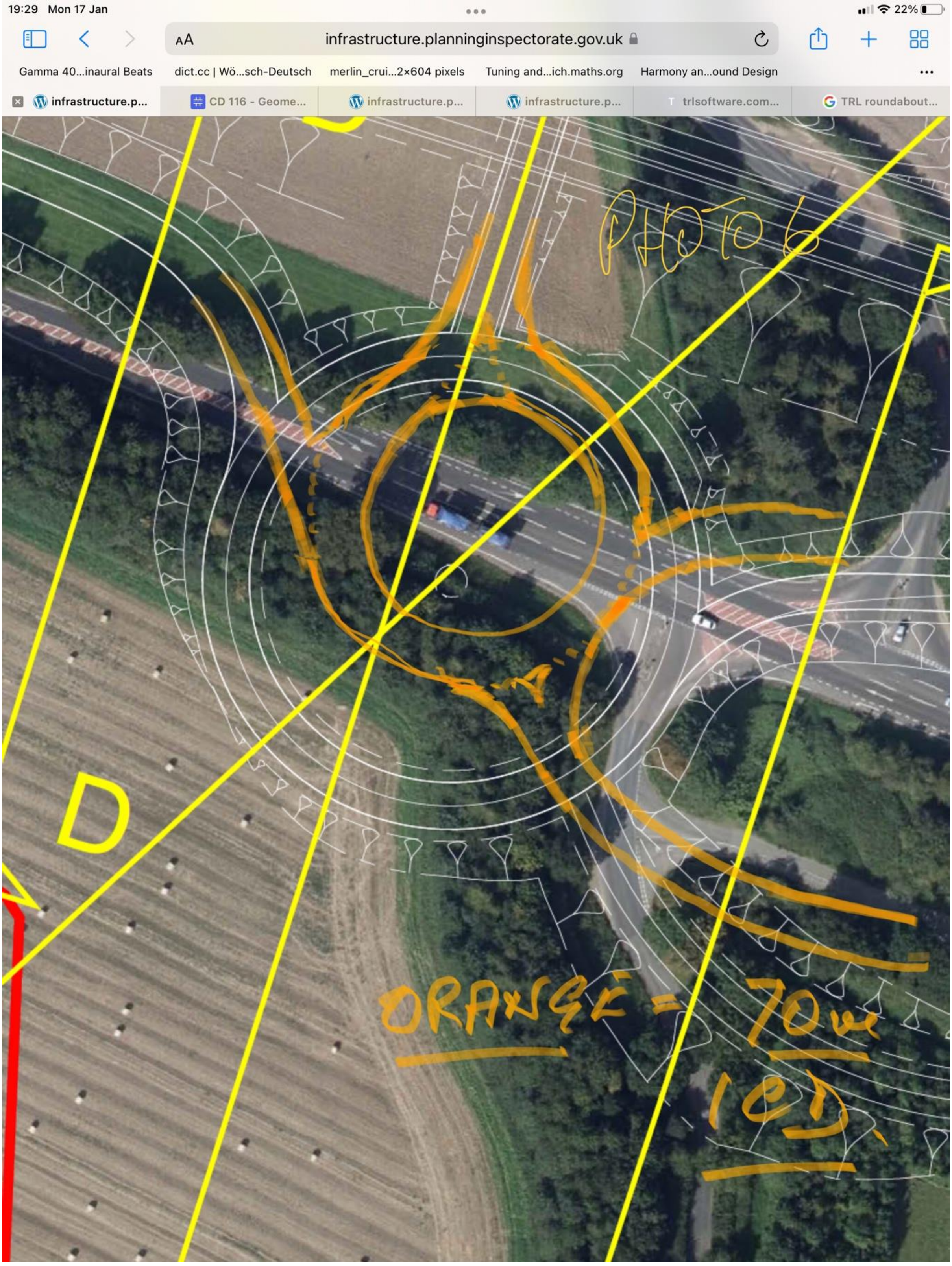


Photo 6 -Wood Lane Junction south dumbbell with 70m roundabout overdrawn, aligned as photo 5.



APPENDIX D

Extracts from GG101, CD122, CD116, TRL RR142, TRL PPR206 and TRL LR942

Introduction

1) GG101 Introduction to the Design Manual for Roads and Bridges (DMRB) and its subsidiary documents (version 0.1.0, Sept 2021)

AppD 1 Para 2.1.1 (highlighted at APP C, page 1) states that where a road is to be reduced in status, eg detrunked, or where works are to be carried out on roads that are not part of the trunk road network, and the use of the DMRB could result in significant over-specification, alternative documents such as the Manual for Streets or Designing Streets, may be used with the approval of the Overseeing Organisation.

This confirms Mr Joe Ellis' comments at REP4-023 Appendix A, at para 1.2 (fifth bullet) that the use by the Applicant of DMRB in the design of the non-trunk elements of the Wood Lane Junction should not be necessary.

2) CD122 Geometric design of grade separated junctions (version 1.1.0 published November 2021)

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AppD 4 Page 5 applies the GG101 assumptions to the document

AppD 5 Page 11, Para 2.1 Note 1 refers to Appendix A for examples of typical grade-separated junctions

AppD 6 Pages 59-60, in Appendix A, describes and contains an example of a Dumbbell roundabout. The second paragraph of the description (page 59, penultimate para) states "*the dumb-bell roundabout has the advantage of requiring less land than both the diamond and the two bridge roundabout options. It also requires only one bridge*".

This paragraph (with particular reference to the "*takes less land*" has been quoted by the Applicant to support its choice of dumbbells at the Wood Lane Junction, in reply to the Ex A's First Written Questions (ExQ1, Q1.0.6 – see **REP2-014**, page 4, fifth paragraph). The Applicant has also relied in the same answer at REP2-014 page 4, fifth para), on the second part of the second sentence of the first para on page 59 of CD122 "*a dumbbell roundabout can be considered an intermediate between the diamond/ half cloverleaf and the two bridge roundabout*".

The reason for these statements being made by the writers of CD122 in this section of CD122 App A, becomes apparent from looking at the illustration on the next page,

page 60, which is of two small roundabouts linked by a short overbridge carrying four lanes of traffic between the roundabouts above a mainline dual carriageway.

The Applicant did not refer the Ex A to this illustration when quoting the words to him.

AppD 6 Compared with the two bridge roundabout described in the next section of CD122 on page 60 as “the most common grade separated junction” the illustrated exemplar dumbbell in CD122 does take less land and has less capacity. But not when the dumbbells are far larger than the exemplar and much more widely separated, as at the Wood Lane Junction, where they take double the lateral width of a two bridge roundabout (300m total width compared with 160m for a single roundabout) – see also photo 1 in App c compared with photos 2 and 3.

The first paragraph on page 60 of CD122 states that the requirements and advice on the geometric design of the roundabout elements of the layout are provided in CD116 (Ref 3.1)

3) CD116 Geometric design of roundabouts (revision 2, April 2020)

AppD 8 The Introduction on page 6 (second para) confirms “*the principal objective of minimising delay whilst maintaining safe passage … is achieved by a combination of geometric layout features that, ideally, are matched to the flows in the traffic streams, their speed, <u>and to any local topographical or other restraints such as land availability that apply</u>*” [emphasis added]

AppD 9 The table of terms (page 10) confirms that the geometric design of grade separated roundabouts follows the requirements for a normal roundabout: this is repeated in the Note to para 2.1 (page 15)

AppD 11 Para 2.13 (page 22) illustrates a double roundabout (with an illustrated similar short four lane connector to the dumbbell at CD122 App A page 59) and note 2) confirms its use

AppD 12 Figure 3.4 (page 27) illustrates how the Inscribed Circle Diameters (ICD) of a double roundabout relate to the entry traffic to each individual roundabout and how the roundabouts in consequence are able to differ in diameter from each other.

Para 3.5 on the same page 27 advises that the ICD of a normal roundabout should not exceed 100 metres and warns “***Large ICD can lead to excessive vehicle speeds on the circulatory carriageway***”.

AppD 13 The notes to Para 3.7 (page 30) advise that central islands on a grade separated roundabout can be non-circular due to staggered road arrangements, land constraints, to allow for dominant mainline flow capacity (Note 1) and that the layout of the slip roads can influence the shape of the central island. In other words, if the Wood Lane Junction south dumbbell were thought to need to be larger, but there were agreed to be a land constraint to the south, a “squeezed” circle would be permissible if the entries and slip roads allowed for it.

AppD 14 Figure 3.11 (page 34) illustrates entry width and Note 3 to it explains that "***entry width** and **sharpness of flare** are the most important denominators of capacity,* whereas ***entry deflection is the most important factor for safety as it governs the speed of vehicles through the roundabout***". The following Note 4 states that advice on calculating the capacity of the roundabout is provided in Appendix B (for which see below). (These factors ultimately derive from RM Kimber's report TRL LR942 "The Traffic capacity of roundabouts" (1980) (see AppD 41-62 below))

AppD 15 Section 10 (page 121) gives as Informative References the following papers, among others:

Ref 9.1	TRL, Marie Semmens – TRL RR142 stated to be "The Capacity of entries to very large roundabouts" (published 1982) but on searching online for that reference one is taken to TRL's document "Roundabout Capacity: the UK Empirical Methodology" which is based on "Roundabout design for capacity and safety: the UK empirical Methodology", JR Peirce, 1998
Ref 10.1	TRL, Marie Semmens – TRL SR721 – "The capacity of some grade-separated roundabouts" (published 1982)
Ref 16.1	TRL, LR942 "TRL LR942 – The traffic capacity of Roundabouts" (by RM Kimber, published 1980)

AppD 16 CD116 Appendix B (pages 124/5) gives the roundabout capacity formula for what is stated to be "*the best predictive equation for the capacity of any roundabout entry (Qe)* ***found by research to date*"**, being the equation set out at Equation B.1, with a refinement added for grade separated junctions.

This equation is incorporated in the ARCADY program used by the Applicant and is said to derive from TRL SR721 (Marie Semmens, 1982, ref 10.1) and refined by TRL RR142 (in fact now a summary of "Roundabout Capacity: the UK Empirical Methodology" (JR Peirce, 1998). As will be seen below both of these reports (including not only the formulae but many of the illustrations) derive heavily from the third report above Ref 16.1, "The Traffic capacity of roundabouts" by RM Kimber, published in 1980 as TRL LR942 (AppD 40 et seq). The formulae in essence have remained the same.

The first of these reports (Ref 9.1 – TRL RR142 at AppD 19-22) and the third (Ref 16.1 – TRL LR942, Kimber, 1980 at AppD 40-65) just referred to therefore should be looked at to understand the principles on which the design of a roundabout using the ARCADY software are based. Relevant extracts from each of these reports are included within this App D (see below). The second, (TRL SR721) although referring to grade separated roundabouts and resulting in refinements to the equation was a survey in 1982 limited to seven existing motorway junctions with traffic problems, so is not included.

In addition to these three informative papers an important report was published in April 2007 by TRL, TRL PPR206 "International comparison of roundabout design guidelines". This was the first time that roundabouts in the UK (which are far more ubiquitous than on the continent) were compared in detail and their relative safety records examined in the UK. As a result of this report the compact roundabout was introduced to the UK and some roundabouts have adopted more continental designs. The report influenced TD 16/07 produced in 2007, a precursor to CD116 (see AppD 22A). The report is relevant to the present case because of its warnings also about excessive ICD. Extracts from it will be found in this App D at AppD 23-39) after the next report, TRL RR142

4) TRL RR142 (as found – see Ref 9.1 above) “Roundabout Capacity: the UK Empirical Methodology” based on “Roundabout design for capacity and safety: the UK empirical Methodology”, JR Peirce, 1998

AppD 19 Sect 4 (page 3) explains the geometries measured in the research, highlighting (see penultimate para on the page) those found significant and emphasising “***of the significant variables, three are of particular importance, most of all entry width, and then approach width then flare length. The remaining geometries (ie including ICD) have lesser effects***”. The effect of entry width and flare length on capacity are then illustrated by graphs and described with examples showing the capacity benefits of additional width and flare.

AppD 20 The charts on this page illustrate the relationship between increased flow capability into (Qe) and around (Qc) the roundabout, depending on increases in entry widths and flare lengths.

AppD 21 The same factors are described in Section 4.1 “Entry width and flaring” in relation to the queuing lengths on entry, where the reality of what happens in the entry queuing is illustrated to show how capacity increases through the use of increasing entry width on the same length of flare (although it counsels against too short a flare length).

AppD 22 The importance of this paper (see section 5 on page 8 at the end of it) is that the empirical relationships described in it form the basis of the ARCADY software package. Even so, it is itself derived from the earlier TRL research report by RM Kimber (1980) “*The Traffic capacity of Roundabouts*” **TRL LR942** (see below at AppD 41-62).

5) TRL PPR206 International comparison of roundabout design guidelines, Kennedy J (April 2007)

AppD 24, 28 Prepared for the Highways Agency, the introduction to the report in the Executive summary (page i) explained that concerns had arisen with the designs promoted by the papers previously described, over accidents of pedal cyclists and motor cyclists and the junction type resulting from use of the formulas derived from the standard then promoted under TD 16/93, and more recently pedestrians and horse riders.

AppD 29 The first conclusion from the report listed in the Executive Summary (page ii) is that “***The inscribed circle diameter should not be unnecessarily large. In particular, if the roundabout is at grade, the inscribed circle diameter should not exceed 100m***” Recommendations were also made to limit the entry and exit kerb radii, the entry angle and the entry path radius.

AppD 32 The report found that the UK tradition *"has led to large roundabouts with high speed circulating traffic*" contrasted with the continental main emphasis being on their speed reducing capability and safety (para 2.3)

AppD 33-34 At section 3.2.1 (page 8) Inscribed Circle diameter is examined. It explains that the British history of large ICD's arose historically from the 1960's when the priority rule was for circulating vehicles to give way to traffic entering the roundabout which led to gridlock and "weaving lengths" were used. It finds "*although beneficial from the point of view of capacity, **large roundabouts encourage higher speeds and increased geometric delay (journey time)***". It continues "*Roundabouts at grade separated junctions (fig 5) are particularly large unless replaced by a 'dumbbell ' interchange with a single bridge and two roundabouts (fig 6)".* The illustrations it will be seen are for a single roundabout similar to that at Photo 1 in Appendix C above and twin dumbbells of an ICD not much wider than the dual carriageway linking into the junction from one side. In other words considerably smaller than the ICD on the two dumbbell interchanges shown at Photos 2 and 3 in Appendix C and far smaller than the Applicant's proposal. Also, Since there is only one road in the illustration on each side apart from the slip roads (as with the south dumbbell (and the north dumbbell in a "no NWL" situation)) fig 6 contains a note "*a superfluous circulating carriageway if no U-turns present".*

At the time of the report there was no maximum in the UK standard.App

AppD 35 Table 1 compares the minimum and maximum ICD's (where set) of five European countries plus Australia and the USA with the UK's (none of the other countries who had a maximum had one of over 90m) and then notes reports from French, German and Swedish experts who all concluded that larger ICDs (the German definition of larger being 40-142m) posed more of an accident risk. The Swedish experts had found that islands with diameters greater than 50m also result in straighter paths, enabling higher speeds and that an island of between 20 and 50m was probably optimal (the central island diameter minima and maxima are compared at Table 3 on the following page 11 (AppD 36)

AppD 35 It is in this section (at AppD 35) that the report concludes "***The inscribed circle diameter should not be unnecessarily large. If the roundabout is at grade it should not exceed 100m***".

AppD 37 This conclusion is repeated at the Conclusion section 6.2 (page 55 – AppD 37)as the first conclusion of the report, with conclusions also being given for suitable values for the entry and exit kerb radii, the the entry path radius and entry angle, with a recommendation that flaring should continue to be used in preference to a segregated left hand turn.

AppD 38 Section 7 confirms a design hierarchy including Grade Separated as the second.

AppD39 Table B4 sets out UK accidents at grade separated roundabouts by number of arms, 1999-2003.

Commentary on TRL PPR206

From the emphatic nature of this report's conclusions on the risks of larger roundabouts and the recommendation of the 100m maximum ICD which has been taken up by NH, the question arises which has been posed by Mr Foster in all his reports, as to whether the Applicant has for safety before Deadline 6 considered alternatives (in the way here of smaller ICD's) and to what extent it did so in the course of developing its design before selecting that now proposed. (see for its explanation the Junction and Sideroads report, section 2.4 where it states that "*two roundabouts were proposed during PCF stage 2 and initially designed as the preferred option. The [ICD] was increased to 100m diameter (the maximum recommended in DMRB CD 116) to assess the predicted traffic flows*".

6) TRL LR942 "The Traffic capacity of roundabouts", by RM Kimber, (1980)

AppD 41 Published for the Dept of Environment and Dept of Transport by Transport and Research Laboratory, Crowthorne, 1980

This is the seminal paper in which the current methodology used still by ARCADY was first developed, although over the years since then refined, but it remains an Informative reference in CD116 now.

AppD 47 Section 2 sets out the prime issues to be resolved; whether there is a difference between the factors determining the capacity of the then still used "conventional" (priority to traffic entering) and Offside priority (priority to traffic circulating) roundabouts, and if not what is the best single procedure for predicting the capacity of roundabouts? Because capacity prediction and overall design are intimately linked a coherent design strategy could not be developed at that point until the issues had been settled.

AppD 49 At section 4 (page 5) the paper develops the empirical model used now by ARCADY, setting out the geometric characteristics used in the equation in CD116, Appendix B1 and then goes on to develop the equation in the following pages

AppD 50 Section 6.1 finds that 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.*"

At 6.1.1 "*the entry capacity is determined primarily by the number of queues,* n, *at entry and this in turn is determined by the entry width and flare*". An equation for predicting *n* is then shown. As seen in the later papers, these two first items, entry width and flare have not changed their importance.

AppD 51 Next considered at 6.1.2 is the inscribed circle diameter (D)

Kimber finds (second para) “*the effect on the entry capacity of increasing D is to decrease the magnitude f, of the slope of the entry/circulating flow relationship*.” The relative variation is shown by a table in Fig 3 (at AppD 56), which demonstrates that the rate of change decreases as the size of D increases. The size of D (third para) is split into two groups: the first, D = less than 50m, and the second, D = more than 50m. Kimber then finds “*the overall mean value for the first group being about 40% higher than for the second”.* From the vertical lines added to Fig 3 (AppD 56) it will be seen that the rate of change of the slope, and thus the increase in capacity, arising from a 20m increase in D from 80 to 100m is less than the increase of 10m between 70m and 80m and far less than the 10m increase from 50m to 60m or from 60m to 70m. There is therefore a very real diminishing return from making changes to anything over 70m.

AppD 53 Section 7.2 sets out a design strategy. It emphasises (first para) that by far the most important factors determining the capacity of an entry are the entry width and the flare. A small excess width with a long gradual flare might lead to the same capacity as a larger excess width with a more severe flare. Where gradual flares are not possible, significant (if not large) contributions can still be made by the extra width.

Kimber proposes (third para) that the design approach for new roundabouts should be in overall terms as follows (looking at the defined terms at AppD 49 and described and illustrated in the diagrams in Appendix 1 at AppD 58-60):

- to ascertain first for each entry (a) a value for the length of flare to give a reasonably efficient flare consistent with land take and site constraints and (b) a value for the entry width to provide approximately the required entry capacity.
- Then to take (c) a minimum value for D (the ICD) that is consistent with the resulting set of entry widths and flares.
- That will then enable the entry radius and angle of entry to be established, aiming to achieve smaller rather than larger values. The entry radius should be set at a reasonably large value if possible.

A steps plan to do this in the most efficient way to achieve the desired result in terms of capacity with the minimum land take is set out in Appendix 3 (AppD 61-62 - see below).

AppD 54 The Summary (section 8, page 18) confirms that a unified formula for predicting the capacity of roundabout entries has been developed and described and repeats that “the most important factors influencing the capacity are the entry width and flare. The inscribed circle diameter, used as a simple means of overall size, is more effective as a predictive variable than the (previous) 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 is then set out, with the ranges for the various geometric parameters in the data base, are then set out and are the same as subsequently used in the other documents described above.

The final paragraph of the section (on page 19) caveats that a further report will be prepared, based on the present work taking account of slight differences of operation, would be prepared for grade-separated interchanges.

AppD 61 <u>Appendix 3 "A procedure for Design"</u> provides a steps plan for reaching the optimum design for new roundabout using the equations developed in the report and taking each factor in turn.

It is pointed out (first para) that "*the process of selecting appropriate values for the parameters that determine the capacity is interactive, for two reasons. Firstly, that the parameters are subject to constraints arising from the minimum land take requirement -* ***for example D (the ICD) cannot be chosen until the values of e (the entry width) 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 … and the capacity determining factors must be chosen with these in mind*."

Step 1) involves calculating preliminary values for the two critical factors of entry width and flare length, sufficient for taking the required traffic movement into (Qe) and through (Qc) the roundabout at each entry using morning and evening peak flows, based for the moment on an assumed "central" value for each of the subsidiary factors: ICD (at 60m), the angle of entry (at 30 degrees) and the entry radius (of 20m). This will calculate:

i) roughly, the maximum acceptable value of the flare length, and
ii) for both peaks, a variable called x2 which is determinative of the proportion of entry width (at the junction) *e*, and the half width of the carriageway at the commencement of the flare *v*; and from these together, using the appropriate equations
iii) values for e (the entry width) which can provisionally be used to take the design to Step 2

AppD 62 **Step 2)** Taking the larger *e* (entry width) values, and the associated flare length and v (half width at commencement of flare) values, drawing a plan of the junction using the minimum overall size possible consistent with established geometric standards. This will give a first iteration of the roundabout, taking account of all the requirements for design principles laid down in the relevant departmental technical manuals, ie visibility standards, deflection standards, central island design, circulation width etc, and site constraints.
Having arrived at an acceptable layout, the values of D (the ICD), the flare length, the angle of entry and the entry radius can be measured from the drawing.
From these the variable x2 can be calulted for each entry and using that variable the corresponding values of e (the entry width) can be obtained using equation (16) in the report.

Step 3) involves repeating the drawing using the new e values, and then continuing to repeat steps 2) and 3) 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 in successive repetitions. The report states that at the end of this process "***The junction***

represented by the final plan should have the required entry capacities for a minimum land-take."

At the end of Step 3 Kimber comments that the entry capacity values can be checked directly using his equation (13) or calculated together with the expected average queue lengths in the ARCADY programme as then developed. At that point the ARCADY programme had not been developed to perform the *optimisation* programme described in the steps plan but it was hoped to do so in the near future.

Conclusion

1. It will be apparent from the steps plan in TRL LR942 above, App 3 (AppD 61) that the requirements for capacity of a new roundabout junction will be met primarily by the use of appropriate entry widths and flare lengths at each entry point. The ICD of the junction will follow on after those optimum criteria have been established (AppD 61, (TRL LR942, Appendix 3) in the absence of an overriding physical obstruction which has determined a maximum size for it.

4. Further, it is evident that the slope coefficient which determines the increase in capacity derived from an increase in the ICD, is virtually flat for a roundabout at 80m ICD and above (see AppD 56) so there will be very little capacity benefit from an increase from 80m to 100m.

5. The Applicant's clearest explanation of its design process for the roundabouts at the Wood Lane Junction is in its Junction and Sideroad Strategy of 5 February 2020 (at its website for the project under 2020 consultation documents) at para 2.4 where it confirms two roundabouts were proposed at PCF stage 2 and initially designed as the preferred option. It states then "The inscribed circle diameter (ICD) was increased to 100m diameter (the maximum recommended in DMRB CD116) to assess the predicted traffic flows" and goes on to say "The Ratio of Flow to Capacity (RFC) and maximum queue length from ARCADY are the two primary measures of junction-arm performance for a roundabout." While the second part of the last sentence accords with the conclusions in the above reports, what the Applicant does no mention is that it is the entry widths and flare lengths that determine the performance, not to any great degree in a large roundabout as we have seen, the ICD.

6. The Applicant having used ARCADY presumably in accordance with Appendix B of CD116 (AppD 16-17 above), appears here to have adjusted the ICD in the belief that that would improve the capacity without having first designed a junction with its entry widths and flare lengths appropriately adjusted. It has recently confirmed that it intends not to design the entry widths and flare lengths until after the DCO.

7. ACM believes in light of the Applicant's suggestion at Deadline 6 to reduce the south dumbbell from 100m to 80m ICD, that it might assist the Ex A if it were to prepare a design for the junction before the end of the DCO process using, in conjunction with the current ARCADY software, a steps plan on the lines recommended by Kimber in TRL LR942 and to start with assessing true values for as yet undesigned factors there described (entry width, Flare length and half approach distance) (AppD 61) in order

to arrive at an optimised design which the Ex A will be satisfied includes all relevant criteria and thus minimises land take.

It may then be found that with the correct entry widths and flares, and if appropriate increasing the width of the link road to four lanes as shown in the exemplar in CD116, dumbbells will be achievable which are significantly smaller than the present design to the benefit of users and well as the local community and the [redacted].

GHJ 18 January 2022

APPENDIX D DOCUMENTS START ON THE NEXT PAGE

2. Application of the DMRB

2.1 All works, including inspections on motorway and all-purpose trunk roads, on land owned, leased or managed by the Overseeing Organisation shall be undertaken in accordance with DMRB requirements appropriate to the intended use of the asset or road.

NOTE *The requirements appropriate to the new use or status of an asset or road are applied where there is a change in use or status. For example, the change in use or status can be improving a road to remove lower mandatory speed limits, or the upgrading of an all-purpose trunk road to motorway.*

2.1.1 Where the road is to be reduced in status, e.g. de-trunked or where the works are to be carried out on roads that are not part of the trunk road network and the use of the DMRB could result in significant over-specification, alternative documents such as the Manual for Streets [Ref 3.I] or Designing Streets 2010 [Ref 2.I] may be used with the approval of the Overseeing Organisation.

National Application Annexes of the Overseeing Organisations

2.2 National Application Annexes (NAA) shall be used where they exist.

NOTE 1 *NAAs allow Overseeing Organisations to complement, supplement or replace the requirements and advice contained in the main DMRB document.*

NOTE 2 *Other highway authorities or local authorities can develop their own application annexes to complement, supplement or replace the requirements and advice contained in the main DMRB document.*

Departures from requirements

Scope

2.3 Statutory and legislative requirements must always be followed.

NOTE *Departures are not applicable to statutory and legislative requirements.*

2.4 Where requirements of the Overseeing Organisation are not met, a departure application shall be submitted in accordance with the procedures required by the relevant Overseeing Organisation and approved:

1) before the design is finalised; and,
2) prior to their incorporation into the works.

2.4.1 Where requirements of the Overseeing Organisation are not met, departures should be submitted where:

1) it can be justified that a requirement is inappropriate in a particular situation;
2) the application of a requirement would have unintended adverse consequences;
3) innovative methods or materials are to be proposed;
4) a requirement not in the DMRB, NAA or MCHW is adopted as more appropriate in a particular situation; or,
5) an aspect not covered by requirements is identified.

NOTE *Departure applications are approved on a location-specific basis and relate to the particular circumstances identified in each submission; however, an approved departure can be quoted to support a new and similar submission.*

2.4.2 Bulk departure applications should be submitted in preference to a number of individual departures, where the individual departures share common methods or materials.

2.5 Each departure application shall be approved in accordance with the Overseeing Organisation's procedures before the design is finalised and prior to its incorporation into the works.

Design Manual for Roads and Bridges

Road Layout
Design

CD 122
Geometric design of grade separated junctions

(formerly TD 22/06, TD 39/94, TD 40/94)

Version 1.1.0

Summary

This document provides requirements for the geometric design of grade separated junctions.

Application by Overseeing Organisations
Any specific requirements for Overseeing Organisations alternative or supplementary to those given in this document are given in National Application Annexes to this document.

Feedback and Enquiries
Users of this document are encouraged to raise any enquiries and/or provide feedback on the content and usage of this document to the dedicated National Highways team. The email address for all enquiries and feedback is: Standards_Enquiries@highwaysengland.co.uk

This is a controlled document.

2

Latest release notes

Document code	Version number	Date of publication of relevant change	Changes made to	Type of change
CD 122	1.**1**.0	November 2021	Core document, England NAA	Incremental change to requirements

Revision 1.1.0 - new requirements for dual to single carriageway transitions added (para 2.2); datum points for APTR roads added; diverge Layout G moved from the ENAA to the main body of CD 122; A single lane drop with single lane connector road layout has been added; plus various wording improvement/corrections

Previous versions

Document code	Version number	Date of publication of relevant change	Changes made to	Type of change
CD 122	1	January 2020		
CD 122	0	August 2019		

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Introduction

Background

This document provides requirements and advice on the geometrical design of grade separated junctions. It merges and rationalises the content of TD 22/06 and TD 39/94 and incorporates the connector road elements of compact grade separated junctions, which were previously covered by TD 40/94.

With the incorporation of the requirements and advice of TD 39/94, this document covers the geometrical design of grade separated junctions with up to three lanes joining or leaving the mainline.

Notable changes from the previous documents listed above include:

1) merge layout referencing has been updated to better reflect the progression in capacity provision through the types; for example Layout D in TD 22/06 is now Layout A Option 2 in this document. The associated flow diagram references have therefore been updated to reflect this;
2) 3-lane merge and diverge layouts from TD 39/94 have been reviewed and amended to ensure that only those layouts that reflect the safe design ethos of the more contemporary TD 22/06 are included;
3) merge and diverge datum points that were originally included only in Interim Advice Note 149/17 for existing motorways have been included; and,
4) simplification of the curve widening requirements and advice relating to compact connector roads.

Assumptions made in the preparation of this document

The assumptions made in GG 101 [Ref 4.N] apply to this document.

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2. Selection of grade separated junction form

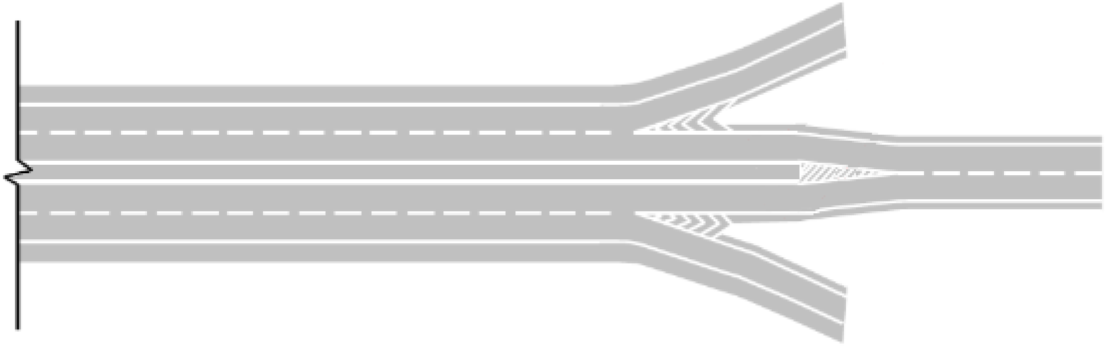
Full grade separated junctions

2.1 Full grade separated junctions shall only be used on dual carriageways and motorways.

NOTE 1 Appendix A provides examples of typical full grade separated junction layouts.

NOTE 2 The transition between a dual carriageway and a single carriageway can be formed using a merge and diverge as illustrated in Figure 2.1N2.

Figure 2.1N2 Dual carriageway to single carriageway transition



2.2 Where transitions between dual carriageway and single carriageways are at lane gain/lane drop grade separated junctions (as illustrated in Figure 2.1N2), there shall be a minimum distance of 400 metres between the end of the physical central reserve and the back of the merge nose.

NOTE A distance of 400 metres allows for an appropriate sequence of lane gain warning traffic signs to be accommodated prior to the merge.

2.3 The transitional section between a dual carriageway and a single carriageway at lane gain/lane drop grade separated junctions shall include hard strips.

2.3.1 A merge forming part of a grade separated junction should not be located within 500 metres upstream of a transition from a dual carriageway to a single carriageway, measured from the end of the merge taper to the start of the lane reduction hatching.

2.3.2 Interchanges may be provided at the intersection of motorways and/or dual carriageways to provide one or more free flow links to accommodate traffic flows that would normally exceed the capacity of priority junctions, roundabouts and signal-controlled junctions.

NOTE Appendix A provides examples of typical interchange layouts.

Compact grade separated junctions

2.4 Compact grade separated junctions shall not be used on motorways.

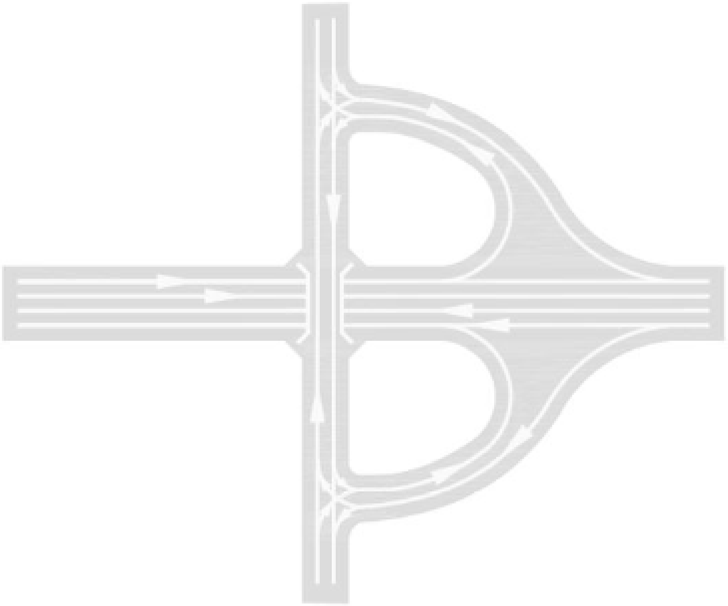
2.4.1 Compact grade separated junctions should not be used on dual- and single-carriageway roads when mainline flows are above 30,000 AADT.

2.5 On single carriageways, compact grade separated junctions shall only be used where the junction layout includes a section of physical central reserve on the mainline to prevent right turn movements.

NOTE Compact grade separated junctions consist of left-in left-out priority junction(s), between the mainline and connector road, designed in accordance with CD 123 [Ref 2.N], and connector roads designed in accordance with this document.

Figure A.3 Typical layout of grade separated junction - half-cloverleaf quadrants 1 and 3

Figure A.4 Typical layout of grade separated junction - half-cloverleaf quadrants 2 and 3



A3 Dumbbell roundabout

A dumbbell roundabout layout includes slip roads leading to/from two roundabouts. In relation to traffic flow capacity, a dumbbell roundabout layout can be considered an intermediate between the diamond/half-cloverleaf and the two bridge roundabout layouts.

The dumb-bell roundabout has the advantage of requiring less land than both the diamond and the two bridge roundabout layouts. It also requires only one bridge.

It is important to ensure that the link road between the two roundabouts can provide queuing storage capacity otherwise queuing could extend back onto the roundabouts.

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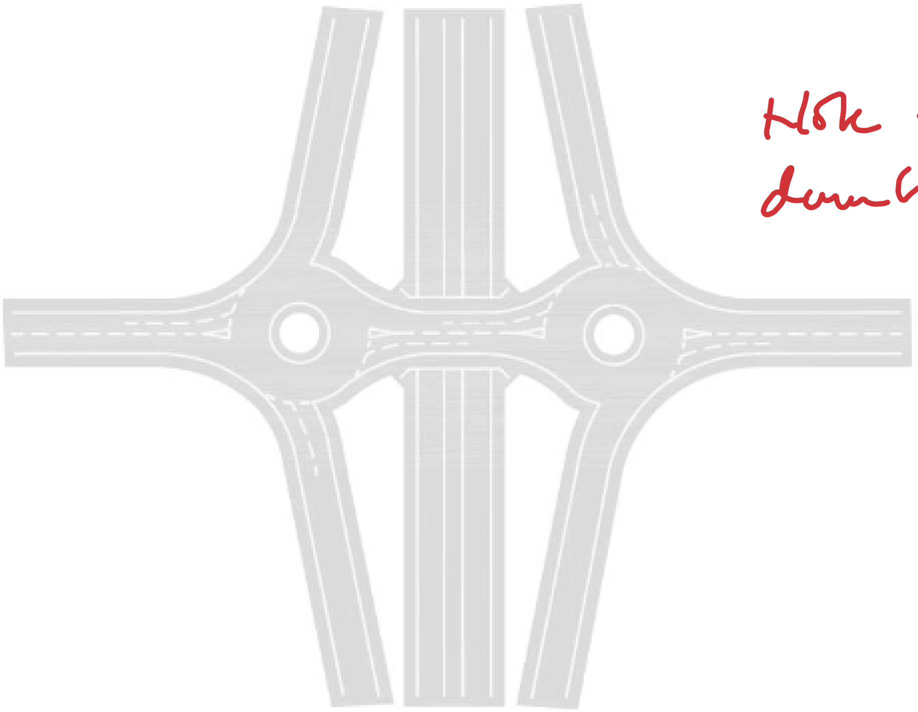
Requirements and advice on the geometric design of the roundabout elements of this layout are provided in CD 116 [Ref 3.I].

Figure A.5 illustrates a dumbbell roundabout layout.

Figure A.5 Roundabout - dumbbell configuration (one bridge & two roundabouts)



Note small dumbbells and four lane link.

A4 Two-bridge roundabout

The most common grade separated junction layout is the the two-bridge roundabout. They provide greater traffic flow capacity than the dumbbell roundabout layout and are less complex from a road user perspective. They do however require two bridges and have a greater footprint.

Requirements and advice on the geometric design of the roundabout elements of this layout are provided in CD 116 [Ref 3.I].

Figure A.6 illustrates a two bridge roundabout layout.

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Design Manual for Roads and Bridges

Road Layout
Design

CD 116
Geometric design of roundabouts

(formerly TD 16/07, TD 50/04, TD 51/17, TD 54/07, TA 23/81, TA 78/97, TA 86/03, TD 70/08)

Revision 2

Summary
This document provides requirements for the geometric design of roundabouts.

Application by Overseeing Organisations
Any specific requirements for Overseeing Organisations alternative or supplementary to those given in this document are given in National Application Annexes to this document.

Feedback and Enquiries
Users of this document are encouraged to raise any enquiries and/or provide feedback on the content and usage of this document to the dedicated Highways England team. The email address for all enquiries and feedback is: Standards_Enquiries@highwaysengland.co.uk

This is a controlled document.

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Introduction

Background

Roundabouts are junctions with a one-way circulatory carriageway around a central island. Vehicles on the circulatory carriageway have priority over those approaching the roundabout. This document provides the geometric design requirements for roundabouts applicable to new and improved junctions on trunk roads.

The principal objective of roundabout design is to minimise delay for vehicles whilst maintaining the safe passage of all road users through the junction. This is achieved by a combination of geometric layout features that, ideally, are matched to the flows in the traffic streams, their speed, and to any local topographical or other constraints such as land availability that apply. Location constraints are often the dominating factor when designing improvements to an existing junction, particularly in urban areas.

This document should be read in conjunction with other documents within the DMRB and other sources of best practice/guidance.

TD 16 2007 was used as the main source of requirements for normal and compact roundabouts. The relevant requirements and corresponding advice from TD 16 2007 are included in Section 3 of CD 116, though elements are also present in Sections 2, 8 and the appendices of CD 116.

TD 50 2004 was used as the main source of requirements for signal-controlled roundabouts. The relevant requirements and corresponding advice from TD 50 2004 are included in Section 4 of CD 116, though elements are also present in Section 2 of CD 116.

TD 54 2007 was used as the main source of requirements for mini-roundabouts. The relevant requirements and corresponding advice from TD 54 2007 are included in Section 5 of CD 116, though elements are also present in Sections 2, 8 and the appendices of CD 116.

TD 51 2017 was used as the main source of requirements for segregated left turn lanes and subsidiary deflection islands. The relevant requirements and corresponding advice from TD 51 2017 are included in Sections 6 and 7 of CD 116, though elements are also present in Sections 2, 8 and the appendices of CD 116.

Elements relating to the placement of pedestrian, cycling and/or equestrian crossings at roundabouts are included within this document. However, the specific details relating to the design of crossings themselves are covered in GG 142 [Ref 18.I], CD 195 [Ref 2.I], CD 143 [Ref 3.I] and CD 143 [Ref 3.I].

Assumptions made in the preparation of this document

The assumptions made in GG 101 [Ref 4.N] apply to this document.

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Terms (continued)

Terms	Definition
Exit width	The width of the carriageway on the exit. NOTE 1: Exit width is measured in a similar manner to the entry width. NOTE 2: Exit width is the distance between the nearside kerb and the exit median (or the edge of any splitter island or central reserve) where it intersects with the outer edge of the circulatory carriageway.
Full-time control	The condition where signals are permanently operating.
Gap acceptance time	The time taken for a vehicle to travel from a stationary position at the give way line to the conflict point.
Grade separated roundabout	A roundabout with at least one approach coming from a road at a different level. NOTE 1: The geometric design of grade separated roundabouts follows the requirements for a normal roundabout.
Gyratory	A road system which consists of one-way links connected together, to make it possible for traffic to circulate along one or more links before exiting.
Indirect signal control	The condition where the signals are situated at such a distance away from the roundabout entry, that the entry continues to operate in a self-regulating manner under normal priority control.
Inscribed circle diameter (ICD)	The diameter of the largest circle that can be inscribed within the roundabout kerbs. NOTE 1: The symbol for the ICD is D.
Intermediate give way line	A give way line at the end of the link between the two roundabouts, on a double roundabout.
Intervisibility zone	At a signal-controlled roundabout, a zone identified for the purpose of assessing visibility within the junction between drivers at each stop line, or between drivers and pedestrians. NOTE 1: The intervisiblility zone facilitates identification of measures to mitigate the effect of obstructions.
Lane bifurcation	One lane widening into two.
Large roundabout	A roundabout with an ICD in excess of 100 metres. NOTE 1: For design purposes, a large roundabout is classed as a normal roundabout.
Lateral shift	The alteration of the vehicle path to the side (laterally). NOTE 1: On the approach to a mini-roundabout, a lateral shift is used to create some deflection and is provided by the use of road markings.
Median line	The centre line (situated between the two opposing streams of traffic) on a single carriageway.

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2. Roundabout types

General

2.1 At-grade roundabouts shall not be provided on motorways.

NOTE A roundabout designed as part of a grade separated junction follows the same requirements as a normal roundabout.

2.1.1 On all-purpose trunk roads, roundabouts should not be located:

1) on rural three-lane dual carriageway roads, as it is difficult to achieve suitable deflection;
2) where an approach road exceeds a gradient of 2% over the desirable minimum stopping sight distance (SSD) measured from the give way or stop line.

2.1.2 A roundabout should have 3 or more arms.

NOTE 1 In addition to operating as a junction, a roundabout can also:

1) *facilitate changes in road standard (for example, between dual and single carriageways or grade separated and at-grade junction roads);*
2) *emphasise the transition between rural and urban environments;*
3) *allow U-turns;*
4) *facilitate heavy right turn flows;*
5) *mitigate against the inconvenience of nearby banned right turns;*
6) *bring a route through a sharp or sudden change of direction.*

NOTE 2 On average, roundabouts are considered safer than other junction types, however, this will not be the case for all road users or site specific situations (based on RCGB 2004 [Ref 8.I]).

NOTE 3 In providing a roundabout, combinations of the following factors are known to result in load shedding:

1) *long straight high speed approach or circulatory of the roundabout;*
2) *inadequate entry deflection;*
3) *low circulating flow combined with excessive visibility to the right;*
4) *significant tightening of the turn radius partway round the roundabout;*
5) *excessive crossfall changes on the circulatory carriageway or the exit;*
6) *excessive outward sloping crossfall on a nearside lane of the circulatory carriageway;*
7) *excessive entry deflection.*

NOTE 4 Roundabouts can include additional design features, such as segregated left turn lanes (SLTL), subsidiary deflection islands (SDI) and differential acceleration lanes (DAL) where these will assist the smooth flow of traffic through the junction.

NOTE 5 At a roundabout, the accident risk is likely to increase with the number of entries provided (based on a research study between 1999 and 2003, TRL UPR/SE/194/05 [Ref 17.I]).

NOTE 6 Designing roundabouts to the requirements and advice provided within this document can help reduce risks of accidents involving powered two-wheelers (PTWs). The IHE Guidelines for Motorcycling Guidelines for Motorcycling. [Ref 19.I] provides guidance on PTW issues.

2.1.3 On single carriageway roads, roundabouts may:

1) be sited to optimise the length of straight overtaking sections; and
2) provide an overtaking opportunity by having a short length of two lanes on the exit arms of the roundabout.

2.1.4 Roundabouts should be made conspicuous through the provision of clear signage and road markings.

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NOTE *Where provided adjacent to prohibited turning movements at other junctions, there is a risk that drivers will use the mini-roundabout for U-turns.*

2.9.3 The introduction of a mini-roundabout should be assessed to check that queues created by the mini-roundabout do not adversely impact upon the operation and safety of the junction or adjoining network.

2.10 Mini-roundabouts shall only have 3 or 4 arms.

2.11 A 3-arm mini-roundabout shall not be used where the predicted two-way annual average daily traffic flow (AADT) on any arm of a junction is below 500 vehicles a day.

2.12 A 4-arm mini-roundabout shall not be used where the predicted two-way annual average daily traffic flow (AADT) on any arm of a junction is below 500 vehicles a day unless the design incorporates features to encourage vehicles to give way on all approaches.

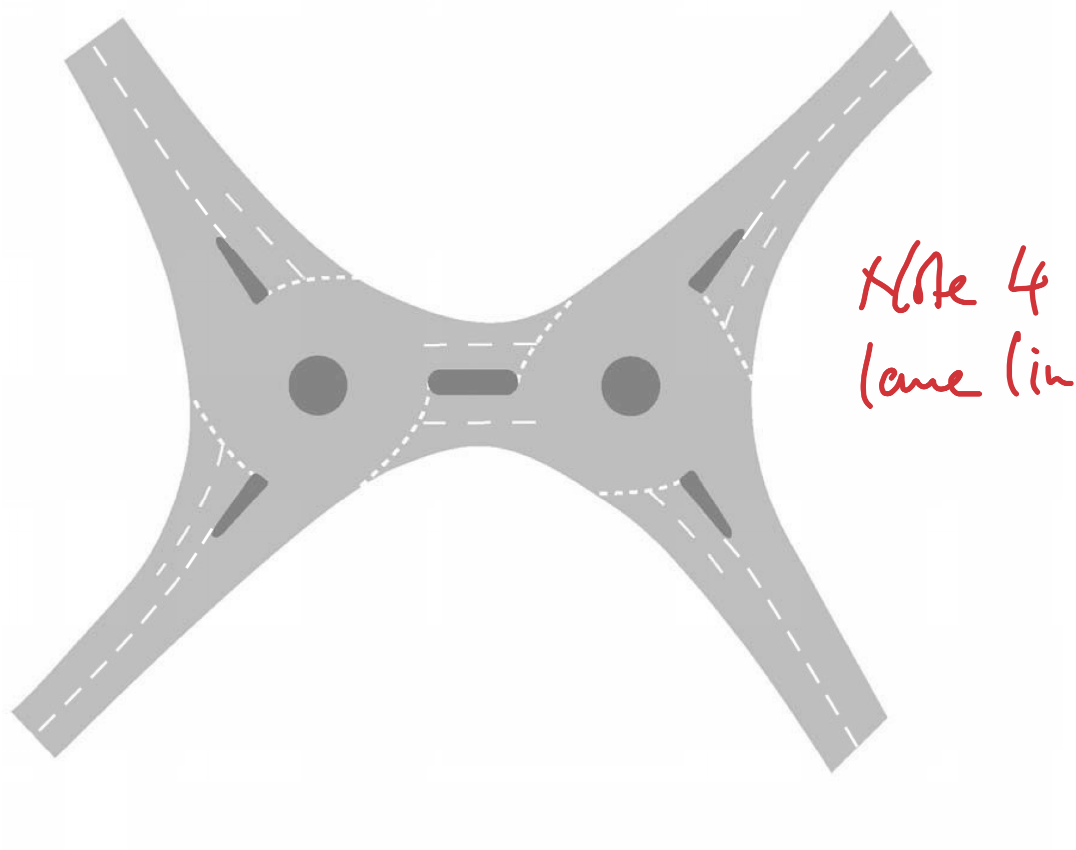
NOTE *Four-arm mini-roundabouts introduce additional conflicts and can create difficulty for drivers' perceptions of the layout and turning flows.*

2.12.1 A 4-arm mini-roundabout should not be used where the sum of the maximum peak hour entry flows for all arms exceeds 500 vehicles per hour.

Double roundabouts

2.13 A double roundabout (as illustrated in Figure 2.13) shall not be designed as two independent roundabouts.

Figure 2.13 Illustrative layout of a double roundabout



Note 4
lane link.

NOTE 1 *A double roundabout can comprise two normal, compact or mini-roundabouts.*

NOTE 2 *Double roundabouts can be used:*

||

1) *to improve an existing staggered junction (since they avoid the need to realign one of the approach roads and can be less expensive to construct than larger single island roundabouts);*
2) *for joining two parallel routes separated by a feature such as a river, a railway line or a motorway;*
3) *at overloaded single roundabouts where, by reducing the circulating flow past critical entries, they increase capacity;*
4) *at junctions with more than four entries (since they can achieve increased capacity and improved safety with a more efficient use of the space, compared to a large roundabout which could generate high circulatory speeds, reducing the capacity and safety).*

NOTE 3 *Double mini-roundabouts separated by a short link can be used to improve traffic flows by replacing:*

1) *a pair of closely spaced or staggered junctions; or*
2) *an existing normal roundabout.*

2.13.1 On a double roundabout, the lane use (based on the turning volumes) on the link between the two roundabouts should be balanced.

NOTE *Often the link between the two roundabouts does not provide distance to change lanes. Reducing entry capacity on entries that feed the link can prevent traffic blocking back onto the roundabouts, increasing the overall capacity.*

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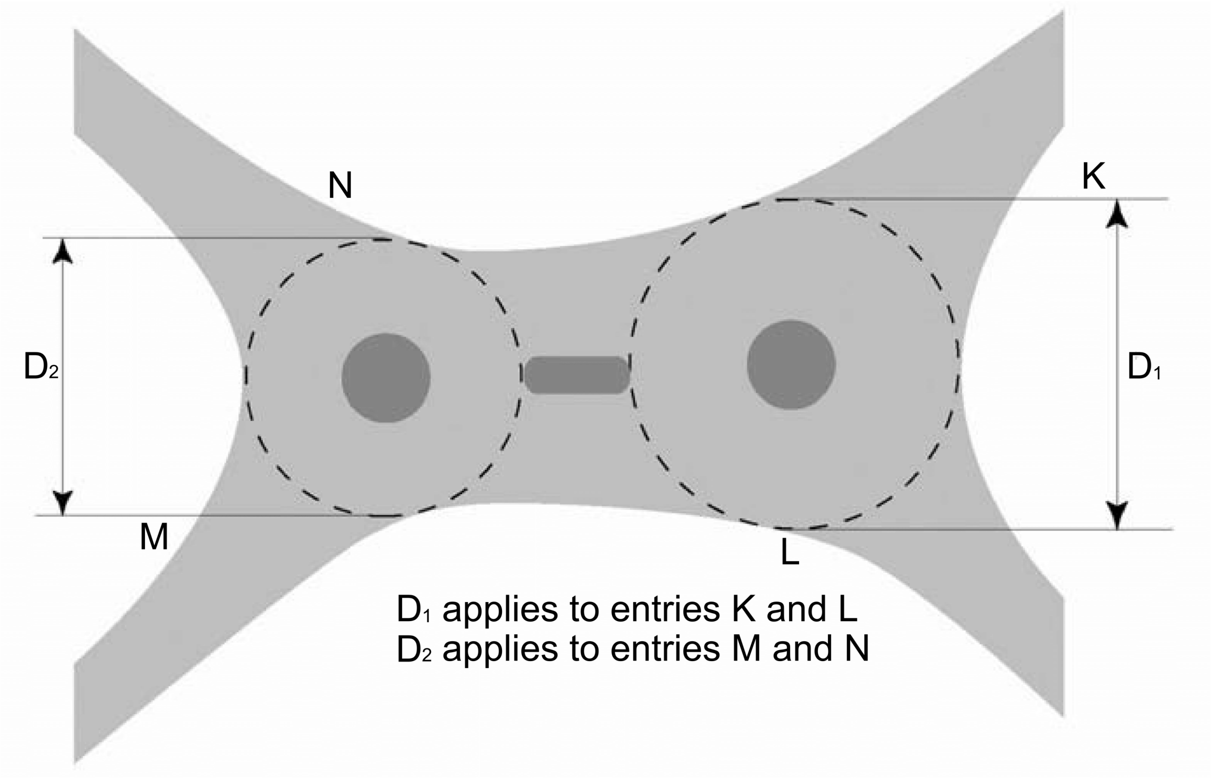
Figure 3.4 Inscribed circle diameter at double roundabouts



3.5 The minimum value of the ICD for a normal or compact roundabout shall be 28 metres; this is the smallest roundabout that can accommodate the swept path of the design vehicle.

3.5.1 The ICD of a compact roundabout should not exceed 36 metres.

3.5.2 The ICD of a normal roundabout should not exceed 100 metres.

NOTE 1 Large ICD can lead to excessive vehicle speeds on the circulatory carriageway.

NOTE 2 More than one roundabout can be used to mitigate against an ICD exceeding 100 metres.

Circulatory carriageway

3.6 The width of the circulatory carriageway for normal or compact roundabouts shall be between 1.0 and 1.2 times the maximum entry width, excluding any overrun area.

NOTE The entry width is shown on Figure 3.11.

3.6.1 The circulatory carriageway of normal or compact roundabouts should be circular and of constant width.

NOTE 1 Roundabouts can be non circular due to staggered road arrangements, land constraints, to allow for dominant mainline flow capacity, and/or to cater for associated structures and slip road layouts for grade separated junctions.

NOTE 2 Varying widths of circulatory carriageways can be used to optimise safety and capacity at roundabouts where traffic flows differ widely between arms.

NOTE 3 Advice on designing road markings on the circulatory carriageway and approaches is provided in Appendix D.

3.6.2 Dedicated lane signs and associated road markings should be used on the approach to a signal controlled roundabout where a single lane divides into separate lanes.

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NOTE 2 *Further guidance is provided in Section 3, "Lane direction markings".*

3.6.15 Lane direction arrows denoting a left turn immediately prior to an exit may be utilised and prove beneficial to signify that a lane drop around the circulatory carriageway is approaching.

NOTE 1 *The use of road markings can be beneficial in reducing three types of accident at roundabouts:*

1) *side-to-side collisions on the circulatory carriageway;*
2) *drivers being forced onto the central island; and*
3) *collisions between entering and circulating vehicles.*

NOTE 2 *Road markings can help reduce accidents by guiding drivers; on the approach, onto and around the circulatory carriageway. This in turn reduces weaving on the circulatory carriageway and can reduce the uncertainty experienced by a driver at the give way line as to the path and destination of circulating vehicles, particularly at larger roundabouts.*

NOTE 3 *On roundabouts where flow patterns have changed since design, road markings can help to:*

1) *improve throughput at high levels of traffic flow;*
2) *cater for particularly high turning movements;*
3) *smooth the flow at roundabouts with irregular geometry;*
4) *improve safety.*

3.6.16 The use of route numbers and/or destinations can also assist drivers' understanding, although their use should not clutter the circulatory carriageway or make the markings unduly confusing, as may happen where destinations are seen to change between circulatory lanes.

3.6.17 Spiral hatch markings should be provided on larger diameter normal roundabouts where the number of circulating lanes is to be varied to aid general operation.

3.6.18 Spiral markings and vehicle paths through roundabouts should:

1) follow smooth flowing alignments;
2) have gradually increasing radius; and
3) avoid reducing radius.

NOTE *Further guidance on spiral markings is provided in Appendix D.*

3.6.19 Spiral marking radii should be gradual to avoid:

1) increasing the likelihood of load shedding by HGV; or
2) causing loss of control accidents (particularly for PTW).

NOTE *Spiral markings can improve lane discipline on the circulatory carriageway. Designation of lanes on the approach can also help.*

Central island

3.7 The central island of normal and compact roundabouts shall be at least 4 metres in diameter.

3.7.1 The central island of normal and compact roundabouts should be circular.

NOTE 1 *The central island can be non-circular due to staggered road arrangements, land constraints, to allow for dominant mainline flow capacity, and/or to cater for associated structures and slip road layouts for grade separated junctions.*

NOTE 2 *At grade separated junctions, the layout of the slip roads and associated structures can influence the shape of the central island.*

3.7.2 The central island of normal and compact roundabouts should be kerbed.

3.7.3 To achieve circulatory visibility requirements, the use of planting on roundabouts within central islands of 10 metres or less should be avoided.

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NOTE As long as visibility is not restricted, planting on central islands less than 1 metre in height can help to mitigate against any see through effect, which can result in failure to give way, particularly on roundabouts with downhill approaches.

3.7.4 Solid features such as statues, trees or rocks should not be placed on the central islands of roundabouts with high speed approaches, or anywhere within the highway boundary adjacent to the roundabout where there is a high risk of collision.

3.7.5 Non-passive infrastructure and landscaping may be located on the central island of urban roundabouts where there is sufficient space to do so and there are low speed approaches on all arms.

NOTE 1 Central islands with diameters greater than 35 metres can provide sufficient space for the provision of non-passive infrastructure or landscaping on urban roundabouts.

NOTE 2 Further requirements and advice for the landscape design of the central island are provided in LD 117 [Ref 4.I].

Overrun areas

3.8 A roundabout shall provide space for the turning movements of the design vehicle in accordance with Table 3.8.1N1.

3.8.1 An overrun area may be necessary (Figure 3.8.1N1) to provide sufficient entry deflection for vehicles at compact or smaller normal roundabouts while still allowing large vehicles to circulate.

NOTE 1 An overrun area for a compact or smaller normal roundabout is illustrated in Figure 3.8.1N1, where:

1) *a, is the main central island;*
2) *b, is the central overrun area (where provided);*
3) *c, is the remaining circulatory carriageway width (1.0 to 1.2 times the maximum entry width);*
4) *d, is the vehicle;*
5) *e, is the 1 metre minimum clearance from the edge of kerbing (provided on both the inside and the outside of the circulatory carriageway);*
6) *f, is the ICD;*
7) *R1, is the radius from the centre of the roundabout to the outside of the inner 1 metre clearance (e) (values for R1 can be found in Table 3.8.1N1); and*
8) *R2, is the radius from the centre of the roundabout to the inside of the outer 1 metre clearance (e) (values for R2 can be found in Table 3.8.1N1).*

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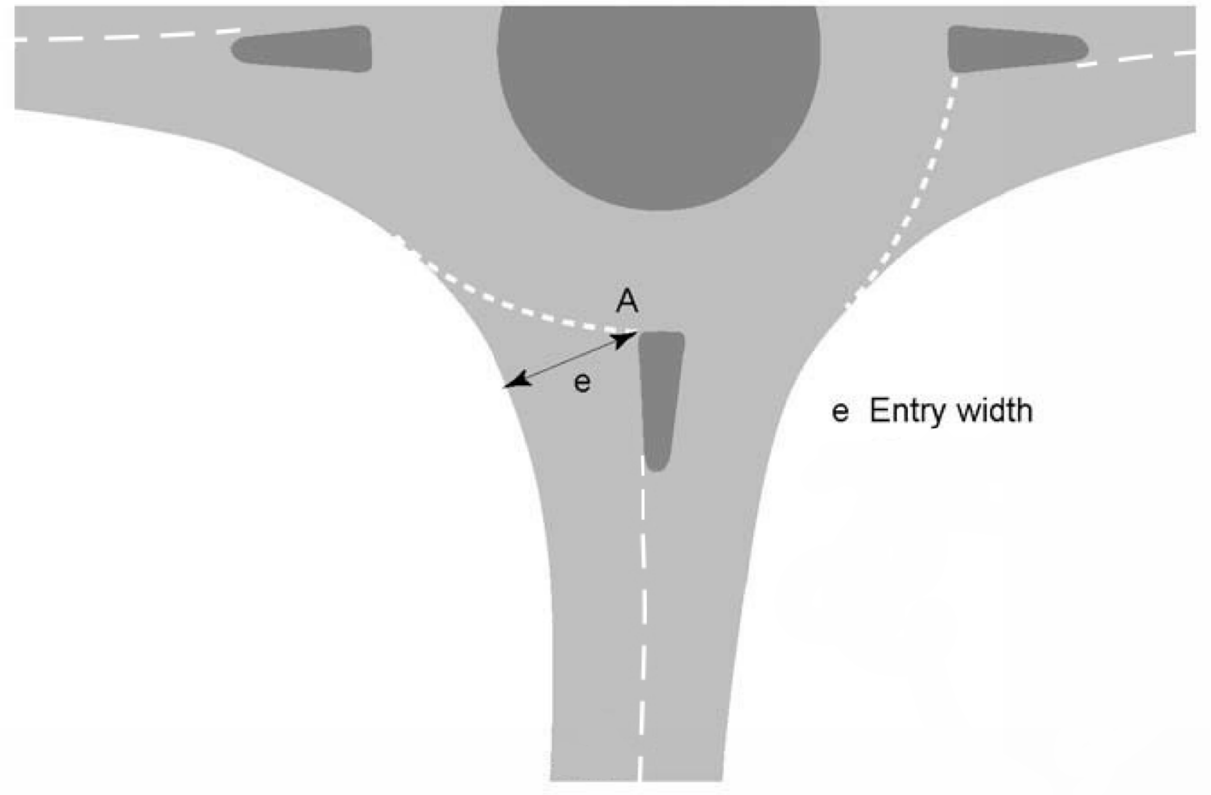
Figure 3.11 Entry width and approach half width



NOTE 1 *The entry width is the width of the carriageway at the point of entry.*

NOTE 2 *For capacity assessment, the measurement is taken as the total width of the lanes which drivers are likely to use.*

NOTE 3 *Entry width and sharpness of flare are the most important determinants of capacity, whereas entry deflection is the most important factor for safety as it governs the speed of vehicles through the roundabout.*

NOTE 4 *Advice on calculating the capacity of the roundabout is provided in Appendix B.*

3.11.1 Where there is white edge lining or hatching the measurement should be taken between the edges of the markings closest to the running lanes rather than kerb to kerb.

3.12 On a single carriageway approach to a normal roundabout, the entry width shall not exceed 10.5 metres.

3.12.1 On a single-carriageway road, where predicted flows are low and increased lane width is not operationally necessary, a compact roundabout with single lane entries should be used.

NOTE *The use of single lane entries can result in entry closures during planned maintenance and would be subject to an agreed traffic management plan with the Overseeing Organisation.*

3.13 On a dual carriageway approach to a normal roundabout, the entry width shall not exceed 15 metres.

3.14 Lane widths at the give way line for normal and compact roundabouts shall be no less than 3 metres and no greater than 4.5 metres.

3.14.1 At the give way line, a lane width value of 4.5 metres should be used at single lane entries.

3.14.2 At the give way line, lane width values of between 3 metres and 3.5 metres should be used at multi-lane entries.

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10. Informative references

The following documents are informative references for this document and provide supporting information.

Ref 1.I	Transport Research Laboratory. TRL LR788, 'Articulated Vehicle Roll Stability - Methods of Assessments and Effects of Vehicle Characteristics'
Ref 2.I	Highways England. CD 195, 'Designing for cycle traffic'
Ref 3.I	Highways England. CD 143, 'Designing for walking, cycling and horse riding (vulnerable users)'
Ref 4.I	Highways England. LD 117, 'Landscape design'
Ref 5.I	The Stationery Office. LTN 1/07, 'Local Transport Note 1/07 - Traffic calming'
Ref 6.I	The Stationery Office. LTN 1/09, 'Local Transport Note 1/09 - Signal controlled roundabouts'
Ref 7.I	The Stationery Office. LTN 1/95, 'Local Transport Note 1/95 - The assessment of pedestrian crossings'
Ref 8.I	The Stationery Office. RCGB 2004, 'Road Casualties Great Britain (The Casualty Report)'
Ref 9.I	TRL. Marie C Semmens. TRL RR142, 'The Capacity of Entries to Very Large Roundabouts'
Ref 10.I	Transport Research Laboratory. Marie C Semmens. TRL SR721, 'The Capacity of Some Grade-Separated Roundabout Entries'
Ref 11.I	The Stationery Office. SI 1999/1025, 'The Highways (Road Humps) Regulations 1999'
Ref 12.I	The Journal of the Institution of Highway Engineers . R. Stockdale. Stockdale Method, 'The Vertical Alignment Design of Roundabouts'
Ref 13.I	Department for Transport. TAL 2/05, 'Traffic Advisory Leaflet 2/05 - Traffic Calming Bibliography'
Ref 14.I	Department for Transport. TAL 7/95, 'Traffic Advisory Leaflet 7/95: Traffic Islands for Speed Control'
Ref 15.I	Transport Research Laboratory. G L Burtenshaw . TRL AG72, 'TRL Application Guide 72 - Junctions 9 User Guide'
Ref 16.I	Transport Research Laboratory. TRL LR942, 'TRL Report LR942 - The Traffic Capacity of Roundabouts '
Ref 17.I	Transport Research Laboratory. TRL UPR/SE/194/05, 'TRL Unpublished Report UPR/SE/194/05'
Ref 18.I	Highways England. GG 142, 'Walking, cycling and horse-riding assessment and review'
Ref 19.I	Institute of Highway Engineers. Guidelines for Motorcycling., 'www.motorcycleguidelines.org.uk'
Ref 20.I	Transport Research Laboratory. R D Helliar-Symons. TRL LR1010, 'Yellow Bar Experimental Carriageway Markings - Accident Study'

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Appendix B. Roundabout capacity formula

This appendix provides the capacity formula utilised in the evaluation of a roundabout design, the formula shown forms the basis of ARCADY software.

B1 Roundabout capacity

B1.1 Roundabout capacity formula

The best predictive equation for the capacity of any roundabout entry (except those at grade-separated junctions and mini-roundabouts, see below) found by research to date is as follows:-

Equation B.1 Predictive equation for the capacity of roundabout entries except at grade separated junctions and mini-roundabouts

$$Q_E = k(F - f_cQ_c)$$

where:

Q_E	Entry flow in pcu/hour (1 HGV = 2 pcu)
Q_c	Circulating flow across the entry in pcu/hour
k	1 - 0.00347 (▯ - 30) - 0.978 {(1/r) - 0.05}
F	$303x_2$
f_c	$0.210t_D$ (1 + $0.2x_2$)
t_D	1 + 0.5 / (1+M)
M	exp {(D-60)/10}
x_2	v + (e-v) / (1+2s)
S	1.6 (e-v) / l'
e, v, l'[1], S, D, ▯	are geometric parameters defined in section 3 and ranges detailed in Tables B.1 and B.2

The value of Q_E will be:

1) the solution of "k (F - f_c Q $_c$)", when f $_c Q_c$ is less than or equal to F; but
2) "0", when f_c Q_c is greater than F.

At grade separated junctions, there are differences of operation and the "F" term in the above equation becomes "1.11F" and the "f_c" term becomes "1.4f_c". These differences are incorporated in the ARCADY program.

The ranges of the geometric parameters input to the ARCADY database were as follows in Table B.1 (see Table B.2 in section B1.1.1 below for the recommended limits to be used in new design):-

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Table B.1 Ranges of geometric parameters within the ARCADY database

Parameter symbol	Parameter	Parameter range (in ARCADY)
e	entry width	3.6 - 16.5 metres
v	approach half width	1.9 - 12.5 metres
l'	average effective flare length	1 - ∞ (metres)
S	sharpness of flare	0.0 - 2.9
D	ICD	13.5 - 171.6 metres
▯	entry angle	0.0 - 77 (degrees)
r	entry radius	3.4 - ∞ (metres)

Research for the original calculation above is contained in TRL SR721 [Ref 10.I], this research was further expanded on in TRL RR142 [Ref 9.I] to improve capacity modelling for large roundabouts and grade separated junctions using ARCADY.

Additionally, current ARCADY software has a queue simulation mode that considerably improves specific limitations of the original software. This queue simulation mode allows lane starvation to be evaluated so that it can be avoided in further roundabout design stages.

Guidance on the calculation for mini-roundabouts can be found in TRL AG72 [Ref 15.I].

B1.1.1 Practical limits of geometric parameters

Trial designs in ARCADY should be calibrated where necessary to obtain operational efficiency by adjusting the entry widths and the effective length of flares. Whilst the formula above gives the range of the parameters for which the predictive equation is valid, the following list gives the normal practical limits of those parameters in a new design.

Table B.2 Practical limits of geometric parameters in new design

Parameter symbol	Parameter	Parameter range (practical limits)
e	entry width	4.0 - 15.0 metres
v	approach half width	2.0 - 7.3 metres
l'	average effective flare length	1.0 - 100.0 metres
D	ICD	15 - 100 metres
▯	entry angle	10 - 60 degrees
r	entry radius	6.0 - 100.0 metres

The circulatory carriageway width around the roundabout should be constant between 1.0 to 1.2 times the greatest entry width, subject to a maximum of 15 metres.

Sections 3, 4, 5, 6 and 7 provide specific requirements and advice for all of the geometric parameters.

B1.2 Entry angle measurement where distance between entry and exit exceeds 30 metres

The methods of measuring the entry angle at conventional large or small normal roundabouts are given in Section 3. For roundabouts, where the distance between the offside of an entry and the next exit is more than 30 metres and is approximately straight, the construction of the entry angle, ϕ , is illustrated in Figure B.1.

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ROUNDABOUT CAPACITY:

THE UK EMPIRICAL METHODOLOGY

1 Introduction

Roundabouts have been used as an effective means of traffic control for many years. This article is intended to outline the substantial research programme undertaken by the UK Government over a period of some 10-12 years which resulted in the establishment of robust, dependable relationships both for the capacity and the likely accident record of roundabouts. These relationships were subsequently used to produce the ARCADY software package, which is still in use today.

The whole purpose of the research programme was to produce information that could be used to design roundabouts that meet operational requirements. There was no intention to produce theoretically pleasing equations that explained the processes involved, but instead purely to give practical links between geometry, capacity/delay and accidents.

2 Basic characteristics of roundabouts

Roundabouts have a number of advantages over traffic signals. Although they take more land, they are self-regulating in that the demands control the distribution of capacity between the arms, so without any form of imposed control, efficient regulation of traffic is achieved. Roundabouts can deal with a range of demands that would definitely require retiming of signals.

UK experience has also shown that for similar traffic loads, roundabouts return an injury accident rate far less than that of traffic signals.

As far as delays are concerned, roundabouts give lower delays during off-peak conditions, due to their inherently flexible operation, even though delays may be higher during peak hours. Over a 24 hour period, total delays are reduced, thanks to the greater number of hours of off-peak operation.

There are of course good roundabouts and bad roundabouts; no amount of clever software can ever get away from the need to have good traffic engineers responsible for the achievement of successful and safe operation.

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4 Research conclusions

All the experimental measurements indicated that the relationship between entry capacity and circulating flow at a roundabout is linear, and that the characteristics of this linear relationship can be successfully predicted from knowledge of the geometry, flows and turning movements. This is a very important result, as it removed any need to understand and define the extremely complex and interactive actions of individual drivers as they use the roundabout.

The research used linear regression to establish statistically significant relationships between entry capacity and various geometric parameters. The dimensions of the study roundabouts were carefully measured and the entry capacity measured during periods of at-capacity operation.

The geometries that were measured, along with the range of values observed, are shown in the following table. Those found to be significant, and subsequently used in ARCADY, are highlighted. The other geometries were found to be insignificant to entry capacity.

Variable	Range
* **Entry width**	**3.6 – 16.5 m**
Entry width on previous entry	3.6 – 15.0 m
* **Approach width**	**1.9 – 12.5 m**
Approach width on previous entry	2.9 – 12.5 m
Circulation width at entry	4.9 – 22.7 m
Circulation width between entry and next exit	7.0 – 26.0 m
Effective flare length (construction 1)	1 – infinity (m)
* **Effective flare length (construction 2)**	**1 – infinity (m)**
Sharpness of flare	**0 – 2.9 m**
Entry radius	**3.4 – infinity (m)**
Entry (conflict) angle	**0 – 77 °**
Inscribed circle diameter	**13.5 – 171.6 m**
Weaving section length (straight-line distance between entry and next exit)	9.0 – 86.0 m

This led to comparatively simple relationships which have proved remarkably robust. Of these significant variables, three are of particular importance: most of all entry width, and then approach width and flare length. The remaining geometries have lesser effects.

The effect of entry width and flare length on entry capacity is illustrated in the following graphs, for an example roundabout.

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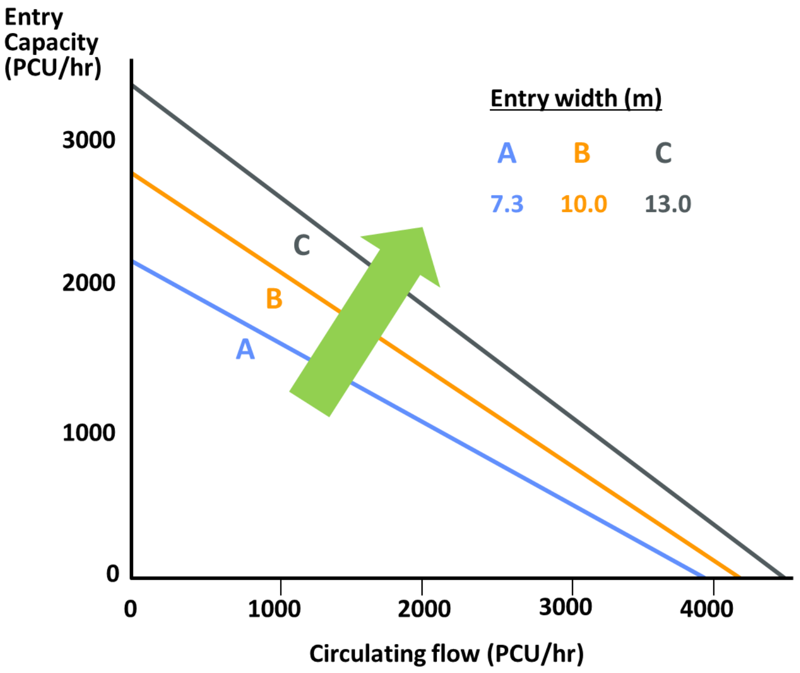
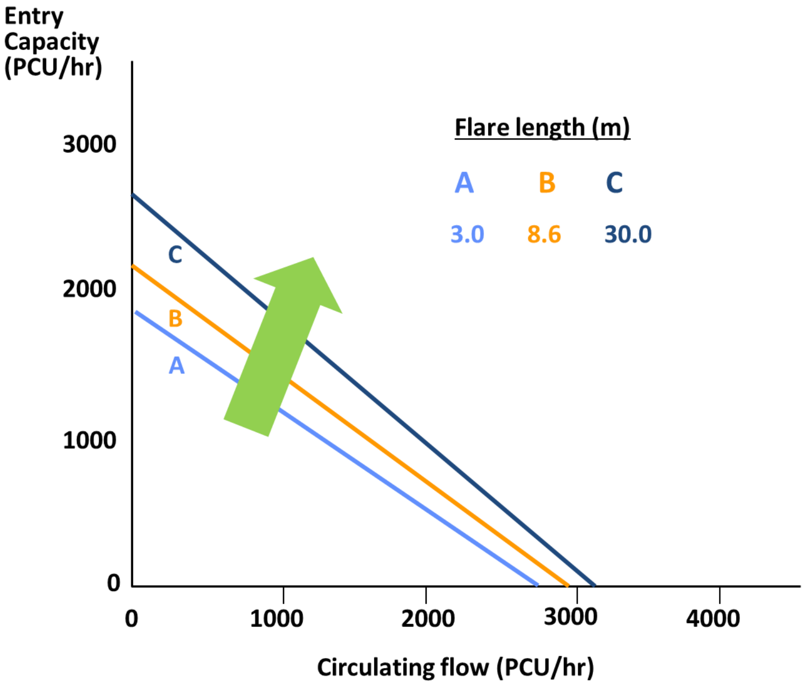

Entry Capacity (PCU/hr)
3000
2000
1000
0
0
1000
2000
3000
4000
Circulating flow (PCU/hr)
Entry width (m)
A
B
C
7.3
10.0
13.0
C
B
A


Entry Capacity (PCU/hr)
3000
2000
1000
0
0
1000
2000
3000
4000
Circulating flow (PCU/hr)
Flare length (m)
A
B
C
3.0
8.6
30.0
C
B
A

20

4.1 Entry width and flaring

A vital area in which the empirical method gives useful results is in dealing with local widening, or flaring.

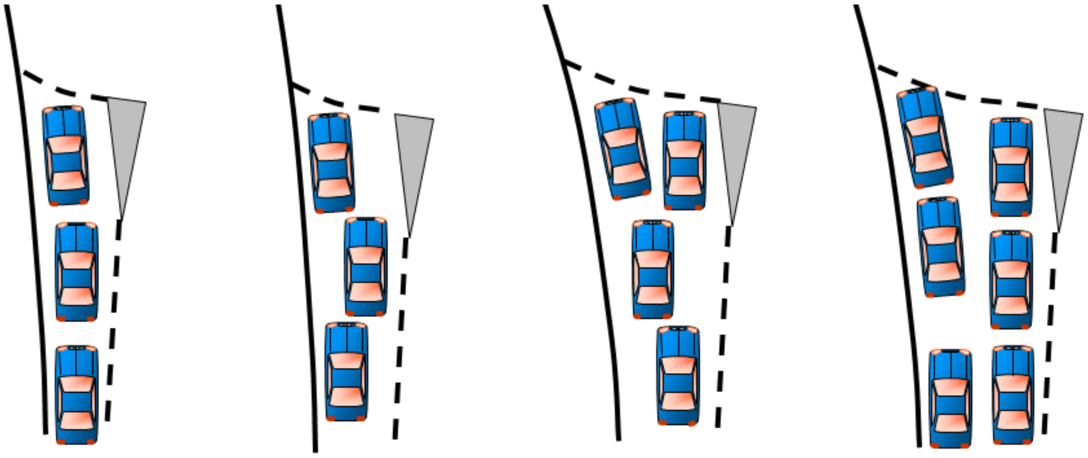
The experimental data from road measurements showed that there is a continuous (smooth) relationship between entry capacity and entry width. This may at first seem unlikely, as surely there must be either one queue or two (or more) queues at entry. Close observation of the real processes at a roundabout entry, however, will show that as entry width increases above one lane, the way drivers queue steadily changes.

Initially, the extra width is used to form a queue in which drivers tend to queue displaced sideways from the vehicle in front; in this mode they are prepared to queue closer to the vehicle ahead, and are therefore able to accept shorter follow on times. Not all drivers do this, but as the entry width increases, more are prepared to, so capacity rises steadily. The extra width also means that there is more freedom for individual vehicles to position themselves, perhaps based on their intended trajectory across the give-way line.

As the entry width increases further, the more adventurous are prepared to squeeze up alongside the driver ahead, introducing a degree of double queuing. This takes two actions - first, the driver ahead must be to one side, not centrally placed, and second the following driver must be prepared to accept a small space. Thus the adventurous and/or the owners of small vehicles (or two-wheelers at smaller widths) will do this.

As entry width increases further, these processes develop until two full queues are achieved all the time, again giving this continuous increase in capacity with entry width. The form of the flared area also affects this process: a very sudden and short flare makes it more difficult for drivers to use the full entry all the time and so gives less capacity than a more gently developed flare, even for the same entry width.

When there are lane markings painted on the road, many of the considerations above still apply. For example, two large vehicles may struggle to queue side by side in two narrow lanes, but would be more likely to do so if both lanes were made slightly wider.



Capacity is a continuous function of entry width. Queueing slowly changes from always single file to staggered (closer) queueing to some double file finally to 2 full queues, as entry width increases.

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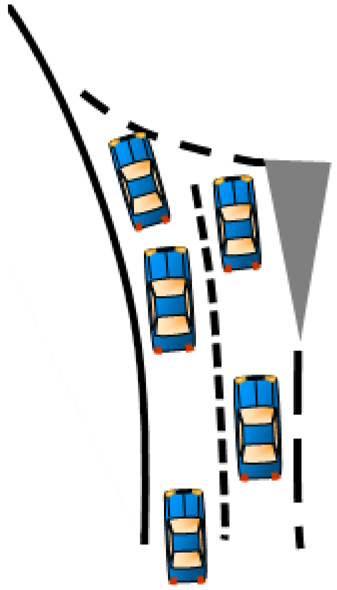
4.2 Use of road space

It has been suggested that the entry width relationships will only work successfully if all the available space is used all the time. This is not true. If space is randomly not used from time to time, just because drivers choose not to, then this behaviour is fully reflected in the road measurements behind the empirical relationships, and therefore they take this into account when predicting the capacity of a proposed roundabout entry.

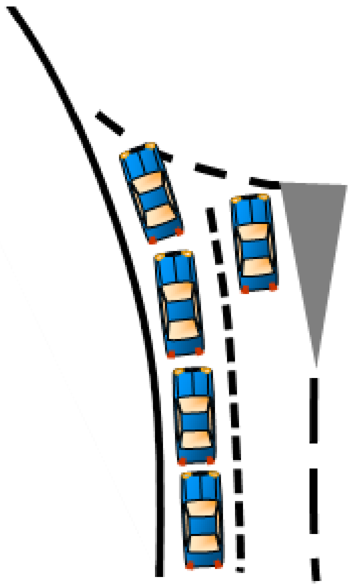
There remains what could be called the systematic failure to use all the space. This could be for a number of reasons, such as:

- Poor geometry or visibility which makes drivers reluctant to use a certain lane.
- Inappropriate lane arrows. If direction arrows are used and the balance of flows does not match the physical capacity assigned by the arrows, then drivers will be unable to use all the entry space as they seek to queue in lanes marked for their intended movement.
- If the approach flares from say two lanes to three at the give-way line, then continuous lane lines will tend to steer traffic away from using the extra space. It may be better to end the lane lines at the beginning of the widening, then to mark them again just before the give-way line.
- If a substantial part of the entry flow wishes to exit the roundabout at a restricted exit that is only able to accept one lane of traffic, then drivers will be unwilling to enter the roundabout side-by-side, knowing that they will then have to merge at the exit.

All of these conditions are predictable by a good traffic engineer. This systematic non-use of space is NOT taken into account by the empirical relationships, but it is predictable. From ARCADY 8 onwards, it is possible to obtain estimates of the effect of systematic lane imbalance by using Lane Simulation Mode.



Random differences in space utilisation: this is fully accounted for in ARCADY



Systematic imbalance: consider using Lane Simulation mode in ARCADY 8 onwards.

21A

4.5 Applicability outside the UK

It has often been said that the UK relationships are only valid in the UK for UK drivers. There is indeed some truth in this given that the relationships were developed using exclusively UK data. However, although there may be some deviations from UK values, and not always the same deviations from one country to another, it is extremely unlikely that a change which improves either capacity or accident rate in the UK is going to have the reverse affect in another country. In other words, the relationships will prove dependable for predicting the major effects of design changes. Detailed results may vary, but this criticism applies at least equally to, for instance, gap acceptance methods calibrated in other countries. For capacity, the UK method, as applied in ARCADY, allows the variation of predicted capacity by a user-selected amount: the capacity line can either be moved up or down by a fixed amount, at the user's discretion. Thus, if it is felt that capacity in general will differ from that achieved in the UK, this can be allowed for.

5 Further reading

The empirical relationships outlined in this article form the basis for the ARCADY software package, which is available as a module within TRL's **Junctions** software suite. For details, please see https://trlsoftware.co.uk/ARCADY.

The TRRL research report which summarises the research findings is: *Kimber, R M (1980). "The traffic capacity of roundabouts", Department of Environment Department of Transport, TRRL Report LR 942: Crowthorne: Transport and Road Research Laboratory.* This is available on request from TRL.

Other relevant papers are listed in the References section of the ARCADY/Junctions user guides.

For further information or enquiries, please visit www.trl.co.uk.

Acknowledgements

This article is based on *"Roundabout Design for Capacity and Safety: the UK Empirical Methodology", J R Peirce, 1998*.

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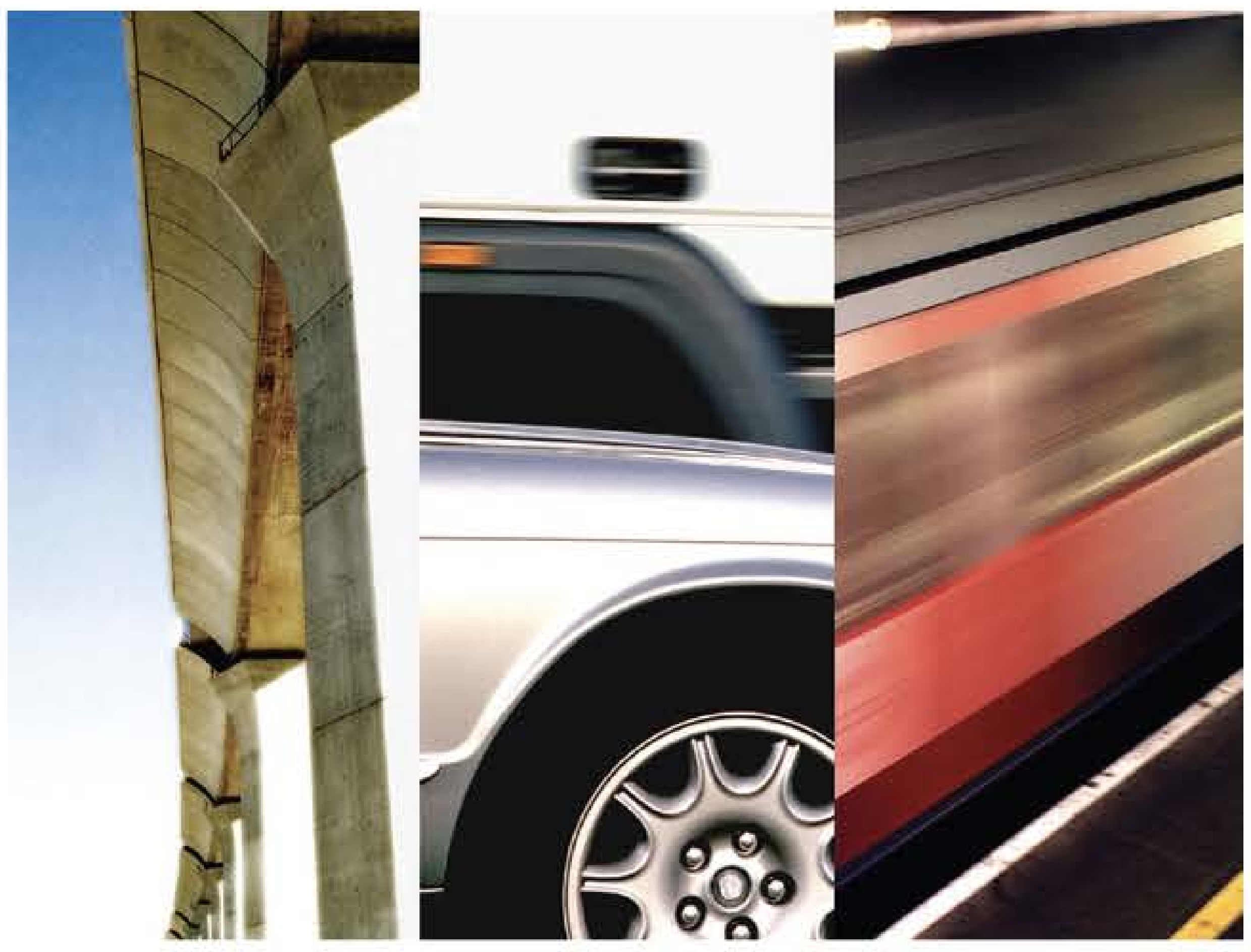

International comparison of roundabout design guidelines

by Janet Kennedy

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Published Project Report
PPR206

TRL Limited

PUBLISHED PROJECT REPORT PPR206

International comparison of roundabout design guidelines

Version: 1

by Janet Kennedy (TRL Limited)

Prepared for: Project Record: **3/372 C06 TD 16/93 Geometric Design of Roundabouts: Review**

Client: **Highways Agency (Ian Sandle)**

This report has been prepared for the Highways Agency is unpublished and should not be referred to in any other document or publication without the permission of the Highways Agency. The views expressed are those of the authors and not necessarily those of the Highways Agency.

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Quality Reviewed	I Summersgill

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Executive summary

Background

Roundabouts have been a key form of junction in the UK for many years. They are used on all classes of road in both urban and rural areas for the efficient and safe control of traffic, particularly where side road flows are high. Roundabouts are the most common type of control used at motorway intersections, and are heavily used throughout the UK's trunk and principal road network, as well as on local authority roads.

The UK Geometric Design Standard for Roundabouts at the time of this review (TD 16/93) is based on extensive research which led to predictive relationships incorporating the critical variables found to influence safety and capacity. Entry width and sharpness of ‘flare’ were established as the primary determinants of capacity/delay whilst a combination of entry deflection and entry width was their equivalent for safety. However, it was recognised that although roundabouts performed well in terms of overall safety, the involvement in accidents of pedal cyclists and motor cyclists at this junction type was relatively high. More recently, concerns about pedestrians and equestrians, and the prevention of large goods vehicle roll-over accidents at roundabouts have become issues.

The main objective of the report is to provide a comprehensive review of international roundabout design that will lead to a revised Design Standard to meet the needs of modern roads. Mini-roundabouts are to be part of a separate UK standard, but a comparison of the key design elements is included for consistency.

Review

Where possible, the review is based on the guidelines or standards for the country concerned that were in current use in early 2004. In a few cases, a conference paper on the main design elements has been used, because of difficulty in obtaining the standard and to avoid the need for translation. It is not known to what extent the standards or guidelines are adhered to.

Compared with TD 16/93, the roundabout designs in the guidelines in Germany, France and the Netherlands are notably smaller and have tighter geometry which leads to lower circulating speeds. This generally smaller design is reflected in the fact that in those countries, roundabouts are mainly used for reasons of road safety. In line with this, design features that are used to increase capacity on UK roundabouts (e.g. flared entries and segregated left turn lanes) are not recommended in Germany, France and the Netherlands, because they tend to lead to higher circulating speeds.

Single lane roundabouts are generally preferred over double lane roundabouts on safety grounds (the French guidelines do not even provide recommendations for urban double lane roundabouts and the German guidelines on urban double lane roundabouts are considerably less detailed and prescriptive than the single lane ones).

Australian guidelines appear to be more comparable with the UK standard, probably because of the greater emphasis given to capacity than in continental Europe.

The American guidelines provide a range of different types of roundabouts, in which higher capacity designs (for use on arterials) are more comparable with the UK and Australian design standards and compact designs (for use on local urban roads) show more similarity to the German, French and Dutch designs.

The amount of information traced on Swedish, Danish and Norwegian guidelines was relatively limited, but showed designs that are generally larger than those in Germany, France and the Netherlands.

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Detailed information on the design of cyclist provision is given in German, French and Dutch guidelines. A more limited description of cycle provision is given in the Danish, Australian, UK and American guidelines.

A notable difference is that all of the overseas guidelines studied recommend outward crossfall on roundabouts, whereas, with the exception of mini-roundabouts, inward crossfall is recommended in TD 16/93.

Conclusions

The conclusions were as follows:

- The inscribed circle diameter should not be unnecessarily large. In particular, if the roundabout is at-grade, the inscribed circle diameter should not exceed 100m.
- A truck apron (overrun area i.e. raised low-profile area around a central island) should continue to be used at small roundabouts if there is sufficient land-take to use a solid island roundabout rather than a mini-roundabout. The edge profile of a truck apron in TD 16/93 is allowed to be up to 50mm. In order to be consistent with the Traffic Calming Regulations, the vertical face should not exceed 15mm. The apron should be capable of being mounted by the trailer of a large goods vehicle, but be unattractive to cars e.g. by having a slope and/or textured surface.
- Outward crossfall should be permitted on smaller roundabouts in urban areas.
- Lane widths at entry should remain at 3m to 3.5m at multilane entries, but at single lane entries, the width should be 4.5m.
- Adding an extra lane at roundabout entries should require justification rather than being automatic. The recommended effective flare lengths of 5m (urban) and 25m (rural) should remain.
- Suitable values for the entry (kerb) radius are 20m at larger roundabouts, 10-15m at smaller roundabouts.
- Suitable values for the exit (kerb) radius are 20-100m at larger roundabouts, 15-20m at smaller roundabouts.
- Suitable values for the entry angle are 20 to 60 degrees, particularly at smaller roundabouts.
- Flaring should continue to be used in preference to a segregated left turn lane as this requires less land take and is safer for non-motorised road users.
- The entry path radius on any approach should not exceed 100m. It should not exceed 70m at small urban roundabouts.

Cycle lanes should not be used on the circulatory carriageway. Cyclists should mix with traffic at urban roundabouts with low flow. External cycle paths that do not form part of the circulatory carriageway are the best facility at larger urban roundabouts.

Where vehicle flow is low, an informal crossing (a dropped kerb) is generally adequate for pedestrians. At medium flows, where there is a substantial pedestrian demand, a formal crossing should be provided close to the roundabout (but upstream of any flaring). Where a signal controlled pedestrian or cycle crossing is provided, it should be either at 20m or at least 50m from the give way line to avoid confusion with the roundabout itself and to minimize queueing back onto the circulatory carriageway.

On dual carriageway roads, or single carriageway roads with a long splitter island, visibility to the right may be limited by use of planting or other screening (at least 2m high) until vehicles are within 15m of the give way line, to reduce excessive entry speeds.

The possibility of rollover of large vehicles should be minimized by keeping approach speeds low and ensuring that roundabouts have no abrupt changes in geometry.

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Recommendations

There is scope for introducing in the UK Standard a new "compact" roundabout with single lane entries, exits and circulatory carriageway. This style of roundabout would be most appropriate on low flow roads. In urban areas, the design would incorporate tighter geometry and outward crossfall, in order to slow traffic; these could have substantial numbers of pedestrians or cyclists. This compact roundabout would form part of a design hierarchy to depend on road type, whether the speed limits on the approach roads exceed 40mph and on the levels of vehicle and non-motorised user flow. If required, pedestrian provision would comprise Zebra crossings at 5m from the give way line. No special provision for cyclists would be necessary.

New design hierarchy

The types of roundabout are Signalised, Grade Separated, Dual Carriageway (one or more approaches is dual carriageway), Normal (all approaches are single carriageway and design broadly follows TD 16/93), Compact ("continental style", with single lane entry, exit and circulatory carriageway) and Mini Roundabout.

The various factors for the design hierarchy are as follows:

- Speed limit within 100m of give way line (>40mph, ≤40mph)
- Single or dual-carriageway
- Level of vehicle flow
- Level of cyclist flow
- Level of pedestrian flow

At a roundabout with one or more dual carriageway arms, or a busy single carriageway roundabout, the design should be similar to that in TD 16/93. If there is a non-motorised user need, it should be catered for by use of a signalised crossing (Puffin, Toucan or Equestrian as appropriate). In circumstances where there is a need for a signalised crossing on more than one arm, a signalised roundabout may be preferable.

At a single carriageway roundabout with medium flow, the design will again be similar to that in TD 16/93. If warranted, either a signal controlled or a Zebra crossing should be used, depending on the speed limit and the level of flow.

Where total inflow is below 8,000 vehicles per day, cycle facilities are not necessary, but on some occasions, a pedestrian crossing (a Zebra or possibly a signal controlled crossing) should be provided.

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- Double lane roundabouts have two lane entries and exits on all arms and a two-lane circulatory carriageway
- Three lane roundabouts have three lane entries and exits on all arms and a three-lane circulatory carriageway (only in the Australian and French guidelines)

There are often separate designs or recommendations for rural and urban roads, and in some countries, for arterial and local roads. Mini-roundabouts and compact urban roundabouts are used mainly on local roads.

The categories used in this report to compare the different design guidelines are:

1. *Mini-roundabouts*
2. *Urban roundabouts*
    - 2a. Single lane
    - 2b. Double lane
3. *Rural roundabouts*
    - 3a. Single lane
    - 3b. Double lane

2.3 Capacity versus safety

Although the safety record of roundabouts is generally better than that of other junction types, roundabouts in the UK are mainly regarded as a high capacity junction. This tradition has led to large roundabouts with high speed circulating traffic.

In most other countries, roundabouts have been introduced much more recently. The main emphasis is on their speed-reducing capability and safe performance compared to other junction types, with the high capacity seen as a bonus. This emphasis on safety is, not surprisingly, reflected in the design standards. Roundabouts are usually smaller and the geometry tighter, than in the UK.

Features such as entry flares and segregated left turn lanes (right turn lanes in countries that drive on the right) that are used in the UK to increase capacity tend to be considered poor design in many countries, because they allow higher speeds.

Early examples of roundabouts other than in the UK were all single lane as these were expected to have a lower accident rate than double lane ones. This has been confirmed by various studies (e.g. Brüde and Larsson, 1999, both in Sweden, and van Minnen, 1998, in the Netherlands), although double lane roundabouts still have lower accident rates than other junction types (van Minnen, 1998). More recently, double lane (and occasionally three-lane) roundabouts have been introduced on dual-carriageway roads, although they are not universally recommended. It is known that some roundabouts in other countries have a mixture of single and double lane arms, but this design is not included in any of the guidelines.

The use of roundabouts for safety is particularly notable in Germany, France and the Netherlands. Scandinavian designs mainly address safety concerns, but are somewhat larger with less tight geometry. Herland and Helmers (2002) attribute these differences to a larger Swedish design vehicle.

Although safety aspects play an important role in roundabout design in Australia, more importance is given to capacity than in most countries on the European continent. Correspondingly, Australian designs show greater similarity to the UK.

Use of roundabouts in the USA is relatively recent and therefore design draws on guidelines from the UK, France and Australia. For larger roundabouts, greater emphasis is placed on the Australian and UK Standards, whereas for smaller roundabouts, design is more similar to that in Northern Europe. This is illustrated by the use of two types of urban single lane roundabout. The "urban compact" type is similar to designs in Germany, France and the Netherlands, whereas the design for arterials is closer to that used in Australia and the UK.

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2.4 Design guidelines

The UK Standard is intended for trunk roads, but is widely used by local highway authorities. Some sections of the Standard are mandatory on trunk roads, others are advisory. Some of the information traced for other countries is in the form of recommended guidelines rather than a standard. Details of Scandinavian designs were taken from conference proceedings because of difficulty in obtaining the relevant standards and to avoid the need for translation. For simplicity, all of the sources are referred to as guidelines in this report. They vary considerably in the level of detail given, ranging from minimum dimensions and general recommendations to the prescription of different combinations of design dimensions. The Australian and American guidelines provide methods for calculating dimensions rather than a range of values.

3 Roundabout design features

3.1 Number of arms

In the UK, the recommended number of arms is 3 or 4, but larger roundabouts with more than 4 arms are relatively common. There is no mention of roundabouts with more than 4 arms in guidelines from most countries. However, it is known that these exist (e.g. France has roundabouts with up to 7 arms and the new German guidelines illustrate a 5-arm roundabout).

3.2 Central area of roundabout

3.2.1 Inscribed circle diameter

For a symmetrical roundabout, the *inscribed circle diameter* is the diameter of the largest circle that can be fitted into the junction outline (Figure 4). Where the outline is asymmetric, the local value in the region of the entry should be used.

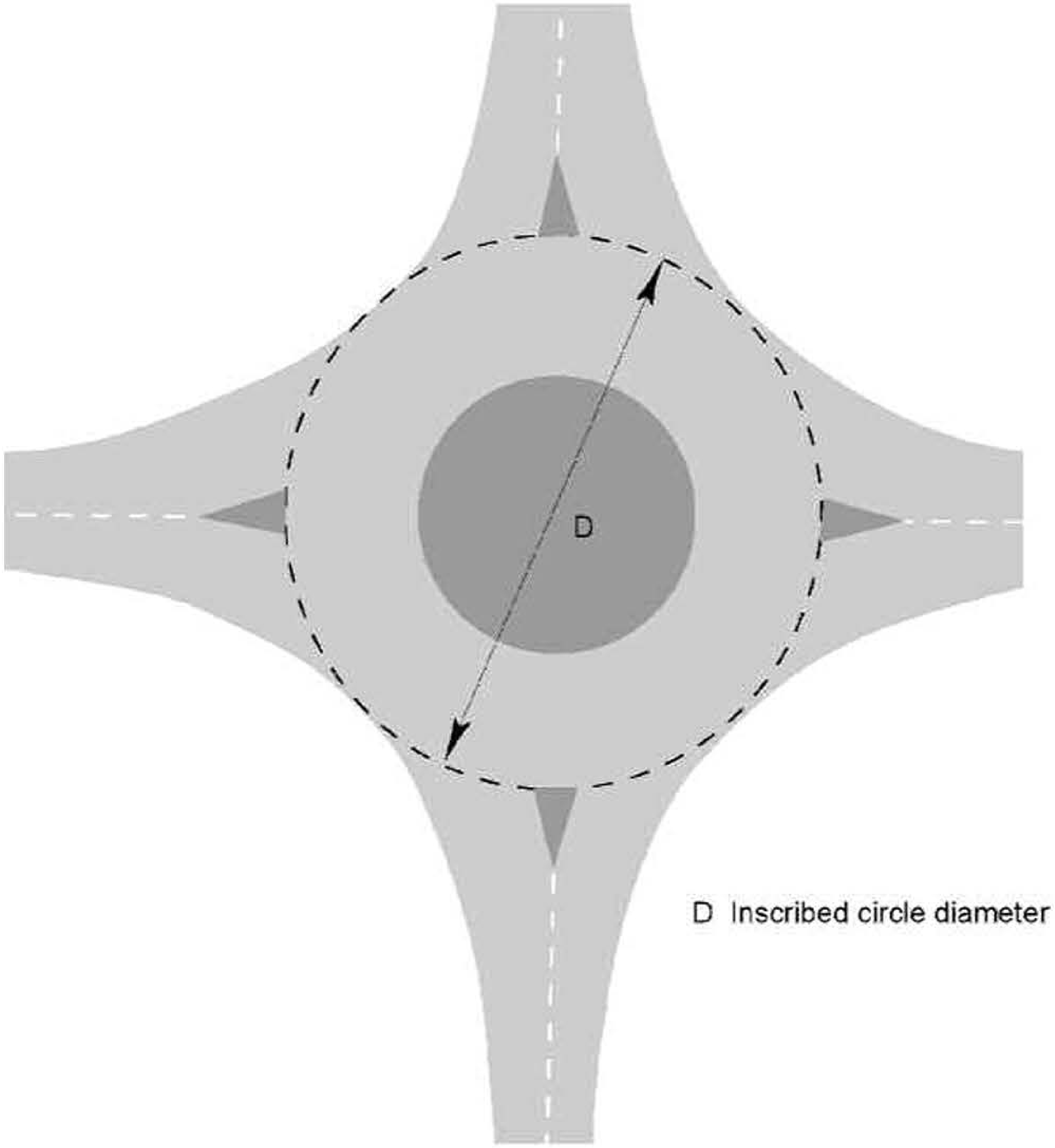

Fig 4: Inscribed circle diameter at a normal roundabout

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UK roundabouts often have large inscribed circle diameters. This arose historically, from the 1960s when the priority rule was to give way to traffic entering the roundabout which could lead to gridlock when traffic demand was high and therefore long 'weaving lengths' were used. This tradition of designing for capacity also led to flaring and tangential entries. Although beneficial from the point of view of capacity, large roundabouts encourage higher speeds and increase geometric delay (journey time) not just for vehicles but also, in urban areas, for pedestrians, and for cyclists who cross as pedestrians. Roundabouts at grade separated junctions (Figure 5) are particularly large unless replaced by a 'dumbbell' interchange with a single bridge and two roundabouts (Figure 6).

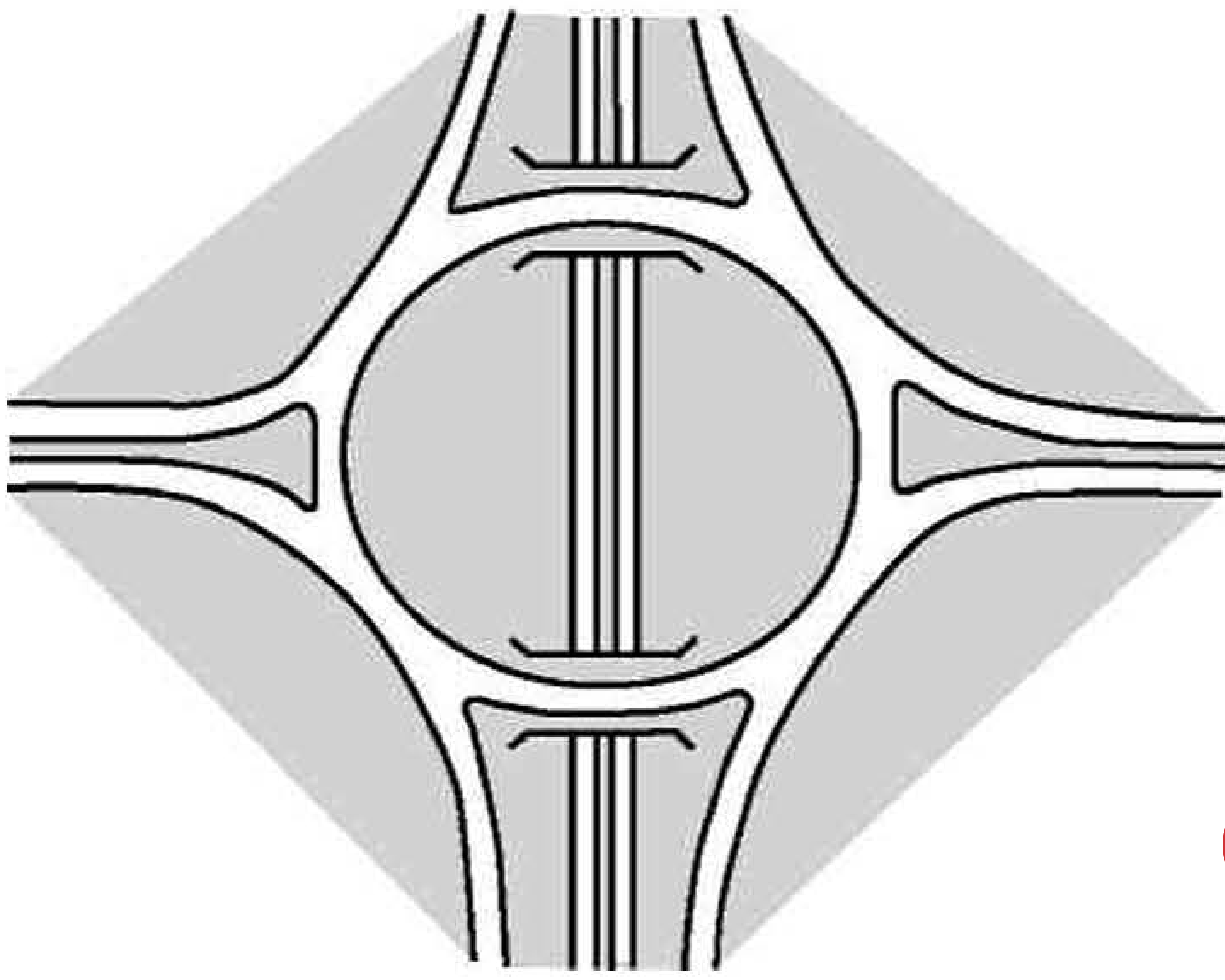
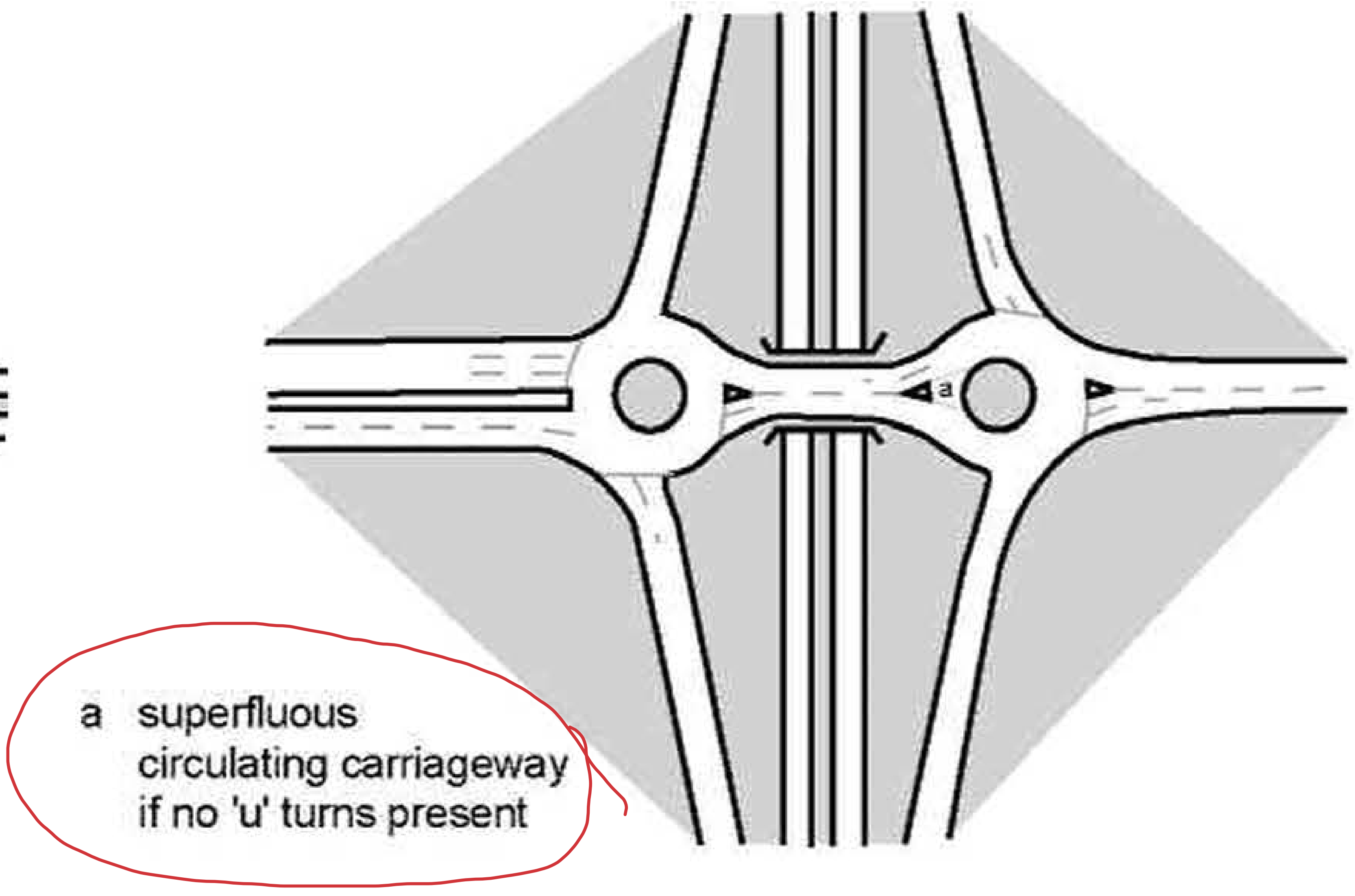


Fig 5: Grade separated roundabout



a superfluous circulating carriageway if no 'u' turns present

Fig 6: Dumbbell interchange

The UK standard recommends a minimum inscribed circle diameter of 28m for both urban and rural roundabouts. This is the minimum diameter that, with a central island diameter of 4m, can be negotiated by the design vehicle (a 15.5m long articulated vehicle with a single axle at the rear of the trailer). For inscribed circle diameters below this, a mini-roundabout should be used. No maximum is given in the standard, although the version of TD 16/93 used by Essex County Council advocates a maximum of 100m to avoid high circulating speeds. In practice, values for roundabouts at grade-separated junctions may exceed 250m. Many large roundabouts in the UK have been signalised in recent years, particularly grade-separated roundabouts of the design shown in Figure 5.

Other countries specify both a minimum and a maximum inscribed circle diameter, as shown in Table 1. Minima range from 24 to 36m. Maxima range from 30 to 90m for a single lane roundabout and from 20 to 90m for a double lane roundabout.

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Table 1: Inscribed circle diameter

Country		Single lane		Double lane	
		Min (m)	Max (m)	Min (m)	Max (m)
Australia	Urban / rural	-	80	-	80
France	Urban	30	-	-	-
	Rural	24	30	24	50
Germany	Urban	26	35	40	-
	Rural	35	45	40	-
Netherlands	Urban / rural	32	32	20	38
	Rural	36	36	20	38
Norway	Urban / rural	26	45	26	45
Sweden	Urban / rural	30.8	90	30.8	90
UK	Urban / rural	28	-	28	-
USA	Urban	25-30	30-40	45	55
	Rural	35	40	55	60

Both Alphand et al (1991) in France and Brilon and Stuwe (1991) in Germany concluded that larger roundabouts have higher accident rates than smaller ones. The German definition of larger roundabouts was those with an inscribed circle diameter of 40 to 142m, with smaller roundabouts having an inscribed circle diameter of 28 to 40m.

Brüde and Larsson (1999) in Sweden found that a central island diameter greater than 50m increased accident risk and suggested that a diameter between 20 and 50m is probably optimal. Islands with diameters of less than 10m often give a straight driving path with potentially high speeds, whilst those with diameters greater than 50m also result in straighter paths, enabling higher speeds.

- *Conclusion: The inscribed circle diameter should not be unnecessarily large. If the roundabout is at-grade, it should not exceed 100m.*

3.2.2 Shape of central island

Most guidelines advise against the use of non-circular central islands, which arise mainly for historical reasons or where roundabouts are conversions from other junction types rather than being new-build. Alphand et al (1991) concluded from an analysis of accidents in France that oval shaped roundabouts had considerably higher accident rates than circular ones.

3.2.3 Width of circulatory carriageway

The *width of the circulatory carriageway* is determined by the maximum entry width and should be constant. In the UK, flared entries give rise to a circulatory carriageway that tends to be wider than in many other countries (Table 2), with values ranging from 1 to 1.2 times the maximum entry width, up to a maximum of 15m. The maximum recommended width for double lane roundabouts in the guidelines studied (other than in the UK) is 10.8m. As might be expected, rural values tend to be larger than urban ones. Circulatory carriageways in Germany and the Netherlands are the narrowest, with those in France more similar to the UK.

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Table 2: Width of circulatory carriageway

Country		Single lane Min (m)	 Max (m)	Double lane Min (m)	 Max (m)
Australia	Urban / rural	4.6	7.6	8.4	10.3
France	Urban	6-7	9	7	9
	Rural	6	9	7.2 - 8.4[2]	10.8[2]
Germany	Urban	4.65	5.6	-	-
	Rural	5.75	6.5	-	-
Netherlands	Urban	5.5		8	10
	Rural	5.25		8	10
Sweden	Urban / rural	5	10.4	5	10.4
UK[1]	Urban / rural	7.2	15	10.8	15
USA	Urban / rural	calculated		8.7	9.8

1 UK minima are based on 1.2 x an entry width of 6m for single carriageways (2 lanes of 3m width) and 1.2 x 9m (3 lanes of 3m width) for dual-carriageway roads

2 Double lane roundabouts are not recommended; dual-carriageway roads should be narrowed upstream of the junction (lower value only where heavy vehicle flow is very low)

3 Australia also gives values for 3-lane roundabouts

3.2.4 Central island diameter

The inscribed circle diameter, the width of the circulatory carriageway and the *central island diameter* are not independent, the third being determined automatically once the other two are decided. In the UK, a mini-roundabout should be used where the central island diameter is 4m or less. Most normal roundabouts have considerably larger values for the central island diameter. In other countries, the range is from a minimum of 5m to a maximum of 80m – although not all countries give a maximum value (Table 3). Where quoted, Germany and the Netherlands have low maxima, with Norway and Sweden allowing rather higher values.

Table 3: Central island diameter (including truck apron where applicable)

Country		Single lane Min (m)	 Max (m)	Double lane Min (m)	 Max (m)
Australia	Urban / rural	5	8-10+	5	10+
France	Urban	5	18	-	-
	Rural	16	-	30	-
Germany	Urban	14.6	25.7	10	-
	Rural	22	33.5	10	-
Netherlands	Urban	21	21	10	30
	Rural	25.5	25.5	10	30
Norway	Urban / rural	>5	>25	>5	>25
Sweden	Urban / rural	10	80	10	80
UK	Urban / rural	4	-	4	-
USA	Urban / rural	Depends on design vehicle		25.4	41.8

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6 Summary and recommendations

6.1 Summary

Compared with the UK standard, the roundabout designs in the guidelines in Germany, France and the Netherlands are notably smaller and have a tighter geometry which leads to lower circulating speeds.

This generally smaller design is reflected in the fact that in those countries, roundabouts are mainly used for reasons of road safety. Other differences that also reflect this different approach are that design features that are used to increase capacity on UK roundabouts (flared entries, segregated left turns and tangential entries) are not recommended in Germany, France and the Netherlands, because they tend to lead to higher circulating speeds.

Single lane roundabouts are generally preferred over double lane roundabouts on safety grounds (the French guidelines do not even provide recommendations for urban double lane roundabouts and the German guidelines on urban double lane roundabouts are considerably less detailed and prescriptive than the single lane ones).

Australian guidelines appear to be more comparable with the UK standard, probably because of the greater emphasis given to capacity than in continental Europe.

The American guidelines provide a range of different types of roundabouts, in which the higher-capacity types (for use on arterials) are more comparable with the UK and Australian design standards and the compact type (for use on local urban roads) shows more similarity to the German, French and Dutch designs.

The amount of information traced on Swedish, Danish and Norwegian guidelines was relatively limited, but showed designs that are generally larger than those in Germany, France and the Netherlands.

Detailed information on the design of cyclist provision is given in German, French and Dutch guidelines. A more limited description of cycle provision is given in the Danish, Australian, UK and American guidelines.

A notable difference is that none of the overseas guidelines studied recommend inward crossfall on roundabouts. Except for mini-roundabouts, inward crossfall is recommended for UK roundabouts on all or part of the circulatory carriageway.

6.2 Conclusions

The conclusions were as follows:

- The inscribed circle diameter should not be unnecessarily large. In particular, if the roundabout is at-grade, the inscribed circle at diameter should not exceed 100m.
- A truck apron (overrun area i.e. raised low-profile areas around a central island) should continue to be used at small roundabouts if there is sufficient land-take to use a solid island roundabout rather than a mini-roundabout. The edge profile of a truck apron in TD 16/93 is allowed to be up to 50mm. In order to be consistent with the Traffic Calming Regulations, the vertical face should not exceed 15mm. The apron should be capable of being mounted by the trailer of a large goods vehicle, but be unattractive to cars e.g. by having a slope and/or textured surface.
- Outward crossfall should be permitted on smaller roundabouts in urban areas.
- Lane widths at entry should remain at 3m to 3.5m at multilane entries, but at single lane entries, the width should be 4.5m.

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- Adding an extra lane at roundabout entries should require justification rather than being automatic. The recommended effective flare lengths of 5m (urban) and 25m (rural) should remain.
- Suitable values for the entry (kerb) radius are 20m at larger roundabouts, 10-15m at smaller roundabouts.
- Suitable values for the exit (kerb) radius are 20-100m at larger roundabouts, 15-20m at smaller roundabouts.
- Suitable values for the entry angle are 20 to 60 degrees, particularly at smaller roundabouts.
- Flaring should continue to be used in preference to a segregated left turn lane as this requires less land take and is safer for non-motorised road users.
- The entry path radius on any approach should not exceed 100m. It should not exceed 70m at small urban roundabouts.

Cycle lanes should not be used on the circulatory carriageway. Cyclists should mix with traffic at urban roundabouts with low flow. External cycle paths are the best facility at larger urban roundabouts.

Where vehicle flow is low, an informal crossing (a dropped kerb) is generally adequate for pedestrians. At medium flows, where there is a substantial pedestrian demand, a formal crossing should be provided close to the roundabout (but upstream of any flaring). Where a signal controlled pedestrian or cycle crossing is provided, it should be either at 20m or at least 50m from the give way line to avoid confusion with the roundabout itself and to minimize queueing back onto the circulatory carriageway.

On dual carriageway roads, or single carriageway roads with a long splitter island, visibility to the right may be limited by use of planting or other screening (at least 2m high) until vehicles are within 15m of the give way line, to reduce excessive entry speeds.

The possibility of rollover of large vehicles should be minimized by keeping approach speeds low and ensuring that roundabouts have no abrupt changes in geometry.

6.3 Recommendations

There is scope for introducing in the UK Standard a new “compact” roundabout with single lane entries, exits and circulatory carriageway, with minimal flaring (see Figure 41). This style of roundabout would be most appropriate on low flow, local roads, where there were substantial numbers of pedestrians and cyclists. In urban areas, the design would incorporate tighter geometry and outward crossfall, in order to slow traffic; it would be suitable for regular pedestrian and cyclist use. This compact roundabout would form part of a design hierarchy (see Section 7) to depend on road type, whether the speed limits on the approach roads exceed 40mph and on the levels of vehicle and non-motorised user flow. If required, pedestrian provision would comprise Zebra crossings at 5m from the give way line. No special provision for cyclists would be necessary.

37 A

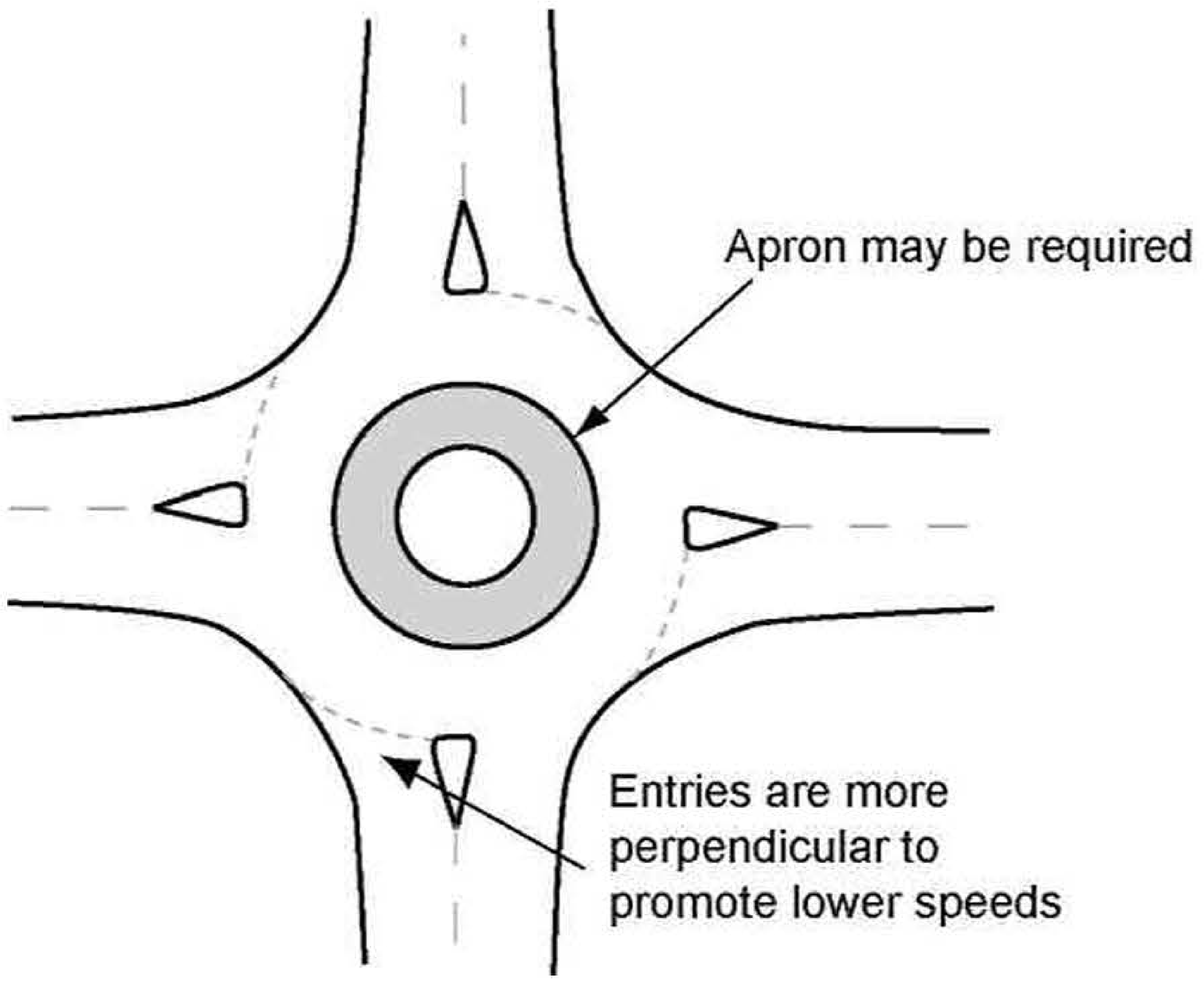

Figure 41: Possible layout for compact roundabout

7 Design hierarchy

The types of roundabout are Signalised, Grade Separated, Dual Carriageway (one or more approaches is dual carriageway), Normal (all approaches are single carriageway and design broadly follows TD 16/93), Compact ("continental style", with single lane entry, exit and circulatory carriageway) and Mini-roundabout.

The various factors for the design hierarchy are as follows:

- Speed limit within 100m of give way line (>40mph, ≤40mph)
- Single or dual-carriageway
- Level of vehicle flow
- Level of cyclist flow
- Level of pedestrian flow

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At a roundabout with one or more dual carriageway arms, or a busy single carriageway roundabout, the design should be similar to that in TD 16/93. If there is a non-motorised user need, it should be catered for by use of a signal controlled crossing (Puffin, Toucan or Equestrian as appropriate). In circumstances where there is a need for a signal controlled crossing on more than one arm, a signalised roundabout may be preferable.

At a single carriageway roundabout with medium flow, the design will again be similar to that in TD 16/93. If warranted, either a signal controlled or a Zebra crossing should be used, depending on the speed limit and the level of flow.

Where total inflow is below 8,000 vehicles per day, cycle facilities are not necessary, but on some occasions, a pedestrian crossing (a Zebra or possibly a signal controlled crossing) should be provided.

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Acknowledgements

The work described in this report was carried out in the Safety Group of TRL Limited. The author is grateful to Ian Summersgill who carried out the quality review and auditing of this report.

Table B4: Accidents and accident frequency at grade separated roundabouts by number of arms (1999 to 2003)

No. of arms	No. of sites	Number of accidents Fatal	Serious	Slight	Total	Accident frequency	Severity (% fatal and serious)
3	8	1	10	97	108	2.70	10.2
4	60	5	79	1520	1604	5.35	5.2
5	36	9	85	1287	1381	7.67	6.8
6	14	3	26	581	610	8.71	4.8
All	118	18	200	3485	3703	6.28	5.9

Table B5: Accidents, accident frequency and accident rate at roundabouts with flow data, by number of arms (1999 to 2003)

No. of arms	No. of sites	Number of accidents Fatal	Serious	Slight	Total	Severity (% fatal and serious)	Accident frequency	Accident rate
3	11	0	6	121	127	4.7	2.31	22.2
4	29	2	42	464	508	8.7	3.50	36.2
5	4	0	4	130	134	3.0	6.70	50.6
All	44	2	52	715	769	7.0	3.51	7.1

Table B6: Accidents by number of vehicles involved (1999 to 2003)

No. of vehicles	1	2	3	4	5	6	Total
No. of accidents	1605	8602	568	70	8	3	10856
% of accidents	14.8%	79.2%	5.2%	0.6%	0.1%	0.0%	100.0%

Table B7: Accidents by type of vehicle involved (1999 to 2003)

	Number of accidents Fatal	Slight	Serious	Total	% of Accidents	Severity
Pedal cycles	2	782	80	864	8.0%	9.5%
Pedestrians	4	233	64	301	2.8%	22.6%
Motorcycles	11	1265	291	1567	14.4%	19.3%
Cars and taxis	23	7822	480	8325	76.7%	6.0%
Public Service Vehicles	2	259	20	281	2.6%	7.8%
Light goods vehicles	2	660	37	699	6.4%	5.6%
Heavy goods vehicles	8	934	73	1015	9.3%	8.0%

Table B8: Accidents by year (1999 to 2003)

Year	1999	2000	2001	2002	2003
Number of accidents	2251	2285	2147	2076	2097
Ratio	1.04	1.05	0.99	0.96	0.97

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Coefficients in some formulae have been obscured.

he traffic capacity of roundabouts

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. M. Kimber

Alterations

① P.17, line 2, Appendix 2

~~② Fig. 3, vertical axis~~
~~$b_a(s)/b_o(s)$~~

③ P.39, line 7, Calculated in (ii)

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TRANSPORT and ROAD
RESEARCH LABORATORY

Department of the Environment
Department of Transport

TRRL LABORATORY REPORT 942

THE TRAFFIC CAPACITY OF ROUNDABOUTS

by

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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].

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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:

$$Q_e = F - f_c Q_c \qquad \text{. . . . . (1)}$$

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.

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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

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

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:

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

ie equation (1) with

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

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

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 $x_C Q_c$ 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

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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 $b_0(s)/b_0(s)$, 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:

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

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

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

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 $d_2 = 60\text{m}$ and $d_3 = 10\text{m}$, 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 ~ 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 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 $f_cQ_c > F$) 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).

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:

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

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' : $1 - \infty$ (m)
S : 0–2.9
D : 13.5–171.6 (m)
ϕ : 0–77 (^{o})
r : $3.4 - \infty$ (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.

9. ACKNOWLEDGEMENTS

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The author is also grateful to Dr R Ashworth and Mr C J D Laurence of the University of Sheffield and Mr M McDonald and Mr D J Armitage* of the University of Southampton for useful discussions. Data sets 2 and 5 were prepared by the University of Sheffield.

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* Now with the Department of Roads, Grampian Regional Council

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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		

$\overline{b_0(s)}$ 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.

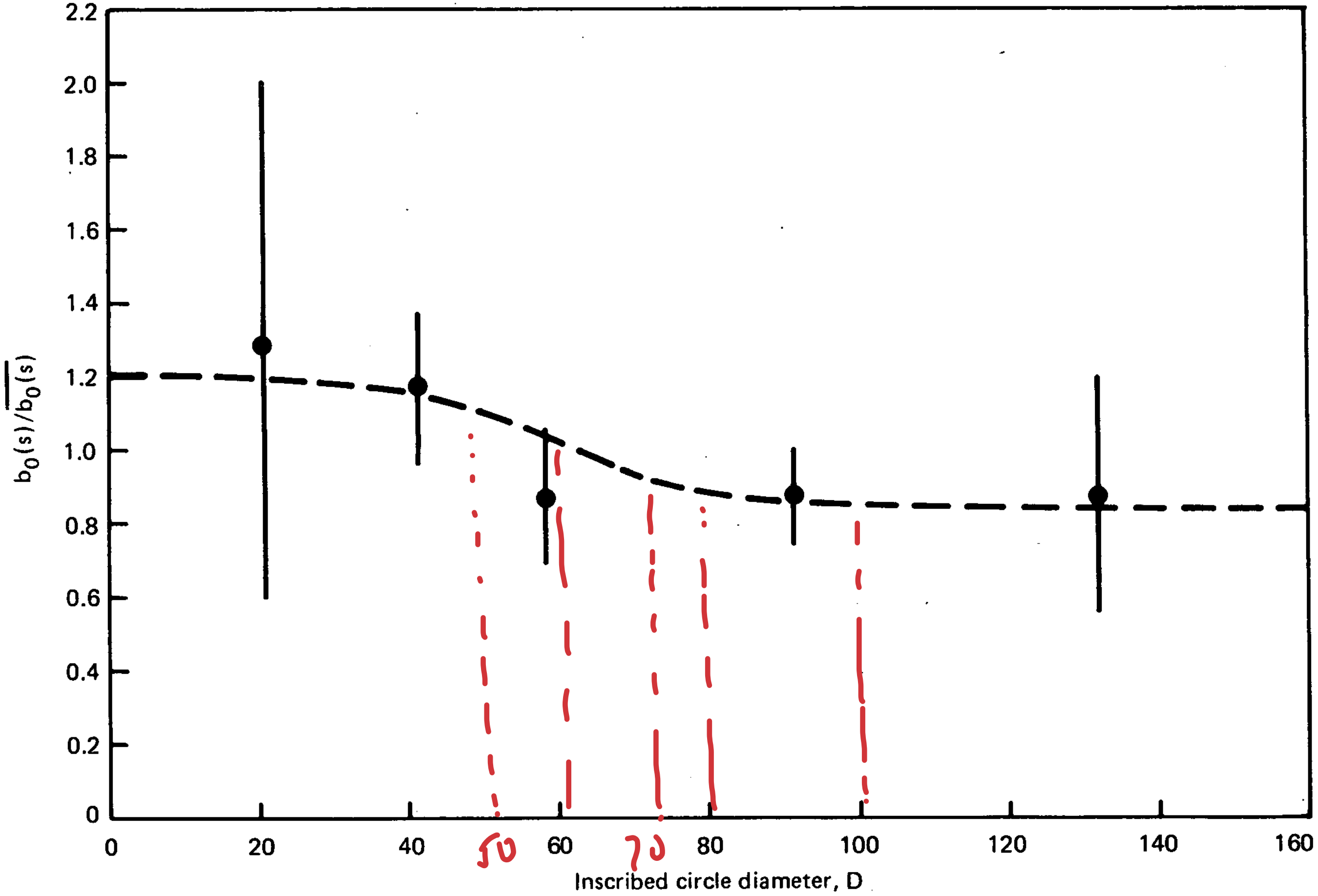

Fig. 3 RELATIVE VARIATION OF SITE–SPECIFIC SLOPE COEFFICIENTS WITH INSCRIBED CIRCLE DIAMETER

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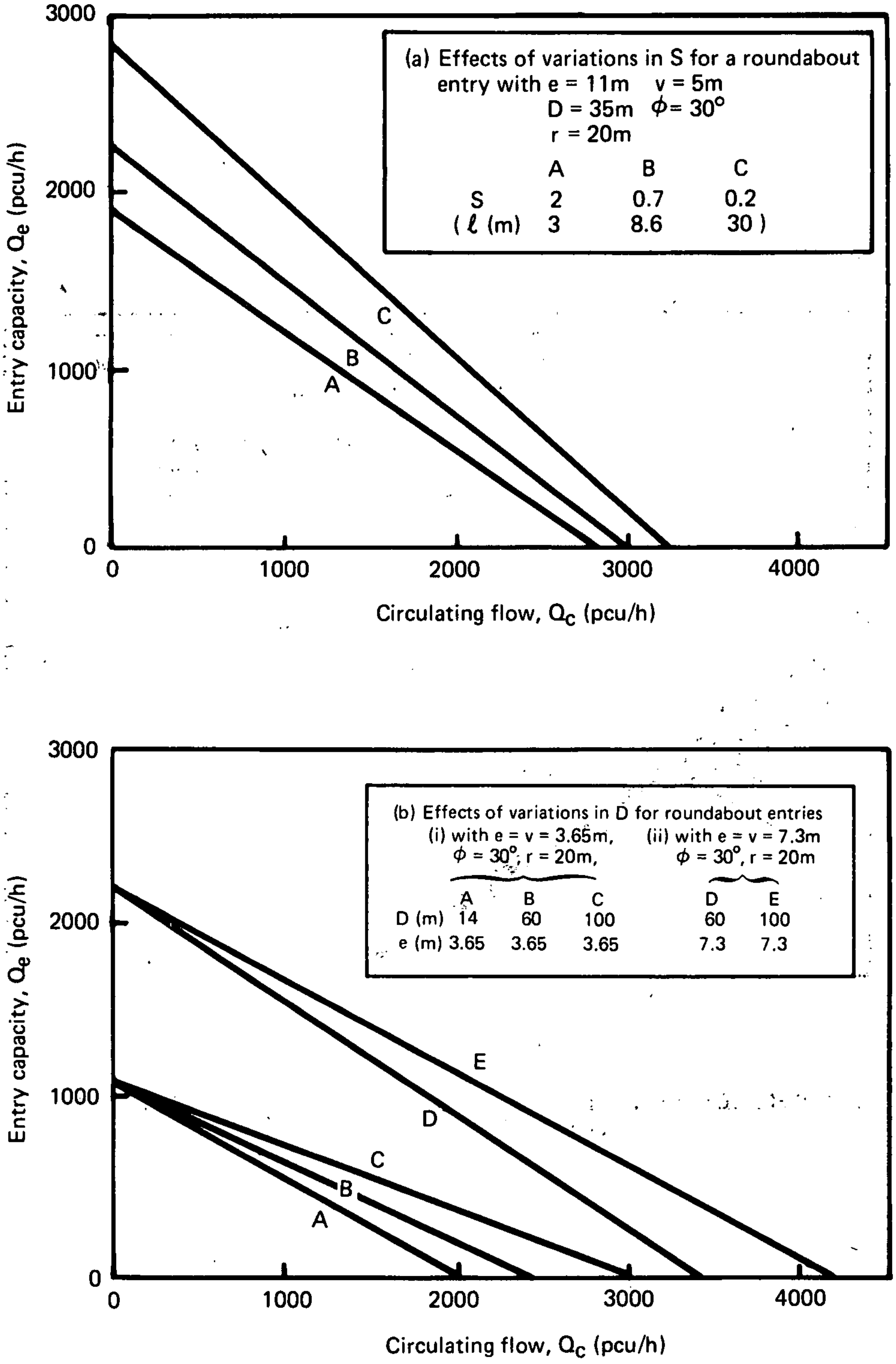
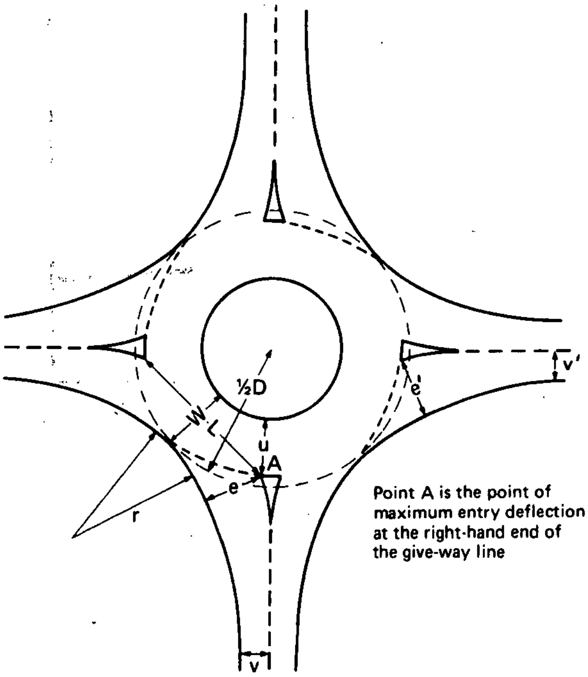


Fig. 7 DEPENDENCE OF THE ENTRY CAPACITY RELATIONSHIP ON THE ENTRY GEOMETRY ACCORDING TO EQUATION (13)

11. APPENDIX 1

DEFINITIONS OF GEOMETRIC PARAMETERS



Point A is the point of maximum entry deflection at the right-hand end of the give-way line

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).

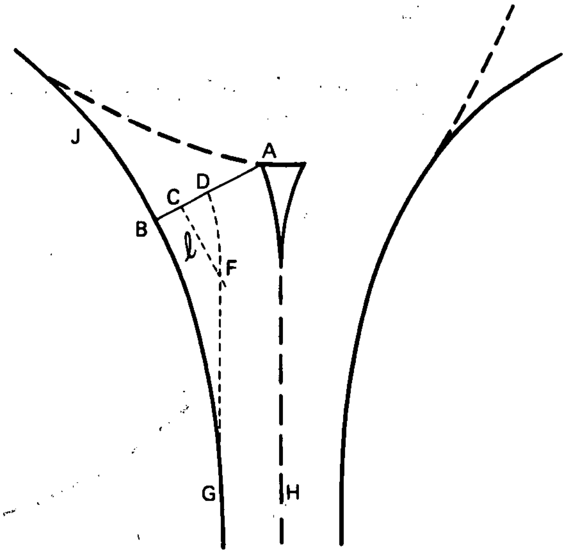


Diagram (b)

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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.

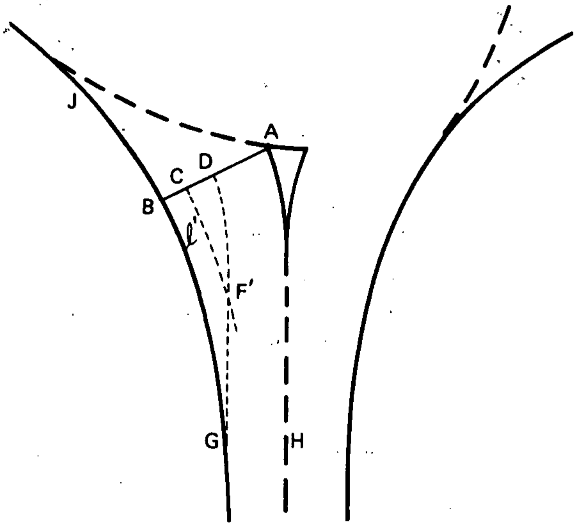


Diagram (c)

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).

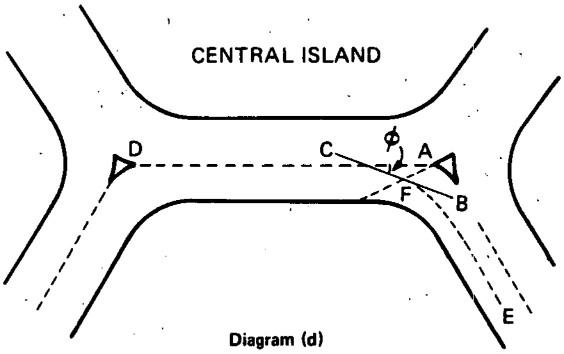


Diagram (d)

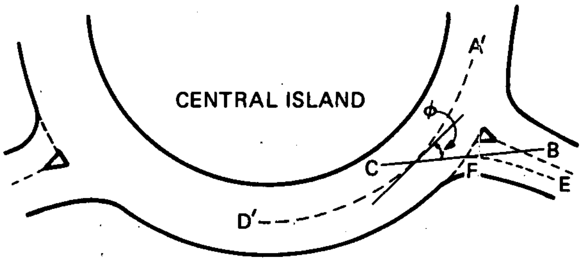


Diagram (e)

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).

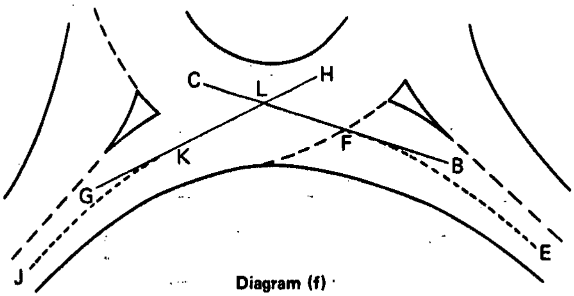


Diagram (f)

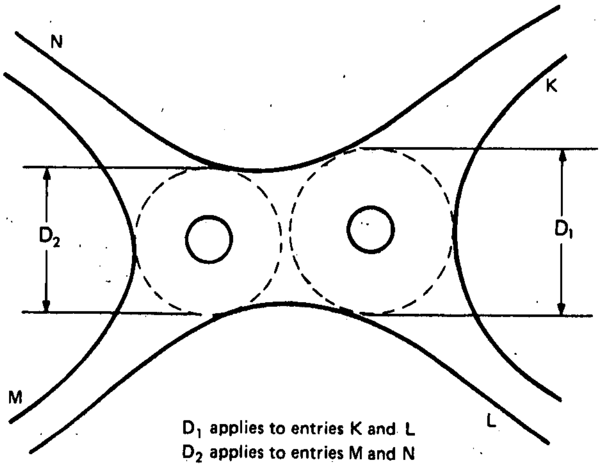
Here, the line BC is as in Diagram (d), and the line GH is the tangent to the line, JK, in the following *exit* midway between the nearside kerb and the median line and nearside edge of any median island at the point where this line joins the outer boundary of the roundabout circulation. BC and GH intersect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

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

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.



D_1 applies to entries K and L
D_2 applies to entries M and N

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.

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.

STEPS

(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), $\phi = 30^{\circ}$, 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:

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

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.