ROUNDABOUT DESIGN FOR CAPACITY AND SAFETY
THE UK EMPIRICAL METHODOLOGY

The UK has used roundabouts as an effective means of traffic control in the modern high traffic density era for some 25 years or more. The key decision was to change to giving circulating traffic priority. From this moment, heavy traffic loads could no longer cause a roundabout to lock up, provided the exits could accept all the traffic passed to them. This paper is intended to cover 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. The whole purpose of the research programme was to produce information that the traffic engineer could use to design roundabouts that would meet his operational requirements; there was no intention to produce theoretically pleasing equations that explained the processes involved, just to give practical links between geometry, capacity/delay and accidents.

The paper will cover:

A brief description of the main results as established by the empirical relationships determined in the UK, both for capacity and injury accidents.

The details of the size and range of the research data behind the relationships.

A description of the resulting ARCADY design software, and its advantages to the traffic engineer.

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.

Secondly, and of at least equal importance, UK experience has shown that for similar traffic loads, roundabouts return an injury accident rate half that for traffic signals. Other countries that have recently (the last 10 or so years) introduced roundabouts have also reported results at least as good as the UK. Examples are France (1), Germany (2) and Poland (3).

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. Only the human touch can take into account all the factors involved in the design of an individual roundabout.

All the experimental measurements made in the UK have indicated that the relationship between entry capacity and circulating flow is linear, and that both the intercept on the entering flow axis and the slope of the relationship can be successfully predicted from a knowledge of the geometry and the flows and turning movements. This is a very important result, as it obviates any need to understand and define the extremely complex and interactive actions of individual drivers as they use the roundabout.

UK research not only measured capacity, but also investigated in detail ways of calculating delay during operation at or near capacity. Previous theory could give satisfactory results when loading was either well below capacity or well above it. For practical junctions under today's conditions, it is this area close to capacity that is of prime importance. The research work showed that good approximations to the actual build up of queues and therefore delays could be achieved by developing a transformation that progressively moved delay from the predictions of the steady state theory (good at low demand levels) to the those of the deterministic theory (accurate when demand is well above capacity) as traffic loads increased through capacity.

The research, targeted on developing direct geometric relationships to capacity, used linear regression to establish statistically significant relationships between entry capacity and geometric parameters (4). The dimensions of the study roundabouts were carefully measured, with every likely variable recorded, many in several forms, and the entry
capacity was measured during periods of at-capacity operation. The size and generality of the database is covered later in this paper. The outcome of the regression analysis was that there were only 6 significant geometric parameters that played a role in determining capacity. They were entry width, approach width, flare length (the length over which local widening of the approach is developed), entry angle, inscribed circle diameter and the radius of the kerb at entry. All other parameters proved insignificant. This lead to comparatively simple relationships which have proved remarkably robust. Of these six, three are of particular importance, most of all entry width, and then approach width and flare length. The remaining three have comparatively minor effects. Typical examples of the effects are shown in Figs 1 & 2, for entry width and flare length.

**Effect of variation of entry width 'e'**

![Effect of variation of entry width 'e'](image)

**Effect of variation of flare length 'l'**

![Effect of variation of flare length 'l'](image)

Fig 1 Effect of variation of entry width 'e'

Fig 2 Effect of variation of flare length 'l'
A vital area in which the empirical method scores over gap-acceptance methods is in dealing with local widening, or flaring. The experimental data from road measurements has shown that there is a continuous relationship between entry capacity and entry width. This may at first seem unlikely, as surely there must be either one queue or two queues at entry. Close observation of the real processes at a roundabout entry 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 deliberately queue displaced sideways from the vehicle in front (see fig 3); 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. 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/owners of small vehicles will do this. As entry width increases further, this process develops until two full queues are achieved all the time, again giving this continuous increase in capacity with entry width, which goes on as the width increases to 3 or 4 lanes. 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.

It has been suggested that the 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:

a) Poor geometry which leads the offside lane straight at the centre island (see Fig 4).
b) 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 feel unable to use all the entry space as they seek to queue in lanes marked for their intended movement. Even if arrow markings fit the demands at one time of day, it is unlikely that they will suit all day long. In most instances no arrow markings near the give way line is the best option.
c) 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. Best advice is to end the lane lines at the beginning of the

**CAPACITY AND ENTRY WIDTH**

*Fig 3 - Capacity and Entry width*

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c) 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. Best advice is to end the lane lines at the beginning of the
widening, then to mark them again in the last 20 feet before the give-way line.
d) If a substantial part of the entry flow wishes to exit the roundabout at a restricted exit 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.

![Incomplete Lane Use Diagram](image)

**Fig 4 - Incomplete Lane Use**

All of these conditions are predictable by a good traffic engineer who knows his intersection and neighbourhood traffic flows. This systematic non-use of space is not taken into account by the empirical relationships, but since it is predictable, the engineer can make allowances for it in the way he models junctions.

**Size of the empirical database.**

The key to success in any study of this type is data - lots of it! In the 1970's, following the change to off-side priority at roundabouts which had clearly completely revolutionised roundabout operation, and made all previous design methods obsolete, the British Government began a major programme of research to investigate ways of predicting roundabout performance. The research programme, aimed at establishing both capacity and accident relationships, was carried out through the Government-owned Transport and Road Research Laboratory (TRRL). Initial work led to the rejection of gap acceptance methods as being over-complicated and very sensitive to small parameter changes, and also of giving a weak link between junction geometry and performance. As junction geometry is the key thing that road designers need to determine, this is a very real weakness of gap acceptance methodology. The British approach was therefore very much slanted towards the needs of practical designers, rather than academic purity.

The method selected was to collect a massive amount of data at carefully selected operational junctions. Information was collected on all the geometric parameters, and entry/circulating flow measurements were made at peak times. In a separate study, the safety records of another set of roundabouts were also collected, along with the geometric parameters. Statistical analysis was then used to determine which parameters were significant and what their effect was. The work that followed is probably now unrepeatable anywhere in the world, including Britain. At the time, Britain had many roundabouts in everyday use whose design was essentially the result of historic accident unrelated to motor traffic. This meant that the range of variable values, and particularly the combinations of variable values were very wide indeed, and included combinations which no modern designer using well-founded design software would ever produce. This wide variety is essential to producing robust results, giving data at the extremes to stabilise relationships. Today's roundabouts in Britain have been largely updated to meet current traffic conditions, using modern design processes, so we no longer have available junctions giving this very wide data spread. The size of the
databases speak for themselves; for capacity studies:

* 86 roundabout entries studied
* 11,000 minutes of capacity operation recorded
* 500,000 vehicles observed

There were also a number of extensive track trials carried out at TRRL’s facilities at Crowthorne, to add further data at the extremes. The data generated by these trials were not added to the public road data, as it was recognised that results from the test track are not necessarily compatible with public road data. They were used to fill in gaps in the work that could not be filled with real road data. The results were that the relationships found from the public road data were supported in general form by the test track data, giving confidence that the results were generally applicable.

In addition, a team averaging 5-6 scientists worked for 10-12 years establishing the databases, carrying out the statistical analysis, and developing the necessary theory to support the work.

On the safety front, an equally impressive database and body of supporting theory was built up:

* 84 roundabouts were studied
* 431 junction years of accident data were accumulated
* 1427 injury accidents studied
* over 5 years of accident data at each roundabout

Table 1 shows all the variables and factors considered. Along with their range of values.

### TABLE 1 - Variables and factors used in the analysis.

#### VARIABLES AND FACTORS USED IN THE ANALYSIS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>VARIABLES (arm specific)</td>
<td></td>
</tr>
<tr>
<td>1 Entry Path Curvature</td>
<td>-0.01-0.053m</td>
</tr>
<tr>
<td>2 Entry width</td>
<td>4.6 - 18.8m</td>
</tr>
<tr>
<td>3 Approach half-width</td>
<td>2.6 - 11.0m</td>
</tr>
<tr>
<td>4 Angle between arms</td>
<td>44 - 152 degrees</td>
</tr>
<tr>
<td>5 Gradient category</td>
<td>-3 - +3</td>
</tr>
<tr>
<td>6 Sight distance to the right</td>
<td>20 - 400m</td>
</tr>
<tr>
<td>7 Approach curvature category</td>
<td>-3 - +3</td>
</tr>
<tr>
<td>8 Distance of first sight of the roundabout</td>
<td>40 - 650m</td>
</tr>
<tr>
<td>9 Number of signs on the approach</td>
<td>0-10 0-10</td>
</tr>
<tr>
<td>10 Width of central reserve</td>
<td>0 - 16.7 m</td>
</tr>
<tr>
<td>11 Weaving length</td>
<td>7 - 11 m</td>
</tr>
<tr>
<td>12 Circulating width</td>
<td>6.5 - 19m</td>
</tr>
<tr>
<td>13 Weaving Width</td>
<td>7 - 25m</td>
</tr>
<tr>
<td>14 Number of chevrons on central island</td>
<td>0 - 12</td>
</tr>
<tr>
<td>15 Entry angle</td>
<td>0 - 74 degrees</td>
</tr>
<tr>
<td>16 Average flare length</td>
<td>0 - 99m</td>
</tr>
<tr>
<td>17 Sharpness of flare</td>
<td>0 - 2.8</td>
</tr>
<tr>
<td>18 Visibility round central island</td>
<td>8 - 90m</td>
</tr>
<tr>
<td>19 Entry path curvature from opposite arm</td>
<td>-0.01 - 0.053m</td>
</tr>
<tr>
<td>20 Entry path curvature from previous arm</td>
<td>-0.01 - 0.053m</td>
</tr>
<tr>
<td>FACTORS (arm specific)</td>
<td></td>
</tr>
<tr>
<td>21 Road class</td>
<td>3 levels</td>
</tr>
<tr>
<td>22 Carriageway type</td>
<td>2 levels</td>
</tr>
<tr>
<td>23 Approach speed limit category</td>
<td>5 levels</td>
</tr>
<tr>
<td>24 Approach lighting category</td>
<td>2 levels</td>
</tr>
</tbody>
</table>
GENERAL VARIABLES

25 Inscribed circle diameter 25 - 110m
26 Central island diameter 5 - 90m

The key to the robustness of the relationships is the wide variety of data; the roundabouts used were extremely varied in shape and size, some regular, reflecting modern trends, and some asymmetric in shape, and many with non-circular islands. The data did not just include a few roundabouts with extreme dimensions, but a representative sample across the data range - see figure 5. This continuity of data values across the range again gives stability to the relationships, and enables good predictions to be made even for unusual designs.

So far, mainly capacity issues have been discussed, however safety is of at least equal importance. Again, links have been positively established between geometry and injury accidents. Key parameters here are entry width and deflection on the approach, (entry path curvature and, of lesser importance, approach curvature) and central island diameter.

Entry path curvature is of particular importance as it has a vital effect on safety but no effect on capacity. If the entry is too straight, then vehicles tend to arrive at the conflict point too fast, leading to unnecessary accidents between entering and circulating vehicles. On the other hand, if the curvature is too sharp, then there is a rise in single vehicle accidents resulting from loss of control on the approach to the roundabout. Entry radius should not be less than 100 metres for best results, and with flared entries, values down to 30 metres are beneficial. Figures 6.1 and 6.2 show typical variation with entry curvature for parallel (unflared) and flared entries.

The resulting model gives accurate prediction overall, although for some categories there are notable differences between observed and predicted accident rates.

The UK empirical approach to capacity and accident prediction has proved remarkably successful, table 2 lists the junction types for which research has produced significant relationships between geometry, capacity and accidents. There are no cases where research has failed to identify such relationships - the gaps in the table are merely those
where no research has yet been undertaken. A thorough review of the UK research work is contained in a paper by Edmund Wadell of Michigan DOT (5).

Fig 6.1 - The predicted effect of entry curvature on accidents (Parallel entry)

Fig 6.2 - The predicted effect of entry curvature on accidents (Flared entry)

Table 2 Success of empirical methodology: junction types for which relationships have been successfully identified
<table>
<thead>
<tr>
<th>Junction type</th>
<th>Capacity</th>
<th>Accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundabouts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Normal</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Mini</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Priority T-junctions</td>
<td>*</td>
<td>*(rural)</td>
</tr>
<tr>
<td>Cross-Roads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-junctions</td>
<td>*</td>
<td>*(urban)</td>
</tr>
<tr>
<td>Cross-Roads</td>
<td>*</td>
<td>*(urban)</td>
</tr>
</tbody>
</table>

Earlier in this paper, a reason was given for this research being unrepeatable even in the UK; another is the cost of the work carried out in the seventies and early eighties. The work however represents exceptional value, and for the estimated equivalent of $11.5 million dollars, at 1998 values, the following were achieved:

- Large data base for capacity research (public road data)
- Track trial data to fill in gaps in public road data
- Development of the empirical capacity relationships
- Development of time dependent queuing theory
- Large injury accident data base
- Development of the accident analysis methodology
- Development of the empirical accident relationships

Despite the wide range of useful work completed, $11.5m dollars represents a lot of government funding, and it is unlikely that governments in today's financial climate would be prepared to commit this level of resources to developing roundabout design methodology.

Gap acceptance methods have been briefly alluded to in this paper - they are extremely complex and require the solution of a number of intransigent problems, for example:

- Gap acceptance itself - where waiting vehicles manage to accept gaps without in any way affecting the behaviour of circulating vehicles.
- Gap forcing - where entering vehicles fail to wait for a suitable gap and 'push' into the circulating stream, forcing a circulating (priority vehicle) to modify its chosen path/speed.
- Priority reversal - where for (short) periods priority completely reverses at times of high demand.
- Driver behaviour types - gap acceptance parameters change with driver attitude/type; aggressive drivers will accept much smaller gaps than timid ones. This in itself is complicated enough, but these characteristics are not even fixed for a driver, but will be modified by the behaviour of drivers around each individual, or by events which have just occurred away from the roundabout. An example would be the effect of a timid driver 'missing' a gap or gaps that the following driver thinks acceptable; this will tend to make the following driver more aggressive than he would have been had he been following a more adventurous driver.
- Interaction between circulating and entering traffic - this takes in priority reversal and gap forcing mentioned earlier, but there are also more subtle forms of interaction. Priority reversal and gap forcing are achieved on the initiative of entering traffic accepting risk by refusing to accept the declared priority, and the priority vehicles have to accept this state of affairs and modify their behaviour or risk an accident. However, it is also quite common, especially at busy times for circulating traffic to deliberately slow down or change their intended path to create space for an entering vehicle, where they know from experience that life is difficult for entering vehicles. This is done without pressure from the entering vehicles.
These are amongst the problems that have to be fully solved to produce a reliable gap acceptance model. 'Fully solved' means not just developed and demonstrated at a handful of junctions, and perhaps supported by simulation trials, but by a massive programme at real junctions such as lies behind the UK empirical methods. These are difficult problems even without the need to involve reliable connections to junction geometry. Having established all the above, it still remains to include satisfactory coverage of the effects of local flaring, and the offset queuing process and the progressive change from one lane queuing to two and then three, that leads to the continuous growth of capacity with entry width. There are probably a number of problems as yet unrecognised that will have to be solved.

How much neater, from the practical designer's point of view, just to step entirely around this minefield by using empirical methods and studying the performance of a wide range of real junctions.

Remember also, that all of this can only give capacity and delay estimates, there is nothing here to allow the prediction of injury accidents. In today's safety conscious world, injury accidents should have the same priority as capacity/delay in the designer's mind. Only the UK design methods can give this support to the designer. Again the methods are empirical, with relationships drawn from the study of nearly 1500 injury accidents at a carefully selected sample of 83 roundabouts (6).

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, 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 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, at least in the early years, will be down on that achieved in the UK, then this can be allowed for easily in the design process.

In summary, the traffic engineer needs design methods that will enable him to get directly from his proposed geometry to realistic estimates of capacity and safety. He needs to have confidence that his design method will give sound, dependable results even when he is forced to design an unusual layout. Through its wide underlying database, the UK methodology as exemplified by the ARCADY 4 software, gives this sense of security to the designer. ARCADY has been used to design literally thousands of successful roundabouts in Britain since its introduction more than 15 years ago.

There are a few basic requirements to achieving success with roundabout designs. The first is to choose the right locations, and a few guidelines can be put forward. The proposed roundabout should have reasonably balanced flows and turning movements. This doesn't mean that all approaches should have more or less the same flows, but that problems can be experienced if a road with very low flows is crossing one with very high flows. Turning proportions are important - it is traffic crossing an entry which breaks up the entering flow and allows the next entry access. For safety, it is crucial to design in sufficient deflection on the approach. The idea is to slow vehicles down before they reach the give way line, not as they reach it, or even after they have entered. With wide entries, necessary for high capacities, selection of a central island large enough to ensure that drivers cannot take a straight line across the roundabout is vital.

It is vital to have good flow predictions for the design year. These will be based on accurate measurements of the existing situation plus good forecasting of the future, always a problematic topic.

The next requirement is a good design model/software, to allow good prediction of capacity, delay and safety. Before committing to any particular product, take time to check its background, how substantial the data behind it is, that it has been well proven against real road data, not against simulation, and above all that there is a strong link to geometry, and particularly the effects of flaring, which are so important in the correct operation of modern roundabouts. Check too that you can design for safety with your intended software.

Finally, in achieving successful designs, there is an ingredient that can never be ommitted - a skilled traffic engineer. The importance of this cannot be overstated, to bring to the design a good understanding of conditions surrounding the roundabout and there likely affects, an awareness of what the software is saying, and how best to amend an initial
design. ARCADY helps the designer here, in that it predicts the effects of small changes in all the key capacity and safety parameters, so a designer can easily determine for a particular design which parameter to vary for best effect.

In conclusion, a few words about the latest version of ARCADY - ARCADY 5I (I for International). ARCADY 5I is the latest version of ARCADY, and is fully converted for countries which drive on the right, removing the irritating conversion to left hand rule of the road of all flow data etc before running the program. ARCADY 5I also gives users the convenience of 'Windows' with easy visual input arrangements. Another major development launched in ARCADY 5I is the addition of completely new algorithms for assessing the capacity and injury accident record of mini-roundabouts. Mini-roundabouts are characterised by a central island of not more than 4 metres diameter, with no kerbs or street furniture. The island is designed to be driven over by large vehicles as they negotiate the intersection, allowing this type of roundabout to be successfully used where space is extremely limited. The algorithms were developed as a result of a major UK Government research programme, and work on exactly the same principals as those for conventional roundabouts.

Roundabouts and the ability to use them are transferable. Many have said in the past that roundabouts were uniquely British and only the British would ever understand and use them well. Over the last ten years, roundabouts have spread to Continental Europe, with good results reported. Several countries have already reported greatly reduced injuries compared to equivalent signalled junctions. Some use roundabouts more as traffic calming devices than as effective control for high flow junctions and they are effective as both. The writer has observed a total of 7 roundabouts in Vail, Nederland and Loveland, Colorado, and saw no evidence that US drivers experienced particular difficulty in negotiating them. American drivers also expressed satisfaction with the roundabouts, considering them to be positive additions to their communities. There may be some loss of capacity compared to Britain, especially in the early years when drivers are unfamiliar with the concept, but given that designs are intended to satisfy demands on a 15 to 20 year horizon, a capacity loss of 15 - 20% initially should be easily supportable. Also, remember that capacity matters most at peak times, and in peak hours most drivers are more than familiar with their routes to work and back, so gaining familiarity should take weeks, possibly a few months to achieve.

In using ARCADY, a designer can be confident of a product based on first-class research, of continued support by the world-renowned TRL. Added comfort comes from the knowledge that TRL's reputation is behind the product, and that there have been over 15 years successful use in the UK and other countries. ARCADY is available from TRL's Software Bureau, E-mail softwarebureau@trl.co.uk. Information and demonstration versions are available on our software web site, www.trlsoftware.co.uk.

References


