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.

3 UK empirical model for roundabout capacity

In the 1970s the UK 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 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 UK approach was therefore very much slanted towards the needs of practical designers, rather than academic purity.

The method chosen was to collect a very large amount of data at carefully selected operational junctions. Information was collected on various geometric parameters and entry/circulating flow measurements were made at peak times. Statistical analysis was then used to determine which parameters were significant and what their effect was.

The work that followed is probably now unrepeatable. This is because, at the time, the UK 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 geometries, and particularly the combinations of values, were very wide indeed, and included combinations which no modern designer would ever produce. This wide variety is essential to producing robust results, giving data at the extremes to stabilise relationships. Today's roundabouts 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 database speaks for itself:

* 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 points 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 however 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 of scientists worked for 10-12 years establishing the databases, carrying out the statistical analysis, and developing the necessary theory to support the work.

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.

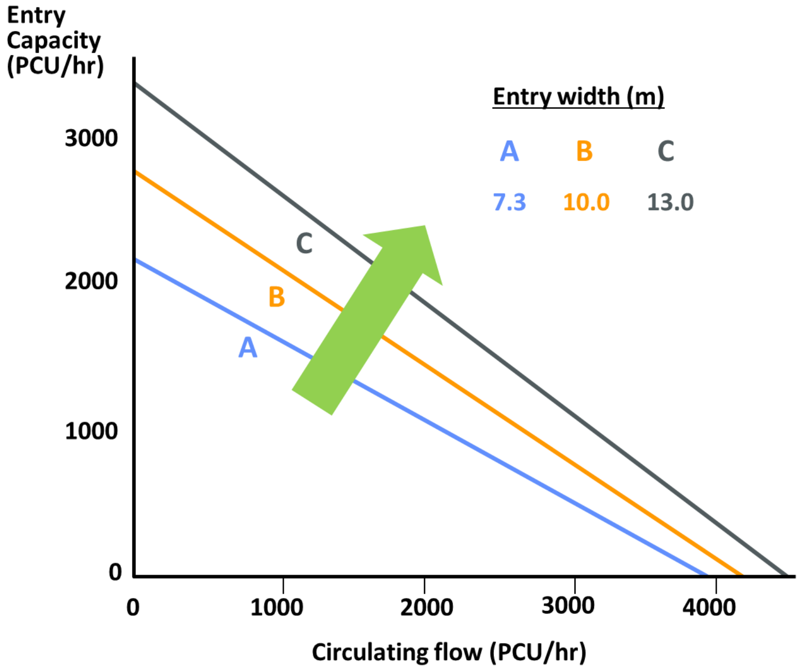
The research used linear regression to establish statistically significant relationships between entry capacity and various geometric parameters. The dimensions of the study roundabouts were carefully measured and the entry capacity measured during periods of at-capacity operation.

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.

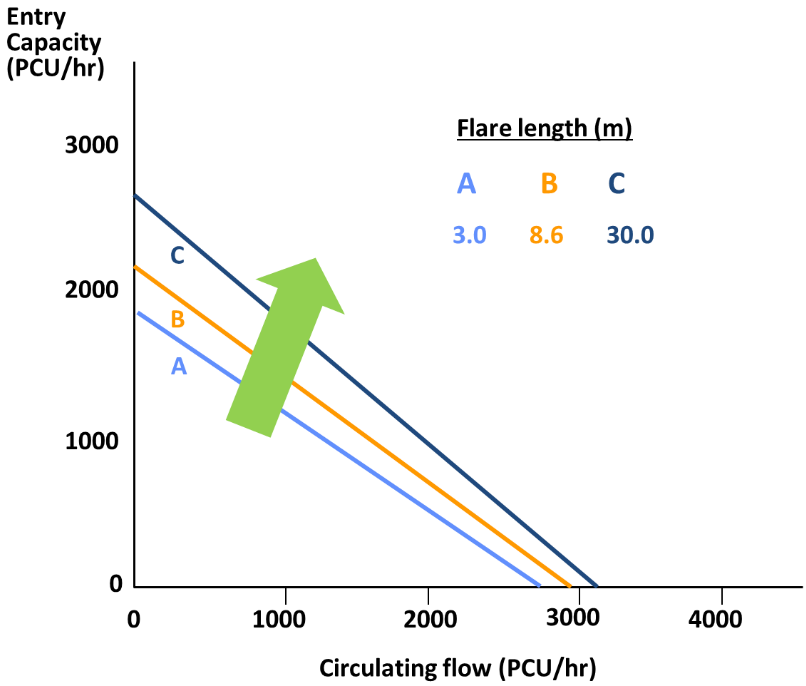
Variable	Range
Entry width	**3.6 – 16.5 m**
Entry width on previous entry	3.6 – 15.0 m
Approach width	**1.9 – 12.5 m**
Approach width on previous entry	2.9 – 12.5 m
Circulation width at entry	4.9 – 22.7 m
Circulation width between entry and next exit	7.0 – 26.0 m
Effective flare length (construction 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.



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



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

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.

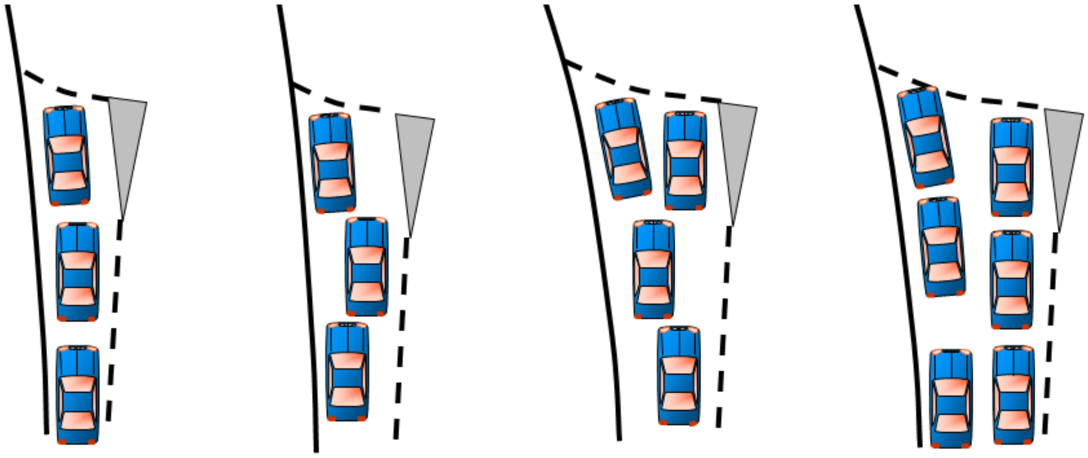
The experimental data from road measurements showed that there is a continuous (smooth) relationship between entry capacity and entry width. This may at first seem unlikely, as surely there must be either one queue or two (or more) queues at entry. Close observation of the real processes at a roundabout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

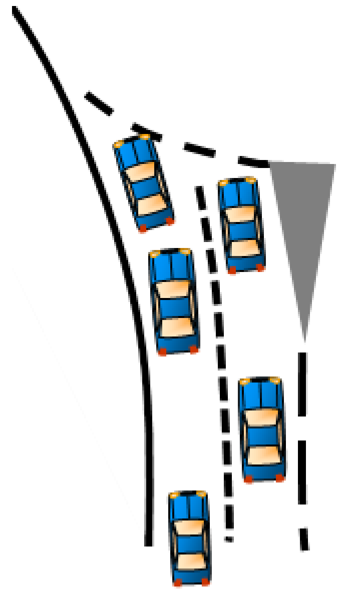
4.2 Use of road space

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.

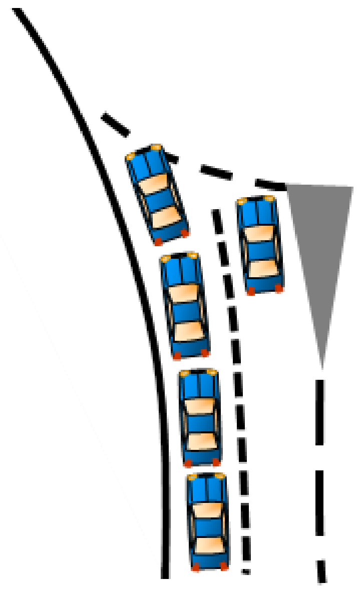
There remains what could be called the systematic failure to use all the space. This could be for a number of reasons, such as:

- 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.

4.3 Queues and delays

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 typical 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.

4.4 Empirical models versus gap acceptance and microsimulation

In addition to the UK empirical model described in this paper, roundabouts can also be modelled using gap acceptance and/or microsimulation methods.

These methods are extremely complex and require the solution of a number of problems, including:

- 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 nervous drivers. This in itself is complicated enough, but these characteristics are not even fixed for a driver, but will be modified by how the driver is feeling at the time, the behaviour of drivers around each individual, or by events which have just occurred away from the roundabout.

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, the offset queuing process and the progressive change from one lane queuing to two and then three, which leads to the continuous growth of capacity with entry width. There are probably also a number of problems as yet unrecognised that will have to be solved.

How much neater it is just to step entirely around this minefield by using empirical methods and studying the performance of a wide range of real junctions.

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*.