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Dutch-style Roundabout Capacity Report

Research into the Capacity of a Dutch-style Roundabout

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Executive Summary

As part of a wider programme of off-street trials of innovative cycling infrastructure, TRL investigated a 'Dutch style' roundabout which separates motor vehicles from cyclists in the circulating part of the roundabout while giving cyclists priority over turning vehicles, with the aim of improving cyclists' safety while reducing delay when using the roundabout.

Whilst other parts of the programme consider the safety and behavioural aspects of this type of roundabout, this report concentrates on the vehicular capacity (and delay) implications of such a type of roundabout and reviews how to incorporate the findings into current advice on modelling the vehicle capacity and delays at roundabouts. It should be noted however that this report should be read in conjunction with the Safety report (PPR751) to ensure that the designer fully understands the design criteria and impacts of these.

The estimation of the capacity of the cycle facilities (orbital cycle track and entry and exit arms) of such a roundabout was not investigated, although the impact that cyclists had on the vehicular capacity of such a roundabout was. Even were such research to be done the findings could not be directly incorporated into current roundabout capacity modelling software. The impact of the composition of the traffic flow on the vehicular capacity was also not investigated, although a trial was undertaken to investigate the effect of long vehicles on the capacity of the circulating lane.

Using tests on a trial layout in an off-street location it has been possible to estimate a UK-based relationship between the vehicle entry-arm capacity and the circulating flow for this type of roundabout -both measured in Passenger Car Units (PCUs). In addition, it has been found that drivers require greater gaps in the circulating bicycle flow to exit the roundabout than would be estimated simply based on the time it takes a cycle to cross the exit arm. This, additional, perceived gap time amounted to some 5 seconds and can have a significant effect on the capacity of the previous entry arm, because there will be an increased risk of vehicles, queuing on exiting the roundabout, blocking the exit of the previous entry arm. There was a similar but smaller effect noticed for drivers entering a roundabout. This lesser effect was expected because they tend to have a better view of circulating cyclists than drivers exiting a roundabout.

The impact of the trialled layout, which would conform to DMRB's 'compact' roundabout definition as far as vehicular capacity is concerned, compared with an equivalent 'conventional' roundabout (DMRB Vol. 6 section 2), with the same travel patterns was to reduce capacity by a little over 40%. Much of this reduction in capacity was due to the trial layout having single-lane entries and exits with little or no flaring. The scale of the reductions should be treated with caution since they are just one illustrative example based on a given layout and travel patterns. The impact of converting other conventional roundabouts (or other junction types) with other types of layouts or with different travel conditions to a Dutch-style roundabout could well be different.

Studies in the Netherlands and Germany suggest that the number of entry lanes, the number of circulating lanes, and in the Dutch research work the separation of the exit and entry arms at an arm, have a significant impact on capacity while other geometric variations did not appear in the final equations. However, a roundabout with two or more entry lanes, and more than one circulating lane, conforms more towards a conventional roundabout whose vehicle capacity can be predicted using the relationships within LR942.

The report also gives advice on modelling the capacity of such Dutch-style roundabouts with a pedestrian or a cycle crossing on the entry arms, or both. It also provides advice on how to model such crossings within the ARCADY roundabout modelling program.

In addition, whilst ARCADY input values currently do not discriminate between long vehicles and other classes of vehicles (everything is entered as PCU) the results of one of the trials suggested that particular care will be needed where the roundabout is likely to be used by a significant number of long vehicles such as buses, coaches or articulated lorries. Such vehicles may block both entry to the roundabout and the circulation of other vehicles on the roundabout. This is not only because of their length but also the way that drivers manoeuvre such vehicles in order to be able to see circulating cyclists clearly.

1 Introduction

1.1 General introduction to the Dutch-style Roundabout (DRB)

As part of the Cycle Facility Trials project, which TRL is undertaking for TfL, TRL has been tasked with investigating the implications of implementing a design which separates cars from cyclists in the circulating part of the roundabout in an attempt to improve cyclists' safety while minimising delay.

The 'Dutch-style Roundabout' is based on a design of roundabout that is used in The Netherlands (and other European countries such as Germany and Italy). It uses 'continental' geometry (short turning radii to reduce speeds and a single lane circulating carriageway) and has a kerb-segregated cycle track at carriageway level, orbiting around the outside of the roundabout. In urban areas cyclists are given priority across the entry and exit lanes, however this is not usually the case outside urban areas. Past work by TRL (Davies et al, 1997) on roundabouts with continental geometry suggested that they would have a lower vehicle capacity than roundabouts with more traditional, to the UK, layouts

In the version trialled at TRL, Zebra crossings are placed across each arm. On Arms 1, 3 and 4 the Zebra crossing are directly alongside the cycle crossings of the exit and entry arms, whereas on Arm 2 there is a 5m gap between the Zebra crossing and the cycle crossing.

The trial layout varies slightly at each arm, involving varying distances and angles of separation between the cycle track and circulating carriageway, and the extent to which cyclists are guided into the orbital cycle track. This approach permits different design elements to be tested and compared within the same trial (see below for more detail).

The design drawings were developed with TfL and further background information is provided in the planning sheet previously discussed with TfL (WS2.DRBb.M5). The layout is shown in Figure 1.

The different designs of the entry and exit layouts tested were:

- Arm 1: Cyclists approach in a segregated cycle track which connects with the segregated orbital track. Cyclists also exit the orbital cycle track using a segregated cycle track.
- Arm 2: Cyclists approach in a mandatory cycle lane with a fairly sharp left turn into the orbital cycle track, encouraged by an island which is shaped to direct the cyclists into the segregated orbital track. When exiting, cyclists leave the orbital cycle track taking a fairly sharp left turn directly into the main carriageway.
- Arm 3: Cyclists approach on the carriageway with a fairly sharp left turn into the orbital cycle track. The island separating the cycle track from the main carriageway is neutral in terms of directing cyclists into the orbital segregation. When exiting, cyclists leave the orbital cycle track taking a fairly sharp left turn into a mandatory cycle lane.
- Arm 4: Cyclist approaches roundabout in a normal vehicle lane, with a segregated track leading to the orbital track turning off to the left. Cyclists leave the orbital track via a segregated cycle track which eventually merges with the main carriageway.

While the initial build of the roundabout used in trials M5 and M6 used standard Dutch markings on the roundabout, an important aspect of this build of the roundabout is that it used mainly UK style markings. The changes included the following:

- Application of zigzag markings on either side of the Zebra crossings
- Different marking delineating the cycle lane crossings of the entry and exit arms (single or double dashed lines rather than elephants feet/sharks teeth), although elephants feet were left on Arm 4 and sharks teeth left on the Arm 1 exit
- A "give way" marking was used on Arm 2 exit to reinforce the cycle priority
- The Dutch markings indicate the outside of the circulating carriageway by a dashed line; UK practice only lines the entry-lanes, not the exit lanes.

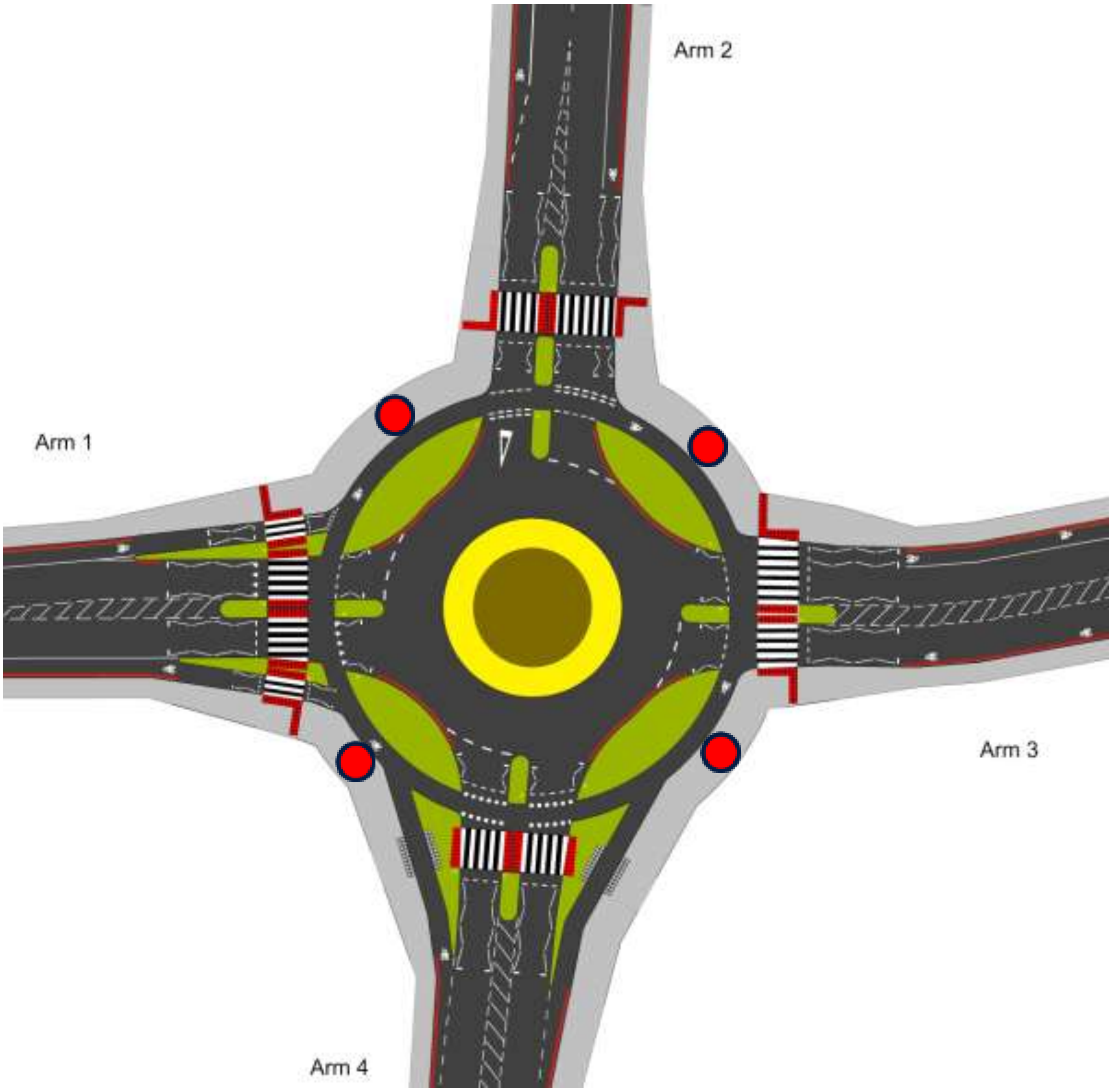

Figure 1: Layout of the Dutch-style Roundabout with UK road markings

In addition, cycle symbols were painted on the cycle track to highlight their presence. Note also that the red dots shown on the pedestrian paths in Figure 1 are the start/end points for pedestrians (see later) and are not actually markings on the roundabout.

1.2 Introduction to the capacity implications of the Dutch-style Roundabout (DRB)

Whilst other parts of the programme consider the safety and behavioural aspects of this type of roundabout, this report concentrates on the capacity (and delay) implications of such a type of roundabout and reviews how to incorporate the findings into current advice on modelling the capacity and delays at roundabouts.

1.3 Objectives of study

Specifically the key research questions for the trials discussed in this report were:

- How does the vehicular capacity of an entry arm vary with the number of cars circulating the roundabout?
- How does cyclists' behaviour at an exit affect drivers' behaviour in terms of capacity effects?
- What is the effect of the different layouts at two of the exit arms on capacity?
- How does the layout of the roundabout affect the number of vehicles that can queue up on the exit of the roundabout before blocking-back the preceding exit arm? This question particular looked at the role of 'long' vehicles.
- How does the behaviour of pedestrians and cyclists effect the entry capacity of this type of roundabout
- What changes to current modelling practices are needed to model the capacity effects of such a roundabout?

In order to answer these questions a review of current roundabout capacity literature was undertaken to identify what continental practices were used in modelling the capacity of such roundabouts, and how this differs from current UK modelling practice. A summary of this review is given in Section 1.2.

As a result of the review a series of three trials was designed to answer these questions, using the trial roundabout layout shown in **Figure 1**. These trials are briefly described in Section 2. The results of the trials are described in Section 3 and the implications of these results, in terms of UK modelling practice, are discussed in Section 4 by way of an illustrative example. In addition, results from a simulator trial aimed at assessing whether car drivers reliably make safe decisions when entering a Dutch-style roundabout were used. One of its objectives was to find out what sized gap, on average, do drivers accept when entering the Dutch-style roundabout faced with different levels of pedestrian, cyclist and vehicle crossing flows. These results were used to estimate the parameters for modelling how cyclists (and pedestrian) crossing flows affect vehicular entry capacities.

1.4 Review of roundabout capacity models

The layout tested at TRL had been designed to mimic a number of characteristics of Dutch-style roundabouts which are expected to provide priority for cyclists, in comparison with navigating a UK-style roundabout amongst other traffic. The behavioural implications of this type of roundabout have been studied in a number of associated trials by TfL. However, previous work by TRL for the DETR and DfT, trialling on-site roundabouts displaying such continental characteristics as single lane circulating flows and reductions in flaring, have shown that there can be significant reductions in vehicle capacity leading to increases in delays to traffic using the roundabout (Davies et al, 1997, and Lawton et al, 2003).

As part of the assessment of the practicality and usefulness of the new design being trialled, there is a need to assess its impact on the capacity of the roundabout and on delays to vehicles. Part of this assessment can be carried out using standard traffic modelling techniques; however, some aspects of the new design are not explicitly covered in current traffic modelling advice and led to the need for specific off-site trials.

Considered as a vehicle roundabout only, the Dutch-style type of roundabout being tested in the trials would come under the DMRB 'Compact Roundabout' type as defined below.

'Compact Roundabouts[1]

3.3 A Compact Roundabout (Figure 3/2) has single lane entries and exits on each arm. The width of the circulatory carriageway is such that it is not possible for two cars to pass one another.

3.4 On roads with a speed limit of 40mph or less within 100m of the give way line on all approaches, Compact Roundabouts may have low values of entry and exit radii in conjunction with high values of entry deflection. This design has less capacity than that of Normal Roundabouts, but is particularly suitable where there is a need to accommodate the movement of pedestrians and cyclists. The non-flared entries/exits give the designer more flexibility in siting pedestrian crossings.

3.5 On roads with speed limits exceeding 40mph, the design of Compact Roundabouts is similar to that for Normal Roundabouts, but the single-lane entries and exits are retained.'

Much of the advice on the modelling roundabouts in the UK is derived from research by Kimber, reported in LR942 (Kimber, 1980). This work was based on earlier trials at TRRL[2] and on-site analysis of existing roundabouts. This, and later work, led to advice on modelling the capacity both of conventional roundabouts and of mini-roundabouts, as defined in the DMRB advice, which is incorporated in the current version of the junction software ARCADY[3]. With this approach, the vehicle capacity of an entry arm is a function both of the traffic circulating on the roundabout and the geometric characteristics of the entry arm. This approach is referred to in this report as UK (LR942) method. Unfortunately, there were no 'compact' roundabouts in the sample of roundabouts on which Kimber's capacity and delay relationships were estimated so there is no guarantee that the relationships within LR942, and incorporated in ARCADY, are suitable for Dutch-style roundabouts.

However, such compact roundabouts are common on the continent and examples of capacity estimation of such single-lane entry, single circulating lane were found for the

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[1] DMRB Section 6/2 - TD 16/07

[2] TRRL = Transport and Road Research Laboratory (renamed to Transport Research Laboratory (TRL) in 1992)

[3] ARCADY8 is now incorporated within TRL's Junctions8 suite.

Netherlands (De Leeuw et al, 1998) and for Germany (Brilon, 1997). The Dutch reference proved particularly useful in that it provided the relationships that were used to develop the roundabout capacity model. Two aspects of the vehicle capacity relationships were different from that in LR942. Firstly, the relationship between entry arm capacity and the geometric characteristics of the roundabout is much simplified, probably reflecting the smaller range of variation in these characteristics for compact roundabouts. Secondly, the vehicle entry arm capacity was itself a function of the vehicle flows exiting at that arm (this was not the case for Brilon's function).

Partly because an estimation of the capacity of a roundabout depends on the actual geometric characteristics of that roundabout (especially in LR942) and its traffic pattern, and partly because of the desire to anchor any research to actual examples of potential sites for such a compact roundabout in London, details were provided by TfL for a candidate junction in Central London. This junction is currently a conventional roundabout with significant pedestrian flows crossing each arm by way of zebra crossings.

Figure 2 shows a comparison the entry-arm capacity/circulating flow relationship for one arm of this roundabout. The LR942 relationship was modelled within ARCADY and the Dutch relationship through the relationships within de Leeuw's paper; that of Brilon from his paper. All three relationships show that the entry-arm capacity falls as the circulating flow increases but the Dutch and LR942 relationships are significantly different with the Dutch relationship showing a much steeper relationship between vehicle entry-arm capacity and the circulating flow than in LR942.

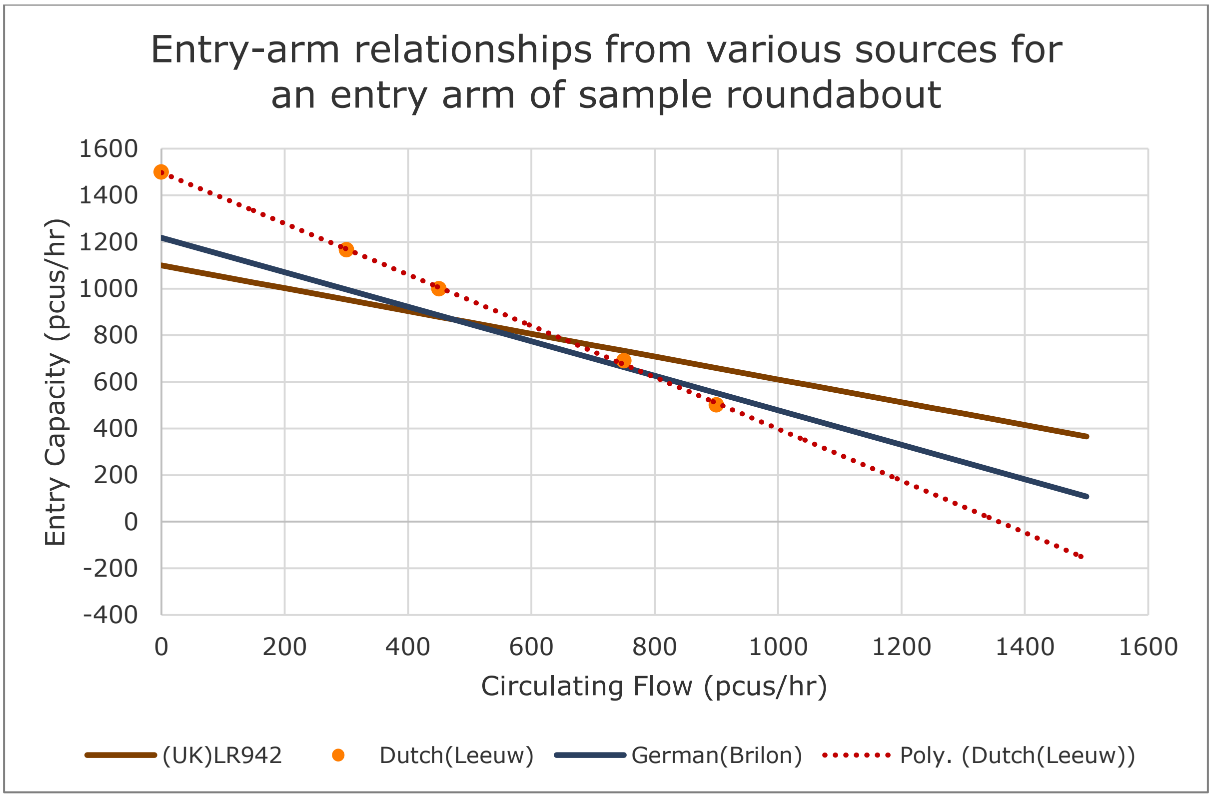

Figure 2 Relationships between entry-arm capacity and circulating flow - International comparisons

Whilst the above discussion of the impact of the circulating flow on vehicle entry capacities is important it is only part of the capacity estimating process. The estimation of the vehicular capacity of a roundabout is traditionally undertaken as a series of stages:

1. Estimate the vehicular capacity of an entry arm as a function of the circulating flow and the roundabout geometry
2. Estimate the reduction factor to the entry capacity caused by any crossings (pedestrian, and/or cycle) to that entry arm. This is undertaken with a theoretical model (in ARCADY, based on Marlow and Maycock, 1982) and so far all existing models have only considered a single crossing per entry arm (i.e. pedestrian or cyclists but not both). It should be noted that all the common roundabout models presuppose that the impact of crossing vehicles on the circulating lane is more important than any effect of the pedestrian crossing on overall capacity. If this is not true then the theoretical underpinnings to stage 2 are undermined and, because the crossing is now the critical factor in the capacity of the entry/exit arm rather than the circulating flow on the roundabout, the basis for uncontrolled crossings on the roundabout arms needs to be revaluated.
3. Estimate the reduction factor to the entry capacity of an arm as result of blocking back from the next exit arm, caused by any crossing on that arm.

From the literature review, it appears that the method used for modelling the impact of pedestrians is largely based on theoretical work by Marlow and Maycock (1982) and that de Leeuw extended the impact to cyclists by analogy (as 'fast pedestrians'). However, there are a number of unresolved issues, not all of which can be addressed in this report.

- The impact of pedestrian crossings is modelled within ARCADY using equations based on Marlow and Maycock's theoretical work. They also looked at the impact of the distance between the pedestrian crossings and the circulating lane. ARCADY assumes that drivers only start to respond to pedestrians once they reach the start of the crossing. Brilon's paper states that the theoretical model may overestimate the impact of pedestrians on vehicle capacity. This is an issue for pedestrian modelling rather than specific to this project.
- The Dutch research, whilst based on Marlow and Maycock's findings, simply translates cyclists as 'fast pedestrians' and assumes that, like pedestrians, cyclists only influence drivers once they reach the crossing itself. This issue is covered with respect to exit arm strategies in section 3.2 and for entry-arm strategies in section 3.3.2.
- Neither ARCADY nor the Dutch research considered the impact of two parallel crossings, one for pedestrians and one for cyclists on an entry/exit arm. Because of the possible safety considerations an exploration of this issue was not thought suitable for practical trials but it is an issue considered in other work in the Cycle Facility trials, using a simulator rather than a trial.

In order to provide answers to these issues a series of trials (given trial codes M28a-c) were organised at TRL using the DRB roundabout.

Specifically:

M28a – to estimate the vehicular capacity of an entry arm as a function of the circulating flow i.e. Stage 1 above.

M28b – to estimate the impact of cyclists crossing the exit arm on the capacity of the exit so that the reduction factor in Stage 3 could be estimated.

M28c – to assess the impact of long vehicles on the ability of the roundabout to function effectively. Whilst not directly relevant to current calculations in stage 3, it does impact on the probability of an entry arm being blocked because the circulating lane is much narrower than assumed in traditional UK roundabouts.

No site trial was considered for Stage 2 at this stage because there were possible safety issues with running entry-arm capacity trials along with cyclists crossing in front of the entry arm. However results have also been used from another trial:

M52 - minimum safe gap time when entering the roundabout.

The possible impact of Stage 2 on the full modelling of the capacity of this type of roundabout is returned to in section 4.

The next section provides a brief summary of the three site trials.

2 Methodology for trials

2.1 Overview

The trials made use of the Dutch-style roundabout as set out in **Figure 1** with predominantly UK road markings. Each trial was set up specifically for that trial.

2.1.1 *M28a – vehicle capacity*

In this trial the vehicle entry-arm capacity of one arm was estimated by ensuring that a fully saturated flow of cars attempted to enter the circulating lane as the number of circulating cars varied. Only cars were used for this trial since roundabout capacity is normally estimated in passenger-car units (PCUs). The capacity of only one entry arm was studied - Arm 3, the arm with the least limitations in terms of the position of the entry arm relative to the central area used for the experiment. Since all the arms had very similar geometry, at least as far as entry-arm capacity based on LR942 was concerned, the choice of entry arm did not make much difference. Every 10 minutes the circulating flow on the roundabout was altered so that the relationship between the observed entry-arm capacity and the volume of circulating flow could be estimated. Counts of both were taken every 5 minutes. Some 29 observations were made. In addition, the proportion of the circulating flow that exited at the tested entry arm was also varied to investigate if the Dutch finding that the capacity of the entry arm declined as the number of vehicles exiting at the entry arm increased.

2.1.2 *M28b – impact of cyclists on vehicle exit behaviour*

The procedure for the second trial was somewhat different from the first. Firstly, the emphasis was on observing the behaviour of vehicles exiting the roundabout when faced with circulating cyclists on the cycle track. In terms of the requirement for the modelling of the capacity of roundabouts, the primary aim was to estimate the parameters that would dictate the probability that the exit arm would be blocked, so causing an exiting vehicle to queue. Depending on the observed estimate of the number of queued vehicles needed to block the previous exit, this trial would provide the parameters need to undertake stage 3 of the vehicle *entry-arm* capacity estimate.

Theoretically, the probability of a large enough gap between cyclists in a traffic stream for a driver to pass through use is a function of the numbers of cyclists crossing, the time for a cyclist to cross and the saturation flow of the exit arm (actually the ‘follow-up’ time) so that

$$P_G = e^{-\mu(\alpha-0.5\beta)}$$ ....Equation 1

Where

P_G = probability of a suitable gap (i.e. a driver not having to stop)

μ = mean cyclist flow rate (cyclists/sec)

ɑ = ‘crossing time for cyclist (seconds)’- the minimum size of the gap between cyclists that a driver requires before they will cross the stream of cyclists.

β = car follow-up time (=1/saturation flow) (seconds)

gives the probability that the crossing is not blocked.

As an example, if one assumes that there is a cycle flow rate of 600 per hour (0.167 per second) and a crossing time of the exit arm by cyclists of 2 seconds and a 'follow-up rate' of (3600/1375 = 2.6 seconds)[4] then the probability that the exit will not be blocked for a given vehicle trying to exit would be 89%. If the cycle flow rate was doubled to 1000 cycles per hour the probability of the exit not being blocked drops to 79%.

This equation has been used as the basis for gap acceptance theory, either for major/minor vehicle crossings (see Troutbeck and Brilon (1997) for discussion) or pedestrian crossings (Griffiths, 1981). This simple relationship only holds if cyclists and car flows are random. In practice, as vehicle flow nears saturation flow then the car flow becomes more constant and the equation becomes more complex and an intermediate variable 'virtual capacity of the exit' calculated. For pedestrians there has not been the same degree of empirical observation but random flows may be a better assumption than for vehicle flows. In the case of cyclists we have found no references to alternative, better, assumptions.

Equation 1 above is based on crossing times and gaps relating to actual cyclist crossing times of the exit arm, however a more flexible version of the relationship which allows for the existence of firstly, drivers requiring gaps that are not directly related to the actual cyclists' crossing time, and secondly for there to be an effect caused by cyclists exiting at this arm is given in equation 2.

$$P_G = e^{-(\mu+\omega x)*((\alpha+\varphi)-0.5\beta)} \qquad \text{……………Equation 2}$$

Where,

P_G = Probability of a gap in the cycle flow is deemed sufficient for a car to pass though i.e. the car does not stopped/not delayed

μ = the mean rate of bicycle flow (per sec)

ω = the impact of cyclists exiting at that exit arm (to be estimated). This parameter was found important in research by De Leeuw et al (1999) where the vehicle capacity of an exit arm declined as the number of cyclists exiting at the arm increased.

x = cyclists exiting at this exit arm (per sec)

α = The time for a cyclist to actually cross the exit arm (secs). Given the observed speed of cyclists in this trial of 4.35 m/s and the exit-arm lane width of 5 metres, this equated to a time of 1.15 seconds.

φ = Any time that a driver requires for a suitable gap in addition to the bicycle crossing time (to be estimated). With pedestrians, it is assumed that drivers only take notice of pedestrians at the kerbside but drivers may need to take notice of cyclists who

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[4] The follow-up time is the inverse of the saturation flow for an exit, estimated in this trial to be about 1375 pcus/hr

have not yet reached the kerb-side so one expect a positive value for this. The size of this value may depend on the speed of cyclists and their visibility to drivers exiting the roundabout.

β = the 'follow-up time' - the inverse of the vehicle exit-arm saturation flow (secs). This was estimated to be about 1/(1350 pcus/hr) from the results of the first trial but because each car was independent of each other this factor can be ignored in this trial.

For the purposes of analysis this equation was reworked into the following form:

$$\ln(P_G) = -(\mu + \omega x) * b$$ ………………Equation 3

Where $b = \alpha + \varphi$

This parameter b is what is being estimated in this trial. Given that we know what α is we can work out $\varphi = b - \alpha$.

This exercise was carried out for two of the exit arms simultaneously (Arm 2 and Arm 4). These two arms have different layouts where the cycle crossing meets the exit arm. At Arm 2 the cycle crossing meets the exit arm at a right angle so that bicycles exiting at this arm must enter the vehicle lane and turn sharply left. At Arm 4, in contrast, cyclists exiting at this arm have a separate exit lane so that cyclists do not enter the exit lane until much further from the circulating lane.

Secondly, whilst the flow of cyclists was altered every 10 minutes they were not controlled in any other sense and were assumed to be randomly distributed; however, cars were input into the roundabout individually so that they did not interact with each other. The times that it took each car to exit the roundabout was recorded, as was the position of cyclists as the car approached the exit arm (assumed to be from the time they passed the previous entry arm), and if they stopped, at the exit arm cycle crossing line. The distribution of times from the trial is given in Figure 3 by arm[5] and the figure shows the contrast between the times of vehicles that are not impeded by cyclists and those that appear to be impeded by cyclists.

Whilst observations were made of each individual car, car flow and bicycle flow averages over 5 minutes were also calculated and the proportion of cars that had to stop in that period counted.

Whilst the timings were calculated by using tube counters with bespoke software revisions, video evidence was also collected and used to estimate the relative position of cyclists to stopped cars.

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[5] Note. The exit times in the graph are rounded up, so that 5 seconds represent 4-5 seconds.

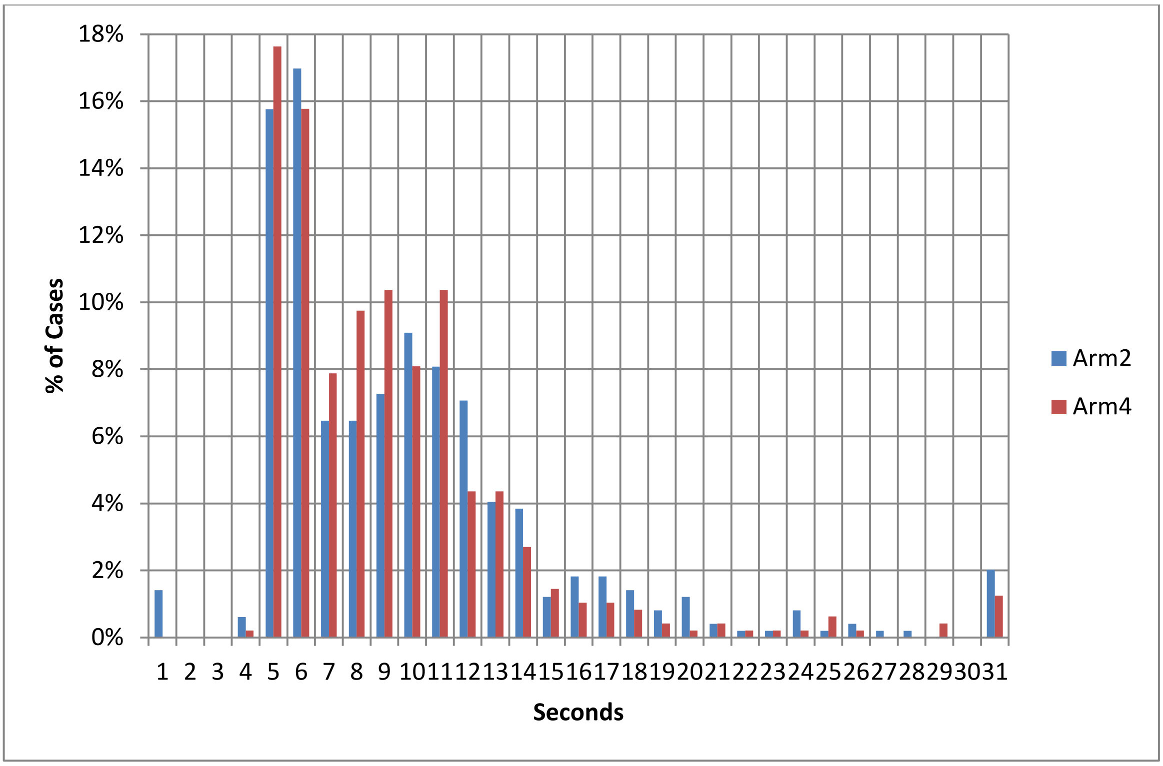

Figure 3 Distribution of exit times by exit arm

2.1.3 M28c – Impact of long vehicles on capacity

This trial was undertaken specifically to test the impact that long vehicles had on the use of the roundabout. As such the trial was largely concerned with the behaviour of car drivers in response to 'long' vehicles (>6m) exiting the roundabout, in the presence of circulating cyclists. Table 1shows the length of the vehicles involved in the trial.

Table 1 Length of vehicles in trial

Vehicle	Length
LWB Van	6m
18t Truck	10m
Bus	12m
Coach	14m
Articulated Lorry	18m

However, there are capacity implications in the results of this trial. A number of types of long vehicle, from a long-wheelbase van to an articulated lorry were driven onto and then exited the roundabout both directly opposite the entry arm, and the next arm. These two manoeuvres resulted in the longest vehicles, coach and the articulated lorry, taking different paths within the exit arm. Car drivers were also making use of the roundabout at the same time and cyclists were using the orbital track.

The main objective, from a capacity modelling view point was to see what the number of PCUs[6] that could be queued at an exit arm before they blocked the preceding entry arm when those PCUs were made up of long vehicles. The long vehicles impact on the circulating flows was also of interest from a capacity point of view even though current roundabout models do not take into account the specific presence of long vehicles.

Figure 4 Impact of a long-vehicle on circulating traffic movements

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[6] PCUs - Passenger Car Units (a unit of traffic flow used in traffic modelling packages to take into consideration the effect of larger vehicles).

3 Trial findings

3.1 Vehicular capacity of roundabout

Figure 5 shows the best-fit regression line, along with the individual data points on which it is based. Each point represents a 5 minute average. The line follows the data closely, apart from a number of points at high circulating flows which gave lower than expected entry arm capacities. It indicates that, for this type of roundabout, the entry arm capacity, in the absence of any circulating flow, is about 1360 veh/hr. As the circulating flow approaches this value, the entry capacity becomes zero and no vehicles will be able to enter the roundabout. Incidentally, the video data from the trial suggested that at these flow levels the circulating flow would have reached capacity itself.

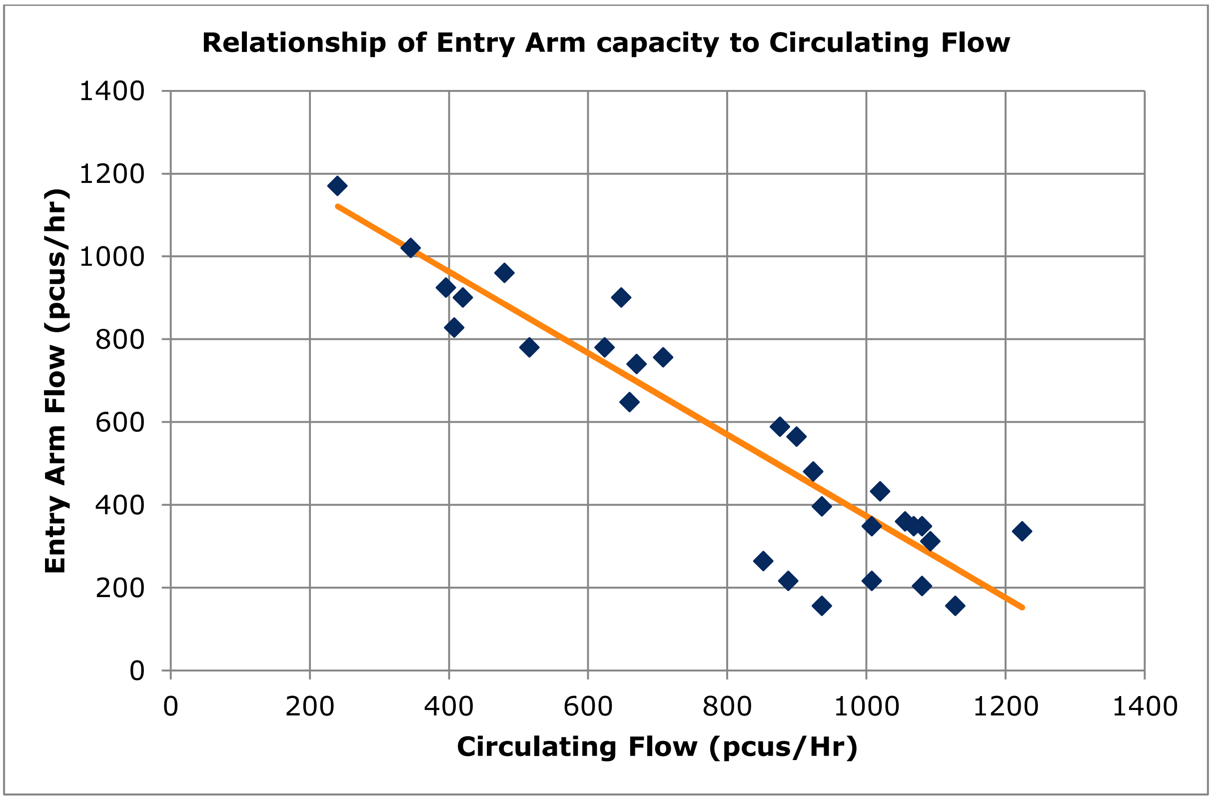

Figure 5 Observed entry arm and capacities and circulating flows

The relationship between the entry-arm capacity and the circulating flows, estimated from the trial observations was:-

Entry arm capacity (pcus/hr) = 1357-0.98***Circulating flow** (pcus/hr). Equation4

More details of this relationship can be found in Appendix A.1. The relationship of this equation (TfL trial) is compared with the relationships estimated from the literature review in Figure 6. It is evident that the trials relationship is most similar to that for the Dutch relationship but with a slightly lower capacity. The estimated maximum circulating flow before all entry flow is cut-off is much lower for the TfL trial relationship (1375 pcus/hr) than for the LR942 relationship[7] used within ARCADY.

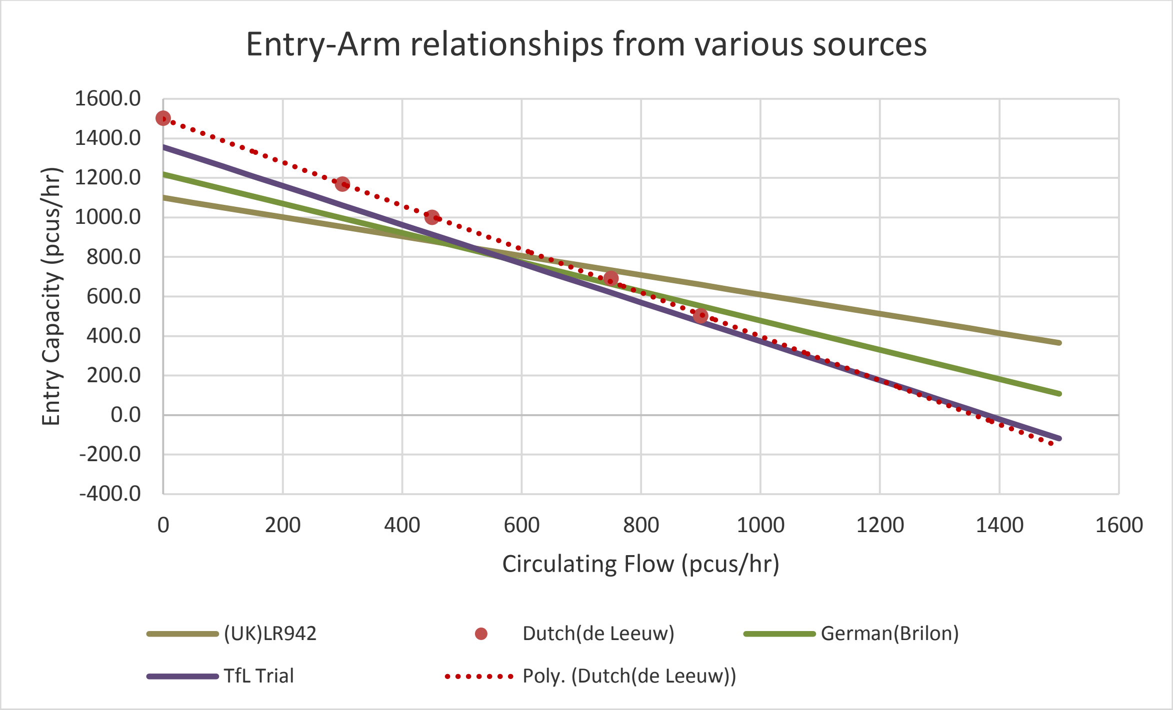

Figure 6 Comparing the trial relationship with other entry-arm capacity relationships

Observations of the videos taken at the same time as the counts indicated that the exit-arm capacity was also around 1375 pcus/hr. At exit flows above this, queuing on the exit arm was seen.

The data were re-estimated to see if the amount of exit flow reduced the entry arm capacity, as expected from the Dutch relationship. In fact the estimated relationship suggested that the amount of exit flow increased the entry arm capacity rather than decreased it. However, theoretical considerations suggest that there is no causal link between exit flow and entry capacity of an arm even if the regression line is 'significant'[8]. See (Appendix 4 to LR942, Kimber, 1980) for the detailed reasoning.

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[7] The LR942 (see section1.4) relationship depends on the geometric properties of the entry arm and the relationship plotted in figure 6 corresponds to the geometric layout of the trial arm.

[8] I.e. it is an example of two variables being *correlated* but one variable does not *influence* the other. For instance, both may be *caused* by a common third variable.' In fact Kimber showed that depending on whether the variations in the circulating flow or the proportions turning-off were greater the relationship between entry capacity and proportion turning off could be positive or negative. i.e. The relationship was a function of the type of variation in the data-set.

3.2 Impact of cyclists on exit capacity

Based simply on the proportion of cars that stopped for cyclists on the exit, Equation 3 was estimated for Arm 4 as:

$$\ln(P_G) = -2.41 * (\text{Circulating cycle flow(cycles/s)}) \qquad \text{.......Equation 5}$$

with the exiting cycle flows having no significant effect. This mirrors the result found by de Leeuw in the Netherlands for cycle paths more than 5m from the vehicle circulating path.

The corresponding basic equation for Arm 2 was:

$$\ln(P_G) = -2.65 * (\text{Circulating cycle flow(cycles/s)}) \qquad \text{....... Equation 6}$$

with, again, exiting flows having no significant effect when added to this relationship. The difference (2.65 secs and 2.41 secs) in the perceived critical gap to cyclists is not significant. The finding that exiting flows did not affect the probability of not stopping was surprising given that car drivers commented in a post-trial debriefing that it was difficult to take account of cyclists who left at this arm and distinguish them from those crossing the exit arm.

Given that the exit arms for Arm 2 and Arm 4 are about 5m wide then at the average cycle speeds noted here of 4.35m/s it took a cyclist on average some 1.15 seconds to cross an exit arm, implying that the car drivers were requiring an extra 1.3-1.5 seconds gap to exit (i.e. φ = 1.3-1.5 seconds), which equates to an additional perceived distance of 5.7m-6.5m –i.e. they act as if the exit arm is about 11m wide.

However, it was very noticeable from the accompanying video evidence that simply counting the number of cars that actually stopped would be underestimating the impact of the circulating cyclists. Many cars simply reduced their speeds to match gaps in the cycle traffic that they could see coming, even if that meant they slowed down to a crawl.

This slow speed will have a similar effect to actually stopping in terms of blocking the previous entry arm. An approach to allowing for the effect of these slow speeds is to assume that all exit times over a certain value are 'equivalent to a stop'. An inspection of the distribution of exit times in Figure 3 indicated that a value of 6 seconds was the best estimate of the minimum value indicative of an 'equivalent stop'. An 'equivalent stop' variable was created which took the value '1' for of all cars that stopped or took longer than 6 seconds to exit the roundabout. Equation 3 (repeated below) was then rerun with (1- (P_G)) based on the proportion stopping or slowing down sufficiently to take over 6 seconds to exit the roundabout, rather than just the proportion actually stopping.

$$\ln(P_G) = -(\mu + \omega x) * b \qquad \text{................. from Equation 3}$$

The values for the critical gap (b) were much greater than those based solely on the proportions actually stopping with a much greater level of explanation of the variability-see Table 2.

- The difference between the values of the critical gap for the arms was again not significant although the value for arm 4 was now slightly higher.
- The numbers of cyclists exiting at an arm again had no significant effect on the size of the 'critical gap' at either arm.

Table 2 Critical gap parameters based on using the notion of an 'equivalent stop' - 6 second limit.

Arm	Critical gap (secs)	Standard Error	% Deviance explained[9]	Implied value of φ (secs)
Arm 2	5.96	0.32	95.0	4.8
Arm 4	6.31	0.47	91.7	5.2

The implications of these values are best explained with reference to the roundabout itself. Figure 7 shows the set of critical gaps estimated from the trial superimposed on a photograph of the trial roundabout.

Figure 7 Spatial implications of critical gaps for exiting vehicles

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[9] Equivalent to % variance explained for relationships where the error distribution is not normally distributed.

Bearing in mind that the average cycle speed of 4.35 m/s was noted, if drivers were treating crossing cyclists as simply 'fast pedestrians' then the critical gap would have been the time taken for a cyclist to cross the exit arm (1.2 secs). Based on stopping drivers only, the results were equivalent to drivers requiring a critical gap of about 2.6 seconds – that is the 1.2 seconds to cross the exit arm plus some 1.4 seconds approaching the exit arm – which equates to an extra 6 metres. However many drivers were slowing down approaching the exit arm and taking notice of cyclists approaching the exit arm. Including these drivers as well as those stopping gave a critical gap of about 6 seconds; that is about 3.4 seconds longer than the equivalent critical gap for stopping drivers only. At the observed cycling speed of 4.35m/s this was equivalent to a gap of 26 metres (5m + 6m + 15m); some 15 metres more than for purely stopping drivers. Thus, with these cycle speeds, drivers were slowing down/stopping for almost any cycle within the arc from the exit arm the arm preceding the exit arm. These distances are superimposed on the trial roundabout in Figure 7. If cycle speeds were lower, then the corresponding distances would be shorter.

Estimated critical gaps for cycle crossing for exit arm

Based on actual average crossing time (exit-arm)		1.2 seconds
M38 -	Driver entering roundabout	6.0 seconds
Perceived additional time required		6.0-1.2 = **4.8 seconds**

This finding accords well with the data collected on the drivers' behaviour with respect to the position of cyclists approaching the exit arm where the percentage of cars that stopped if there were any cyclists between the exit arm and the preceding entry arm on the cycle circulating path was 53% for Arm 2 and 33% for Arm 4.

More details of these relationships can be found in Appendix A.2.

3.3 Other issues

Whilst the analysis above provides all the parameter values that were sought in terms of exit-arm capacity, there are a number of other issues relating to the estimation of the capacity of a Dutch-style roundabout and these are considered below.

3.3.1 Long vehicles

The results from the M28c trial had two implications for the capacity of such compact roundabouts in the presence of long-vehicles. Firstly, the very long vehicles (articulated lorry and coach) can have a significant impact on the capacity of such a roundabout because of not only their length but also the way that drivers manoeuvre such vehicles in order to be able to see circulating cyclists clearly. Drivers attempted to exit the exit-arm as close to right-angles as possible. This meant that drivers of other vehicles could/would not be able to pass the vehicles if it were stopped on an exit arm by circulating cyclists, even though the truck apron is theoretically available for such a manoeuvre. Thus there would be implications both for the modelling of the capacity of the exit arm but also of the vehicle circulating flow. Secondly, because the drivers of such very long vehicles had difficulty in checking for the presence of cyclists on the cycle circulating path, and so proceeded cautiously they will also reduce the exit capacity of the arm (and so reduce the entry arm capacity of the preceding entry arm).

These observations on the behaviour of long vehicles at a Dutch-style roundabout have important implications for the cycle safety as well as the capacity of the roundabout. These implications are discussed in more detail in RPN 3007 (Vermaat, et al, 2014).

3.3.2 Impact of cyclists crossing the entry arm

The work described in section 3.2 was only concerned with the impact of cyclists crossing the exit arm. No equivalent work has been done on entry-side parameters as part of the site trials, although one would expect the critical gap value to lie between 1.15 seconds for a 5m crossing (as if drivers did not take account of cycles until they reached the start of the crossing) and the 6 seconds found for the exit arm because drivers waiting at the cycle crossing line to enter the roundabout would have a better view of the progress of cycles than drivers who are exiting the roundabout.

Whilst the on-site trials produced values for estimating the impact of circulating cycle traffic on the exit capacity of the roundabout – which would then have a knock-on effect on the entry capacity of the preceding entry arm, there was no equivalent trial of the impact of the cycle crossing on the vehicular enter capacity directly. However, the opportunity was taken to make use of the results of another of the TfL Cyclist Facility Trials – trial code "M52" to provide estimates of the equivalent gap values for vehicles entering the roundabout. The M52 trial was designed to study the effects of 'cognitive loading' on drivers, that is how they cope with facing multiple crossings (of pedestrians, cyclists and vehicles) as they enter a Dutch-style roundabout. This was done using a simulator to mimic London-like conditions. Novis et al (2014) gives the background and details of the results of this trial but a number of characteristics of the trial do have a bearing on the use of its results in estimating critical gaps.

In the M52 trial, participants approached the Dutch-style roundabout from arm 3. At arm 3, the zebra crossing and orbital cycle lane are adjacent and cyclists approach the roundabout on the carriageway with a fairly sharp left turn into the orbital cycle lane. The effect of cognitive loading at the Dutch-style roundabout was investigated by using two traffic flow conditions: high and low. A high flow of a particular road user type (pedestrian, cyclist and car) was considered a high cognitive load; a low flow as a low cognitive load. The high load corresponded to a flow of 2,160 movements per hour and a low flow 1,080 movement per hour.

The high and low flows differed across the three road user types:

- Pedestrians using the zebra crossing
- Cyclists using the orbital cycle lane (clockwise movements only)
- Cars on the main circulatory flow

Drivers undertook a series of drives through the roundabout, facing different combinations of flows. Some 1,148 drives were undertaken by 96 participants.

The various combinations of high and low flows across the three road user types created different cognitive loadings. For the purposes of estimating the critical gap, a category of trials with no pedestrian flows would have greatly simplified the estimation of critical gaps but such a trial would have presented fewer decisions of the driver. So the results obtained were influenced by the presence of multiple crossings of pedestrians and cyclist. The layout at Arm 3 has the pedestrian and cycle crossings adjacent to each other but then a 5m gap to the vehicle crossing stop line. Fortunately, for this work, one of the findings from the M52 study was that the gap acceptance of drivers at the pedestrian and cycle crossings were not influenced by the vehicle crossing – the pedestrian/cycle crossing and the vehicle entry process were two separate decisions in the eyes of most drivers.

The issue of the potential interaction of the pedestrian and cycle crossings will be considered in the section 3.3.3.

The flow of pedestrians and cyclists across their respective crossings was not wholly random. For a given average flow level, into a random flow pre-defined gaps were introduced at intervals the size of these gaps increased has the trial went by 1 second intervals. These introduced gaps went across all crossings. In 693 of 1,148 drives, the participant drove through the three crossing points during a predefined gap(s). In over half of these drives (373) the participant drove through all three gaps in one continuous manoeuvre; most commonly the 7 second gap. In the majority of the drives where the participant chose not to go through all three crossing points in one manoeuvre, the participant crossed the pedestrian crossing and cycle lane crossing point in one manoeuvre, stopped and then entered the roundabout in the next vehicle gap.

Almost a third of the drives resulted in participants driving through a gap between pedestrians that was not one of the predefined time gaps. This compares to around 10% of drives where participants drove through a non-gap when crossing the cycle lane and main circulatory flow.

Excluding those who crossed in a non-gap, Table 3 shows the mean gap duration chosen by participants for each of the three crossing points.

Table 3: Mean gap taken when entering the Dutch-style roundabout, by crossing point (M52 trial)

Crossing point	Mean gap (seconds)
Crossing pedestrian flow	5.3
Crossing cycle flow	**5.6**
Entering main circulatory flow	6.0

In the case of the cycle crossing, they indicate that although drivers had to go through the pedestrian flow before crossing the cycle flow .i.e. they had to allow time to complete that manoeuvre over 90% used a pre-defined gap so that the 'mean Gap' of 5.6 seconds is a reasonable approximation of the critical gap although an over-estimate of a best estimate. In fact, when the pedestrian flow was 'low' the mean gap was 5.1 seconds as opposed to the mean gap of 5.9 seconds when the pedestrian flow was 'high'. Extrapolating these two values to a zero pedestrian flow produces a value of 4.3 seconds for the gap size.

This value can be compared to the 6.0 second critical gap estimated for drivers leaving the roundabout. As expected the value for drivers entering the roundabout is less than that for those leaving, probably because they have a better view of cyclists circulating the roundabout. This value of 4.3 seconds relates to a cycle crossing adjacent to a pedestrian crossing so the driver is making a judgement some 0.9 seconds before reaching the start of the cycle crossing[10]. Based on this, the critical gap for an individual cycle crossing (i.e. no pedestrian crossing on the arm) would be about 3.4 seconds. In reality the actual critical gap may be somewhere between 3.4 and 4.3 seconds because drivers may slow down before reaching the cycle crossing in a similar manner to what was observed in on-site trial.

Estimated critical gaps for cycle crossing for entry arm capacity

M52 - Driver entering roundabout	4.3 seconds
Based on actual average crossing time (entry-arm)	1.4 seconds
Allowance for traversing the pedestrian crossing	0.9 seconds
Perceived <u>additional</u> time required	4.3-1.4-0.9 = **2.0 seconds**

As an aside the results from this trial can also be used to give an indication of how well the simulator results and the theoretical model for pedestrian crossings match. For a 4.3m crossing the entry arm with a pedestrian speed of 4 km/hr assumed in the simulator trial gives a time for a pedestrian to cross of 3.9 seconds. This simulator trial estimated a value of 4.5 seconds from those who chose a pre-determined gap size. However, some 32% of drivers used gaps in the pedestrian flows other than the pre-determined gaps. In 85% of the 370 drives where a non-gap between pedestrians was used, a predefined gap between cyclists was used. This supports the theory that some participants were basing the decision on when to cross the zebra crossing on the basis of seeing a suitable gap between cyclists[11]. It is likely that their mean gap was less than those drivers who used per-determined gaps, so the estimate of 4.5 seconds, based on those using pre-determined gaps only, is likely to be on the high side.

Estimated critical gaps for pedestrian crossing

Based on actual average pedestrian crossing time - 3.9 seconds

M52 -Based on drivers using pre-determined gaps – 4.5 seconds

Driver leaving roundabout - 6.0 seconds

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[10] This applies just as well to the exit arm where the pedestrian crossing appears after the cycle crossing for the driver. a

[11] The mean gap of those drivers NOT using the pre-determined gaps was not collected.

3.3.3 *Impact of multiple crossings for vehicle entry capacity*

So far we have considered a Dutch-style/compact roundabout with either only a pedestrian crossing (ARCADY default) or only a cycle crossing (discussed above). However, there may be circumstances where both a cycle crossing and a pedestrian crossing are deemed necessary (as in the trial layout).

In the absence of specific advice to the contrary, the crossings can be seen as sequential and independent, with no gap between them. This has the great advantage in that ARCADY can then be used to estimate the impact of such a 'joint' crossing. The implications of this assumption are spelt out in Appendix A.3.

If this assumption is made then the 'gap time' to be used in ARCADY is the flow-weighted average 'gap time' for the two flows and the total flow is the sum of the flows. This is of course only a simplifying assumption and would not hold if there was a gap between the two crossings[12].

In theory, the results from the M52 simulator trials could be used to test this assumption. If we take the mean gap of those crossing the cycle crossing at low flows as being the best representative of those crossing multiple crossings with a good chance of having gaps big enough to use, then the mean gap from the M52 study was 5.6 seconds whilst the best estimate of the individual 'critical gaps' was 4.3 seconds for cyclists and 4.5 seconds for pedestrians – the weighted mean is less than the mean gap for drivers using pre-determined gaps. However, this is not a conclusive rebuttal of the assumption because M52 does not attempt to provide the distribution of gaps seen in real-life and the simulated pedestrian and cycle flows were not purely random flows so the distribution of gaps faced by the drivers wanting to cross both streams would not mirror real-life.

Estimated Parameters for adjacent pedestrian/cycle crossings

ARCADY crossing time=
Flow-weighted perceived critical gaps for cycle and walk crossings (from section 3.2 for exit arms and section 3.3.3 for entry arms)
+
0.9 seconds

ARCADY Flow =
Sum of pedestrian and cycle flows (units per sec)

---

[12] The trial layout did include one arm with such crossing layout. However, DfT regulation change that will be consulted on as part of TSR&GD 2015 for parallel crossings will be worded and described as such to exclude the ability for a vehicle to stop between or fit between the two crossings. So, in reality, one would not be able to use this type of layout for an arm.

However, it is true that the two crossing flows are adjacent to each other and not occupying the same crossing so, by analogy with the discussion on the entry-arm cycle crossing results from M52, it is recommended that 0.9 seconds should be added to the flow-weighted average gap times, for both entry and exit arms, to account for the fact that the driver must allow this much time to pass through the pedestrian crossing (on entry or exit) before reaching the cycle crossing, even if coincident gaps occur (see the text box above for a summary of the recommendations).

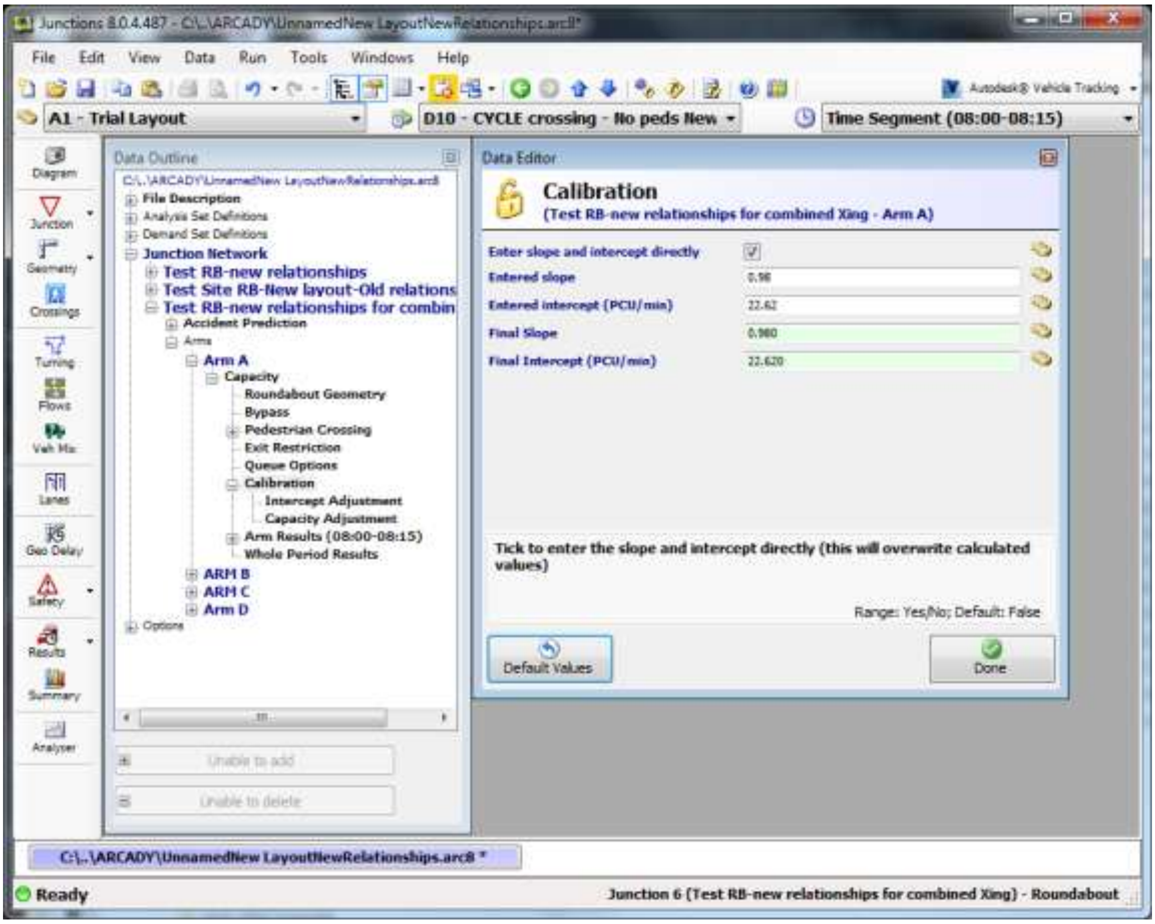
4 Implications for modelling the capacity of Dutch-style roundabouts

The results discussed in the previous section can be used to model the capacity implications of Dutch-style roundabouts. The junction program ARCADY8 (now part of TRL's Junctions8 suite) has the required flexibility to allow the use of the updated parameters, given a number of assumptions. This section describes how the new findings can be used within the ARCADY program.

These findings apply equally to the use of TRANSYT15 to model more complex junction/network layouts that may include elements of Dutch-style roundabouts. The findings also have relevance to micro-simulation models of complex junctions and/or cycle movements.

4.1 Vehicle entry-arm capacity

Although ARCADY can estimate a relationship between the entry-arm capacity of a roundabout and the circulating flow, based on the geometric characteristics of the roundabout, it also has the facility for the user to input their own straight line relationship as an input slope and intercept (see Figure 8 below). Figure 8 shows the relationship calibrated on the TfL trial data input direct into ARCADY for an entry arm (in terms of units of pcus/min).



Calibration
(Test RB-new relationships for combined Xing - Arm A)

Enter slope and intercept directly	☑
Entered slope	0.98
Entered intercept (PCU/min)	22.62
Final Slope	0.980
Final Intercept (PCU/min)	22.620

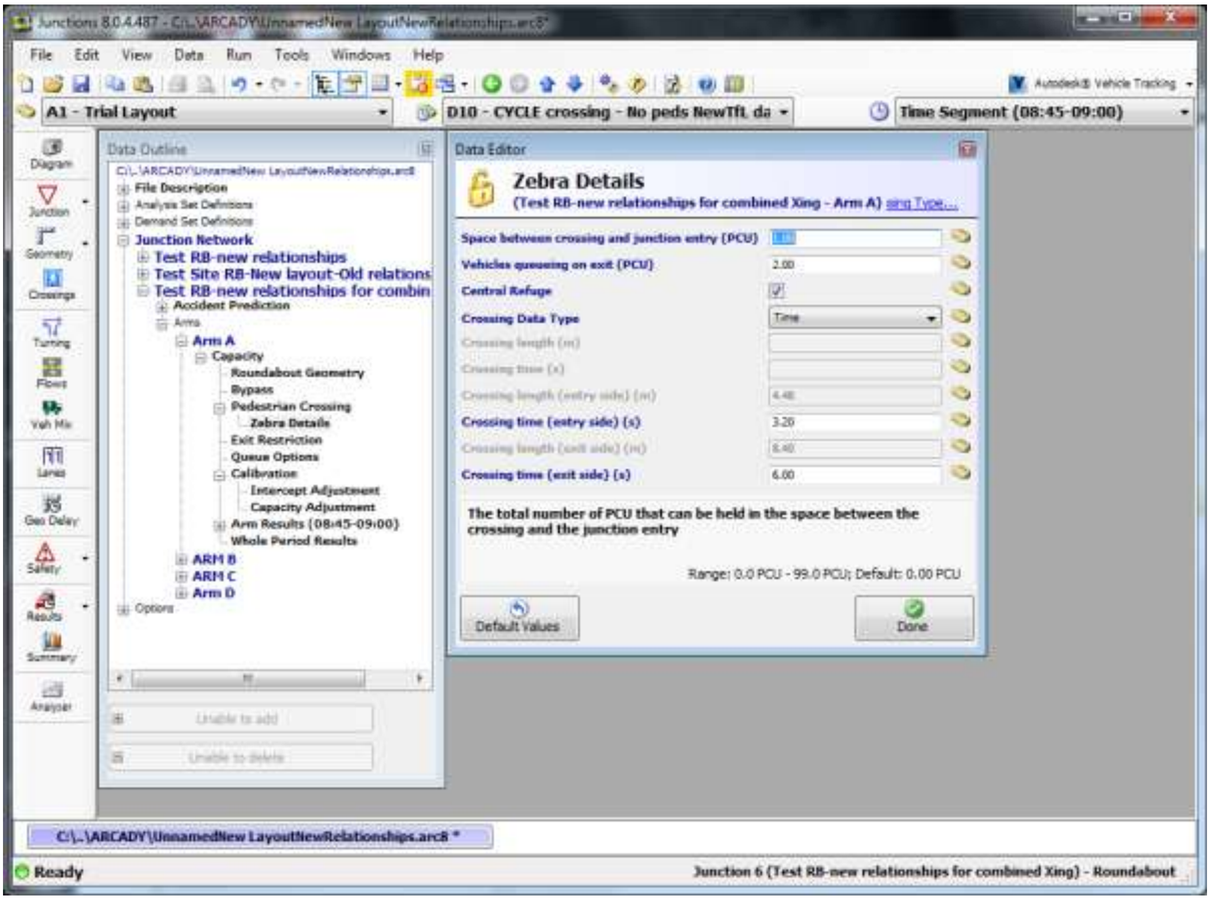
Tick to enter the slope and intercept directly (this will overwrite calculated values)

Range: Yes/No; Default: False

Figure 8 Entering the TfL entry-arm relationship directly into ARCADY

4.2 Impact of a cycle crossing

ARCADY was developed with the facility to assess the impact of pedestrian crossings (especially zebra crossings) on the capacity of a roundabout. To do this it needs to know either entry arm distance and walk speed, or the time to cross the entry arm. Similar data are required for the exit arm. In most cases these will be the same but may vary if, for instance, the pedestrian crossing across the entry arm is longer than that across the exit arm. Figure 9 below shows an example were the exit side is longer than the entry side.



Zebra Details
(Test RB-new relationships for combined Xing - Arm A)

Space between crossing and junction entry (PCU): [illegible]
Vehicles queueing on exit (PCU): 2.00
Central Refuge: ☑
Crossing Data Type: Time
Crossing length (m):
Crossing time (s):
Crossing length (entry side) (m): 4.48
Crossing time (entry side) (s): 3.20
Crossing length (exit side) (m): 8.40
Crossing time (exit side) (s): 6.00

The total number of PCU that can be held in the space between the crossing and the junction entry

Range: 0.0 PCU - 99.0 PCU; Default: 0.00 PCU

Figure 9 Entering specific gap times into ARCADY

All that is needed to model cycle crossings instead of pedestrian crossings is to insert suitable 'perceived' gap times.

Estimated critical gap for cycle crossing for exit arm

Actual/observed crossing time by bicycle (seconds)

\+

4.8 seconds

Figure 10 shows how the variation in the exit crossing time affects the vehicle entry capacity of the previous entry arm. This case relates to the test layout and reflects a situation where the roundabout is over capacity. Where the roundabout has ample capacity the shape of the graph may be different.

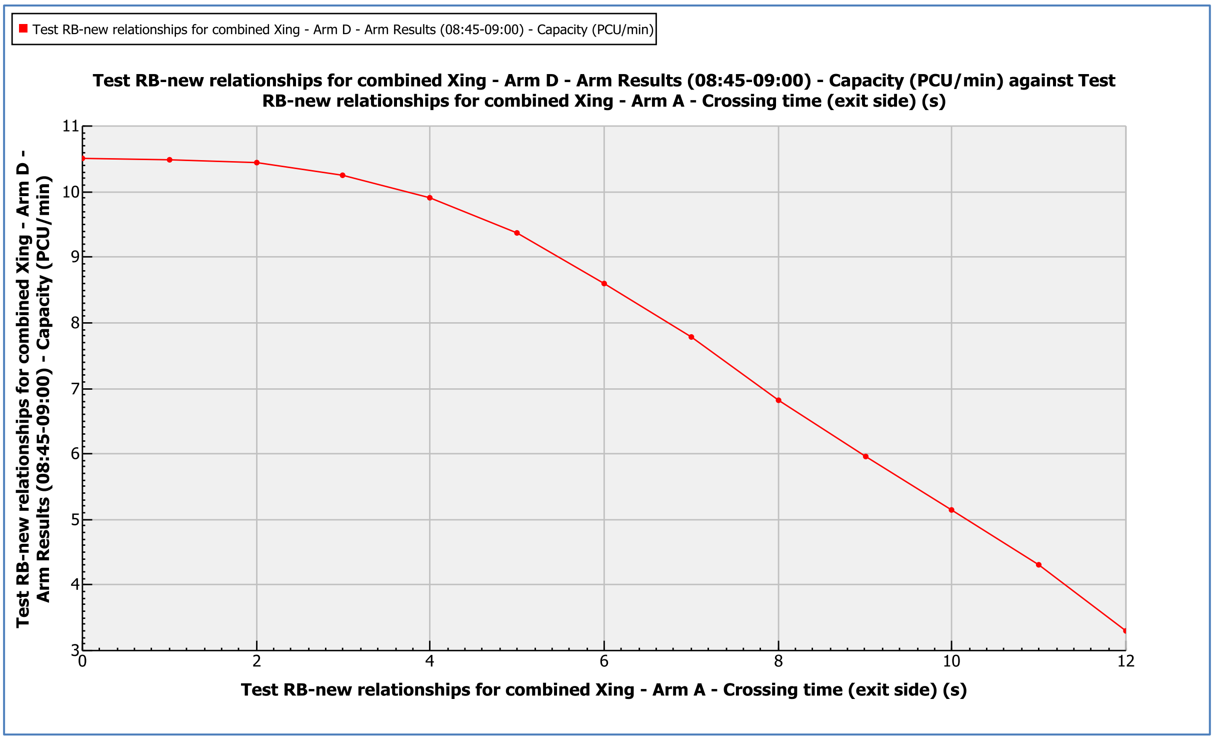


Figure 10 Variation in capacity of an entry arm on the exit 'gap-time' for the next exit arm (current value is 6 seconds).

4.2.1 *Entry arm crossing time*

The argument set out in section 3.3.2 suggests a parameter value somewhere between 1.15 seconds and 6 seconds for the additional perceived crossing time. Results from the M52 simulator trial suggest the following values in addition to any actual/observed crossing time.

Estimated critical gap for cycle crossing for entry arm

Actual/observed crossing time by bicycle (seconds)

+

2.0 seconds

Figure 11 shows how the variation in the entry-arm crossing time affects the vehicle entry capacity of that entry arm. This case relates to the test layout and reflects a situation where the roundabout is over capacity. In this case the capacity of the entry arms are more sensitive to variations in the perceived exit arm crossing time than to variations in the perceived entry-arm crossing time but this may not always be so. Where the roundabout has ample capacity the shape of the graph may be different.

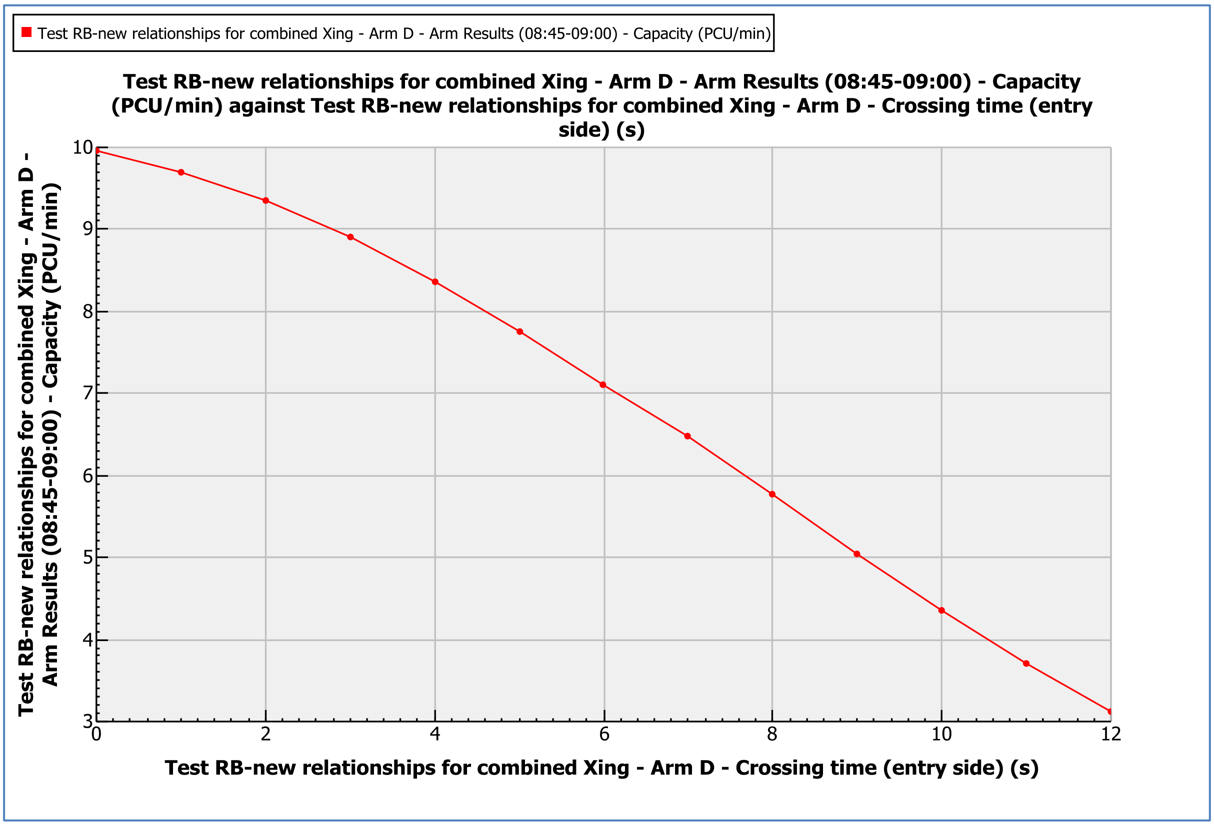


Figure 11 Impact on capacity of an entry arm of the entry-arm gap time

4.3 Multiple crossings

So far we have considered a Dutch-style/compact roundabout with either only a pedestrian crossing (ARCADY default) or only a cycle crossing (discussed above). However, there may be circumstances where both a cycle crossing and a pedestrian crossing are deemed necessary (as in the trial layout).

The recommendation is to treat the two adjacent crossings as one combined crossing for the reasons set out in section 3.3.3.

The relevant parameter values are repeated in the following textbox.

Estimated Parameters for adjacent pedestrian/cycle crossings

ARCADY crossing time=
Flow-weighted perceived critical gaps for cycle and walk crossings
+
0.9 seconds

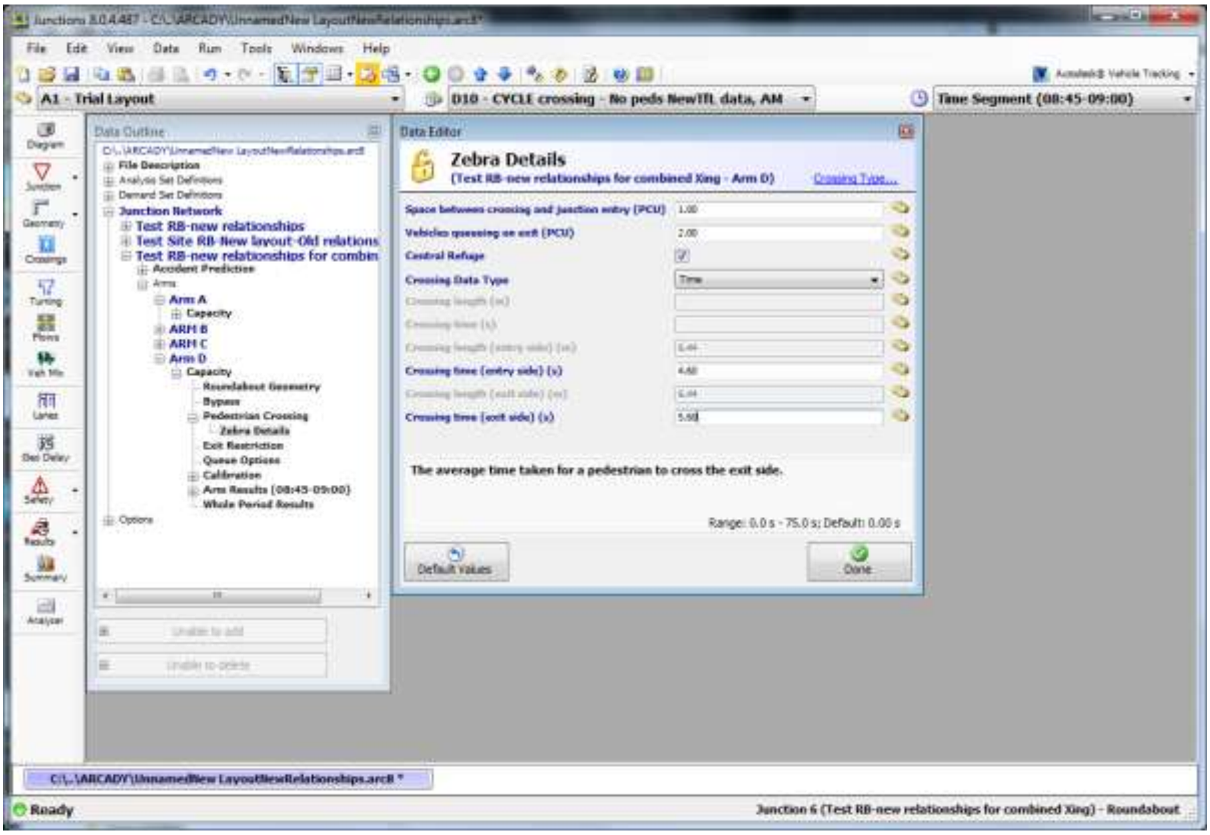
ARCADY Flow =
Sum of pedestrian and cycle flows (units per sec)

As an example of how these values are calculated, assume the following values for the two crossings.

Table 4 Illustrative example of estimating parameter values for adjacent crossings

	Entry Arm	Exit arm
Pedestrian crossing		
Actual crossing time (s)	4.0	4.0
Perceived crossing time (s)	4.0	4.0
Flow (peds/s)	1.0	1.0
Cycle crossing		
Actual crossing time (s)	1.2	1.4
Perceived crossing time (s)	1.2+2.0 = 3.2	1.4+4.8 = 6.2
Flow (cycles/s)	0.5	0.5
Combined		
Combination penalty	0.9	0.9
Perceived crossing time (s)	0.9+(4.0*1+3.2*0.5)/(0.5+1.0) =4.6	=0.9+(4.0*1+6.2*0.5)/(0.5+1.0) =5.6
Combined Flow (units/s)	1.0+0.5 = 1.5	1.0+0.5 = 1.5

Figure 12 shows an example in ARCADY where the crossing times reflect a combined crossing with the values from Table 4.



Zebra Details
(Test RB-new relationships for combined Xing - Arm D)

Space between crossing and junction entry (PCU): 1.00
Vehicles queueing on exit (PCU): 2.00
Central Refuge: ☑
Crossing Data Type: Time
Crossing length (entry side) (m): 6.44
Crossing time (entry side) (s): 4.60
Crossing length (exit side) (m): 6.44
Crossing time (exit side) (s): 5.60

The average time taken for a pedestrian to cross the exit side.

Range: 0.0 s - 75.0 s; Default: 0.00 s

Figure 12 Example of parameter values (in seconds) when modelling a combined crossing.

4.4 Variations in the layout of Dutch-style roundabouts

All the above recommendations are based on the trial layout and no research was undertaken to estimate how variations in the geometric layout would affect the capacity calculations.

Studies in the Netherlands and Germany suggest that small variations in the geometric layout will not have a significant effect on capacity, apart from the number of entry lanes and the number of circulating lanes. However, once one gets to having two or more entry lanes and more than one circulating lane then the roundabout design for vehicles conforms more towards the conventional roundabout capacity predictions in LR942, at least as far as vehicular capacity is concerned.

4.5 Overall Impact of the Dutch-style roundabouts on capacity

All the changes in the relationship between vehicular capacity and circulating flow, and the recommendations for modelling the impact of cycle (adjacent cycle/pedestrian crossings) will have an impact on the capacity of a roundabout.

As an illustrative example a Dutch-style roundabout was designed to fit into the footprint of an existing roundabout that had high flows of vehicles, cyclists and pedestrians. The impact on the vehicular capacity (capacity defined for this work as the total flow per hour into the roundabout at the point when one arm reaches 85% of capacity).

Table 5 shows the cumulative impact of the changes from a conventional 4-arm roundabout to a Dutch-style roundabout with adjacent cycle and zebra crossings on each arm. The greatest impact is simply the redesign of the layout, reducing the entry and exit arms to a single lane and tightening-up the geometry so that there is little flaring. This change of layout reduced capacity by 30%. The impact of the new vehicular relationship was actually quite small on this roundabout but the provision of new cycle crossings on each arm reduced capacity by a further 11%.

Table 5 Impact of new layout and capacity relationships on the vehicular capacity of a roundabout

Model assumptions	Capacity (pcus/hr)	As % of conventional
Conventional roundabout	3000	100
Dutch roundabout layout – traditional (LR 942) relationships	2100	70
Dutch roundabout layout – new capacity relationships	2040	68
Dutch roundabout layout – new capacity relationships with pedestrian and cycle crossings modelled.	1700	57

These results should be treated with caution since they are just one illustrative example based on a given layout and travel patterns. The impact of converting other conventional roundabouts with other types of layouts or with different travel patterns to a Dutch-style roundabout could well be different.

4.6 Capacity issues not covered by TfL trials

Whilst the trials conducted at TRL have covered a variety of issues relating to the capacity of a ‘Dutch-style’ roundabout they were not designed to cover all issues. The trials were not designed to provide direct evidence for the following issues that could affect aspects of the capacity of a ‘Dutch-style’ roundabout.

4.6.1 Impact of geometric variations in layout on the vehicular capacity of the roundabout

The capacity trials focused on estimating the entry-arm /circulating flow relationship for the Dutch-style roundabout so the trial layout shown in **Figure 1** was not changed during the capacity trials. The Dutch research quoted in De Leeuw suggested that increasing the number of entry lanes and/or the number of circulating lanes would significantly affect the vehicular entry capacity of such a roundabout. De Leeuw’s model also had the entry-arm capacity a function of the distance between the exit-arm and the entry arm of an arm. This possible variation was not trialled as there was a fixed layout and the variations between entry arms was related to different forms of cycle path/vehicle lane interaction, not to variations in the relative layout of entry and exit arms for vehicular traffic. Other geometric variations were not mentioned by De Leeuw, probably because the range of variation in geometric layout for such ‘compact’ roundabouts would be much less than the variation in the characteristics of ‘conventional’ roundabouts in the UK so any significant relationships between layout and entry-arm capacity harder to identify.

In the case of the current advice on modelling ‘conventional’ roundabouts the geometric layout of the roundabout does make a significant impact on the capacity of an entry arm. However, the relationships described in LR942 are the result of the analysis of a wide range of observations at roundabouts with different layouts.

On the basis of this Dutch and UK research, it is probable that the impact of variations in the geometric layout for a ‘compact’ or Dutch-style roundabout (especially with a separate cycle lane) would be much less than expected for a ‘conventional’ roundabout, because the range of possible variation in layout is less. This being so, the advice, in the absence of any evidence to the contrary, would be that the vehicle capacity relationship, calculated from this trial should be suitable for Dutch-style roundabouts in general, but the robustness of the capacity calculations will be impacted by changes to the geometric layout[13].

4.6.2 Impact of variations in the vehicle classification of the entry and circulating flows.

The trial at TRL was purposely conducted using only cars which are, by definition, assumed to have a value of one Passenger-Car Unit (PCU) and, as is the case with other current roundabout capacity relationships in this country and abroad, the resulting relationship from this study is couched in terms of PCUs. However, there was some evidence from Trial M52 that the behaviour of car drivers at the pedestrian and cycle crossings was influenced by the presence of cyclists sharing the road space. However, the impact that this would have on the relative impact of cars and bicycles (PCUs) on capacity is uncertain since it is not the only behaviour affecting the crossing capacity.

This phenomenon was not examined in this trial since it would require very many more runs with combinations of different type of vehicles. If this issue is thought important it would need to be examined as part of research on the relative impacts of different vehicles; that is the variation in PCU values for different vehicle types, at roundabouts with different layouts. Recent research for TfL on the saturation flows at signalised junctions suggested that the PCU value of vehicle types, especially bicycles, did vary significantly with the layout of the signalised junction (Emmerson, 2013).

4.6.3 The capacity of the bicycle orbital track

The capacity trials focused on vehicle capacity of the Dutch-style roundabout and not that of the orbital cycle track (nor of the entry and exit arms to that track). The Dutch research quoted in De Leeuw did not mention any research on this although it did indicate that the capacity of the orbital cycle track was assumed to be 1500 cycles per hour. In the course of trial M28b flows of up to the equivalent of 2,000 cyclists per hour were obtained for up to 10 minutes. However, this may be an overestimate of the

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[13] Since the entry-arm relationship can be input directly into ARCADY, the recommended relationship could be adjusted to take account of the entry-arm/exit-arm relationship in De Leeuw’s work if its impact were to be tested.

practical capacity of a cycle circulating path since all the trial cyclists were making the same route decisions and were familiar with the cycling behaviour of each other so the degree of conflict between cyclists within the cycle path was probably less than would occur in practice as the circulating flow was disrupted by cyclists entering and leaving the circulating path. As well as estimates of the saturation flow of the circulating path any specific modelling of the capacity of the cycle facility would need to take account of the entry-arm capacities, which would be expected to be influenced by the layout of the cycle paths within and around the roundabout.

4.6.4 The impact of pedestrian crossings on entry capacity

It was not the intention within this project to validate or research the impact of crossings on the capacity of the Dutch-style roundabout, rather the emphasis was on seeing if existing assumptions could be used to cope with the presence of cycle crossing instead of, or as well as, as a pedestrian crossing. Brilon is quoted as considering that the theoretical work underlying the pedestrian-crossing relationship within ARCADY may be conservative in respect to observed delays to vehicles but the extent to which this is true in the UK is not known and cannot be inferred from any of the work within this project. By extension the same conclusion is true for cycle crossings. What the work has shown is that the current assumptions within ARCADY on modelling pedestrian crossings can be adapted to account for the presence of a cycle crossing instead of, or as well as, a pedestrian crossing which was a required outcome.

5 CONCLUSIONS

As part of a wider programme of off-street trials of innovative cycling infrastructure, TRL is investigating a 'Dutch style' roundabout which separates motor vehicles from cyclists in the circulating part of the roundabout while giving cyclists priority over turning vehicles, with the aim of improving cyclists' safety while reducing delay when using the roundabout.

Whilst other parts of the programme consider the safety and behavioural aspects of this type of roundabout, this report concentrates on the capacity (and delay) implications of such a type of roundabout and reviews how to incorporate the findings into current advice on modelling the capacity and delays at roundabouts.

Using tests on a trial layout in an off-street location it has been possible to estimate UK-based relationship between the vehicle entry-arm capacity and the circulating flow for this type of roundabout. In addition, it has been found that drivers require greater gaps in the circulating bicycle flow to exit the roundabout than would be estimated simply based on the time it takes a cycle to cross the exit arm. This additional, perceived, gap time amounted to some 5 seconds and can have a significant effect on the capacity of the previous entry arm, because of the increased risk of vehicles blocking the entry arm as they queue/slow down to exiting the roundabout at the next exit arm. There was a similar but smaller effect noticed for drivers entering a roundabout. This was expected because they tend to have a better view of circulating cyclists than drivers exiting a roundabout.

The impact of the new layout compared with an equivalent conventional roundabout with the same travel patterns was to reduce capacity by a little over 40%. Much of this reduction in capacity was due to the new layout with single lane entries and exits with little or no flaring. These results should be treated with caution since they are just one illustrative example based on a given layout and travel patterns. The impact of converting other conventional roundabouts with other types of layouts or with different travel patterns to a Dutch-style roundabout could well be different.

The report also gives advice on modelling the capacity of such Dutch-style roundabouts both with a pedestrian or a cycle crossing on the entry arms, or both. Studies in the Netherlands and Germany suggest that variations in the geometric layout will not have a significant effect on capacity, apart from the number of entry lanes and the number of circulating lanes. However, once one gets to having two or more entry lanes and more than one circulating lane then the roundabout design for vehicles conforms more towards the conventional roundabout capacity predictions in LR942, at least as far as vehicular capacity is concerned.

In addition, whilst ARCADY input values currently do not discriminate between long vehicles and other classes of vehicles (everything is entered as PCU) the results of one of the trials suggested that particular care will be needed where the roundabout is likely to be used by a significant number of long vehicles such as buses, coaches or articulated lorries Such vehicles may block both entry to the roundabout and the circulation of other vehicles on the roundabout. This is not only because of their length but also the way that drivers manoeuvre such vehicles in order to be able to see circulating cyclists clearly.

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Appendix A Main statistical results

The data from the M38 trials were analysed using the GENSTAT statistical modelling package. For simple linear regression (for the estimation of vehicular capacity, for example), where the residual errors are assumed to be normally distributed the standard measure of goodness of fit (R^2) was used.

However, such a measure is not applicable were the errors are not assumed to be normal. So for the estimation of the Critical Gap, where the error distribution is expected to be Poisson-based, a more general goodness–of-fit measure has been used - that of the % deviance explained. For a linear model with normally-distributed errors the R^2 and 'percentage deviance explained' are the same.

A.1 Vehicular capacity

Estimates of parameters

Parameter	estimate	s.e.	t(29)	t pr.
Constant	1356.6	83.2	16.31	<.001
Circulating Flow	-0.9837	0.0979	-10.05	<.001

Summary of analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Regression	1	2112763.	2112763.	100.91	<.001
Residual	29	607204.	20938.		
Total	30	2719967.	90666.		
Change	-1	-2112763.	2112763.	100.91	<.001

R^2 (Percentage variance accounted for) 76.9%
Standard error of observations is estimated to be 145.

A.2 Estimation of critical gap parameters for exiting traffic

For the estimation of the critical gap required for a driver <u>not</u> to be stopped by a flow of circulating cyclists, a log-linear model with an assumed Poisson-error distribution is the correct form of relationship. The process of estimating the perceived additional gap over and above the actual time taken for a cyclist to cross the exit arm is shown in detail for the first example for Arm 2.

A.2.1 Arm 2

Regression analysis

Summary of Analysis

Source	d.f.	deviance	mean deviance	deviance ratio	approx F pr.
Regression	1	*	*		
Residual	29	1.805	0.06225		
Total	30	*	*		

Dispersion parameter is estimated to be 0.0623 from the residual deviance.

% Deviance accounted for = 61.1%

Estimates of parameters

Parameter	estimate	s.e.	t(29)	t pr.	antilog of estimate
CIRC	-2.653	0.299	-8.86	<.001	0.07043

i.e.

$\mathrm{Ln}(P_G)$ = -2.653*(Circulating cycle flow(cycles/s)) ……. Equation 6

(P_G) = (the proportion not stopping)

With $\varphi = b-\alpha$.

φ (additional perceived gap needed) = 2.653 – 1.15 secs = 1.503 secs

As explained in the report, it was felt that a better predictor of exit behaviour would be to look at 'equivalent stopping' behaviour; that is cars that either stopped or took longer than 6 seconds to clear the exit.

The following results were obtained.

Regression analysis

Summary of analysis

Source	d.f.	deviance	mean deviance	deviance ratio	approx F pr.
Regression	1	*	*		
Residual	27	0.7085	0.02624		
Total	28	*	*		
Change	-1	-15.9943	15.99434	609.56	<.001

Dispersion parameter is estimated to be 0.0262 from the residual deviance.

Estimates of parameters

Parameter	estimate	s.e.	t(27)	t pr.	antilog of estimate
CIRQ	-5.959	0.322	-18.52	<.001	0.002581

Message: s.e.s are based on the residual deviance.

% deviance explained = 95.8%

Ln(P_G) = -5.959*(Circulating cycle flow(cycles/s)) ……. Equation 6a

Where

(P_G) = (the proportion not stopping is based on those not stopping and taking less than 6 seconds to exit the roundabout.)

Figure 13 shows a comparison between the fitted relationship and the observed values. It shows that the fit is reasonable. There are likely to be more complex formulations that could be fitted to these data but they could not be used easily to derive the required critical gap parameter.

A.2.2 Arm 4

Regression analysis

Response variate: PCLEAR
Distribution: Poisson
Link function: Log
Fitted terms: CIRC

Summary of analysis

Source	d.f.	deviance	mean deviance	deviance ratio	approx F pr.
Regression	1	*	*		
Residual	29	1.044	0.03601		
Total	30	*	*		

Dispersion parameter is estimated to be 0.0360 from the residual deviance.

Message: the following units have large standardised residuals.

Unit	Response	Residual
1	0.100	-2.19
3	0.091	-2.59

Estimates of parameters

```
                                                                  antilog of
Parameter            estimate          s.e.       t(29)     t pr.   estimate
CIRC                   -2.411         0.219      -11.01     <.001    0.08974
```

% Deviance explained = 71.8%

The result from the ‘equivalent stop’ analysis was:-

Regression analysis

Summary of analysis

```
                                               mean    deviance   approx
Source             d.f.      deviance      deviance       ratio    F pr.
Regression            1             *             *
Residual             29         24.12        0.8316
Total                30             *             *

Change               -1       -265.00      265.0007      318.68    <.001
```

Dispersion parameter is estimated to be 0.832 from the residual deviance. (the residual error was about 83% of that expected from a pure Poisson-distribution of errors)

Message: the following units have large standardised residuals.

```
          Unit      Response      Residual
            27         0.857          2.26
```

Estimates of parameters

```
                                                                  antilog of
Parameter            estimate          s.e.       t(29)     t pr.   estimate
CIRQ                   -6.306         0.467      -13.50     <.001   0.001826
```

Message: s.e.s are based on the residual deviance.

% of Deviance explained = 91.7%

Figure 14 shows a comparison of fitted values and observed data, and although the fit is better than for Arm 2 it has the same bias. A better-fit relationship was obtained where the proportion of driver not stopping was a function of the square of the cycle circulating flow and the circulating flow which would imply that the ‘critical gap’ increased with the circulating flow - that is as the cycle flow increased, drivers became more cautious. However, this result cannot be translated for use in the current pedestrian/cycle crossing model in ARCADY and the simpler model still has a very good explanatory power.

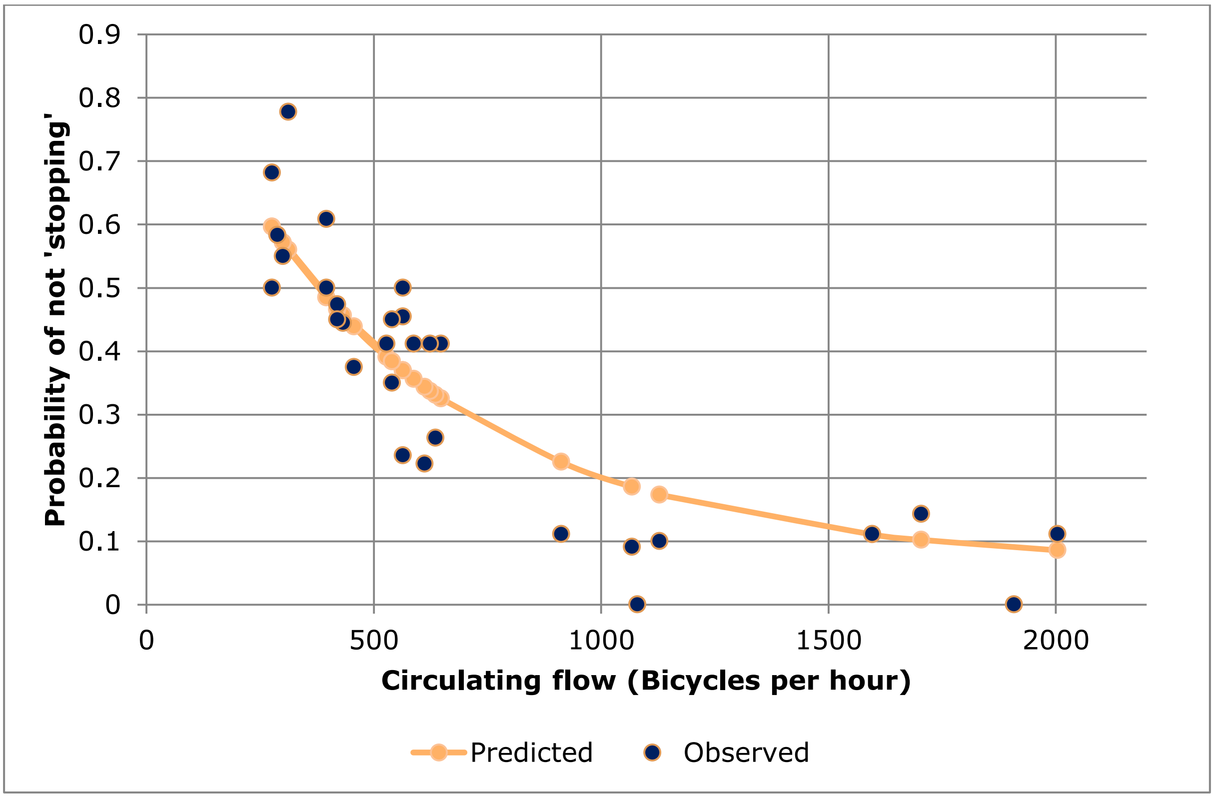

Figure 13 Comparing fitted and observed values for Arm 2

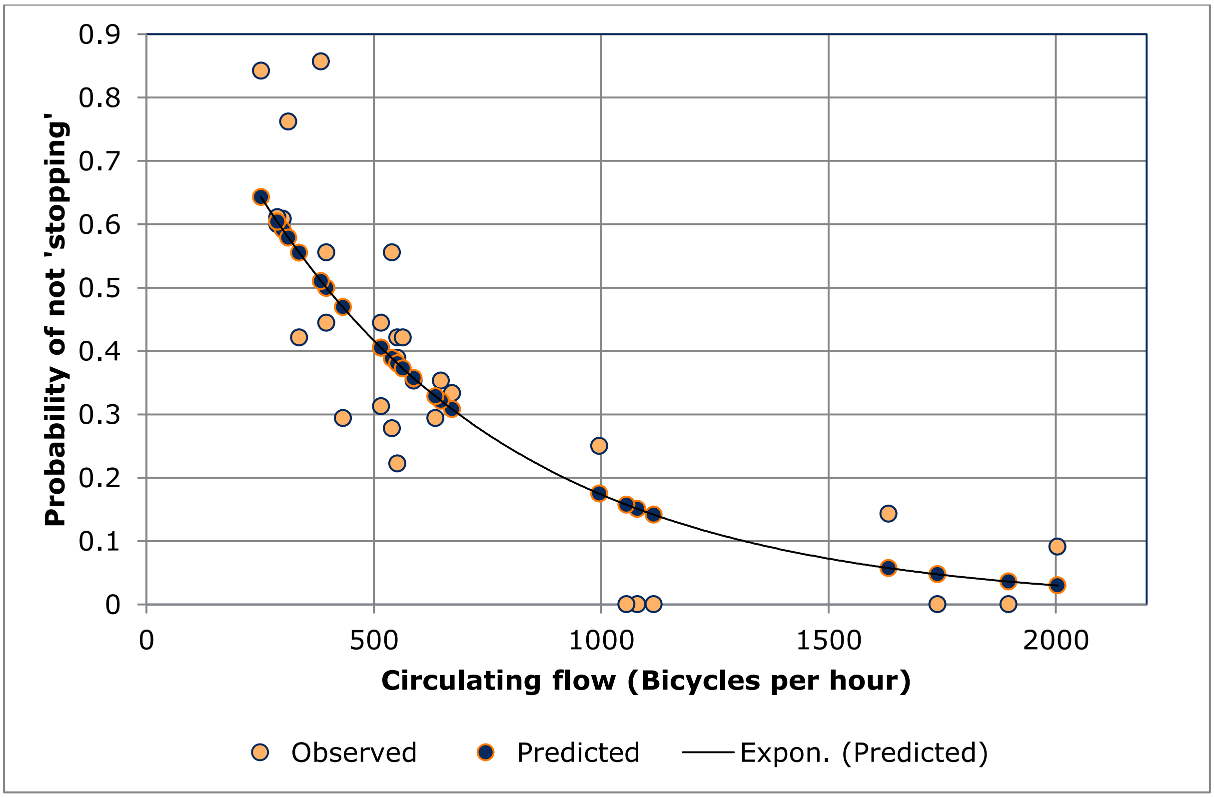

Figure 14 Comparing fitted and observed values for Arm 4

A.3 Theoretical assumption behind the use of a 'combined crossing' within ARCADY.

In the absence of any empirical evidence to the contrary, the simplest assumption to make when modelling two crossings (pedestrian, then cyclist, adjacent to each other) on an entry arm is to assume that each crossing can be treated as independent of each other.

Assuming that both the pedestrian and cyclist flows are independently random then the probability of the entry arm not being blocked, based on work by Griffiths (1981) can be given as:-

Probability of the pedestrian crossing not being blocked (Equation 2, used for pedestrians)

$$P_p = \quad e^{-(\mu_P)*((\alpha_P+\varphi_P)-0.5\beta)}$$

multiplied by the probability of the cycle crossing not being blocked (Equation 2)

$$P_c = \quad e^{-(\mu_c)*((\alpha_c+\varphi_{Pc})-0.5\beta)}$$

Ignoring the impact of the follow-up time, the above equations can be simplified to:-

$$P_{pc} = \quad e^{-(\mu_P+\mu_c\ )*((\alpha_p+\varphi_p)*\mu_p+(\alpha_c+\varphi_c)*\mu_c\ )/(\mu_P+\mu_c\ )}$$

Where:-

P_p = Probability of the pedestrian crossing not being blocked.

P_c = Probability of the cycle crossing not being blocked.

P_{pc} = Probability of the pedestrian crossing and the cycle crossing not being blocked.

μ_P = the mean pedestrian flow (pedestrians per second)

μ_c = the mean cycle flow (cyclists per second)

α_p = time for pedestrian to cross the entry arm (secs)

α_c = time for cyclist to cross the entry arm (secs)

φ_p = additional perceived time drivers need for pedestrians (secs) – assumed to be 0 secs i.e. drivers only notice pedestrians at the kerbside.

φ_p = additional perceived time drivers need for cyclists (secs) – assumed to be between 0 secs and 5 seconds i.e. drivers take notice of cyclists approaching the entry arm.

In order to use this assumption for a combined crossing the two quantities that ARCADY requires are:-

$(\mu_P + \mu_c\ )$ = The sum of the pedestrian and cycle flows.

$((\alpha_p + \varphi_p) * \mu_p + (\alpha_c + \varphi_c) * \mu_c\ )/(\mu_P + \mu_c\ )$ = The flow-weighted average perceived crossing time for pedestrians and cyclists.

The example below shows the impact on mean flows and crossing times when combining pedestrian and cycle flows.

PEDESTRIANS						**Crossing time assumptions (secs)**[14]	
Arm/time period	08:00-08:15	08:15-08:30	08:30-08:45	08:45-09:00	**Total**	entry time	exit time
1	3.33	3.33	5.13	4.00	15.80	2.01	2.94
2	4.53	4.20	3.87	4.53	17.13	1.97	2.01
3	3.00	2.47	2.87	5.27	13.60	1.88	1.92
4	6.73	7.67	7.27	11.47	33.13	2.72	1.83
CYCLES						Crossing time assumptions (secs)	
Arm/time period	08:00-08:15	08:15-08:30	08:30-08:45	08:45-09:00	**Total**	entry time[15]	exit time[16]
1	5.35	7.21	6.43	5.85	24.83	*4*	6
2	8.10	10.69	8.89	9.30	36.98	*4*	6
3	14.70	16.60	18.19	11.81	61.31	*4*	6
4	15.37	17.53	18.47	12.17	63.53	*4*	6
COMBINED						Crossing time assumptions (secs)	
Arm/time period	08:00-08:15	08:15-08:30	08:30-08:45	08:45-09:00	**Total**	entry time	exit time
1	8.68	10.54	11.57	9.85	40.63	3.2	4.8
2	12.63	14.89	12.76	13.83	54.11	3.4	4.7
3	17.70	19.07	21.06	17.08	74.91	3.6	5.3
4	22.10	25.19	25.74	23.63	96.67	3.6	4.6

The combined mean flows can be added into ARCADY's 'pedestrian flows by time period, and the 'combined' mean entry and exit 'crossing' times inserted under ARCADY's Zebra crossing inputs as in Figure 12.

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[14] These time are simply based on the entry/exit arm distance in metres, multiplied by 1.2 m/s. There is assumed to be no additional perceived time for pedestrian crossings.

[15] This is the perceived time (i.e. actual crossing time plus additional perceived time). Assumed to be 4 seconds in total.

[16] This is the perceived time (i.e. actual crossing time plus additional perceived time). In this case, based on the analysis in the report, totalling 6 seconds.