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Literature review of road safety at traffic signals and signalised crossings

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Transport Research Laboratory

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Literature review of road safety at traffic signals and signalised crossings

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Client:	**TfL, London Road Safety Unit**
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The views expressed are those of the author(s) and not necessarily those of TfL.

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Executive summary

Collisions occurring at traffic signals and signalised crossings are an important road safety issue: between 2004 and 2006, 19% of all collisions in London occurred at signal-controlled junctions; in the same period, 17% of all pedestrian casualties recorded in STATS19 occurred on signalised pedestrian crossings.

There are currently approximately 6,200 permanent traffic signals in Greater London of which 5,700 have pedestrian phases. These are located at junctions and at stand alone (mid-block) locations on both Borough and Transport for London Road Network (TLRN) roads. In addition temporary traffic signals can be found at street work locations. In London, there are several different traffic signal technologies, designs and control techniques.

LRSU has commissioned TRL to undertake a literature review of road safety studies at traffic signals and signalised crossings in London or other urban centres. The review is intended to inform the policy and practice of TfL.

The review included literature back to 1980 in the UK and 1990 elsewhere, or earlier for a few key references. Most of the references are studies in the UK or the US, with about half being post 2000. The literature mainly comprised before-and-after studies, with small numbers of sites, not necessarily with controls, and sometimes with flawed methodology.

The main types of collision at signal-controlled junctions are single vehicle, rear shunts and lane changing collisions on the approach to the junction, right angle collisions, principal right turn collisions and pedestrian collisions. Right angle collisions are those between two vehicles going ahead on different roads and account for about 13% of the total in the UK; these collisions could not occur if all drivers acted in accordance with the signals. Right angle collisions and those involving non-motorised users have the highest mean severity. Principal right turn collisions are those between a right turning vehicle and an oncoming vehicle.

Effect of signalisation

On average, signalisation reduces collisions by 15% at 3-arm junctions and 30% at 4-arm junctions. However, it will not always be advantageous as, although it reduces right angle collisions at 4-arm junctions, it can increase rear shunts. There is limited evidence that signal-controlled roundabouts are safer than normal roundabouts for pedestrians and cyclists.

Pelican crossings enable users to cross the road more easily but there is some evidence that users take less care than when crossing in the absence of a facility. Puffin crossings have a number of potential advantages over Pelican crossings and appear to have a similar safety record.

Signal timings and type of signal control

The period between the end of green on one approach and the start of green on a conflicting approach is known as the intergreen. Intergreen periods in the UK were set many years ago; recent research confirmed that the amber period should remain at three seconds and the starting amber (red with amber) period at two seconds. Periods when a red light is shown to all vehicles appear to reduce collisions if kept short. Longer all red to vehicle periods have been found to be associated with increased principal right turn collisions.

In the US, amber periods of between three and six seconds are used, with longer periods at junctions on high speed roads. Increasing US amber periods to the values recommended by the Institute of Transport Engineers (ITE) (which are calculated on a site-specific basis) reduces collisions. Amber periods that are shorter than the ITE recommended values are associated with increased collisions. However, intergreen periods that are too long may also increase collisions. As in the UK, there is often, but not invariably, an all red period. There is no starting amber period in the US.

Shorter cycle times benefit pedestrians and improve pedestrian compliance, but provide increased opportunities for red running. Cycle times are generally set to minimise vehicle delay but crossings or lightly trafficked junctions in an Urban Traffic Control (UTC) system can sometimes be double-cycled (allowing the pedestrian green to appear twice in every cycle).

Although the type of signal control is generally selected on delay grounds, it can have an effect on safety. For example, when correctly configured, Microprocessor Optimised Vehicle Actuation (MOVA) reduces collisions by a statistically significant 26% compared with Vehicle Actuation (VA). UTC is estimated to reduce collisions by 19%.

A separate right turn stage substantially reduces principal right turn collisions; however, its use implies a different distributed allocation of time in the cycle. This may increase delays for both vehicles and pedestrians. The use of early cut-off or late release is less effective but still gives a good safety benefit.

Red light running

Red light running occurs for three main reasons. It may be inadvertent if the driver fails to see the signal, deliberate if the driver tries to beat the lights, or the driver may be caught in the dilemma zone with the choice between braking and continuing through the junction not clear cut. The dilemma zone is mainly a problem at 'high speed' junctions. Strategies such as MOVA seek to ensure that motorists do not have to face such a situation.

Measures to reduce red-running include extending the intergreens, giving advance warning of the start of amber, improving the conspicuity of the signal head and introducing red light cameras.

Broadly speaking, red light cameras can be viewed as successful and are well supported by the general public. Although evaluative studies reported in the literature tend to be of low statistical power and rather poorly controlled, so that the results are often unreliable, the consensus appears to be that they are effective in improving compliance (estimated to reduce red-running by about 50%) and safety (estimated to reduce right angle collisions by about 30%). However, there can be a corresponding increase in rear shunt collisions and some studies have reported a small increase in total collisions. Because rear shunts are on average less severe than right angle collisions, there is considered to be a reasonable benefit-cost return with red light cameras at sites where red-running is an issue.

The potential for long-term expansion of the use of red light cameras in the UK may be limited, as some police forces have suggested that most of the sites where a camera would be cost-effective have already been treated.

Vulnerable road users at signals

The review found that most of the research relating to pedestrian behaviour is for mid-block crossings rather than junctions. There is far more research on pedestrian behaviour, specifically on compliance with the pedestrian signal, than there is on safety.

Pedestrians are more likely to comply with a signal if they are older, female, have impaired mobility (physical disability or because they are carrying something heavy or accompanying a young child or pushing a pram etc), the traffic is heavy, other pedestrians are waiting, or they have been waiting less than 30 seconds. They tend to cross the road at their own convenience and they will take shortcuts and accept gaps in traffic rather than wait for the signal to change if they think they can do so safely.

Puffin (or Puffin-style) crossings with kerbside and on-crossing detectors may benefit pedestrians and vehicles at mid-block crossings. On-crossing detectors are particularly helpful for those with a slower walking speed, whether because of age, infirmity or simply carrying a heavy object.

Reducing delay to pedestrians might be expected to increase compliance and may consequently increase safety for example by:

- Increasing responsiveness by switching to the green man as soon as possible after a demand is made (e.g. VA with pre-timed maximum)
- Keeping cycle times as short as possible
- Increasing the proportion of the cycle available for pedestrians

Relatively little literature was found on pedal cyclists or powered two-wheelers and safety at traffic signals, although as at other junction types, these road users are known to be over-represented in collisions.

Features not currently used in the UK

Right turn on red (RTOR) (for countries that drive on the right) was introduced as a fuel saving device in the 1970s oil crisis. It allows vehicles to pull out into gaps in the traffic even when other turning movements are not permitted due to the potential conflicts with other streams of traffic. It reduces vehicle delay and emissions but has generally been shown to increase pedestrian and cycle collisions; it is widely used in countries such as the US, but not in the UK (where the equivalent would be 'left turn on red'). The more definitive results all showed an increase in right turn collisions with RTOR. There were no schemes reported that had right turning permitted for cyclists only.

'Flashing amber' refers to traffic lights which permit drivers to proceed with caution. It therefore prevents drivers from waiting unnecessarily when the traffic lights might otherwise be red. Flashing amber is used at night in the US and in some northern European countries at low flow junctions. The use of flashing amber rather than the full signal sequence has generally been found to increase collisions. Schemes can go further and switch lights off altogether. In a Swedish study, switching lights off altogether was found to improve safety compared to the use of flashing amber, but the authors did not report on how this compared with full signal operation.

Countdown timers that count down the remaining crossing time for pedestrians are popular in the US and could offer useful information to pedestrians in the UK.

While the results are of interest, they do not necessarily provide any indication of how the features not currently used in the UK might operate in the London environment. The results from assessments can be mixed and the conditions at sites are often quite different from those found in London. It is recommended that, if these features were to be tried, pilot projects should be closely monitored, especially for any potential road safety risks.

Abstract

A review of safety at signal-controlled junctions and mid-block crossings was undertaken for Transport for London with the aim of informing practice and policy. It covers all aspects of signal design and strategy. A large number of studies on all aspects of signal control were reviewed, the most common topics being red light running and countdown timers. Studies were mainly before-and-after with or without control sites and were found to be very mixed in terms of quality with many having small sample sizes or flawed methodology or both. For some aspects of signal design, there is a conflict between safety and delay. The behaviour of pedestrians has been much more widely studied than their safety.

1 Introduction

1.1 Background

Collisions occurring at traffic signals and signalised crossings are an important road safety issue: between 2004 and 2006, 19% of all collisions in London occurred at signal-controlled junctions; in the same period, 17% of all pedestrian casualties recorded in STATS19 occurred on signalised pedestrian crossings (2008 data).

There are currently approximately 6,200 permanent traffic signals in Greater London of which 5,700 have pedestrian phases. These are located at junctions and at stand alone (mid-block) locations on both Borough and Transport for London Road Network (TLRN) roads. In addition temporary traffic signals can be found at street work locations. In London, there are several different traffic signal technologies, designs and cycle timings.

LRSU has commissioned TRL to undertake a literature review of road safety studies at traffic signals and signalised crossings in London or other urban centres. The review is intended to inform the policy and practice of TfL.

1.2 Objectives of review

The aim of the review is to identify, integrate and synthesise the existing evidence concerning road safety at traffic signals and signalised crossings and to identify gaps where robust evidence may not yet exist.

Specific objectives are:

- To identify research that can supply evidence on road safety at traffic signals to support the Mayor’s transport strategy in terms of collisions, casualties, attitudes, conflicts, behaviour and road user interactions.
- To consider different aspects of traffic signals including:
    - Criteria for installation or removal of traffic signals
    - Innovative design or equipment including Intelligent Transport Systems
    - Design of junctions/approaches and traffic signals
    - Traffic signal phase timings and safety

Section 3 summarises data on particular collision types at signals and reviews the effect on safety of introducing signal-control. Section 4 reviews the effect on safety of various aspects of signal control, whilst Section 5 reviews the effectiveness of interventions intended to improve safety. Section 6 considers pedestrian behaviour, whilst Section 7 looks at the safety at signals of other road user types. Section 8 summarises the main findings. Appendix C contains a meta-analysis of data from a variety of studies on countdown timers.

2 Methods

2.1.1 Type of review

The review undertaken was a standard literature review. Part of the study brief was to consider whether any of the topics would be suitable for a meta-analysis. The latter is a statistical analysis of results from earlier studies, in order to determine the mean effect size of the treatment. The intention was to undertake a meta-analysis of findings where this would provide additional value to the study, either because the effect of an intervention was unclear, or because it was of particular value to TfL.

2.1.2 Identification of studies

In order to ensure that the methods used in the review are reproducible, the search terms used and the initial exclusion criteria, as agreed with LRSU, are listed in Appendix A. A major issue was how far back to take the search. Initially, in September 2008, a search of the Transport Research Information Services (TRIS) database was undertaken from 1980 onwards. From this, it was decided that studies earlier than 1990 would be excluded unless they were undertaken in the UK or looked particularly useful from the abstract. In the UK, 1980 was used as the main cut-off date, but earlier reports from London and from TRL were included, whether published or not, as were reports in the technical press. Any papers cited as major references in the documents obtained were added where it was possible to obtain copies, particularly where these studies were the subject of a meta-analysis. All studies included in the review are listed in the reference section.

There were a number of definitional issues e.g. the use of the terms 'junction' and 'intersection' differ by country and to some extent by author. This issue was covered by including a number of different search terms for each topic (see Appendix A).

All studies traced were assessed as to their usefulness including:

- relevance to London
- general applicability of findings
- size of study
- reliability of methodology

2.2 Limitations of review

The review covers information from a number of different countries, mainly the UK, the US and Australia and New Zealand. Overseas material needs to be treated with some caution for various reasons:

- different countries have different laws e.g. relating to jay-walking
- different countries have different signal timings e.g. intergreens – the period between the end of green on one approach and the start of green on a conflicting approach
- some countries allow non-exclusive pedestrian phases e.g. the use of 'right turn on red'
- there are differences in the way in which countries record their collision data

Some countries include data relating to collisions involving only damage to property. There are differences in the definitions of junction collisions. Where casualty data is provided, there are differences in the definitions of serious, slight and fatal injury severities (the latter relating to the length of time between the collision and the actual death, for example 30 days in the UK).

The review is based on a number of studies that were intended to evaluate the effect on safety of a particular intervention. There are various difficulties that arise in this type of research, principally bias in the selection of the treatment sites and small numbers of collisions, the latter making it difficult to obtain adequate statistical power.

Selection bias and regression to the mean (RTM) arise from the need to prioritise on the most appropriate locations for the intervention. RTM arises because of selection bias in the sites chosen for treatment, so that sites with a high 'before' collision count have a lower 'after' count purely by chance, even without an intervention. It can be minimised by using long 'before' periods to ensure that the high counts have been sustained over time, making it more likely that they are representative of the underlying collision rate at the site.

However, if the 'before' period is too long, general trends in collisions may also affect the results. For this reason, control sites are commonly used. The empirical Bayes method is the main method of taking account of both RTM and trend effects. However it has only been applied during the last ten years and requires specialist statistical knowledge.

The use of long 'before' and 'after' periods can be less important when considering behavioural changes such as the extent of red-running as it is less likely that high incidence of red running would change purely by chance at a particular site, and the numbers involved are much larger.

The main methods of analysis in studies traced for this review are as follows:

- Before-and-after studies without control sites
- Before-and-after studies with control sites
- Empirical Bayes method (EB)
- Full Bayes method (FB)
- Cross-sectional studies

In before-and-after studies without control sites, no account is taken of either RTM or trend effects. With control sites, trend effects are taken into account, but not RTM.

Where there are long 'before' and 'after' periods, it is particularly important to allow for trend effects, either by including control sites, or by using models to take account of changes, for example in flow. Control sites need to be carefully selected to ensure they are as similar as possible to the treated sites but are not affected by the intervention.

An example of a difficulty with the use of control sites, pointed out by Aeron-Thomas and Hess (2005) and others (see Section 5.3), is the spillover effect of red light cameras, when drivers have been influenced by publicity or are uncertain whether or not the intervention applies to a particular junction. Authors in a number of studies have used different arms of the same junction, or junctions on the same road as controls. Although these may be similar in terms of flow and geometry, driver behaviour may be affected by publicity or signage relating to red light cameras.

Because interventions are not assigned at random, it is very difficult to avoid the flaws relating to either before-and-after or cross-sectional studies described above. This should be borne in mind when reading the review. The sample size and analysis methods of studies included in the review are described in the report. In addition, brief summaries are provided in Appendix B. It should be noted that most studies do not quote confidence intervals.

2.2.1 Empirical Bayes method

Where the empirical Bayes method (EB), described by Hauer (1997), is used for the analysis, both trend and RTM effects can be taken into account. EB is an advanced statistical technique currently regarded as the gold standard and has been applied by many authors in recent years, for example, Gorell and Sexton (2005) in their analysis of safety cameras for TfL. However, this technique was not available for the older studies and can be difficult to apply.

2.2.2 Full Bayes method

The full Bayes method has very rarely been used for analysis of road safety before-and-after studies. It has all the attributes of empirical Bayes, but has a number of advantages, potentially taking better account of uncertainty in data and requiring less data (see e.g. Lan *et al*, 2009).

2.2.3 Cross-sectional studies

An important alternative to before-and-after studies is the use of cross-sectional studies that look at the combined effect of different features and develop models relating collisions to flow, geometry and signal timings. They are not subject to RTM as such or (depending on the time scale considered) trend effects. Their difficulties include the following:

- there are often too few suitable sites to cover the full range of possible features
- many of the variables of interest are highly correlated making it difficult to estimate the separate effects of the correlated variables
- they are expensive
- where there are sites with a particular feature, there may be too few sites without the feature that are similar in other aspects to determine its effect
- the relations uncovered in cross-sectional studies may not be causal

The findings of cross-sectional studies can be included in a meta-analysis with before-and-after studies where relevant.

2.3 Study quality criteria

One example of study quality criteria in the area of safety at signal-controlled junctions is given in the meta-analysis of red light cameras undertaken by Aeron-Thomas and Hess (2005). They required studies to be either:

- randomised or quasi-controlled trial, or
- before-and-after study with controls

As explained in Section 2.2, in the context of traffic safety, randomised or quasi-controlled trials are not generally possible and it is before-and-after studies, with or without control sites that form the basis of much of the available literature.

For example in their meta-analysis, Aeron-Thomas and Hess (2005) required the 'before' and 'after' periods for collision or casualty data to be at least 12 months each. For other measurements, such as red light violations, the 'after' survey was required to be undertaken at least 12 months after the intervention. As regards collisions, the view taken in this report is that studies with a 'before' or 'after' period of less than 24 months should be excluded from any formal meta-analysis (though not necessarily from any tentative conclusion where there is no better data available). However, periods shorter than a year (say a minimum of three months), though not ideal, are often satisfactory for behavioural data.

In this review, the results quoted are for injury collisions and statistical significance refers to the 5% level unless otherwise stated.

2.4 Search strategy

The following electronic databases were searched for this review in September 2008 by the TRL library, using the terms set out in Appendix A.

- Transport Research Information Services (TRIS) (1980 onwards)
- International Road Research Documentation (IRRD) (1980 onwards)
- Science Direct (1998 to 2008)
- Ingenta Connect (1998 to 2008)
- Google Scholar (1998 to 2008)
- TRL unpublished research (all)
- Major conferences (part of TRIS / IRRD search from 1980 onwards)
- UK technical press (part of TRIS / IRRD search from 1980 onwards)
- TfL published and unpublished research (as supplied)

A process map of the search is shown in Figure 1.

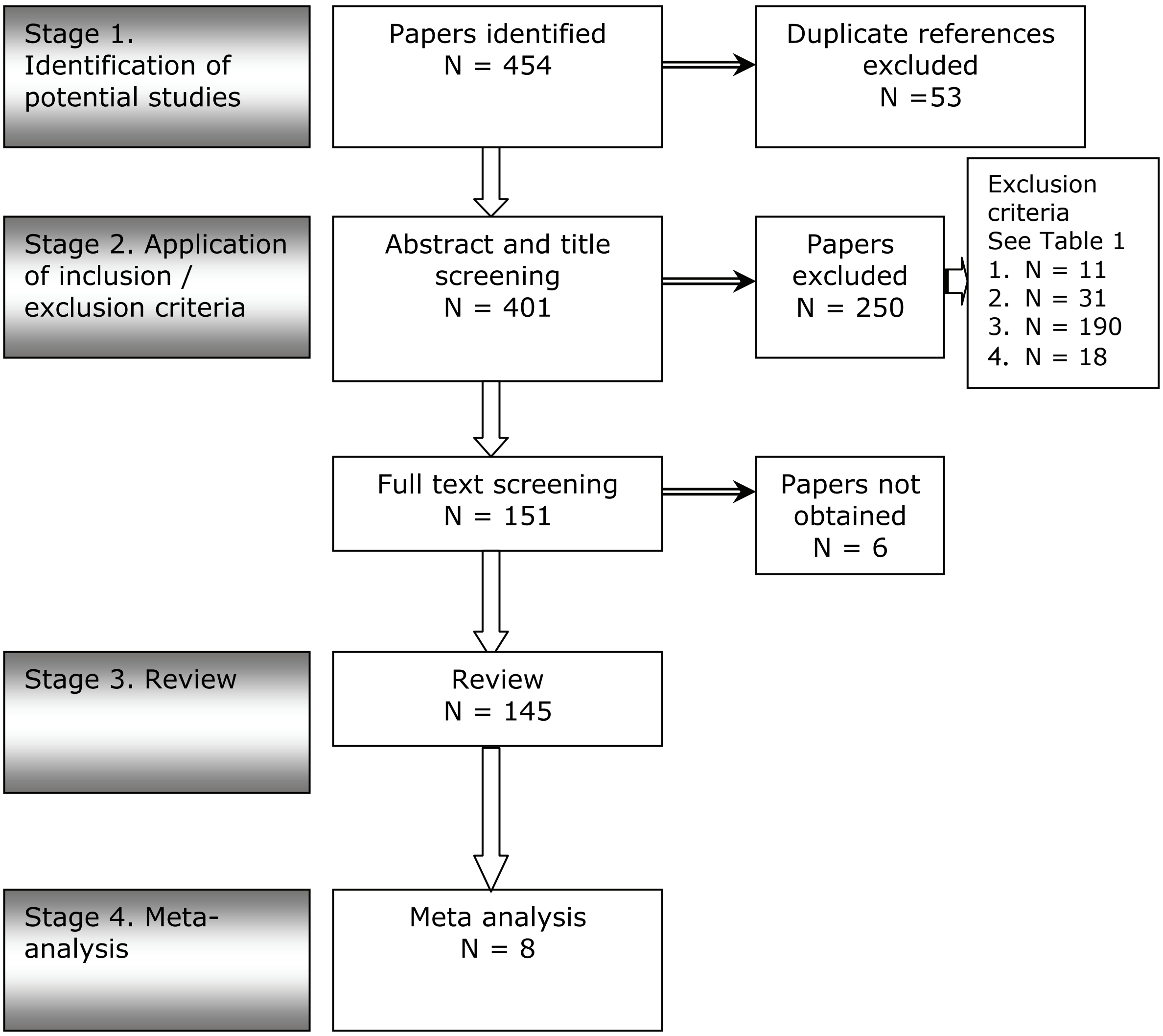

Figure 1: Process map of literature search

2.5 Results of search

All abstracts were read for relevance and copies of the actual reports requested from the TRL library where there was any likelihood of the paper being useful in the review.

The search of TRIS and IRRD led to 363 abstracts, of which 116 were obtained and 86 reviewed. Science Direct yielded 20 abstracts, of which six were obtained and five reviewed. Ingenta led to 19 abstracts of which only three were obtained and two reviewed as there was some duplication with the other searches.

Reasons for excluding studies on the basis of their abstracts are listed in Table 1.

Table 1: Reasons for excluding reports on the basis of their abstracts

Number	Reason	Total	%
1	Country	11	4
2	General rather specific research topic	31	12
3	Irrelevant	190	76
4	Old (outside age limit criteria)	18	7
	Sub-total	250	100
	Duplicate or presents same results	53	
	Total	303	

In addition, 68 reports were already known to the authors from previous reviews (24) or were cited as major studies in the papers obtained (42). A further 12 papers were found from TfL and 25 from TRL. The original decision to exclude flashing amber lights was reversed partway through the project and this added a further eight reports.

Of the 234 reports in the list of references, 62 are background material, leaving 172 that were actual research studies or meta-analyses, of which 57 are summarised briefly in Appendix B. Of these 172 research documents, 61 (35%) were from the UK and 76 (45%) from the US or Canada (see Table 2). The US and Canada have different laws to the UK such as those relating to jay-walking and therefore findings from these studies should be interpreted with caution. Half were published after 2000 (Table 3).

Table 2: Study source

	Number	%
Australia and New Zealand	14	8
Europe (other than UK)	11	6
UK	61	35
US and Canada	78	45
Singapore	4	2
Israel	4	2
Total	172	100

Table 3: Study publication dates

	Number	%
1960-1969	2	1
1970-1979	12	7
1980-1989	27	16
1990-1999	43	25
2000 onwards	88	51
Total	172	100

3 Collisions at traffic signals

3.1 Collision types at traffic signals

The main collision types at 3- and 4-arm traffic signals were classified by Taylor *et al* (1996) and by Hall (1986) respectively and are summarised in Table 4[1].

Table 4: Percentages of collisions and collision severity by type at 3- and 4-arm signal-controlled junctions on 30mph UK roads

	% of collisions		Severity of collisions (% fatal or serious)	
	3-arm	4-arm	3-arm	4-arm
Single vehicle	7.6	8.9	20.0	16.9
Approaching	21.6	8.8	6.7	7.8
Right angle	-	13.4	-	29.5
Principal right turn	15.8	26.7	16.0	18.5
Other turns	12.3	9.7	16.2	15.1
Other vehicle	11.2	4.4	18.4	14.2
Pedestrian	34.6	28.1	25.9	24.3
Total	100	100	17.9	20.0

Single vehicle collisions include vehicles losing control and hitting street furniture, cyclist and motorcyclists falling off their vehicles and collisions in which bus passengers fall either inside the bus or whilst boarding or alighting. Approaching collisions involve more than one vehicle on the approach to the signals, and are typically rear shunts or lane changing collisions.

Right angle collisions are those between two vehicles going ahead on adjacent approaches. They only occur at 4-arm junctions and should of course be avoided by the use of signals, but accounted for over 13% of collisions at this junction type in the UK in 1986. Much of the literature traced has been aimed at reducing right angle collisions, for example by the use of red light cameras (see Section 5.3). In the US, Bonneson *et al* (2002) reported that red-running is considered to account for 16 to 20% of injury collisions.

The other major group of vehicle collisions is that of principal right turn collisions, in which a right turning vehicle collides with a vehicle from the opposite approach. The main mitigation measures are the use of a separate right turn stage or early cut-off / late release (see Section 4.6.6). The use of red light cameras is likely to reduce the incidence of this type of collision.

At 4-arm signal-controlled junctions, right angle collisions were found to have the highest severity (29% fatal or serious), although the development of side-impact protection may mitigate this to an extent, followed by pedestrians (24% fatal or serious). At 3-arm signals, where there can be no right angle collisions as defined above, pedestrian collisions have the highest severity (26%).

By comparison, Ogden (1994) in Australia found the following proportions of collisions at signal-controlled junctions, but included both rural and urban junctions: 9% pedestrian

[1] The collision groups have been changed slightly for ease of comparison

collisions, 22% rear shunts, 22% adjacent approaches (mainly right angle) and 34% principal right turn collisions.

3.2 Casualties at signals in London

Data supplied by TfL shows that in London during 2008, there were 5519 casualties at signal-controlled junctions, accounting for 20% of all casualties on the road. Of these, 19% were pedestrians, 12% pedal cyclists and 13% powered two-wheelers. At signal-controlled junctions with a pedestrian phase, the proportions of casualties were 23% pedestrians, 12% pedal cyclists and 14% powered two-wheelers.

At Pelican or Puffin mid-block crossings, the proportions of casualties were 31% pedestrians, 8% pedal cyclists and 17% powered two-wheelers.

3.3 Effect of signalisation at junctions

3.3.1 Priority junctions

The main safety benefit of signal-controlled junctions as compared with priority junctions is the reduction of right angle collisions. However, their installation may be accompanied by an increase in rear shunt collisions and therefore the total number of collisions may increase. This may be one reason that results are mixed (see e.g. Hakkert and Mahalel, 1978, Golias, 1997). Another possible reason is that signals are sometimes introduced not for safety reasons but to regulate vehicle flows. These two factors have made it difficult to discern the extent to which signalisation is beneficial. One way of analysing the effect of conversion is to compare casualties rather than collision numbers because of the much greater mean severity of right angle collisions; it may be cost beneficial to introduce signals even if there is an increase in collision frequency since fatal and serious casualties may reduce. However, most authors only present the numbers of collisions. Several authors (e.g. Hakkert and Mahalel, 1978) have commented that collisions are reduced at sites where the collision rate is high before signals were introduced, and increased when it was low, but it is unclear how much of this results from regression to the mean. Elvik and Vaa (2004) undertook meta-analyses of various interventions related to signals. They concluded that, following signalisation, collisions decreased by 15% (95% confidence interval from -25% to -5%) at 3-arm junctions and 30% (95% confidence interval from -35% to -25%) at 4-arm junctions. However, most of the literature they refer to relates to countries other than the UK and was undertaken before 1990, pre-dating the period surveyed. This is also the case with the literature survey undertaken by Golias (1997). It is not clear from Elvik and Vaa whether any of the studies allowed for RTM, although they do state that none of those relating to improvements to traffic signals did so. Hakkert and Mahalel (1978) in Israel studied the effect of signalisation at 34 urban junctions for 38 months before and a similar period after signalisation. At sites with fewer than 15 collisions in the 'before' period, there was a non-statistically significant increase of 5% in collisions, whereas at sites with 15 or more collisions, there was a significant reduction of 48%. No account was taken of RTM.

In Greece, Golias (1997) used a before-and-after study to investigate the effect of signalisation on safety at 48 4-arm junctions. He adopted a seven year 'before' period and a three to five year after period to minimise regression to the mean effects and took into account traffic flow characteristics in order to allow for trend effects, rather than using control sites. He found that the number of collisions decreased at some junctions but was unchanged at others and developed a discriminant function dependent on the road width, gradient and traffic flow to determine whether or not signals would reduce collisions.

Persaud *et al* (1997) examined the effect of removal of traffic signals at 199 sites in the USA where their continued presence did not satisfy the Manual on Uniform Traffic Control Devices, or MUTCD, warrants for signals (the signals being converted to all-way stop sign control). The removals were typically at low flow junctions on one-way non-arterial streets with short cycle times and parking on both sides of the approach road. Flow data was available for all sites. A total of 71 control sites were used in an empirical Bayes analysis. Persaud *et al* found an overall reduction of 24% in collisions when signals were removed, with substantially greater reductions in serious than in slight injury collisions. They also investigated collision by type, finding a 25% reduction in right angle and turning collisions, a 29% reduction in rear shunts and a 26% reduction in pedestrian collisions. Local traffic engineers speculated that this may be as a result of the "elimination of the local habit to speed up at signals to beat the red" (p809). As might be expected, collisions at the higher flow sites tended to increase when signals were removed.

A study by Lan *et al* (2009) in California gives an example (the only one traced for this review) of the application of the full Bayes method to investigate the safety of signalisation of 28 rural junctions. The method gave similar results to empirical Bayes analysis of the same data, finding statistically significant reductions in total collisions of 19% (95% confidence interval from -29% to -9%) and 81% in right angle collisions (95% confidence interval from -85% to -77%), with a non statistically significant increase of 23% (95% confidence interval from -21% to +67%) in rear shunts. Lan *et al* did not state whether or not the collisions included those involving only damage to property as well as injury.

Overall, the findings seem to indicate that those sites with high levels of cross traffic on the more minor road are most likely to benefit from signalisation in safety terms. It should be noted that many of the studies identified on the effect of signalisation at junctions are from outside the UK.

3.3.2 Roundabouts

Research into the safety effects of the signalisation of roundabouts is limited. The different nature of roundabouts in other countries which are largely single lane entry and the late arrival of modern roundabouts in the US mean that very few are signalised. Signalisation is usually undertaken for capacity reasons or at large grade separated roundabouts where circulating speeds in the absence of signals may be very high or to provide a pedestrian or pedal cycle crossing facility.

A benefit of signalisation of roundabouts is that the signals can sometimes be coordinated, most commonly under an Urban Traffic Control (UTC) system. Signalised roundabouts can also be useful where there is high pedestrian demand on more than one arm. They minimise the need for pedestrians to have to detour in order to cross the road, e.g. to a pedestrian crossing sited upstream of the flare at a normal roundabout, a further benefit being that pedestrians can be routed across the central island (see Department for Transport, DfT 2009). However, at most roundabouts, signalisation would not be justified on either safety or capacity grounds, although signalised roundabouts may be part of wider urban realm or traffic management schemes.

The original safety research into signalised roundabouts was a before-and-after survey undertaken by the County Surveyors' Accident Reduction Working Group, SAGAR (CSS, 1993). The CSS obtained collision data for 34 roundabouts, of which ten had traffic flow data. They found little change in the overall number of injury collisions following signalisation with a small decrease in the collision rate for those roundabouts with flow data. There were more rear end shunts but fewer entering circulating collisions (in which an entering vehicle hits a circulating vehicle) and fewer collisions involving vulnerable road users. For example there were about a third fewer collisions involving powered two-wheelers; however, although indicative, none of the results were statistically significant. An unpublished study by TRL using the same data (the 28 sites that had full before-and-after collision data broken down by road user type) found a statistically significant reduction in collisions involving cyclists at signalised entries, mainly from the arms that were fully signalised. The study did not include collisions involving a circulating cyclist or at non-signalised entries.

A more recent before-and-after study by TfL (Martin, 2003) included ten at-grade roundabouts, of which two had part-time signal control, and ten grade-separated roundabouts, of which three had part-time or partial signal control, in London. At the at-grade roundabouts, the effect of signalisation was an overall reduction of 28% in collisions, the greatest reductions being for entering-circulating collisions and for collisions involving a pedal cycle. At the grade-separated roundabouts, there was an overall reduction of 6% following signalisation, but this change was not statistically significant. The biggest reductions were in pedestrian collisions, cycle collisions and entering–circulating collisions; however there was an increase in collisions reported by the Metropolitan Police as being speed-related. The effect of vehicle flow was not taken into account and there were no control sites. No details were given on the basis for which sites were selected so the potential for the results to be influenced by regression to the mean cannot be assessed.

In general, then, there appears to be a small overall safety benefit from signalisation of roundabouts, in particular for pedestrians and cyclists. Pedestrians have the additional benefit that they can be routed across the central island rather than having to detour upstream of the flaring as is the case at normal roundabout. Cyclists may be safer at signalised roundabouts but these large junctions are likely to continue to deter more cautious cyclists.

3.4 Pedestrian facilities at signals

3.4.1.1 Mid-block (standalone) crossings

Modern types of mid-block or standalone pedestrian crossings in the UK are Pelicans, Puffins and Toucans, the latter being for both pedestrians and cyclists. Pelican crossings (PEdestrian LIght CONtrolled crossings) were first used in 1968. They have a short period with a fixed green walking man ('invitation to cross') of four to nine seconds, during which vehicles are shown a red signal, followed by a clearance period with a flashing green man for pedestrians and flashing amber to drivers (see DfT LTN 2/95). If a pedestrian has already started to cross, s/he may continue; vehicles may proceed if the crossing is clear. There is a further period of one to three seconds with a red man for pedestrians before the flashing amber changes to green for vehicles. The clearance period should be long enough for pedestrians who have already started to cross to complete their crossing.

Dean (1982) pointed out that Pelicans are more suitable than Zebra crossings where there are both high vehicle and high pedestrian flows (e.g. mixed priority routes) or where speeds are high and there are comparatively few pedestrians (suburban areas).

The Puffin crossing (Pedestrian User Friendly INtelligent) performs in a similar way to the Pelican, but was specifically designed (Davies, 1992):

- to detect waiting pedestrians in order to eliminate unwanted pedestrian phases (e.g. where a pedestrian makes a request and subsequently crosses before it is met)
- to detect crossing pedestrians in order to enable pedestrian green time to be extended so that they can complete their crossing safely

Flashing signals are not used and there is no far side signal for pedestrians. The location of the signal head on the nearside, in the direction of approaching traffic, is intended to encourage pedestrians to look at approaching traffic before stepping off the kerb.

Figure 2: Nearside signal

One disadvantage with Puffin crossings has been problems with unreliable detectors, particularly kerbside detectors. Faulty detectors at the kerbside increase pedestrian delay, whilst faulty detectors on the crossing can lead to longer than necessary clearance periods, increasing vehicle delays. Both these faults can lead to an increase in pedestrian non-compliance, possibly leading to false conclusions regarding the safety of this type of crossing. Both the initial cost of installing detectors and the cost of maintaining them makes Puffin crossings more expensive than Pelican crossings.

Exact numbers of mid-block crossings in the UK are not known, but it was estimated by Billings and Walsh in 1991 that there were approximately 9,000 Pelican crossings compared with 8,000 Zebra crossings and 8,000 signal-controlled junctions (of which fewer than 30% had pedestrian stages). A more recent survey by the Traffic Control Users Group (TCUG, 2000) estimated that there were around 13,800 mid-block pedestrian crossings and 12,300 signal-controlled junctions, of which 60% had pedestrian facilities. About one-third of signal-controlled crossings are believed to be Puffins. According to Hunt (1995), the UK has many more mid-block pedestrian crossings than in other countries. In London 3,000 of the 6,000 current signal locations are on UTC, see Section 4.6.4; of these, 2,000 are on SCOOT. Of the 6,000 signals, approximately 2,500 are mid-block and, of these crossings, 200 are Puffins; the remainder are Pelicans or Toucans.

3.4.1.2 Junctions

Junction signals with an exclusive pedestrian phase have a fixed period 'green man' signal with a recommended duration of between six and twelve seconds. When the pedestrian phase operates concurrently with a vehicle phase at a junction (as opposed to an all-red pedestrian stage during which there are no traffic movements), the green man period is usually of fixed length and values higher than twelve seconds are commonly used. However, in the UK, although non-conflicting vehicular traffic can make movements elsewhere in the junction whilst pedestrians are crossing, vehicles are not permitted to proceed over the pedestrian crossing while a pedestrian green walking man signal is displayed. Unlike other countries, where right turn on red (for countries where driving is on the right) may be allowed, turning traffic is not allowed to conflict with pedestrians (that is, left turn on red is not permitted in the UK).

Pedestrian timings at junctions are set following guidance from the DfT and vary throughout the UK. Junction operation also varies depending on the technology and equipment present. For example a Puffin style junction would operate in a different way to a conventional junction.

Recent research for TfL (Sterling *et al*, 2009) considered the effect of reducing the duration of the 'invitation to cross' period at nine signal-controlled junctions from between eight and ten seconds to the recommended minimum of six seconds. The 'before' and 'after' periods were only one month apart and conflict analysis was used rather than collision data. Control sites were not used. The study concluded that the change was safety neutral, although pedestrian surveys suggested that some pedestrians were less comfortable with the shorter green man period.

An exclusive pedestrian stage in addition to the minimum of two traffic stages clearly requires a substantially longer minimum cycle time than is the case at mid-block crossings and this leads to longer waiting times for pedestrians at junctions than at mid-block crossings (Japs, 2000).

Typically traffic engineers use imaginative site-specific solutions to enable the provision of pedestrian signals on one or more arms where an exclusive pedestrian phase would lead to excessive vehicle delays, but this usually means that pedestrians have to cross the road in two (or more) 'hops' with a wait at a median or refuge in the centre of the road.

At the end of the 'green man' period there is a fixed length 'blackout' period of up to 12 seconds, intended to allow pedestrians sufficient time to clear the crossing. In the past, this period was believed to be a potential source of confusion since it was not always clear to pedestrians whether the signal was simply faulty. The 'blackout' period is followed by an 'all-red' period of between one and three seconds. It is recommended in DfT TAL 5/05 that the sum of the 'all red' and 'blackout periods' equals the carriageway width in metres divided by 1.2 (the 15th percentile pedestrian crossing speed in metres per second) – see Section 6.1.4. Both kerbside and on-crossing detectors can be used at signal-controlled junctions. With Puffin-style operation, the red man (displayed at the nearside) is shown immediately after the end of the green man and there is no blackout period.

Not all signal-controlled junctions in the UK have a pedestrian signal, leaving pedestrians to make their own decision as to when to cross. This is in contrast to other countries where most junctions have pedestrian facilities. Some European countries have a legal requirement for pedestrians to obey the signals, but this is not always enforced.

3.5 Effect of signalisation on collisions with pedestrians

3.5.1 Signal-controlled pedestrian crossings

Elvik and Vaa (2004) undertook a meta-analysis of the effect of introducing a mid-block signal-controlled pedestrian crossing and concluded that there were mean decreases of 12% (95% confidence interval from -18% to -4%) in collisions with pedestrians, 7% (95% confidence interval from -12% to -2%) in total collisions, and 2% in vehicle collisions, the change in vehicle collisions was not statistically significant. These figures apply to the crossing itself and to the 50m either side of the crossing. Elvik and Vaa do not appear to make any distinction between sites with no prior crossing and those which previously had a Zebra crossing.

Elvik and Vaa point out that the reduction in collisions was greatest on the crossing itself (27%), with a small increase in the area up to 50m from the crossing. This is in line with various UK studies (see Section 6.1.13), which found that risk was greatest for pedestrians who cross within 50m of the crossing but not on it. Elvik and Vaa also note that there can be an increase in rear shunt collisions when mid-block crossings are introduced, as do other authors, (e.g. Summersgill and Layfield, 1996).

Craddock (1992) suggested that pedestrians assess crossing opportunities by observing vehicle movements rather than relying on signals and that this can lead to problems at signal-controlled crossings where there are misleading vehicle movements (e.g. at junctions) or obstructed visibility (e.g. due to queuing traffic).

Likely causes of pedestrian collisions at signal-controlled crossings were identified in a TRL study for DfT reported in Wall (2000) and Hughes (1999) as:

- Lack of pedestrian compliance with the signal (driver compliance is generally good at signal-controlled crossings)
- Crossing close to the facility but not on it
- Failure to look before / during crossing / running across the road
- Crossing through stationary traffic
- Vehicle manoeuvres

In addition, these authors reported that signal-controlled junctions are more complex than mid-block crossings, increasing the difficulty for pedestrians particularly where there is:

- asynchronous signalling (i.e. the turning and straight ahead movements operate independently for all or part of the signal stage)
- opposed right turn flow
- unusual imbalances in opposite direction timings
- vehicles queuing over crossings

3.5.2 Before-and-after studies of Pelican crossings

Converting Zebra crossings to Pelicans might be expected to improve safety as drivers generally stop at a red light. However, except on very busy roads, Hunt (1994) showed that signal-controlled crossings increase delay to pedestrians on average and, if the level of compliance is poor, the main benefit of the conversion will be to create a facility to help those who have difficulty in crossing the road, for example older people or children. In addition, pedestrians may not take as much care in crossing at a Pelican as they would at a Zebra crossing or a location without a crossing. Overall, the results of studies comparing Zebras and Pelicans have been mixed.

Shortly after Pelicans were introduced, a DoE Roads Circular 19/74, cited in Lalani (1977), reported an average reduction of 60% in collisions where Pelican crossings replaced Zebra crossings. However, in London, there was only a marginal change in collisions. As a result, Lalani (1977) recommended that Pelicans should only be introduced at sites with five or more collisions per year or where there was substantial delay to pedestrians or substantial delay to traffic due to the presence of pedestrians. The use of guard railing and anti-skid surfacing was also recommended. Lalani (1974) found a mean *increase* in collisions of 65% when Pelican crossings were introduced at sites with no prior crossing, when comparing the 100m of road centred on the crossing. No account was taken of RTM in either of these studies; the control was the Greater London area. However, unless sites which had low collision rates were selected for treatment, any RTM effect would be expected to produce an apparent reduction in collisions, so the observed increase cannot be explained by RTM.

Rayner (1975) found a 31% increase in pedestrian collisions when Zebras were converted to Pelicans and the site of the crossing was kept broadly unchanged, although there was a safety benefit at crossings that were relocated.

Bagley (1985) undertook a before-and-after study at 37 sites where a Pelican replaced a Zebra and 42 sites where a Pelican was installed but there were no previous facilities, all in south Yorkshire. The study used either two or three years of before and after data.

At the crossing sites that were converted from Zebra to Pelican crossings, there was a decrease of 26% in pedestrian collisions at or within 50m of the crossing and a corresponding decrease of 11% in total collisions. Effects varied dramatically from site to site. At sites with no previous facilities, there was a decrease of 23% in pedestrian casualties, but an increase of 1% in total collisions. Bagley used these results in conjunction with the flow values to develop criteria for sites where a Pelican should be installed, based on the 'PV squared value' then used to assess the need for a crossing. [2]

Bagley also found that the use of a pedestrian guardrail was beneficial at Pelican crossings, particularly where there had been no previous crossing.

Harper (1985) found a reduction of 63% in injury collisions at 14 sites in Swindon where a Pelican crossing replaced a Zebra.

None of these studies appear to have included control sites or tested for statistical significance. Nor did they comment on RTM.

In London, Murray-Clarke (1986) considered the effect on safety of installing Pelican crossings at 12 sites with no prior crossing. Murray-Clarke was aware of RTM finding that the change in collision numbers was dependent on the frequency prior to the installation of the crossing. For sites with above average collision frequencies (more than 3.5 collisions per year over five years); collisions decreased following installation, for average rates (between 2.5 and 3.5 collisions per year in five years) there was little change; whilst for below average collision sites (fewer than 2.5 collisions per year in five years), pedestrian collisions increased following installation. When regression to the mean was taken into account, the magnitude of these effects was greatly reduced and none were statistically significant.

3.5.3 Cross sectional studies of Pelican crossings

Inwood and Grayson (1979) studied 140 Pelican and Zebra crossings in locations, away from junctions and with good visibility. They excluded collisions involving a turning or junction manoeuvre, or a person boarding or alighting from a bus or coach. Results showed a lower total collision rate at Pelican crossings (based on collisions within 100 yards of the crossing). However, although the pedestrian collision rate was also lower, the difference was not statistically significant, even at the 10% level. Inwood and Grayson estimated that, under the same flow conditions, the total collision rate at a Pelican crossing would be 26% lower than at a Zebra.

Hunt and Griffiths (1989) undertook a cross-sectional study of pedestrian collisions based on 132 Pelicans and 111 Zebra crossings in Hertfordshire, based on collisions between 1981 and 1986 within 50m of the crossing. Generalised linear modelling was used to derive relationships between collision frequency and appropriate explanatory variables. Based on the assumption that the flow dependency is identical, they estimated that the pedestrian collision frequency was 34% lower at Pelicans than at Zebras. No statistically significant difference was found between Pelicans under fixed time control and those that were vehicle-actuated; the latter were more likely to be installed at higher speed sites and had both a lower pedestrian flow and a lower mean collision rate than fixed time Pelicans.

3.5.4 Before-and-after studies of Puffin crossings

Replacing Pelican crossings with Puffins should theoretically improve safety in three ways:

[2] Whether or not PV squared (the product of P and the square of V, where V is the vehicle flow and P is the pedestrian flow over the busiest four hours of the day) exceeded a certain value was the criterion used for installing a crossing during the 1980s and early 1990s

- Removal of the flashing green man / flashing amber to vehicles period should improve driver compliance
- Extending the clearance period should enable pedestrians who start to cross during the green man period to complete their crossing before the signals change (using on-crossing pedestrian detectors)
- Use of nearside signal encouraging pedestrians to look in the direction of approaching traffic

In addition, kerbside detection of the continued presence or not of waiting pedestrians can be used to retain or cancel the pedestrian demand respectively. The call cancel facility avoids the situation where the pedestrian presses the button, but then crosses during the red man, and the pedestrian phase runs unnecessarily. However, early installations in particular had problems with detectors (see e.g. Reading *et al*, 1995) and it is necessary to follow suitable maintenance regimes to minimise the risk of detector faults.

Since Puffin crossings were first introduced, further guidance had been issued, for example:

- Puffin Good Practice Guide (DfT, 2006)
- DfT Traffic Advisory Leaflet TAL 5/05 Pedestrian Facilities at Signal-controlled Junctions
- Local Transport Note LTN 2/95 – The design of pedestrian crossings

The most recent of these, the Puffin Good Practice Guide, claims to establish 'crisp but safe operation' (page 24), by keeping clearance periods to a minimum provided all pedestrians have completed crossings. A 'Pedestrian Comfort Time' (or 'Pedestrian Comfort Factor') is used to adjust clearance times for local needs, for example high pedestrian flow or a high proportion of slow moving pedestrians. In addition, there is now increased expertise in the use of Puffins and the detection equipment itself has become more reliable. At busy crossings, nearside high level pedestrian repeater signals can be used to ensure that the pedestrian's view of the signal is not blocked by other pedestrians waiting at the same side.

Several authors concluded from trials of signal-controlled crossings / junctions in various European countries including the UK (Carsten *et al*, 1998) and the US (Hughes *et al*, 2000) that there were fewer conflicts and fewer pedestrians crossing on red at sites with pedestrian detectors. The improvements were obtained without any major effect on vehicle delay as they only extend the pedestrian green when necessary.

Using a simulation technique, Hunt and Chik (1996) reported that reductions in the numbers of pedestrians crossing during the red man at a Puffin could be obtained with a combination of reduced cycle time and better targeting of the times when pedestrian precedence periods occur.

Although Puffins are intuitively safer than Pelicans, it is only recently that work seems to have been undertaken to try to demonstrate this directly. The topic is currently being researched by DfT through a before-and-after study. A study for TfL compared pedestrian behaviour at five Puffins with five similar Pelicans (Walker *et al*, 2004) but failed to draw firm conclusions on the safety benefits of these crossing types as the Puffin crossings did not appear to follow the latest DfT advice. TfL also undertook a before-and-after study (Webster, 2006) of 23 mid-block Puffin crossings that were either new or converted from existing crossings. This study showed that, on average, the total number of collisions on or within 50m of the crossing was 15% lower and the number of pedestrian collisions was 26% lower at Puffins. However, these results were not statistically significant.

3.5.5 Cross-sectional studies of pedestrian facilities at junctions

The cross-sectional studies cited in Section 3.1 used generalised linear modelling to develop collision-flow-geometry relationships at 3-arm (Taylor *et al*, 1996) and 4-arm (Hall, 1986) signal-controlled junctions. As regards pedestrian safety, there was no evidence that the presence of pedestrian crossing facilities (red/green man signals) at the junction reduced risk for pedestrians. The more complex signalling arrangements were associated with increased risk of pedestrian collisions.

3.6 Summary of Section 3

- A substantial proportion of collisions involve a red-running vehicle; this type of collision and those involving non-motorised users have the highest severity on average
- Signalisation on average reduces collisions by 15% at 3-arm signals and 30% at 4-arm signals, but will not always be advantageous as although it reduces right angle collisions, it can increase rear shunts
- There is limited evidence that signal-controlled roundabouts are safer than normal roundabouts particularly for cyclists
- Mid-block Pelican crossings enable users to cross the road more easily but there is some evidence that users take less care than when crossing in the absence of a facility
- Mid-block Puffin crossings have a number of potential advantages over Pelican crossings and appear to have a similar safety record

4 The effect on safety of aspects of geometric layout and signal operation

4.1 Geometric layout

Very little research was found on the safety of junction layout, probably because it is largely driven by the presence of existing buildings. Hall (1986) in a cross-sectional study of 4-arm signals found that after taking account of vehicle flow:

- wider approach widths were associated with increased right angle collisions and approaching collisions
- Where there were more lanes at the stop line, there was increased risk of pedestrian collisions with entering vehicles
- There were fewer right angle (involving vehicles on adjacent roads) and principal right turn collisions (in which a vehicle turning right is hit by an on-coming vehicle) where the opposite arm was displaced, effectively staggering the junction (although only small displacements of up to 13m were included in the study).

4.2 Intergreens

The intergreen period is the period between the end of green on one approach and the start of green on a conflicting approach. It comprises the amber period on the approach losing right of way, any all-red time, and the red and amber (known as the starting amber) on the approach gaining right of way, if used.

In the UK, the amber period is set to three seconds and the red and amber to two seconds. Very occasionally the two periods can overlap, giving a sub-five second intergreen. Often there is a period of all-red giving a total intergreen of six-plus seconds. These values were set up many years ago and therefore fall outside the scope of this review. However, in recent years, they have been re-visited and this work is described below (see Section 4.2.2.1).

It is generally recognised that increasing intergreens that are too short can reduce right angle collisions but making them too long can increase red-running and hence increase collisions.

4.2.1 Starting amber (red with amber) period

'Starting amber' is the red with amber signal immediately preceding the green and conveys the same prohibition as the red signal. It helps to maximise the capacity of the junction and reduces pressure to get away quickly at the start of green by providing an indication of the impending green, giving drivers time to prepare to move (Maxwell and York, 2005). It is fixed at two seconds in the UK, but is not used in the US, Canada, Australia or New Zealand or in several European countries, including France, Belgium, Netherlands and most of southern Europe. Where it is used in mainland Europe, for example in Germany and Scandinavia, the length varies between one and three seconds.

The main research into starting amber was undertaken in the UK by Older (1963) and Branston (1979). Older (1963) considered the effect of removing the starting amber period (three seconds duration) altogether for a trial period at 18 sites, whereas Branston (1979) considered the effect of reducing its length. Older found a large reduction in the proportion of drivers entering the junction during the red (from 2.2% before to 0.9% after), mostly drivers who would previously have started during the starting amber period. Without this period to forewarn drivers, the first vehicle entering the junction was delayed 1.7 seconds. Both Older and Branston found that the saving in lost time from omission of the starting amber was offset by an increase of similar magnitude in the time taken for drivers to react to the start of the green. Older calculated that removing the starting amber period led to a loss in capacity of 6%, but he found no effect on the number of collisions.

More recently, experiments were undertaken using the TRL driving simulator into the effect on safety and capacity of removing the starting amber period (Maxwell, 2006) and video observations were made of current driver behaviour (Maxwell and York, 2005). Maxwell and York (2005) suggested that the benefit of having a starting amber arises in part because drivers start to move, or at least prepare to move, during the amber, although they delay starting when there is a potential conflict. In the absence of a starting amber signal, drivers are more likely to be watching traffic on the side roads and might therefore fail to see vulnerable road users. A small reduction (to 1.5 seconds) was proposed by Maxwell (2006) in order to reduce the violation rate of drivers crossing the stop line before the start of green. However, there is no safety evidence to support this suggestion.

One problem with the starting amber can arise when there is a double headed signal using green arrows to indicate two different phases. In this case drivers can and do mistake the starting amber as indicating that their phase is about to start, because they cannot tell from the full amber which direction is about to gain right of way. 'Intelligent amber arrows' (Pleydell and Gillam, 2002, Ridding and Gillam, 2005) may reduce the problem by showing an amber arrow that indicates which direction is about to gain right of way, but still show a full amber aspect for the leaving amber (hence the term 'intelligent'). The safety aspects have not been investigated.

4.2.2 Amber and all-red periods

4.2.2.1 UK

In the UK, York and Al-Katib (2000) used the TRL Driving Simulator to investigate the effect of varying the duration of the amber period at high speed sites (i.e. those with an 85th percentile speed greater than 35mph). They concluded that the current duration of three seconds should be retained. Longer times increased hesitancy, indecision and the size of the 'dilemma zone' (see Section 5.2). York and Al-Katib also found that drivers quickly adapted to the change and entered the junction longer after the start of amber. The recommendation was therefore to keep the amber period fixed at three seconds for all traffic signals.

Maxwell and Wood (2006) estimated that a four second amber period would mean that the high speed criterion could be increased to 45mph. However, there are concerns that the use of a longer amber period could affect junction capacity at critical sites, and it may also worsen driver behaviour, especially at lower speed sites.

Variable amber periods have been suggested, but concerns about their safety have been expressed by a number of authors (e.g. Webster and Ellson, 1965, York and Al-Katib, 2000); drivers facing a shorter amber period than expected may be more likely to run the red.

Brownfield studied the effect on collisions of increased all-red periods both at night between 8pm and 6am (1977a) and during the full 24 hour period (1977b). The change was one or two seconds for one or more of the intergreen periods at each junction. The study of night time collisions (Brownfield, 1977a) was based on nine sites, selected on the basis of their poor night time collision record. It involved increasing the all-red period by two seconds at night. The result was a statistically significant 50% reduction in night time collisions. The study used night time collisions at all other signal-controlled junctions in the London boroughs where the treated junctions were located as a control. The method of site selection means that the observed reduction in collisions is likely to have been at least partly caused by RTM, and cannot therefore be reliably attributed to the increase in the all-red period.

The 24 hour period study (Brownfield, 1977b) was based on five sites, where at least one of the intergreens was increased by either one or two seconds. Sites were selected on the basis of their poor collision records and the results will therefore have been affected by RTM. Brownfield used the collisions at all other signal-controlled junctions in the London boroughs having the treated sites as a control. The result was an overall decrease of 24% in total collisions (statistically significant, but only at the 10% level) and a decrease of 82% in crossroad collisions (significant at the 5% level). Crossroad collisions are those involving vehicles from different roads and therefore include right angle collisions and also those involving turning vehicles. Again, the possibility of uncorrected RTM in this study means that the observed decreases in collisions cannot be reliably attributed to the increases in intergreen period.

The intergreen is typically extended where there is no special staging for right turning traffic, to allow drivers to clear the junction. In a cross-sectional study, Hall (1986) found that longer intergreen times were associated with higher collision rates for principal right turn collisions, in a model with flow, geometric and other signal control variables. Over the range from three to ten seconds, the collision rate more than doubled all other things being equal, suggesting that a separate right turn stage, or early cut-off or late release are safer methods of allowing for right turners. Hall found no effect of intergreens on right angle collisions when flow, geometric and other control variables were included in a model.

4.2.2.2 US

In the US, the intergreen period is termed the 'signal change interval' and comprises the amber period and any all-red period only, as there is no red and amber signal. Extending the signal change interval, generally the amber period (up to a maximum of about six seconds) is one of the main mitigation measures for red light running in the US, other than red light cameras. Currently, the US Federal Highway Administration MUTCD (FHWA, 2003) recommends a value of between three and six seconds, depending on site-specific conditions, but states that the value can be longer on higher speed approaches. Both the Institute of Transportation Engineers (ITE, 2003) and the Federal Highway Administration (FHWA, 2004) found that longer amber periods reduce collision rates marginally.

The effect of the signal change interval on safety has been investigated by various authors. Zador *et al* (1985) showed that amber periods that were too short were associated with increased collision risk. Both Bonneson and Zimmerman and Retting and Greene (1997) suggested increasing the length of amber to the value recommended by the Institute of Transportation Engineers (ITE, 2003) to decrease the likelihood of inadvertent red running. The Institute of Transport Engineers equation for determining the length of amber is based on the 85th percentile speed of vehicles approaching the junction, the deceleration rate and the gradient:

$$Y = T + V / (2d + 2gG)$$

where Y is the length of the amber

d = deceleration rate, taken as 10 ft/s^2

g = gravitational acceleration, 32.2 ft/s^2

G = approach grade, ft/ft

T = driver perception-reaction time, taken as 1.0 s

V = speed of vehicle approaching the intersection, typically the 85th percentile speed, ft/s

For level approaches, this gives amber lengths ranging from 3.2 seconds at 30 mph to 5.0 seconds at 55 mph.

Retting, Chapline and Williams (2002) assigned junctions at random to treatment and control groups. For the 51 junctions in the treatment group, they checked the signal change interval and extended it to the value recommended by the Institute of Transportation Engineers (ITE, 2003) wherever necessary. The result was statistically significant reductions of 12% in injury collisions and 37% in pedestrian and cyclist collisions. Interestingly there was a non statistically significant increase of 6% in right angle collisions. Retting *et al* conjectured that this was because the timing changes were relatively modest and may not have been large enough to prevent right angle collisions, whereas pedestrian collisions may have been reduced "because of the tendency of many pedestrians to begin crossing within one second of the start of the 'Walk' signal" (page 218). Increasing the clearance period may help to protect pedestrians from drivers who enter the junction on amber.

Bonneson and Zimmerman (2004c) found that increasing the length of amber by one second (provided that the total did not exceed 5.5 seconds) decreased red light violations by at least 50%. This benefit remained even though drivers adapted to the longer amber period and is in line with the finding that 80% of red-running is unintentional. Bonneson and Zimmerman used an empirical Bayes method to investigate two four-arm junctions in different towns, with one arm acting as a control and the remaining three as test sites at each junction. Increases in amber period varied between 0.6 and 1.5 seconds (mean of 0.8 seconds) and the mean reduction in red light running was 70%.

Most recently, Retting *et al* (2008) undertook a small study in Pennsylvania in the US in which the amber period at six approaches to two junctions was increased by about one second, followed one year later by the introduction of red light cameras. Three control sites in a different town were used. All the junctions, including the control sites, had high collision rates but the effect on safety was not investigated and red light violations are unlikely to be affected by RTM. Retting *et al* found that red light violations reduced by a statistically significant 36% about six weeks after the changes in the amber period (95% confidence interval –57% to -6%). However, the addition of red light cameras led to a further reduction in red light violations of 96% (95% confidence interval -97% to -93%), suggesting that the combined longer amber and cameras was highly successful.

An extension of the all-red period by one or two seconds has been recommended by various authors in the US (e.g. Kent *et al* 1995) as a means of reducing the number of collisions resulting from red-running. Datta *et al* (2000) found that an all-red period following an extended amber period reduced red light violations compared with the absence of an all-red period. The danger is that drivers become accustomed to the extended all red period and abuse it. Souleyrette *et al* (2004) in Minnesota undertook a comparison study, based on 38 junctions and 38 controls, and a before-and-after study based on 22 junctions and 47 controls. Even when variables such as flow were controlled for, they found that junctions with an all-red period were associated with higher collision rates. The before-and-after study indicated a benefit in the first year following the introduction of an all-red period, but this was not sustained. Souleyrette *et al* concluded that all-red periods should not be introduced at low speed urban junctions as there was no safety benefit and their use increased delay.

4.2.2.3 Other countries

Menzies and Nicholson (2003) in New Zealand developed a Monte Carlo simulation of the dilemma zone that did not fully replicate driver behaviour but allowed driver reaction time and braking to vary. A Monte Carlo simulation allows model parameters to have a distribution of values rather than a single fixed value and is aimed at determining which parameters are important in the modelled situation. Menzies and Nicholson concluded that extending the intergreen time beyond the local value of 4.8 seconds (3.8 seconds of amber and one second all-red time) gave little extra safety benefit, in that the model predicted that the probability of a conflict would decrease from an already low value of 0.01 to 0.0006. Such an increase would have the effect of increasing delay.

4.3 Flashing signal operation

A number of European countries and some US states replace the normal sequence of signals when traffic flows are reduced (at night and in some cases at weekends) with flashing signals that act as a warning of the presence of a junction. In some cases, the signals are turned off completely. Where the normal signals are switched off in the US, flashing amber signals (indicating proceed with caution) are used on the major road and flashing red signals (stop before proceeding) on the minor road, but red/red and amber/amber can also be used. In other countries amber/amber is used but there may be signs adjacent to the signal face, indicating whether or not there is right of way. Flashing signal operation is mostly used with fixed time rather than vehicle-actuated signals.

In general, flashing amber is popular with the general public as it reduces delay. However, it has been shown to increase right angle collisions both in the US (e.g. Akbar and Layton, 1986, Barbaresso, 1984, Mahalel *et al*, 1985, Polanis, 2002b and Srinivasan *et al*, 2008) and in Germany (Brilon, 2009). Akbar and Layton (1986) cited a report to the Federal Highway Administration recommending that flashing signals should not be used where the major road has a two-way flow exceeding 200 vehicles per hour, unless the ratio of major to minor road flow is greater than three. Kacir *et al* (1995) suggested a maximum of 500 vehicles per hour on the major road and 100 on the minor, with the major to minor flow ratio at least three. In Israel, Mahalel *et al* (1985) undertook a conflict study that compared data collected at two junctions under flashing and two under normal operation. They concluded that, with volumes up to 600 vehicles per hour flashing signal operation did not increase conflicts.

Following a Swedish study (Dinivietis, 1979) which compared flashing amber operation with full signals or lights switched off, flashing amber operation is no longer used in Scandinavia. Switching lights off was associated with fewer collisions, less energy consumption and lower operational costs than flashing operation, and was therefore preferable if full signals were not used. The authors did not report on how switching off the signals compared with full signals, or whether any direction had priority in this case. In the US, Barbaresso (1984) conducted a before-and-after study of six 4-arm junctions where night time flashing operation had been removed, with ten control sites that retained flashing operation. In addition, 82 sites with flashing operation were compared with 21 sites with full signal operation. Detailed results were not presented, but a figure of 97% for mean reduction in the right angle collision rate is quoted when flashing operation was replaced with full signals. Barbaresso found that alcohol impairment was significantly over-represented in collisions at junctions with flashing operation.

In Oregon, Akbar and Layton (1986) compared before-and-after night time collision rates (collisions per million entering vehicles) at 30 junctions where flashing operation (flashing amber on major roads and flashing red on the minor roads) was replaced with full signals. They found a statistically significant decrease in total (decrease in mean rate from 5.4 to 0.6) and right angle collision rates (decrease in mean rate from 3.3 to 0) where the ratio of major to minor road flow was between 2 and 4 (14 junctions). The severity rate also decreased when flashing operation was removed. Removal of flashing operations was most beneficial when both streets were two-way. There were no control sites. No details were given on site selection but no account was taken of RTM.

Gaberty and Barbaresso (1987) in a follow-up study to Barbaresso (1984) of 59 intersections in Oakland, found a statistically significant reduction in mean right angle collision frequency from 31 to 1.7 collisions per year at night at all 59 sites taken together, following conversion from flashing to normal operation, a reduction of 95%.

Control sites were not used. All sites had at least three years of 'before' data and one year of 'after' data.

Viney and Pretty (1988) in Brisbane reviewed flashing signal operation with a view to its possible use in Australia, but concluded that because of low operational benefits and increased collision risk, it would not be justified at most junctions.

In a more recent study, Polanis *et al* (2002b) used a before-and-after method to investigate 19 junctions in the city of Winston-Salem in the US and found that collisions reduced by 78% when flashing operation was replaced by normal signals, but they took no account of RTM and did not use control sites.

Using an empirical Bayes method, Srinivasan *et al* (2008) investigated 12 junctions also from Winston-Salem, with 75 control sites. They found that conversion from flashing operation to normal operation reduced total collisions by 35% (statistically significant at the 5% level, 95% confidence interval from -64% to -6%) and right angle collisions by 34% (statistically significant at the 10% level, 95% confidence interval from –70% to +2%).

In their meta-analysis, Elvik and Vaa (2004) found an increase of 55% in total collisions (95% confidence interval from -7% to +165%) when normal operation is replaced by flashing operation. The number of sites where it might be applied in London is limited as many city streets remain busy even at night.

4.4 Cycle time

The cycle time is set on the basis of vehicle and pedestrian delay. Reducing the cycle time will increase the number of times the signals change and therefore might be expected to increase collisions. In a cross-sectional study, Hall (1986) used the average number of cycles between 7am and 7pm on a weekday as a proxy for cycle time which covered both vehicle actuated (VA – see Section 4.6.1) and fixed time operation. Taking account of traffic flow and geometric / control variables, he found that both right angle collisions and total collisions increased with the number of cycles.

4.5 Right turn on red (or left turn on red in countries that drive on the left)

'Right turn on red' (RTOR), in which right turning vehicles may turn even on a red signal provided their route is clear of conflicting vehicles and pedestrians, is widely established in the US. It was initially introduced during the oil crisis in 1973 as an energy saving measure as it reduces both vehicle delay and emissions. Drivers are required to come to a complete stop before proceeding. However, Zegeer and Cynecki (1986) found that 57% of drivers fail to do so. RTOR is not permitted in the UK, the nearest equivalent being at some large signal-controlled junctions with a left turn only lane (with no signal head) where drivers must give way.

Hauer (2004) used RTOR as an illustration of how the absence of statistical significance in studies with low statistical power has been used to draw erroneous conclusions. Most early studies did not attain statistical significance at the 5% level because of small numbers of collisions, and therefore it was concluded that there was no evidence that RTOR was unsafe. However, almost all studies showed an increase in collisions following the introduction of RTOR. When RTOR had become almost universally established in the US, several larger data sets became available, statistical power increased, and the adverse effects of RTOR were established, namely an increase in collisions involving a right turning vehicle, especially with pedestrians and cyclists (Zador *et al*, 1982, Preusser *et al*, 1982, and Dussault, 1993– see also Section 6.2.5). Elvik and Vaa (2004) estimated in a meta-analysis that RTOR increased right turn collisions by 60% (95% confidence interval from 50% to 70%).

A meta-analysis was undertaken by Dussault (1993) who included only before-and-after studies that used non-right turn collisions at the test sites as controls. He found statistically significant increases of 44% in pedestrian collisions (based on 8 US states), 59% for cyclists (study by Preusser *et al*, 1982, based on 3 states, and re-analysed to use non-right turn collisions as controls) and 9% for total right turn collisions (based on 17 states). The result for total right turn collisions included collisions involving only damage to property, which form the majority of vehicle collisions since speeds are low. Confidence intervals were not quoted. Dussault commented that the fuel saving usually quoted was only 0.15% of the total used on all roads, and therefore RTOR could not be justified on economic grounds.

A more recent study of 36 mainly three-arm signal-controlled junctions in Singapore by Wong *et al* (2004) of left turn on red (the equivalent of RTOR for countries that drive on the left). The junctions were selected as having a low collision frequency prior to conversion, Wong *et al* found a substantial reduction in delay accompanied by an increase of 17% in total collisions but a small reduction in pedestrian collisions. Controls were not used and RTM was not taken into account.

4.6 Type of signal control

4.6.1 Vehicle Actuation (VA)

Vehicle actuation is probably the most common form of control for isolated junctions. Full details are given in DfT Traffic Advisory Leaflet 1/06. Vehicles approaching a red or amber signal will be detected and the demand registered. A green signal may be extended if approaching vehicles are detected up to a pre-set maximum.

The basic method of detection is known as System D and was developed during the 1960s. Loop detectors are usually placed at 29m, 25m and 12m. The first demands the green if the signals are on red and otherwise extends it, whilst the other two generally extend the green. Extensions are often set to 1.6 seconds but can be varied from that.

Different settings apply on ‘high speed’ roads, that is, where the 85th percentile approach speeds exceed 35mph (see Section 5.2.2.1).

4.6.2 Maximum timings under VA control

There are two types of maxima in common use at mid-block (standalone) pedestrian crossings, the ‘normal’ maximum and ‘pre-timed’ maximum. With the former, the maximum timer starts when a pedestrian demand is registered, which means the signals will either change when the next large gap in the traffic occurs, or when that timer reaches its maximum. The pedestrian is likely to have to wait for the signals to change in this case.

With pre-timed maximum, the maximum timer starts as soon as the signals return to green to traffic. This ensures traffic gets a minimum green, but also means that once the green has been running for the maximum, a pedestrian demand can be serviced instantly. Sometimes a delay of between one and three seconds is introduced before the demand is serviced.

A pre-timed maximum can only be used at sites classified as ‘low speed’ (i.e. 85th percentile speed up to 35mph), as it presents a red to traffic without any consideration of where the vehicle is on the approach. At higher speeds, the driver may be caught in the ‘dilemma zone’ where they could find it difficult to stop before the onset of the red signal, or have to brake uncomfortably hard in order to stop.

At crossings on ‘high speed’ roads, where the 85th percentile speed exceeds 35mph, the all-red period is fixed at three seconds. On other roads, the all-red period will normally be one second for a gap change and one, two or three seconds for a forced change.

4.6.3 Microprocessor Optimised Vehicle Actuation (MOVA)

MOVA (Microprocessor Optimised Vehicle Actuation) is a well-established traffic signal control strategy that was researched and developed on behalf of the Government by the then Transport and Road Research Laboratory (TRRL) in the 1980s to replace Vehicle Actuated (VA) System D. Considerable research was carried out to develop MOVA (Vincent and Peirce, 1988) culminating in the 20-site trial in 1989 (Peirce and Webb, 1990). Research and development, funded by the Department for Transport and the Transport Research Laboratory, has continued and one of the recent outcomes is the development of Compact MOVA (Henderson *et al*, 2005). MOVA is extremely effective at all types of isolated signal control junctions. It can also be applied effectively as 'linked' MOVA in small networks, especially signalised roundabouts. Not only is MOVA effective at minimising delay or maximising capacity (whichever is appropriate at the time) research has shown it to be as safe as VA System D with Speed Assessment or Speed Discrimination Equipment (SA/SDE), with a small safety improvement when the MOVA configuration data contains no serious errors (Crabtree and Kennedy, 2005). The safety improvement was based on 17 sites and used generalised linear modelling to test the effect of conversion to MOVA, finding a statistically significant reduction of 26% in junction collisions. Since MOVA was not installed for safety reasons, no allowance was made for RTM.

The effectiveness of MOVA can be attributed to the application of fundamental traffic theory and the strategic placement of vehicle detection. Operationally, this manifests itself as an ultra-responsive strategy, dealing with the prevailing traffic conditions rapidly and effectively. In the UK, estimates suggest that at the end of 2008 there were approximately 3,000 sites equipped with MOVA (including linked MOVA implementations) with more than 250 per year being added to that.

Full MOVA implementation employs two sets of detectors for each lane; an 'IN'-detector positioned approximately 8 seconds travel time from the stop line and an 'X'-detector placed approximately 3.5 seconds travel time from the stop line. The travel time is based on what is known in MOVA as the cruise speed (CSPEED) which is approximately the 10^{th} - 15^{th} percentile speed of vehicles approaching the junction after any queue has cleared. IN-detectors are still used in the majority of installations. However, in urban areas, the IN-detector requires additional ducting to connect it to the signal controller. This often results in extra costs due to the need to reinstate pavements and avoid existing underground services. To encourage the use of MOVA in urban areas, Compact MOVA was developed to allow selected approaches to operate without IN-detectors. In terms of ducting and detector installation, the requirements are similar to VA System D which means existing duct work can be re-used. A recent study (Crabtree and Wood, 2009) found that pedestrian delay with Compact MOVA on low speed approaches was similar to that with VA and that provided the X-detectors are not placed too close to the stop line, red running was significantly reduced.

As well as being able to operate efficiently at junctions, both standard and Compact MOVA work extremely well at stand-alone signal controlled crossings. Whereas the green-to-traffic too easily extends to the maximum time under VA System D, MOVA finds appropriate gaps in the approaching flow far more readily. This means that, with MOVA control, the pedestrian stage will appear more frequently before the maximum time is reached. Furthermore, pedestrians are unlikely to be able to cross in gaps before the change. (The benefits mainly accrue to pedestrians, though MOVA will deal with vehicles at least as well as VA.) Compact MOVA will be even more inclined to service the pedestrian demand compared with standard MOVA (see Henderson *et al*, 2005) and is appropriate for use in urban areas.

4.6.4 Urban Traffic Control (UTC) / SCOOT

Moore and Lowrie (1976) in Australia reported a large study based on 15,000 collisions (including damage-only) that showed a reduction of 20% in total collisions following signal coordination, the major improvements being in right angle and pedestrian collisions. Only the abstract of this document was retrieved so further details are not available. In their meta-analysis, Elvik and Vaa (2004) reported a reduction in total collisions of 19% (95% confidence interval from -22% to -15%) when signals were coordinated.

Hunt *et al* (1990) undertook a before-and-after study of safety under SCOOT of six areas with controls. Some areas were under UTC and in others signals were uncoordinated prior to conversion to SCOOT control. There were three years of before and after data. Changes in casualty reporting procedures, over the period of the study made it difficult to establish time trends in accident and casualty frequency. There was no clear evidence of any change in accident frequency following the installation of SCOOT with some areas showing an increase and others a decrease, although there were statistically significant decreases of 22% (95% confidence interval from -38% to -1%) and 30% (95% confidence interval from -41% to -16%) in total accidents in two of the six areas studied. Under fixed time Urban Traffic Control (UTC), the pedestrian signal operates only at a fixed time in the cycle and the cycle time is optimized for vehicles for the set of linked signals. Increasing the extent of linked signals in a network can minimise vehicle delay over a larger area. There can therefore be considerable delays to pedestrians unless the crossing can be double cycled (allowing the pedestrian green to appear twice in every cycle), where it is not possible to reduce the cycle time of the linked signals.

Where there is minimal benefit from linking signals, for example where adjacent junctions are well separated, it may be possible to decouple the pedestrian crossing from the UTC system during the off-peak period.

There does not appear to have been much investigation of pedestrian safety at mid-block crossings under linked signals. Hunt *et al* (1987) concluded that pedestrian delay was increased under TRANSYT and SCOOT. A second study by Hunt *et al (*1990) found no significant differences in pedestrian safety at mid-block crossings under SCOOT. It is often stated that if pedestrians have to wait more than 30 seconds to cross, they become impatient (e.g. Hunt and Lyons, 1997). However, if the road is busy, as is usually the case where UTC or SCOOT operates, pedestrians will be likely to wait for the lights to change, or at least until the end of the platoon of vehicles has passed.

4.6.5 Separate right turn stage

The safest option for right turners is to have a separate stage, so that right turners are held on red whilst the opposing ahead and left turning traffic has a green signal, so that there is no need for turning traffic to look for gaps in oncoming traffic. Hall (1986) found using cross-sectional models of 4-arm signal-controlled junctions including flow, geometric and other signal control variables that a separate right turn stage was associated with a reduction of 90% in right turn collisions (95% confidence interval from -97% to -69%).

Simmonds (1987) undertook a before-and-after study into the effect of various arrangements for right turners at signal-controlled junction in London and recorded a 70% reduction in right turn collisions, statistically significant at the 0.1% level, when two stages were replaced by split phasing (in which all traffic movements from one direction were followed by all movements from the opposite direction, on two of the four approaches). No allowance was made for RTM, although there was scope for RTM to affect the results since site selection was on the basis of available sites where the intervention had taken place, and control sites were not used.

In the US, left turners (the equivalent of right turners in the UK) may have a separate stage, known as an 'exclusive left turn phase'. The situation is complicated at junctions where there can be conflicting pedestrians so that 'permissive left turn phases' involve the drivers giving way firstly to oncoming traffic and then to pedestrians. A further option is protected-permissive left turns, which is a combination of permissive and protected modes. In this case, left turners have right of way during the protected left turn phase but can also complete their turn permissively when the adjacent through movement has green. Adaptive permissive/protected left turn phasing can be protected or permissive protected depending on the time of day.

Elvik and Vaa (2004) reported that a separate left turn stage (in countries that drive on the left) reduced left turn collisions by 58%, with a 95% confidence interval from -64% to -50%.

The problem with a separate stage is that it inevitably increases the cycle time and thus delay to vehicles and to pedestrians. Junction geometry or capacity may mean that a separate right turn stage is not possible.

4.6.6 Early cut-off / late release

Where there is no separate stage for right turners, motorists sometimes have a window at either the start (late release) or end (early cut-off) of the green period when the opposing ahead and left turn traffic is stopped, in addition to seeking gaps in the opposing traffic. If there are hooking turns (i.e. there are arrows on the road to indicate that right turning drivers must pass offside to offside), drivers must also give way to opposing right turners. Using cross-sectional models containing flow, geometry and other signal control variables, Hall (1986), found that late release was associated with a reduction of 68% in collisions (95% confidence interval from -96% to -51%) and early cut-off with a reduction of 30% (95% confidence interval from -65% to -15%) in principal right turn collisions.

Simmonds (1987) reported a statistically significant reduction (at the 10% level) of 36% in right turn collisions and 24% in total collisions following the introduction of early cut-off. The conversion of sites with early cut-off to right turn held on red reduced right turn collisions by 70% (statistically significant at the 0.1% level), with a corresponding non-significant decrease in total collisions of 19%. The downside with 'right turn held on red' was that pedestrian collisions appeared to have been adversely affected, with a statistically significant increase of 58% (at the 10% level), and no reason was determined for this. No allowance was made for RTM and there were no control sites. Confidence intervals were not quoted.

4.6.7 Closely spaced secondary signals

Lalani (1976) in a report to the London Accident Analysis Unit found that moving the secondary signal from the far side of the junction to the same side as the primary signals reduced principal right turn collisions (in which a right turning vehicle is hit by an oncoming vehicle) by 46% and this reduction was significant at the 10% level. The change (based on 9 sites) also reduced total collisions (by 29%, significant at the 5% level) and pedestrian collisions (by 30%, although this was not statistically significant). The effect of the change was intended to force drivers and pedestrians to use their judgement rather than relying solely on the signal.

A follow-up study (Lalani, 1977) extended the original 9 sites to 20. The results were more disappointing as the reduction in principal right turn collisions was significant only when collisions involving powered two-wheelers, who figure highly in this type of collision, were excluded. The result was a 36% reduction, significant at the 5% level. No other results were statistically significant. A number of the sites were selected on the basis of their poor collision record and both studies are therefore subject to regression to the mean. No control sites were used.

4.7 Use of LED signals

LED signals have generally been introduced in order to save energy (estimated as a 70% reduction by Clarke, 2007). They could potentially be a safety feature if they were brighter and hence more conspicuous than conventional signals. Alternatively if the signal head was less visible, the result could be an increase in collisions. Only one study was traced that addressed these issues and that is now outdated because the technology has changed and improved in recent years (Sullivan, 1999). Sullivan reported that when LEDs were first developed, red LEDs were found to provide only 50 to 75% of the specified luminance required in the US and although it is difficult to distinguish the difference, there was concern that the intensity might reduce over time. The interim specification was therefore changed to require that "LED modules provide a maintained intensity of at least 85 per cent of the intensity of a new incandescent indication" (page 2). Unfortunately, the measures of luminance used in the US and the UK are not directly comparable, and it is not clear which part of the US specification Sullivan was referring to. No studies were identified that reported on safety or driver behaviour.

More recent generation LED lamps are considered to have brighter illumination, implying greater conspicuity, and can display multiple colours in the same lamp. LEDs last much longer than traditional lamps and bulb failure occurs slowly over time and to individual LEDs, removing the need for urgent replacement. One potential disadvantage of the fact that LEDs fade rather than failing catastrophically is that they may be left to operate after they should have been replaced.

4.8 Summary of Section 4

- Little research was found regarding the effect of geometric layout on safety
- Intergreen periods in the UK were set many years ago; recent research confirmed that the amber period should remain at three seconds and the starting amber (red with amber) period at two seconds
- All-red periods appear to be beneficial to safety if kept short (one or two seconds). Longer all-red periods have been found to be associated with increased principal right turn collisions
- In the US, amber periods of between three and six seconds are used, with longer periods at junctions on high speed roads. Increasing amber periods to the value recommended by the Institute of Transport Engineers reduces collisions. Periods that are shorter than this recommended value may lead to increased collisions. However, intergreen periods that are too long may also increase collisions.
- The use of flashing amber rather than the full signal sequence at night generally increases collisions
- Shorter cycle times benefit pedestrians and improve pedestrian compliance, but provide increased opportunities for red running
- RTOR (or left turn on red where driving is on the left) generally increases pedestrian and cycle collisions but reduces vehicle delay and emissions; it is widely used in countries other than the UK
- Although the type of signal control is generally selected on delay grounds, it can have an effect on safety
- A separate right turn stage substantially reduces principal right turn collisions; the use of early cut-off or late release is less effective but still gives a good safety benefit. However, a separate right turn stage implies a corresponding reallocation of cycle time and this might increase delay for vehicles and pedestrians. Junction geometry or capacity may mean that a separate right turn stage is not possible.

5 Red light running

5.1 Prevalence of red light running

Red light running occurs when a vehicle fails to stop when the signal changes to amber and subsequently passes the stop line when the red light is displayed, continuing into the junction. Red light runners will be in conflict with vehicles on another arm of the junction or the pedestrian phase. Red light running can lead to right angle collisions. It can also affect principal right turn collisions where there is no separate right turn stage as in this case right turning drivers are likely to still be turning when the signals change having been prevented from doing so by oncoming traffic. With the possible exception of pedestrian behaviour, red light running formed the largest set of literature identified in this review.

Red light running can be inadvertent when drivers fail to see the signal, for example through inattention or sun dazzle, or deliberate, when drivers pass the lights at the end of the amber period, in some cases speeding up to do so. Red running due to drivers not paying attention can potentially be reduced by increasing the conspicuity of the signals or by the use of warning signs to alert these drivers to the presence of signals. The risk of prosecution from red light cameras may reduce the number of drivers trying to pass through the junction at the end of the amber period. At high speed junctions, there is a third category of drivers who may be unsure whether they have time to stop or should continue and risk running a red light (the 'dilemma zone', see Section 5.2).

Bonneson and Zimmerman (2004a and 2006) listed a number of factors that affect red light running, for example:

- Traffic volume
- Cycle time
- Delay
- Approach speed
- Gradient
- Whether in a UTC system

As might be expected, the prevalence of red light running increases with traffic volume, with the number of cycles per hour, and with delay, which may cause drivers to become impatient. Where signals are coordinated, vehicles at the end of the platoon may be inclined to follow the vehicle in front. Higher approach speeds and/or downhill gradients are likely to make it more difficult for drivers to stop.

Kent *et al* (1995) made some interesting observations concerning the characteristics of red light running. They found that right turn lanes tended to have higher rates than through lanes, particularly on single carriageway roads, although this may have been an artefact of the data, as dual carriageway roads may have longer amber periods and better right turn provision. Time of day appeared to have no effect and most red running occurred during the all-red period.

Retting, Ulmer and Williams (1999) investigated the characteristics of red light running collisions in the US. They found that red light runners tended to be younger than 30 and have prior speeding or drink driving convictions or invalid licences. Night time collisions involving red light runners were more likely to involve young male drivers with poor driving records and alcohol impairment.

Bonneson *et al* (2002) listed the factors that contribute to a driver's decision to run the red:

- Travel time to stop line

- Speed of travel
- Gradient
- Length of amber period
- Whether being closely followed
- Level of flow on cross street
- Threat of enforcement
- Threat of rear end collision
- Length of expected delay

Heavy vehicles are more likely to run the red than are light vehicles, probably because of longer stopping distances.

Several studies have evaluated the distribution of red-running after the start of red. Bonneson and Zimmerman (2004b) in the US found that 98% of red-running occurs within four seconds of the start of the red signal, with the median entry time less than 0.5 seconds. Inadvertent red-running may occur further into the red period. The same authors in a parallel paper (2004c) reviewed research findings and concluded that it is mainly principal right turn collisions that occur during the first few seconds of red and right angle collisions thereafter.

The main potential mitigation measure for red-running - the use of red light cameras - is one of the most researched topics on signal safety (see Section 5.3). Other mitigation measures are discussed in Sections 5.2 to 5.4.

Approximately eight of the reports reviewed investigated compliance compared with 20 on safety. However, it is likely that improving compliance with red lights for motorists will have an important link to safety.

5.2 Dilemma zone

5.2.1 Background

When approaching signals at the end of green, drivers have to decide whether to stop or to continue. The 'dilemma zone' is the distance over which there is no clear-cut decision. Depending on the vehicle speed and the distance from the junction, the decision can be marginal. Stopping may involve hard braking and continuing may risk running the red light. The decision will be a function of driver and vehicle characteristics; for example, heavy goods vehicles have longer stopping distances which affects both the decision itself and the extent of the dilemma zone (see e.g. Zimmerman, 2007, Maxwell and Wood, 2006). The driver who continues may be at risk of a collision in the centre of the junction (and possible prosecution) whilst the driver who chooses to stop may be at risk of a rear end collision if the driver behind makes the opposite decision or if braking results in loss of control. The dilemma zone is important mainly at junctions on high speed roads where vehicles have greater stopping distances.

Two major studies on the dilemma zone were undertaken more than 30 years ago by Webster and Ellson (1965) in the UK and by Zegeer (1977) in the US. These studies were reviewed by Maxwell and Wood (2006) and by Zhang *et al* (2005), who pointed out that the American definition of the dilemma zone differs from the UK one. In the UK, the dilemma zone is based on the distance that can be covered without running the red light and on the stopping distance estimated using 'acceptable' deceleration and the equations of motion (e.g. Robertson, 1992). In other words, in the dilemma zone, the driver can neither stop safely with comfortable deceleration nor clear the stop line within the amber duration.

The UK dilemma zone boundaries can be determined either from observations of drivers' decisions or from theoretical models based on a driver's perceived travel time to the stop line.

In the US, the definition of the dilemma zone is based on the observed probability of stopping, usually the distance within which, at the onset of amber, 90% of drivers stop, typically five to six seconds from the stop line, and 10% of drivers stop, typically two to three seconds from the stop line. The US dilemma zone is sometimes called the decision zone, since not all drivers are in a dilemma, for example a driver with a powerful car who decides to go ahead may successfully clear the stop line before the onset of red.

The UK Speed Assessment (SA) and Speed Discrimination Equipment (SD) strategies are based on a test track experiment at TRL undertaken by Webster and Ellson (1965) giving the distance in which 90% of drivers could stop comfortably. In view of the improvement to vehicles in the time that has elapsed since that study, the figures were recently reviewed for DfT by Maxwell and Wood (2006). They concluded that there was no reason to change the current strategies.

Webster and Ellson (1965) found in the track trials that 90% of drivers have approximately a one second reaction time and a mean deceleration of 3.6 m/s^2 (Baguley and Ray, 1989). However, the work by Baguley and Ray and by Maxwell and Wood (2006) suggests that drivers were not prepared to use decelerations as high as this. Instead, they based their decision on their expected journey time to the stop line at the onset of amber. Maxwell and Wood found that about three-quarters of drivers who would take three seconds travel time to reach the stop line with no change in speed continued through the junction.

5.2.2 UK strategies for dilemma zone protection

One method of reducing the 'dilemma zone' is to extend the green period in response to an approaching vehicle in order to avoid presenting a driver in the dilemma zone with a red signal. This practice is well-established in the UK, following the research by Webster and Ellson (2005). Current strategies are Speed Assessment SA, Speed Discrimination SD and MOVA (see Sections 5.2.2.1 and 5.2.2.2).

5.2.2.1 SA/SDE

Advice on the use of speed assessment or speed discrimination equipment (SA/SDE) to support vehicle actuation (VA) at signal-controlled junctions or mid-block crossings on high speed roads (where the 85^{th} percentile speed on the approach exceeds 35mph) is given in Traffic Advisory Leaflet TAL 02/03 (Department for Transport, 2003). The principle of the SA/SDE strategy is to avoid presenting an amber signal to a driver when the choice between braking sharply and continuing, with the risk of crossing the stop line during red, is not clear cut. SA/SDE achieves this by measuring vehicle speeds and extending the green to avoid catching drivers in the dilemma zone. Green extensions continue where necessary up to a pre-set maximum. If the maximum is reached, the signals change, and, at junctions, the intergreen is extended by two seconds. At mid-block crossings on high speed roads, the all-red period is normally set to three seconds (whether or not the green to traffic ends on a maximum).

This means that there are two ways in which the change from green to amber can occur under SA/SDE:

- A gap change when there is a sufficiently large gap between successive vehicles to safely change the lights
- A maximum change when there are continuous calls to extend the green and the predefined maximum green is reached.

When a maximum change occurs, at least one driver will be caught in the dilemma zone. To mitigate the risk, SA/SDE delays the next green by an extra two seconds to give time for any red runners to clear the junction. The probability of a maximum change increases sharply with flow for a given speed, and also with speed.

Since the SA/SDE strategy is employed in combination with D-system vehicle actuation (VA) (see Section 4.6.1), the propensity for the green to be extended to maximum is increased. In fact it becomes quite difficult for the signals to change in response to a gap in the traffic. Pedestrians wanting to cross, especially at a mid-block crossing, often have to wait until the maximum green is reached before being serviced. The more able-bodied will often find it possible to cross before the signals change because the gap needed for a gap change is about six seconds in many cases – long enough to cross a two lane road safely at normal walking pace.

If a detector is faulty, the vehicle green will continue until the pre-set maximum, so that pedestrians may have to wait unnecessarily, and may be tempted to cross in gaps. It is therefore important to ensure that the detectors are working so that vehicle speeds are measured accurately.

Baguley and Ray (1989) tested the effect of disconnecting the SDE equipment for a period of two weeks at seven signal-controlled junctions on high speed dual-carriageway roads, five having speed limits of 70mph. They did not see any change in the level of conflicts, but recorded a statistically significant increase in the incidence of heavy braking and red-running. However, even with SDE, they noted that a large number of drivers were caught in the dilemma zone due to maximum green times and other drivers who could have comfortably stopped, elected to continue.

5.2.2.2 MOVA

MOVA does not explicitly try to avoid vehicles being caught in the dilemma zone, but its delay minimisation logic tends to avoid ending the green when vehicles are in this zone. There is an overall small safety benefit in using MOVA, in addition to reduced red-running (see Section 4.6.3)

5.2.2.3 UTC / SCOOT

Neither UTC nor SCOOT responds to individual vehicles and will take no action if vehicles arrive at the traffic signals in the dilemma zone. In any case SCOOT's detectors are at the upstream end on the link which would be unsuitable for detecting vehicles in the dilemma zone. However, both UTC and SCOOT attempt to coordinate traffic and therefore for internal links within a SCOOT network it is not likely that vehicles would arrive in the dilemma zone. For external links where arrivals are random then it is possible that vehicles will arrive in the dilemma zone. It would require additional detection and logic if any action were to be taken.

5.2.3 Strategies in other countries for dilemma zone protection

In the US, Zegeer (1977) found a reduction in collisions with the use of green extensions, similar to SA/SDE.

More recently, 'dynamic dilemma zone protection systems', similar to MOVA, have been developed. In Europe, these are LHOVRA (Peterson et al, 1986, and Peterson, 2003) and SOS (Kronberg and Davidsson, 1997), which stands for Self Optimising Signal Control. In the US, the D-CS or Detection Control System (e.g. Zimmerman and Bonneson, 2004) is used. All of these methods attempt to allocate dilemma zone protection on the basis of vehicle needs at a particular time.

D-CS measures the speed of each arriving vehicle at a distance of 800 ft to 1,000 ft (244m to 305m) upstream of the intersection and predicts the arrival time at the stop line and its individual dilemma zone. The green phase is ended when the number of vehicles in individual dilemma zones is at a minimum. Zimmerman and Bonneson (2004) developed a model for determining the number of vehicles caught in the dilemma zone at the onset of amber. They point out that this could be used as a measure of the success of dilemma zone protection (though further research would be required for it to be an indicator of safety).

D-CS features a two-stage operating scheme specifically to reduce the occurrence of the green running to maximum. In Stage 1, the green phase cannot end if a vehicle is in the dilemma zone. After a predetermined number of seconds following the first call on a conflicting phase, D-CS changes to Stage 2 operation to avoid running to maximum. In Stage 2, D-CS will allow the green phase to end with up to one passenger car per lane in the dilemma zone. However, D-CS also attempts to reduce the total number of vehicles in the dilemma zone, in other words to find a time in the future that minimises the number of vehicles in the dilemma zone.

Alternative strategies to reduce the dilemma zone include those that address the reduction of red-running in general, particularly extending the amber period or all-red periods and/or using red light cameras.

5.3 Red light cameras

5.3.1 Background

Red light cameras work by photographing the vehicle running the red light. They are connected to the signal system and to sensors buried in the road and are triggered when a vehicle passes over the sensors faster than a preset minimum speed at a time which exceeds a specified minimum ‘grace period’ after the signal has turned red. A second photo is taken of the violating vehicle in the junction. The camera records the date, time of day, time elapsed since the start of the red and the speed of the vehicle. There are currently 300 red light camera sites in London. In the UK, tickets are issued by post to vehicle owners. Red light cameras were first developed in the 1970s but were not used in the UK or the US until the 1990s. In the UK, in order to try to engage public support, safety camera guidelines (no longer insisted upon – see DfT Circular 1/07) required that a minimum of two red light related collisions involving a fatal or serious injury occurred at a junction over three years before a red light camera could be installed.

There is a general consensus that cameras improve compliance and reduce collisions associated with red-running, but a number of studies have found an increase in rear shunt collisions. Studies varied as to whether they looked at compliance or safety or both and in their extent and their statistical treatment. Small numbers of sites mean that results are rarely statistically significant. Control sites are not always used, particularly when only compliance is considered. It should also be noted that, as with all interventions, other measures are generally installed at the same time as red light cameras, making it difficult to assess the effect of cameras alone.

Where safety is considered, RTM is an issue, as it is understandable to target resources where they appear to be most needed and therefore the selection of sites for treatment will generally be biased. Spillover is defined as the effect of red light cameras on nearby junctions (other than the ones actually treated); because of area-wide publicity, drivers may have seen warning signs and may be uncertain as to which junctions have cameras. This effect was not fully recognised in the earlier studies and therefore some studies used other approaches at the treated junctions as control sites; this was not necessarily a problem if, for example, signs were used only on the approaches with cameras. Whereas RTM may lead to an over-estimate of the effectiveness of cameras, spillover tends to lead to an underestimate, if unaccounted for.

In some studies (e.g. Retting *et al*, 1999a and b), a distinction is made between control sites which were unlikely to have been subject to the spillover effect and ‘non-camera’ sites, either at the same junction but without a camera or in the same locality and therefore subject to signage and/or publicity. Non-camera sites that were used as control sites are likely to have been affected by spillover.

5.3.2 *Effect on driver behaviour*

It is not always possible to say whether or not violations have been reduced by the introduction of a camera as this type of data is not routinely collected before cameras are introduced, although it may be collected after the cameras are in place but not activated (e.g. Maccubbin *et al*, 2001). Maccubbin *et al* also noted that although there is a substantial body of literature suggesting that the prevalence of red light running is reduced by between 20% and 87% following the implementation of camera enforcement it is not always clear whether cameras continued to be effective, for example after a year or more.

The main studies identified and included in this review on the effect of red light cameras on driver violations are detailed in Table 5.

Chin (1989) in Singapore evaluated the proportion of drivers who ran the red light at 23 camera sites (nine junctions), 20 non-camera sites (approaches at the same junctions) and 14 control sites (at five different junctions). Some reviews e.g. Retting *et al* (2003) have used Chin's data to calculate changes in the mean values and quote statistically significant decreases of 42% in red running at the camera sites and 27% at the non-camera sites, compared with an increase of 17% at the control sites. Chin, however, regressed the before and after red running rates and found a statistically significant reduction of approximately 40% at both camera and non-camera sites (which were almost identical) and a small non-significant increase of 6% at the control sites. The similar results at camera and non-camera sites suggests a substantial spillover effect, probably due to confusion as to whether or not the non-camera sites had cameras, as mentioned above. Chin's 'after' survey was undertaken only one month after the red light camera installation and it is not known whether these positive results persisted.

Thomson *et al* (1989) in the UK considered only two junctions and did not use control sites or non-camera sites. They found a reduction of 21% in red-running at one junction, but an increase of 13% at the other; however, neither of these changes was statistically significant. MVA (1995) investigated six camera sites plus non-camera approaches at the same sites and found a 69% reduction in red running when the cameras were fully operational. The reduction of 37% at the non-camera sites indicates a spillover effect. MVA also found that although red-running was reduced when cameras were introduced, there was no change in the violations that occurred more than five seconds into the red, suggesting that it is deliberate red-running when the lights have just turned to red that is most affected by the installation of cameras, rather than accidental red-running.

Kent *et al* (1995) investigated driver behaviour at 24 approaches with red light cameras, 24 non camera approaches at camera sites with signs and 24 approaches at camera sites with no signs. The results are therefore liable to spillover and it is unsurprising that Kent *et al* observed little difference between the three site types. Two studies were undertaken in the US by Retting, Williams, Farmer and Feldman (1999a, 1999b) in Fairfax and Oxnard, California. They observed drivers at several camera sites, several non-camera sites in the same town to test for any spillover effect and two control sites in different towns. The study in Fairfax was the only one traced where compliance was investigated a full year after camera installation; this study demonstrated an improved effect after 12 months (44%) compared with after three months (7%), although the finding at 3 months was not statistically significant. The reduction of 40% in violations per 10,000 vehicles at camera sites in Oxnard was statistically significant compared to the reduction at the control sites. Retting *et al* also demonstrated a considerable spillover effect in both studies, the reduction at non-camera sites being similar to that at camera sites.

In Canada, Chen *et al* (2001) considered two sites with signage but not cameras relative to two controls in a different town. The study found that the reduction in violations was a statistically significant 69% after one month but that this had dropped to a non-significant 38% after six months.

Recently, Retting *et al* (2008) undertook a study on six approaches to two junctions in the US, and three control sites in a different town. The amber period was increased by about one second giving a reduction of 36% in red running (see Section 4.2.2.2). One year later, red light cameras were introduced, giving a further reduction of 96% (with a 95% confidence interval from -97% to -93%) in red running at six approaches to two junctions, with three control sites in a different town. Aeron-Thomas and Hess (2005) decided to exclude from their meta-analysis all studies that undertook the after survey within 12 months or that did not use control sites; of the studies listed in Table 5, only the one by Retting *et al* (1999a) in Fairfax was retained. As stated in Section 2.3, although desirable, a full year seems excessive as the minimum requirement and was achieved by very few studies, with three to six months a more realistic timescale for a behavioural change. Clearly the likelihood of being prosecuted, and whether there is simply a fine or penalty points on a licence may affect these figures, but this information was not generally provided in the studies reviewed.

Table 5: Effect of red light cameras on driver behaviour (see Retting, Ferguson and Hakkert, 2003)

Study	Country	Number of sites	Percentage change in red light violations	When measured
Chin (1989)	Singapore	23 camera approaches 20 non-camera approaches 14 control sites	-42 -27 +17 based on changes in mean values (see text)	1 month after
Thompson *et al* (1989)	UK	camera site 1 camera site 2	-22 +13	3 months after
MVA (1995)	Scotland	6 camera sites 6 non-camera sites	-69 -37	2 years after
Retting *et al* (1999a)	Fairfax, US	5 camera sites 2 non-camera sites 2 control sites	-7 and -44 -14 and -34 +1 and +5	3 and 12 months after
Retting *et al* (1999b)	Oxnard, US	9 camera sites 3 non-camera sites 2 control sites	-40 -50 -4	3 to 4 months after
Chen *et al* (2001)	Canada	2 camera sites relative to 2 control sites	-69 and -38	1 and 6 months after
Retting *et al* (2008)	Pennsylvania, USA	6 camera sites 3 control sites	-96 +0.5	7 months after

Note: Non-camera sites are sites in the same locality that do not have cameras but may have been affected by spillover, whereas control sites are less likely to have been affected by the presence of cameras

5.3.3 *Effect of red light cameras on safety*

5.3.3.1 Major studies

Much of the literature is from overseas and therefore may not be directly applicable to the UK. In particular, the propensity of drivers to run the red may be different and penalties for doing so also differ. This will in turn affect collisions in that if compliance with signals is good, there may be fewer rear shunts than in countries where compliance is poor.

Where safety is considered, studies varied as to whether they looked at all junction collisions or only at those involving red-running. The definition of the latter is not always clear from the text, and may also have been unclear from the collision data. Table 6 summarises the results for the more major studies; the term 'right angle collisions' in this context does not necessarily exclude collisions involving a turning vehicle. Studies traced in the literature survey but not listed in Table 6 were excluded for a number of reasons, for example, no control sites, insufficient data, or no separation of injury collisions and those that involve only damage to property. They are discussed in Section 5.3.3.2.

In Melbourne in Australia, South *et al* (1988) found a statistically significant reduction of 32% (95% confidence interval from -62% to -2%) in right angle collisions, although the statistical significance was later challenged by Andreassen (1995), and non statistically significant changes in total collisions (increase of 7%) and in rear shunts not involving a turning vehicle (increase of 31%) were reported. The study was based on cameras rotated round 46 junctions with 46 control sites with a five year before and a two year after period.

Also in Australia, Hillier (1993) in Sydney studied six cameras rotated round 16 junctions, with 16 controls. He found that overall, there was a reduction of 50% in right angle and principal right turn collisions, but an increase of between 25% and 60% in rear shunts, including collisions involving property damage only. There were some problems with the controls as some sites had other changes. Injury collisions reduced by 26% (95% confidence interval from -55% to -3%).

Mann *et al* (1994) compared eight camera sites with 14 control sites and found a reduction of 26% in right angle collisions (95% confidence interval from -47% to +7%) in Adelaide, Australia. There was a five year before and after period. Both camera and control sites were selected because they had a poor collision record and high flows. Thus there was some allowance for RTM, but there are doubts over the control sites as other changes appeared to occur, for example to intergreens.

In Singapore, Ng *et al* (1997) compared 42 camera sites with 42 control sites with similar collision histories, thus making some allowance for RTM. They found a 9% reduction in total collisions (95% confidence interval from -26% to +8%), a 10% reduction in right angle collisions (95% confidence interval from -31% to +11%) and a 6% increase in rear shunts (95% confidence interval from -50% to +62%). None of these changes were statistically significant and the control sites were in the same town so may have been subject to spillover effects.

Table 6: Percentage change in injury collisions with red light cameras (cf Retting, Ferguson and Hakkert, 2003)

			Percentage change in:		
Study	**Location**	**Sites**	**Total collisions**	**Right angle collisions**	**Rear shunts**
Studies that took no account of RTM or spillover					
Mann *et al* (1994)	Adelaide, Australia	8 camera sites 14 control sites	-20[2]	-26	-1
Studies that took some account of RTM but not spillover					
South *et al* (1988)	Melbourne, Australia	46 camera sites 46 control sites	-7	-32*[4]	-31[5]
Hillier *et al* (1993)	Sydney, Australia	16 camera sites 16 matched control sites	-26	N/A	N/A
Ng *et al* (1997)	Singapore	42 camera sites 42 matched control sites	-9	-10	+6
Studies that took account of both RTM and spillover					
Retting & Kyrychenko (2002)	California, US	125 sites in Oxnard, 11 with cameras control sites in 3 other towns	-29*[6]	-68*	N/A
Council *et al* (2005)	US	132 camera sites in 7 jurisdictions 408 control sites	N/A	-16*[2]	+24*

Notes:

1 An asterisk * indicates that the result was statistically significant at the 5% level
2 Total collisions comprise pedestrian, right-angle, right-turn and rear-end collisions
3 Right angle collisions comprise all red light running collisions
4 Significance challenged by later authors
5 Excludes rear shunts in which one vehicle is turning
6 Results are for all signal-controlled junctions in Oxnard, not just those with cameras
7 N/A indicates that no results were quoted in the study

Also in the US, Retting and Kyrychenko (2002) used a before-and-after study with generalised linear modelling over 29 months to compare data from 125 signal-controlled junctions in Oxnard, of which 11 had cameras on one approach at any one time. All of the signal-controlled junctions in three other Californian towns were used as control sites. In order to minimise RTM, they looked at collisions at all signal-controlled junctions in Oxnard, not just those with cameras. Total injury collisions at all sites were reduced by a statistically significant 29% (with 95% confidence limits from -40% to -18%). Right angle collisions at all sites were reduced by a statistically significant 68% (with 95% confidence limits from -78% to -58%). There was no significant effect on rear-end collisions when collisions involving only damage to property were considered; figures for injury collisions were not quoted.

Council *et al* (2005) undertook the most extensive study to date using the empirical Bayes method to study 132 camera sites in seven different US jurisdictions. There were about 50 control sites from each jurisdiction, 408 in all. Red light running collisions were defined as 'right-angle', 'broadside' or 'right- or left-turning-collisions' involving two vehicles, with the vehicles entering the junction from perpendicular approaches. Collisions involving a left-turning vehicle and a 'through' vehicle from opposite approaches (principal right turn) were also included. 'Rear end collisions' were those occurring on any approach within 46 m (150 ft) of the junction rather than the 20 m used in the UK. Council *et al* found that cameras were associated with a statistically significant decrease of 16% (95% confidence interval from -27.5% to -4.0%) in red light running collisions but an increase of 24% (95% confidence interval from 0.8% to 47.2%) in rear shunts. There were indications of a weak spillover effect (a reduction in right angle collisions of 8.5% at non-camera sites). This study pointed out some of the general difficulties with comparing red light camera studies, summarised briefly here:

- Spillover effects could affect control sites that are from the same city
- Differences in collision investigation and reporting practice between jurisdictions
- Definition of red light running collisions
- Need to allow for collision severity rather than just frequency in the trade off between different collision types
- Exposure changes between before-and-after periods
- Regression to the mean effects not necessarily taken into account
- Other junction improvements undertaken at the same time as camera installation e.g. changes in amber timing
- Combined effect of cameras with variables such as cycle time not known
- Effect of signage relating to cameras not considered
- Effect of education combined with enforcement not known
- Level of fine, whether licence points are involved and percentage actually penalised not stated
- Definition of red light violation e.g. length of 'grace period' after signal turns red not given
- Effect of camera rotation round different sites not known

They suggested that candidate sites for camera use should be those with a high ratio of right angle to rear shunt collisions. In addition, based on an economic argument, Council *et al* found that signs both at the city limits and at the camera sites were more effective than signs at the camera sites alone and that a fine and points was more effective than just a fine.

5.3.3.2 Other studies (not included in Table 6)

A follow-up study (Andreassen, 1995) to that of South (1988) of 41 sites using other signal-controlled junctions in Melbourne as a control, also found an increase in rear shunt collisions. He found that right angle collisions decreased at sites with more than two per year in the before period, but increased at sites with less than two per year, probably showing the effects of RTM. Andreassen noted that many of the camera sites had very low collision frequencies prior to the introduction of the cameras. The study by Andreassen is excluded from Table 6 as it does not separate property damage only collisions from injury collisions.

Two studies in Glasgow indicated significant benefits from cameras. MVA (1995) found a 59% reduction in collisions caused by red light running at six camera sites in Glasgow with three years' before and after data; however, control sites did not appear to be used and therefore this study is not shown in Table 6. Halcrow Fox (1996) found a 25% reduction in total collisions and a 32% reduction in red light running collisions at eight junctions and three Pelican crossings, based on 2½ years' before and after data, using other signal-controlled junctions in Glasgow as a control. However, they attributed part of the drop in collisions to other causes and the report retrieved from the internet provides only minimal details and therefore this study is not listed in Table 6.

Hooke *et al* (1996) summarised UK data from ten police force areas on red light cameras, finding an 18% reduction in total collisions following camera installation, but did not use control sites or otherwise control for trend or regression to the mean. Very few details are given and therefore this study is not shown in Table 6.

Two UK studies (LAAU, 1997, and PA Consulting, 2005) investigated red light cameras at the same time as speed cameras but did not report separately on red light cameras.

The California State Auditor (2002) in California reported separately on the red light camera programs in various towns: San Diego, Oxnard, Fremont, Long Beach, Los Angeles, Sacramento and San Francisco. The report compared collisions at camera sites with all other signal-controlled junctions in the same town, before and after camera installation. Cameras had been installed much earlier in some towns than in others, so that the after periods varied considerably. Injury collisions were not listed separately for any of the towns and therefore this study was excluded from Table 6. It was also noted that the enforcement rate was low in all towns, for a number of reasons, for example difficulty in identifying the vehicle.

In Australia, Richardson (2003) considered eight camera sites with eight matched controls, each on the same road as its pair. She used five years of before data and five years of after data. The analysis used the EB method, but there was no discussion of spillover effect, which may have been significant since the controls were close to the camera sites. The study failed to make clear whether the collisions did or did not include property-damage-only collisions, although a separate outcome measures was the number of casualties. For this reason, this study is not included in Table 6.

The NCHRP Synthesis 310 (NCHRP, 2003) by McGee and Eccles undertook a detailed survey of the main studies on the impact of red light camera enforcement on collision experience and provided suggestions as to how future studies might best be undertaken.

Recently an extensive series of studies in Virginia in the US by various authors (e.g. Khandelhar and Garber, 2005, Garber *et al*, 2005, and Garber *et al,* 2007) showed an increase in collisions and in some cases in red-running following camera introduction. However the latest study has been strongly criticised on both methodological and data grounds by Persaud *et al* (2008). The EB methodology appears to have been misapplied, some junctions saw very large changes in Annual Average Daily Traffic flows between the before and after periods, and the definition of red-running was based on whether the driver was prosecuted (Persaud *et al* point out that enforcement is likely to have increased following camera installation). As a result, these studies are not included in either Table 5 or Table 6.

Malone *et al* (2005) undertook a study in Ontario in Canada. They selected sites on the basis of their high number of collisions involving red light running and evaluated the effects of cameras (19 sites) and of increased police surveillance (17 sites), compared with 12 local control sites with similar characteristics. A publicity campaign would have affected all sites and therefore a spillover effect. Malone *et al* had five years of 'before' data and two years of 'after' data and undertook the analysis using the EB methodology. There was an overall decrease in total injury collisions of 7%, a decrease of 25% in right angle collisions and an increase of 5% in rear shunts (with a corresponding increase of 50% in property damage only rear shunts). However, results were not presented separately for the effects of cameras and increased police surveillance. Therefore it is not included in Table 6.

Shin and Washington (2007) in Arizona used the EB method to analyse the results from 14 sites and found a 20% reduction in right angle collisions (not statistically significant, 95% confidence interval from -48% to +8%) and a statistically significant 41% increase in rear shunts (95% confidence interval from 30% to 50%). They also studied 10 sites and 13 control sites in Phoenix using a before-and-after method, which gave a 14% reduction in right angle collisions and a 20% increase in rear shunts, the latter statistically significant at the 10% level. Collisions include those involving property damage only and occurring within 100ft (30m) of the junctions.

5.3.3.3 Meta-analyses of studies on red light cameras

A number of meta-analyses on red light cameras exist in the literature.

In a meta-analysis based on six studies (South *et al*, 1988, Hillier *et al*, 1993, Mann et al, 1994, Andreassen, 1995, Ng et al, 1997 and Retting and Kyrychenko, 2002), Hakkert (2002) reported a reduction of 27% in injury collisions following the introduction of red light cameras.

Retting, Ferguson and Hakkert (2003) undertook a meta-analysis, based on the same studies as those included by Hakkert (2002) plus two others, which were not traced in the current review, and found a best estimate of a reduction in total injury collisions of between 25% and 30%.

Aeron-Thomas and Hess (2005) used strict criteria for the inclusion or exclusion of studies in their meta-analysis, including only before-and-after studies with control sites that had at least one year before and after data. They would have ideally restricted their analysis to studies that took account of both regression to the mean and spillover, but found only one eligible study, namely that by Retting *et al* (1999b) in Fairfax; this study considered red light violations rather than collisions. They included the studies by South *et al* (1988), Hillier *et al* (1993), Mann *et al* (1994), Ng *et al* (1997), Retting and Kyrychenko (2002) and some of the towns included by the California State Auditor (2002), namely Los Angeles, Oxnard, Sacramento and San Diego. The study by Andreassen (1995) was excluded on the grounds that the controls did not account for other interventions at the camera sites and that the camera sites had few right angle collisions. Other reasons for rejection were:

- too short an after period (California Bureau of State Audit, 2002, in Fremont and San Francisco)
- lack of control sites or data (e.g. Hooke, 1996, Chen, 2001, MVA, 1995)
- insufficient details in published papers (various studies cited in NCHRP, 2003)

Aeron-Thomas and Hess concluded that when red light cameras are introduced there is a 16% reduction in total injury collisions, a 24% reduction in right-angle collisions and no significant change in rear shunt collisions.

The most recent meta-analysis traced was by Erke (2009), who found an overall increase in collisions, with a large increase in rear shunts and a small decrease of 10% in right angle collisions, but none of these results were statistically significant. Since this study placed a large weighting on the study by Garber *et al* (2007), the results are unlikely to be reliable (see Section 5.3.3.1).

5.3.4 Cost-effectiveness of red light cameras

Several studies have found that even if there is only a small reduction in total collisions, there is a net benefit from the use of red light cameras because of the lower severity of rear shunt collisions compared with red light running collisions, for example based on First Year Rate of Return and the accident costs given in HEN1 (DfT, 2006) (e.g. Hooke *et al*, 1996, Council *et al*, 2005b, Halcrow Fox, 1996, Lawson, 1989, Rocchi and Hemsing, 1999).

5.3.5 Public opinions of red light cameras

Various studies in several countries have found strong public support for red light cameras, ranging from about 60% to 80% of those interviewed (Retting *et al*, 1999b, Maccubbin *et al*, 2001, Retting and Williams, 2000, Wissinger *et al*, 2000, Chen *et al*, 2001, PA Consulting, 2005), although Retting *et al* (1999b) in the US noted that between 10% and 15% of respondents were strongly against them.

In the UK, it is generally believed that red light cameras are far less controversial than speed cameras. A survey by SARTRE 3 (2004) found that 50% of those interviewed in the UK were in favour of red light cameras, compared with 37% for speed cameras. PA Consulting (2005) found 80% agreed with the statement that "the use of safety cameras should be supported as a method of reducing casualties".

5.4 Other methods of reducing red light running

The main mitigation method used in the US is the extension of the intergreen period, as described in Section 4.2. Other methods of mitigating red light running are detailed in the remainder of this section.

5.4.1 Advance warning of the start of amber

Methods of giving advance warning of amber include flashing green (in which the green light flashes for a few seconds immediately before the amber period) and countdown timers for drivers rather than pedestrians. Both have been trialled in the US and flashing green has been trialled in Israel. Advance warning of amber can have the effect of reducing both red-running and vehicle approach speeds and thus potentially reducing collisions. However, flashing green has sometimes resulted in some drivers accelerating to try to beat the lights (e.g. FHWA, 2004, Mahalel and Zaidel, 1985, York and Al-Katib, 2000), resulting in an increase in rear shunt collisions. Another disadvantage is the possible reduction in responsiveness if flashing green must be displayed before the signals can change. Flashing green may also increase the complexity of the driving task.

In Israel, Hakkert and Mahalel (1977) undertook a before-and-after study of ten urban junctions with flashing green of which six were located on one major dual-carriageway road. They found a statistically significant increase in total collisions of 21%, the result of an increase of 70% in rear shunts which outweighed a reduction of 40% in right angle collisions. No account was taken of RTM.

Similarly, Köll *et al* (2004) studied ten sites in Austria, Germany and Switzerland and found that drivers were more likely to stop with flashing green, potentially reducing the risk of right angle collisions but increasing that of rear shunts.

In a meta-analysis, Elvik and Vaa (2004) reported an increase in collisions of 42% (95% confidence interval from 30% to 56%) with green flashing lights as advance warning of amber.

Advance warning of amber for the driver reduces the flexibility of the control strategy, this type of solution has not been tested in the UK, which uses SA/SDE or MOVA at high speed junctions (where drivers are most likely to be caught in the dilemma zone) with the aim of modifying the signals so that changes to the right of way do not normally occur when drivers are unable to stop safely (see Section 5.2.2).

5.4.2 Improving signal conspicuity

Improving signal conspicuity may be helpful in reducing red-running, particularly for older drivers (Greater London Road Safety Analysis Unit, 1974). Where cameras are used, it may be helpful to make the signing and/or the cameras as conspicuous as possible. Methods of improving signal conspicuity include increasing the size of the signal head (e.g. from 8in to 12in) and adding backing boards to it (e.g. Polanis, 2002a, Sayed *et al*, 1998). A recent empirical Bayes study by Srinivasen *et al* (2008) in the US found a statistically significant reduction of 42% (95% confidence interval from -56% to -28%) in right angle collisions at 36 junctions with 75 control sites when the size of the signal head was increased, but little change in total collisions. Any gains in conspicuity will depend on the baseline condition and it will not necessarily be possible to achieve such improvements in Britain.

5.4.3 Reducing speeds

One method of reducing the extent of the dilemma zone is to reduce the speed limit, whilst ensuring that speeds actually reduce as a consequence, on the approach to the junction.

5.4.4 Road markings to indicate where to slow down

In the US, Yan *et al* (2007 and 2009) used a driving simulator to test road markings "SIGNAL AHEAD" to alert drivers to the presence of traffic signals and warn drivers to slow down, at a point where they had time to do so in advance of the junction. He tested two different speed limits, 30mph and 45mph in an urban area, using 42 subjects, and concluded that the road markings were effective in that they could reduce both "conservative stop and risky go decisions", and should be trialled on the road.

5.5 Summary of Section 5

The dilemma zone is mainly a problem at 'high speed' junctions. Strategies such as MOVA seek to ensure that motorists do not have to face such a situation.

Measures to reduce red-running include extending the all-red or amber periods where capacity exists, giving advance warning of the start of amber, improving the conspicuity of the signal head and introducing red light cameras.

Broadly speaking, red light cameras can be viewed as successful and are well supported by the general public. Although evaluative studies reported in the literature tend to be of low statistical power and rather poorly controlled, so that the results are often unreliable, the consensus appears to be that they are effective in improving compliance (estimated to reduce red-running by about 50%) and safety (estimated to reduce right angle collisions by about 30%). However, there can be a corresponding increase in rear shunt collisions and some studies have reported a small increase in total collisions. Because rear shunts are on average less severe than right angle collisions, there is considered to be a reasonable benefit-cost return with red light cameras at sites where red-running is an issue.

The PACTS Report on Policing Road Risk (PACTS, 2005) states that the potential for long-term expansion of the use of red light cameras in the UK may be limited, as some police forces have suggested that most of the sites where a camera would be cost-effective have already been treated.

6 Pedestrian safety and behaviour

6.1 Behaviour at signal-controlled crossings

6.1.1 Introduction

If both drivers and pedestrians complied with signals at signal-controlled crossings and junctions, there should be no conflict between the two. However, in countries where they do not have a legal obligation to comply with the signal displayed, pedestrians regularly cross against the red and even though drivers do so much more rarely, their behaviour may lead to conflicts during the intergreen periods. Most research has focussed on investigating pedestrian compliance with the signals rather than collisions and on mid-block crossings rather than junctions for a number of reasons:

- The average collision frequency for pedestrians at signal-controlled crossings is very low, making it difficult to attain statistical significance in before-and-after collision studies (Kennedy *et al*, 2009 estimated that the mean number of pedestrian casualties per year is 0.29 at a signal-controlled mid-block crossing and 0.27 at a signal-controlled junction)
- Wall *et al* (2000) found that over 60% of serious and fatal pedestrian casualties at Pelican crossings were associated with lack of compliance by pedestrians (see Section 6.1.3)
- Mid-block crossings are less complex than junctions

Researchers have used either video observation techniques (including conflict analysis) or self-report data obtained via surveys and qualitative interviews or focus groups to assess compliance and attitudes.

However, no direct evidence was traced that interventions to improve pedestrian compliance, for example the effect of making pedestrian signals more responsive, reduce collisions. Able adults are likely to continue to cross against the red man where there is a suitable gap in the traffic. Carsten *et al* (1998) observed that risk is highest when a pedestrian crosses against the red man and a free-flowing vehicle or platoon of vehicles is approaching, for example just after the end of the pedestrian stage.

Some of the sections on behaviour are based on Kennedy *et al* (2009).

6.1.2 Pedestrian categories

A potentially useful categorisation of pedestrian crossing behaviour at signalised crossings was provided by Reading, Dickinson and Barker (1995) and modified by Kennedy *et al* (2009):

1. **Compliers who cross when the green man is showing:**
    a. pedestrians who arrive during the red but only start to cross the road during the green man
    b. pedestrians who arrive during the green man and are able to cross without waiting
2. **Non-compliers who cross when the green man is not showing (or is flashing):**
    a. pedestrians who start to cross during the red man, before the leaving amber-to-traffic signal commences
    b. pedestrians who start to cross in anticipation of the green man when they see the amber-to-traffic signal **(anticipators)**

c. pedestrians who start to cross after the steady green man has ended but before the red man appears (in the clearance period)

A number of factors found to influence pedestrian compliance with signals are described in the following sections:

- age and sex
- impairment (in its broadest sense)
- waiting times
- traffic volume and speed
- weather
- social psychological variables such as attitudes and perceived risk
- width of the road
- presence of a median or central refuge and
- familiarity with the crossing

6.1.3 Levels of compliance

Where researchers have measured compliance, the results have been very variable as it is not possible to control for factors such as age and sex or traffic volume listed in Section 6.1.2. The percentage of pedestrians who were non-compliers (including anticipators) varied between 17% and 49% according to Reading *et al* (1995) at a site in Edinburgh, whereas research by TRL for the Department for Transport in a study reported in Wall (2000) found non-compliers ranged from 42% to 92% with 16% to 46% anticipators. These figures relate to a site in Wokingham at which road markings were altered in an attempt to improve pedestrian safety at a crossing. Sterling et al (2009) found 49% non-compliers at sites in London.

Overseas non-compliance rates are generally much lower than in the UK. For example, Tracz and Tarko (1993) reported a mean value of 17% for pedestrian non-compliance in Poland, and Barker, Wong and Yue (1991) a mean value of 19% for pedestrians violating the continuous 'Don't Walk' display in Australia. This difference may be cultural in part but is more likely to be due to differences in the law and its level of enforcement. Because of this, it is difficult to compare overseas pedestrian behaviour with that in the UK. It is not always clear from the literature whether non-compliance is used to apply only to the 'Don't Walk' / red man period or also includes the Flashing 'Don't Walk' period.

6.1.4 Crossing speed of pedestrians

6.1.4.1 Clearance periods

The time taken to cross the road depends on the road width and on walking speed. In the UK, the clearance period is based on a 15th percentile walking speed of 1.2 m/s (3.9 ft/sec). (The 15th percentile walking speed is the speed exceeded by 85% of pedestrians). This walking speed is considered to be a good compromise between operational efficiency and safety. It equates to six seconds to cross a 7.3m road. However, if the clearance period is set to this value, pedestrians with a slower walking speed, whether because of age, infirmity or simply carrying a heavy object may not have sufficient time to cross if they start crossing at the end of the green period. For this reason, mid-block Puffin crossings have a clearance period that includes a 'Pedestrian Comfort' factor, usually set to three seconds, which allows for a variation in timings at sites with a high proportion of younger or older pedestrians. In addition, if a mid-block

Puffin crossing detects that pedestrians have not cleared the crossing, the clearance period can be extended by up to a further five seconds.

In the US, the normal clearance period is also based on a walking speed of 4 ft/sec (1.2 m/sec). According to LaPlante and Kaeser (2004), the 4ft/sec adopted in the US originally referred to the mean or 'normal' walking speed. However, the 1994 Highway Capacity Manual took 4 ft/sec to be the walking speed exceeded by 85% of pedestrians and the latest MUTCD (FHWA, 2003) suggests that engineers should consider using a smaller value at sites with high percentages of pedestrians who cross slowly.

In Australia, the design speed used is similar. The value was recently confirmed by Bennett *et al* (2001), who obtained a mean value of 1.42 m/sec and a value of 1.18 m/sec for the speed exceeded by 85% of pedestrians.

6.1.4.2 Walking speeds of slower pedestrians

Various authors have recorded crossing speeds by age and/or impairment, the latter in the sense of some impediment that affects walking speed. Bennett et al (2001) in Australia found a speed of 1 m/s was exceeded by 85% of pedestrians with a walking difficulty.

A review of the walking speed of pedestrians in the US) also found that older pedestrians had slower walking speeds than their younger counterparts (Stollof *et al*, 2007) and slower speeds for pedestrians with a disability.

Fitzpatrick *et al* (2005) found a statistically significant difference between the walking speeds exceeded by 85% of pedestrians for those aged 60 years and over (3.03 ft/sec or 0.92 m/sec) and under 60 (3.77 ft/sec or 1.15 m/sec), based on 2,445 pedestrians at 42 different sites in 7 states. Gates *et al* (2006) observed a speed of 3.02 ft/sec (0.92 m/sec) was exceeded by 85% of older pedestrians whilst Knoblauch *et al* (1995) observed a speed of 3.19 ft/sec (0.97 m/sec), or 3.08 ft/sec (0.94m/sec) was exceeded by 85% of older pedestrians who complied with the signals.

Various authors (Gates *et al,* 2006, Fitzpatrick *et al,* 2005, Baass, 1989 and Wall, 2000) have pointed out that the ageing population will ideally require signal timings to be based on a slower walking speed for pedestrians than the 4ft/sec (1.2m/sec) currently used. Older people who start to cross just before the 'Walk' period ends will not have reached the other side of the road by the end of the pedestrian clearance interval if it is based solely on crossing distance divided by 4 ft/sec (1.2 m/sec). In the US, the 'Walk' period (invitation to cross) is a minimum of four seconds, with seven seconds more typical, shorter than the six to twelve seconds at junctions in the UK.

Gates *et al* (2006) proposed that clearance intervals should be set using a walking speed between 3.5 ft/sec (1.07 m/sec) and 4 ft/sec (1.22 m/sec) depending on the proportion of pedestrians over the age of 65.

Stollof *et al* (2007) recommended changing the forthcoming 2009 edition of the MUTCD to adopt a clearance period consistent with a crossing speed of 3.5 ft/sec rather than 4 ft/sec, but no slower. They pointed out that if design speeds slower than this are used, a longer cycle time would be required and this may increase waiting times for pedestrians. With a design speed of 3.5 ft/sec, almost all pedestrians who start to cross within the first few seconds of green would be able to reach the kerb before the signals changed. For junctions with poor levels of service (i.e. close to capacity), Stollof *et al* found using the CORSIM simulation package that extending the clearance periods to allow pedestrians to complete their crossings could lead to an 'exponential increase in delay' to traffic. The use of on-crossing detectors which extend the clearance period only when necessary, as in the UK, has potentially considerable benefits.

6.1.4.3 *Walking speeds at different types of signal-controlled crossings*

Research undertaken in Australia suggests that pedestrians may cross slightly more quickly at signal-controlled junctions than at mid-block crossings (Bennett *et al*, 2001), possibly because pedestrians are more concerned for their safety at junctions. In the UK, one study of a crossing that was converted from a Pelican to a Puffin found that older pedestrians crossed more slowly at a Puffin than at a Pelican, suggesting that they felt less pressure to cross quickly (Reading *et al*, 1995). In the US, Gates *et al* (2006) made a similar observation, finding that pedestrians walked 0.5 ft/sec to 0.6 ft/sec (0.15 m/sec to 0.18 m/sec) faster if they were crossing under the 'Don't Walk' or flashing 'Don't Walk' signal than under the 'Walk' signal and concluded that pedestrians should find Puffin-style crossings more comfortable.

In a study of pedestrian countdown timers in California (Berkeley, 2005), a slightly higher mean walking speed was observed when timers were used compared with traditional signals (4.80 ft/sec compared with 4.60 ft/sec), presumably because pedestrians speed up when they see there is little time remaining. However, Botha *et al* (2002) found there was a negligible difference in crossing speeds with timers.

6.1.5 Age and sex

Older pedestrians (typically defined as aged 65 years old and over) are more likely to comply with signals than younger pedestrians (e.g. Daff et al, 1991). They are known to take longer to cross the road (Section 6.1.4), which is likely to have a strong influence on their decision to comply with signals. The health and age of the pedestrian can affect the outcome of a collision. People over the age of 65 are less likely to survive such a collision because of existing poor health or greater frailty. Older people are also less likely to look before and/or during crossing. A number of studies have found that females are more likely to comply with signals than males (e.g. Andrew, 1991; Yagil, 2000; Daff *et al*, 1991).

These age and sex differences are similar to those found across a number of behavioural domains, including car driving, where males and younger people are known to behave in a more unsafe way than females and older people. Reasons for age and sex differences are likely to reflect differences in a number of psychological variables, including level of perceived risk, propensity to obey traffic rules and attitudes to safety.

Elliott and Baughan (2003) found that adolescents (aged 11-16 years) often failed to obey the traffic signals and/or fail to check that the road is clear. This was particularly the case for boys, who were more likely than girls to cross without waiting for the green man. Children are also more likely to run across the road than adults, whether or not they watch for traffic. Knowledge of how to use crossings and encouragement to obey the signals is given to children as part of road safety education and by many parents and it is known (Duperrex *et al*, 2002) that this can improve crossing behaviour. However, children may well copy 'rule-breaking' adults. Simpler and intuitive control strategies are more readily understood by children than complex control strategies.

6.1.6 Impairment

Walking time is usually reduced and correspondingly crossing time is increased by any impairment that affects free movement, whether disability, old age or simply carrying a heavy object (e.g. Stollof *et al*, 2007, Reading *et al*, 1995, Austin and White, 1997, Daff *et al*, 1991).

Williams *et al* (2002) found that children with conditions such as Attention Deficit Hyperactivity Disorder (ADHD) were overrepresented in pedestrian and cyclist casualty data. They also reported that the risk of fatal pedestrian accidents among adults with learning difficulties appears to be two to three times greater than among the general population, although this finding was based on just one study.

Impairment may also affect the perceptual/judgement skills that are necessary to cross a road safely. Alcohol impairment of either driver/rider or pedestrian is recognised as a contributory factor to collisions (Broughton *et al*, 1998) and it is known that a high proportion of pedestrian casualties are recorded as having been drinking. This was researched in the 1990s (TRL research into fatal and serious pedestrian injuries in the study for DfT reported in Wall, 2000). More recently, Broughton and Buckle (2008) found that the most common contributory factor to fatal pedestrian injuries (29% of those occurring between 6pm and 6am at weekends) was 'pedestrian impaired by alcohol'. This compared with 28% of pedestrians who were recorded as 'pedestrian failed to look properly'. Broughton and Buckle's figures above refer to all pedestrian fatalities and are not restricted to fatalities at crossings.

It is likely that many pedestrians with a physical disability or a sensory impairment comply with the signals because they are aware of their impairment and as a result take more care when crossing roads, either by complying with the signals or waiting for longer gaps.

Another form of impairment is the use of listening devices such as MP3 players or mobile phones by pedestrians (or cyclists, or of course drivers), which may distract them and/or deprive them of the ability to hear oncoming traffic. Hatfield and Murphy (2006) found that pedestrians using a mobile phone are less likely to look at traffic both before and during crossing at a signal-controlled junction. Simulator studies have shown poorer driving by those distracted by mobile phones in the car, although the incidence of red-running has not been considered specifically.

6.1.7 Waiting times

A literature review by Baass (1989) showed that the longer pedestrians have to wait at a crossing, the more likely it is that they will cross while the red man is showing. This is supported by various authors (e.g. Hunt, 1995, Wall, 2000) who suggest that pedestrians are normally prepared to wait up to 30 seconds for the green man. Baass reported that a much higher percentage of people having to wait between 40 and 60 seconds cross against the red man than those having to wait less than 30 seconds (and are more likely to have an opportunity to do so).

Waiting times are related to cycle times at signal-controlled junctions and mid-block crossings in a UTC system and can therefore be directly influenced by signal timing plans.

6.1.8 Traffic volume and speed

Traffic volume is one of the most important variables associated with whether people wait for the green man at signal-controlled crossings (e.g. Daff *et al*, 1991; Yagil, 2000). The higher the volume of traffic, the more likely people are to wait, probably because they have less opportunity to cross during the red man in heavy traffic. Speed of traffic is also likely to be a factor in pedestrian crossing decisions; people are more likely to wait for the green man due to the perceived risk caused by fast moving traffic.

6.1.9 Weather/lighting conditions

'Physical' factors other than traffic volume and speed can influence pedestrians' crossing behaviour (Andrew, 1991). For example, poor lighting conditions or bad weather may result in greater compliance or pedestrians taking greater care. Although no references were traced, wet weather may increase the likelihood that pedestrians will take risks in crossing the road and the use of an umbrella may mean that pedestrians have difficulty in seeing oncoming vehicles.

6.1.10 Social psychological variables

Attitudes and perceived risk are known to be related to a number of social behaviours and can explain some of the behavioural differences between different demographic sub-groups, for example between different age and gender groups.

Yagil (2000) used the 'health belief' model (a social psychological theory of behaviour) to investigate non-compliance with pedestrian crossing signals. It was found that pedestrians were more likely to be non-compliant at signals:

- if they did not perceive danger or risk of a collision
- if they thought that non-compliant behaviour led to few losses (e.g. 'endangers lives' and 'annoys drivers') and many gains (e.g. 'saves time', 'prevents boredom' and 'prevents inconvenience')
- if they did not have a strong sense of obligation to obey rules and procedures

In another study, Evans and Norman (1998) explored adult pedestrians' attitudes towards crossing during the red man at a Pelican crossing using the 'theory of planned behaviour'. Pedestrians who believed themselves to be careful road users were more likely to intend to comply with the signals. Younger pedestrians were more likely to find crossing during the red man acceptable and perceived more social pressure to cross during the red man than did older pedestrians.

The mere presence of other people at a signal-controlled crossing can represent a form of social pressure that can influence the way people behave. For example, when a number of people are waiting at a crossing and a few cross during the red man, other people may be likely to follow (Dannick, 1973). Yagil (2000) found that the presence of other pedestrians was important in determining crossing behaviour because they stimulate conformity. In addition, Andrew (1991) found that the fewer pedestrians there were crossing at a junction, the greater the tendency for all age groups to check for traffic before crossing.

6.1.11 Road width and presence of refuge

Longer crossings may deter pedestrians from crossing against the signal unless there is a central refuge to enable pedestrians to cross the road in two 'hops'. However, no literature was traced on this topic.

6.1.12 Familiarity with crossing

Familiarity with a particular signal-controlled crossing or junction may influence behaviour. For example on a regular journey, people will often know the sequence of traffic signals and how long they will have to wait. They may also know how much time they need to cross and whether people usually cross during the red man. This familiarity is likely to have a powerful effect on behaviour, but does not appear to have been the subject of research.

A change in the type of control may lead to more cautious behaviour by pedestrians. For example, in a limited study at one site, Reading *et al* (1995) found that non-compliance with the pedestrian signals was reduced when a Pelican was converted to a Puffin (when controlling for cycle times and vehicular traffic). The researchers speculated that this reduction in non-compliance may reflect lower pedestrian risk-taking at the Puffin crossing (due to the fact that pedestrians are given greater priority over traffic at this type of crossing). However, they also suggested that the results could be explained by the greater attentiveness of pedestrians at an unfamiliar type of crossing.

6.1.13 Crossing outside the studs

In addition to failing to comply with the signals, pedestrians often cross outside the studs bounding the crossing area at signal-controlled crossings (e.g. Wall, 2000), particularly if compliance involves deviation from their desire line. This is potentially unsafe as it is known that when pedestrians cross the road within 50 metres of a crossing, but not actually on the crossing, collision risk is increased by a factor of four (e.g. Mackie and Older, 1965, Older and Grayson, 1976, Grayson, 1987, Preston, 1989). One possible reason for this is that drivers anticipate the need to stop at signals, but not necessarily elsewhere. Wall (2000) found that renewing road markings at signal-controlled junctions reduced encroachment beyond the stop line. DfT Traffic Advisory Leaflet 5/05 reports trials at a single site that suggested a coloured surface between the studs might slightly reduce speeds. Wider crossings may reduce the tendency of pedestrians to veer off the crossing.

6.1.14 Crossing diagonally at a junction

At signal-controlled junctions, pedestrians generally have to cross consecutive arms in order to reach a point diagonally opposite, since except in very low flow conditions, crossing diagonally is only possible if there is a full pedestrian stage (all-red to traffic). No research was traced on the extent of diagonal crossing, which is likely to be site specific and based on desire lines. In the US, junctions with 'scramble' timing (the equivalent of an all-red stage in the UK) sometimes have explicit signs showing that diagonal crossing is permissible (Lalani, 2001). Studies showing improved safety with scramble timing have involved comparisons with RTOR (see Section 6.2.4) and therefore any safety benefits observed are compounded with the removal of RTOR. Only the occasional junction in the UK is known to have lines to encourage diagonal crossing.

6.2 Interventions or strategies to improve pedestrian compliance

6.2.1 Reduction of waiting time for pedestrians

Longer waiting times were associated with more pedestrians crossing on red in a number of studies, but little evidence has been found that this actually resulted in increased pedestrian collisions. In a limited study of collisions at 12 Pelican crossings in Manchester, Preston (1989) showed that, based on pedestrian flows, whereas for males crossing was least risky when the green man was showing, for females, failure to comply with the red man did not appear to affect safety.

Hunt, Lyons and Parker (2000) postulated that "Although no clear relationship has been established between pedestrian delay and casualties, a more balanced and responsive approach to the allocation of time at Pelican/Puffin crossings has the potential to make a substantial contribution to a decrease in pedestrian casualties as well as improving pedestrian amenity". They point out that because pedestrians are more likely to become impatient when a red man continues to be shown during periods of low vehicle flow, the reduction of unnecessary delay for pedestrians should encourage pedestrians to use crossings correctly and reduce risk taking.

One way to reduce pedestrian delay is to reduce the green time for vehicles. However, this is likely to considerably increase delay to vehicles at busy sites. A reduced 'vehicle precedence period' (from 30 or 40 seconds to 20 seconds) was trialled in London in the 1970s; this effectively made the signals more responsive to pedestrian demand. It was found to improve pedestrian compliance by a statistically significant 38% at fixed time Pelicans with a smaller non-statistically significant benefit at vehicle actuated Pelicans (Brownfield, 1976 and 1977c). However, there was a statistically significant increase of 63% in pedestrian collisions on and within 50m at 20 fixed time Pelicans and a non-significant increase of 33% in these collisions at eight VA Pelicans (Brownfield, 1977d and e). The reasons for this are not known. Use of pre-timed maximum with vehicle actuated control (see Section 4.6.2) is also likely to increase the responsiveness of the signals for pedestrians but there appears to be little research into its safety aspects.

Austin and Martin (1996) undertook trials at two Pelicans in Brighton, which were removed from SCOOT control during the off-peak. They tested fixed time operation (with a maximum vehicle precedence period of 30 seconds), vehicle actuation (VA) and VA with a reduced pre-timed maximum. All of these improved the responsiveness of the signals for pedestrians and reduced the level of pedestrian non-compliance. In practice, the VA came into effect only infrequently because of high levels of vehicle flow, but VA with a reduced pre-timed maximum increased the proportion of the cycle available to pedestrians and led to an additional increase in compliance.

Some types of signal control are more responsive than others. For example, MOVA for and Compact MOVA are more responsive than VA; SCOOT is more responsive than other forms of fixed time UTC (see Section 4.6).

Henderson *et al* (2005) compared MOVA, Compact MOVA and VA at a number of sites, including a busy Puffin in Bracknell. Although pedestrian delay was not measured directly, various proxies indicated that pedestrian delay was very substantially reduced by both versions of MOVA and particularly so with Compact MOVA in comparison with standard VA. The authors concluded that at a site with heavy pedestrian demand, Compact MOVA will still give a significant reduction in pedestrian delay when compared with VA with a pre-timed maximum, if set at the normal 18 to 20 seconds (see Section 4.6.2).

6.2.2 Reduction in cycle time

An obvious way to reduce waiting time for pedestrians is to reduce the cycle time or to double cycle the crossing or junction (by allowing the pedestrian green phase to appear twice in every cycle, where signals are linked and it is not possible to reduce the cycle time). Various authors (Reading *et al*, 1995, Keegan and O'Mahony, 2003 and Catchpole, 2003) found that shorter signal cycle times resulted in better compliance by pedestrians. Longer cycle times may increase frustration, but may also provide more gaps in the traffic. Keegan and O'Mahony (2003) found a statistically significant reduction in non-compliance when comparing shorter cycle times with longer ones at the same junction. By contrast, some authors found no relationship between non-compliance and cycle time (e.g. Barker *et al*, 1991 in Australia; and Garder, 1989, in Sweden). Some junctions with walk with traffic pedestrian phases may have the green man displayed on their minor arms during long vehicle phases on the main arm.

It is likely that shorter cycle times are used in off-peak periods and longer ones in peak periods, and this may give rise to differences in both driver and pedestrian behaviour. When traffic volumes are low, many pedestrians will not bother to wait for the green man. In addition, commuters may behave differently from shoppers.

However, it should be noted that shorter cycle times are associated with increased vehicle collisions (Section 4.4).

6.2.3 'Overlap' period

Austin and White (1997) compared a standard Pelican with a Pelican having a two second 'overlap' period (where the invitation green-man period is followed by two seconds of flashing green man whilst red is still showing to traffic) and with a Puffin. Overall, Austin and White considered that the safety benefit for pedestrians from Puffin crossings was likely to be greater than that of an overlap period, because it can if necessary be longer than two seconds. However an overlap period was considered to be a suitable alternative measure where funds did not permit the installation of a Puffin at the time of Austin and White's study.

6.2.4 All-red pedestrian stage

The London Accident Analysis Unit (Simmonds, 1988a) undertook a before-and-after study at 16 signal-controlled junctions in Greater London to evaluate the effect on safety of introducing an all-red pedestrian stage (i.e. traffic is held on all arms of the junctions whilst pedestrians cross). In all cases, the all-red stage had been introduced as part of a programme to improve pedestrian facilities rather than safety so that regression to the mean was unlikely to bias the results. The study found an overall (not statistically significant) decrease of 9% in pedestrian casualties, but a statistically significant increase in casualties in the 10 to 24 age group. The reasons for the latter were unclear. Simmonds concluded that introducing an all-red stage had little effect on safety.

A second study for the London Accident Analysis Unit by Simmonds (1988b) considered seven signal-controlled junctions where a full pedestrian stage had been added as a collision remedial measure. He found there was a reduction of 18% in total collisions (statistically significant only at the 10% level). Because sites were selected on the basis of their collision history, this study will have been subject to RTM, but no allowance was made for this in the analysis. The study will therefore probably have over-estimated the effect of the pedestrian stage on collisions.

Much of the thrust of strategies in countries where, unlike the UK, a green man does not necessarily indicate an exclusive right of way, has been towards the investigation of exclusive pedestrian phases, sometimes referred to as 'scramble' timing. Although the relationships were rather weak, possibly due to small numbers of sites with this type of phasing, Zegeer *et al* (1982 and 1985) in the US found that exclusive pedestrian phases were associated with fewer pedestrian collisions. A similar result was obtained by other authors, for example Garder (1989) in Sweden, provided pedestrian compliance was high. According to the FHWA Informational Guide (FHWA, 2004), exclusive pedestrian phases can reduce pedestrian collisions by 50% in locations with high pedestrian flows and low vehicle speeds and volumes. The Guide did not report whether or not regression to the mean was taken into account.

6.2.5 Mitigation measures for pedestrians where there is right turn on red (or left turn on red in countries that drive on the left)

There have been a number of studies in the US on the effect of right turn on red (RTOR) on safety for pedestrians (see Section 4.5). Statistically significant increases in pedestrian and pedal cycle collisions have been found when RTOR is present at a junction (e.g. Preusser *et al,* 1982, Zador *et al,* 1982). According to Preusser *et al*, collision-involved drivers frequently claimed that they had not seen the non-motorised user and deduced that drivers were probably looking to their left in order to seek gaps in the traffic and failing to watch for these users. Some junctions therefore have a sign to prohibit RTOR at particular times of day or stating no RTOR "when pedestrians are present". Retting *et al* (2002) found that significantly fewer drivers turned right on red when there were signs prohibiting RTOR by time of day whereas signs prohibiting RTOR "when pedestrians are present" were much less effective.

6.2.5.1 Leading (and lagging) pedestrian intervals

Another method of reducing conflicts where there is RTOR is the use of leading or lagging pedestrian intervals. A leading pedestrian interval, typically three seconds, gives pedestrians the 'Walk' signal whilst the signal is still red to turning traffic (see FHWA Informational Guide, 2004). It is intended to make pedestrians more visible to motorists because they will already be established on the crossing before motorists start to turn. A statistically significant reduction in vehicle-pedestrian conflicts compared with the absence of a leading pedestrian interval was reported by Van Houten *et al* (2000) and other studies referenced in the FHWA Informational Guide.

A lagging pedestrian interval gives pedestrians the 'Walk' signal a few seconds after the vehicular green for the turning movement. This treatment gives vehicles turning right a head start to clear the crossing before it is occupied by pedestrians, rather than having to give way. It is used where there is an exclusive lane for right turners. No reports were traced on its safety effects.

6.2.5.2 Reminders to pedestrians to look when crossing where there is RTOR

Van Houten *et al* (1999) found that pedestrians tend not to look for vehicles turning right on red - at locations where this facility is permitted, particularly when the vehicle is turning behind them. They found that a simple reminder was sufficient to ensure that pedestrians looked before crossing. They tested LED signals in the carriageway and concluded that they were very successful, but were too expensive for widespread use. They suggested that an alternative would be to incorporate a prompt into the pedestrian signal, for example an LED pedestrian signal head with animated eyes that scan from side to side at the start of the 'Walk' signal. No explicit evaluation of this intervention was traced.

6.2.6 Countdown timers

Countdown timers for pedestrians have been installed and/or trialled in many countries including Singapore, France, Ireland, the Netherlands and the USA. They are becoming more and more common and the forthcoming 2009 version of the MUTCD is expected to recommend that their use becomes standard at new signal-controlled junctions (slide 253 http://mutcd.fhwa.dot.gov/resources/proposed_amend/08npa_comp_presentn.pdf). The idea of a countdown device is to increase the amount of information available to pedestrians, improve pedestrian compliance and in principle enhance pedestrian safety at signal-controlled crossings by indicating either the length of time before the next green man (or 'Walk') signal or the length of time remaining for pedestrians to safely cross the road on the flashing 'Don't Walk'. This extra information enables pedestrians to make a decision on their ability to cross the road safely in the time available.

With countdown timers, there is unlikely to be any particular bias in site selection except towards busier sites in central business districts, so there is little need to consider regression to the mean, particularly as most studies have considered compliance rather than safety. An overview of studies on countdown timers is presented here; a full meta-analysis is included in Appendix C.

6.2.6.1 Timers that count down to the start of the green man

Timers that count down to the start of the green man have been used in Europe, but not the UK, with an early trial in France (see Druilhe, 1987). With this type of timer, pedestrians may not be prepared to wait if the timer indicates a long wait (Baass, 1989, Hunt and Lyons, 1997). An upper limit of at most 30 seconds should reduce the likelihood that pedestrians will start to cross during the red man.

More recently, countdown timers of this type have been installed at a crossing in Dublin. Keegan and O'Mahony (2003) reported a statistically significant reduction in the proportion of pedestrians crossing when the red man is showing, from 35% to 24%. This study did not state whether any other changes had been made at the same time.

Countdown timers have been little used in the UK to date. They can only work if the time to the start (or end) of the pedestrian phase can be predicted and are therefore not suitable with traffic/pedestrian responsive signal control systems. Specifically SCOOT would be severely restricted by a timer that counted down to the start of the green man. With responsive systems such as MOVA and VA, it is not possible to provide more than a second or so advance notice of when the signals are about to change. Countdown timers that count down to the end of the pedestrian clearance period could be adopted in the UK.

6.2.6.2 Timers that count down to the end of the flashing 'Don't Walk' interval

In the US (where most of the relevant research has been undertaken), timers count down the amount of time remaining to safely cross the road, starting either at the beginning of the pedestrian phase or alternatively at the beginning of the flashing 'Don't Walk' or pedestrian clearance interval (Lalani, 2001). (The pedestrian clearance interval follows the same concept of the blackout and all-red period as in the UK and is set to the time taken for a pedestrian to complete their crossing at the 15th percentile speed). The MUTCD (FHWA, 2003) states that pedestrian countdown timers should count down only during the flashing 'Don't Walk' interval and this appears to be the most commonly used mode of operation in studies identified in this review. However, it is not always clear from the literature which mode was in use.

The reason for adopting timers that count down to the end of the flashing 'Don't Walk' interval in the US is that roads are typically several lanes wide and therefore the flashing 'Don't Walk' interval may be much longer than the 'Walk' interval. The flashing 'Don't Walk' signal is intended to inform pedestrians not to start to cross but is known to confuse many pedestrians in the US who may be unsure whether to continue crossing or return to the kerb.

Figure 3: Example of 'Walk' / 'Don't Walk' signals

With timers that count down to the end of the flashing 'Don't Walk' interval, concern has been raised that pedestrians may be more likely to start crossing during the flashing 'Don't Walk' interval, which could potentially be unsafe. A small, but not statistically significant increase was observed by Markowitz *et al* (2006). This is particularly likely where there is a long clearance interval of, say, 20 to 25 seconds, as pedestrians are more likely to think they will have time to complete their crossing (Huang and Zegeer, 2000, Botha *et al*, 2002). In addition, driver behaviour may be adversely affected, for example if drivers observe the countdown timer and start before the green light, or speed up to clear the junction before the lights change.

A number of studies have been traced on the effect on behaviour of this type of countdown timer, all of them in the US and all having small numbers of sites. They used either before-and-after observations or comparison sites or both (but not before-and-after with controls). Most included a basic statistical analysis. Only one study was traced that looked at pedestrian safety, with Huang and Zegeer (2000) pointing out that a study on safety would require "hundreds or thousands of test sites in order to have an adequate sample". Data from these studies are summarised in Table 7.

Leonard and Juckes (1999) (cited in Schattler *et al*, 2007) in Monterey, California, found that countdown timers discouraged pedestrians from starting to cross at the end of the flashing 'Don't Walk' interval and encouraged them to increase their speed if they were still crossing toward the end of the flashing 'Don't Walk' interval. No statistical analysis was reported.

Huang and Zegeer (2000) compared the effect of countdown timers on behaviour at two junctions in Lake Buena Vista, Florida with three comparison sites. They observed a statistically significant difference in compliance with the 'Walk' signal (47% at the sites with countdown timers compared with 59% at those without). Slightly fewer pedestrians were observed to be still crossing when the steady 'Don't Walk' signal was displayed, but the difference was not statistically significant. Huang and Zegeer also found fewer pedestrians started running during the flashing 'Don't Walk' interval at sites with a timer, suggesting that pedestrians were using the timer effectively.

DKS (2001) reported on a preliminary study of nine junctions in California and concluded that countdown timers appeared to be effective where the road was more than 80ft or 5 lanes wide. They used a before-and-after study to look at changes in behaviour following installation and found only small changes in the mean percentages starting to cross during the flashing green period, although they noted that the percentage of pedestrians who ran across the road or aborted their crossing reduced from 13% to 8% and consequently fewer pedestrians finished crossing on the red signal. They did not appear to test for statistical significance.

Botha *et al* (2002) in San Jose, California investigated four junctions with countdown timers. They found the proportion of pedestrians who started to cross during the flashing 'Don't Walk' interval was statistically significantly *higher* with timers, whereas the proportion of pedestrians who arrived during the flashing 'Don't Walk' interval but waited for the 'Walk' interval to cross was significantly *lower.* There was relatively little difference in pedestrian–vehicle conflicts. In a small survey of 56 pedestrians, Botha *et al* found that 80% thought that they were allowed to start to cross during the flashing 'Don't Walk' at sites with countdown timers if they believed they could complete their crossing before the countdown timer reached zero. Although erroneous, this assumption is safe for most pedestrians.

In Las Vegas, Pulugurtha and Nambisan (2004) compared 10 junctions with countdown timers with four similar junctions without timers. They did not report undertaking any statistical analysis, but found *fewer* pedestrians started to cross during the flashing 'Don't Walk' and steady 'Don't Walk' intervals at the junctions with countdown timers. The figures in Table 7 are averaged from individual sites in Pulugurtha and Nambisan.

Eccles *et al* (2004) undertook a before-and-after study to evaluate the effect of countdown timers on both driver and pedestrian behaviour at five junctions in Maryland. They found a statistically significant increase in the percentage of pedestrians starting to cross during the 'Walk' interval at six out of twenty junction arms with a significant decrease on two arms. There was a statistically significant decrease in observed pedestrian-driver conflicts.

Table 7: Effect of countdown timers on pedestrian behaviour

Study	Location	Number of sites	Change in percentage crossing during		
			'Walk'	Flashing 'Don't Walk'	'Don't Walk'
Comparison studies					
Leonard and Juckes (1999)	Monterey, California	Not known	-	-	-
Huang and Zegeer (2000)	Lake Buena Vista, Florida	2 sites 3 comparisons	With 47% Without 58%*	With 53% Without 42%*	
Pulugurtha and Nambisan (2004)	Las Vegas	10 sites 4 comparisons	With 69% Without 84%	With 15% Without 4%*	With 15% Without 12%
Before-and-after studies					
Botha *et al* (2002)	San Jose, California	4 sites	Decrease 74% to 72%	Increase 13% to 15%	Increase 12% to 13%
DKS Associates (2001)	California	9 sites	No change	Decrease of 2%	Increase 2%
Eccles *et al* (2004)	Maryland	5 sites	Increase 63% to 65%	-	-
PHA Transportation Consultants (2005)	Berkeley, California	11 sites	Increase 83% to 85%	Decrease 14% to 13%	Decrease 3% to 2%
Markowitz *et al* (2006)	San Francisco	14 sites	-	Increase of 1%	
Reddy *et al* (2008)	Florida	8 sites	Increase 55% to 56%	Decrease 14% to 8%	Increase 31% to 36%
Mixed studies					
Schattler *et al* (2007)	Peoria, Illinois	3 sites before-and-after 5 sites 5 comparisons	Increase 65% to 81%* With timer 76% Without 85%*		Decrease 35% to 19%* With 24% Without 15%*

* = Statistically significant at the 5% level

A before-and-after study of countdown timers in Berkeley (PHA Transportation Consultants, 2005), California, considered 11 junctions with a variety of different characteristics. Pedestrian compliance was found to be low, with or without timers, possibly because of relatively narrow streets. With timers, there was a small decrease in the percentage of pedestrians starting to cross during the flashing 'Don't Walk' interval.

Markowitz *et al* (2006) conducted a before-and-after study in San Francisco, California, to assess the effectiveness of countdown timers at 14 junctions. They found a small but not statistically significant increase in the proportion of pedestrians who started to cross during the flashing 'Don't Walk' interval. There was a statistically significant decrease in the proportion of pedestrians who completed their crossing during the steady 'Don't Walk' interval. This was the only study traced that also looked at pedestrian collisions. Markowitz *et al* found that countdown timers reduced the numbers of pedestrian collisions and injuries by a statistically significant 52%. The test sites were chosen for their high pedestrian collision histories, suggesting that RTM may have led the study to overestimate the effects of countdown timers on injuries. Also, changes to the intergreens were made at the same time as the introduction of countdown timers at some sites and this may have affected the results. No other studies were identified that looked at pedestrian collisions.

Schattler *et al* (2007) in Peoria, Illinois conducted a before-and-after study at three junctions with countdown timers and also a comparison study of five junctions with countdown timers paired with five comparison junctions with traditional signals, the comparison sites having similar traffic volumes, geometry and adjacent land use to the test sites. They found that the proportion of pedestrians starting to cross in the 'Walk' interval was statistically significantly higher and the proportion starting to cross in the 'Don't Walk' interval was significantly lower (from 35% to 19%) with countdown timers, with little change for the flashing 'Don't Walk' interval.

Reddy *et al* (2008) used a before-and-after method to study pedestrian behaviour at eight junctions in Florida with countdown timers. Several measures of effectiveness (percentage of pedestrians starting to cross during the 'Walk', flashing 'Don't Walk' and steady 'Don't Walk' intervals, and the percentage of successful crossings i.e. the percentage of crossings started during the 'Walk' interval and completed before the steady 'Don't Walk' signal) were evaluated. The results indicated that with timers, there was a statistically significant *increase* in the percentage of successful crossings, a *decrease* in the percentage of pedestrians who started to cross during the flashing 'Don't Walk' interval and a slight, but not statistically significant increase in the percentage starting to cross during the 'Walk' interval. However, there was a significant, though small, increase in the percentage crossing during the 'Don't Walk' interval.

As regards driver behaviour, various authors (Botha *et al*, 2004, Schattler *et al*, 2007, Schrock and Bundy, 2008) found no evidence of any increase in speed by motorists trying to beat the lights. No reports were traced on whether there was any evidence of motorists who could see the timers starting before the green light.

Conclusions as to the effect of countdown timers on pedestrian behaviour were therefore mixed, although there is a general consensus that there are no overall negative effects. No studies were found that considered visual or mobility impaired pedestrians and countdown signals. Some US states have advocated the use of countdown timers at all signal-controlled junctions, whilst others have developed criteria for their introduction. Stollof *et al* (2007) summarised the types of criteria currently used to identify suitable junctions as:

- Location e.g. school zones, 'downtowns' or urban areas; pedestrian access routes or proximity to pedestrian activity centres, transit stops or subway stations

- Pedestrian characteristics e.g. high numbers of senior citizens; high numbers of very young pedestrians; high pedestrian and/or pedal cycle volumes, inexperienced users; ethnic diversity; and high pedestrian pushbutton usage
- Junction characteristics e.g. history of pedestrian collisions; right-turning and left-turning volumes that conflict with the crosswalk greater than 400 vehicles per hour; long crosswalk distances e.g. at least 60 ft; a pedestrian clearance interval (i.e. crossing distance divided by crossing speed) of more than 15 seconds

A meta-analysis was undertaken of countdown timers and the results are presented in Appendix C. All of the studies in the meta-analysis were from the US where jay-walking laws differ from those in the UK. The main findings were that countdown timers improved pedestrian compliance. A higher proportion of pedestrians crossed during the 'Walk' phase when there was a countdown timer and this finding was statistically significant from study data as well as from individual site data. Results from individual site data also found that the proportion of pedestrians waiting to cross was higher during the 'Don't Walk' phase when there was a countdown timer. However, there was no effect of countdown timers on the proportion of pedestrians crossing during the Flashing 'Don't Walk' phase and therefore it is difficult to see how timers might have affected the other phases.

6.2.6.3 Public opinion surveys of countdown timers in the US

A number of studies in the US have been directed at assessing the popularity of countdown timers and how well they were understood. In a survey of 300 pedestrians at sites with countdown timers, Stollof *et al* (2007) found that a large majority had noticed the timers and over 90% understood their purpose. Similar results were obtained by Eccles *et a*l (2004), Pulugurtha and Nambisan (2004), DKS Associates and Chester and Hammond (1998).

The vast majority of respondents found countdown signals helpful and were in favour of their use, preferring them to traditional signals (e.g. Mahach *et al,* 2002, Allsbrook, 1999, Pulugurtha and Nambisan, 2004 and Markowitz *et al,* 2006).

6.2.7 Pedestrian priority at signal-controlled mid-block crossings

Giving priority to pedestrians at signal-controlled crossings is designed to reverse conventional traffic priorities by making the signals revert to pedestrian green in the absence of any vehicle demand and by registering vehicle demand only once a vehicle has reached the stop line. It was trialled at two sites in Kingston upon Hull for a three year period to the end of 1996 (Totton, 2001). Both sites had high pedestrian and vehicle flows (and a high bus flow). The scheme was successful in reducing injury collisions by 36% over the three years, including a 67% drop in child collisions. However, no account was taken of RTM and there were no control sites, as there were no other suitable sites in the Kingston upon Hull area with the same mixture of high pedestrian and vehicle flows (especially buses).

This approach has also been trialled at junctions in Australia by Lenne et al (2007) as a means of improving safety at locations which are high risk for alcohol affected pedestrians. 'Rest-on-red' was associated with a reduction in approach speeds of 3.9kph (9%) 30m from the stop line and 11kph (28%) at the stop line.

6.2.8 Pedestrian priority on trunk roads

A proposed similar trial on trunk roads was shelved because of the risk that pedestrians could believe it to be safe to cross just as the signals changed to green to traffic. It may not be the vehicle that caused the signal change that is the problem, because it can be arranged such that it is travelling slowly and has a clear view of the pedestrian. It is vehicles arriving slightly later (from either direction) that can be shown a green signal and cross the stop line without the need to slow down which could collide with the pedestrian.

6.2.9 Guard railing

Lalani (1977) and Bagley (1985) both found that the use of guard railing reduced collisions when Pelican crossings were introduced.

In a before-and-after study in London (Simmonds, 1983), there was a reduction in collisions when guard rails were installed, although no account was taken of regression to the mean. On the basis of this study, guard railing was introduced at many crossings and junctions. The cross-sectional studies by Hall (1986) and Taylor *et al* (1996) found no evidence that the provision of guard railing reduced pedestrian collisions, possibly because of a lack of sites with similar characteristics but no guard railing. Recent research for DfT and Transport for London was directed at deriving criteria for the use of guard railing rather than directly considering its effect on safety (Zheng and Hall, 2003, Hall and Hickford, 2005). DfT (2009b) has recently published LTN 2/09 giving the latest policy guidance on guard railing which broadly follows this research.

6.3 Visually-impaired pedestrians

An audible signal is provided at mid-block signal-controlled crossings in the UK in order to tell pedestrians it is safe to cross. This is of particular value to visually-impaired pedestrians. At signal-controlled junctions, the audible signal is only provided if there is an all-red pedestrian stage as it might otherwise cause confusion. In some situations where there are adjacent crossings, for example on a dual-carriageway, it is important that the bleeping is only heard by those using the relevant crossing and a ‘bleep and sweep’ sound that is very directional is used.

In addition to the audible signal, tactile information in the form of a rotating conical knob is often provided to allow pedestrians to feel when it is safe to cross. This and the signal will be the only indication at a junction, if there is no all-red stage. Tactile information is of benefit to those who are both hearing and visually impaired.

The nearside signal at Puffins may assist some visually impaired pedestrians, who can see the nearside but not the far side signal. No studies were found in this review that investigated the safety benefits of nearside request boxes.

Considerable research has been undertaken in the US on the accessibility of different junction types (e.g. Barlow *et al*, 2003, Bentzen *et al*, 2000 and 2004, Barlow *et al*, 2005). In general, visually impaired pedestrians find signal-controlled junctions much easier to negotiate than roundabouts or priority junctions because of the audible signal. However, the larger and more complex the junction, the more difficult it will be for the visually impaired and the more important it is that accessible pedestrian signals are used. Sweeping entries and exits can increase vehicle speeds. Multiple lanes make it difficult to determine which lanes are moving, particularly where there is right turn on red.

6.4 Summary of Section 6

The main findings from the literature review are as follows:

- Most of the research relating to pedestrian behaviour is for mid-block crossings rather than junctions.
- There is more research on pedestrian behaviour, specifically on compliance with the pedestrian signal, than there is on safety.
- Pedestrians are more likely to comply with a signal if they are older, female, have impaired mobility (physical disability or because they are carrying

something heavy or accompanying a young child or pushing a pram etc), the traffic is heavy, other pedestrians are waiting, or they have been waiting less than 30 seconds.

- Pedestrians crossing the road act according to their own convenience and will take shortcuts and accept gaps in traffic rather than waiting for the signal to change.
- Pedestrians are at increased risk at junctions that have more complex staging arrangements (e.g. where some signals apply to particular lanes).
- Risk to non-compliant pedestrians is increased if the pedestrian phase ends just as a platoon of vehicles is approaching, which is likely to be the case in a UTC system.
- Pedestrians with a slower walking speed, whether because of age, infirmity or simply carrying a heavy object, benefit from Puffin-style operation, at least in theory.
- Puffin (or Puffin-style) crossings with kerbside and on-crossing detectors are generally beneficial for pedestrians.
- Reducing delay to pedestrians might be expected to increase compliance and may consequently improve safety for example by:
    - Increasing responsiveness by switching to the green man as soon as possible after a demand is made (e.g. VA with pre-timed maximum)
    - Keeping cycle times as short as possible
    - Increasing the proportion of the cycle available for pedestrians
- Countdown timers that count down the remaining time to cross are popular in the US and could be used in the UK. They were found to improve compliance with the 'Walk' period.

7 Safety of other vulnerable road users

7.1 Pedal cyclists

Relatively little literature was found on pedal cyclists and safety at traffic signals. A study by Mills (1989) compared Stats 19 with hospital records and found that there was considerable under-reporting of cyclist collisions. Like pedestrians, cyclists are vulnerable at signal-controlled crossings and junctions. Right turning vehicles searching for a gap in the opposing traffic at a junction may fail to see on-coming cyclists (see e.g. Mills, 1989) or powered two-wheelers. In the UK pedal cyclists going ahead may be in conflict with vehicles turning left across their path (e.g. Keigan *et al*, 2009), particularly large vehicles leading to high involvement rates in left turning collisions. Right turning cyclists have to change lane, leading to high involvement rates in approaching collisions at signals (Mills, 1989). Although pedal cyclists are over-represented in collisions at traffic signals, their relative involvement rate compared to cars is similar to that at priority junctions and lower than those at roundabouts or mini-roundabouts (Kennedy *et al*, 1998). Keigan *et al* (2009) undertook a study of fatal collisions involving pedal cyclists. They cite various ideas for reducing pedal cycle casualties at signal-controlled junctions in addition to advanced stop lines, including education (training and publicity). They suggest that collisions between left-turning large vehicles and pedal cyclists going ahead or turning left could be avoided by, for example, the use of cycle paths bypassing the junction, cycle slip lanes, or the use of a separate signal for cyclists giving them green before other traffic.

Attempts to improve cyclist safety at signals include the use of advanced stop lines for cyclists. Advanced stop lines allow cyclists to position themselves at the front of the queue. They comprise a cycle lane on the approach, usually on the nearside, and a waiting area, approximately 5m deep, with a second stop line for all other motorised road users. The idea is that cyclists are more visible to other traffic and can therefore negotiate the junction more safely. This design dates from the early 1990s and is slightly simpler than the original design which required a second signal head at the motorists' stop line. Wheeler *et al* (1993) found that injury collisions had reduced following installation but that the numbers were too low to be statistically significant. Later work (Wheeler, 1995) introduced a simplified layout; safety was not considered explicitly but no obvious concerns were identified.

More recently, Allen *et al* (2005) reported on the behaviour of cyclists and other road users at advanced stop lines at 12 sites in London. They observed a general tendency of road users to encroach onto the cyclist area. However, encroachment at the control sites was onto the pedestrian crossing, suggesting that the advanced stop line acted as a buffer. There was a slightly higher rate of cyclists running the red light (17%) compared with the control sites (13%).

The effect of advanced stop lines for cyclists on capacity was considered by Wall *et al* (2001). Because the stop line for vehicles is further back, an additional second of intergreen time may be required for vehicles to negotiate the junction. In London, the length of the additional intergreen is set on a site by site basis and varies between zero and two seconds . There was a small increase in saturation flow with a nearside cycle lane, provided the number of lanes at the stop line was unchanged, because traffic was no longer adjacent to the kerb, in line with theoretical predictions.

Some of the literature suggests that pedal cyclists can sometimes have a somewhat cavalier attitude to traffic signals and may act more like pedestrians than motorised vehicles (e.g. Kennedy *et al*, 2009, Walker *et al*, 2004). Toucan crossings are intended for pedestrians and cyclists to share and allow cyclists to ride across the road rather than pushing their cycles.

A study of cyclist safety which used conflict analysis to compare different junction layouts was undertaken in Sweden by Linderholm (1992). Three different layouts for cycle paths were studied at 57 approaches to 15 junctions with a total of over 1000 hours observations:

- Cycle path that continues across the junction entry so that the only conflict is with turning traffic (in this case, the path can be two-way and located on either the right or the left side of the road) as shown in Figure 4 below

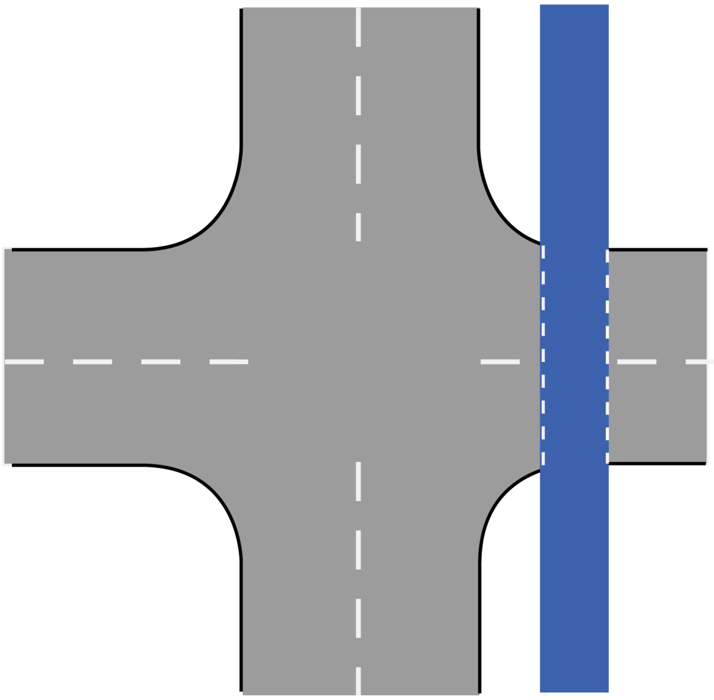

Figure 4: Cycle path at 4-arm signal controlled junction in Sweden

- Cycle path that stops just short of the junction so that the cyclists mix with traffic at the junction itself (either within 1 or 2m of the junction or joining a cycle lane)
- Cyclists mix with traffic

Linderholm concluded that cyclists who were going ahead on cycle paths were more likely to run the red light than if they mixed with traffic and this meant that the risk of a collision was higher with a cycle path. For left turning cyclists (Sweden drives on the right), the risk was lower if the proportion of left-turning cyclists exceeded 6%of the total flow. In a before-and-after conflict study at three junctions, Linderholm also estimated that colouring the surface of the cycle path blue reduced conflicts by 16%.

The use of blue surfacing to mark cycle crossings at junction entries is intended to alert motorists to possible conflict with cyclists and to provide cyclists with a lane through the junction area. The effect of blue cycle crossings compared with no cycle crossing was also investigated by Jensen (2007) who undertook a before-and-after study of 65 signal-controlled junctions that were marked in this way in Copenhagen. Jensen used roads in Copenhagen for which flows were known as a control group, allowing him to take into account flow changes and trend effects. The study also attempted to take account of RTM. The results were mixed, with reduction of 19% in collisions at junctions with one cycle crossing but increases at junctions with two (48%) or four (139%) crossings. These changes were either statistically significant or very close to being so. Jensen found that collisions not only with cyclists but also with pedestrians on the adjacent crossing were reduced. However, rear shunts among motor vehicles and right angle collisions tended to increase and these types of collisions tended to dominate at junctions with more than one cycle crossing (which tended to be larger than those with a single crossing). Jensen reported on an earlier study in the US that showed that cyclists were likely to follow the blue surfacing and thus take the 'correct' path though the junction. However, they tended to take less care, looking round less often than if no cycle crossing was present. Motorists were more likely to give way to cyclists on a marked crossing when turning.

Copenhagen has pre green lights for cyclists at signal-controlled junctions, which work on a similar basis to early release for pedestrians in that cyclists get established in the middle of the junction before other vehicles move off.

In the US, Steinman and Hines (2004) set out criteria for determining the level of service for pedal cyclists (and pedestrians) at a signal-controlled junction. These include:

- Presence of a leading cycle phase (by detecting the presence of pedal cyclists on a dedicated cycle lane and giving them a green light several seconds before other traffic)
- Minimum green and amber period based on cycle speeds
- In the US, a vehicle left turn phase opposing cyclists which is protected or permissive or better, or no left turn conflict (e.g. because on a one-way street) (see Section 4.6.5); the equivalent in the UK would be a separate right turn stage
- Approaches and exits sufficiently wide to accommodate cyclists either in wide lanes or with separate cycle lanes
- Separate right turn lane with cycle lane if possible

There is scope for innovative site-specific junction treatments to aid cyclists – see for example the ideas for a diagonal cycle crossing from Wilke *et al* (2007) in New Zealand. Australia already uses the idea of a hooking turn for cyclists at some junctions (see Figure 5), in which cyclists who are turning right are required to keep as far to the left as possible until they almost reach the other side of the adjacent approach, adjust their position so that they are facing the desired direction of travel and then, when the signal changes, continue straight ahead. There is a waiting area in front of the stop line on the adjacent road.

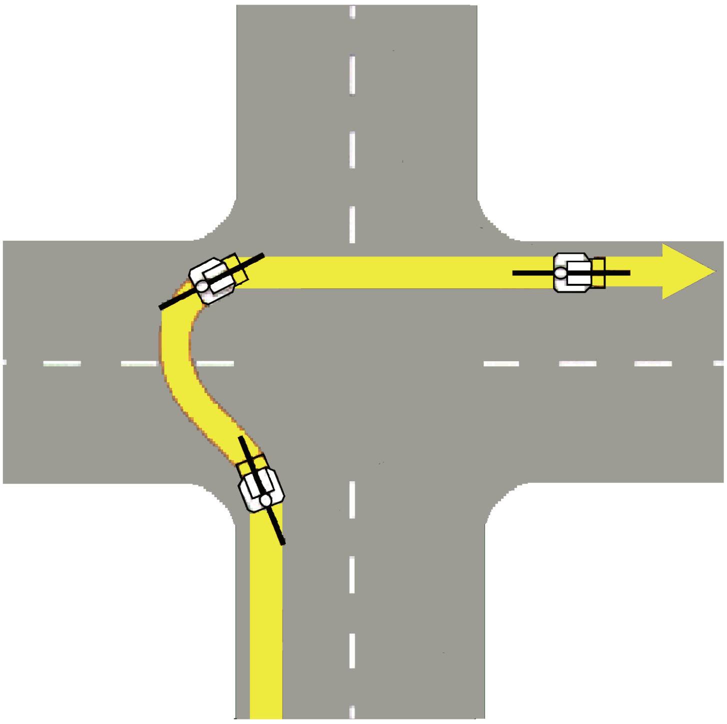

Figure 5: Hooking turn in Western Australia showing cyclist route through junction

7.2 Powered two-wheelers

Very little research was traced concerning powered two-wheelers at traffic signals. As is the case for cyclists, although powered two-wheelers are over represented in casualty statistics at signals, they fare no worse at these junctions than any other and better than at roundabouts or mini-roundabouts (Kennedy *et al*, 1998). There do not appear to be any safety interventions aimed specifically at powered two-wheelers at signals. Since one type of collision that particularly affects powered two-wheelers (and cyclists) is where a right turning vehicle hits an oncoming two-wheeler, a separate right turn stage is likely to reduce collisions (see e.g. Lynam *et al*, 2001). Powered two-wheelers also tend to be over-represented in single vehicle collisions.

A current project for DfT is looking at the possible use of advanced stop lines by powered two-wheelers.

8 Conclusion

8.1 Review methodology

The review included literature back to 1980 in the UK and 1990 elsewhere, or earlier for key references. Of the 454 studies identified 145 passed all inclusion and exclusion criteria to be reviewed in full. The majority of the references are to studies in the UK or the US, with about half being post 2000. The literature mainly comprised before-and-after studies, with small numbers of sites, not necessarily with controls, and sometimes with flawed methodology.

The main types of collision at signal-controlled junctions are single vehicle, rear shunts (and lane changing) on the approach to the junction, right angle collisions, principal right turn collisions and pedestrian collisions. Right angle collisions account for about 13% of the total in the UK; these collisions could not occur if all drivers acted in accordance with the signals. Right angle collisions and those involving non-motorised users have the highest mean severity.

Around 60% of serious and fatal pedestrian injuries that occur at signals were found to be associated with the pedestrians not using the crossing in compliance with the Highway Code (Wall et al, 2000).

8.2 Effect of signalisation

Although the evidence is limited, overall it seems reasonable to conclude that on average, signalisation reduces collisions by 15% (95% confidence interval from -25 to -5%) at 3-arm junctions and 30% (95% confidence interval from -35 to -25%) at 4-arm junctions. However, it will not always be advantageous as, although it reduces right angle collisions, it can increase rear shunts. There is limited evidence that signal-controlled roundabouts are safer than normal roundabouts, particularly for cyclists.

Pelican crossings enable users to cross the road more easily but there is some evidence that users take less care than they do when crossing in the absence of a facility. Puffin crossings have a number of potential advantages over Pelican crossings and appear to have a similar safety record.

8.3 Signal timings

Intergreen periods in the UK were set many years ago and are based on where collision points occur on the junction. Recent research has confirmed that the amber period should remain at three seconds and the starting amber (red with amber) period at two seconds. All-red periods appear to be beneficial if kept short (generally one or two seconds). Longer all-red periods have been found to be associated with increased principal right turn collisions.

In the US, amber periods of between three and six seconds are used, with longer periods at junctions on high speed roads; increasing amber periods to the these values or longer periods on high speed roads as recommended by the Institute of Transport Engineers reduces collisions. Amber periods that are shorter than the ITE recommended values are associated with increased collisions. However, intergreen periods that are too long may also increase collisions. As in the UK, there is often, but not invariably, an all-red period. There is no starting amber (red with amber).

Shorter cycle times benefit pedestrians and improve pedestrian compliance, but provide increased opportunities for red running. Cycle times are generally set to minimise vehicle delay but crossings or lightly trafficked junctions in a UTC system can sometimes be double-cycled during off peak periods.

Although the type of signal control is generally selected on delay grounds, it can have an effect on safety. For example, when correctly configured, MOVA reduces collisions by a statistically significant 26% compared with VA. UTC is estimated to reduce collisions by 19% (95% confidence interval from -22 to -15%).

A separate right turn stage substantially reduces principal right turn collisions; however, its use implies a corresponding increase in cycle time and this increases delay for both vehicles and pedestrians. The use of early cut-off or late release is less effective but still gives a good safety benefit.

8.4 Red light running

Red light running occurs for three main reasons. It may be inadvertent if the driver fails to see the signal, deliberate if the driver tries to beat the lights, or the driver may be caught in the dilemma zone with the choice between braking and continuing through the junction not clear cut. The dilemma zone is mainly a problem at 'high speed' junctions. Strategies such as MOVA seek to ensure that motorists do not have to face such a situation.

Measures to reduce red-running include extending the intergreens, giving advance warning of the start of amber, improving the conspicuity of the signal head and introducing red light cameras.

Broadly speaking, red light cameras can be viewed as successful and are well supported by the general public. Although evaluative studies reported in the literature tend to be of low statistical power and rather poorly controlled, so that the results are often unreliable, the consensus appears to be that they are effective in improving compliance (estimated to reduce red-running by about 50%) and safety (estimated to reduce right angle collisions by about 30%). However, there can be a corresponding increase in rear shunt collisions and some studies have reported a small increase in total collisions. Because rear shunts are on average less severe than right angle collisions, there is considered to be a reasonable benefit-cost return with red light cameras at sites where red-running is an issue.

The potential for long-term expansion of the use of red light cameras in the UK may be limited, as some police forces have suggested that most of the sites where a camera would be cost-effective have already been treated. However, further investigation of this point would be needed in order to establish the scope for expansion.

8.5 Vulnerable road users

The review found that most of the research relating to pedestrian behaviour is for mid-block crossings rather than junctions and there is far more research on pedestrian behaviour, specifically on compliance with the pedestrian signal, than directly on safety.

Pedestrians are more likely to comply with a signal if they are older, female, have impaired mobility (physical disability or because they are carrying something heavy or accompanying a young child or pushing a pram etc), the traffic is heavy, other pedestrians are waiting, or they have been waiting less than 30 seconds. They cross the road at their own convenience and will take shortcuts and accept gaps in traffic rather than wait for the signal to change if they think they can do so safely.

Pedestrians may be at increased risk at junctions that have more complex staging arrangements (e.g. where some signals apply to particular lanes).

Risk to non-compliant pedestrians is increased if the pedestrian phase ends just as a platoon of vehicles is approaching, which is likely to be the case in a UTC system.

Puffin (or Puffin-style) crossings with kerbside and on-crossing detectors benefit pedestrians. On-crossing detectors are particularly helpful for those with a slower walking speed, whether because of age, infirmity or carrying a heavy object.

Reducing delay to pedestrians might be expected to increase compliance and potentially safety for example by:

- Increasing responsiveness by switching to the green man as soon as possible after a demand is made (e.g. VA with pre-timed maximum)
- Keeping cycle times as short as possible
- Increasing the proportion of the cycle available for pedestrians

Relatively little literature was found on pedal cyclists or powered two-wheelers and safety at traffic signals, although as at other junction types, these road users are known to be over-represented in collisions.

8.6 Features not currently used in the UK

Right turn on red (RTOR) (for countries that drive on the right) was introduced as a fuel saving device in the 1970s oil crisis. It allows vehicles to pull out into gaps in the traffic even when other turning movements are not permitted due to the potential conflicts with other streams of traffic. It reduces vehicle delay and emissions but has generally been shown to increase pedestrian and cycle collisions; it is widely used in countries such as the US, but not in the UK (where the equivalent would be 'left turn on red'). The more definitive results all showed an increase in right turn collisions with RTOR. There were no schemes reported that had right turning permitted for cyclists only.

'Flashing amber' refers to traffic lights which permit drivers to proceed with caution. It therefore prevents drivers from waiting unnecessarily when the traffic lights might otherwise be red. Flashing amber is used at night in the US and in some northern European countries at low flow junctions. The use of flashing amber rather than the full signal sequence has generally been found to increase collisions. Schemes can go further and switch lights off altogether. In a Swedish study, switching lights off altogether was found to improve safety compared to the use of flashing amber, but the authors did not report on how this compared with full signal operation.

Countdown timers that count down the remaining crossing time for pedestrians are popular in the US and could offer useful information to pedestrians in the UK.

While the results are of interest, they do not necessarily provide any indication of how the features not currently used in the UK might operate in the London environment. The results from assessments can be mixed and the conditions at sites are often quite different from those found in London. It is recommended that, if these features were to be tried, pilot projects should be closely monitored, especially for any potential road safety risks.

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Glossary of terms and abbreviations

EB	Empirical Bayes
FB	Full Bayes
FDW	Flashing Don't Walk (US)
ITE	Institute of Transport Engineers
MOVA	Microprocessor Optimised Vehicle Actuation
MUTCD	Manual on Uniform Traffic Control Devices (US)
Pedestrian clearance interval	Crossing distance divided by walking speed
Pre-timed maximum	Used at mid-block crossings with VA on low speed roads. Maximum green for vehicles started as soon as vehicle green signal appears rather than following pedestrian demand, thus reducing pedestrian delay (see Section 4.6.2)
PDO	Property Damage Only, collision not involving injury
RTM	Regression to the mean
RTOR	Right turn on red (left turn in countries that drive on the left)
SA / SDE	Speed Assessment / Speed Discrimination Equipment
SCOOT	Split, Cycle and Offset Optimisation Technique
UTC	Urban Traffic Control
VA	Vehicle-actuated

Appendix A Search terms

- Traffic signal* AND (safety OR accident OR collision OR casualty OR injury)

AND

- Junction OR intersection OR pedestrian crossing OR midblock crossing OR Pelican OR Puffin OR roundabout OR standalone crossing OR Toucan OR diagonal
- MOVA OR vehicle activated OR VA OR SCOOT OR Urban Traffic Control OR UTC
- Pedestrian* OR *cycl* OR PTW OR P2W OR motorcycle OR powered two wheeler OR HGV* OR bus OR transit OR road user
- Driver behaviour OR Pedestrian behaviour OR road user behaviour OR compliance OR cyclist behaviour
- Signal timings OR strategy OR cycle time OR all red OR right turn OR left turn OR right turn on red OR signal phase
- Secondary signals OR road markings OR anti-skid OR stagger
- Countdown timers
- Red light camera*
- Blind OR visually impair* OR mobility impair*
- LED* OR halogen OR conspicuity OR candela OR signal head
- Dilemma zone
- Red*running
- Stop*line OR ASL OR advanced stop line OR cycle box
- Intergreen
- Speed discrimination OR speed assessment OR speed measur* SA OR SDE
- Signal design
- Traffic signal installation OR traffic signal removal'

Inclusion criteria:

- Published research UK / Australia / New Zealand / US / Canada / Europe / Israel / Hong Kong / Singapore (English language or abstract)
- Post 1980 in UK, 1990 elsewhere
- Roads with speed limits ≤ 50mph
- Single and dual carriageways
- Signalised junctions
- Signalised roundabouts (part or full time)
- Midblock signalised crossings

Exclusion criteria:

- Pre-1980 in the UK, pre 1990 elsewhere, except what appear to be key studies
- Material requiring translation
- Railway crossings
- Non-signalised intersections
- Roads with speed limits > 50mph

- Fuel consumption

Appendix B Descriptions of before-and-after studies

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Conversion of flashing amber to full signal operation	Akbar and Layton (1986)	Portland, Oregon, US	Before-and-after 1 or 2 years before 1 or 2 years after No control sites Basis of site selection not stated. No account taken of RTM	30 sites	Change in Total collision rate Right angle collision rate Rear shunts rate (Example for all two-way roads – 15 sites) Change in total collision rate is significant at 10% level	 -73% -78%* -93%*
Red light cameras	Andreassen (1995)	Melbourne, Australia	Before-and-after with controls 4 years before 5 years after Possible spillover Selected sites had low numbers of collisions No account taken of RTM	41 camera sites from study by South et al All Melbourne signal-controlled junctions (whether or not they had cameras) as controls	Change in: Total collisions Right angle collisions Rear shunts Collisions include PDO	 +7% (-2 to +16%) -13% (28 to +2%) +20% (2 to 38%)
Introduction of Pelicans	Bagley (1985)	UK	Before-and-after No control sites	37 sites converted from Zebras 42 sites with no previous crossing	Change in Pedestrian collisions at or within 50m of crossing Sites converted from Zebras Sites with no previous crossing	 -26% -23%

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Conversion of flashing amber to full signal operation	Barbaresso (1984)	Michigan, US	Before-and-after with controls 3 years before 3 years after No account taken of RTM	6 sites 10 control sites	Change in Right angle collisions Collisions include PDOs	 -97%*
Longer intergreens	Bonneson and Zimmerman (2004c)	US	EB Method takes account of RTM	6 sites 2 control sites (sites at 2 junctions)	Change in Red light violations	 -70%*
Countdown timers	Botha et al (2002)	San Jose, California	Before-and-after No control sites	4 sites with timers	Change in % crossing on 'Walk' signal	From 72 to74%
Longer intergreens at night	Brownfield et al (1977a)	UK	Before-and-after with controls No account taken of RTM	9 sites All signal-controlled junctions in same London boroughs as controls	Changes in Night time collisions Night time right angle collisions Night time pedestrian collisions (significant at the 10% level)	 -45% * -54% * -74%
Longer intergreens	Brownfield et al (1977b)	UK	Before-and-after with controls No account taken of RTM	5 sites All signal-controlled junctions in same London boroughs controls	Total collisions Crossroad collisions Pedestrian collisions Result for total collisions significant at the 10% level	-24% -82% * +20%

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Red light cameras	California State Auditor (2001)	California, US	Various before-and-after studies with controls over period 1 Jan 95 to 30 Sep 01 Cameras installed at different times Possible spillover effects No account taken of RTM. Controls were other signal-controlled junctions in same town	Sacramento -10 sites Fremont – 7 sites LA County – 5 sites Oxnard – 11 sites San Diego – 19 sites San Francisco –17 sites	Changes in Total collisions at camera sites at controls at camera sites at controls at camera sites at controls at camera sites at controls at camera sites at controls at camera sites at controls Collisions include PDOs	 -44% 0% -11% +7% -29% -3% -55% -14% -16% -8% -37% -14%
Red light cameras	Chen et al (2001)	Canada	Before-and-after with controls using GLM. Sites selected on basis of collision history. Study and control sites at least 1km from cameras	2 non-camera sites in Kelowna with signage 2 control sites in Kamloops	Change in red light violation rate at non-camera sites with signage After 1 month After 6 months	 -69% * -38%

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Red light cameras	Chin (1989)	Singapore	Before-and-after with controls At least 1 month after Both non-camera sites and controls may have been affected by spillover	23 camera sites (11 junctions) 20 non-camera sites (at 11 camera junctions) 14 control sites (5 junctions)	Change in Percentage of vehicles running the red per cycle at Camera sites Non-camera sites Control sites See also main text	 -41%* -27%* +17%
Red light cameras	Council et al (2005)	US	EB 3 years before 1½ years after Method takes account of RTM Some attempt to investigate spillover	132 camera sites 408 control sites	Change in Right angle collisions Rear shunts	 -16%* +24%*
Countdown timers	Eccles et al (2004)	Maryland, USA	Before-and-after No control sites	22 sites with timers (5 junctions)	Change in % crossing on 'Walk' signal	From 63% to 65%
Conversion of flashing amber to full signal operation	Gaberty and Barbaresso (1987)	Michigan, US	Before-and-after At least 3 years before At least 1 year after No controls No account taken of RTM All converted sites with full collision data	59 sites No control sites	Change in Right angle collisions Rear shunts occurring at night	 -95%* -22%
Red light cameras	Garber et al (2005)	US	EB 6 years with different before-after periods at each junction Method takes account of RTM See also main text	20 camera sites No. of control sites not stated	Change in Total collisions Red running collisions	 +7% to -24% -20% to -33%

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Red light cameras	Garber et al (2007)	US	EB Total of 7 years before and after data Control sites not comparable with camera sites See also main text	29 camera sites 44 control sites 15 spillover sites within 0.6 miles of a camera	Change in Total collisions Red light running collisions	 +17% -30%
Removal of traffic signals	Golias (1997)	Greece	Before-and-after 7 years before 3 to 5 years after Use of flow and geometric data rather than control sites to allow for trend effects	48 sites of which 28 showed an decrease and 20 showed no change in collisions following signalisation	Change in Right angle collisions Rear shunts at 28 sites Change in: Right angle collisions Rear shunts at 20 sites	 44% to 28% * 21% to 32% * 36% to 22%* 37% to 42%
Flashing green	Hakkert and Mahalel (1977)	Israel	Before-and-after with controls	6 sites 7 control sites	Change in Total collisions	 +34%*
Introduction of signals	Hakkert and Mahalel (1978)	Israel	Before-and-after 38 months before 38 months after No control sites	34 sites	Change in Total collisions at sites with fewer than 15 in before period Total collisions at sites with 15 or more in before period	 +5% -48%*
Introduction of flashing green			Before-and-after 24 months before 24 months after No controls	10 sites	Change in Total collisions Right angle collisions Rear shunts	 +21%* +71%* -40%

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Red light cameras	Halcrow Fox (1996)	Glasgow, UK	Before-and-after with controls 2½ years before 2½ years after Some investigation of spillover effect, but junctions furthest from cameras showed greatest reduction, suggesting other factors involved. No account taken of RTM	8 camera sites at junctions Control sites were signal-controlled junctions in Scotland	Change in Total collisions Red light running collisions at camera sites Changes in Total collisions at signal-controlled junctions in Scotland	 -31% -33% -20%
Conversion of Zebra crossings to Pelicans	Harper (1985)	Swindon, UK	Before-and-after No control sites	14 sites	Change in Pedestrian collisions at or within 50m of facility	 -63%
Red light cameras	Hillier (1995)	Sydney, Australia	Before-and-after with controls 2 years before 2 years after Possible spillover Some allowance for RTM since controls selected on basis of collision history	16 camera sites 16 matched control sites however some problems noted with controls	Change in: Total collisions	 -26%* (-55 to -3%)
Red light cameras	Hooke (1996)	UK	Before-and-after No control sites No account taken of RTM	N/A	Change in Total collisions	 -18%
Countdown timers	Huang and Zegeer (2000)	Lake Buena Vista, Florida, USA	Comparison	2 sites with timers 3 comparison sites without	Difference in % crossing on 'Walk' signal	47% with timers 58% without

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Countdown timers	Keegan and O'Mahony (2003)	Dublin, Ireland	Before-and-after No control sites	1 site with timer	Change in % crossing on green or amber Timers count down to start of green	From 65% to 76%"
Red light cameras	Kent et al (1995)	Victoria, Australia	Comparison with non-camera sites Possible spillover Sites chosen had history of red light running collisions.	24 camera approaches 24 non-camera approaches on opposite arms to camera with sign 24 non-camera approaches on other arms of camera sites with neither sign nor camera	Percentage of vehicles running red light at: Camera approach Signed approach Other approach For right turners, there was more red running on single carriageways with a 60kph speed limit than on dual carriageways with an 80kph limit.	 0.44% 0.31% 0.22%
Introduction of Pelicans / Conversion of Zebra crossings to Pelicans	Lalani (1974)	London, UK	Before-and-after Control was Greater London area Between 6 and 24 months before and after	40 sites converted from Zebras 11 sites with no previous crossing	Change in Pedestrian collisions at or within 50m of crossing Sites converted from Zebras Sites with no previous crossing	 +3% +65%
Signalisation of rural junctions	Lan et al (2009)	California, US	Full Bayes 10 years before and after Method allows for RTM and trend effects	28 sites, 2,888 controls All rural	Change in: Total collisions Right angle collisions Rear shunts	 -19%* (-29 to -9%) -81%* (-85 to -77% +23% (-21 to +67%)

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Red light cameras	Malone et al (2005)	Canada	EB 5 years before 2 years after Method takes account of RTM	19 camera sites 17 sites with increased police surveillance 12 control sites	Change in Total collisions Right angle collisions Rear shunts at camera and police sites	 -7% -25% +5%
Red light cameras	Mann et al (1994)	Adelaide, Australia	Before-and-after with controls 5 years before 5 years after Possible spillover No account taken of RTM	8 camera sites 14 control sites	Change in Total collisions Right angle collisions Rear shunts	 -20% (-47 to +7%) -26% (-79 to +27%) -1% (-54 to +52%)
Countdown timers	Markowitz et al (2006)	San Francisco, California	Before-and-after with controls 21 months before 21 months after Sites selected on basis of pedestrian crash history, controls similar, so some account taken of RTM Changes to amber period at some sites when timers installed so results confounded.	9 sites with timers Number of control sites not stated, but all had two collisions during 'before' period	Change in % crossing on 'Walk' signal Change in pedestrian collisions	Slight decrease -52%* (-93% to -25%)
Signalisation of roundabouts	Martin (2003)	London, UK	Before-and-after No controls No allowance for RTM	10 at-grade 10 grade-separated roundabouts	Change in Total collisions at normal roundabouts Total collisions at grade-separated roundabouts	 -28% * -6%

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Introduction of Pelicans	Murray-Clarke (1986)	London, UK	Before-and-after with controls 3 years before 3 years after Took some account of RTM	45 sites Controls were collisions in remainder of boroughs where sites located	Change in: Total collisions at sites with: Low mean rate Medium mean rate High mean rate Pedestrian collisions at or within 50m of crossing at sites with: Low mean rate Medium mean rate High mean rate	 +1% -1% +7% +4% -38% -2%
Red light cameras	MVA (1995)	Glasgow, UK	Before-and-after 3 years before 3 years after Possible spillover No account taken of RTM	6 camera sites Number of control sites not stated and only used for rate of red light running	Change in Red light violations at camera sites Red light violations at control sites Change in Red light running collisions at camera sites	 -59% -37% -62%
Red light cameras	Ng et al (1997)	Singapore	Before-and-after with controls Possible spillover 3 years before 3 years after Some account of RTM since controls selected to have similar collision history	42 camera sites 42 control sites	Change in: Total collisions Right angle collisions Rear shunts	 -9% (-26 to +8%) -10% (-31 to +11%) +6% (-50 to +62%)

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Removal of traffic signals	Persaud et al (1997)	US	EB 15 years total before and after period Method takes account of RTM and trend effects	199 sites 71 controls	Change in Total collisions	Approximately -24%
Countdown timers	PHA Transportation Consultants (2005)	Berkeley, California	Before-and-after No control sites	13 sites with timers	Change in % crossing on 'Walk' signal	From 83% to 85%
Conversion of flashing amber to full signal operation	Polanis (2002)	Winston-Salem, US	Before-and-after (Report not obtained, no further details)	19 sites	Change in Right angle collisions occurring at night	-78%
Improved signal conspicuity (8 inch signal heads replaced with 12 inch)				55 sites	Change in Total collisions Right angle collisions Not clear whether collisions include PDOs	-10% -47%
Countdown timers	Pulugurtha and Nambisan (2004)	Las Vegas, US	Comparison	10 sites with timers 4 comparison sites without	Difference in % crossing on 'Walk' signal	69% with timers 84% without
Conversion of Zebra crossings to Pelicans	Rayner et al (1975)	UK	Before-and-after No control sites At least 6 months before and after	30 sites that were moved by less than 15m 8 sites that were moved by more than 15m	Change in Pedestrian collisions at or within 50m of crossing	31% -39%
Countdown timers	Reddy et al (2008)	Florida, USA	Before-and-after No control sites	8 sites with timers	Change in % crossing on 'Walk' signal	From 55% to 56%

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Red light cameras	Retting and Kyrychenko (2002)	Oxnard, US	Before-and-after with controls using GLM 29 months before 29 months after Spillover minimized by using controls in different towns; RTM avoided by looking at collisions at all signal-controlled junctions, not just camera sites	125 sites (11 with cameras) Signal-controlled junctions in 3 different towns as controls	Change in collisions at all signal-controlled junctions in Oxnard: Total collisions Right angle collisions	 -29% * (-40 to -18%) -68% * (-78 to -58%)
Longer intergreens	Retting, Chapline and Williams (2002)	US	Before-and-after with controls Sites selected on basis of low collision record	51 sites 56 controls	Change in Total collisions Right angle collisions Pedestrian and cyclist collisions	 -12% * +3% -37% *
Signs prohibiting RTOR at certain times of day "when pedestrians present"	Retting et al (2002)	Arlington County, VA, US	Before-and-after with controls	5 sites with signs No RTOR at certain times of day 5 sites with signs "No RTOR when pedestrians present" 5 control sites	Whether drivers stopped Whether drivers turned right on red Whether drivers stopped Whether drivers turned right on red	21% before, 40% after 77% before, 19% after 24% before, 31% after 72% before, 62% after

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Longer intergreens and red light cameras	Retting et al (2008)	Pennsylvania, US	Before-and-after with controls Six weeks after amber period increased by approximately one second to value recommended by ITE One year after cameras introduced at same sites Control sites in different county	6 camera sites (2 junctions) 3 control sites	Change in red light violations per 10,000 vehicles After change in amber After cameras	 -36%* (-57 to -6%) -96%* (-96 to -93%)
Red light cameras	Retting, Williams, Farmer and Feldman (1999a)	Fairfax, US	Before-and-after with controls Use of non-camera sites to demonstrate spillover effect Control sites in different town	5 camera sites 2 non-camera sites 2 control sites	Change in: Red light violations per 10,000 vehicles after 3 and 12 months: Camera sites Non-camera sites Control sites	 -7% and-44% -14 and -34% +1 and +5%
Red light cameras	Retting, Williams, Farmer and Feldman (1999b)	Oxnard, US	Before-and-after with controls Use of non-camera sites to demonstrate spillover effect Control sites in different town	9 camera sites 3 non-camera sites 2 control sites in Santa Barbara	Change in: Red light violations per 10,000 vehicles after 4 months at: Camera sites Non-camera sites Control sites	 -40% -50% -4%

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Red light cameras	Richardson (2003)	Australia	EB 5 years before 5 years after Possible spillover effects Method takes account of RTM	8 camera sites 8 control sites	Change in Total collisions Right angle collisions Rear shunts Unclear whether or not collisions include PDO Change in casualties	 -12% +6% +9% -29%
Improving signal conspicuity (8 inch signal heads replaced with 12 inch)	Sayed et al (1998)	British Columbia, Canada	EB (simplified) 1 year before 2 years after Method takes account of RTM	10 sites	Change in Total collisions	 -24%
Countdown timers	Schattler et al (2007)	Peoria, Illinois, USA	Before-and-after No control sites Comparison	3 sites with timers 5 sites with timers 5 comparison sites without	Change in % crossing on 'Walk' and FDW signals Difference in % crossing on 'Walk' and FDW signals	From 65% to 81%* With timer 76% Without 85%*

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Red light cameras	Shin and Washington (2007)	US	Before-and-after with controls and EB Total of 14 years before and after data in Scottsdale, 5 years in Phoenix Spillover effects examined by considering changes on all approaches at camera sites	14 camera sites in Scottsdale 10 camera sites in Phoenix 13 control sites in Phoenix	Change in Right angle collisions Rear shunts at camera sites in Scottsdale Change in Right angle collisions Rear shunts at camera sites in Phoenix Collisions include PDOs	 -20% (-48 to +8%) +41%* (+30 to +50%) -14% (-38 to +10%) +20%* (0 to 30%)
Change from two stage to early cut-off	Simmonds (1987)	London, UK	Before-and-after No controls No account taken of RTM At some sites, other changes took place, meaning that the results were confounded	6 sites	Change in Right turning collisions	-36% (significant at 10% level)
Change from early cut-off to 'right turn held on red'				10 sites	Change in Right turning collisions	-70%*
Change from two stage to split phase				8 sites	Change in Right turning collisions	-73%*
All-red pedestrian phase	Simmonds (1988)	London, UK	Before-and-after with controls No account taken of RTM, however, sites not selected on basis of collision history	16 sites	Change in Total collisions Pedestrian collisions within 50m	 -6% -6%

Intervention	Study	Country	Study design	Number of sites	Outcome measures	Results (95% confidence interval)
Red light cameras	South et al (1988)	Melbourne, Australia	Before-and-after with controls 6 years before 3 years after Possible spillover Some account taken of RTM since controls had similar collision record to camera sites	46 sites 46 control sites	Change in Total collisions Right angle collisions Rear shunts (not turning)	 -7% (-23 to +9%) -32%* (-62 to -2%) -31% (-65 to +3%) Result for right angle collisions claimed significant, challenged by later studies
Improving signal conspicuity (8 inch signal heads replaced with 12 inch)	Srinivasen et al (2008)	Winston-Salem, North Carolina, US	EB 15 years before and after Method takes account of RTM	26 sites 60 control sites	Change in Total collisions Right angle collisions	 -3% (-15% to +8%) -42%* (-56% to -28%)
Conversion of flashing amber to full signal operation				12 sites 60 control sites	Change in Total collisions Right angle collisions occurring at night	-35%* (-65 to -5%) -34% (-70 to +2%)
Red light cameras	Thompson et al (1989)	UK	Before-and-after Up to 3 months after No control sites	2 camera sites	Change in Percentage of vehicles running the red Site 1 Site 2	 -27% +13%
Adoption of RTOR	Zador et al (1981)	US	Before-and-after with controls 4 years before and after	6 states which changed their laws between 1974 and 1977 to allow RTOR 3 control states which did not change their laws	Change in right turn collisions	+21%

* indicates statistical significance at the 5% level or better
EB Empirical Bayes
RTM Regression to the Mean
PDO Collisions involving property damage only, no injuries

Appendix C Meta-analysis of Countdown Timers

C.1 Introduction

Meta-analysis is an analytical process of using statistical methods to combine the results from different studies in order to objectively estimate the reliability and overall size of an effect. Meta-analysis is often used in road safety because of the small number of studies undertaken with homogeneous methods. Examples of this are the meta-analysis by Aeron-Thomas and Hess (2005) and Elvik and Vaa (2004). In the literature review it was noted that the most commonly researched aspect of signal safety in recent years had been countdown signals. Several studies were available for inclusion in a meta-analysis for an analysis to provide an overall estimate of the effect countdown timers on pedestrian crossing behaviours.

An explanation of the methods used and data used in this meta-analysis can be found in Appendix D.

C.2 Data and measures

There were eight suitable studies identified for a meta-analysis and these were all conducted in the USA (see Appendix E). Each of these studies looked at data from several sites, and so a meta-analysis has been conducted at study level (combining all sites within the study) and at site level. Analysis at study level is based on larger numbers of observations and hence each data value has a higher associated confidence than at site level, however there are more sites than studies and so there is value in looking at more data points (albeit with less confidence about each).

C.3 Results: Study level

The eight studies observed the number of pedestrians crossing in the ‘Walk’, flashing ‘Don’t Walk’ and ‘Don’t Walk’ phases. Results for crossing during the ‘Walk’ phase from the eight studies are summarised in Table 8. It can be seen that most of the odds-ratios are larger than one[3], indicating that a greater proportion of pedestrians crossed during the ‘Walk’ phase when there was a countdown timer compared with when there was no countdown timer.

As illustrated in the example given in Table 21, the odds of a pedestrian crossing during the ‘Walk’ phase were increased by an average of nearly 30% when there is a countdown timer, i.e. if 100 pedestrians were observed before and after a countdown timer was installed and 85% and 88% crossed on the ‘Walk’ phase, then their odds of crossing during the ‘Walk’ phase are 5.667 and 7.333 respectively. This represents about a 30% increase in the odds, (i.e. an odds ratio of 1.294) due to a 3% increase in the percentage crossing.

The odds ratio of 1.294 indicates that for these hypothetical data the proportion of people who decide to cross in the ‘Walk’ phase is higher when a countdown timer is present.

[3] Note that an odds ratio which is greater than one indicates that a higher proportion of pedestrians cross when there is a countdown timer and a value less than one indicates that a lower proportion of pedestrians cross when there is countdown timer. However, if there is no effect on the proportion crossing due to countdown timers then the odds ratio will not be statistically different from one and the associated confidence interval will span one.

Table 8: Study data for 'Walk' phase

Study	Reference	Type of study	Number of pedestrians: Arrive	Cross	Wait	% Cross	Odds ratio
4	PHA Transportation Consultants(2005)	Before	12,775	11,483	1,292	89.9	0.998
		After/ Countdown	12,188	10,953	1,235	89.9	
5	Botha (2002)	Before	3,390	2,522	868	74.4	0.857
		After/ Countdown	5,390	3,846	1,544	71.4	
6	Eccles (2004)	Before	9,398	6,406	2,992	68.2	1.213
		After/ Countdown	9,250	6,679	2,571	72.2	
11	Pulugurtha (2004)	Countdown	6,291	5,226	1,065	83.1	2.187
		Control	2,517	1,741	776	69.2	
12	Reddy (2008)	Before	1,788	984	804	55.0	1.054
		After/ Countdown	1,255	707	548	56.3	
14	Schattler (2007) (before and after study)	Before	891	576	315	64.6	2.354
		After/ Countdown	801	650	151	81.1	
14	Schattler (2007) (control study)	Countdown	1,237	880	357	71.1	1.494
		Control	1,113	693	420	62.3	
16	DKS Associates (2001)	Before	691	543	148	78.6	0.984
		After/ Countdown	1,010	791	219	78.3	

C.3.1

The following figure, Figure 6, shows how the estimated effect (odds-ratio) relates to the associated weight. This is a 'funnel' plot and is a way of illustrating possible publication bias towards studies that found an increase in crossing on the 'Walk' sign when there was a countdown timer. Such a bias sometimes occurs because there is a tendency to select positive findings for publication, which could, in turn, lead to the meta-estimate of the effect being biased towards a positive result. However, in this case, there are very few studies and only a suggestion of a central cluster, thereby illustrating that there is no particular bias in reports found or indeed published. A one-sided funnel would indicate possible publication bias since only results in certain directions have been reported (or found).

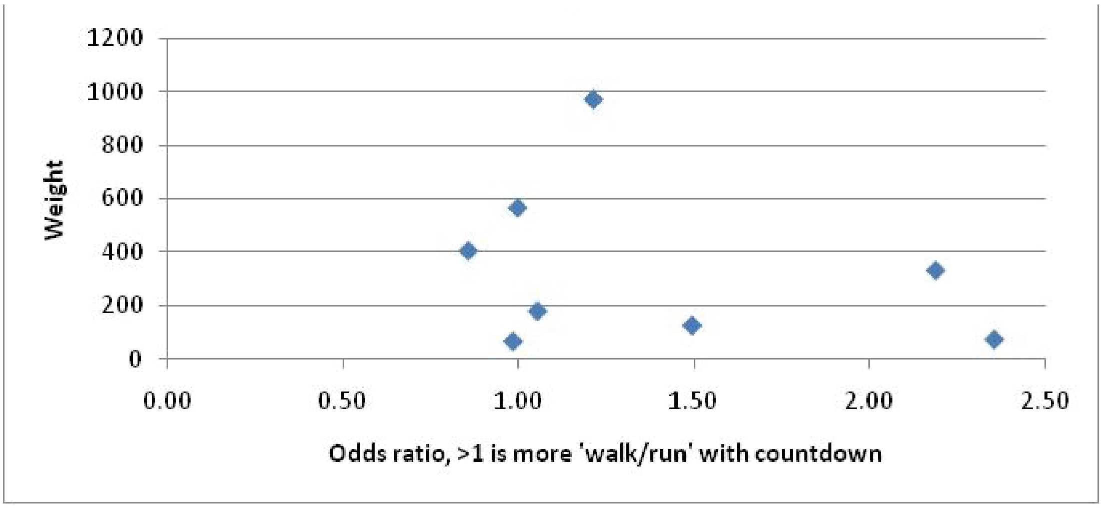

Figure 6: Funnel plot for odds ratio from studies during 'Walk' phase

The weighted analysis of the odd-ratios found that there was heterogeneity in the sample (probability of the Q value Chi-square is <0.001), i.e. we need to adopt a random effects model.

Table 9: Odds ratio for those crossing during the 'Walk' phase, study data

Odds-ratio on crossing	Overall estimate	Standard error	Lower 95% estimate	Upper 95% estimate	Q value: chi-squ on 7df.	Random effects variance (σ^2)
Fixed effects model	1.205	0.019	1.160	1.251	232.5	0.104
Random effects	1.297	0.117	1.020	1.574	9.1	

The summary results, Table 9, indicate that the effect of countdown timers is to increase the odds that pedestrians will decide to cross during the 'Walk' phase, i.e. the odds ratio is larger than one. The random effects 95% confidence interval[4] does not span one indicating that this is a statistically significant effect.

C.3.2 Results: Site level

The funnel plot, Figure 7, for the 61 sites with data on the percentage of pedestrians who cross in the 'Walk' phase is given below. The point with the highest weight was a study where the data was available only at study level and was hence based on more data than the other points which are based on site level data. It can be seen that that there is an outlier point (value 5.7 for odds-ratio), this was due to a fairly low total count of pedestrians (n=82) at the control site together with a low percentage crossing during the 'Walk' phase. The effect of excluding the outlier point has been investigated and is shown below. There is some indication of bias, in that there are more data points to the right of the average estimated odds ratio, (average value about 1.1 to 1.2). However, this slight publication bias has not been adjusted for in the analysis.

[4] If we could repeat the studies say 100 times, this is the interval within which we would expect 95 of the estimates to lie, i.e. we can be 95% confident that the actual estimate lies in this interval.

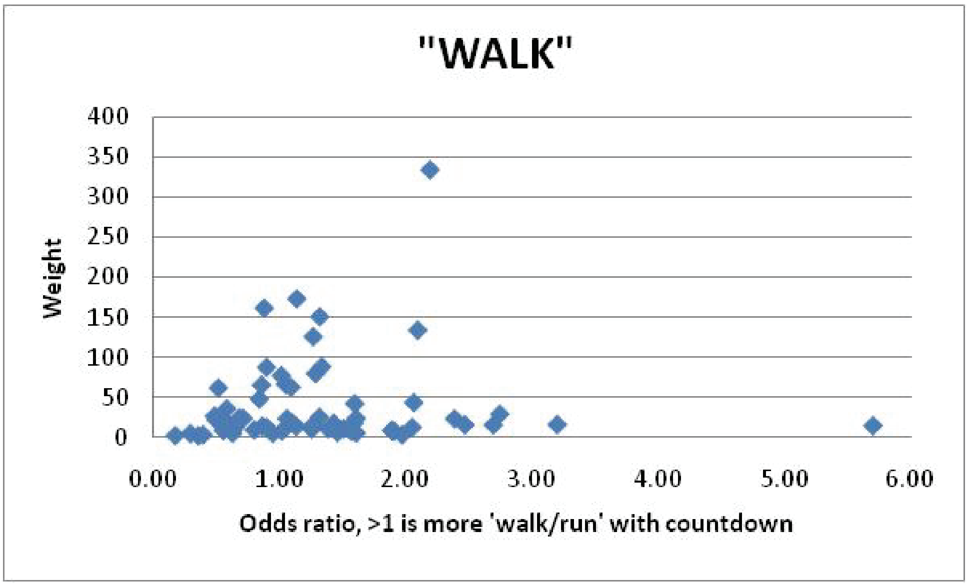

Figure 7: Funnel plot for odds ratio from sites during 'Walk' phase

The weighted analysis of the odd-ratios found that there was heterogeneity in the sample (probability of the Q value Chi-square is <0.001), i.e. we need to adopt a random effects model.

Table 10: Odds ratio for those crossing during the 'Walk' phase, site data (all data points)

Odds-ratio on crossing	Overall estimate	Standard error	Lower 95% estimate	Upper 95% estimate	Q value: chi-squ on 60df.	Random effects variance (σ^2)
Fixed effects model	1.249	0.020	1.209	1.290	526.4	0.200
Random effects	1.147	0.066	1.016	1.278	76.6	

The summary results for crossing during the 'Walk' phase, Table 10, indicate that the effect of countdown timers is to increase the odds that pedestrians will cross in the 'Walk' phase, i.e. the odds ratio is larger than one. The random effects 95% confidence interval does not span one indicating that there is a statistically significant effect due to countdown timers and that it would tend to increase the proportion of people who decide to cross during the 'Walk' phase.

Table 11: Odds ratio for those crossing during the 'Walk' phase, site data (excluding single outlier data point)

Odds-ratio on crossing	Overall estimate	Standard error	Lower 95% estimate	Upper 95% estimate	Q value: chi-squ on 59df.	Random effects variance (σ^2)
Fixed effects model	1.238	0.020	1.197	1.278	491.9	0.187
Random effects	1.118	0.064	0.989	1.247	70.0	

The summary results (excluding the outlier), Table 11, also indicate that the effect of countdown timers is to increase the odds that pedestrians will cross on the 'Walk' phase. The random effects 95% confidence interval just spans one indicating that (strictly) there is not a statistically significant effect due to countdown timers, i.e. excluding the outlier causes the significant effect to become non-significant at the usual 95% confidence level (2-sided) test. In practice the analysis suggests that there is probably an effect due to the countdown timer on the proportion crossing in the 'Walk' phase, but that it is fairly small, i.e. 11.8% increase on the odds ratio due to countdown timers.

In summary, the outlier which had a low associated weights does affect, to a degree, the conclusion that countdown timers have an effect on the proportion of pedestrians crossing on the 'Walk' phase. The overall estimated odds ratio indicates that the ratio of those crossing to not crossing increases by about 12% when there are countdown timers present.

C.3.3 Forest plot for 'Walk'

A 'forest' plot, Figure 8, for all site data is given below. It illustrates the odds ratio for each site with the associated 95% confidence interval. The weighted summary point is also given at the bottom of the plot. It shows that, even though there is considerable uncertainty with some estimates, the overall effect is (as is shown above) significantly greater than unity, i.e. countdown facilities at crossings increases the odds of crossing in the 'Walk' phase.

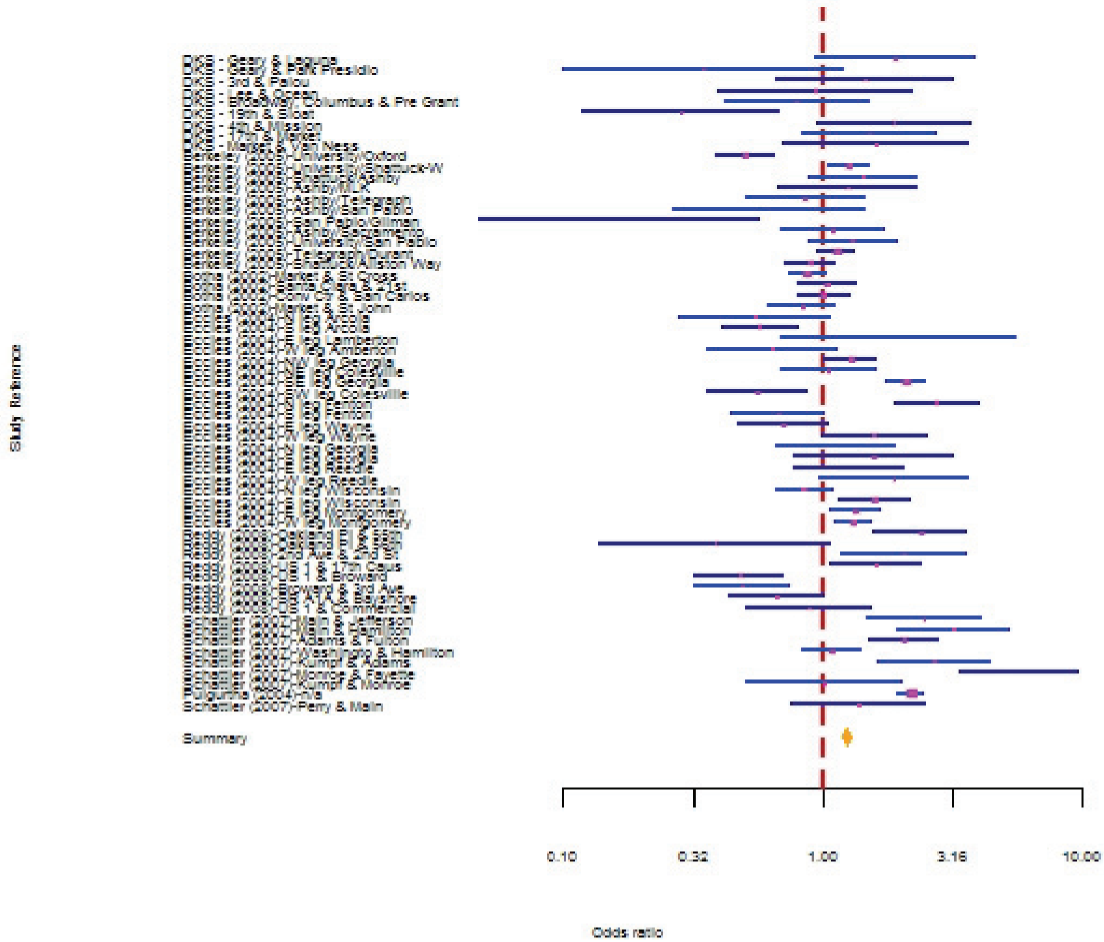

Figure 8: Forest plot of odds ratio and 95% confidence intervals for sites during 'Walk' phase

C.4 Results when sign is flashing and says 'Don't Walk'

C.4.1 Results from six studies

The numbers of pedestrians at the intersection when the sign is flashing 'Don't Walk' and deciding to cross during this phase are given in Table 12. It can be seen that the odds-ratios varied considerably, indicating a lack of consistent effect when there was a countdown timer compared when there was no countdown timer.

Table 12: Study data for Flashing 'Don't Walk' phase

Study	Reference	Type of study	Arrive	Cross	Wait	% Cross	Odds ratio
4	PHA Transportation Consultants (2005)	Before	12,775	1,054	11,721	8.3	1.048
		After/Countdown	12,188	1,050	11,138	8.6	
5	Botha (2002)	Before	3,390	446	2,944	13.2	1.135
		After/Countdown	5,390	791	4,599	14.7	
11	Pulugurtha (2004)	Countdown	6,291	224	6,067	3.6	0.211
		Control	2,517	375	2,142	14.9	
12	Reddy (2008)	Before	1,788	245	1,543	13.7	0.557
		After/Countdown	1,255	102	1,153	8.1	
14	Schattler (2007) (Control data)	Countdown	1,237	170	1,067	13.7	1.031
		Control	1,113	149	964	13.4	
16	DKS Associates	Pre	691	103	588	0.149	0.873
		Post	1,010	134	876	0.133	

The following figure, Figure 9, shows how the estimated effect (odds-ratio) relates to the associated weight. This is a 'funnel' plot and illustrates how few data points there are and how there is no obvious cluster or funnel. It suggests there is a lack of adequate or useful data for this analysis.

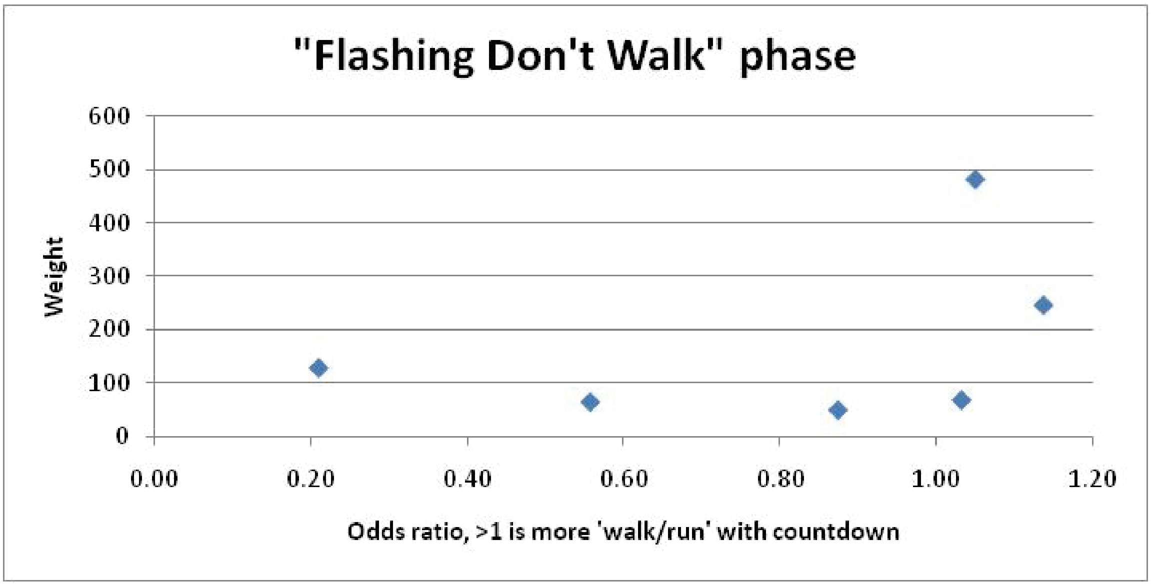

Figure 9 Funnel plot for odds ratio from studies during Flashing 'Don't Walk' phase

The weighted analysis of the odd-ratios found that there was heterogeneity (probability of the Q value Chi-squ is <0.001), in the (inadequate) sample, i.e. we need to adopt a random effects model.

Table 13: Odds ratio for those crossing during the Flashing 'Don't Walk' phase, study data

Odds-ratio on crossing	Overall estimate	Standard error	Lower 95% estimate	Upper 95% estimate	Q value: chi-squ on 5df.	Random effects variance (σ^2)
Fixed effects model	0.834	0.031	0.754	0.913	305.9	0.408
Random effects	0.708	0.264	0.029	1.387	5.0	

The summary results, Table 13, indicate that the observed effect of countdown timers is to decrease the odds that pedestrians will cross during the Flashing 'Don't Walk' phase, i.e. the odds ratio is less than one. However the random effects 95% confidence interval spans one indicating that there is no statistically significant effect due to countdown timers.

C.4.2 Results from 38 sites

The funnel plot, Figure 10, for the 38 sites of the percentage that cross on the Flashing 'Don't Walk' phase is given below. It can be seen that that there are three outlier points (value 5.4, 5.6 and 4.4 for odds-ratio), this was not due to any specific study just associated with relatively low numbers of pedestrians crossing in the before data. The effect of excluding these outlier points has been investigated and is shown below. There is no strong evidence of bias once the outlier points have been removed.

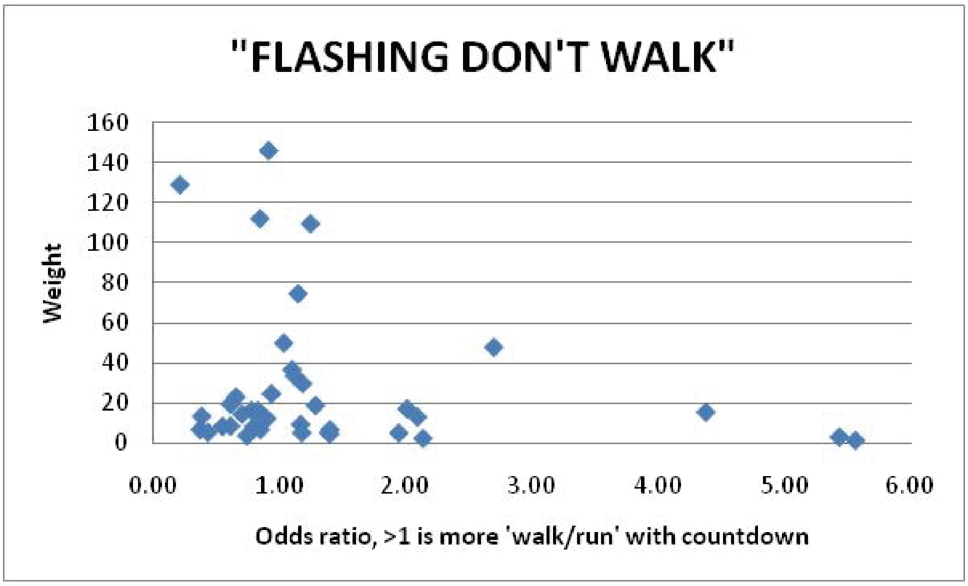

Figure 10 Funnel plot for odds ratio from sites during Flashing 'Don't Walk' phase

The weighted analysis of the odd-ratios found that there was heterogeneity in the sample (probability of the Q value Chi-square is <0.001), i.e. we need to adopt a random effects model.

Table 14: Odds ratio for those crossing during the Flashing 'Don't Walk' phase, site data (all data points)

Odds-ratio on crossing	Overall estimate	Standard error	Lower 95% estimate	Upper 95% estimate	Q value: chi-squ on 37df.	Random effects variance (σ^2)
Fixed effects model	0.873	0.031	0.810	0.936	455.0	0.428
Random effects	1.018	0.119	0.778	1.258	29.1	

The random effects summary results, Table 14, indicate that the effect of countdown timers is to slightly increase the odds that pedestrians will cross during the Flashing 'Don't Walk', i.e. the odds ratio is slightly larger than one. However, the random effects 95% confidence interval spans one indicating that no statistically significant effect due to countdown timers was found.

Table 15: Odds ratio for those crossing during the Flashing 'Don't Walk' phase, site data (excluding three outlier data points)

Odds-ratio on crossing	Overall estimate	Standard error	Lower 95% estimate	Upper 95% estimate	Q value: chi-squ on 34df.	Random effects variance (σ^2)
Fixed effects model	0.848	0.031	0.784	0.911	404.0	0.387
Random effects	0.931	0.117	0.693	1.168	20.9	

The summary results (excluding the outliers), Table 15, indicate that the effect of countdown timers is to slightly decrease the odds that pedestrians will cross during the Flashing 'Don't Walk' phase, i.e. the odds ratio is less than one. However, the random effects 95% confidence interval spans one indicating that no statistically significant effect due to countdown timers was found. The outliers have not affected the conclusions.

C.4.3 Forest plot for 'Walk' during the Flashing 'Don't Walk' phase

A 'forest' plot, Figure 11, for all site data is given below. It illustrates the odds ratio for each site with the associate 95% confidence interval. The weighted summary point is also given at the bottom of the plot. It shows that there is considerable uncertainty with some estimates and that the overall effect is not statistically significant, i.e. countdown facilities at crossings do not change the odds of crossing on the Flashing 'Don't Walk' phase.

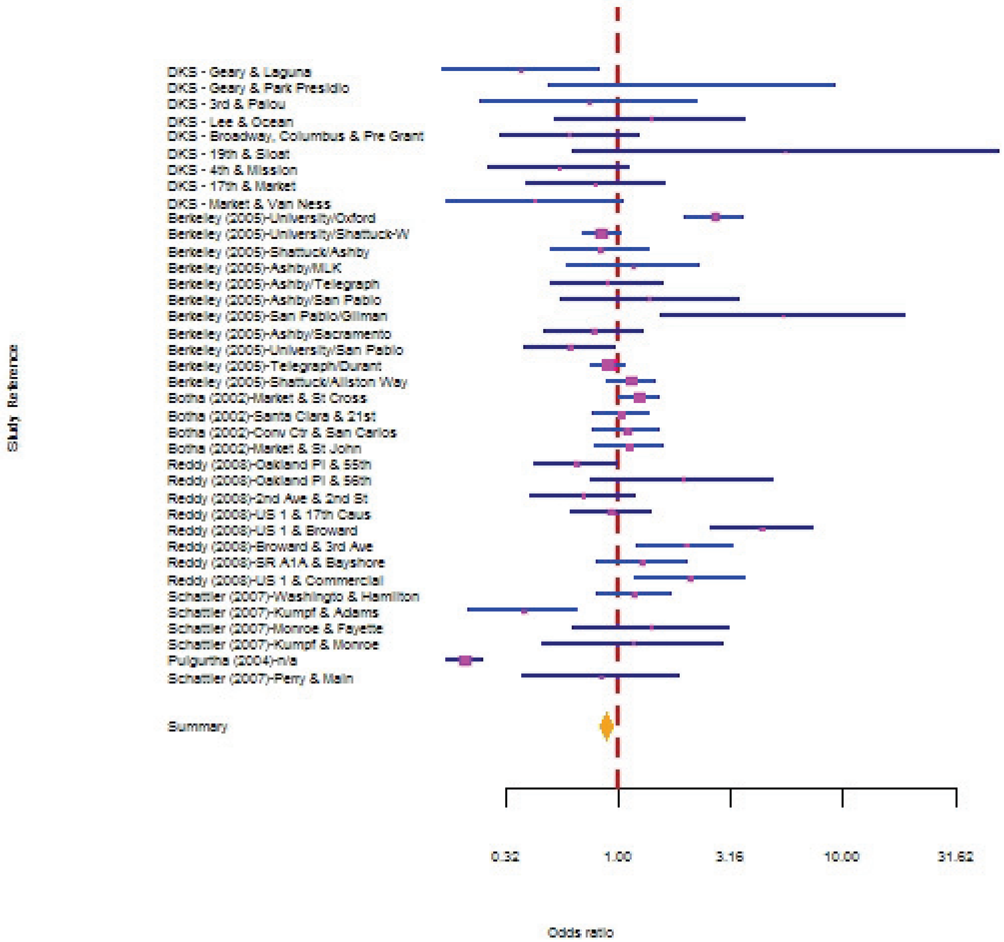

Figure 11 Forest plot of odds ratio and 95% confidence intervals for sites during Flashing 'Don't Walk' phase

C.5 Results when sign says 'Don't Walk'

C.5.1 Results from seven studies

The total numbers of pedestrians arriving at the intersection and those waiting when the sign said 'Don't Walk' are given in the following table, Table 16. It can be seen that most of the odds-ratios are larger than one, indicating that a greater proportion of pedestrians were waiting on the 'Don't Walk' sign when there was a countdown timer compared with when there was no countdown timer.

Table 16: Study data for 'Don't Walk' phase

Study	Reference	Type of study	Arrive	Cross	Wait	% Wait	Odds ratio
4	PHA Transportation Consultants (2005)	Before	12,775	238	12,537	98.1	1.232
		After/Countdown	12,188	185	12,003	98.5	
5	Botha (2002)	Before	3,390	425	2,965	87.5	0.957
		After/Countdown	5,390	702	4,688	87.0	
11	Pulugurtha (2004)	Countdown	6,291	840	5,451	86.6	1.222
		Control	2,517	399	2,118	84.1	
12	Reddy (2008)	Before	1,788	559	1,229	68.7	0.825
		After/Countdown	1,255	446	809	64.5	
14	Schattler (2007)	Before	891	315	576	64.6	2.354
		After/Countdown	801	151	650	81.1	
14	Schattler (2007)	Countdown	1,237	187	1,050	84.9	1.807
		Control	1,113	271	842	75.7	
16	DKS Associates	Pre	691	46	645	0.933	0.747
		Post	1,010	88	922	0.913	

The following figure, Figure 12, shows how the estimated effect (odds-ratio) relates to the associated weight. This is a 'funnel' plot and illustrates a possible publication bias towards studies that found an increase in waiting on the 'Don't Walk' sign when there was a countdown timer. However there are very few studies and only a hint of a cluster.

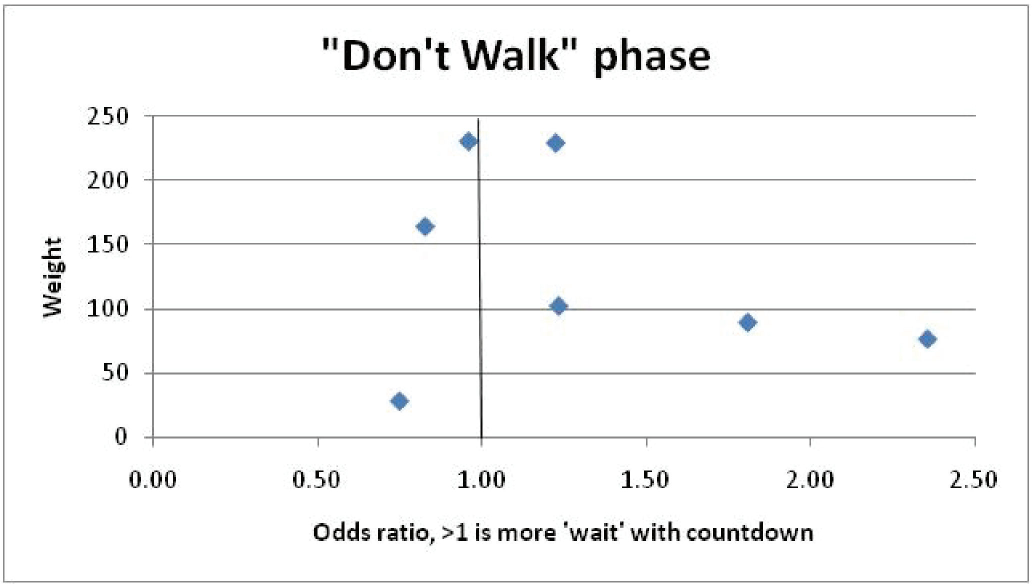

Figure 12 Funnel plot for odds ratio from studies during 'Don't Walk' phase

The weighted analysis of the odd-ratios found that there was heterogeneity in the sample (probability of the Q value Chi-squ is <0.001), i.e. we need to adopt a random effects model.

Table 17: Odds ratio for those waiting during the 'Don't Walk' phase, study data

Odds-ratio on 'waiting'	Overall estimate	Standard error	Lower 95% estimate	Upper 95% estimate	Q value: chi-squ on 5df.	Random effects variance (σ^2)
Fixed effects model	1.159	0.033	1.078	1.240	89.9	0.109
Random effects	1.216	0.131	0.895	1.538	8.3	

The summary results, Table 17, indicate that the effect of countdown timers is to increase the odds that pedestrians will wait on the 'Don't Walk' phase, i.e. the odds ratio is larger than one. However, the random effects 95% confidence intervals span one indicating that no statistically significant effect due to countdown timers was found.

C.5.2 Results from 38 sites

The funnel plot for the 38 sites where there are data on the proportion that wait on the 'Don't Walk' phase is given below, Figure 13. It can be seen that that there are two outlier points (value 9.3 and 13.3 for odds-ratio), one was associated with high numbers of pedestrians waiting in the 'before' data and the other due to a large change in the proportions waiting between the 'before' and 'after' observations. Once the outlier points are removed there is no particular evidence of bias. The effect of excluding these outlier points has been investigated and is shown below.

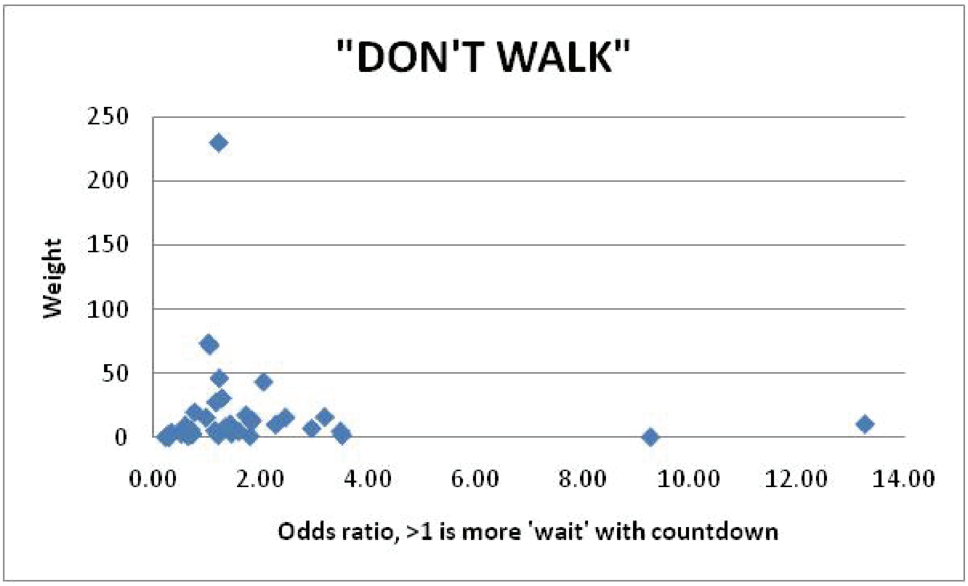

Figure 13 Funnel plot for odds ratio from sites during 'Don't Walk' phase

The weighted analysis of the odd-ratios found that there was heterogeneity in the sample (probability of the Q value Chi-square is <0.001), i.e. we need to adopt a random effects model.

Table 18: Odds ratio for those waiting during the 'Don't Walk' phase, site data (all data points)

Odds-ratio on 'waiting'	Overall estimate	Standard error	Lower 95% estimate	Upper 95% estimate	Q value: chi-squ on 37df.	Random effects variance (σ^2)
Fixed effects model	1.309	0.036	1.235	1.382	162.9	0.187
Random effects	1.366	0.093	1.179	1.554	58.9	

The random effects summary results, Table 18, indicate that the effect of countdown timers is to slightly increase the odds that more pedestrians will wait on the 'Don't Walk' phase, i.e. the odds ratio is larger than one. Further the random effects 95% confidence interval does not span one indicating that there is a statistically significant effect due to countdown timers.

Table 19: Odds ratio for those waiting during the 'Don't Walk' phase, site data (excluding two outlier data points)

Odds-ratio on 'waiting'	Overall estimate	Standard error	Lower 95% estimate	Upper 95% estimate	Q value: chi-squ on 35df.	Random effects variance (σ^2)
Fixed effects model	1.262	0.037	1.188	1.337	100.1	0.097
Random effects	1.276	0.077	1.120	1.431	49.8	

The summary results (excluding the outliers), Table 19, indicate that the effect of countdown timers is to slightly increase the odds that pedestrians will wait on the 'Don't Walk' phase, i.e. the odds ratio is larger than one. Further, the random effects 95% confidence interval does not span one indicating that there is a statistically significant effect due to countdown timers.

In summary, the outliers which have very low associated weights have not affected the conclusion that countdown timers have an effect on the proportion of pedestrians waiting on the 'Don't Walk' phase. The overall estimated odds ratio indicates that the ratio of those waiting to not waiting increases by about 30% when there are countdown timers.

C.5.3 Forest plot for "Wait" during the 'Don't Walk' phase

A 'forest' plot for all site data is given below, Figure 14. It illustrates the odds ratio for each site with the associate 95% confidence interval. The weighted summary point is also given at the bottom of the plot. It shows that there is considerable uncertainty with some estimates; however the overall effect is (as is shown above) significantly greater than unity, i.e. countdown facilities at crossings increase the odds of waiting on the 'Don't Walk' phase.

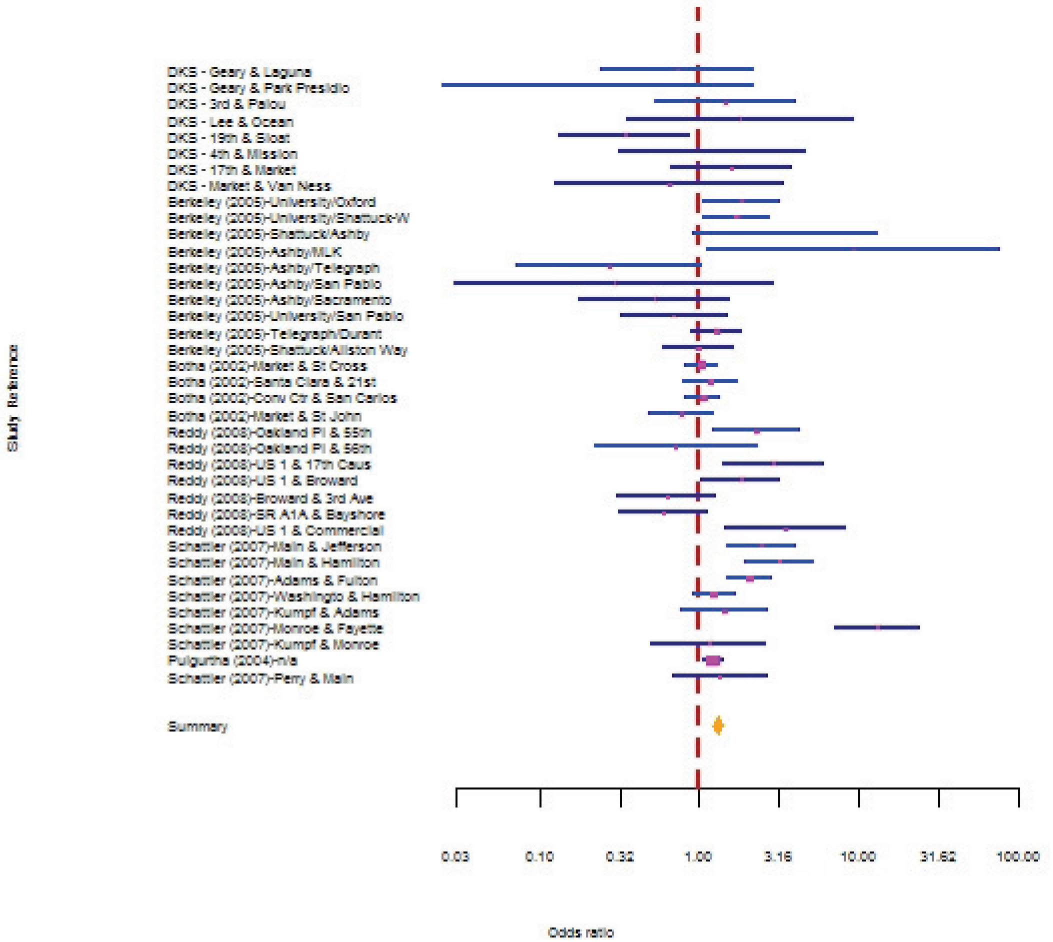

Figure 14 Forest plot of odds ratio and 95% confidence intervals for sites during 'Don't Walk' phase

Overall, the meta-analysis found that countdown timers had a beneficial effect on pedestrian crossing compliance. A higher proportion of pedestrians crossed during the 'Walk' phase during that phase when there was a countdown timer and this finding was statistically significant from study data as well as from individual site data. Results from individual site data also found that the proportion of pedestrians waiting to cross was statistically significantly higher during the 'Don't Walk' phase when there was a countdown timer. However, there was no effect of countdown timers on the proportion of pedestrians crossing during the Flashing 'Don't Walk' phase.

Appendix D Countdown Meta-analysis Theory

There are two basic types of study:

- before-after studies where intersection sites have had a countdown timer installed and pedestrian counts have been obtained before and after installation. These studies did not have control sites.

- countdown site v control studies where existing sites with countdown timers are compared to other intersections without countdown timers over a similar time period

Neither of these types of study are ideal, because the before and after studies should have matched control sites and the countdown v control sites may differ and hence have different characteristics which will be confounded with the countdown timer effect. However, this is what data are available and it has been combined in order to conduct an investigation into three related measures:

- the proportion of pedestrians crossing when the crossing sign says ‘Walk’
- the proportion of pedestrians crossing across when the crossing sign is flashing and says ‘Don’t Walk’
- the proportion of pedestrians waiting when the crossing sign shows a continuous ‘Don’t Walk’

The odds ratio measure has been used to assess the impact on pedestrians crossing or waiting in different phases. We consider a 2x2 matrix of counts of pedestrians who either cross or not by countdown timer installed or not, e.g.

For study or site i	Pedestrians crossing	Pedestrians not crossing
Without a countdown timer	A_i	B_i
With a countdown timer installed	C_i	D_i

The odds ratio is a ratio of odds, i.e. the ratio of the odds of those crossing to not crossing with and without the installation of a countdown timer, i.e.

$OR_i = (C_i/D_i) / (A_i/B_i)$ for the i^{th} study or site, i=1 to k (where there are k studies or sites)

An odds ratio of one indicates that the variables (in this case probability of crossing and existence of a countdown time) are independent. An odds ratio greater than one would indicate that people are more likely to cross when a countdown timer is present.

For example suppose that we have the hypothetical data of 100 pedestrians observed crossing within the three crossing phases, Table 20, when no countdown crossing was in use and 100 pedestrians observed when a countdown timer was installed, as shown below:

Table 20: Hypothetical data of pedestrians crossing during different phases

EXAMPLE Number of pedestrians	Walk	Crossing Phase Flashing Don't Walk	Don't Walk	Observed
No countdown timer	85	10	5	100
With countdown timer	88	9	3	100

Then the odds ratio for those who cross during the 'Walk' phase is given by Table 21:

Table 21: Hypothetical data and odds ratios of pedestrians crossing during the 'Walk' phase

Example	'WALK' phase						
	Cross	Do not cross	Observed	% Walk	Odds	Standard error	Weight
No countdown timer	85	15	100	85%	(85/15)= 5.667		
With countdown timer	88	12	100	88%	(88/12)= 7.333		
			Odds ratio		(7.333÷ 5.667) =1.294	0.416	5.78

The odds ratio is calculated for each study (or site) and has an associated weight. The weight typically used is the inverse of the variance, where the odds ratio variance (fixed effects model) is computed by:

$Var_i = (1/A_i + 1/B_i + 1/C_i + 1/D_i)$ where i=1 to k

And hence the weight is calculated by $W_i = 1/ (Var_i)$

If we have a random effects model there is a random effects variance (σ^2) which needs to be included in the weight (the σ^2 term also needs to be estimated). The weight is then calculated by $W_i = 1/ (Var_i + \sigma^2)$.

D.1 Some detailed background

The odds-ratio is asymmetric and has a complex standard error formula. An odds ratio of one indicates that the odds of an event (e.g. crossing the road) happening are the same whether or not a countdown timer is present. An odds ratio greater than one indicates that the pedestrians are more likely to cross if there is a countdown timer present. An odds ratio less than one would show that pedestrians are less likely to cross when a countdown timer is present. Odds ratios can take values between infinity and 0.
In order to combine odd-ratios from different studies the odds-ratio is transformed by taking the natural log, and then $\log_e$(odds-ratio) signifies that:

- Negative relationship < 0.
- No relationship = 0.
- Positive relationship > 0.

Studies generally vary in size and an effect size, e.g. odds-ratio, based on 100 subjects is assumed to be a more "precise" estimate of the population than an effect size that based on 10 subjects. Therefore, larger studies should carry more "weight" in the analyses than smaller studies. As indicated above we weight by the inverse variance. The standard error (SE) is a direct index of effect size precision. The SE is used to create confidence intervals and the smaller the SE, the more precise the effect size.

We can form a weighted average of $\log_e$(odds-ratio) and results can be converted back into odds-ratios by the inverse of the natural log function. Hence the overall weighted estimate of the effect size is given by:

Overall effect size (odds-ratio) = $\exp (\Sigma \{W_i . \log_e(OR_i) \} / \Sigma \{W_i\})$

We need to test for homogeneity to see whether the assumption that all of the effect sizes are estimating the same population mean is a reasonable assumption, this (a Q test is used which is distributed as a chi-square statistic) assumes a fixed effects model. If homogeneity is rejected, the distribution of effect sizes is assumed to be heterogeneous. In this case we can then fit a random effects model.

A random effects model is used if the total Q is significant and it is assumed that the excess variability across effect sizes derives from random differences across studies (sources that cannot be identified or measured). A fixed effects model assumes that all of the variability between effect sizes is due to sampling error. In other words, the instability in an effect size is due simply to subject-level "noise".

A random effects model assumes that the variability between effect sizes is due to sampling error ***plus*** variability in the population of effects (unique differences in the set of true population effect sizes). In other words, the instability in an effect size is due to subject-level "noise" and true unmeasured differences across studies (that is, each study is estimating a slightly different population effect size).

Fixed effects model weights each study by the inverse of the sampling variance.

Random effects model weights each study by the inverse of the sampling variance ***plus*** a constant that represents the variability across the population effects.

The random effects variance (σ^2) is estimated from calculations under the assumption of a fixed effect model.

(In theory, one can generate 'missing' publication data and so eliminate any bias.)

Appendix E Studies of countdown timers on crossings

EUROPEAN

Study number	**1**
Authors	Baass K G
Country	Germany, France, Canada and USA
Year	1989
Publication	*Review of European and North American practice of pedestrian signal timing.* Prepared for RTAC Annual Conference Calgary, Alberta.
Type of estimate	Considers waiting times and the effect on crossing on 'red', also crossing time allowances
Study design	This is a review of various European and N American findings.
Aggregate effects	Some reported findings on waiting time effects and time to cross
Comment	Consideration of length of time pedestrians prepared to wait indicates that this may only be a few seconds and an upper limit of 30secs is suggested. A German study was quoted where 38% of pedestrians crossed if waiting time between 40 and 60secs as compared to only 18% if waiting time <30secs.
Quality assessment	Some results quoted, but no sample sizes or study designs – hence this review cannot be incorporated into a meta-analysis.
Inclusion in meta-analysis	No

Study number	**2**
Authors	Druilhe M
Country	France
Year	1987
Publication	Pietons: une si longue attende. TEC No. 84-85, Sept., pp36-40
Type of estimate	
Study design	
Aggregate effects	
Comment	Study finding that timers facilitated compliance.
Quality assessment	
Inclusion in meta-analysis	No

Study number	**3**		
Authors	Keegan O and O'Mahony M		
Country	Ireland (Dublin)		
Year	2003		
Publication	*Modifying pedestrian behaviour*. Trans. Res A 889-901.		
Type of estimate	Proportion crossing		
Study design	Single crossing, 1 in 5 pedestrians surveyed for attitude. Video survey to estimate proportion that cross or begin to cross during the 'green man' period. Before period 5 days in June/July 2002 and after period 4 days in August 2002 – not matched on days of week.		
Aggregate effect of countdown indicator	Reduction in % crossing on 'red man' from 35% to 24%		
Comment	Video and attitude survey to evaluate impact of a 'new' type of crossing which has a countdown to how long until the 'green man' phase. Particular interest was in the illegal proportion crossing on 'red man'. Before the timers were installed 65% started crossing on 'green man' which increased to 76% after the timers were installed.		
Quality assessment	Large samples sizes albeit day of week not fully matched nor are times of day (but considerable over-lap between them), only a single site and no control.		
Data for inclusion in meta-analysis	Yes, albeit no control and a single site.		
	Video based data:	'before'	'after'
	Start to cross during 'green man' /'amber'	17516	18189
	Start to cross during 'red man' phase	9431	5871

USA

Study number	**4**		
Authors	PHA Transportation Consultants		
Country	USA (Berkeley, California)		
Year	2005		
Publication	Pedestrian Countdown Signal Evaluation, City of Berkeley. PHA Transportation Consultants, 2711 Stuart Street Berkeley CA 94705		
Type of estimate	Proportion crossing compliance		
Study design	Before and after of 11 junctions with different characteristics		
Aggregate effects	Small decrease in proportion of pedestrians who started to cross during flashing ‘Don’t Walk’ phase with timers		
Effect of countdown timer, ‘before’ to ‘after’	‘Walk’ and cross	Flashing ‘Don’t Walk’ and cross	‘Don’t Walk’ and wait
	89.9% to 89.9%	8.3% to 8.6%	98.1% to 98.5%
Comment	Before data collected Sept/Oct 2002 and July 2003 for 3 intersections, after data collected Spring 2003 and 2004.		
Quality assessment	Samples sizes of 12,000+ in before and after, but no controls and possible seasonality effect.		
Inclusion in meta-analysis	Yes. Probably most useful in looking at change in proportion compliant during the ‘Don’t Walk’ phase, no controls.		

Study number	5
Authors	Botha J L, Zabyshny A A and Day J E
Country	USA (San Jose, California)
Year	2002
Publication	*Countdown Pedestrian Signals: An Experimental Evaluation.* City of San Jose Department of Transportation, California, May 2002.
Type of estimate	Proportion crossing in different phases, driver behaviours, pedestrian v driver conflicts
Study design	Four countdown junctions v two control junctions
Aggregate effects	Increase in proportion of pedestrians who started to cross during flashing 'Don't Walk' phase.
Effect of countdown timer, 'before' to 'after'	'Walk' and cross: 74.4% to 71.4% Flashing 'Don't Walk' and cross: 13.2% to 14.7% 'Don't Walk' and wait: 87.5% to 87.0%
Comment	Details of counts of pedestrians for before and after introduction of countdown timers are provided for the treatment sites in the paper. Before studies March/May 2001 and after studies Sept/March 2001/2. Countdown on FDW phase (flashing 'Don't Walk').
Quality assessment	Only 4 sites were used in the assessment, no data appear to be given for the control sites (which were only observed for a limited period). There were a total 3,390 of pedestrians observed in before stage and 5,390 during after stage when looking at those entering the crosswalk.
Inclusion in meta-analysis	Yes. Can be included as a before v after comparison analysis on the % of pedestrians crossing by phase, and illegal crossing is of most interest. However will have to assume that no seasonal effect and no trend effect since control data not seem to be available.

Study number	**6**		
Authors	Eccles K A, Tao R, and Mangum B C		
Country	USA (Maryland)		
Year	2004		
Publication	*Evaluation of Countdown Pedestrian Signals in Montgomery County, Maryland*. Transportation Research Record TRR 1878, pp. 36–41. Transportation Research Board		
Type of estimate	Percentage starting to cross during ‘Walk’ phase and pedestrian-driver conflicts		
Study design	Before / after study on effect of countdown timers on driver and pedestrians at 5 intersections (22 ‘arms’ of counts)		
Aggregate effects	Significant increase in % starting to cross during ‘Walk’ phase and decrease in pedestrian v driver conflicts		
Effect of countdown timer, ‘before’ to ‘after’	‘Walk’ and cross	Flashing ‘Don’t Walk’ and cross	‘Don’t Walk’ and wait
	68.2% to 72.2%	-	-
Comment	Counts and percentages entering on the ‘Walk’ phase for ‘before’ and ‘after’ on each arm of each intersection are given. Before data collected Sept/Oct 2002 and after data March/June 2003.		
Quality assessment	No control data so would need to assume no trend or seasonal effects. There were a total 9,398 of pedestrians observed in before stage and 9,250 during after stage when looking at those entering crosswalk on the ‘Walk’ phase.		
Inclusion in meta-analysis	Yes. Can be included as a before v after comparison analysis on the % of pedestrians crossing on ‘Walk’ phase, not able to control for trend or seasonality.		

Study number	7		
Authors	Huang H and Zegeer C		
Country	USA (Lake Buena Vista, Florida)		
Year	2000		
Publication	*The Effects of Pedestrian Countdown Signals in Lake Buena Vista.* Florida Department of Transportation, Tallahassee.		
Type of estimate	Compliance with instruction phases		
Study design	Comparison study at 2 junctions compared with 3 comparison sites, no before and after data just reference to control		
Aggregate effects	Statistically significant reduction in compliance on 'Walk' phase		
Effect of countdown timer, 'treatment' to 'control'	'Walk' and cross	Flashing 'Don't Walk' and cross	'Don't Walk' and wait
	58.6% to 46.8%	-	92.3% to 89.5%
Comment	Data collected during different periods during May and November 1999. The characteristics of the countdown v control may have been different; it is thus difficult to assess the impact of the use of a countdown timer.		
Quality assessment	Countdown site data had about 307 observations on the 'Walk' phase and control sites 265 observations.		
Inclusion in meta-analysis	No. Without a before v after element it is not possible to know if differences are simply due to sites, i.e. site and use of a countdown timer are confounded.		

Study number	8		
Authors	Lalani N		
Country	USA		
Year	2001		
Publication	Alternative treatments for at-grade pedestrian crossings. Inst of Transport Engineers. Washington. DC.		
Type of estimate			
Study design			
Aggregate effects			
Effect of countdown timer, 'before' to 'after'	'Walk' and cross	Flashing 'Don't Walk' and cross	'Don't Walk' and wait
Comment			
Quality assessment			
Inclusion in meta-analysis	No		

Study number	**9**		
Authors	Leonard J and Juckes M		
Country	USA (Monterey, California)		
Year	1999		
Publication	*Safety and Behaviour: Behavioral Evaluation of Pedestrians and Motorists Toward Pedestrian Countdown Signals: Final Report*. Dessau-Soprin, Inc., Laval, Quebec, Canada		
Type of estimate	n/a		
Study design	Effects on driver behaviour		
Aggregate effects	No statistically significant results reported		
Effect of countdown timer, 'before' to 'after'	'Walk' and cross	Flashing 'Don't Walk' and cross	'Don't Walk' and wait
	-	-	-
Comment	No evidence that tried to 'beat the lights'		
Quality assessment	n/a		
Inclusion in meta-analysis	No		

Study number	**10**	
Authors	Markowitz F, Sciortino S, Fleck J L, and Bond M Y	
Country	USA (San Francisco, California)	
Year	2006	
Publication	*Countdown Pedestrian Signals: Experience with an Extensive Pilot Installation.* ITE Journal, Vol. 76, No. 1, pp. 43–48.	
Type of estimate	Proportion crossing at difference phases and pedestrian collisions	
Study design	Before and after study at 14 intersections selected because of a range of factors, including pedestrian injury collision record; pedestrian volumes; crossing distance; public complaints about perceived safety i.e. a selection bias.	
Aggregate effects	Decrease in proportion of pedestrians who completed crossing during 'Don't Walk' phase from 14% to 9%. Reduction of pedestrian collisions (52%).	
Effect of countdown timer, 'before' to 'after'	'Walk' and cross	Flashing 'Don't Walk' or 'Don't Walk' and wait
	-	1% increase?
Comment	Did not take RTM into account and sites had possible selection bias. Before data collected March to May 2001 after data April to Dec 2002. Two-phase collection on 8 sites. Impossible to extract source data on pedestrians and crossing compliance, albeit the results suggest that some benefit due to countdown timers.	
Quality assessment	No controls, RTM a possibility due to site selection bias.	
Inclusion in meta-analysis	No. Cannot extract data from report as well as design problems.	

Study number	**11**		
Authors	Pulugurtha S S, and Nambisan S S		
Country	USA (Las Vegas)		
Year	2004		
Publication	*An evaluation of the effectiveness of pedestrian countdown signals.* Proc Institute of Transportation Engineers Annual Meeting, Lake Buena Vista, Florida.		
Type of estimate	Proportions of pedestrians crossing in each phase.		
Study design	Compare 10 countdown junctions with 4 control junctions, no before and after results.		
Aggregate effects	There is greater compliance at countdown timer sites than for control sites.		
Effect of countdown timer, 'control' and 'countdown'	'Walk' and cross	Flashing 'Don't Walk' and cross	'Don't Walk' and wait
	69.2% to 83.1%	14.9% to 3.6%	84.1% to 86.6%
Comment	No statistical analysis reported, but data available		
Quality assessment	Not a before and after but a countdown timer v control study. Countdown timer site counts of 6,291 pedestrians and control site count of 2,517 pedestrians.		
Inclusion in meta-analysis	Yes. Albeit there is an underlying assumption that sites are comparable and no selection bias.		

Study number	12		
Authors	Reddy V, Datta T, Savolainen P, Pinapaka S		
Country	USA (Florida)		
Year	2008		
Publication	*A study of the effectiveness of countdown pedestrian signals.* Florida Department of Transportation, Tallahassee, Florida.		
Type of estimate	Proportions during each phase		
Study design	Before and after study at 8 junctions with countdown timers.		
Aggregate effects	Small increase in % of successful crossings, a decrease in % who started to cross during flashing 'Don't Walk' phase and decrease in % waiting during the 'Don't Walk' phase		
Effect of countdown timer, 'before' to 'after'	'Walk' and cross	Flashing 'Don't Walk' and walk or run	'Don't Walk' and wait
	55.0% to 56.3%	13.7% to 8.1%	68.7% to 64.5%
Comment	Before data collected between June06 and April07 and after data between July07 and Nov07, with respectively 1,788 pedestrians and 1,255 pedestrians. No control sites.		
Quality assessment			
Inclusion in meta-analysis	Yes. Albeit no control sites.		

Study number	13		
Authors	Schrock S D and Bundy B		
Country	USA		
Year	2008		
Publication	*Pedestrian countdown timers: Do drivers use them to increase safety or to increase risk taking?* Transportation Research Board Annual Meeting 2008.		
Type of estimate	n/a		
Study design	Findings on driver behaviour		
Aggregate effects			
Effect of countdown timer, 'before' to 'after'	'Walk' and cross	Flashing 'Don't Walk' and cross	'Don't Walk' and wait
	-	-	-
Comment	Driver behaviour not affected by countdown timer, not try to 'beat the lights'		
Quality assessment	n/a		
Inclusion in meta-analysis	No		

Study number	**14**		
Authors	Schattler K L, Wakim J G, Datta T K and McAvoy D		
Country	USA (Peoria, Illinois)		
Year	2007		
Publication	Evaluation of Pedestrian and Driver Behaviors at Countdown Pedestrian Signals in Peoria, Illinois *Transportation Research Record: Journal of the Transportation Research Board, No. 2002,* Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 98–106.		
Type of estimate	Percentage crossing at different phases		
Study design	Before and after at 3 junctions with countdown timers and 5 countdown v control junctions with similar characteristics		
Aggregate effects	Significant increase in % starting to cross in 'Walk' phase and significantly lower in 'Don't Walk' phase		
Effect of countdown timer, 'before' v 'after'	'Walk' or Flashing 'Don't Walk' and cross 64.7% to 81.2%		"Don't Walk" and wait 64.6% to 81.1%
Effect of countdown timer, 'countdown' v 'control'	'Walk' and cross 62.3% to 71.1%	Flashing 'Don't Walk' and cross 13.4% to 13.7%	'Don't Walk' and wait 75.7% to 84.9%
Comment	Data collected for before and after study in Jan 06 and Nov 06 with 891 and 801 pedestrians respectively. Data for the countdown timer v control study collected in June 06 with 1237 and 1113 pedestrians observed.		
Quality assessment			
Inclusion in meta-analysis	Yes, albeit there is no control on the before and after study.		

Study number	**15**		
Authors	Stollof E R. McGee H and Eccles K A		
Country	USA		
Year	2007		
Publication	*Pedestrian signal safety for older persons*. AAA Foundation for Traffic Safety, Washington, DC		
Type of estimate	n/a		
Study design	n/a		
Aggregate effects	n/a		
Effect of countdown timer, 'before' to 'after'	'Walk' and cross	Flashing 'Don't Walk' and cross	'Don't Walk' and wait
	-	-	-
Comment	This paper focuses mainly on the crossing time and use of pedestrian countdown crossings for the older population. A summary of types of criteria currently used to identify suitable junctions is provided.		
Quality assessment	n/a		
Inclusion in meta-analysis	No		

Study number	**16**		
Authors	DKS Associates		
Country	USA, San Francisco		
Year	2001		
Publication	*Pedestrian Countdown Signals: Preliminary Evaluation, Final Report*.		
Type of estimate	Counts of pedestrians crossing in each phase		
Study design	Pre and post (installation of countdown timer) observation		
Aggregate effects	n/a		
Effect of countdown timer, 'before' to 'after'	'Walk' and cross	Flashing 'Don't Walk' and cross	'Don't Walk' and wait
	0%	-2%	2%
Comment	As supplied by TfL following a visit to USA. 14 sites of which 9 had pre and post data usable within the meta-analysis.		
Quality assessment	n/a		
Inclusion in meta-analysis	Yes		

Literature review of road safety at traffic signals and signalised crossings

A review of safety at signal-controlled junctions and mid-block crossings was undertaken for Transport for London with the aim of informing practice and policy. It covers all aspects of signal design and strategy. A large number of studies on all aspects of signal control were reviewed, the most common topics being red light running and countdown timers. Studies were mainly before-and-after with or without control sites and were found to be very mixed in terms of quality with many having small sample sizes or flawed methodology or both. For some aspects of signal design, there is a conflict between safety and delay. The behaviour of pedestrians has been much more widely studied than their safety.

Other titles from this subject area

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