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Improving Pedestrian Facilities At Signalised Crossings

by

Sitti Asmah Hassan

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

Traffic signal control systems are usually designed to maximise vehicle capacity and minimise vehicle delay with the needs of pedestrians considered separately as necessary. Therefore, the aim of this research is to improve the signal control at pedestrian crossings, so that optimisation takes into account the total delay to all road users including pedestrians. Upstream Detection and Volumetric Detection at pedestrian crossing facilities have been identified as potential alternatives that might enhance pedestrian amenity. These new possibilities were evaluated using a micro-simulation software. Research to date has shown that the VISSIM model is suitable for this evaluation and the latest algorithm for signal controlled pedestrian crossing, the Puffin has been coded into the model and tested. The Puffin then formed a base control strategy against which new strategies were evaluated. The new strategies were then evaluated based on travel delay to both vehicle and pedestrian and also financial benefit to the road crossing. After calibration and validation in VISSIM model, an Upstream Detection and Volumetric Detection were developed. In the Upstream Detection, a push button was located 5 meters at an upstream location of the crossing. In the Volumetric Detection, the optimum maximum green was determined based on the lowest total person delay and total delay costs. Generally, an Upstream Detection caused a reduction in total person delay and total delay costs at a lower vehicle flow. The Volumetric Detection caused a reduction in total person delay and total delay costs at all vehicle and pedestrian flow combinations. The results showed that both Upstream Detection and Volumetric Detection have promising benefits to implement at Puffin crossing. Upstream Detection has a clear benefit at a lower vehicle flow while the Volumetric Detection shows there are changes on maximum green settings at a lower vehicle flow as pedestrian flow increases.

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DECLARATION OF AUTHORSHIP

I, SittiAsmah Hassan

declare that the thesis entitled

Improving Pedestrian Facilities At Signalised Crossings

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
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- I have acknowledged all main sources of help;
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- none of this work has been published before submission.

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1. Introduction

1.1 Background of the Study

Traffic congestion in urban roads and freeway networks leads to a less effective network infrastructure and consequently reduced throughput, which can be overcome via suitable control measures and strategies. As traffic congestion and air pollution became problems in many cities in the world, the consequences for the urban environment and for pedestrians has grown enormously and government agencies of all levels showed an increased interest in promoting walking as the best mode of travel for short journeys (Bowman and Vecellio, 1994b; Kukla et al., 2001; Papageorgio et al., 2003; Southworth, 2005; Tsukaguchi et al., 2007).

Walking is such a fundamental mode of travel that it is often taken for granted and overlooked. Walking is widely recognized as the most environmentally friendly form of transport (Hunt and Al-Neami, 1995; Tsukaguchi et al., 2007). To encourage pedestrians to walk rather than returning to vehicles and increasing traffic congestion, safe and comfortable pedestrian facilities are very important.

A key facility for pedestrians on busy urban streets is the pedestrian crossing. This can take many forms, ranging from 'informal' facilities such is pedestrian 'refuges' in the middle of single carriageway roads through to 'formal' facilities involving street crossings controlled by traffic signals. With the increase in the density of traffic signal installations in most towns and cities, this form of control becomes an integral component of pedestrian crossing opportunities. This itself gives rise to both problems and opportunities with respect to the pedestrians.

1.2 Problem Statement

In the UK, pedestrians are often not given the same priority as vehicle traffic at signalled intersections, as traffic signal control is usually designed to maximise vehicle capacity and/or minimise vehicle delay. Usually, the amenity of vehicles and their occupants are the primary objective in improving traffic system performance, while the needs of pedestrians may not be considered explicitly. For example, pedestrians are often only given an ‘invitation to cross’ (the ‘green man’) after traffic detection has confirmed that this can be done without delaying general traffic significantly – despite the waiting time this may cause for pedestrians. This often leads to an inequity in the facilities provided for these two groups of road users, with delays to pedestrians often greatly exceeding delays to traffic at the same facility. This situation is contrary to the current policies to encourage walking and this can lead to reductions in pedestrian traffic.

Two key features of modern traffic signal control in the UK, such as MOVA (Department for Transport, 1997) and SCOOT (Department for Transport, 1995c) are (i) the detection of vehicles upstream of the junction and (ii) real-time estimates of vehicle delay used for the optimisation of signal timings (Department for Transport, 1995c). Pedestrians are detected only at the junction itself, sometimes only through the activation of the pedestrian ‘push button’ and their presence/numbers are usually not considered in the optimisation process. It is this inequity which has prompted the research described in this thesis – particularly the potential for upstream and/or volumetric pedestrian, with correspondingly improved control, to provide improved pedestrian crossing facilities and enhanced amenity. This theme underlies the same specific research aims and objectives set out in the next section.

1.3 Research Aim and Objectives

The overall aim of this research is to improve the signal control at pedestrian crossings, so that optimisation takes account of all road users.

To accomplish the aim, this research is based on the following objectives:

(a) To identify and understand the current facilities available in the UK for pedestrian crossings.

(b) To examine and develop potential new detection and control strategies for improving pedestrian facilities at signalised crossings.
(c) To develop the required analytical/modelling approaches to enable the new detection and control strategies to be evaluated.
(d) To explore the impacts of the new strategies on pedestrians and all other road users in a range of scenarios.
(e) To develop recommendations based on the research.

1.4 Research Methodology

This research is based on a Puffin signalised crossings. Figure 1.1 shows the flow chart of research methodology adopted in this research.

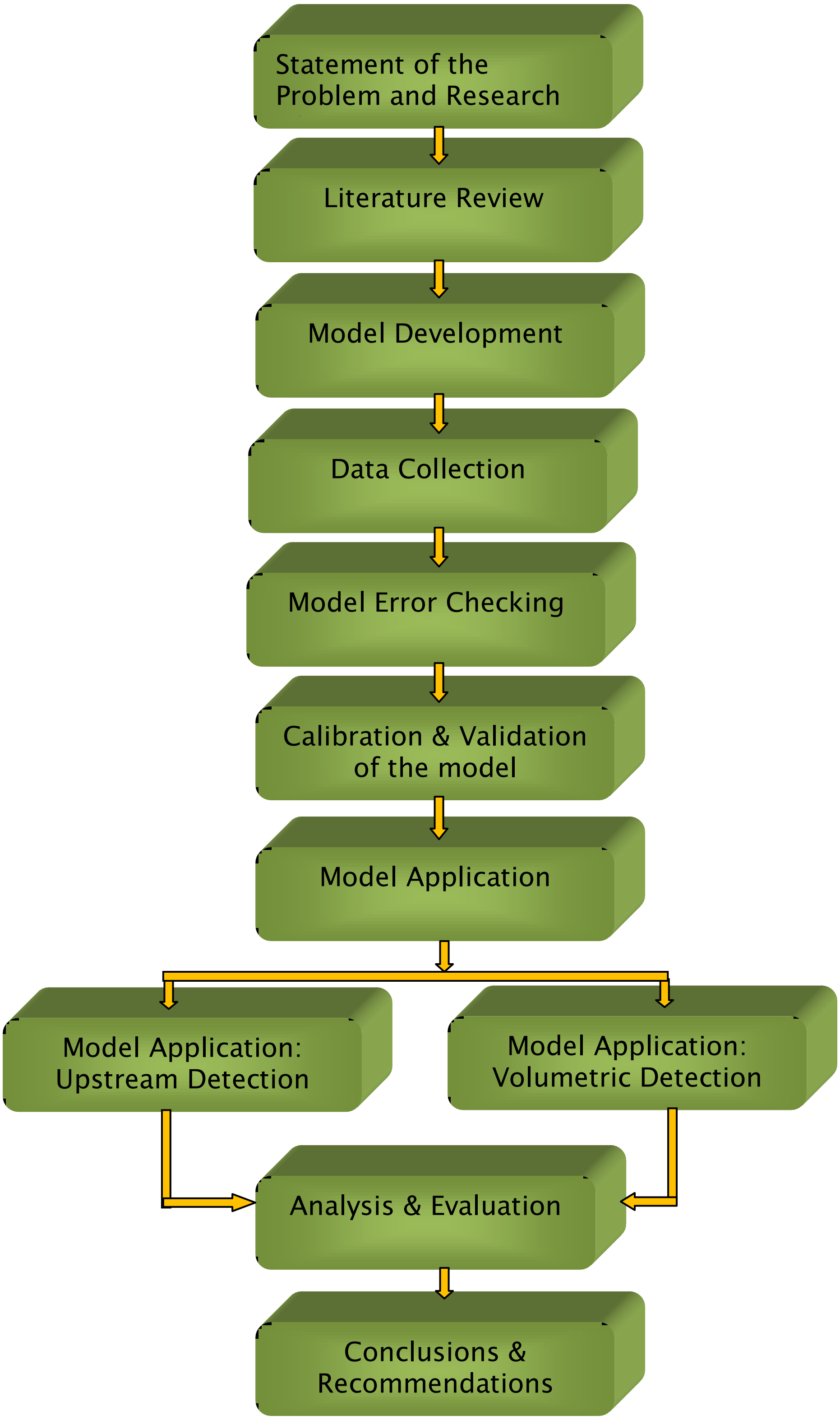


Figure 1.1 Research Methodology Flow Chart

In order to achieve the aim and objective of this study, a comprehensive review on Puffin crossings, pedestrian behaviours, evaluation methods and economic evaluations need to be conducted. Then, Puffin model was developed using VISSIM microsimulation.

Data collection was conducted at two different sites for calibration and validation purposes. Prior to calibration and validation procedures, the code error checking was conducted to eliminate any coding error in Puffin logic. Once the model was successfully calibrated and validated, the model was ready to be used for other applications.

The calibrated and validated model was then developed further into two different strategies: Upstream Detection and Volumetric Detection. These two strategies were evaluated based on measure of effectiveness (MOEs) and economic assessment.

Then, conclusions and recommendations were made from the research.

1.5 Thesis Outline

The dissertation is comprised of 7 chapters. Chapter 1 presents the background of the study, the problem statements, the aim, objectives and the methodology.

Chapter 2 highlights the importance of walking as a mode of transport. This chapter includes review on various aspect of this research such as traffic signal control, pedestrian crossing facilities, pedestrian behaviours, potential evaluation methods used in this research and values of time.

Chapter 3 introduces and justifies the analytical/modelling approach adopted and describes the development and implementation of these approaches.

Chapter 4 describes the calibration and validation process adopted in this research. This includes the details of site selection and data collection for calibration and validation procedures. The results of calibration and validation of vehicle and pedestrian traffic are discussed in detail in this chapter.

Chapter 5 demonstrates the application of the model to evaluate strategies for detecting pedestrians upstream of a pedestrian crossing. Results and discussions from various scenarios are presented and discussed.

Chapter 6 shows the application of the model to consider volumetric pedestrian detection. Again, results and discussions from various scenarios are presented and discussed.

Finally, Chapter 7 is the conclusions and recommendations from the research and summarises requirements/ideas for further word.

2. Literature Review

2.1 Introduction

This chapter presents a literature review covering the topics related to the objectives of this research for which a detailed understanding of the state-of-the-art is required. The review therefore, covers the importance of walking, pedestrian crossing facilities on UK roads (signalised and non-signalised), traffic signal operations and strategies, pedestrian behaviour, and evaluation methods for new strategies covering both operational and economic evaluation. Given the breadth of this review, and the need to understand existing control strategies in detail, it was decided to limit the scope of this research to the UK situation.

This review formed the basis for the subsequent quantitative research, where new control strategies were developed and tested.

2.2 The Importance of Walking

21st century transport policy has given greater weight to environmental considerations by encouraging walking and the use of public transport (Bowman and Vecellio, 1994b; Hunt and Al-Neami, 1995; Hunt and Lyons, 1997; Higgitt and Gleave, 1999; Hunt and Evans, 1999). However, most cities around the world are more concerned with improving vehicular traffic conditions, with most road infrastructure designed to meet the requirements of motor vehicles. Policies to limit the environmental impacts of motor vehicles have focused on traffic management, reducing vehicle travel times to allow smooth movement, more stringent emission legislations and greater investment in public transport schemes (Department for Transport, 2003; Ishaque, 2006). Schemes often have a significant impact in reducing interrupted travel, shortening journey times and giving a greater convenience for car users. This attracts more road users to the car usage. However, the improvements for motor vehicles can have harmful consequences on the pedestrian traffic (Noland, 1996), particularly if they lead to more exposure and conflicts with traffic for pedestrians and to traffic generation.

The increase in car dependency gives a greater negative impact on the environment in the long term. Not only does it reduce walking accessibility, it causes pedestrians to have longer exposure to pollutant concentrations at pedestrian crossings on busy roads which is harmful to health. A study by Ishaque (2006) indicated that there is clearly a trade-off between pedestrian exposure and the reduction in emissions as a result of smooth traffic flow. A reduction in vehicle emissions could increase pedestrian delay and cause a longer exposure to pollutants for pedestrian traffic. It should, however, be kept in view that the level of exposure is much higher at pedestrian crossings in comparison to pedestrian paths further away from vehicle paths.

Emissions and pollution produced by motorised transport come from dangerous or undesirable pollutants such as carbon dioxide, noise and vibrations. Creating an environment for pedestrians that is safe and pleasant involves both positive and negative measures. On the other hand, it means designing pleasure and enjoyment into the environment, and on the other, it may mean restraining traffic, which can causes stop-and-go phenomena for vehicles which can make the environment unpleasant.

It is relevant to note that most people will not walk more than about ½ mile, thus there has been a focus on increasing urban densities and mixing land uses (Noland, 1996). This could increase walking accessibility. The use of the car for short distance journeys is undesirable on environmental grounds (cold starts and the dominance of acceleration and deceleration operations). Therefore, for short trips, walking is a particularly important travel mode and should be further encouraged over the use of motorised transport.

There are a number of reasons why walking is important in transport nowadays. Encouraging walking could not only reduce the car dependency, it also promotes a more healthy lifestyle for pedestrians (Pucher and Dijkstra, 2003; Halden, 2005; Heuman and Buchanan, 2005; Ishaque, 2006). A focus on improving environmental quality not only helps the quality of life but can also make people value walking positively compared to other modes of transport.

Walking as well as cycling is a mode of travel that does not produce any emissions and pollutions to the environment. Walking is seen as one of the alternative exercises that could bring benefit to health and environment and is also accepted as the cheapest mode of transport. Walking is the only mode of travel that does not cost anything and does not impose any cost to society.

The most important factors influencing travellers modal choice are travel time, travel distance and interaction with vehicular traffic (Hatoyama and Kenzaki, 2007). Travel time and travel distance are linked with each other. Increases in both travel time and travel distance reduce the possibility of walking among road users. Land use policies could play a significant role in reducing the effect of travel distance in walking. The interaction between pedestrian and motorised traffic is focused around the activity of street crossings (Hine, 1996).

Since current transport policies are focusing more on the need to encourage the use of public transport, cycling and walking, better facilities to cater for all these road users are becoming more important. Realistically, public highways have to cater for all kinds of transport, and conflicts are bound to arise. So some compromise is inevitable between the conflicting priorities of different road-users. At a minimum, however, pedestrians should expect to receive equal consideration with other road-users in terms of provision for their needs and with regard to their safety on the roads (National Consumer Council, 1987).This is especially true of safety measures, simply because pedestrians are the most vulnerable of road users.

At signalised crossings pedestrians have received far less attention than other modes, particularly compared with motorised vehicles (National Consumer Council, 1987; Wigan, 1995; Keegan and O'Mahony, 2003). Pedestrian travel is often treated as a road safety problem which is treated by ad hoc safety measures and given less consideration than motorized modes. In reality, delays and conflicts with motor vehicles are also highly important for pedestrians and should be considered in any new pedestrian crossing facility.

This chapter now sets out traffic signal operations and then provides a literature review for pedestrian facilities at signalised crossings. This provides a background description of systems and strategies against which new strategies for pedestrians are developed later in the thesis.

2.3 Traffic Signal Control

The main purpose of installing traffic signal control at junctions in or near urban areas is to increase safety and to enhance the capacity of junctions (Salter and Hounsell, 1996; Department for Transport, 2006b; Wong et al., 2007).The installation of traffic signal control is a common control measure at junctions to control conflicting traffic streams and to provide pedestrian crossing facilities. Efficient signal phasing in traffic signal control contributes to the reduction of conflicts between different road users such as cyclists, pedestrians and vehicles where all road users are assisted by traffic signal control to move safely between the conflicting traffic. The successful installation of traffic signal control at junctions can minimise the delay on all traffic, consistent with safety.

Traffic signal control in the UK can be either phase based or stage based, according to the method of control. In designing a safe traffic signal operation, it is important to understand how ‘stages’ and ‘phases’ work. The (electronic) traffic signal controller determines the stages, whilst the signal timings and traffic demand are phase based. The controller operation is designed to optimise both the duration selection and the order of the stages to give right-of-way to the phase (Department for Transport, 2006c). To clarify:

(a) A ***Stage*** is defined as part of signal cycle during which a particular set of phases or movements given green (Salter and Hounsell, 1996; Department for Transport, 2006c). It is defined by numbers, normally starting at either 0 or 1 as the all red stage.
(b) A ***Phase*** is described as a set of movements which can take place simultaneously during the signal cycle. Phases are defined by letters, starting at *a* for vehicular phases.

At signal-controlled junctions, movements of conflicting traffic are separated by setting different signal timings to avoid conflicts (Roess et al., 2004).

Conflicting traffic streams do not receive a green signal simultaneously with other traffic unless permitted in some circumstances such as opposed right-turning traffic.

Figure 2.1 shows a typical four arm approach junction in the UK where the major conflicts occur between north-south traffic and east-west traffic, with right turning traffic also evident on the east and west approaches.

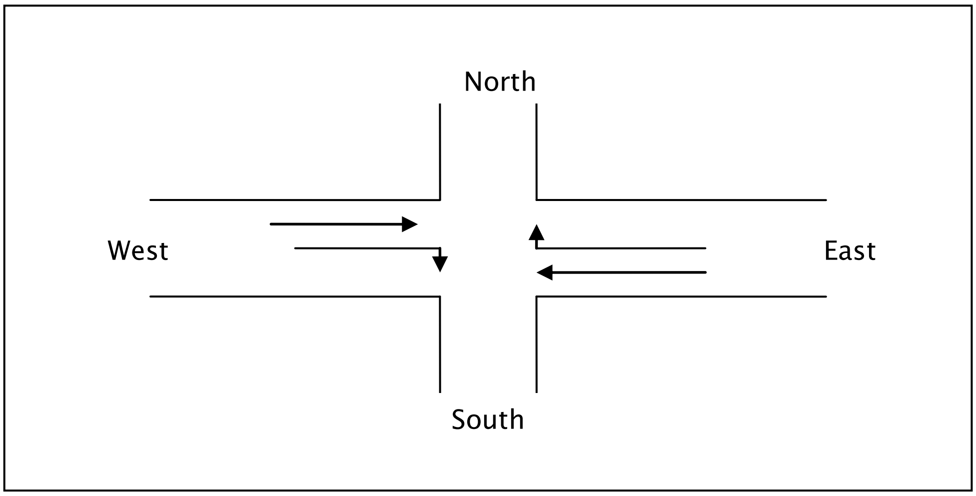


Figure 2.1 Four approaches junction

Referring to Figure 2.1 above, the ‘stages’ and ‘phases’ are illustrated respectively in Figure 2.2 below. Phase A southbound, Phase B westbound, Phase C northbound and Phase D eastbound.

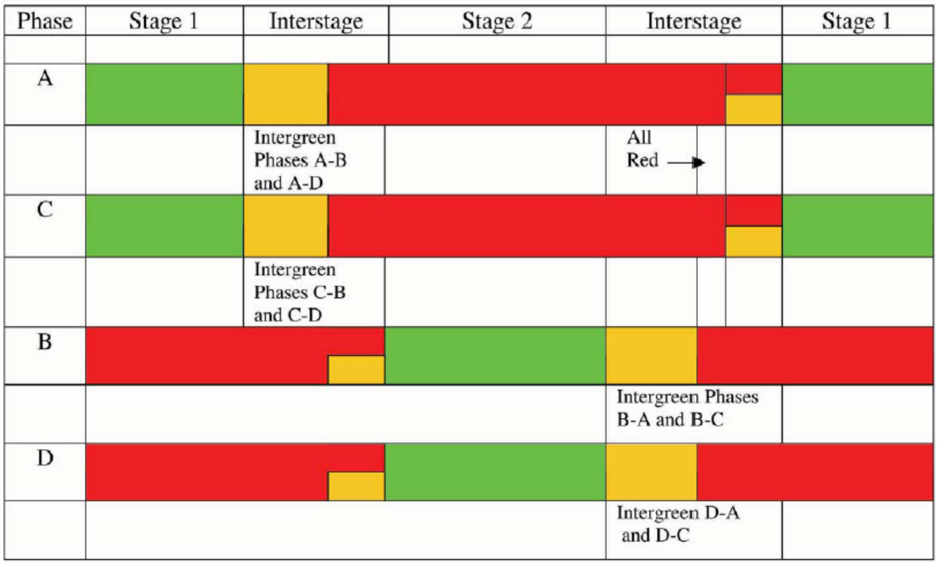


Figure 2.2 Phase and Stage Diagram (Source: Department for Transport, 2006d)

From Figure 2.2 above shows that a stage may consist of several phases and a phase may run in more than one stage. In Stage 1, through movements from southbound and northbound are allowed to move, they are denoted as Phase A and Phase C respectively. Phase B is allowed to move together with Phase D in Stage 2. It is vital to separate conflicting traffic, to minimise accident risk at junctions.

The method of control determines whether a traffic signal is stage based or phase based. An example of phase based microprocessor control is at isolated junctions operating under D-system VA (vehicle actuation). On the other hand, Urban Traffic Control (UTC) systems incorporating TRANSYT or SCOOT are stage based (Salter and Hounsell, 1996).

2.4 Junction Control Strategies

As has been discussed in the above section, there are several methods of control at junctions. Junction control falls broadly into two categories which are isolated junction control and coordinated junction control. Traffic control strategies for both isolated and coordinated junctions may be grouped into two principal classes: fixed time strategies and traffic responsive strategies (Papageorgio et al., 2003). This is shown in Figure 2.3 below.

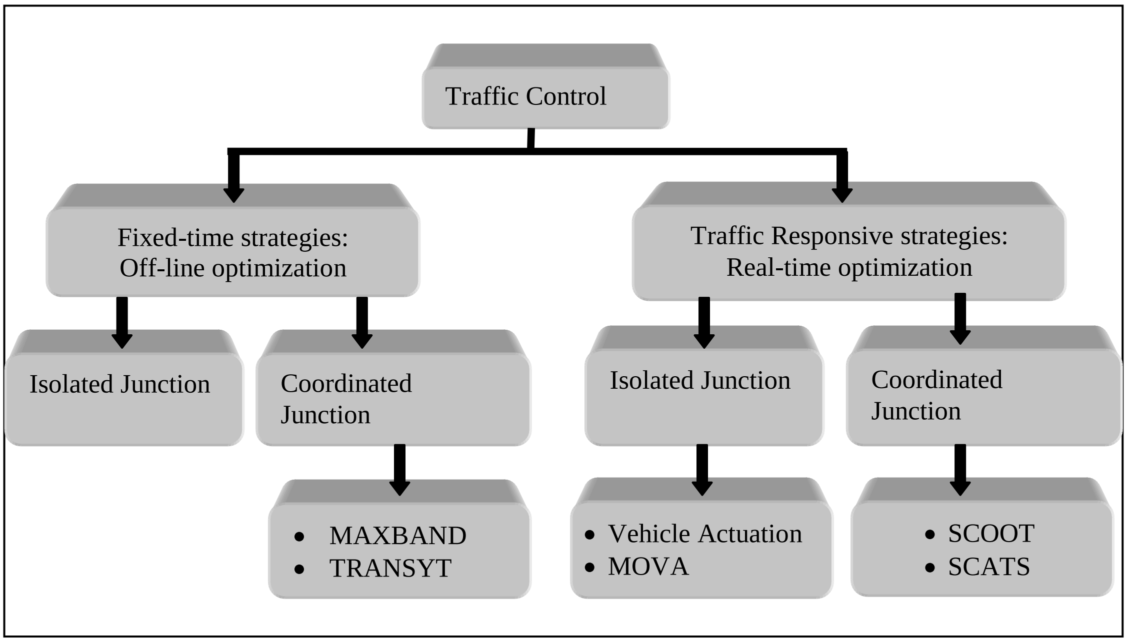


Figure 2.3 Junction Control Strategies

Isolated junction control is normally used where the traffic signals are sufficiently far from neighbouring junctions that any traffic interactions between junctions are insignificant (Hounsell and McDonald, 2001). This occurs mainly in smaller towns and cities or in the outer areas of larger cities. Where a number of signal controlled junctions operate in an area, these are often coordinated under a UTC system to optimize the progression of traffic through the network (Hounsell and McDonald, 2001).

Fixed time strategies are derived off-line by use of optimization codes based on historical data for each stream such as traffic arrival rates, saturation flow rates obtained from traffic surveys and traffic counts (Slinn et al., 2005; Dotoli et al., 2006). MAXBAND and TRANSYT are examples of fixed-time strategies for coordinated junctions.

Traffic responsive strategies perform an on-line and real-time optimisation and synchronization of the signal timing plan. The strategies use information on the actual traffic situation provided by detectors so that the signal timing plan responds automatically to traffic conditions (Papageorgio et al., 2003; Dotoli et al., 2006). This can also be known as vehicle-actuated signal control. Traffic responsive strategies adapted for isolated junction control usually are MOVA and D-system VA in the UK. For coordinated junctions, SCOOT signal control is by far the most common in the UK and SCATS developed in Australia.

2.4.1 Fixed-Time Control at Isolated Junctions

Isolated fixed-time control is relatively unusual in the UK (Department for Department for Transport, 1997; McLeod et al., 2004). The signal control settings such as the timings and order of stages are fixed and not varied regardless of the current traffic conditions. It is rarely satisfactory as it is usually causes more delays and driver inconvenience (Department for Transport, 2006c).

2.4.2 Fixed-Time Control at Coordinated Junctions

A coordinated junction is one within a network of two or more junctions where the signal timings are co-ordinated between the junctions (Papageorgio et al., 2003). In particular, co-ordination requires optimisation of the offset of the start of green between adjacent junctions, so that, ideally, a platoon of vehicles exiting one junction on green can proceed through the next junction on green without vehicles having to stop. As with isolated junctions, coordinated junction controls also can be classified into fixed-time strategies and traffic-responsive strategies.

MAXBAND and TRANSYT (Traffic Network Study Tool) are the popular strategies for fixed-time coordinated control for urban networks. MAXBAND specifies the offsets so as to maximise the green wave which allows more vehicles to travel on a main road within a given speed range without stopping at any traffic signal (Papageorgio et al., 2003).

TRANSYT (TRAffic Network StudY Tool) is an offline computer program for calculating the optimum fixed time plans with which to co-ordinate the traffic signals in any network of roads for which the average traffic flows are known

(Department for Transport, 1995c). It is a well known program and often used as a reference method to test improvements enabled by real-time strategies. Since TRANSYT is an off-line model, no vehicle detection is required to implement it (Hounsell and McDonald, 2001).However, it is usual to develop and implement a range of TRANSYT plans to cater for the variability of traffic flows in a network between days and between times of day. The main problem with fixed-time control for coordinated junctions is that the plans can become outdated through time, particularly where traffic patterns are changing rapidly.

2.4.3 Traffic Responsive Control at Isolated Junctions: Vehicle Actuation Control

In the UK, vehicle actuated control strategies (VA) have been used for many years. It is still probably the most common control strategy for isolated junctions. A vehicle detected in the detection zone, or at the detector locations on the approach will register a demand when approaching the traffic signal. If the signals are on amber or red, the demand is stored in the controller and green will be given when the other stages which have demand are serviced, according to a pre-defined order (Salter and Hounsell, 1996; Department for Transport, 2006c). Vehicles detected on green can extend the green signal up to the pre-set maximum green time. In general, phase changes occur either because a pre-set maximum phase duration has been reached or a gap of sufficient size has occurred in the traffic stream and there is a demand from a competing phase. The maximum green time is set so that if there are calls on other phases they can be serviced without waiting for the first phase to ‘gap out’.

There are two standard methods of detection used at isolated VA sites. These are buried loop detectors, providing what is known as ‘D-system VA’ and Above Ground Detectors (AGDs) (Department for Transport, 2006c). In D-system VA, there are normally a series of three buried loop detectors placed on the approaches with the initial detector some 39 metres distant from the stopline as shown in Figure 2.4.

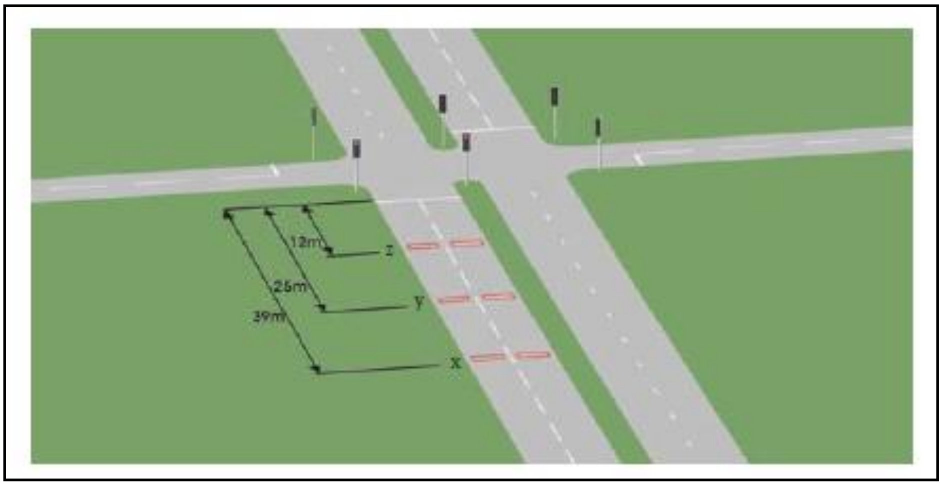


Figure 2.4 D-system VA (Source: Department for Transport, 2006c)

Where AGDs are used, they record vehicle presence within a zone of detection. This is normally set to a zone covering 0 to 40 metres upstream of the stopline. A ‘gap out’ then occurs when no vehicles are detected within this zone.

2.4.4 Traffic Responsive Control at Isolated Junctions: MOVA

Another control tool for traffic-responsive isolated junctions is MOVA (Microprocessor Optimised Vehicle Actuation), developed by the Transport Research Laboratory (Salter and Hounsell, 1996; Department for Transport, 1997).

MOVA is very flexible and can vary signal timings in response to traffic conditions, given the physical layout of the junction, the signal stages available and the traffic conditions at the time (Salter and Hounsell, 1996; Department for Transport, 1997). MOVA can control junctions more efficiently than D-system VA, because of its detector configuration and real-time optimisation based on a queuing/delay model rather than the simpler ‘gap-out’ approach adopted in D-system VA. Nevertheless, MOVA is a more expensive system to install and its actions can be more difficult to interpret by traffic signal engineers. Its rate of implementation has therefore been quite slow in many locations.

2.4.5 Traffic Responsive Control at Coordinated Junctions

Traffic responsive co-ordinated junctions are those usually operating within an Urban Traffic Control (UTC) system with real-time optimisation capabilities. The two main systems in widespread use around the world are SCOOT and SCATS (Department for Transport, 1995c; Liu et al., 2010), although there are many other systems in use in different countries according to national preference.

SCOOT (Split, Cycle, Offset, Optimisation Technique) was developed by the Department for Transport, Transport Research Laboratory (TRL) and industry to tackle problems associated with fixed-time strategies. Traffic responsive strategies require several main components such as vehicle detectors, central controlling computer and implementation of signal settings within the traffic signal controller (Slinn et al., 2005).

SCOOT uses traffic data from vehicle detectors (usually inductive loop detectors) to optimise traffic signal settings (Department for Transport, 1995c; Slinn et al., 2005). SCOOT is an online computer model for receiving and processing traffic data continuously and adjusting the signal timing settings to reduce delay and improve traffic flow. The SCOOT computer runs an on-line traffic model of the network(s), which then calculates the optimum signal settings and transmits the new timings to the signal controller (Slinn et al., 2005).

SCOOT optimises the signal setting by using three procedures, known as (Department for Transport, 1995c):

(a) the Split Optimiser,
   The split optimiser works at every change of stage by analysing the current red and green timings to determine whether it is better to advance or delay the stage up to 4 seconds, or leave it unaltered.

(b) the Offset Optimizer and
   Then the offset optimizer works once per cycle for each node by analysing the current situation at each junction and assessing whether it will be better to change the offset earlier, later or unchanged.

(c) the Cycle Time Optimiser.

In a similar means, the cycle time optimiser adjusts the cycle time a few seconds every few minutes to maintain the critical junction at 90% saturation, if possible.

Thus, by the combination of these three procedures, SCOOT makes a great number of small decisions and can respond to traffic demand effectively. However, SCOOT only benefits vehicles by allowing vehicles to move smoothly but it can impose much higher delays to pedestrians (McLeod et al., 2004). This is because traffic signal co-ordination requires signals within a network to operate to a common cycle time controlled by the busiest junction. This results in a number of junctions operating at a cycle time higher than they would if operating in isolation, which can cause longer waiting times for pedestrians.

SCATS (Sydney Coordinated Area Traffic System) was developed in Australia, in the late 1970s (Hounsell and McDonald, 2001). SCATS is a bi-level optimisation: the upper level involves offset plan selection by time of day according to optimized plans generated by historic data, while the lower level (junction) allows optimization of junction parameters (e.g. green splits) according to local junction traffic conditions (Hounsell and McDonald, 2001). It consists of a central monitoring computer at the control centre, remote regional computers, and local traffic-signal controllers. SCATS uses dynamic cycle length changes (up to 3 seconds per cycle) to meet varying demands of traffic (Homburger et al, 1996).

All traffic control strategies in the UK whether fixed-time strategies or traffic responsive strategies such as D-system VA and MOVA for isolated junctions and SCOOT for coordinated junctions are based on vehicle optimisation with no optimisation for pedestrians.

The following sections review pedestrian detection, current crossing facilities and recent published research on strategies for improving these facilities.

2.5 Pedestrian Detection

The main goal here is to determine the capability of detection technologies in detecting pedestrians efficiently and to discover the strengths and limitations of detectors in pedestrian detection. This provides a background description of this study.

A number of pedestrian detection technologies exist to ensure the safety of pedestrians crossing roads including those visually or physically impaired and elderly people. Generally, detection technologies can be divided into two: active and passive detection (Beckwith and Hunter-Zaworski, 1998). Active detection requires physical touch or movement by pedestrians such as push button and pressure mats. Passive detection does not require physical touch by pedestrians and includes infrared, micro-wave and video detection.

1) Pedestrian Push Buttons

A pedestrian push button is the traditional pedestrian detector. At pedestrian signalised crossings, the push button is used to register pedestrian demand and to enhance safety by decreasing conflicts between pedestrians and vehicles passing through the crossing (Sisiopiku and Akin, 2003). Push button detection is a kind of active detection that requires pedestrian action to show their intention to cross the road.

However, not every pedestrian uses the button to register the demand to cross (Transport for London, 2006; Ishaque and Noland, 2007a). Some pedestrians simply cross the road by accepting a suitable gap between vehicles to cross the road.

2) Pressure Mats

A pressure mat detector uses some form of sensors installed below the surface of the mat to identify an object's presence on the mat (Sherbone, 1992). A pedestrian is detected when he/she is standing on the pressure sensitive mat. The pressure mat detector does not trigger a pedestrian demand to cross, but can cancel demand if the pedestrian should move away.

Due to its operation strategy, this kind of detector is suitable only for waiting pedestrians. However, this principle makes them inconvenient and expensive if they were installed to cover all pedestrian approaches to a crossing. Therefore, currently the pressure mat detector is no longer widely used at the kerbside (Hounsell et al., 2001).

3) Video Detection

Video detection is now gaining acceptance as a more effective technology which requires less maintenance, easy installation, less disruption to traffic flow and in the long term, it is a cost-effective option (Versavel, 2007). It can provide a wide range of traffic data information, given appropriate software for image analysis. Video detection can identify/record traffic events such as stopped vehicles, pedestrian movements, lane changes, speed drops and traffic jams.

However, some studies for video detection of pedestrians reveal that this technology is not yet mature enough for consideration because of problems over false calls and missed calls due to glare and other lighting issues (Hagen, 2006; Zhang et al., 2007). The process of video detection has also had difficulties in detecting objects in darkness.

4) Infrared Detection

Infrared detection is a static detector system in which it has ‘memory’, holding the presence of a pedestrian. Passive infrared detectors rely on detecting the heat emitted from a body by comparison with the background (Beckwith and Hunter-Zaworski, 1998; Department of the Environment et al., 2000). However, the limitation of passive infrared detection is it is possible that no detection occurs if the pedestrians temperature is similar to the ambient condition. Infrared devices cannot discriminate the direction of pedestrian movement, nor can they determine the number of objects detected.

5) Microwave Detection

Microwave detector is a dynamic detector system which reacts to radiation changes produced when an object is in motion; if the object stops, no detection is possible (Department of the Environment et al., 2000). A microwave detector works by analysing the change in radio wave frequencies bouncing off an object moving within its detection zone (the Doppler principle). It can extend the pedestrian clearance interval and would be very useful for pedestrians with special needs. The shortcoming of this detector is the performance of the detector can be affected by adverse weather conditions where heavy rain, for example, can trigger a false call to the detector. Microwave detectors have the advantage of being able to discriminate direction (Sherbone, 1992).

Microwave or infrared systems are widely utilised currently as passive detectors to detect pedestrians (Hagen, 2006). The installation of 'above ground' detection using microwave or infrared detectors have a lower installation costs and less traffic delay during maintenance.

6) Other Detection

Several other technologies were found to be useful in passive detection such ultrasonic detection and piezometric (Beckwith and Hunter-Zaworski, 1998). Ultrasonic detection works on the basis of ultrasonic sound and from the echo bouncing off the objects within its detection zone. However, the operation of the detector is affected by temperature and humidity. Piezometric detection works based on hydrostatic pressure which detects a change of pressure on a material or object.

The main requirement for pedestrian detection is reliability. It may be acceptable if a detector produces a few false calls, but not detecting a pedestrian at all could be a hazardous problem at a crossing, as no 'green man' will be provided when one is needed (Beckwith and Hunter-Zaworski, 1998).

This chapter now proceeds with a review on pedestrian crossing facilities available in the UK.

2.6 Pedestrian Crossing Facilities

A pedestrian crossing can be defined as any location where the pedestrian leaves the kerbside and enters the road, which is designed to assist pedestrians crossing the road (U.S Department of Transportation, 2008). Such ‘isolated’ crossings are sometimes called ‘standalone’ crossings or ‘mid block’ crossings’. Pedestrian crossing facilities are required to accommodate a wide variety of user types, needs, and abilities. Figure 2.5 shows the type of pedestrian crossings adapted in UK.

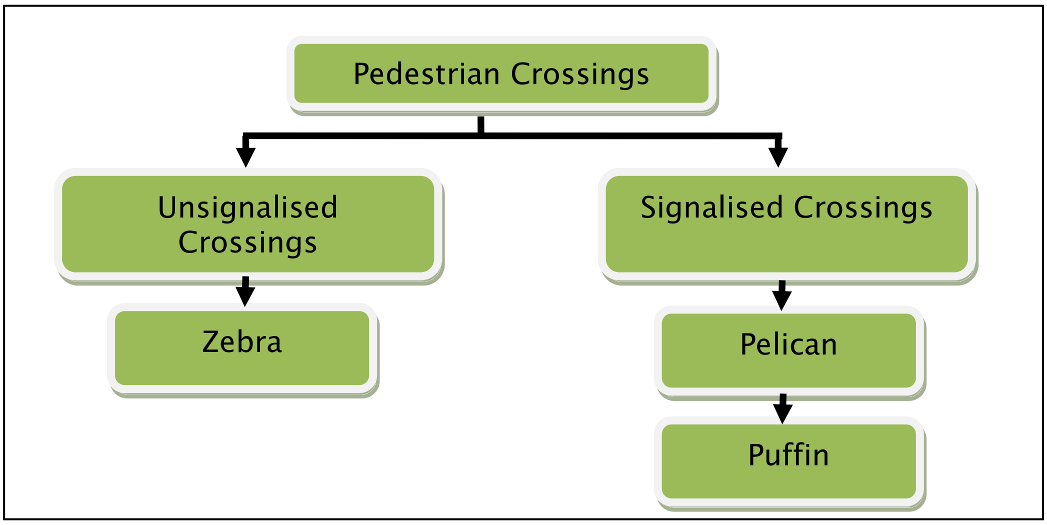


Figure 2.5 Pedestrian crossings type

As shown in Figure 2.5, there are two types of pedestrian crossings commonly used in Britain – categorised as unsignalised and signal-controlled crossings (Ishaque and Noland, 2006). According to Local Transport Note 1/95 (Department for Transport, 1995a), signal-controlled crossings are used where

- *Vehicle speeds are high, and other options are thought unsuitable*
- *There is normally a greater than average proportion of elderly or disabled pedestrians*
- *Vehicle flows are very high and pedestrians have difficulty in asserting precedence*
- *There is a specific need for a crossing for cyclists or equestrians*

- *Pedestrians could be confused by traffic management measures such as contra-flow bus lane*
- *There is a need to link with adjacent controlled junctions or crossings*
- *Pedestrian flows are high and delays to vehicular traffic would otherwise be excessive.*

Pedestrian crossings can be at midblock crossings or junctions. At mid-block crossings, pedestrians encounter traffic moving in one or two directions. Mid-block crossings are often installed in areas with heavy pedestrian traffic to provide more frequent and safe crossing opportunities. In many situations, mid-block crossings are easier for pedestrians to use because traffic flow is not more than two directions. At signal-controlled junctions, traffic is usually moving in multiple directions because of turning vehicles.

A Zebra crossing is an unsignalised crossing type. Pelican and Puffin crossings are signalised pedestrian crossings; both have the same operational function where pedestrians have to register their demand for the ‘green man’ by pressing the push-button. However, Puffin crossings have additional pedestrian detection at the kerbside and on the crossing area, allowing a more pedestrian oriented control strategy. These types of crossings are described below.

(i) Zebra Crossings

A Zebra crossing is an unsignalised pedestrian crossing as shown in Figure 2.6 below. The advantage of a Zebra crossing is it gives precedence to pedestrians to cross the road over vehicular traffic once they have stepped onto the crossing (National Consumer Council, 1987).

Figure 2.6 Zebra Crossing

However it can be argued that the Zebra crossing lacks safety protection for pedestrians to some extent because there is no clear signal indication to either pedestrians or vehicles. In theory a pedestrian can step on the crossing when they arrive, having immediate right-of-way. However, in practice, for safety reasons, pedestrians will wait for a suitable gap in the traffic, or until an approaching vehicle is clearly decelerating, before entering the crossing. Where traffic flows are high, some pedestrians can incur high waiting times; conversely, when pedestrian flows are high, pedestrians may dominate the crossing and cause high vehicle delays. In these situations, signal controlled crossings may be preferred.

(ii) Pelican Crossings

In the UK, most signalled mid-block crossings are Pelican type crossings, which are based on giving a priority to vehicles to minimise the vehicle delay, while the pedestrian phase is only activated based on demand (Lyons et al., 2001). Pelican crossings do not have any pedestrian detection technologies other than the push button which is used to register pedestrian demand on the mid-block crossings.

The Pelican Crossing uses far-side pedestrian signal heads and a flashing amber/flashing green crossing period, of a fixed duration, which is demanded solely by a push button. Figure 2.7 shows the signal timing sequence at Pelican crossings.

	A	B	C	D	E	F	G
VEHICLE SIGNAL	Green	Steady Amber	Red			Flashing Amber	
VEHICLE INSTRUCTION	Proceed if clear	Stop if safe	Wait at stop line			Give way to pedestrians	
PEDESTRIAN SIGNAL	Red			Green	Flashing Green		Red
PEDESTRIAN INSTRUCTION	Wait			Proceed if clear	Do not start to cross		Wait

Figure 2.7 Pelican Signal Timing Sequence
(Source: Department for Transport, 1995b)

The Pelican Signal Timing Sequence shown in Figure 2.7 consists of minimum green time to vehicles (Period A), mandatory 3 seconds stopping amber signal to vehicles (Period B), 3 seconds all red period (Period C), green walking figure to pedestrians (Period D), flashing green and red standing figure to pedestrians. Detailed explanations of the Pelican signal timing sequence can be obtained from Local Transport Note 2/95 (Department for Transport, 1995b).

The Pelican has a flashing amber display to the drivers during most of the clearance period, where drivers are allowed to proceed if the crossing is clear from pedestrians. A flashing green man begins at the end of signal demand cycle to warn pedestrians that they should not start crossing.

A study by Walker et al. (2005) revealed that the flashing green man display can cause confusion to pedestrians – which is one of the reasons for the introduction of the Puffin crossing.

(iii) Puffin crossings

Puffin crossings are the form of signalised mid-block crossing now recommended in the UK (Department for Transport, 2006a). One reason for this is that they provide a uniform approach at signal-controlled junctions and mid-block crossings, with the standard traffic signal sequence - a steady red, amber and green signal to drivers - without flashing amber. By using a steady red signal to vehicular traffic instead of flashing amber at pelican crossings, it is expected that the Puffin gives more safety protection to pedestrians.

A Puffin is a new type of signal controlled facility that consists of pedestrian push button, signals and detectors (Department for Transport, 2001). The red man/green man indicator is positioned above the push button on the nearside signal pole to facilitate pedestrians with visual impairments and, the lack of a far side signal display encourages pedestrians to watch approaching traffic when crossing (or about to cross).

Pedestrian detector systems have been introduced in Puffin crossings to improve the operational efficiency of pedestrian crossings and as an alternative/improvement to the Pelican crossing. Pedestrian presence on the kerbside and on the crossing itself is sensed using appropriately sited Above Ground Detectors (AGDs) (Department for Transport, 2006a).

A pedestrian approaching a Puffin crossing will still register a demand to cross by activating the push button. When the signals are ready to change from vehicle precedence to pedestrian precedence – according to the traffic state – then the kerbside detector checks whether its detection area is still occupied. If so, the signals will change; if not (i.e. the pedestrian has left the waiting area, perhaps already crossing the road in a gap), the signals will remain on vehicle green. When pedestrians have precedence, the vehicle red duration will depend on the length of time pedestrians are detected on the crossing itself. These innovations achieve a reduction in traffic delays and reduce conflicts between drivers and pedestrians (Department for Transport, 2002b; McLeod et al., 2004; Walker et al., 2005).

As the Puffin crossing is the most advanced signal controlled pedestrian crossing facility in the UK, and is becoming commonplace, it is appropriate to review the strategy in full, including its operational sequence and timings. This is set out below, in terms of mid-block crossing operation for clarity.

2.7 Puffin Crossings: Operational Details

At Puffin crossings, the pedestrian stage consists of a fixed green walking man (invitation to cross period), followed by a red standing man (variable clearance period) controlled by the pedestrian on-crossing detectors. The operational diagram for Puffin control is shown in Figure 2.8 below.

	1	2	3	4	5	6	7	8	9
VEHICLE SIGNAL	Green	Amber	Red						Red Amber
VEHICLE INSTRUCTION	Proceed if clear	Stop if safe	Wait at stop line						Wait at stop line
PEDESTRIAN SIGNAL	Red			Green	Red	Ext Red	Red		
PEDESTRIAN INSTRUCTION	Wait			Proceed if clear	Do not start to cross		Do not start to cross		

Figure 2.8 Puffin Signal Timing Sequences (Source: Department for Transport, 2001)

The diagram in Figure 2.8 shows the signal timing sequence for both vehicles and pedestrians. Descriptions of the timing allocations, Period 1 to Period 9 in the operational diagram are described clearly in Local Transport Note 2/95 (Department for Transport, 1995b).

Footpath or kerbside pedestrian detectors detect and monitor pedestrians on the footpath. Kerbside detection is used as an initial detector to confirm the pedestrian presence on the kerb and has not crossed the road before the pedestrian phase initiates. Otherwise, the call for pedestrian phase will be cancelled (Department for Transport, 2002b). It is to ensure that traffic is kept moving when there are no pedestrians waiting on the footpath before the pedestrian phase is initiated. This reduces the number of 'unnecessary' pedestrian phases which can affect the traffic delay.

Another detection system on the Puffin crossing is on-crossing pedestrian detectors which are used to monitor pedestrians on the crossing. They are also based on Above Ground Detectors. The intent is to reduce traffic delay, by starting the vehicle green period as soon as pedestrians are clear of the crossing. They are also used to ensure pedestrian safety by extending the pedestrian clearance period when there is a need for a longer time to cross the road especially for slow walkers (McLeod et al., 2004; Walker et al., 2005). Figure 2.9 shows the kerbside detection and on-crossing detection with their detection zones.

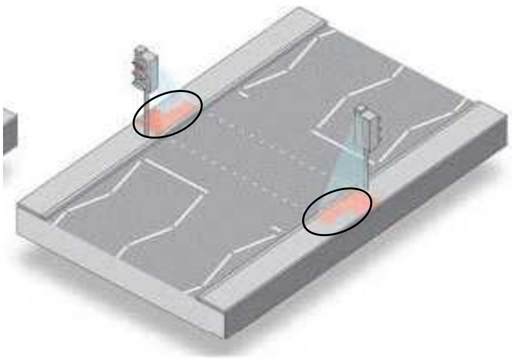
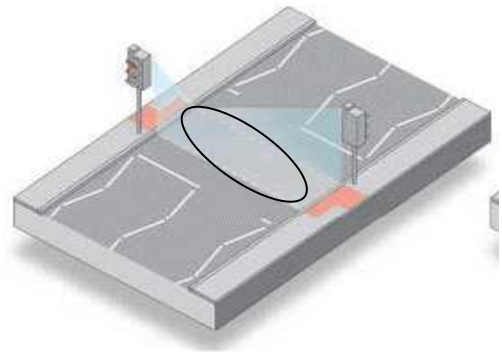
	
(a) Kerbside Pedestrian Detector	(b) On-crossing Pedestrian Detector

Figure 2.9 Kerbside and On-crossing Pedestrian Detector (Source: Department for Transport, 2002b)

On-crossing pedestrian detectors as shown in Figure 2.9 (a) and (b) are normally mounted one on each side of the crossing and are focused on the crossing area between the two lines of studs. At some sites more than two detectors may be needed to provide adequate coverage of detection zone. The detectors respond to all pedestrians within the crossing area walking at speeds ½ metre/second and upwards (Department for Transport, 2002b). Following the green man period, the all-red “clearance period” can be extended by the pedestrian on-crossing detection if there is still pedestrian presence on the crossing. The variable clearance period to account for variable duration of pedestrian presence on the Puffin crossing creates variable cycle times at the crossing.

Installing pedestrian detectors on Puffin crossings should reduce unnecessary delays to traffic and allowing more efficient use of road capacity by making the drivers keep on moving unless a pedestrian is detected on the crossing (Department of the Environment, Transport and the Regions2001; Walker et al., 2005). It also gives greatest benefit to slow moving pedestrians such as the elderly and/or pedestrians with a mobility impairment. The detectors control the traffic lights so that people have enough time to cross safely, but also change them to green as soon as the crossing is clear and there is no-one else waiting to cross.

A main concern with Puffin crossings is in spite of extending the pedestrian clearance time and to make a clear safety protection to road users, the Puffin operational strategy is still based largely on traffic conditions; so pedestrian precedence only occurs when traffic conditions are suitable – suitable gaps or low delay – whereas no account is taken of pedestrian volumes (because these are unknown) or delay. This concern becomes a main focus of the research described later in this thesis. At this stage, it is necessary to review pedestrian behaviour at crossings, to understand key aspects potentially relevant to the development of improved crossing strategies.

2.7.1 Real-time pedestrian information at pedestrian crossings

Pedestrian Countdown at Traffic Signals (PCaTS) is a recent deployment at pedestrian crossings in London, to enhance pedestrian information and amenity. It also has the potential to improve junction efficiency and help optimise the allocation of green time between pedestrians and road traffic (York et al., 2011). A number of similar systems are already operational in other cities around the world.

The need for PCaTS arose from the fact that most pedestrians do not understand the blackout period which occurs with pedestrian crossing signalling at signal controlled junctions. This blackout period is the safe clearance period following the green man indication and it can cause pedestrians to feel uncertain (York et al., 2011). The PCaTS unit displays a visible countdown timer indicating the time remaining to safely clear the crossing before the appearance of the 'Red Man', which is, of course, soon followed by green for traffic and potential danger for pedestrians. PCATS is intended to give pedestrians a better understanding of the time available for them to complete crossing (Transport Research Laboratory, 2012).

International research has demonstrated that PCaTS has a promising benefit in improving pedestrian safety (e.g. in Dublin - (Keegan and O'Mahony, 2003)) and it received positive support from the public due to the increase in the perceived pedestrian safety (Wanty and Wilkie, 2010). The on-street trials of PCaTS in London showed that PCaTS has been positively received by the public; pedestrians felt less rushed and safer using PCaTS and it has reduced pedestrian uncertainty to cross safely (York et al., 2011; Transport Research Laboratory, 2012). The London trials also demonstrated how the implementation of PCaTS can cause a reduction in vehicle delay – in this case by simultaneously reducing the 'green man' (invitation to cross) period (York et al., 2011; Transport Research Laboratory, 2012).

2.8 Pedestrian Behaviour

Realistically, the movement of pedestrians are dynamic and not subject to rules unlike vehicular traffic. Compared to vehicular traffics, pedestrians (Hoogendoorn, 2001; Schroeder and Rouphail, 2007) :

- *are not properly channelised,*
- *can occupy any part of the road space dedicated to them* - pedestrians are free to choose their direction in two-dimensional space.
- *can bump into each other and*
- *have almost instantaneous acceleration or deceleration profiles.*
- *are sensitive to the environment*

The behaviour of pedestrians can be categorised into three levels: Strategic level, Tactical level and Operational level as shown in Figure 2.10 below (Hoogendoorn and Bovy, 2004):

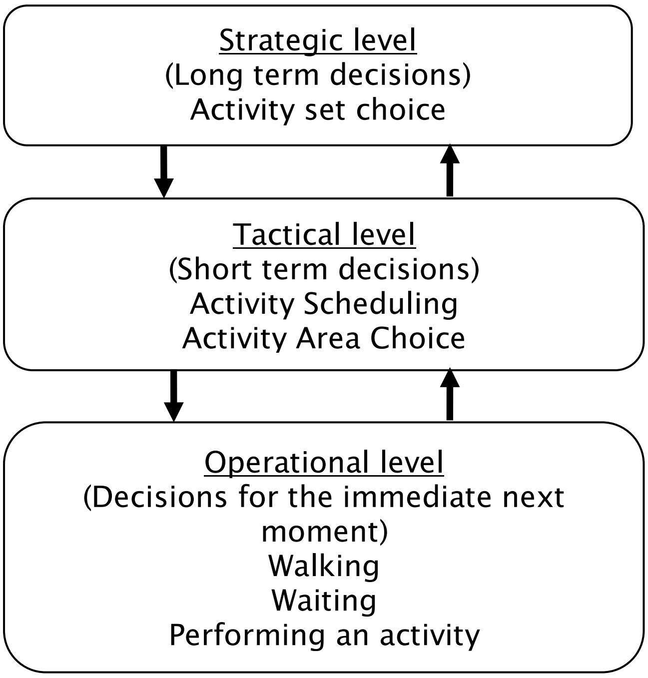


Figure 2.10 Levels in pedestrian behaviour (Source: Daamen, 2008)

Figure 2.10 shows the overall framework of pedestrian behaviours. At the strategic level (minutes to hours), a pedestrian plans his/her route. He/she generates several options to reach his/her destination. At the tactical level (seconds to minutes), the pedestrian decides on the route between the destinations, making a rough routing decision. At the operational level (milliseconds to seconds), the actual movement is performed. This includes avoiding other pedestrians, moving through a dense crowd, or simply continuing the movement towards the destination (PTV, 2008b). Pedestrian behaviour at the operational level is affected by the choices made at the strategic level and tactical level. For instance, to save time, a pedestrian might decide to walk faster (operational level), and take a route that involves crossing roads that have no signalised pedestrian crossings (tactical level), in order to reach a destination by walking (strategic level).

In making recommendations to optimise pedestrian facilities it is therefore essential to study relevant behavioural aspects of pedestrians at pedestrian crossings. These characteristics include pedestrian walking speed (a parameter central to most microscopic simulation models), pedestrian compliance (to the 'green man') and gap acceptance (time and distance gap available in approaching traffic when crossing a road) (Chu and Baltes, 2001; Sisiopiku and Akin, 2003; Schroeder and Rouphail, 2007).

2.8.1 Pedestrian Walking Speed on Road Crossing

Speed is an important parameter for all modes of transport. Pedestrian walking speeds become a major issue in the design and optimisation of pedestrian facilities. Pedestrian desired speed is the speed with which a pedestrian would walk when pedestrian densities are low and the presence of other pedestrians do not have any effect on them. This desired speed varies according to a range of factors, including age, gender, trip purpose, group size, weather and crossing location (ITE Technical Council Committee, 1976; Bowman and Vecellio, 1994a; Transportation Research Board, 2000; Chu and Baltes, 2001; Willis et al., 2004; Martin, 2006). Individual pedestrians have been shown to cross a street at mid-block locations at higher speeds than in groups depending on group size (Gates et al., 2006).

Most of the reviewed studies demonstrate some connection between age and walking speed (Griffiths and Marlow, 1984; Coffin and Morrall, 1995; Pitcairn and Edlmann, 2000; Gates et al., 2006). In their study, Coffin and Morrall (1995) found out that the average walking speeds of elderly pedestrians (over age 60) ranged from 1.17 m/s (4.21 km/h) to 1.31 m/s (4.72 km/h) with elderly women walking slower than elderly men. Men walked faster than women with average walking speeds of 1.29 m/s (4.65 km/h) and 1.24 m/s (4.46 km/h) respectively. Each group of pedestrians is likely to have varied perception of dangers when crossing. Coffin and Morrall (1995) found out that elderly pedestrians are more cautious at crossings due to their inability to judge driver's behaviour and confusion with the pedestrian signal indications. Similar correlation of age and gender to walking speed was found in a study in Australia. Wigan (1995) found out that pedestrians aged over 65 years were walking at an average 2.8 km/h and 3.6 km/h respectively for women and men. Younger pedestrians had a higher walking speed compared to elderly pedestrians. The average walking speeds for younger pedestrians aged 9 to 64 varied between 3.5 km/h and 5.8 km/h for women while for men the average walking speed varied between 4.3 km/h and 6 km/h.

Fruin suggested a wide range of walking speeds ranging from 3.0 km/h to 7.0 km/h (Transportation Research Board, 2000). This range corresponds to the free flow speed from Fruin's speed flow relationship for unidirectional pedestrian flow.

In a study conducted by Williss et. al. (2004), the mean walking speed of individuals was 1.47 m/s (5.3 km/h).In line with several previous studies, the authors found that men walked, on average, faster than women. The speed at which participants chose to walk declined, on average, with increasing age. Pedestrians who appeared to be over 65 years walked significantly more slowly than everyone else. The mean walking speed of younger pedestrians ranged from 1.38 m/s to 1.53 m/s (4.97 km/h to 5.51 km/h) for different age groups while the elderly pedestrians (65 years old and over) walked at an average speed 1.16 m/s (4.18 km/h) .

Gates et. al. (2006) concluded that age has the most significant effect on walking speed. The authors found out that mean walking speed for younger pedestrians and elderly pedestrians (over 65 years old) were 4.79 ft/s (5.26 km/h) and 3.81 ft/sec (4.18 km/h) respectively. The data consisted of 17% of elderly pedestrians. Similar to other studies, walking speed based on gender showed that males had higher speeds than females which were 4.83 ft/sec (5.29 km/h) and 4.60 ft/sec (5.04 km/h) respectively, although it was revealed in the study that gender did not has a significant effect on walking speed choice. The walking speeds for younger and older pedestrians presented by the authors were very similar to those reported by Knoblauch (1996), who found the mean walking speeds for younger pedestrians and persons aged 65 and older to be 4.79 ft/sec (5.26 km/h) and 3.94 ft/sec (4.32 km/h) respectively. The 15th percentile walking speeds for those pedestrians were 3.97 ft/sec (4.36 km/h) and 3.08 ft/sec (3.38 km/h) respectively.

A wide range of pedestrian desired speed is needed to consider elderly pedestrians and pedestrians with walking difficulties. Table 2.1 shows the results of pedestrian speeds from previous researches that have differentiated the speeds based on age.

Table 2.1 Pedestrian speeds at road crossing for adults and elderly

Study	Mean Speed (km/h)			
	Adults		Elderly (over 65 years old)	
	Men	Women	Men	Women
Coffin and Morrall(1995)	-	-	4.65*	4.46*
Wigan (1995)	4.3 – 6.0	3.5 – 5.8	3.6	2.8
Knoblauch et al.(1996)	5.26		4.32	
Fruin(Transportation Research Board, 2000)	3.0 – 7.0			
Willis et al. (2004)	4.97 – 5.51		4.18	
Gates et al.(2006)	5.29	5.04	4.18	

*over 60 years old

Pedestrian crossing speed also depends on what stage of a cycle the pedestrian arrives at the road crossing. Those arriving during the red clearance period following the pedestrian green period who tried to cross the road increased their speed, rather than wait for the next pedestrian phase (Virkler, 1998b). Gates et. al. (2006) found higher speeds for pedestrians crossing outside of the pedestrian green phase (1.52 m/s = 5.47 km/h) in comparison to those crossing during the pedestrian green phase (1.37 m/s = 4.93 km/h). Similarly, Knoblauch et. al. (1996) found that those who cross against the signal tend to walk more quickly.

2.8.2 Pedestrian Compliance and Gap Acceptance Behaviour

Crossing compliance is defined as the percent of pedestrians who cross the road in compliance with the crossing designated area and with the WALK signal indication (Sisiopiku and Akin, 2003). HCM2000 has defined pedestrian non-compliance as disregard for signal indications where pedestrians would cross the road against the signal indication. According to previous studies, pedestrians can be categorised into three types - those who wait for the green man and obey signal indication, those crossing in the red clearance period and those crossing against the red indication or gap-crossed when there is an opportunity (Knoblauch et al., 1996; Virkler, 1998b; Schmocker et al., 2008; King et al., 2009; Wang, 2009).

Pedestrian push buttons at signalised crossings are commonly used to regulate pedestrian crossing demand and to decrease conflicts between vehicular traffics and pedestrians; hence, to increase safety. Pedestrians are supposed to register their demand manually by activating the push-button when they wish to cross a street in a conflict-free phase; however, they frequently do not do so (Rouphail, 1984; Carsten et al., 1998). Davies (1992) found that more than half of the pedestrians at signalised crossings in the UK did not activate the push button to cross. A more recent study by Transport for London (2006) revealed that 28% of users of five Puffin crossings at London did not use the pedestrian demand button. However, this proportion varied from 2% to 49% between sites.

Previous studies have shown a variety of pedestrian compliance to signal indication at pedestrian signalised crossings around the world. An earlier study by Rouphail (1984) in Ohio, USA indicated that pedestrian non-compliance rates at signalised stand-alone midblock crossings were 15%. A study by Virkler (1998a) revealed that 69% of pedestrians crossed outside the green man indication and some of them increased their speeds to enter during the red period rather than waiting for the next pedestrian phase. A study conducted by Eustace (2001) at signal controlled junctions in Kansas found that 81% to 98% of pedestrians arriving during the red period just crossed the road as if it was a pedestrian green phase. Sisiopiku and Akin (2003) revealed that the non-compliance rate of pedestrians at signalised crossings is 45%. A study by Yang et. al.(2006) at mid-block pedestrian crossings in Xi'an, China revealed that between 48 to 100 percent of pedestrians crossed during the pedestrian red phase with a mean value of 85 percent. Hao et. al. (2008) indicated that the probability of pedestrians crossing the road at signalised junctions during the pedestrian red phase was 33.1%. Research by King et. al. (2009) conducted in Brisbane, Australia found out that 21 % of pedestrians did not wait for the green man before crossing the road.

Pedestrians' crossing choices during red phases are seriously impacted by the current traffic conditions, especially the vehicle gaps (Palamarthy et al., 1994; Yagil, 2000; Hamed, 2001; Keegan and O'Mahony, 2003; King et al., 2009) and vehicle volume (Griffiths and Marlow, 1984; Eustace, 2001; Chu et al., 2004). Once a sufficient gap occurs in traffic, pedestrians who want to 'gap cross' will cross the road immediately. A gap in this context has been defined as the distance and time between the pedestrian crossing point and the nearest approaching vehicle reaching the crossing (Moore, 1953; Cohen et al., 1955; Transportation Research Board, 2000; Rouphail et al., 2005). Accepted gaps were measured both in terms of distance and time taken to cover that distance at the instant when the pedestrian started to cross the road (Ishaque, 2006).

An earlier study by Moore (1953) and DiPietro and King (1970) have found a correlation between pedestrian speed variation with the pedestrian's gap acceptance in traffic. Moore (1953) found that pedestrians increased their speed when accepting gaps shorter than 7 sec to cross a road but at time gaps higher than 7 sec there was little change in pedestrian speed of 1.2 m/s as shown in Figure 2.11. DiPietro and King (1970) found that the minimum acceptable gap in a single stream of traffic was 10 seconds for both nearside and farside traffic.

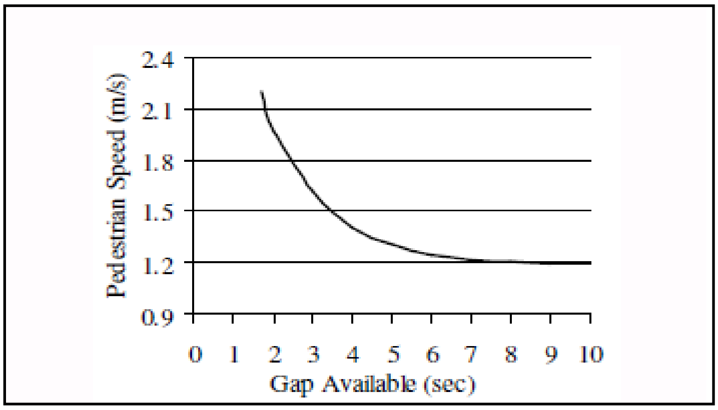


Figure 2.11 Relationship of pedestrian speed with accepted time gap in approaching traffic for a crossing distance of 5.5 m (Source: Ishaque, 2006 cited Moore, 1953)

As shown in Figure 2.11, the shorter the gap accepted by pedestrian, the greater is his/her crossing speed. Crossing in a smaller gap indicated that a level of impatience had been achieved and the pedestrians were willing to take a risk that was previously unacceptable to them.

Cohen et. al.(1955) conducted research on the proportion of pedestrians accepting various gaps in traffic for a 7 m long crossing (from kerb to pedestrian refuge) in Manchester. The results as shown in Figure 2.12 below indicated that 92% of pedestrians would cross the road when the available gap was 7 sec while no one crossed the road when gaps were shorter than 2 secs; everyone crossed the road when gaps were 10 sec or greater. About half of pedestrians would cross the road if the vehicle was 4 to 5 sec away from them.

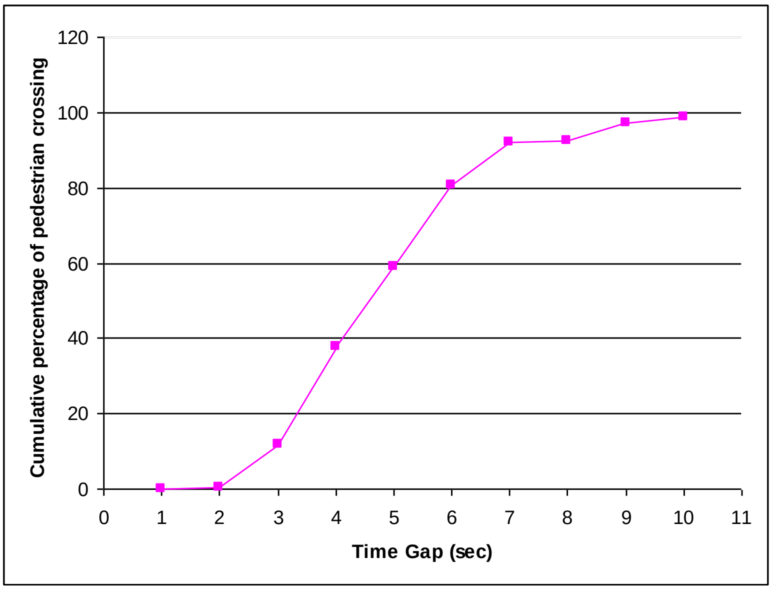


Figure 2.12 Distribution of accepted gaps in traffic (based on results tables from Cohen et al., 1955)

Oxley et. al. (2005) found a similar finding to Cohen et. al. (1955).
Oxley et. al. (2005) found out that 91 % of pedestrians aged 30-45 cross the road when the vehicle was more than 7 sec away from them. A recent study done by Ishaque (2006) showed that most pedestrians will accept a gap of 6 secs while crossing a road with two lanes.

Other studies have also shown that longer pedestrian waiting time at kerbside was the main reason for pedestrians to cross during the pedestrian red phase (Forsythe and Berger, 1973; Hamed, 2001; Houten et al., 2007). A high pedestrian delay might bring frustration to a younger pedestrian whilst for the elderly it might be tiring and uncomfortable to stand and wait at the kerbside for a longer period. Virkler (1998a) and Hao et. al. (2008) found out that the

action of non-compliance behaviour had proved to reduce the pedestrians' delay time compared to pedestrians with complete signal compliance. Research conducted by Transplan Associates (1996) indicated that pedestrians are willing to wait an average of 15 seconds before crossing the street.
Hunt and Lyons (1997) found that pedestrians tend to exhibit more risky behaviour when waiting 30 seconds or more seconds at a crossing. Table 2.2 shows the HCM guide for the likelihood of pedestrian non-compliance at signalised junctions.

Table 2.2 Likelihood of risk-taking behaviour at signalised junctions (Source: Transportation Research Board, 2000)

Pedestrian Delay (sec/ped)	**Likelihood of non-compliance**
< 10	Low
≥ 10 - 20	
> 20 - 30	Moderate
> 30 - 40	
> 40 - 60	High
> 60	Very high

As shown in Table 2.2, the HCM2000 predicts an increasing likelihood of non-compliance with pedestrian signals as pedestrian delay increases. It is clear that pedestrians are willing to engage in risk-taking behaviour when they experience more than a 30 seconds delay. Therefore, a maximum 30 seconds pedestrian waiting time needs to be maintained, otherwise pedestrian non-compliance to the traffic signal could increase (Hounsell et al., 2001; Walker et al., 2005; Schroeder and Rouphail, 2007).

On a contrary, DiPietro and King (1970) and Sun et. al. (2003) found that the pedestrians with longer waiting time at the kerbside need longer gaps in traffic to cross the road. Sun et. al. (2003) explained this trend because pedestrians who still wait at the crosswalk after long waiting times tend to be careful in nature and therefore would never accept a short or risky gap; an argument in support of the heterogeneity discussion above.

Based on this review, the following aspects of pedestrian behaviours are taken into account in modelling:

1) Wider range of walking speeds at signalised pedestrian crossings.
2) Pedestrians are categorised into three types:
    (a) Obey signal indication (whether he/she press the push button or not. He/she always follow the signal indications)
    (b) Press the button but do not necessarily obey the signal indication (gap-cross when there is an opportunity)
    (c) Do not press the push button (gap-cross or cross on the 'green man', whichever occurs first).

Strategies to improve pedestrian crossing facilities have a significant effect on pedestrian and vehicles. Therefore, it is vital to measure the performance of the modelled strategies. The next section covers the evaluation approaches for the new traffic control strategies.

2.9 Evaluation Approaches for New Traffic Control Strategies

There are several ways to evaluate new traffic control strategies including on-street trials, analytical methods and simulation methods. On-street trials are usually justified only after 'desk-top' methods have shown predicted benefits of new strategies, and have been used to specify the on-street trial requirements. This research has to focus on 'pre-trial' evaluation although it is hoped that recommendations will be able to be made for on-street trials.

An analytical method is another option to evaluate potential improvements in pedestrian crossing facilities. This method uses a mathematical approach to calculate the measure of effectiveness of the improved system based on theoretical considerations supported by field data. However, this method is difficult to apply to unusual or non-standard layouts where there is time and space-dependent variability in parameters (traffic flows, pedestrian flows, etc). Critically, systems involving traffic or pedestrian detection and real-time strategy response are too dynamic to be analysed realistically using analytical techniques.

Simulation modelling is considered as one of the ways to evaluate any improvement to optimise the traffic signal control. It allows more realistic and dynamic representation of the hugely varied choice situation that arises in practice (Kolmakova et al., 2005; Slinn et al., 2005). In transportation research applications, simulation methods are often used due to their efficient evaluation of a range of circumstances in a non-destructive method and the ability of the models to capture the interactive effects of different components of the traffic system. Traffic simulation models use numerical techniques on a digital computer to create a description of how traffic behaves over extended periods of time for a given transportation facility or system (Transportation Research Board, 2000; Ahmed, 2005).

The need to use a simulation method for this research arose from the fact that both on-street trial methods and analytical methods have significant shortcomings in assessing the strategies being developed. On-street trials would require a significant investment by a Local Authority in strategies which do not yet exist, It is very unlikely that such investment would be forthcoming at least without robust results from a 'desk top' analysis first.

Regarding a 'desk-top' analysis, a particular complication in this case with the use of analytical or mathematical techniques is the variable nature of pedestrian behaviour, which can only really be represented by using a microscopic simulation approach.

Looking more deeply at this issue, Upstream Detection and Volumetric Detection systems take into account dynamic behaviour of both drivers and pedestrians. Vehicle actuation signal control has a dynamic signal timing which depends on the presence of vehicles and pedestrians. There are interactions between drivers and pedestrians and among themselves in the modelled junctions. Pedestrians do interact with vehicles, for example gap-crossing whenever there is an opportunity. The systems involve uncertainty (stochastic elements) thus the system's behaviour cannot be expressed by mathematical equations. In all the cases, a simulation method would allow the testing of various scenarios without imposing any risks to road users.

The main advantages of simulation modelling as listed in Highway Capacity Manual 2000 are given below (Transportation Research Board, 2000):

1) *The simulation models may offer a methodology when analytical approaches may not be appropriate.*
2) *The simulation models can be used to experiment off line without using on line trial and error approach*
3) *It is also possible to experiment with new situations that do not exist today.*
4) *Simulation models can yield insight into what variables are important and how they interrelate*
5) *These models provide time and space sequence information as well as means and variances*
6) *Systems can be studied in real time, compressed time, or expanded time*
7) *It is possible to conduct potentially unsafe experiments without risk to the system users*
8) *More importantly simulation models can replicate base conditions for equitable comparison of alternatives and the effects of changes on the operation of a system*
9) *It also can handle interacting queuing processes, transfer un-served queued traffic from one time period to the next, vary demand over time and space*
10) *It can model unusual arrival and service patterns that do not follow a traditional mathematical distribution.*

2.9.1 Simulation Models

Due to the dynamic behaviour of vehicles and pedestrians and the complex nature of vehicle-pedestrian interactions, the simulation method was chosen for evaluation. As there are different types of simulation models; microscopic, mesoscopic and macroscopic models, detailed reviews need to be done to configure the best simulation methods as an evaluation tool in this research. The difference of these models are related to the level at which the traffic flow phenomena are being represented (Transportation Research Board, 2000). The level of these models is shown in Figure 2.13 below.

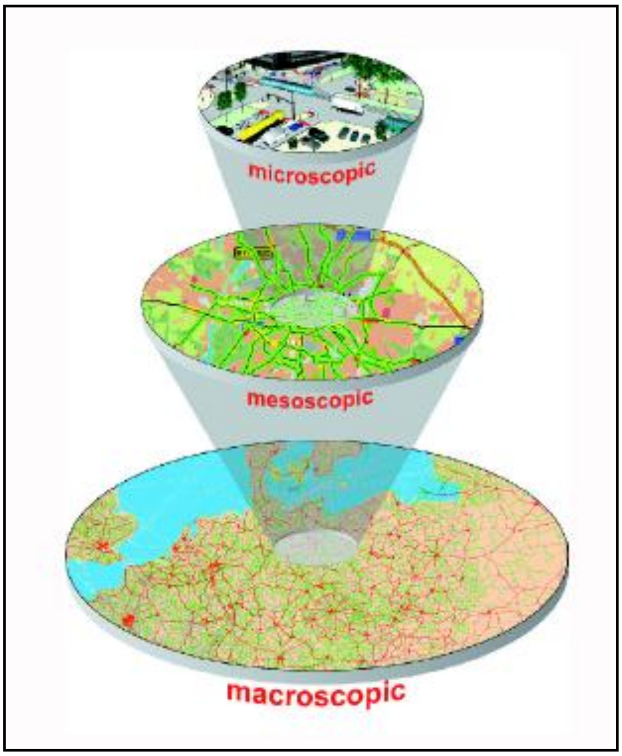


Figure 2.13 Level of simulation models (Source: PTV, 2007)

Figure 2.13 shows three different levels of simulation models: microscopic, mesoscopic and macroscopic. Microscopic models capture the movement of every vehicle or individual entities in the system (Transportation Research Board, 2000). Individual entities either vehicle or pedestrian can be traced through the network, and their time-space trajectories can be plotted. Such models contain processing logic that describes how the individual entities behave.

Mesoscopic models fall between microscopic and macroscopic models. They typically model the movement of clusters or platoons of vehicles and incorporate equations that indicate how these clusters of vehicles interact (Transportation Research Board, 2000).

Macroscopic models are at the other end of the spectrum. They tend to employ flow rate variables and other general descriptors of how the traffic is moving (Transportation Research Board, 2000).

Traffic control needs to replicate the traffic signal system, detectors and various behaviour of road users. Pedestrian modelling comprises complex behavioural issues such as how pedestrians move in relation to other pedestrians, how they interact with vehicular traffic, how they vary their speed and how traffic control systems affect pedestrian travel times. Therefore, for this research purpose, microscopic simulation modelling is used to capture the key entities in the road network such as the traffic signal system, detectors and the individual movement of pedestrians and vehicles in the road network. In particular, microscopic simulation can provide the analyst with a wealth of valuable information on the performance of the system being modelled and potential improvements to it. With the aid of sophisticated computer technology, micro-simulation has become an increasingly popular and effective tool for many applications, which are difficult to study or evaluate by any other methods.

Three most widely used microscopic simulation software VISSIM, AIMSUN and PARAMICS, are compared here in terms of their capability to model all the requirements needed to model Puffin crossing facilities. In order to select the best possible simulation model to assess the system performance, it is first necessary to understand modelling requirements for modelling the interaction between vehicles and pedestrians at signalised crossings. These are listed below:

1) The model should be capable to represent the vehicle actuation traffic control strategy devices and their control logic.
2) The model should be able to model any kind of traffic detectors used for vehicles and pedestrians.
3) The model should be able to model the interaction between vehicles and pedestrians at signalised crossings.
4) The model should be able to control and vary pedestrian demand and arrival patterns.
5) The model should be able to model pedestrian behaviours such as various walking speed and non-compliance behaviour.

6) The model should be able to capture various measures of effectiveness such as travel time and delay to both vehicles and pedestrians.

A well-developed microscopic simulation model must be able to satisfy the modelling requirements above.

1) AIMSUN

AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) developed by Transport Simulation Systems (TSS), Spain, is a software tool capable of reproducing real traffic conditions in different traffic networks such as urban networks, freeways, highways, ring roads, arterials and any combination thereof. It is based on a microscopic simulation approach and was proved to be efficient for testing new traffic control systems and transport policies, both on traditional technologies or on the implementation of the Intelligent Transport Systems (Kolmakova et al., 2005).

AIMSUN needs three types of input data: the network description, the traffic signal control plans and the traffic conditions or traffic demand data (TSS2006a). The simulation outputs provided by AIMSUN include an animated graphical representation of the traffic network, a printout of statistical data (flows, speeds, journey times, delays, stops, fuel consumption and pollution emissions) and data gathered by the simulated detectors (counts, occupancy, speeds, queue lengths).

AIMSUN can model different traffic control types including fixed time control, actuated control and adaptive control through the use of extension applications. It can simulate various types of detectors such as pressure, magnetic, loop, and video but all of them are characterized by their measuring capabilities including vehicle count, presence, speed, occupancy, density and others (Xiao et al., 2005; TSS2006b).

It was claimed by Daamen et. al. (2001) that AIMSUN can model other modes of transport such as transit vehicles, bikes and pedestrians as well as vehicles. However, AIMSUN was especially designed for vehicles and pedestrians can only be modelled at crossings and one cannot enter specific origins and destinations for pedestrians, as is possible for vehicular traffic (Daamen, 2008; TSS2008).

2) PARAMICS

PARAMICS (PARAllel MICroscopic Simulation) was used as a tool for on-line simulation and various studies under a traffic system with various Intelligent Transportation Systems (ITS) components including actuated or adaptive signal control, ramp metering, traffic surveillance cameras, Changeable Message Sign (CMS), loop detectors, and the ITS communication system (Chu and Recker, 2004; SIAS Limited, 2007).

PARAMICS is also capable of simulating pedestrian footpaths, pedestrian flows and pedestrian crossings, including modelling the effects of pedestrians on vehicles (SIAS Limited, 2007; Cumbria County Council, 2008). PARAMICS can simulate various types of pedestrian crossing such as zebra, pelican, puffin, toucan or pedestrian signals at junctions and has an ability to model various ITS detector types giving information such as journey time, queue and pollution monitor.

Paramics can model vehicle behaviour such as car following, lane changing and gap acceptance as well as drivers behaviour. One major limitation of Paramics is its inability to explicitly model pedestrians in a default mode of travel without the need for an application programming interface, or API. The outputs provided by PARAMICS include delay, travel time, speed, queue lengths and vehicle emissions (Hughes et al., 2002; SIAS Limited, 2007).

3) VISSIM

VISSIM, developed by Planung Transport Verkehr (PTV) in Germany, is the most sophisticated micro-simulation traffic tool available (Moen et al., 2000; Hughes et al., 2002; Choa et al., 2003; Tonndorf, 2006; PTV, 2007). It is a microscopic, time step and behaviour based simulation tool, meaning that all vehicles and pedestrians are simulated individually. It also became the first multi-modal microscopic simulation program to include real interaction between pedestrians and vehicles which in detail can model and simulate traffic lights, pedestrian crossings, and normal parts of streets (Ishaque and Noland, 2007b; PTV, 2008a).

It is used off-line to develop and analyse a wide range of traffic control and information measures by using actual measurements and historic data to make predictions. Various signal controls can be modelled by VISSIM including fixed time control, actuated or adaptive control using VAP and various different junction layouts and control methods such as signalised and unsignalised roundabouts and junctions (Fellendorf, 1994; Ahmed, 2005; Xiao et al., 2005). The Vehicle Actuated Programming logic in VISSIM can be used to simulate the operation of Puffin crossings.

There are three major components in VISSIM: an input module, a simulator, and an output module (Hughes et al., 2002; PTV, 2008b). The input module to key in the input values is a Windows-based user interface. While the simulator also known as processor is used for generating and moving traffic, updating system status, and collecting statistics. The output module produces output files or results.

VISSIM can produce various measures of effectiveness such as total delay, stopped-time delay, stops, travel time and queue lengths for all default or user-input travel modes, including pedestrians and bicycles. VISSIM is also capable of modelling the effect of signal cycle timings on delay and travel time costs for both pedestrians and vehicles (Ishaque and Noland, 2007b).

Internally, VISSIM consists of two different programs which are exchanging detector calls and signal status through an interface (PTV, 2005). Figure 2.14 below shows the communication between the traffic simulator and the signal state generator.

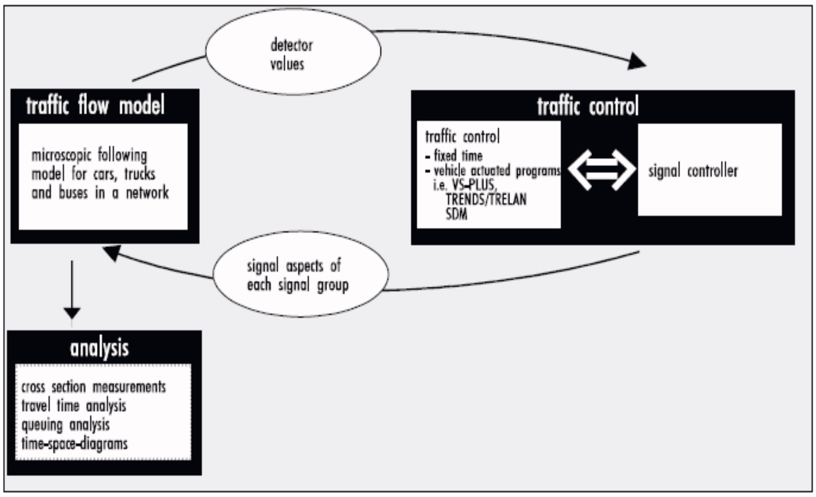


Figure 2.14 Communication between traffic simulator and signal state Generator (Source: PTV, 2001)

As seen in Figure 2.14, the VISSIM traffic simulator consists of a microscopic traffic flow model including car following and lane change logic for vehicles in a network. Detectors pass the information from the traffic simulator on a discrete time step basis. It then determines the signal status for the following second and returns this information to the traffic simulator.

Table 2.3 below shows the summary of the aspects that have been compared between three micro-simulation programs: VISSIM, AIMSUN and PARAMICS.

Table 2.3 Capability Analysis of Micro-simulation Tools

	AIMSUN	**PARAMICS**	**VISSIM**
Actuated traffic signal control	√	√	√
Pedestrian walking paths (sidewalk and pedestrian crossing)	√	√	√
Pedestrian behaviour	√ Only with the addition of particular algorithm created by user.	No	√
Interaction between vehicle and pedestrian at signalised crossing	No info	√	√
Traffic detector for both vehicle and pedestrian	√	√ Lack info but prone to be YES	√
Vary pedestrian demand and arrival patterns	No info	No info	√
Various measure of effectiveness for vehicle and pedestrian such as travel time and delay	√ But no further information on pedestrian perspective.	√	√

On the basis of the stated comparisons in Table 2.3, VISSIM is showing better modelling capabilities for pedestrians compared to other simulation tools, AIMSUN and PARAMICS. Therefore, VISSIM was selected as the best suited model for this research for its better pedestrian modelling capabilities over other leading micro-simulation software. In addition, it has been shown in previous studies that VISSIM has a good ability to model various pedestrian behaviours and the interaction between pedestrians and vehicles

(McLeod et al., 2004; Kolmakova et al., 2005; Rouphail et al., 2005; Ishaque, 2006; Tonndorf, 2006; Schroeder, 2008). AIMSUN and PARAMICS appear to have less facilities for pedestrian behaviour modelling (Kolmakova et al., 2005).

VISSIM is a microscopic simulation tool meaning that all vehicles and pedestrians are simulated individually. The behaviour of each pedestrian and vehicle can be defined individually. VISSIM itself is not a signal optimisation tool. It is rather a signal evaluation tool. However, the Vehicle Actuated Programming (VAP) interface within VISSIM offers a viable tool to develop and test optimisation techniques.

2.9.2 Overview of Pedestrian Modelling in VISSIM Micro-Simulation

VISSIM offers three different ways to model pedestrian flow (PTV, 2008b). One of the ways is to model pedestrians as the 'no interaction' type, in which pedestrians do not recognise any other pedestrians and their movements are not subject to the presence of any other pedestrian in their vicinity. This option allows all waiting pedestrians to proceed simultaneously when the pedestrian green phase starts. The pedestrian speed remains equal to the desired speed when they are moving independently of pedestrian density level. They are able to maintain their speed in a high pedestrian volume and are not slowed down when following slower pedestrians. This option can be reasonable at low pedestrian flows, but becomes increasingly less realistic at higher pedestrian flows.

The second option is to model pedestrians as vehicles, in which pedestrians are set to follow a car-following model. In such a situation pedestrians react to the presence of other pedestrians in front of them, although under the rules developed for vehicles rather than for pedestrians. Pedestrians are modelled as individual entities with a user defined speed distribution. In such a situation pedestrians react to the presence of other pedestrians and are allowed to overtake other pedestrians from any side. However, in practice, pedestrian behaviour differs significantly from vehicle behaviour, so the realism of the modelling in this option has to be questionable.

The third option is to model pedestrians under the *Social Force* model developed by Professor Dirk Helbing and Peter Molnar (Helbing and Molnar, 1995; PTV, 2008b). The *Social Force* model is the most recent development in VISSIM to model the behaviour of pedestrians. The model simulates interactions between pedestrian and vehicle flows and it is now possible to model either pedestrians or vehicles who intentionally violate traffic regulations (PTV, 2008a). In reality, there will be various levels of non-compliance behaviour among pedestrians. The proportion of pedestrians who do not comply with the traffic signal can be entered in the VISSIM network in relation to the time interval being modelled.

In the *Social Force Model*, the movement behaviour of pedestrians is described based on Newtonian mechanics, the interaction of particles. Pedestrians' movement is influenced by other forces from social, psychological and physical forces as shown in Figure 2.15.

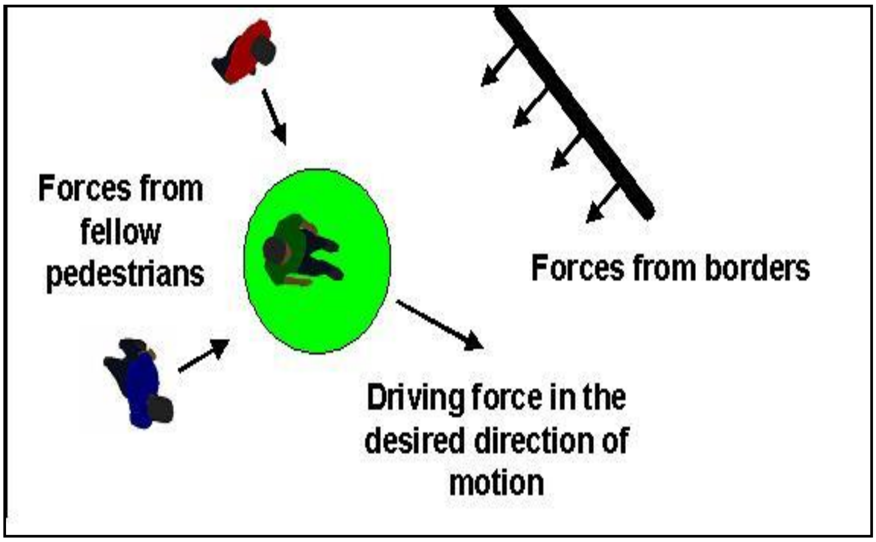


Figure 2.15 Forces in *Social Force Model* (Source: PTV, 2005)

As seen in Figure 2.15, a pedestrian's intention to reach his/her destination is affected by 'forces' from other pedestrians and obstacles to avoid collisions. Other pedestrians can have both an attractive and a repulsive influence. In reality, a kind of safety margin or personal space is always sought by pedestrians to minimise interaction and to avoid collisions between pedestrians and other obstacles such as buildings (Helbing and Molnar, 1995;

Teknomo, 2006). Here, the *Social Force Model* controls the operational level and parts of the tactical level which is shown in Figure 2.10 in section 2.8, whereas the strategic level is defined by the user input.

VISSIM has been used widely to model pedestrians in a range of situations. Therefore, it is important to understand how pedestrians behave at a microscopic level. In this research, the third option which is to model pedestrians under *Social Force Model* was used as it better in modelling the behaviour of pedestrians compared to other two options (no interactions and car-following model).

In VISSIM, the behaviour of pedestrians can be defined individually, in the same way as vehicles. With available pedestrian speed distributions, the modeller can allocate to each pedestrian their own individual maximum walking or running speed. Pedestrian crossing choices are seriously impacted by the current traffic conditions, especially the vehicle gaps. Upon arrival at the crossing location, a pedestrian is exposed to two types of gaps, safe or unsafe. Safe gaps can be thought of as a combination of large gaps in moving traffic as well as gaps created by yielding drivers. The pedestrian then makes a decision to accept or reject the gap To represent the interaction between pedestrians and vehicles in VISSIM, the critical gap is the most important parameter. Simply stated, a pedestrian seeking to 'gap cross' in VISSIM will cross, on average, when a gap occurs that is greater than his/her critical gap. Otherwise, he/she will wait until an acceptable gap occurs. Once a suitable gap occurs, pedestrians will go through immediately (if eligible).

The critical gap model in VISSIM is deterministic. The assumption in deterministic critical gap models is that the driver and pedestrian population are both homogeneous & consistent (all have constant values for critical gap and follow-up time). By defining multiple vehicle and pedestrian classes and estimating separate critical gaps for each, the homogeneity assumption can be partly overcome. This approach will be referred to as a *quasi-heterogeneous* driver population, because the homogeneity assumption still holds within each vehicle class (Schroeder and Rouphail, 2007).

In real life, human decision-making and action processes are very complex and dependent on many factors. For instance, some pedestrians whom initially obey a signal indication may follow other pedestrians who cross on red. Or a pedestrian may not press the push button and look for a gap - but when he/she does not find any gap, he/she presses the push button to register demand. However, in VISSIM, the decision to press the button or not is not a function of the encountered traffic conditions.

The strategies for improving the signal control on pedestrian crossings needs a better understanding on specific issues associated with pedestrian activity. The specific operational issues on pedestrian activity have to be understood as a basis to implement the design strategies in urban areas. These are the pedestrian travel speed, the variation of pedestrian speeds by individual and by situation, and the pedestrian compliance behaviour with the street crossing regulations (Ishaque and Noland, 2007a). These aspects have been reviewed and the following aspects of pedestrian behaviour have been included in the modelling in this research:

1) Wider range of walking speeds at signalised pedestrian crossings.
2) Pedestrians are categorised into three types:
    (a) Obey signal indication
    (b) Press the button but do not necessarily obey the signal indication (gap-cross when there is an opportunity)
    (c) Do not press the push button and gap-cross

Due to the stochastic nature of the pedestrian and driver behaviour, a simulation model was chosen as the best initial evaluation method of the performance of the strategies tested: Upstream Detection and Volumetric Detection. There are various micro-simulation models available in current practice. However, it is important to choose a simulation model that can integrate the modelling of pedestrian and vehicular traffic with specific behaviour as above.

VISSIM has been used widely to model pedestrian behaviour and the interaction between pedestrians and vehicles (McLeod et al., 2004; Kolmakova et al., 2005; Rouphail et al., 2005; Ishaque, 2006; Tonndorf, 2006; Schroeder, 2008). Ishaque (2006) used the vehicle car following model to model the pedestrian behaviour with some modifications on vehicle behaviour parameters to reflect the pedestrian behaviour. However, in practice, pedestrian behaviour is much more complex and differs significantly from vehicle behaviour (car following and lane changing behaviour), so the realism of the modelling in this option has to be questionable.

Recently, VISSIM offers a new method to model the behaviour of pedestrians closer to reality which is the *Social Force Model* (PTV, 2008b). In the *Social Force Model*, pedestrian movements are influenced by other social, psychological and physical factors. For example, pedestrians avoid close contact with other pedestrians or with other objects, such as vehicles. Therefore, VISSIM micro-simulation model with *Social Force Model* was used in this research to model the behaviour of pedestrians and the interaction between vehicles and pedestrians.

Then, the method to optimise the performance of the signal control strategies tested (Upstream Detection and Volumetric Detection) were reviewed in terms of total person delay and total delay costs. The method seeks to build on earlier research by Noland (1996), Bhattacharya and Virkler (2005) and Ishaque and Noland (2007b) that analysed the trade-offs in pedestrian and vehicle delays in a hypothetical network and taking into account the relative values of time for various modes including pedestrians.

2.10 Evaluation of Effectiveness

The reduction of pedestrian-vehicle conflicts can be considered a basic factor promoting safety. Ease of movement in walking is considered part of safety (Khisty, 1994). Particularly in heavily trafficked street networks, the provision of properly designed control devices, providing adequate time and space separation from vehicular movement is an essential part of safety. A key reason for traffic signals is to manage conflicts at junctions which in turn brings about safety benefits. However, a safety assessment is beyond the research objective here due to unavailability of data. To maintain safety, all strategies tested incorporate all traffic signal features which are mandatory under current UK legislation (e.g. adequate intergreen time, minimum 7 seconds green time and fixed amber duration).

Given that safety impacts cannot be quantified in this research, the principle performance measures used have been travel time and delay to traffic and pedestrians. Journey time savings are usually the most important item in the total benefits from a new road/transport scheme (Bamford, 2001; Litman, 2002). It was importantly noted by the DETR (1999) that:

> *"Travel time savings are the single most important component in the measured transport benefits/disbenefits of most schemes and policies. Hence the methods of valuing them critically affect the measurement of the economic impacts of schemes."*

Pedestrian delay is one measure of effectiveness (MOE) to explain the interaction between vehicles and pedestrians at signalised crossings (Transportation Research Board, 2000). Any time spent waiting to cross, either at the kerbside or at the central refuge island is considered as pedestrian delay. Delays for pedestrians and vehicles are used as the key parameter for the design and evaluation of improvements in pedestrian crossing facilities using traffic signal controls (Transportation Research Board, 2000; Liu et al., 2010).

It is natural to use pedestrian delay as a measure of pedestrian quality of service for midblock street crossing (Chu and Baltes, 2001). First, the amount of delay is typically used as the measure of effectiveness for intersections where conflicts frequently occur just as in the case with pedestrian midblock street crossings. Second, the amount of delay also reflects several aspects of the operational conditions faced by pedestrians crossing streets as midblock locations. These include speed, travel time, and convenience. From an economic perspective, pedestrian's delay should be taken into account in signal timing optimisation for a better road network performance (Noland, 1996).

The Highway Capacity Manual defines pedestrian delay as "additional travel time experienced by a pedestrian" (Transportation Research Board, 2000). The delay time in VISSIM is computed for every vehicle completing the travel time section by subtracting the theoretical (ideal) travel time from the real travel time (PTV, 2008b). The theoretical travel time is the time when there are no other vehicles or pedestrians and no obstruction from traffic signal controls or other stops in the network.

The analysis of average vehicle delay per vehicle and average pedestrian delay per pedestrian have also been converted into total person delays and total delay costs. This is to examine the impact of the new strategies on all road users at the pedestrian crossing. Therefore the next section will set out the economic assessment of the total delay of the new strategies.

2.11 Economic Evaluation

In any transport plan improvement, an assessment is usually made of the impacts of the scheme on the transport users. Travel is a ‘cost’ in the sense that an individual has to spend time and money making a journey, so a reduction in those travel costs is considered to be an economic benefit. Travel time costs play a major role in the selection of transportation network improvements, such as improved control strategies for pedestrians. The users in this respect are the travellers using different modes to traverse the network.

2.11.1 Total Person Delay

For this economic evaluation, the total person delay was first calculated using average delay time per person, occupancy rates and number of people completing their journey in the simulation period. The calculation of total delay person is shown in Equation 2.1 below.

Total Person Delay = $D_v O_v N_v + D_p N_p$ Equation 2.1

Where subscript v = vehicles

subscript p = pedestrian

D = average delay time per person

O = vehicle occupancy

N = number of vehicles or pedestrians completing their journey in the simulation period

Vehicle occupancy rates from the Department for Transport (2011b) were used in the calculation, as shown in Table 2.4 below.

Table 2.4 Average Vehicle Occupancies (Source: Department for Transport, 2011b)

Mode	Average vehicle occupancies
Car	1.58
Bus	13.2
HGV	1
Pedestrian	1

2.11.2 Total Delay Costs - Standard Value of Time

Then, the analysis of total delay person was converted into financial assessment by assigning values of time for different modes of transport. Equation 2.2 below shows the calculation of total delay costs.

Total Delay Costs = $D_v O_v N_v V_v + D_p N_p V_p$. Equation 2.2

Where V = values of time per person

Current practice for UK values of time in evaluation of multi modal transport is using the standard average value from Department for Transport (2011b) as indicated in Table 2.5 below (Mackie et al., 2003a; Ortuzar and Willumsen, 2008; Department for Transport, 2011b).

Table 2.5 Monetary values of time for various mode of transport (Source:Department for Transport, 2011b)

Mode	Values of Time per vehicle (£ per hour, 2002 prices and values)
Car	10.46
Bus	71.62
HGV	10.18

Table 2.5 shows the standard values of time per vehicle for car, bus and HGV for 2002. These values were derived by applying values of working and non-working time per person, journey purpose split as weights, vehicle occupancies and annual percentage change in car passenger occupancy. To turn the values of time per vehicle into values of time per person, the values of time per vehicle were divided by the vehicle occupancy for each modes of transport. Table 2.6 below shows the values of time per person for various vehicle types.

Table 2.6 Values of Time per person for various vehicle types

Mode of transport	Values of Times per person
Car	£6.62
Bus	£5.43
HGV	£10.18

*the values were extracted from Table 2.4 and Table 2.5

Pedestrian values of time for three different journey purposes as recommended by Department for Transport (2011b) are indicated in Table 2.7 below.

Table 2.7 Pedestrian Values of Time

(Source: Department for Transport, 2011b)

Journey Purpose		Values of Time per pedestrian (£ per hour, 2002 prices and above
Working Time		29.64
Non-working Time	Commuting	10.08
	Other	8.92

According to Department for Transport (2011b), 'Commuting' is travelling to and from the normal work place and 'Other' is travel for other non-work purposes, for example leisure trips. Different journey purpose has different values of time. Therefore, it was then considered appropriate to take into account the journey purpose splits for pedestrian in the assessment of the impact of different transport plan. The proportion of pedestrians by journey purpose was determined using TEMPRO and National Transport Survey 2010 shown in Figure 2.16.

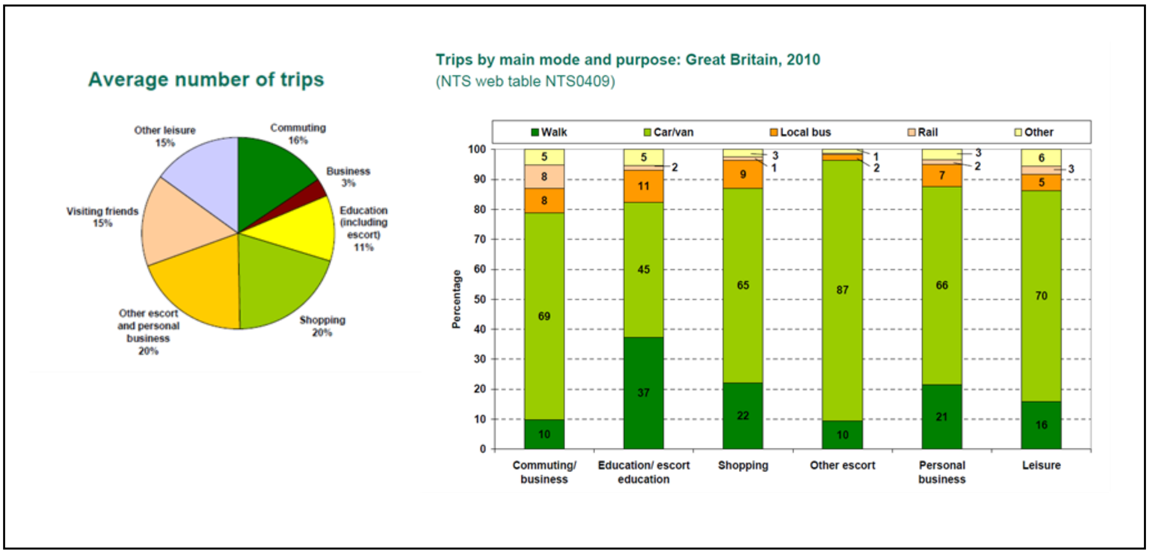
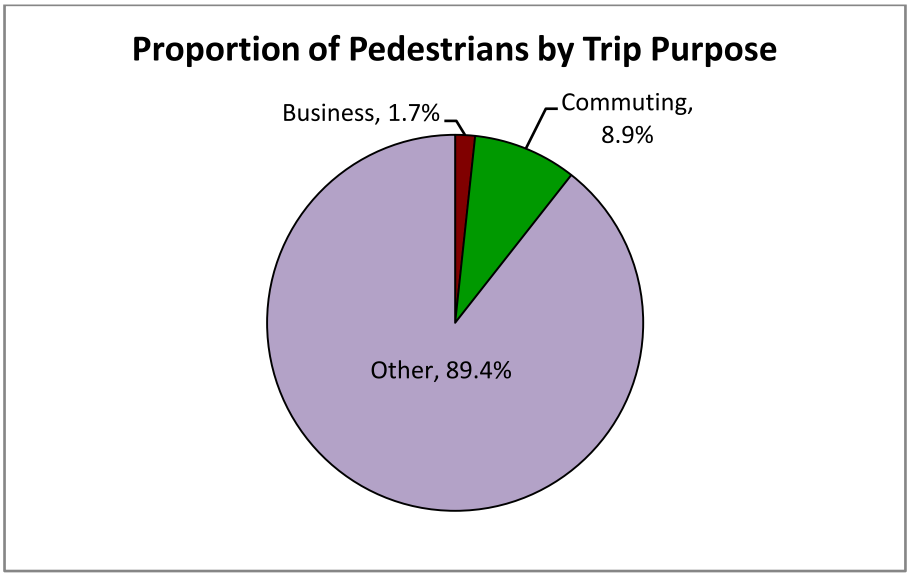


Figure 2.16 Average Number of Trips by purpose share

(Source: Department for Transport, 2011a)

Figure 2.16 illustrates the average number of trips by various journey purposes (that is Business, Commuting and Other purposes) and the proportion of trips by various modes of transport and journey purposes derived from National Transport Survey 2010.

The journey purpose splits for pedestrians were calculated by multiplying the average number of trips (Business, Commuting and Other) and trips by walking for various purposes as weight factor. This resulted in the proportion of pedestrians by different journey purposes as shown in Figure 2.17 below.



*the illustration was derived from the average number of trips and trips by walking for various purposes as in Figure 2.16

Figure 2.17 The Journey Split for Pedestrians

Figure 2.17 shows that 1.7% of pedestrians are on business trips, 8.9% on commuting trips and 89.4% on other trips. The standard pedestrian values of time were produced by multiplying journey purpose splits and pedestrian values of time per pedestrian for various journey purposes. Therefore, the standard values of time per person for pedestrians are shown in Table 2.8 below.

Table 2.8 Values of Times for pedestrians

Proportion of pedestrians by trip purposes			Values of Time per person (£ per hour)			Standard values of time per person
Business	Commuting	Other	Business	Commuting	Other	**£9.38**
1.7%	8.9%	89.4%	29.64	10.08	8.92	

*the values were derived from Table 2.7 and Figure 2.17

Therefore, the standard values of time per person for various modes of transport to be used in Equation 2.2 are shown in Table 2.9 below.

Table 2.9 Values of Time per person for Various Modes of Transport

Mode of Transport	Values of Times per person
Car	£6.62
Bus	£5.43
HGV	£10.18
Pedestrians	£9.38

*Source: Table 2.6 and Table 2.8

2.11.3 Total Delay Costs - Relative Value of Time

Rather than being based on assumptions about the standard values of time as in section 2.11.2, adjusting the weightings applied to pedestrian and vehicle travel time savings would provide an understanding of the strategic importance to be attached to pedestrians if the improvements were to be supported.

The value of time of each mode must be determined first to determine the optimal trade-offs between various modes. Walking is more costly than driving. Walking time is usually considered twice the value of in-vehicle travel time (Noland, 1996; Wardman, 2001; Department for Transport, 2002a; Litman, 2007; Ortuzar and Willumsen, 2008). That is, a person travelling to work would be willing to pay 2 times more per hour to shorten a walking trip than a driving trip. The consideration was originally revealed by Quarmby (1967), then supported by the first UK national value of time study (MVA Consultancy, 1987).

Walking time can be expected to have a high value since it incurs greater effort than in-vehicle time (Wardman, 2004). In general the reasons for pedestrian values of time being higher is described by Braun and Roddin (1978). The authors gave two strong arguments to assign higher value of time to pedestrian *'… (the) pedestrian is frequently a purchaser. All of the face-to-face business transacted in a city, except for a limited number of drive-in facilities, is conducted by pedestrians. Because he makes shorter trips than the motorist, a given delay will account for a larger fraction of his total trip, and thus causes more inconvenience'.*

Noland (1996) and Ishaque (2006) had done a study on the impact of different value of times to pedestrians on traffic signal optimisation. The higher the value of time for pedestrians, the more favourable the traffic signal control to pedestrians. This is true if the ratio of automobiles to pedestrians is not at optimal level, it could imply that the traffic signal control needs to be changed to favour the pedestrian. However, the authors found out that by assigning equal value of time to both vehicle and pedestrian, the result still favours pedestrians. Pedestrian delay constitutes a significant proportion of the network delay (Bhattacharya and Virkler, 2005), therefore by assigning a lower value of time to pedestrians could bring disbenefit to the road network optimisation.

Table 2.10 below shows the relative values of time for three vehicle types and pedestrians from various studies (Haight, 1994; Fowkes, 2001; Mackie et al., 2003b; Wardman, 2004; Bhattacharya and Virkler, 2005; Ishaque, 2006).

Table 2.10 Relative Values of time for various modes

Mode	Values of time per person
Car	1.0
HGV (Fowkes, 2001)	4.0
Bus (Haight, 1994)	0.5
Pedestrian (Mackie et al., 2003b; Wardman, 2004; Bhattacharya and Virkler, 2005; Ishaque, 2006)	0 to 4

For evaluation purpose of alternative transport schemes, very often the value of time used for evaluation purpose is an equity value, taken as being the same for all road users (Mackie et al., 2003b; Ortuzar and Willumsen, 2008).

According to Lyons and Urry (2004), a standard 'national average' value is used in evaluation purpose to avoid equity implications and a bias towards measures that benefit travellers with high income. The majority of journey does not take place during working hours (Department for Transport, 2011b). Therefore, for this reason, the assessment of the impact of different transport strategies should normally adopt the values for non-working time from Department for Transport (2011b), which is £4.46 per hour per person, 2002 prices and values. The user cost computed by assigning different weighting factors to pedestrian and vehicles as shown in Equation 2.3 below (Bhattacharya and Virkler, 2005).

$$\text{Total Delay Costs} = D_v O_v N_v T_v W_v + D_p N_p T_p W_p \qquad \text{Equation 2.3}$$

Where subscript v = vehicles

subscript p = pedestrian

D = average delay time per person

O = vehicle occupancy

N = number of vehicles or pedestrians completing their journey in the simulation period

D x O x N = total person delay

T = values of time, £4.46 per hour per person

W = weighting factors (shown in Table 2.10)

2.12 Summary

This part of the literature review discussed some of the urban traffic signal control systems applied in the UK, pedestrian signalised facilities, the existing pedestrian detection technologies, Puffin signal timings, micro-simulation software and measures of effectiveness and values of time.

Compared to Pelican crossings, Puffin crossings can eliminate unnecessary pedestrian precedence periods and extend the crossing time for pedestrians to help them safely cross the road. However, the operational strategies for both Pelican and Puffin crossings are still based on default priority for vehicles with pedestrian right of way available, on demand, at times and with frequencies that are consistent with minimising delay to vehicle occupants.

With these considerations, the PUFFIN crossing is the clear candidate to be the ‘base case’ for this research; It is the most advanced and flexible form of crossing currently operational in the UK and has the potential for further enhancements to its detection and control functions.

The control system on the Puffin crossings is still based on vehicle delay where the vehicle arrival patterns or gaps are calculated to set up the signal timing for pedestrians. The control strategies should be improved to make them fairer for pedestrians and vehicles. Upstream pedestrian detection and the volumetric detection are proposed for the next puffin crossing improvement and they might bring benefits to pedestrians and other road user as well.

Pedestrian behaviours at signalised crossings are varied and dynamic. The walking speeds and the compliance behaviour to the signal indication also varies among pedestrians. VISSIM appears to support most of the modelling features required for Puffin crossing improvement. Hence, it is chosen as an evaluation tool in this research.

Chapter 3 will describe the model development for the base case scenario at a Puffin crossing. The modelling of this base case scenario is an essential procedure so that the impacts of the improved scenarios can be made to the base case scenario.

3 Model Development

3.1 Introduction

The previous chapter presented a discussion on pedestrian facilities at signalised crossings, signal control practice in UK, detection technologies adopted in Puffin crossings and micro-simulation tools to be used in this research. It was found that VISSIM was the most suitable software for modelling a Puffin crossing because of its more advanced pedestrian behaviour modelling capabilities.

With the literature review being completed and key findings drawn, this chapter therefore presents the methodology used to model a Puffin crossing using VISSIM. The chapter is divided into three sections which discuss the initial modelling procedure, the procedure to collect measures of effectiveness (MOEs) and a summary.

3.2 Model Requirements

The VISSIM simulation model enables a wide application/variety of functions to be modelled and to alter them to investigate different scenarios. The key model requirements, which set the development basis, are to:

(a) Represent vehicle actuated signal control at Puffin crossings
(b) Model the interaction of vehicles and pedestrians at Puffin crossings: gap-crossing behaviour
(c) Model traffic detectors for both vehicles and pedestrians
(d) Model the new strategies on Puffin crossings
(e) Measure the impacts of the base case model and new strategies on the key performance of the model.
(f) Evaluate the impacts of new strategies over the base case strategy.

3.3 Initial Modelling: Base Case Model

The first step in the modelling was to model a Puffin base case scenario in VISSIM. The base case scenario is a hypothetical mid-block Puffin crossing with a geometry typical of UK urban roads. The use of a hypothetical crossing allowed full control and greater flexibility over various modelling conditions and illustrated the applicability of the results in a wide variety of environments. It was also more straightforward in these early stages of testing to focus on a mid-block crossing where only one road is involved, rather than a signalised crossing which would typically have three or four arms/crossings. Vehicle Actuation is the most common form of signal control at Puffin crossings. Detectors are installed on all approaches: vehicle paths and pedestrian paths. Each second, the detectors check if there are any vehicles or pedestrians in the detection areas and deliver this information to the signal control system to determine the signal status for the next step.

The main parameters in Vehicle Actuation signal control are as follows:

- ***Minimum Green***: The minimum green time was assigned to the vehicle phase for safety considerations. This is usually set at 7 seconds in practice.

- ***Maximum Green*** or ***Max-Out***: This is the maximum limit of an extension for a vehicle phase when there was a demand from conflicting movement. In the presence of a conflicting movement, the current phase terminates at this limit despite any demand for further green extensions. The maximum green is pretimed at the beginning of the vehicle phase as to allow a quicker response to pedestrians.

- ***Extension time***: Every time there was a vehicle being detected, an additional 4 seconds was added to the green signal indication. They are not added to the end of the previous extension time, as this would accumulate unused green times.

- ***Gap-out***: This was the maximum time gap between two consecutive detections of vehicles. When the gap-out limit was reached, if there was no vehicle detected and at the same time there was green demand from conflicting movements, the green time for current phase was then terminated.

- Vehicle Green was terminated in one of two ways:
  (a) Gap Out: An extension time of 4 seconds expired without an additional actuation.
  (b) The Maximum Green was reached.

Figure 3.1 illustrates the operation of a Vehicle Actuation signal control at a Puffin crossing based on three critical settings: minimum green, maximum green and extension time.

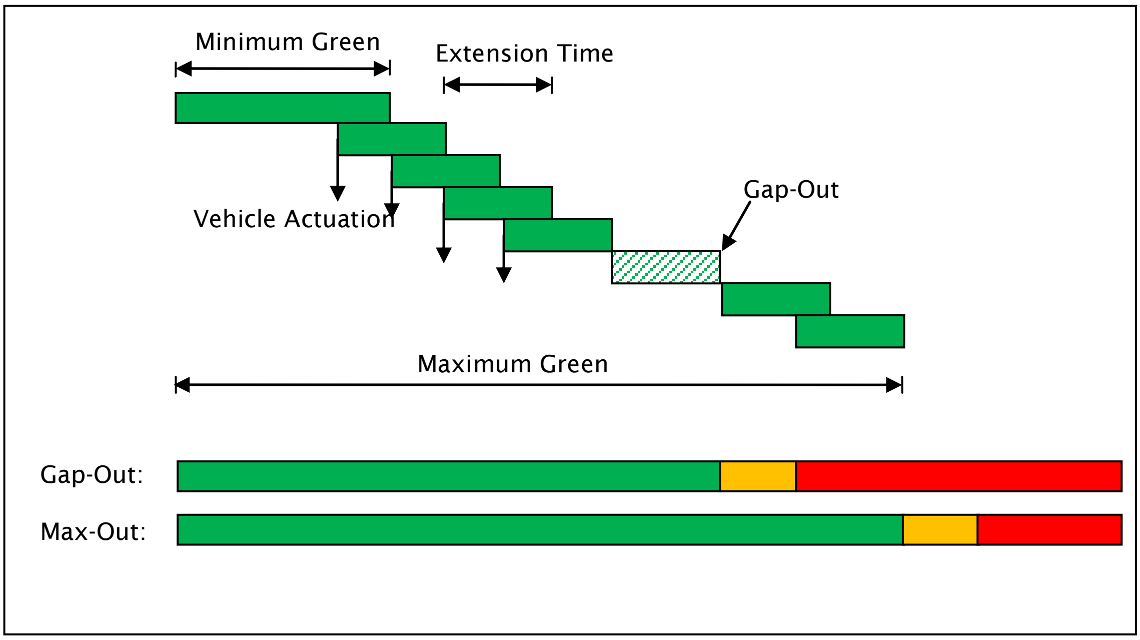


Figure 3.1 Vehicle Actuation signal control at Puffin crossings

The vehicle actuation signal logic was written for Puffin mid-block crossing using Vehicle Actuated Programme (VAP), a built-in programming logic in VISSIM. Coding for this logic is as shown in Appendix A. The vehicle stage is actuated as well as pedestrian phase. When the vehicle detection is active, the green time for vehicle stage can be extended for another 4 seconds and up to the maximum green time. When pedestrian phase is active, pedestrian presence at on-crossing detector can extend the red clearance time up to the maximum value to make sure pedestrians cross the road safely. The push button, kerbside detectors and the on-crossing detectors were simulated in VISSIM to enable the recording of the Puffin operations. Figure 3.2 shows the flowchart of a Puffin logic coded in VISSIM network.

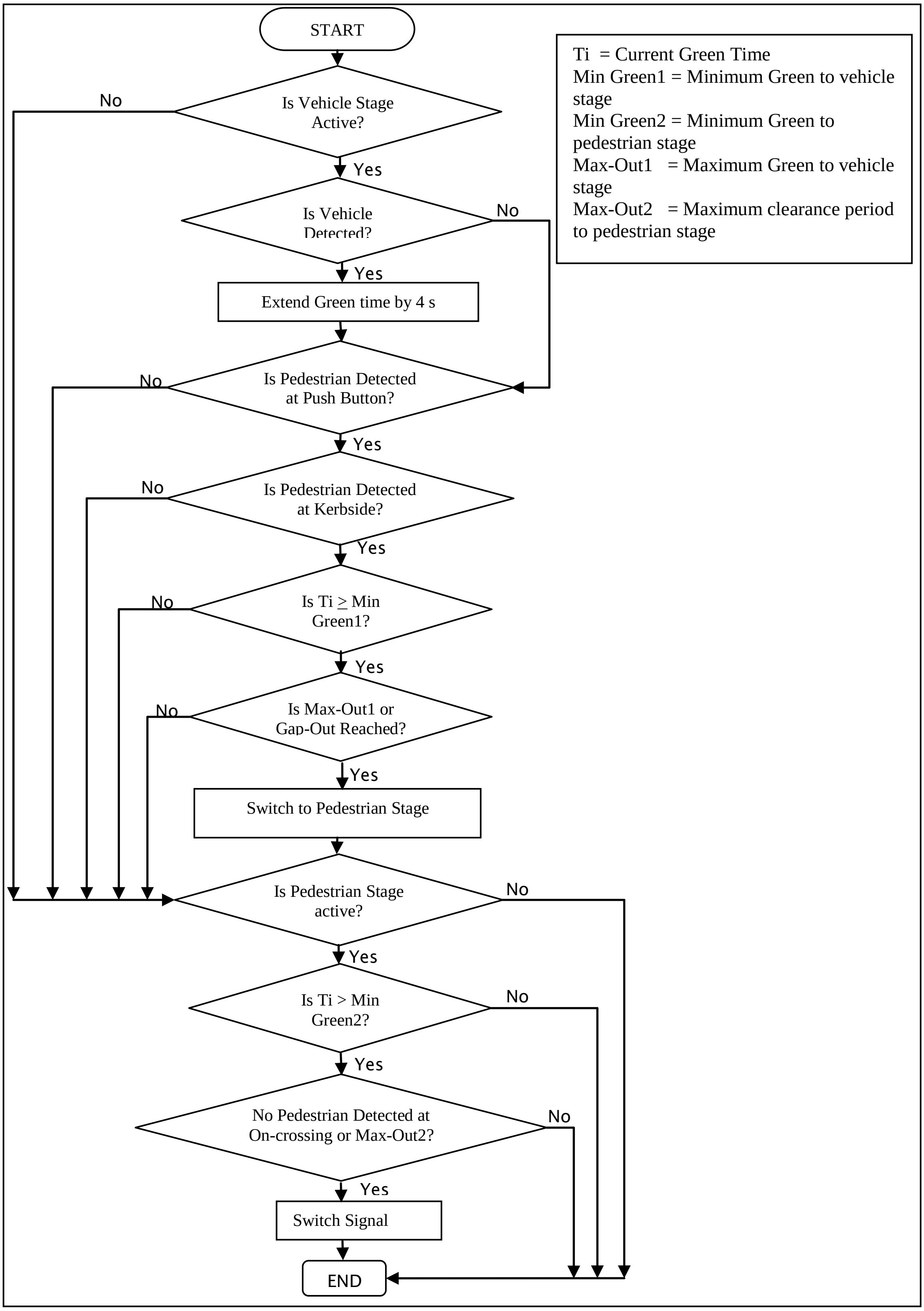


Figure 3.2 Flow chart of Puffin logic

Figure 3.3 shows an illustration of Puffin crossing facilities respectively.

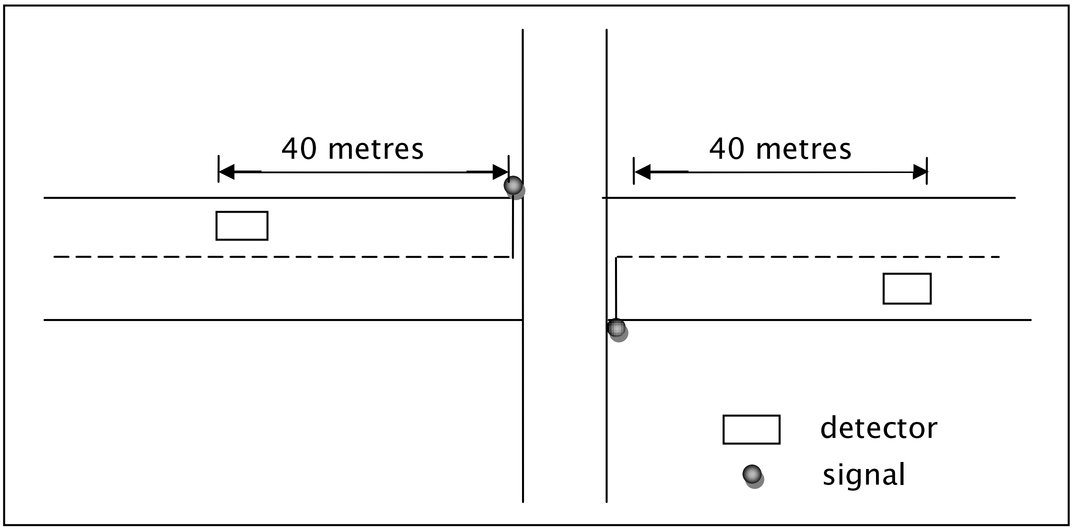


Figure 3.3 Layout of Puffin signalised crossing

Puffin crossings adopt three pedestrian detection systems: push button, kerbside detection and on-crossing detection. Push button is used to register pedestrian demand at signal control. Kerbside detection is used to confirm the pedestrian demand just before changing to the pedestrian stage, or to cancel it if there is no pedestrian waiting on the kerbside. The principle of kerbside detection is to reduce unnecessary pedestrian phase by cancelling the pedestrian demand. On-crossing detection is used to extend the pedestrian clearance period up to maximum clearance period if there is still pedestrian on the crossing.

If the pedestrian push button is activated, the pedestrian demand is sent to the signal controller. As long as a vehicle still detected, vehicle green is extended by 4 seconds up until maximum green time. For safety protection, the pedestrian phase can be given only after the minimum green to vehicles. After minimum green is reached, two traffic requirements are checked: gap-out and maximum green. After minimum green, if there is a pedestrian demand and either one of these two requirements satisfied: gap out or maximum green, the pedestrian phase is then initiated. In the Puffin operational system, if both vehicles and pedestrians are detected at the same time, the priority is given to vehicle. After a pedestrian has registered his/her demand at push button detection, the signal controller checks the pedestrian presence at kerbside detection.

In the base case model, typical traffic attributes were set such as vehicle volumes, pedestrian demands, desired speed distribution, pedestrian behaviours and signal control properties. The graphical interface in VISSIM was used to create this simple road crossing containing road links, signal heads and detectors. Signal heads and detectors are part of the underlying signal control strategy. Desired speed distributions for vehicles and pedestrians were set in the road crossing. It is an actual speed of a vehicle or pedestrian at free flow traffic condition.

The road crossing consisted of a two way level road with 3.5 meters lane width each. Three vehicle compositions were used in the initial model: 95% car, 3% HGV and 2% bus. Standard signal timing parameters such as intergeen time, 7 seconds minimum green time, 30 seconds maximum green time and pedestrian phase were coded in the road crossing. For the initial modelling purpose, the data on desired speed distribution was collected at historical video at Market Street, Manchester. Vehicle desired speed distribution was set at 30.0 km/h to 48.0 km/h while pedestrian desired speed distribution was set at 1.9 km/h to 7.2 km/h.

Based on the review in Chapter 2, pedestrians were classified into three types according to their behaviour when arriving in pedestrian red indication:

(a) Obey signal (whether he/she press the push button or not)
(b) Press the button but ignore red (gap-cross when there is an opportunity)
(c) Do not press the button and ignore red (gap-cross when there is an opportunity)

Upon arrival at the crossing location, a pedestrian is exposed to two types of gaps, safe or unsafe. Safe gaps can be thought of as a combination of large gaps in moving traffic as well as gaps created by yielding drivers. The pedestrian then makes a decision to accept or reject the gap. To represent the interaction between pedestrians and vehicles in VISSIM, the critical gap is the most important parameter. Simply stated, a pedestrian in VISSIM will cross, on average, when a gap occurs that is greater than his/her critical gap. Otherwise, he/she will wait until an acceptable gap occurs. A pedestrian's crossing decision can be described as a function of the pedestrian's critical lag time. A 'lag' is the time between a pedestrian's arrival at the crossing and the arrival of the next conflicting vehicle at the crossing (Schroeder and Rouphail, 2007). The pedestrians will cross if the lag time to the next vehicle arrival is greater or equal to the critical lag time. Pedestrians were coded to accept a minimum 6 seconds gap for two way traffic.

3.4 Procedure to Collect Measures of Effectiveness

Each road lane was divided into one travel time section consisting of a start and a destination cross section. The average travel time was determined as the time a vehicle crosses the first cross section to crossing the second cross section (PTV, 2008b). The travel time measurement points were long enough to cover the acceleration and deceleration section of vehicles, as shown in the next section.

3.4.1 Measurement Distance

Initially, 600 meters travel time distance which consist of 6 travel time sections was tested in the simulated network. Each travel time sections have 100 meters length as shown in Figure 3.4 below. Then the vehicle speed profile was determined over these travel time sections.

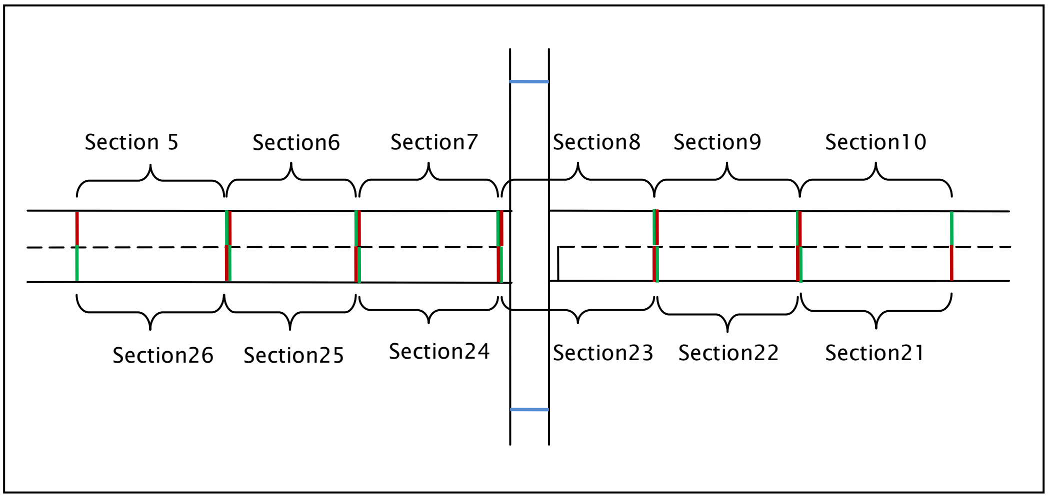
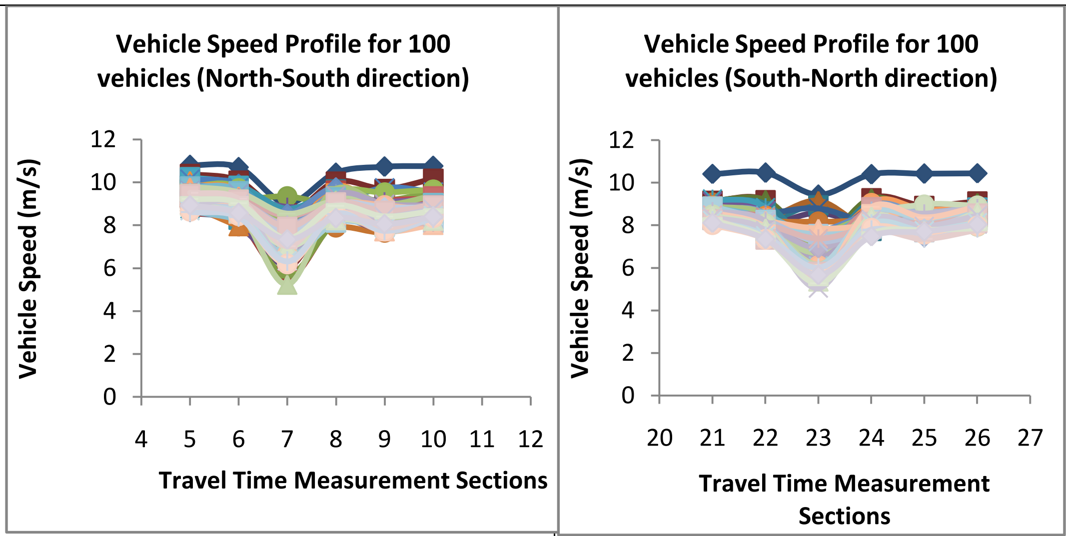


Figure 3.4 Travel Time Measurement Areas

10 simulation runs at 1408 veh/h and 300 ped/h were conducted to determine the acceleration and deceleration sections of vehicles on the road crossing. It was expected that the realistic behaviour of vehicle acceleration and deceleration can be recorded at high vehicle flow (1408 veh/h) with the presence of medium pedestrian flow (300 ped/h). Figure 3.5 shows individual vehicle speed profiles for 100 vehicles over 600 meters travel time section for two way directions.



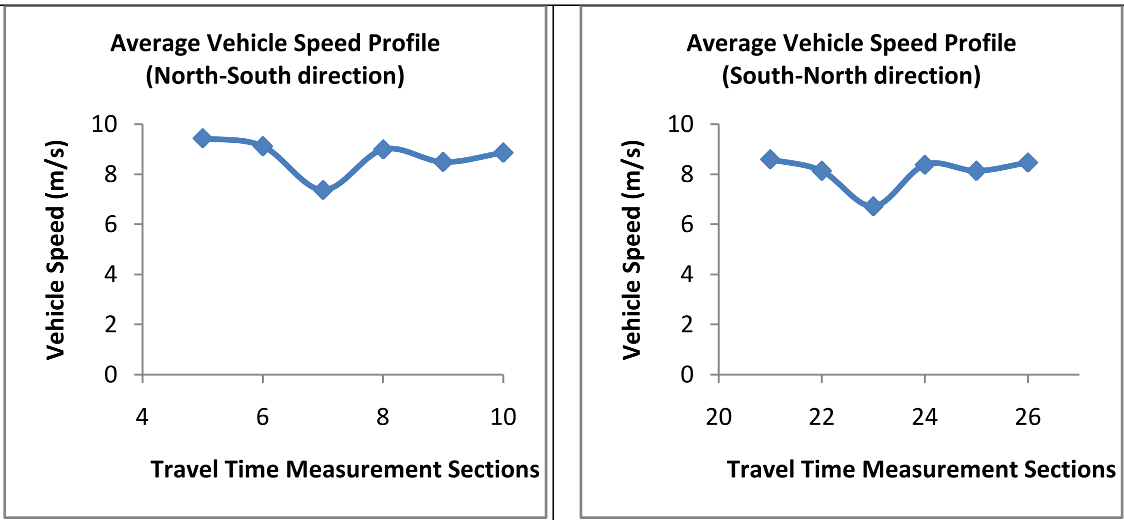
(a) North – South Direction (b) South-North Direction

Figure 3.5 Vehicle Speed Profile for both directions

Figure 3.5 shows the trend of individual vehicle speed for 100 vehicles based on the average of 10 simulation runs for 10 hours duration. It can be seen in Figure 3.5 that most vehicles started to decelerate when approaching section 7 and section 23 respectively for North-South direction and South-North direction. Section 7 and section 23 were located before the pedestrian crossing. Then, from section 7 onwards, vehicle started to accelerate and there was an increment of vehicle speed. Vehicles started to accelerate when the crossing was free from any disturbances (such as red signal indication or the presence of pedestrian on the crossing). Similarly, the same scenario happened at section 23 onwards for South-North direction.

However, some vehicle profiles showed a contradict trend in which they accelerate when approaching pedestrian crossing at section 7 and section 23. This was due to the absence of disturbances on the pedestrian crossing. Vehicles were shown green signal indication and no pedestrian on the crossing, hence the increase of speed at this travel time measurement points.

Figure 3.6 shows the average vehicle speed profile from 100 vehicles.



(a) North-South direction (b) South-North direction

Figure 3.6 The Average Vehicle Speed Profile

The graph in Figure 3.6 shows a similar trend for both directions. Generally, vehicles start to reduce their speed when approaching the pedestrian crossing (section 7 and section 23) and then accelerate after these points.

It was found in the results that 600 meters travel time sections for both directions was enough to cover the accelerations and decelerations profile of vehicles on the road network. Therefore 600 meters travel time section in the road network was used in vehicle delay measurement. And for pedestrians, the pedestrian delay time measurement was conducted from Start-Destination area.

3.4.2 Delay Measurements

The delay estimation in VISSIM is based on travel time measurements. The delay time in VISSIM is computed for every vehicle completing the travel time section by subtracting the ideal travel time from the real travel time. The ideal travel time is a free flow travel time when there are no other vehicles or pedestrians and no obstruction from traffic signal controls or other stops in the network (written in chapter 2). Therefore, to get the VISSIM delay time measurement due to signal control, delay time is measured as the difference of travel time between base case and free flow scenario.

In order to determine the delay time due to signal control, a comparison of vehicle travel time was conducted between the base case scenario and the free flow scenario. In the base case scenario, vehicles are delayed by the signal control (due to the appearance of the pedestrian crossing). In the vehicle free flow scenario, pedestrians were taken out from the road crossing so that vehicles were free to move without disturbances from signal control and received continuous green time indications. Vehicle delay as a result of signal control was measured as the difference of travel time between base case and free flow scenarios. The vehicle delay was then compared to analytical delay model to check the validity of the results. 10 simulation runs were conducted at vehicle flow 1408 veh/h and pedestrian flow 300 ped/h. The results are shown in Table 3.1 below.

Table 3.1 Vehicle Delay Measurement

Length of vehicle travel time sections (meters)	600
Sample size	14016
Average Vehicle Travel Time at free flow (seconds)	70.9
Actual Average Vehicle Travel Time with pedestrian crossing operational (seconds)	81.7
Vehicle delay (seconds)	10.8
Analytical vehicle delay (seconds)	9.5

Compared to the analytical vehicle delay, 9.5 seconds, the results of vehicle delay time 10.8 seconds in Table 3.1 are reasonable. The analytical vehicle delay was based on the equation below.

$$d = \frac{c(1-\lambda)^2}{2(1-\lambda x))} + \frac{x^2}{2q(1-x)} - 0.65\left(c \middle/ q^2 \right)^{1/3} x^{2+5\lambda}$$ Equation 3.1

where d = average delay per vehicle

c = cycle time

λ = effective green time/cycle time

x = degree of saturation

q = flow

A similar test was conducted to measure the pedestrian delay time. In contrast to the previous test, vehicles were taken out from road network to create a pedestrian free flow scenario. The test used the same traffic flow as previous test: 1408 veh/h and 300 ped/h. The results are shown in Table 3.2 below.

Table 3.2 Pedestrian Delay Measurement

	Base Case
Sample size	3043
*VISSIM pedestrian delay at free flow (seconds)	11.6
*VISSIM pedestrian delay with pedestrian crossing operation (seconds)	20.0
Average Pedestrian Travel Time at free flow (seconds)	41.2
Actual Average Pedestrian Travel Time with pedestrian crossing operation (seconds)	59.3
Pedestrian delay (seconds) = 59.3 – 41.2	18.1
Analytical pedestrian delay (seconds)	21.0

It was expected that at pedestrian free flow conditions when there is no vehicle on the road crossing, pedestrians do not incur any delay. However, at free flow scenario, pedestrian experiences 11.6 seconds delay time due to interaction between pedestrians (shown in Table 3.2 above). In VISSIM, pedestrians do have some interaction between them even in a lower pedestrian flow (Social Force Model). The VISSIM delay will underestimate the delay time measurement due to the interactions between pedestrians. Therefore, pedestrian delay due to signal control was measured as the difference of travel time between base case and free flow scenario.

As shown in Table 3.2 above, the difference of pedestrian travel time between base case and free flow scenario is 18.1 seconds. The analytical pedestrian delay is 21.0 seconds. The analytical pedestrian delay was based on the equation below.

$$d = \tfrac{1}{2}\left(\tfrac{R^2}{C}\right) \qquad \text{Equation 3.2}$$

Where R = pedestrian red time indication

C = cycle length

The analytical pedestrian delay was based on the assumptions that the signal control was fixed time, uniform pedestrian arrival rate and 100% compliance rate. The comparison between these two results: VISSIM and analytical pedestrian delay shows a reasonable value in VISSIM pedestrian delay output.

3.5 Summary

This chapter has explained the modelling procedure for the base case scenario at a Puffin crossing and the measurement of delay time in the simulated road network. A 600 meters vehicle travel time section was used for vehicle travel time measurement as it covered the acceleration and deceleration sections of vehicle.

Delay time due to signal control, which would include time spent decelerating, waiting in a queue and accelerating to normal running speed, was evaluated as the difference in travel times for delayed and undelayed vehicles (without signal control). Therefore, vehicle delay was calculated by subtracting travel time between base case and free flow scenario. Similarly for pedestrians, pedestrian delay was measured as the difference between delayed travel time and undelayed travel time when there was no vehicles on the road crossing.

4 Calibration and Validation

4.1 Introduction

The previous chapter presented the model development of a Puffin crossing using VISSIM microsimulation. The next requirement was model calibration and validation. This required the use of real Puffin crossing sites.

Video data was available from a range of Puffin and other types of pedestrian crossings in the UK from another Government funded research study. After a careful site selection process, two sites in Manchester were selected for detailed study – Market Street and Howell croft.

One of these sites chosen was in the busy city centre whilst the other had lower pedestrian flows, being further out from the centre. The sites were not ideal in all respects (e.g. the crossing was on a gentle bend at one site, whilst the other was affected to some extent by a nearby staggered junction). However, these sites both offered good camera vantage points and offered good ranges of traffic and pedestrian flows, so that realistic strategy testing could be undertaken. Again mid-block crossings were chosen to offer the best chance of clear results – so that, given sufficient research time, modelling could move on to signalised junctions in due course.

The developed VISSIM microsimulation model was calibrated and validated to the traffic conditions of Market Street and Howell Croft, Manchester. Selected model parameters in VISSIM were calibrated using actual on-street data to ensure reasonable correspondence between the simulation model and on-street performance. Several default values for the parameters such as the number of observed vehicles and the distance required in changing lane were modified to replicate field conditions at Market Street, Manchester. The simulated performances were then compared to field performances to check the realistic representation of the model.

To validate the calibrated model, it was applied on another site in Howell Croft, Manchester using a different data set. Model validation was regarded as a final stage to investigate if each component adequately reproduced observed travel characteristics and the overall performance of the model was within an acceptable error.

This chapter therefore presents the calibration and validation procedure of the model. It is divided into five sections which discuss the data collection, model checking, model calibration, model validation and followed by a summary.

4.2 Methodology

Setting up the simulation model was the first step and comprised tasks and activities that were conducted prior to the commencement of model calibration and validation. The tasks consisted of site selection, field data collection, network coding and model error checking. The flow of the procedures is shown in Figure 4.1.

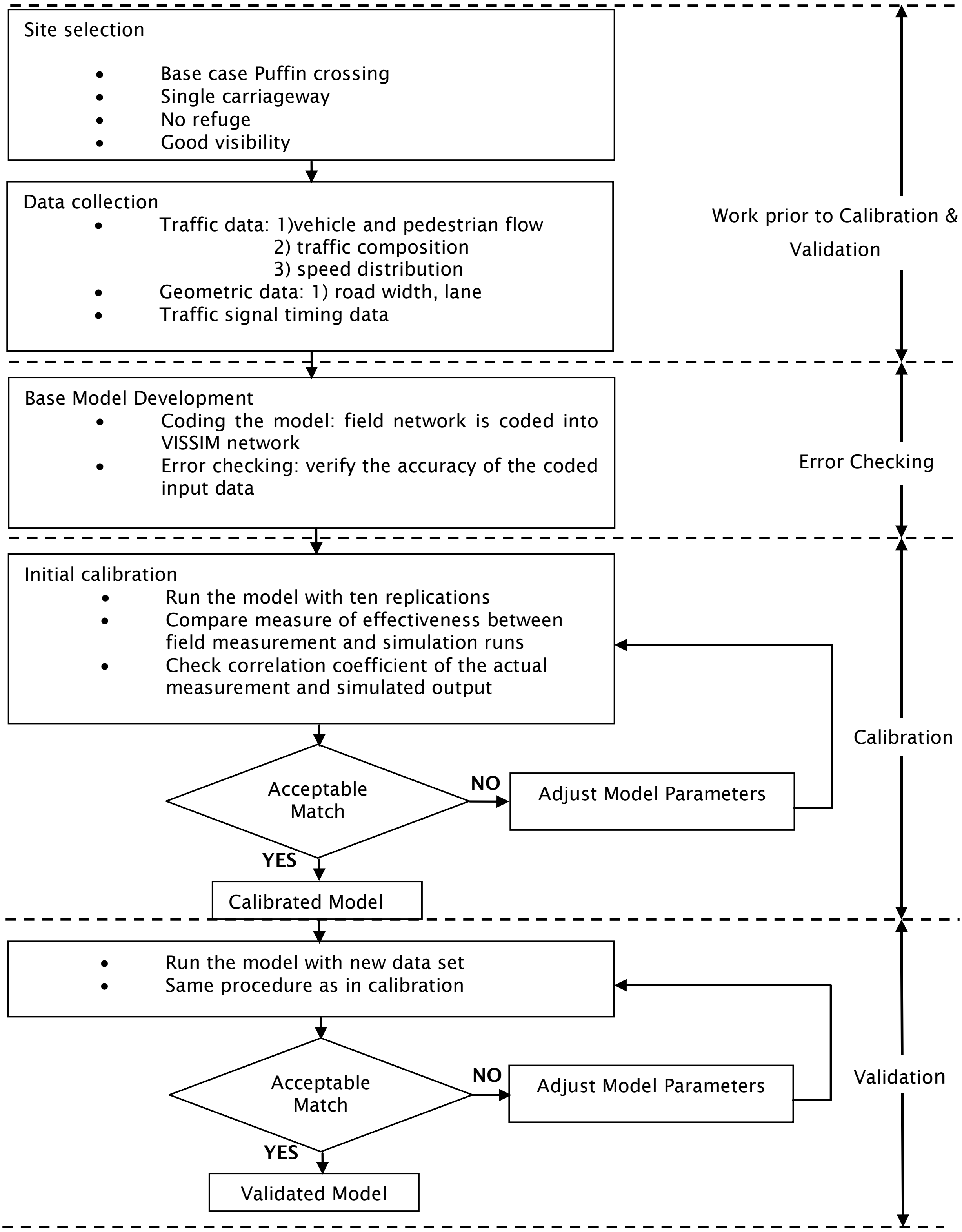


Figure 4.1 Calibration and Validation Flow Chart
(Dowling et al., 2004)

4.3 Data Collection

Several data were required for the VISSIM model and were categorised into two types:

(a) Basic Input data: road geometry, traffic data and traffic signal timing
(b) Calibration data

The first type is the basic input data used for network coding of the simulation model. The second type is the observation data employed for calibration of simulation parameters. Basic input data included data of road geometry, traffic volume data, turning movements, traffic composition, speed data and traffic control systems. The coded VISSIM simulation network needed to be further calibrated to replicate the local traffic conditions. This involved comparing the simulation results against field observed data and adjusting model parameters until the model results fall within an acceptable range of convergence. Data collected for model calibration included traffic volume data and travel time. A summary of data collected for both the sites for this study is shown below in Table 4.1.

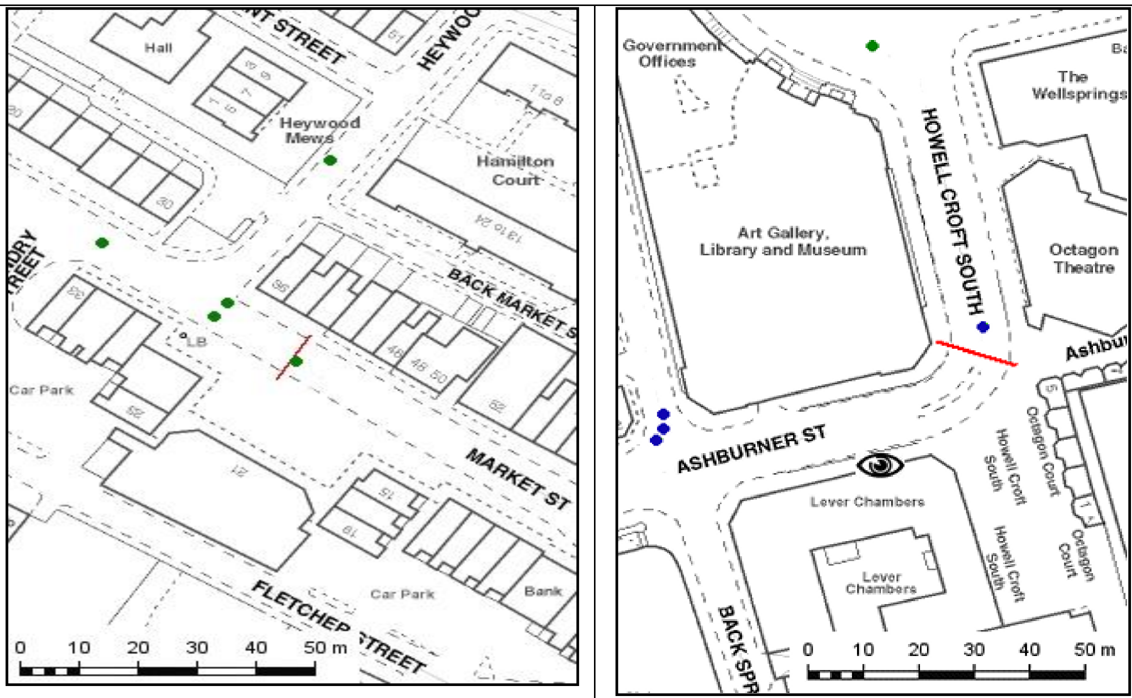
Table 4.1 A Summary of Data Collected

Category		Data Type
Input Data	Road geometry data	• Links with start and end point • Link lengths • Link width • Number of lanes • Connectors between links to model turning movements • Position of signal heads/stop lines
	Traffic demand data	• Through and turning traffic volume counts • Vehicle composition • Pedestrian volumes • Pedestrian composition
	Speed data	• Vehicle desired speed • Pedestrian desired speed
	Signal control data	• Signal timing
Data for Calibration	Vehicle and Driver Performance Data*	• Car following behavior • Lane change behavior • Lateral behavior • Signal control
	Performance data*	• Vehicle travel time • Pedestrian travel time
	Traffic Counts*	• Vehicle and pedestrian volume

*these parameters were described in section 4.5 Model Calibration

An exploratory approach using data from an historical video record from Market Street, Manchester and Howell Croft, Manchester have been used to collect the data. The sites were chosen as they satisfied the requirements in section 4.2.

Market Street is a single carriageway Puffin crossing. The road has through movements, right turning and left turning movements. Howell Croft site was used as a validation site. In contrast to Market Street road, the Howell Croft site has no turning movements. Both sites have Puffin crossings operating under Vehicle Actuation signal control. Traffic flows, traffic speeds, travel times, pedestrian behaviour and signal timing for both vehicles and pedestrians were retrieved over the 1 hour video recording (0800-0900) for both sites. These data were used for calibration and validation of a simulation model to represent pedestrian-vehicle interactions realistically. Figure 4.2 shows the basic layout of the road section studied.



(a) Market Street, Manchester

(b) Howell Croft, Manchester

Figure 4.2 Road layout at Market Street and Howell Croft, Manchester

Figure 4.2 (a) and (b) show the road layout of the calibration and validation sites respectively. Data on road geometry was obtained from a 1:20 scale map of the site. The location of specific road features necessary for modelling, such as the location and width of pedestrian crossings, vehicle stop lines, width of road links and number of lanes per link were retrieved from the video and map above.

Standard signal timing parameters such as intergreen time, minimum green time and pedestrian phase time for both sites were provided by the Greater Manchester Authority. Some of the parameters were cross-checked with the site observation. The site observation confirmed that the parameters were followed and up-to-date.

4.3.1 Traffic Demand Data

Traffic counts of both vehicles and pedestrians were necessary in order to introduce site representative flows in the micro simulation model. The video recordings were used to measure traffic flows and traffic composition on the Market Street and Howell Croft sites. Table 4.2 and Table 4.3 below show the vehicle flows per hour and pedestrian flows per hour at both sites; Market Street and Howell Croft.

Table 4.2 Vehicle Flows per hour

	Market Street, Manchester		Howell Croft, Manchester	
	Southbound	Northbound	Southbound	Northbound
Through movement	809	484	420	353
Right turning	35	38	-	-
Left turning	26	16	-	-
Total	870	538	420	353

Table 4.3 Pedestrian Flows per hour

	Market Street, Manchester		Howell Croft, Manchester	
	Westbound	Eastbound	Westbound	Eastbound
Total	15	65	255	186

As seen in Table 4.2 and Table 4.3, both sites have different traffic flow characteristics. The calibration procedure was conducted at the Market Street site which has high vehicle flows and low pedestrian flows. The validation procedure was conducted at a different traffic flow combination at Howell Croft site which has lower vehicle flows and higher pedestrian flows compared to the calibration site.

Three vehicle classes as in the video were defined for use in the modelled road crossing: Car, Heavy Goods Vehicle and bus. Table 4.4 shows traffic composition at both sites.

Table 4.4 Traffic Composition at Market Street and Howell Croft, Manchester

	Market Street	Howell Croft
Car	95%	94.5%
Heavy Goods Vehicle	3%	4.5%
Bus	2%	0.7%

Both sites are located at busy city centre roads. Therefore, car composition is higher compared to other vehicle types as shown in Table 4.4 above.

4.3.2 Vehicle Desired Speed Distributions

In a moving traffic stream, each individual vehicle travels at a different speed. Thus, the traffic stream does not have a single characteristic speed but rather a distribution of individual vehicle speeds. The desired speed distribution of vehicles is required as a VISSIM input data. If not hindered by other vehicles, a driver will travel at his desired speed (with a small stochastic variation). If overtaking is possible, any vehicle with a higher desired speed than its current travel speed is checking for the opportunity to pass without endangering other vehicles.

Desired speed distributions for vehicles were coded in the model based on the actual speeds of vehicles at free flow conditions. Figure 4.3 below shows a cumulative distribution of vehicle desired speed at Market Street.

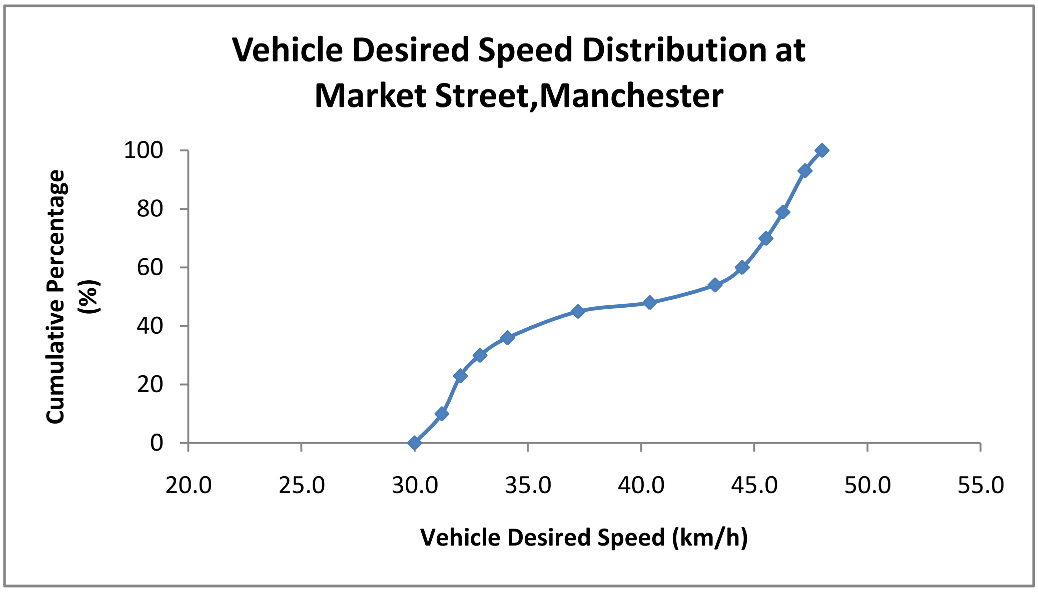


Figure 4.3 Vehicle Desired Speed Distribution at Market Street, Manchester

As shown in Figure 4.3 the vehicle desired speed distribution at Market Street, Manchester varies from 30.0 km/h to 48.0 km/h. As can be seen in Figure 4.3, about 50% of the sample has free-flow speeds under 45 km/h. The vehicle desired speed distribution was taken from 324 vehicles at free flow. The mean of the vehicle desired speed distribution is 40.1 km/h with standard deviation 6.5. Figure 4.4 below shows the vehicle desired speed at Howell Croft, Manchester.

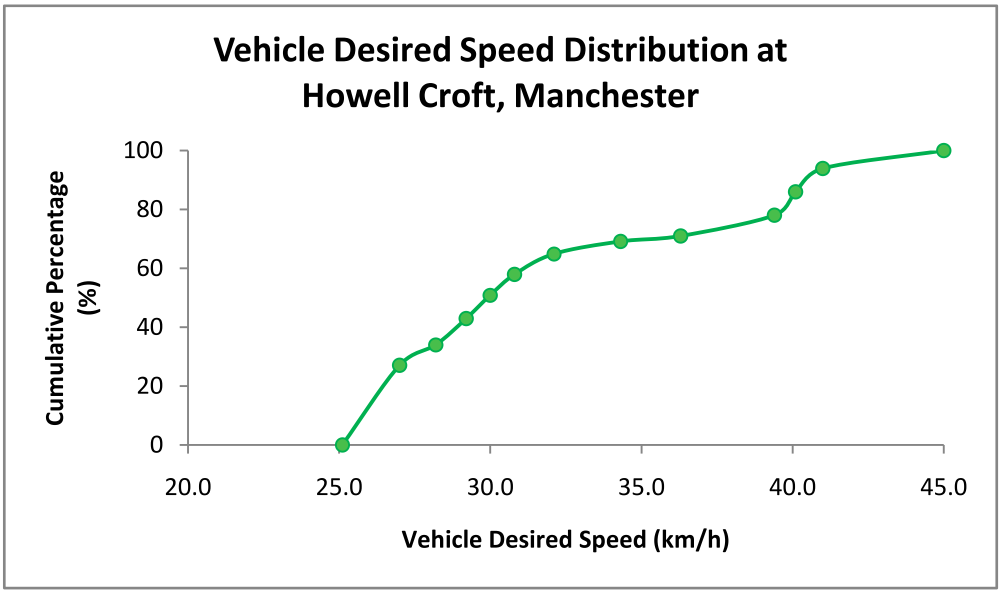


Figure 4.4 Vehicle Desired Speed Distribution (km/h) at Howell Croft, Manchester

As shown in Figure 4.4, vehicle desired speed at Howell Croft site ranged between 25 km/h and45 km/h. The vehicle desired speed distribution was taken from 214 vehicles at free flow. The mean of the vehicle desired speed distribution was 32.7 km/h with a standard deviation of 5.9. About 80 percent of the vehicles had speeds under 40 km/h (25mph). The reason for the lower speed is the influence of the geometric road layout on driving behaviour and the location of the crossing on a busy high street road. The Howell Croft site has a bend on the pedestrian signalised crossing hence encouraging driver to move very slowly on the curve. High pedestrian flows at the High Street road were observed to slow down the speed of vehicles considerably.

4.3.3 Pedestrian Desired Speed Distributions

Then, pedestrian speed data at Market Street and Howell Croft, Manchester were measured from video recordings. The length of the pedestrian crossing at Market Street and Howell Croft was 10m and 11m respectively. Desired speed distributions for pedestrians were coded in the model based on the pedestrians' actual speeds at free flow condition.

In order to determine the free-flow speeds, the complete sample was reduced to include only those observations where a subject was not in the middle or trailing in a platoon and not facing a high opposing flow. These conditions resulted in a mean speed of 5.70 km/h from 51 observations at Market Street site with standard deviation 0.81 km/h. Figure 4.5 below shows the pedestrian desired speed at Market Street, Manchester.

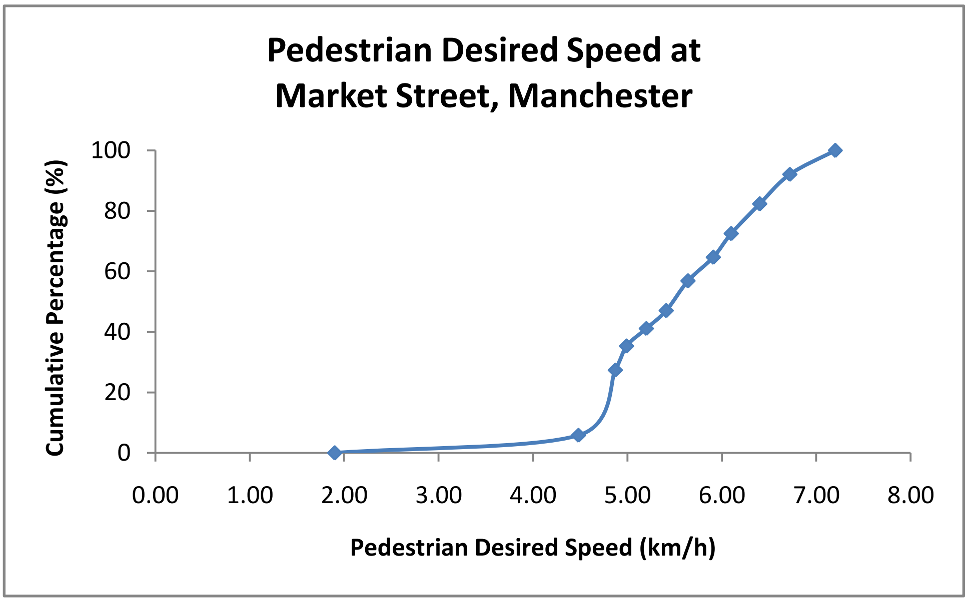


Figure 4.5 Pedestrian desired speed distribution (km/h) at Market Street, Manchester

Based on the video observations, pedestrian desired speed at Market Street, Manchester ranged from 1.9 km/h to 7.20 km/h as shown in Figure 4.5 above with the 15th percentile speed at 4.8 km/h and 85th percentile speed at 6.6 km/h. The mean of pedestrian desired walking speed was calculated as 5.70 km/h which is faster than the normally used standard pedestrian walking speed found in literature (Knoblauch et al., 1996; Willis et al., 2004; Gates et al., 2006). One factor that may contribute to the faster walking speeds on the crosswalk is pedestrians try to minimise the delay they encountered on the kerbside. It was expected that the pedestrians on the site were used to walk faster due to high vehicle flow on the site which caused a longer and frequent vehicle phase.

At Howell Croft site, the filtering of the data to determine the desired speed distribution resulted in 285 observations (down from the original data set of 441 observations). The mean of pedestrian desired walking speed on the crossing at Howell Croft site was calculated as 4.3 km/h with a standard deviation of 0.71 km/h. Note that the standard speed often used in design – 1.2 metres/sec – equates to 4.32 km/h. Figure 4.6 shows the pedestrian desired speed at Howell Croft, Manchester.

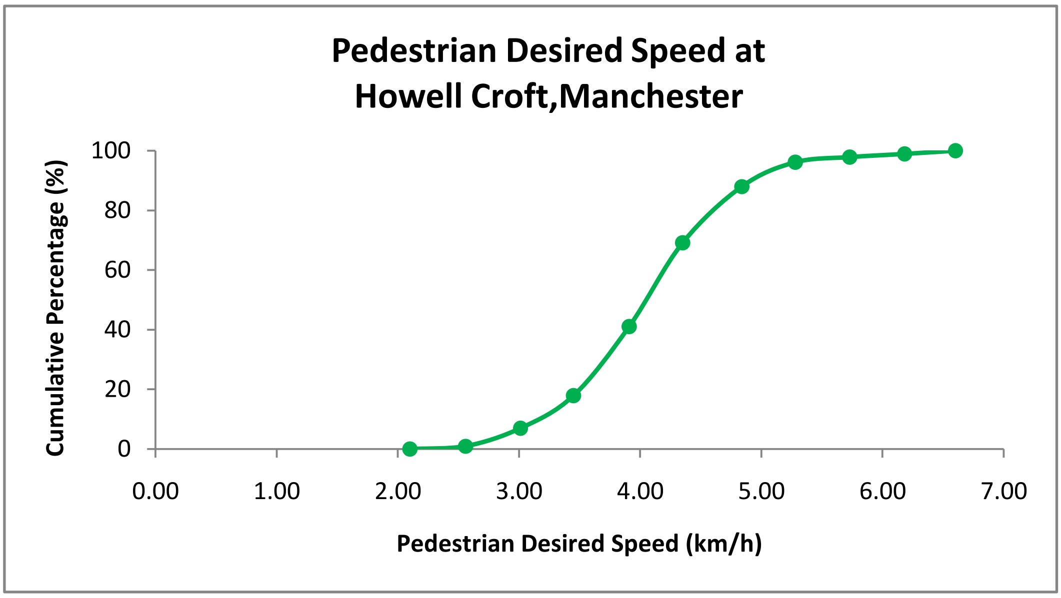


Figure 4.6 Pedestrian desired speed distribution (km/h) at Howell Croft, Manchester

Pedestrian desired speed at Howell Croft shows a similar trend to Market Street site with the speed ranged from 2.1 km/h to 6.6 km/h as shown in Figure 4.6 above, with the 15th percentile speed and 85th percentile speed at 3.3 km/h and at 4.7 km/h respectively. The pedestrian desired speed trend as in Figure 4.6 follows the walking speed graph studied by Fruin (Transportation Research Board, 2000) as mentioned in Chapter 2.

4.3.4 Pedestrian Behaviours

From the video observation, pedestrians were classified into three types according to their behaviour when arriving in pedestrian red phase (Red Man):

1) obey signal
2) press the button but ignore red (gap-crossing when there is an opportunity)
3) do not press the button and ignore red (gap-crossing when there is an opportunity)

For the present study, gap selection attributes of pedestrians at signalised crossing were derived from field data collected at signalised crossing in Market Street and Howell Croft, Manchester. The methodology by which these data were collected is described in Transportation Research Board (2000).

In VISSIM, a pedestrian's crossing decision can be described as a function of the pedestrian's critical lag time. A 'lag' is the time between a pedestrian's arrival at the crossing and the arrival of the next conflicting vehicle (Ishaque, 2006; Schroeder and Rouphail, 2007). The pedestrians will cross if the lag time to the next vehicle arrival is greater or equal to the critical lag time, where the vehicle arrival time is a function of that vehicle's speed and distance to crosswalk. Therefore, in this study, a gap was measured as the difference between the time a pedestrian started to cross and the time when the leading vehicle in the vehicle platoon reached the pedestrian crossing on the opposite direction. Total gap for two-way directions of traffic flow is defined as the sum of the near-side traffic gap and the far-side traffic gap (DiPietro and King, 1970).

Two hours of data was analysed to determine the accepted gap by pedestrians. It is the measurement of the actual gap, which pedestrians perceived was sufficient to cross the road of two-way traffic. Figure 4.7 shows the results of the study for Market Street site with the width of the road was 10 meters.

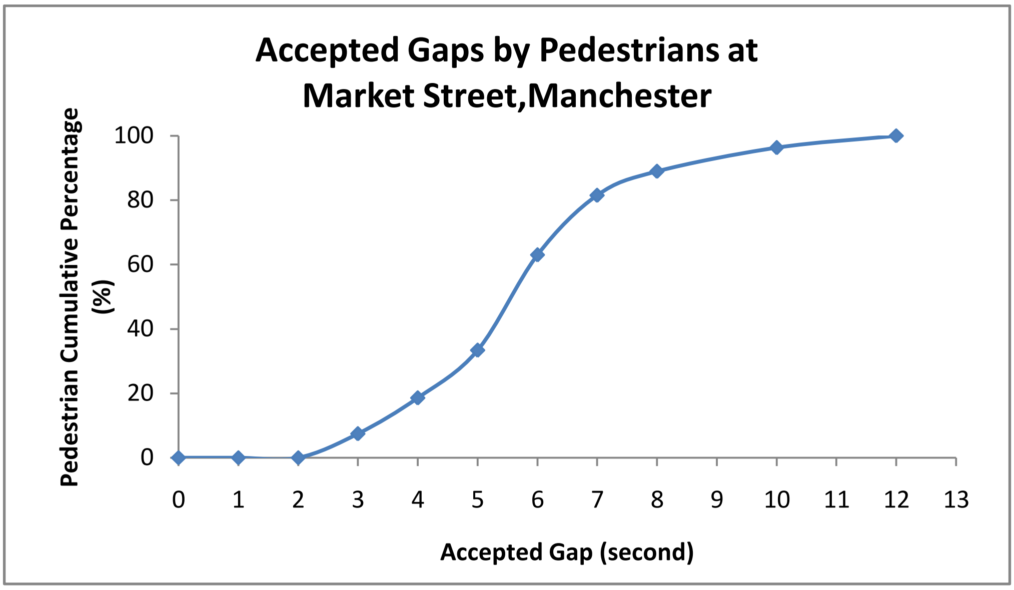


Figure 4.7 Accepted Gap at Market Street, Manchester

The results in Figure 4.7 show that when the available gap was 7 seconds, about 80% of pedestrians at Market Street would cross the road. The accepted gap data at Market Street was taken from 27 pedestrians out of 80 pedestrians who gap-crossed on the crossing. The mean of accepted gap at Market Street was 6.3 seconds with standard deviation 2.3 seconds. This result was similar to a previous study done by Cohen et. al. (1955). Figure 4.8 below shows the accepted gap by pedestrians at Howell Croft, Manchester.

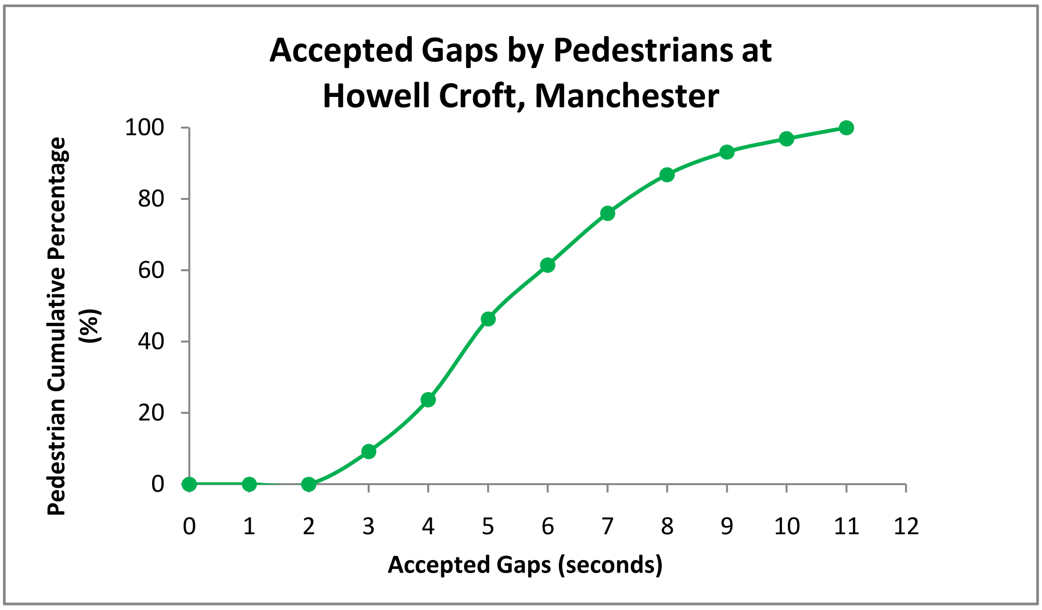


Figure 4.8 Accepted Gap at Howell Croft, Manchester

The results in Figure 4.8 show that approximately 76% of pedestrians at Howell Croft would cross the road of 11 meters width when the available gap was 7 seconds. At the Howell Croft site, the accepted gap data were taken from 220 pedestrians out of 441 total pedestrians at the site. The mean of the accepted gap at Howell Croft was 6.1 seconds with standard deviation 2.0 seconds.

Result in Figure 4.7 and Figure 4.8 show that about half of the pedestrians would cross the road if the vehicle was 5 to 6 seconds away from them. And almost everyone crossed the road when the gap was 10 seconds and above. The results for gap-acceptance shown in Figure 4.7 and Figure 4.8 are in close agreement to those found in the previous study done by Cohen et. al. (1955). The percentage of pedestrians crossing the road increased with longer gap. Table 4.5 shows the summary of gap acceptance behaviour of pedestrians at Market Street and Howell Croft sites.

Table 4.5 A Summary of Pedestrians' Gap Acceptance at Market Street and Howell Croft

	Market Street	Howell Croft
Total number of pedestrians	80	441
Total number of pedestrians who gap-crossed	27	220
Mean of accepted gap (seconds)	6.3	6.1
Standard deviation of accepted gap (seconds)	2.3	2.0

Based on the summary in Table 4.5 above, the mean of accepted gap by pedestrians is approximately 6 seconds. Therefore, all pedestrians who gap crossed in the Market Street and Howell Croft site were coded to accept a gap of 6 seconds while crossing a road with two way traffic. The 6 seconds gap was measured as the difference between the time a pedestrian started to cross and the time when the leading vehicle from conflicting direction reached the pedestrian crossing after pedestrian has safely arrived on the opposite kerbside.

From the observation on the video, most pedestrians either crossed at the beginning of the pedestrian phase or the vehicular traffic was very far from the crossing. However, some of those pedestrians who entered the road during vehicle phase walked at high walking speeds due to the anticipation that the vehicular traffic was about to come at any time.

4.4 Model Error Checking

Model error checking was conducted to determine the validity of the logic for Puffin signal control. It was necessary to identify any model coding errors. Coding errors can distort the model calibration process by adopting incorrect values for calibration parameters. Such errors can be found at any time during the process of the calibration parameters. Accordingly, fixing model coding errors was an important task throughout the whole modeling process.

The code checking was conducted to test the ability of the model to reflect the Puffin crossing operations, including gap acceptance and call-cancels. A series of simulation runs were conducted to determine if the model was functioning as intended. Input data of the model such as traffic volumes, traffic signal timing was based on the data collected at Market Street network (refer section 4.3). VISSIM allowed visual viewing of the simulation runs.

From visual observation in VISSIM model, all pre-determined pedestrians behaved as they should - obeying the signal indication or ignoring the signal indication and gap-crossing if possible. There was no fatal problem in the model such as collision between pedestrians and vehicles or any errors in Puffin signal control operation. Visual output showed that each phase was changing as intended, where the vehicles will hold green time until there is a pedestrian demand. The pedestrian stage commences when there is a gap in the vehicle traffic or the vehicle stage has reached its maximum green. The modelled Puffin signal control was then checked further on the offline output text file for confirmation. The model error checking was then performed on the number of signal cycles and traffic volume.

4.4.1 Number of Signal Cycles

Signal stage changes were analysed initially as an accurate representation of the actual Puffin control is the first and fundamental requirement. If this is inaccurate, then other performance parameters (e.g.: average journey time) will be in inaccurate, because they are, in part, dependant on signal timings.

Model error checking based upon the number of signal cycles was performed by comparing the stage change frequency between simulation runs and field measurements. Ten simulation runs of the model with different random seed numbers were conducted using default model parameters in order to get the necessary output. Figure 4.6 shows the cycle number measured on the calibration site, Market Street and average cycle number from 10 simulation runs.

Table 4.6 Numbers of Signal Cycle: Field vs Simulation

Frequency of signal timing changes		
Field	Average Simulation Runs	RMSP
38	39	1.9%

Figure 4.6 shows the cycle number of signal control from both real site and simulation model is 38 and 39 respectively. Root Mean Square Percentage (RMSP) was conducted to check the goodness of fit between cycle number of calibration site and simulation model. RMSP 1.9% shows a high satisfaction of goodness of fit between simulated and field signal timing changes, which is less than 15%. The simulation model was able to produce a close matched signal timing changes as in the field measurements.

4.4.2 Traffic Demand and Pedestrian Composition

Second, to check the traffic demand and pedestrian composition in the model to best match observed demand. Table 4.7 shows a comparison of vehicle demand between field and simulation model.

Table 4.7 Vehicle Volume: Field vs Simulation

Approach	Vehicle Volume			
	Field Observation	Average Simulation	Percentage Difference,	RMSP
Southbound	870	869.7	-0.00039	0.07 %
Northbound	538	537.9	-0.00011	0.02 %

In Table 4.7 above it is shown that the RMSP value of vehicle demand between field measurement and simulation model for both southbound and northbound direction is 0.07% and 0.02% respectively. The error between these two observations is very low, in which the RMSP value of nearly 0% shows a high satisfaction of goodness-of-fit between field measurement and simulation model. However, this simply confirms that traffic flow data input to the model was correct, rather than being (strictly) a calibration process.

Table 4.8 shows a comparison of pedestrian volume between field measurement and simulated network.

Table 4.8 Pedestrian Volume: Field vs Simulation

Approach	Pedestrian Volume			
	Field	Average Simulation	Percentage Difference,	RMSP
Westbound	15	14.3	-0.05	5.2 %
Eastbound	65	62.8	-0.03	3.5 %

As shown in Table 4.8, the Root Mean Square Percentage (RMSP) value is 5.20% and 3.50% for both Westbound and Eastbound approach respectively. The RMSP value of pedestrian volume is less than 15% which shows a satisfactory goodness-of-fit between field and simulation model. Again, this confirms that pedestrian flow data input to the model was correct, rather than being (strictly) a calibration process.

The error checking on pedestrian composition was also conducted to check that the model can reproduce the pedestrian composition as measured in the field. There were three types of pedestrians measured on the crossing: obey signal, press button (PB) and gap-crossed, and not press button (PB) but gap-crossed. Table 4.9 shows the pedestrian composition both at field and simulated road crossing from Westbound and Eastbound approach.

Table 4.9 Pedestrian Composition: Field vs Simulation

Approach	Pedestrian Types	Pedestrian Composition			RMSP
		Observed at Field	Estimated at VISSIM model	Percentage Difference, %	
Westbound	Obey signal	0.57	0.61	0.08	8.6%
	PB, gap-crossed	0	0	0	0
	No PB, gap-crossed	0.43	0.39	-0.10	11.4%
Eastbound	Obey signal	0.71	0.73	0.04	3.9%
	PB, gap-crossed	0.13	0.12	-0.07	10.3%
	No PB, gap-crossed	0.16	0.14	-0.10	13.0%

As shown in Table 4.9 the percentage difference on pedestrian composition for both observed and model estimated is very small hence it produces a satisfactory goodness-of-fit with Root Mean Square error Percentage values are less than 15% for each of the pedestrian types.

The model error checking on traffic demand (vehicle and pedestrian) and pedestrian composition achieved a high goodness-of-fit between field measurement and simulation model. The model is able to produce the correct input parameters for the Market Street road crossing with a small error.

4.5 Model Calibration

Calibration is the process of adjusting the simulation model parameters to replicate field measurements or observed traffic conditions. There are various parameters in VISSIM microsimulation model to describe traffic flow characteristics, driver behavior and traffic control operations. These parameters are shown in Table 4.10 below.

Table 4.10 VISSIM Model Parameters

Model	Parameters		Default Value		New Value	
Following	Look ahead distance	Min	0			
		Max	250.0 m			
		Observed Vehicles	4		2	
	Look back distance	Min	0			
		Max	150.0			
	Temporary lack of attention	Duration	0 s			
		Probability	0 %			
	Car Following Model: Wiedemann74	Average Standstill Distance	2.0 m			
		Additive Part of Safety Distance	2.0 m			
		Multiplicative Part of Safety Distance	3.0 m			
Lane Change	General Behaviour	Free Lane Selection				
			Own	Trailing	Own	Trailing
	Necessary lane change (route)	Maximum deceleration (m/s²)	-4.0	-3.0		
		1 m/s² per distance	100 m	100 m	50 m	50 m
		Accepted deceleration (m/s²)	-1.0	-1.0		
	Waiting time before diffusion		60.0 s			
	Min. headway (front/rear)		0.50 m			
	Safety distance reduction factor		0.60			
	Maximum deceleration for cooperative braking (m/s²)		-3.0			
Lateral	Desired position at free flow		Middle of lane			
	Min. lateral distance	Distance (m) at 0 km/h	1.0			
		Distance (m) at 50 km/h	1.0			
Signal Control	Reaction to amber signal	Decision model	Continuous check			
	Behaviour at red/amber signal		Go (same as green)			
	Reduced safety distance close to a stop line	Reduction factor	0.60			
	Start upstream of stop line (m)		100			
	End downstream of stop line (m)		100			

Most of default values in the model parameters were left unchanged as seen in Table 4.10 above except the number of observed vehicles in the car following model and -1 m/s^2 per distance in the lane change model. The parameters which deal with driving behavior such as the number of observed vehicles and the distance required in changing lane were adjusted based on observation on Market Street, Manchester. Ten simulation runs were conducted with the new values on these two parameters. The new values of these two calibration parameters (observed vehicles and the distance required in changing lane) were adopted in Market Street sites.

The effectiveness of calibration was evaluated by comparing the measure of effectiveness (MOEs) based on traffic count and travel time between field measurement and model estimation (Hourdakis et al., 2003; Dowling et al., 2004).

4.5.1 Calibration of Vehicle Flows and Travel Time

Ten repetitions of the calibrated data set were performed and the link output was processed to produce performance measures to be compared with the field data. The calibration procedure employed here is based on aggregating travel time data into 1 second bins, as suggested by Ishaque (2006). Figure 4.9 shows the results of vehicle count and vehicle travel time between field measurement and model estimation from simulated junction.

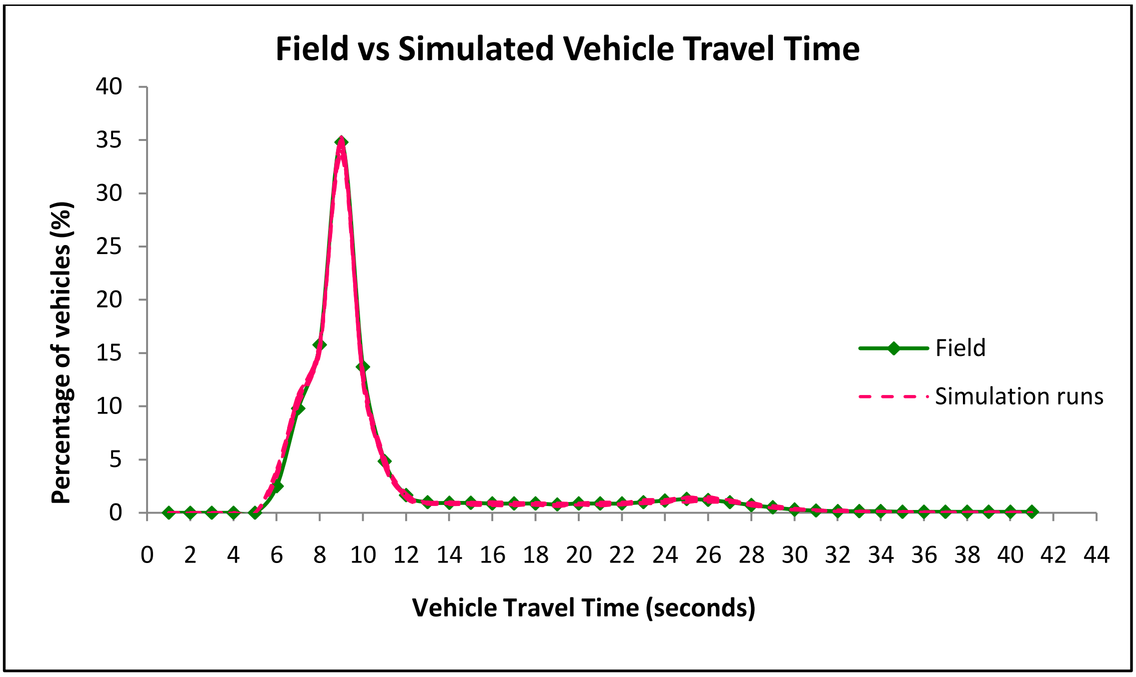


Figure 4.9 Vehicle travel time plots from field data and simulation runs

It can be seen from Figure 4.9 above that the vehicle count on travel time of the VISSIM runs is close to the actual measurement on the site. The travel time plot for both field measurement and simulation result shows one travel time, ranging between 8 seconds to 10 seconds. About 35% of vehicles need 8 seconds to 10 seconds to travel between two travel time measurement points. As can be seen in the graph above, the vehicles were able to travel smoothly on the road and did not experienced longer travel time between the two measurement points. This is due to the low pedestrian volume at the site. The calibration of vehicle count and vehicle travel time was true over the section observed in the field.

Preliminary analyses were performed to assess the normality and linearity of the data before performing the statistical analysis of the results. Correlation of individual travel times between field measurement and average of ten simulation runs was performed using Spearman's rho correlations coefficient as shown in Table 4.11.

Table 4.11 Correlation coefficient for vehicle travel time between field measurement and simulation runs

			Field Travel Time	Average Simulated Travel Time
Spearman's rho	Field Travel Time	Correlation Coefficient	1.000	0.994**
		Sig.(2-tailed)	.	0.000
		N	41	41

**. Correlation is significant at the 0.01 level (2-tailed).

As shown in Table 4.11, there was a strong positive correlation between the field travel time and simulated travel time, correlation of coefficient, r is 0.994 with $p < 0.05$. The correlation is statistically significant at above the 99 percent confidence level.

The comparison of Market Street system performance is shown in Table 4.12. The values represent the mean value of travel time based on the field measurement and ten VISSIM runs.

Table 4.12 System performance results for Market Street network

Mean of Vehicle Travel Time			
Field	Average Simulation	Percentage Difference, %	RMSP
11.1	10.6	4.5 %	4.5%

The results in Table 4.12 indicate that the model satisfies the criteria for calibration with the RMSP is 4.5%. The Root Mean Square Percentage (RMSP) value for individual vehicle travel time is 11.70%. It shows a satisfactory goodness-of-fit between field measurement and simulation model. Both the Spearman's rho correlation and RMSP test achieved satisfactory results.

4.5.2 Calibration of Pedestrian Flows and Travel Time

All default values in the pedestrian behaviour model in the *Social Force Model* were kept unchanged. Then, the overall performance of the model in predicting the pedestrian travel time was evaluated. Pedestrian travel time data was aggregated into bins of 1 sec duration each. Figure 4.10 below shows the results of travel time plots of field measurement and ten simulation runs.

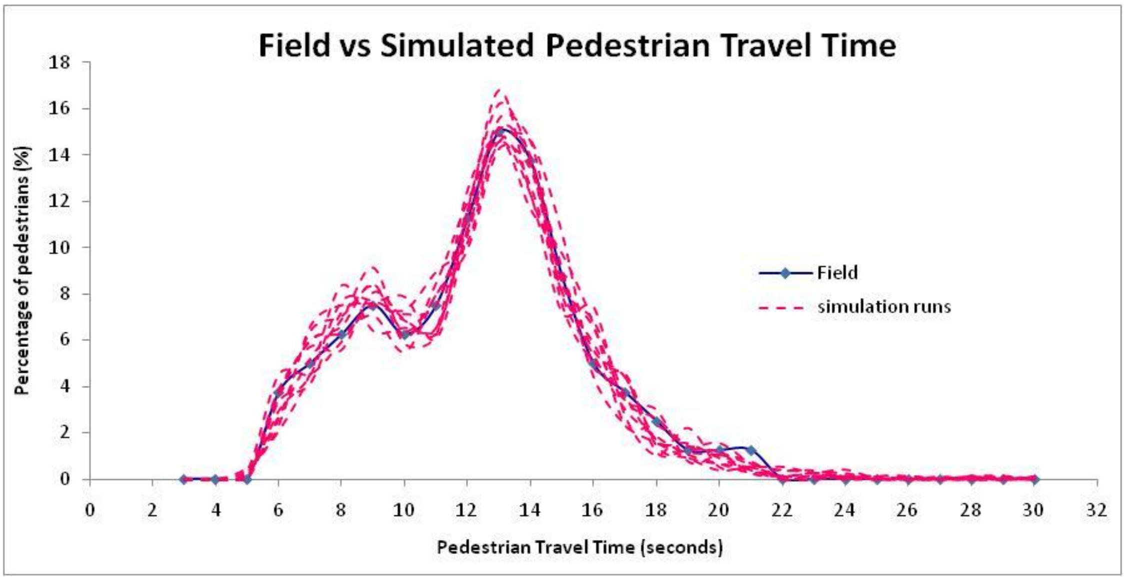


Figure 4.10 Pedestrian travel time plots from field data and simulation runs

As seen in Figure 4.10 above, ten runs of the simulation models produce a closely match pedestrian travel time to field measurement. Ten simulation runs with ten different random seeds produced a slight variation in simulated pedestrian travel to account the stochastic variation in traffic movement. Statistical tests were conducted to determine the correlation between simulated and actual pedestrian travel time.

It can be seen in Figure 4.10 that some pedestrians have a lower travel time between 3 seconds to 11 seconds. It was found that those pedestrians who travelled between 3 seconds and 11 seconds were predominantly the pedestrians who arrived in the Green Man indication - thus they can cross the pedestrian crossing immediately. And pedestrians whose travel time was more than 11 seconds were the pedestrians who arrived in the Red Man indication, thus they have to wait longer at the kerbside. The pedestrian travel time plot in Figure 4.10 shows that the simulation can reproduce the pedestrian travel time plot as in the Market Street site.

Table 4.13 shows the correlation of individual point of pedestrian travel time between field measurement and average of ten simulation runs was performed using Spearman's rho correlations coefficient.

Table 4.13 Correlation coefficient for pedestrian travel time between field measurement and simulation runs

			Field Pedestrian Travel Time	Average Simulated Pedestrian Travel Time
Spearman's rho	Field Travel Time	Correlation Coefficient	1.000	0.959**
		Sig.(2-tailed)		0.000
		N	28	28

**. Correlation is significant at the 0.01 level (2-tailed).

As seen in Table 4.13 above, a strong correlation coefficient was found between the mean of ten simulation runs and the actual data. Correlation of coefficient, r is 0.959 with $p < 0.05$. The comparison between field and simulated pedestrian travel time showed that at the 99 percent confidence level, there was no statistically significant difference between the actual data and simulation runs.

Table 4.14 shows the comparison of Market Street performance based on pedestrian travel time between field measurement and model estimation. The values represent the mean value of travel time based on the field measurement and ten VISSIM runs.

Table 4.14 System performance results for Market Street network

Mean of Pedestrian Travel Time			
Field	Average Simulation	Percentage Difference, %	RMSP
12.4	11.9	4.0%	4.0%

As seen in Table 4.14, the Root Mean Square Error of pedestrian travel time between field measurement and model estimation is less than 15%. The RMSP value of 4% shows a good degree of fit between field measurement and model estimation.

The successful calibration of the model demonstrated that the model is robust enough to predict the system performance (vehicle and pedestrian travel time) at this site, with its unique sets of flows and traffic characteristics. Therefore, the next step adapted in this study is to validate the model under different site condition with different traffic characteristics.

4.6 Model Validation

Validation is the process of establishing if the model accurately and reliably represents the real world systems over the range of anticipated conditions. All model parameters used in the calibration site were used in the validation site. The validation procedure was conducted as for the calibration procedure but with a completely new set of data under different conditions such as: traffic flow, traffic speed, and different geometric layout. Howell Croft, Manchester was used as a validation site. The prediction of system performance based on travel time was compared between field measurements and model estimation.

4.6.1 Validation of Vehicle Travel Times

First, the overall performance of the model was tested in predicting the vehicle travel time. Vehicle travel time data was aggregated into bins of 1 sec duration each. The travel time plots from the validation site and ten runs of the simulation models are shown in Figure 4.11 below.

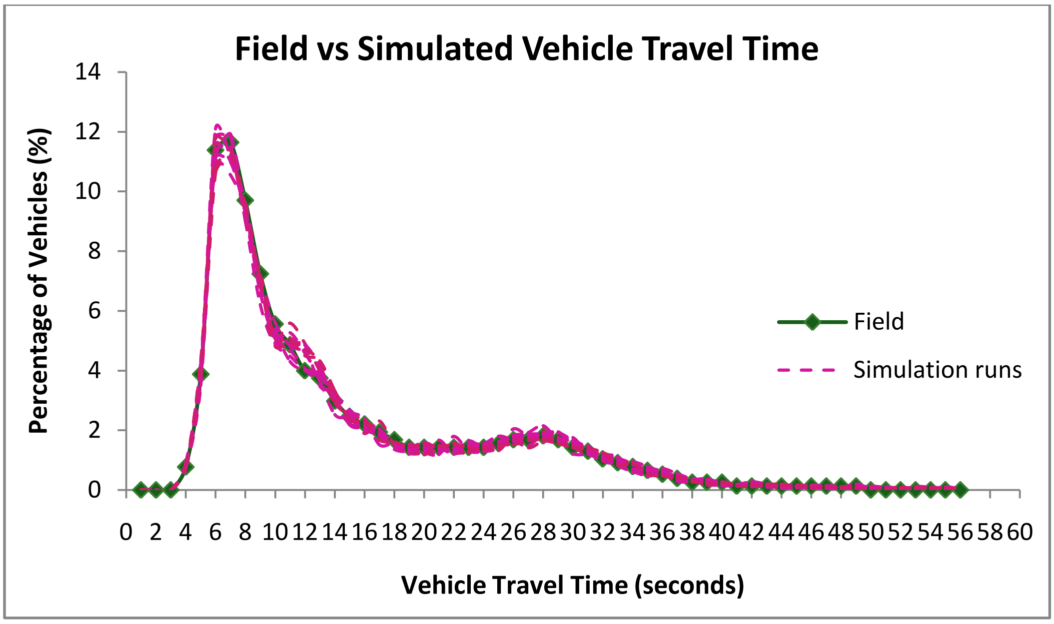


Figure 4.11 Vehicle travel time plots from field data and simulation runs

As can be seen in the Figure 4.11 above, the vehicles were able to travel smoothly on the road and did not experience particularly long travel time between the two measurement points. This is due to the low pedestrian volume at the site. Table 4.15 below shows the correlation of individual travel time between field measurement and average of ten simulation runs using Spearman's rho correlations coefficient.

Table 4.15 Correlation coefficient for vehicle travel time between field measurement and simulation runs

			Field Travel Time	Average Simulated Travel Time
Spearman's rho	Field Travel Time	Correlation Coefficient	1.000	0.978**
		Sig.(2-tailed)	.	0.000
		N	70	70

**. Correlation is significant at the 0.01 level (2-tailed).

As can be seen in Table 4.15 above, there was a strong positive correlation between the field travel time and simulated travel time, correlation of coefficient, r is 0.978 with $p < 0.05$. The correlation is statistically significant at above the 99 percent confidence level. Then, the average system performance at Howell Croft based on vehicle travel time was compared between field measurement and model estimation. The result is shown in Table 4.16 below. The values represent the mean value of travel time from field measurement and ten VISSIM runs.

Table 4.16 Vehicle Travel Time performance at Howell Croft

Mean of Vehicle Travel Time			
Field	Average Simulation	Percentage Difference, %	RMSP
14.2	14.2	0.0%	0.0%

The results in Table 4.16 indicate that the model satisfies the criteria for validation with the RMSP is less than 15%.

4.6.2 Validation of Pedestrian Travel Times

After satisfactory validation on vehicle travel time, the capability of the model to reproduce measured pedestrian travel time was tested. Pedestrian travel time data was aggregated into bins of 1 sec duration each. Figure 4.12 shows travel time plots from the validation site and ten runs of the simulation models.

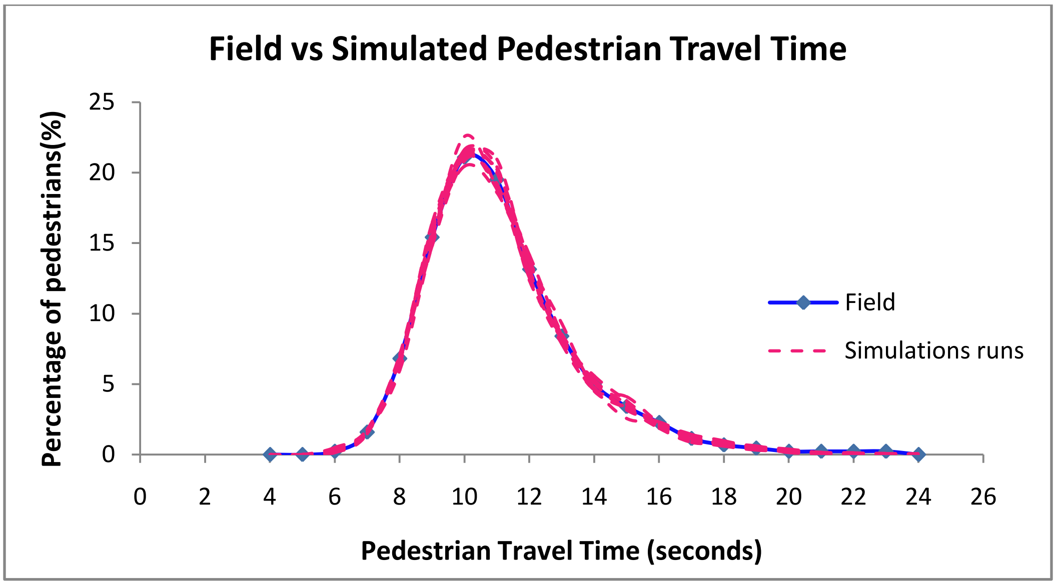


Figure 4.12 Pedestrian travel time plots from field data and simulation runs

Pedestrians can be divided into two types according to the travel time trend in Figure 4.12. Those pedestrians who travelled between 4 and 10 seconds were found to be pedestrians who arrived in the Green Man indication thus they can cross the pedestrian crossing immediately. Pedestrians who arrived in the Red Man indication had to wait longer at the kerbside hence the longer travel time of more than 10 seconds. The pedestrian travel time plot in Figure 4.12 shows a close match between simulation runs and field observation at Howell Croft site.

The pedestrian travel time profile at this site without a kink (Figure 4.12) is different from Market street site (Figure 4.10). The kink in the Market Street site represents the travel time of pedestrians who initially hesitated to cross at the end of Green but then crossed anyway. However, Howell Croft site being the busy city centre road such phenomenon did not happen.

Then a statistical test was conducted to determine the correlation between simulated and actual pedestrian travel time. The result is shown in Table 4.17 below.

Table 4.17 Correlation coefficient for pedestrian travel time between field measurement and simulation runs

			Field measurement	Average Simulation runs
Spearman's rho	Field measurement	Correlation Coefficient	1.000	0.992**
		Sig. (2-tailed)		0.000
		N	21	21

**. Correlation is significant at the 0.01 level (2-tailed).

As shown in Table 4.17 the correlation of coefficient, r is 0.992 with $p < 0.05$.A high correlation is found between actual pedestrian travel time and simulated pedestrian travel time. The comparison between field and simulated pedestrian travel time showed that at the 99 percent confidence level, there was no statistically significant difference between the actual data and simulation runs.

Table 4.18 shows the comparison of Howell Croft system performance based on pedestrian travel time. The values represent the mean value of travel time based on the field measurement and ten VISSIM runs.

Table 4.18 Pedestrian Travel Time performance at Howell Croft

Mean of Vehicle Travel Time			
Field	Average Simulation	Difference, %	RMSP
11.1	10.7	3.6%	3.6%

The results in Table 4.18 indicate that the model satisfies the criteria for validation with the RMSP is less than 15%.

The successful validation of the model demonstrated that the model is robust enough to predict vehicle travel time and pedestrian travel time.

4.7 Limitations of the modelling

There are limitations on the ability of the driving behaviour models (car-following and lane changing) and pedestrian behaviour models (Social Force Model) in VISSIM to sufficiently represent the complicated traffic situations and driver behaviour as well as pedestrian behaviour. This is expected because the human behaviour, including drivers and pedestrians, is complex, dynamic and combined results of many factors. For example, human psychology in driving and moving are difficult to fully quantified and modelled even using the most advanced mathematical methods. These limitations on this aspect undoubtedly exist in this study as well.

In real life, human's decision-making and action process is very complex, and it is impacted and restricted by many factors. Pedestrians' behaviours may vary with external factors. For instance, some pedestrians whom initially obey signal indication may follow other pedestrians to jump the red. Due to the influences of all these external factors, traffic system becomes more complex, unpredictable, with strong randomness.

Another example in real life, someone arrives at crossing and does not press the push button and at the same time looks for a gap. But when he does not find any gap, he presses the push button to register his demand. In VISSIM microsimulation model, the decision to press the button or not itself cannot be the function of the encountered traffic conditions. This is the limitation of VISSIM microsimulation model.

Based on the reviews in pedestrian behaviours section in Chapter 2, pedestrians can be categorised into three different types: obey signal, press the push button but gap-cross and do not press the push button and gap-cross. Therefore, to partly overcome the limitation, the proportion of each pedestrian type needs to be distinguished and pre-determined in the simulation network.

It is also needed to point out that the selection of VISSIM microsimulation model version 5.2 was conducted at the early stage of this PhD study. As a rapid developing area, VISSIM and other models may have been improved in these aspects as well.

4.8 Summary

The successful calibration and validation of the model demonstrated that the model was robust enough to reproduce the traffic demand and predict travel time as in the real field. The model can produce approximately the real situation criteria such as the signal timing changes, traffic volume, pedestrian composition, vehicle travel time and pedestrian travel time. Therefore it was promising to adapt the VISSIM model to the local traffic situation. Although there are limitations in VISSIM, they are not fatal to the model.

The Base Case model in this chapter was then improved to test various scenarios at Puffin crossings. The model was extended further to test two new strategies at Puffin crossing: Upstream Detection and Volumetric Detection. These new improvement scenarios at Puffin crossing are described in the next chapter.

5 Upstream Detection

5.1 Introduction

This chapter describes the development of the model outlined in Chapter 3 to assess the potential for upstream pedestrian detection and presents results from the scenario testing. The aim of the Upstream Detection scenario was to minimise the pedestrian delay time without major disbenefit to vehicular traffic. The principle of Upstream Detection was to provide an earlier activation of the pedestrian stage (pre-arrival detection).

A simple hypothetical pedestrian crossing based on the calibrated and validated model as described in Chapter 4 was used as a base case scenario. The use of a hypothetical model allows a full control and greater flexibility over various traffic, pedestrians and signalling conditions.

At this stage, upstream pedestrian detection was assumed to occur through conventional push button(s) system, with the pedestrian demand registered some distance/time upstream of the crossing. If the strategy proves beneficial, a later stage in the research could be to consider other means of registering upstream pedestrian demand (e.g. personal Bluetooth communication, wider image processing, etc.). Variations in pedestrian behaviour were considered within this new strategy such as walking speed and gap acceptance behaviour among pedestrians.

Simulation results and discussion on the performance of this approach are also described in the section that follows the methodology. The performance of the Upstream Detection strategy was then compared from two aspects: efficiency (vehicle delay and pedestrian delay) and economic benefits. The final section is a summary and recommendations.

5.2 Methodology

The Upstream Detection strategy has the same operating system as the standard Puffin except it has an extra detection (push button) upstream of the crossing. With this method, pedestrians could register their demand earlier at the upstream location, therefore the pedestrian phase could be initiated earlier upon receiving the demand from the upstream detection. It was expected to reduce the waiting time at the kerbside without disturbing the vehicle flow. Figure 5.1 shows the flowchart for the operation of the Upstream Detection strategy.

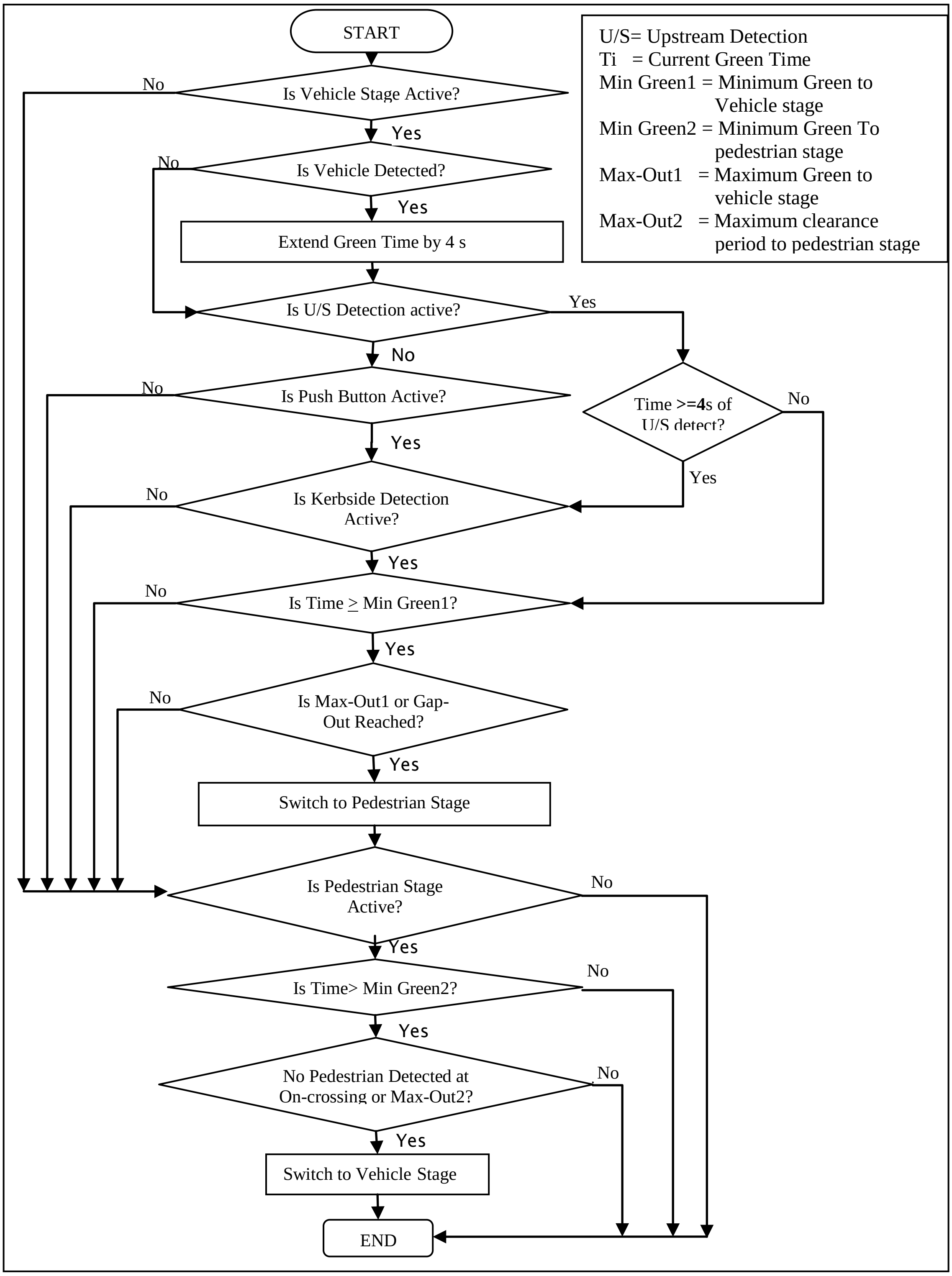


Figure 5.1 Flowchart of Upstream Detection Logic

When the Upstream Detection is activated by a pedestrian, the pedestrian demand is sent to the signal controller. There are two traffic conditions checked before a pedestrian phase is given:

a) Minimum green to vehicles and
b) Gap-out event or maximum green to vehicles.

If the first requirement is satisfied (minimum green time has expired), the next requirement is to check for gap-out or max-out events. If either of these requirements is satisfied (i.e: there is a gap more than 4 seconds between vehicles or maximum green to vehicles has been reached) then the pedestrian stage can be given instantly to pedestrians. It was assumed that if all these requirements are satisfied upon the activation of upstream detection, the interstage would happen in 4 seconds intergreen time. This principle is further illustrated in Figure 5.2.

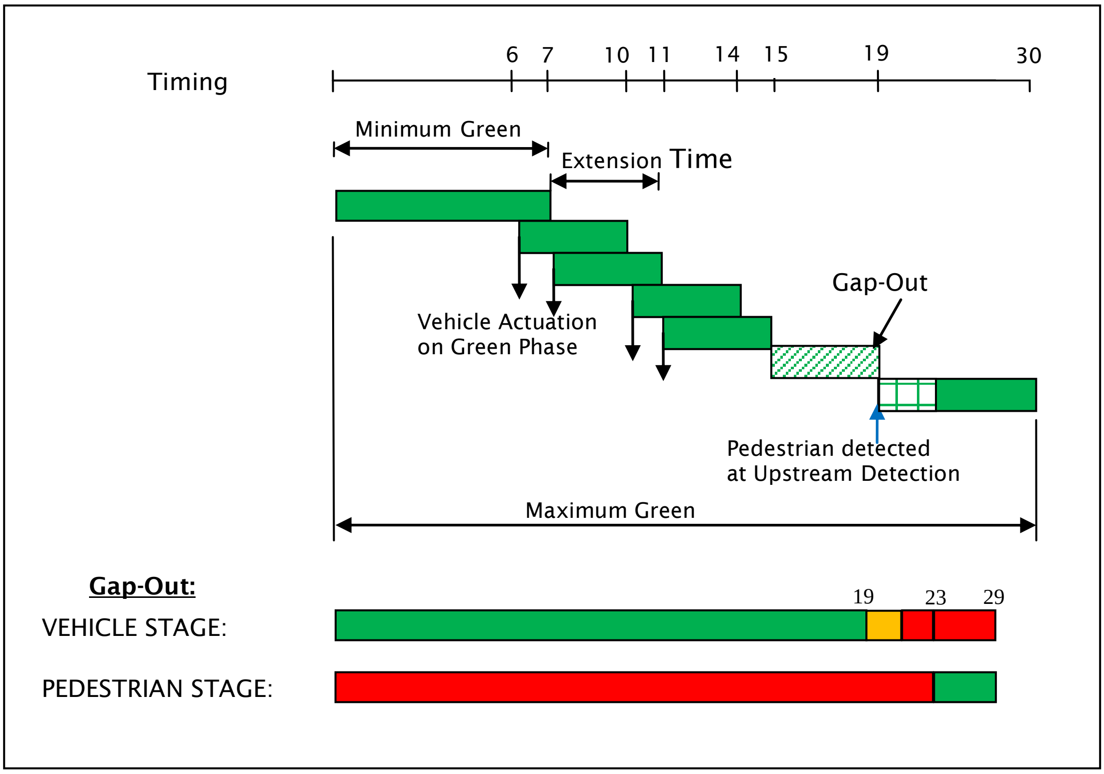


Figure 5.2 The principle of Upstream Detection

Figure 5.2 shows an example where detection could extend the vehicle green time up to its maximum of 15-seconds. At 19-seconds, Upstream Detection is activated by pedestrian. The first requirement is satisfied (more than minimum green time). Then the second requirement is checked (gap-out or max-out event). A gap-out event occurs at 19-seconds (there is a gap of 4 seconds or more since the last vehicle was detected), therefore the interstage happens upon the activation of Upstream Detection (rather than kerbside detection activation), and thus the pedestrian stage is initiated earlier at 23-seconds.

However, if the interstage does not occur in the first 4 seconds, pedestrian presence at kerbside is also checked. The principle is to cancel the demand if there is no pedestrian waiting on the kerbside. Figure 5.3 shows an illustration of Upstream Detection at the crossing.

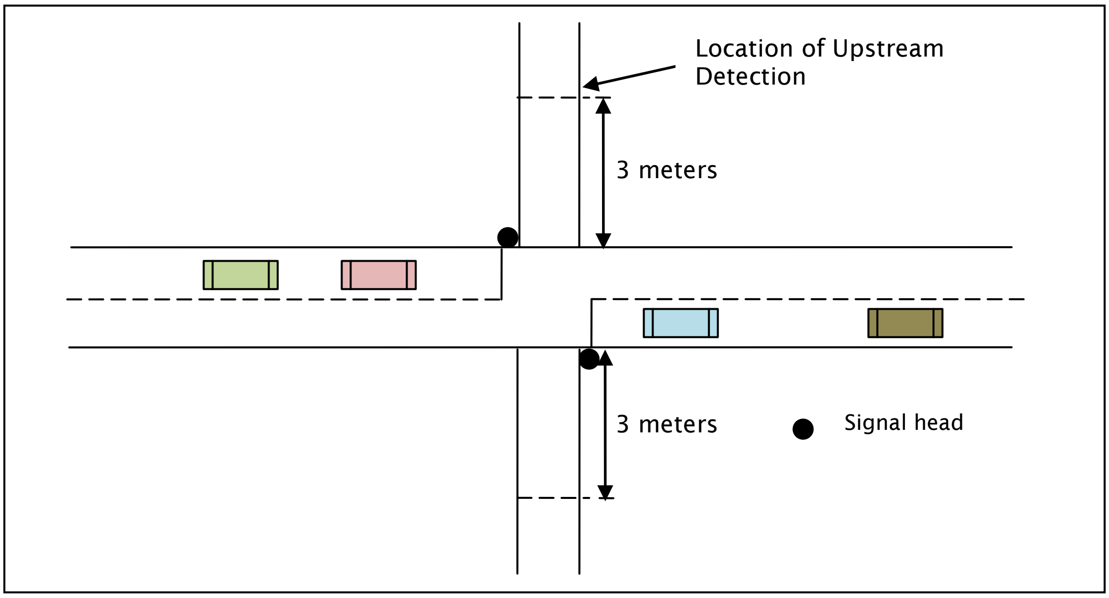


Figure 5.3 Upstream Detection scenario

Based on a simple calculation using the 15th percentile speed 2.7 km/h and 4 seconds intergreen time, the initial location of Upstream Detection is 3 meters upstream of the crossing as shown in Figure 5.3 above. The 15th percentile speed is the speed below which 15% of pedestrians would walk.

With a walking speed range 1.9 km/h to 7.2 km/h and 3 meters distance of Upstream Detection, the pedestrian arrival time range on the pedestrian crossing is between 1.5 seconds and 5.7 seconds. 85% of pedestrians would arrive in 1.5 - 4 seconds. And the remaining 15% of pedestrians would arrive in 4 -5.7 seconds.

If the interstage happens immediately after Upstream Detection activation (within 4 seconds), the pedestrian green indication can be initiated 4 seconds earlier. Therefore, the slowest pedestrians should still have the green man indication on when they arrive and the fastest pedestrians would have a shorter wait at the crossing than before (with just kerbside detection). The idea is to accommodate all pedestrians including the slower walkers. This will give everyone the benefits from the earlier pedestrian stage.

The validated features of the Market Street crossing were adopted in the pedestrian crossing but some aspects of the Market Street were not included to simplify the analysis. The characteristic of the pedestrian crossing is as stated below:

- The pedestrian crossing has through movements with each lane was 3.5 m wide.
- Four user classes were defined for use in this network, including cars, heavy goods vehicles (HGV), buses and pedestrians.
- The desired speed distribution for pedestrians and various vehicle classes were the same as found in Market Street.
- Traffic composition was set as occurred at the Market Street crossing, being 95% cars, 3% HGVs and 2% buses.
- Pedestrian compliance to signal control was the same as in calibrated and validated site: all pedestrians in the hypothetical network were coded to accept a gap of 6 seconds while crossing a road with two lanes.
- The fixed aspects of the signal timings used in the simulated crossing were the same as occurred at Market Street. Each vehicle green was preceded by 2 a sec red-amber, followed by 3 sec amber and 1 sec minimum red, while pedestrian green was 6 seconds followed by the variable red-clearance period.

Simulation resolution was kept at one second, the same resolution at which the Market Street crossing was validated. Previous research has shown that this resolution can give sufficiently accurate results for most applications of VISSIM micro-simulation e.g Fellendorf and Vortisch (2001).

The initial model used 3 meters distance of Upstream Detection. The best distance of Upstream Detection was then determined by modelling different distances of Upstream Detection location in the next sub section.

5.3 Simulation Scenarios

The impacts of Upstream Detection were assessed for the following three scenarios:

- Case 1: Different Upstream Detection Locations
- Case 2: Different Vehicle and Pedestrian Flow Combinations
- Case 3: Different Pedestrian Compliance Rates

The simulation results were analysed for all vehicles and pedestrians that had completed their journeys within the simulation duration. Two measure of effectiveness (MOEs) were collected from the simulated junction: average vehicle delay and average pedestrian delay.

Two free flow traffic conditions were modelled to measure the delay due to signal control: free flow vehicle traffic and free flow pedestrian traffic. In free flow vehicle traffic, pedestrians were taken out from pedestrian crossing so that vehicles had smooth movement on the road without disturbances from the changes of signal indications. Similarly, for free flow pedestrian traffic, vehicles were taken out from the pedestrian crossing and pedestrians given a continuous green man to allow smooth movement on the pedestrian crossing. Vehicle delay measurements were determined by subtracting the average free flow vehicle travel time from the average vehicle travel time with signal operation. Pedestrian delay measurements were determined by subtracting the average free flow pedestrian travel time from the average pedestrian travel time with signal operation.

5.3.1 Case 1: Different Locations of Upstream Detection

Initially, upstream detection was located at 3 meters upstream of the crossing. Then, an upstream detection was located at different locations: 5 meters and 10 meters upstream of the crossing. These three different locations of upstream detection were modelled to determine the optimal distance of upstream detection by comparing the delay experienced by vehicles and pedestrians. The modelling was conducted under the assumption that 64% of pedestrians pressed the push button and obey the signal indication, 6.5% of pedestrians pressed the push button but gap-crossed when there was an opportunity and another 29.5% ignored the signal control and gap-crossed in vehicle traffic when there was an opportunity.

For this purpose, simulation runs were conducted at one vehicle and pedestrian flow combination: 700 veh/h and 300 ped/h (for both directions). The total number of simulation runs carried out for the experiment is shown in Figure 5.4 below.

Pedestrian Compliance Rate	Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Upstream Detection Location (meters)	Number of Simulation Runs
64%	700	300	Base Case	10
			3	10
			5	10
			10	10
Free Flow Traffic	700	No Pedestrian	-	10
	No Vehicle	300	-	10
	Total Number of Simulation Runs			60

Figure 5.4 Simulation Scenarios for Various Upstream Detection locations

Average delay to vehicles for each scenario was calculated by subtracting the free flow travel time for vehicle between the entry and exit points, assuming continuous green time, from the actual average travel time for the signalling scenarios concerned. The same procedure was carried out for determining pedestrian delays-in this case with the 'invitation to cross' showing green continuously. In each of the simulation scenarios above, ten simulation runs were carried out each with a different random seed.

Therefore, in total there were 60 simulation runs carried out to determine the impact of different locations of upstream detection. Figure 5.5 and Figure 5.6 show the results of vehicle delays and pedestrian delays for the Base Case and three different Upstream Detection locations: 3 meters, 5 meters and 10 meters in advanced of the crossing.

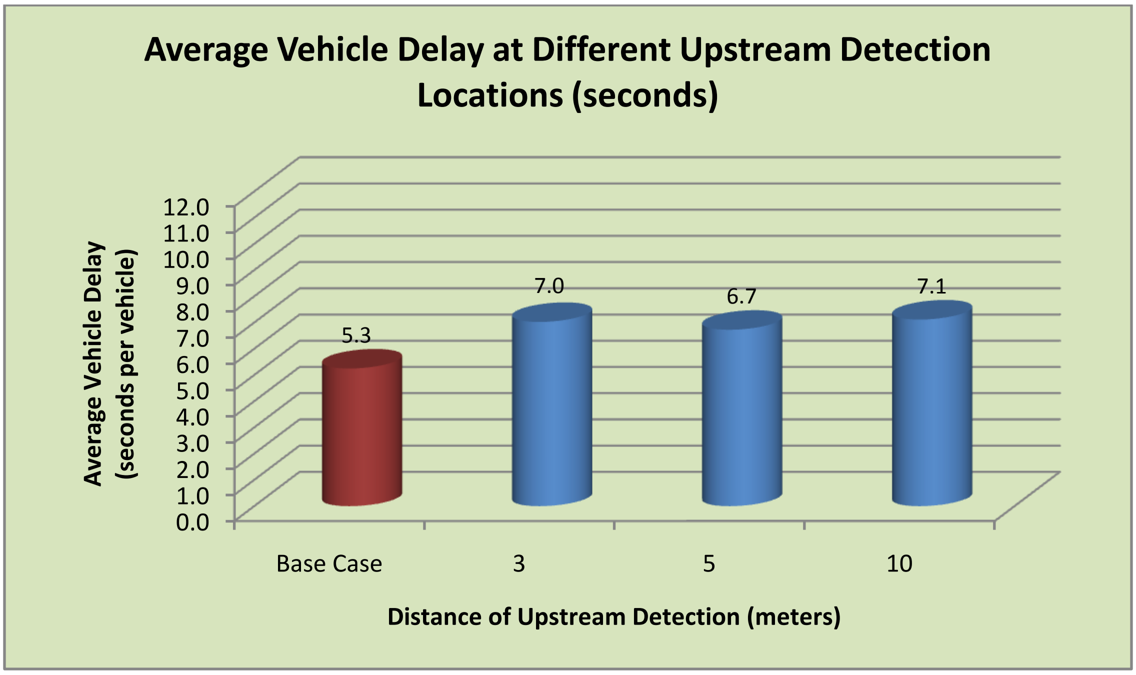


Figure 5.5 The Impacts of Different Upstream Detection locations on Vehicle Delay

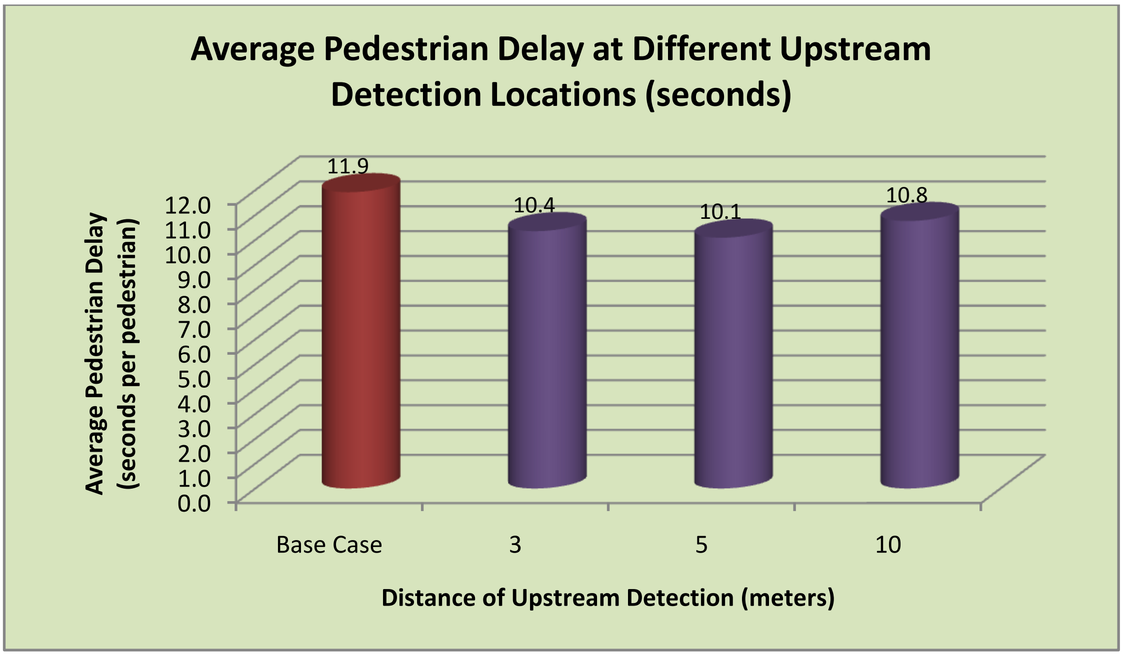


Figure 5.6 The Impacts of Different Upstream Detection location on Pedestrian Delay

Results in Figure 5.5 show that upstream detection increased the delay to vehicles in all cases. Results in Figure 5.6 show that upstream detection reduced the delay to pedestrian in all cases. This was expected because upstream detection strategy caused more frequent pedestrian phases compared to base case. This can be seen in Figure 5.8. Thus it caused frequent stopping to vehicle movement hence the increase in vehicle delay and it caused frequent pedestrian phase were given to pedestrian hence the reduction in pedestrian delay.

The earlier calculation of 3 meters distance of Upstream Detection was only based on the pedestrian perspective (pedestrian walking speed). Therefore, further analysis was conducted for three different distances of Upstream Detection: 3 meters, 5 meters and 10 meters. By considering both vehicle and pedestrian delays in the analysis, it was found that 5 meters gave the lowest delay to both vehicle and pedestrian. Both Figure 5.5 and Figure 5.6 indicate that the best upstream detection location from those tested was 5 meters, so this value was carried forward to the next modelling stages.

5.3.2 Case 2: Different Traffic Flow Conditions

The Upstream Detection strategy could have different impacts under different levels of vehicle flow and pedestrian flow combinations. A number of combinations of pedestrian and vehicle flows were modelled to identify any trends in the results. For example, it is possible that at high pedestrian flows and low traffic flows, the signals may run predominantly on a minimum green to traffic. In that case, signal timings and vehicle or pedestrian delays would be unaffected by further increases in pedestrian flow. This would cause a 'break point' in the delay and flow relationship which would need to be identified.

Therefore, the impact of the Upstream Detection strategy under various traffic flow conditions was examined at twelve vehicle and pedestrian flow combinations as shown in Figure 5.7 below. The vehicle flows and pedestrian flows below are for both directions.

Pedestrian Compliance Rate	Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Signal Control Scenario	Number of Simulation Runs
64%	100	100	Base Case	10
			Upstream Detection	10
		300	same as above	20
		500	same as above	20
	300	100	Base Case	10
			Upstream Detection	10
		300	same as above	20
		500	same as above	20
	700	100	same as above	20
		300	same as above	20
		500	same as above	20
	1408	100	same as above	20
		300	same as above	20
		500	same as above	20
Free Flow Traffic	100	No Pedestrian	-	10
	300	No Pedestrian	-	10
	700	No Pedestrian	-	10
	1408	No Pedestrian	-	10
	No Vehicle	100	-	10
	No Vehicle	300	-	10
	No Vehicle	500	-	10
		Total Number of Simulation Runs =		310

Figure 5.7 Simulation Scenarios for Various Traffic Flow Combinations

Figure 5.7 shows the overview of simulation scenarios at twelve vehicle and pedestrian flow combinations. Simulations were carried out for four vehicle flows (100 veh/h, 300 veh/h, 700 veh/h, 1408veh/h) and three pedestrians flows (100 ped/h, 300 ped/h, 500 ped/h). 1408 veh/h was initially chosen from Market Street site. For each combination of vehicle and pedestrian flow, two signal control scenarios were simulated: base case and upstream detection strategy. 5 meters distance of upstream detection location was used in the modelling as been determined in previous sub section. For both vehicle and pedestrian, average delay for each scenario was calculated by subtracting the free flow travel time from the actual average travel time for the signalling scenarios concerned.

Each scenario was carried out with 10 simulation runs each with ten unique random seeds that vary the random input of vehicles into the junction entry. This resulted in a total of 310 simulation runs for 10 hours simulation period as shown in Figure 5.7 (i.e. 3100 hours of modelling). Results are discussed below. Figure 5.8 shows the number of signal cycles for the base case and the upstream detection strategy for twelve different vehicle and pedestrian flow combinations.

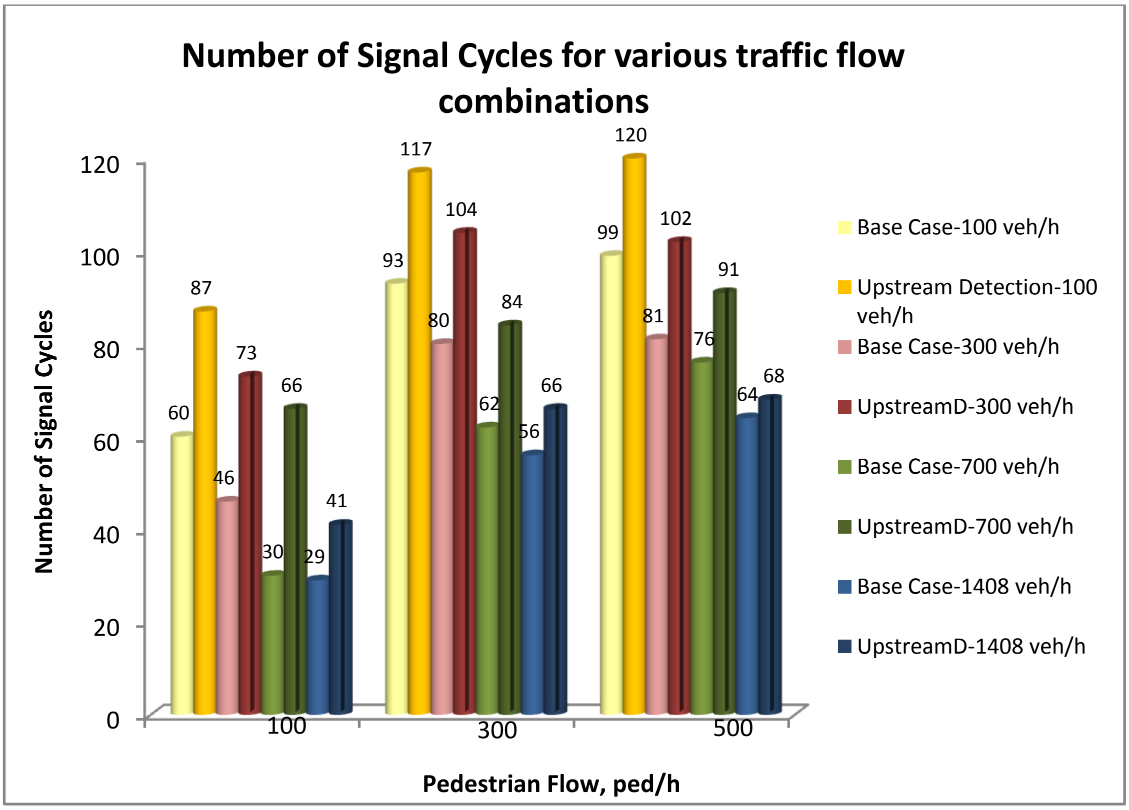


Figure 5.8 Number of Signal Cycles: Base Case versus Upstream Detection

It is shown in Figure 5.8 that for both Base Case and Upstream Detection strategies, an increasing demand from pedestrians caused an increase in the number of signal cycles. In contrast, increasing vehicle volumes caused a reduction in the number of signal cycle to cater for the higher vehicle demand. These results were as expected. It was also noticeable that more signal cycles were called in the Upstream Detection case than in the Base Case. Upstream Detection provided an additional earlier opportunity to request the pedestrian green phase 5 meters in advanced of the crossing. Therefore, the pedestrian stage was called more frequently in the Upstream Detection compared to the Base Case. This situation can also be illustrated through recording changes in average vehicle green. This can be seen in Figure 5.9 below.

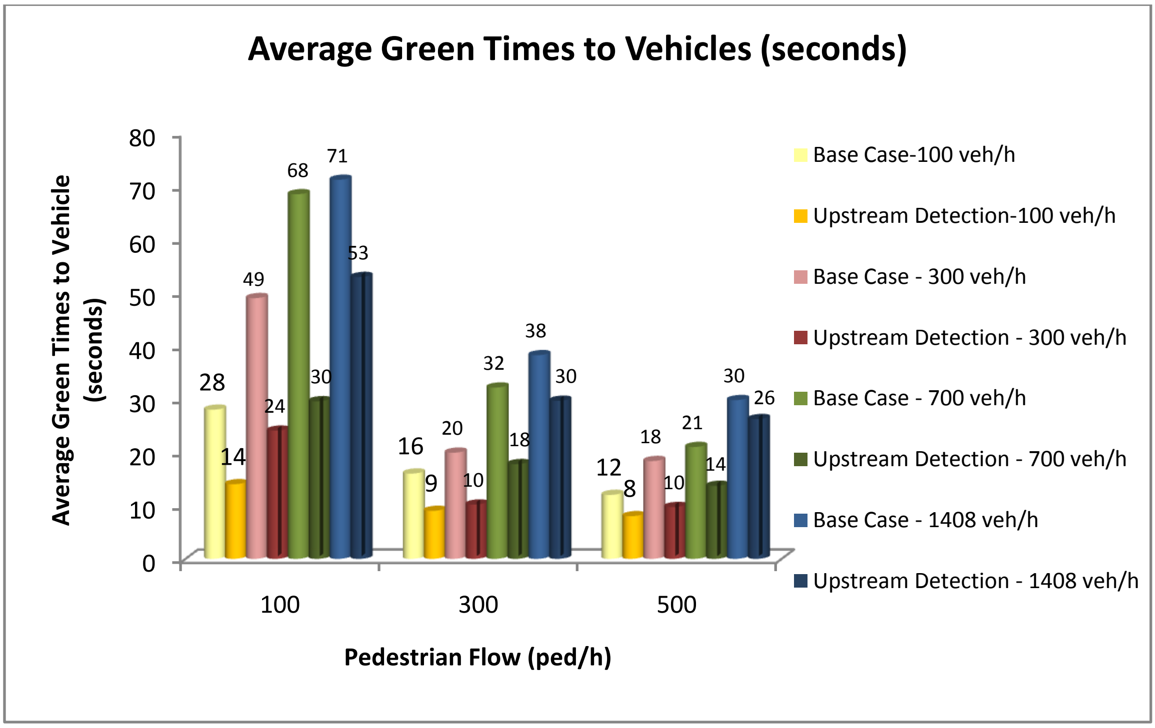


Figure 5.9 Average Green Time to Vehicle: Base Case versus Upstream Detection

The more frequent signal cycle changes caused by upstream pedestrian detection reduced the average green time available to vehicles as shown in Figure 5.9. It is shown in Figure 5.9 that at high levels of pedestrian and vehicle flow (1408 veh/h and 500 ped/h) the signals at both Base Case and Upstream Detection operated in near fixed-time mode with maximum green to vehicles of 30 seconds and 26 seconds respectively. At lower vehicle flows (100 veh/h and 300 veh/h) the implementation of upstream detection caused a reduction in effective green time by approximately half from the base case. It is because at lower vehicle flow (100 veh/h and 300 veh/h), two requirements of vehicle traffic conditions as below were easily satisfied:

a) The minimum green time
b) Gap-out event and max-out event

Figure 5.10 shows the vehicle delay results for both base case and upstream detection at twelve vehicle and pedestrian flow combinations.

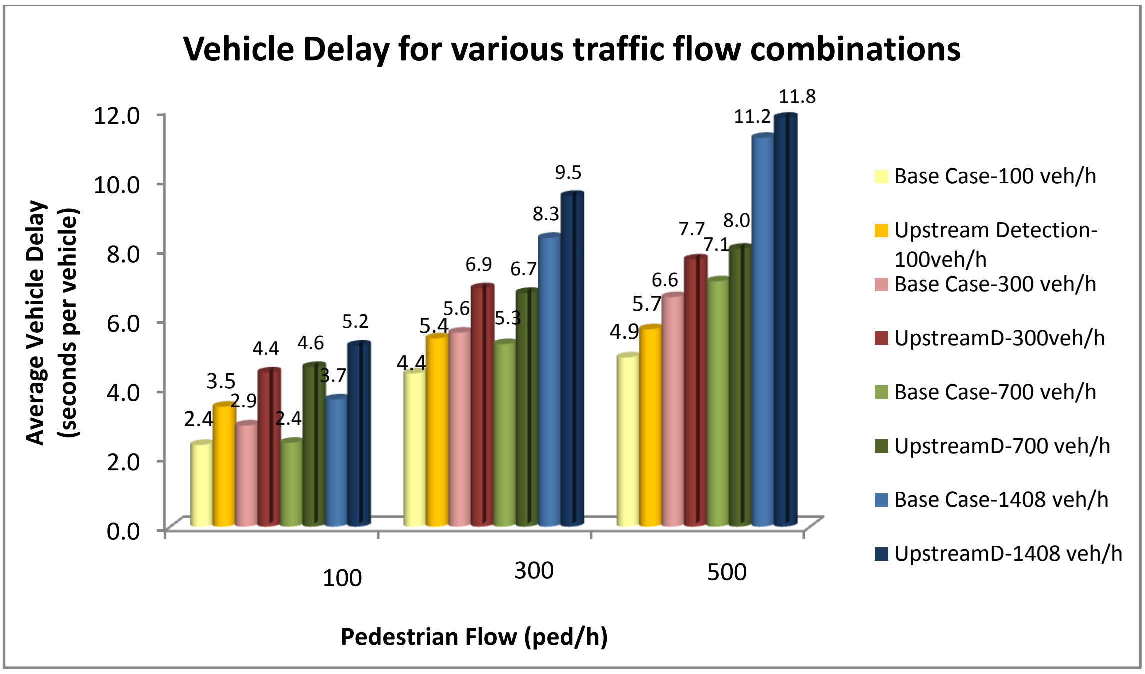


Figure 5.10 Vehicle Delay: Base Case versus Upstream Detection

In all traffic flow combinations, upstream detection resulted in higher delay to vehicles compared to base case. This was a direct impact of the more frequent pedestrian calls, which resulted in more frequent stage changes and reduced overall green time for vehicles. Results of the simulation runs in Figure 5.10 showed, as expected, vehicle delay increased steadily with an increase in the volumes of pedestrian or vehicle traffic. As pedestrian flow increased, the change in vehicle delay between base case and upstream detection for twelve vehicle flows (100 veh/h, 300veh/h, 700 veh/h, 1408 veh/h) occured at a lower rate. At higher pedestrian flow (500 ped/h), as vehicle flow increased from 100 veh/h to 1408 veh/h, the gap-out event in vehicle traffic reduced, hence allow vehicles to receive longer green time as shown in Figure 5.9 hence the small change in vehicle delay between base case and upstream detection as shown in Figure 5.10 above. Figure 5.11 shows the pedestrian delay results for both base case and upstream detection at twelve vehicle and pedestrian flow combinations.

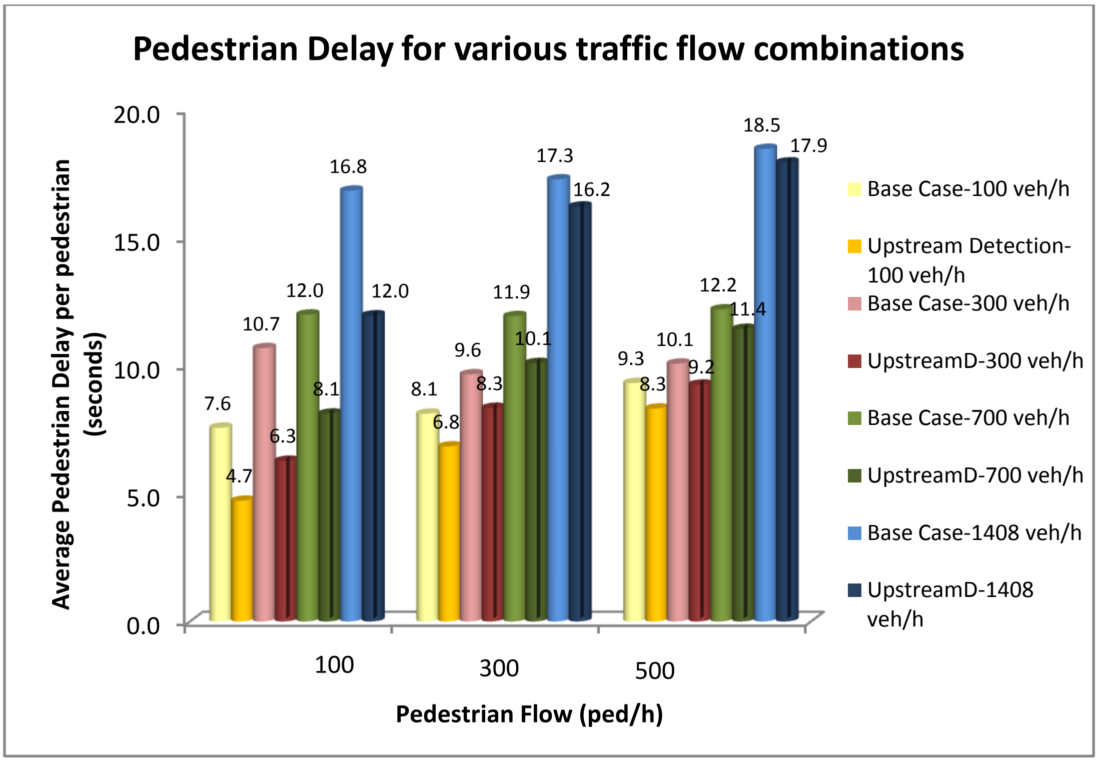


Figure 5.11 Pedestrian Delay: Base Case versus Upstream Detection

Results in Figure 5.11 show that in all twelve vehicle and pedestrian flow combinations, upstream detection reduced pedestrian delay compared to base case. At low level of pedestrian flow (100 ped/h), upstream detection caused a big reduction in pedestrian delay. Similar to vehicle delay, as pedestrian flow increased to 500 ped/h, the change in pedestrian delay between base case and upstream detection for twelve vehicle flows (100 veh/h, 300 veh/h, 700 veh/h and 1408 veh/h) occurred at a lower rate. This happened as a result of reduced gap-out event at 500 ped/h for twelve vehicle flows (100 veh/h, 300 veh/h, 700 veh/h and 1408 veh/h) hence reduced the chances of pedestrian getting green man.

Further testing on upstream detection performance was conducted for different pedestrian compliance rates. This modelling strategy is described in the next sub-section.

5.3.3 Case 3: Different Pedestrian Compliance

Simulations were also conducted for different scenarios of pedestrian behaviour; specifically pedestrian compliance. In reality, there will be various pedestrian compliance behaviours at signalised crossings. Three different levels of pedestrian compliance to push button and signal control were simulated in VISSIM; 100 % compliance to signal control, 64% compliance rate and 30% compliance rate. The behaviour of pedestrian compliance is shown in Table 5.1 below.

Table 5.1 Pedestrian Compliance Rate

	100% compliance	64% compliance	30% compliance
Obey signal	100%	64%	30%
PB, gap-crossed	-	6.5%	20%
No PB, gap-crossed	-	29.5%	50%

As shown in Table 5.1, pedestrian compliance behaviour was categorised into three types:

a) Obey the signal indication (require green time from signal control)
b) Press the push button but gap-cross if there was an opportunity
c) Do not press the push button and gap-cross in vehicle traffic

Pedestrian crossing decisions were based on the acceptance of 6 seconds gap in conflicting vehicle traffic.

In the 100% pedestrian compliance scenario, all pedestrians waited for the pedestrian phase at the crossing. Therefore all pedestrians were simulated to obey the signal indication. In the 64% pedestrian compliance scenario, 64% of pedestrians were simulated to obey the signal indication, 6.5% of pedestrians pressed the push button but gap-crossed in the vehicle traffic whenever there was an opportunity and another 29.5% were simulated to ignore the signal control and gap-crossed in vehicle traffic. The pedestrian composition in 64% compliance rate scenario was taken based on Market Street. In the 30%

pedestrian compliance scenario, 30% of pedestrians were simulated to obey the signal control indication, 20% of them pressed the push button but gap-crossed given the opportunity and the remaining 50% were simulated as gap-crossed who did not press the button.

The performance of Upstream Detection strategy was determined at three different levels of pedestrian compliance rates shown in Figure 5.12 below. The modelling was conducted for one vehicle and pedestrian flow combinations: 700 veh/h – 300 ped/h (for both directions).

	Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Pedestrian Compliance Scenario	Signal Control Scenario	Number of Simulation Runs
	700	300	30%	Base Case	10
				Upstream Detection	10
			64%	same as above	20
			100%	same as above	20
Free Flow Traffic	700	No Pedestrian			10
	No Vehicle	300	30%		10
			64%		10
			100%		10
Total Number of Simulation Runs					100

Figure 5.12 Simulation Scenarios for Various Pedestrian Compliance Rate

Figure 5.12 shows the simulation scenarios carried out at three levels of pedestrian compliance rates for base case and upstream detection strategy. Free flow vehicle traffic and free flow pedestrian traffic were simulated to be used in delay measurements. Ten simulation runs were conducted for each of the scenarios. Overall, 100 simulation runs were carried out to determine the impact of various pedestrian compliance rates on the success of the Upstream

Detection strategy. The impact of each of the pedestrian compliance scenarios was compared between Base Case and Upstream Detection.

Figure 5.13 shows the signal cycle changes for both Base Case and Upstream Detection at three different pedestrian compliance rates.

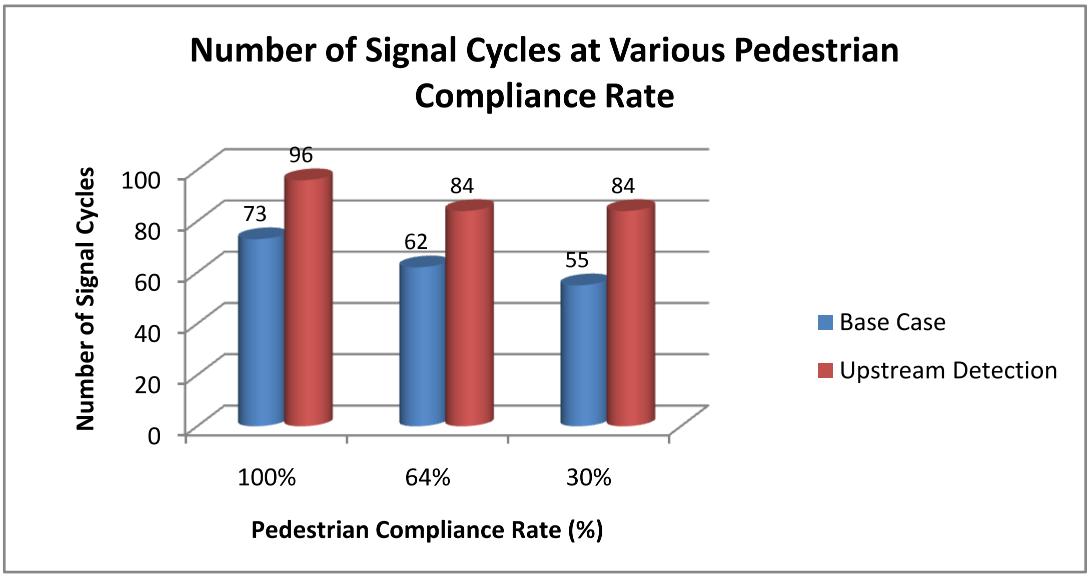


Figure 5.13 Number of Signal Cycles: Base Case vs Upstream Detection

In general, it can be seen in Figure 5.13 that Upstream Detection caused more frequent signal cycles compared to Base Case. As pedestrian compliance reduced, there were less signal cycles in both the Base Case and the Upstream Detection case. Pedestrians who do not comply do not have any influence on signal control operation as they do not demand green time. In the case of lower compliance, more pedestrians look at the suitable gap in vehicle traffic and cross in the vehicle gap to reduce their waiting time at the kerbside. These pedestrians do not register their demand at the crossing or upstream and hence not influence traffic signal control. Therefore, lower pedestrian compliance resulted in a less frequent pedestrian phase given. This results in changes in effective green times to vehicles, as shown in Figure 5.14.

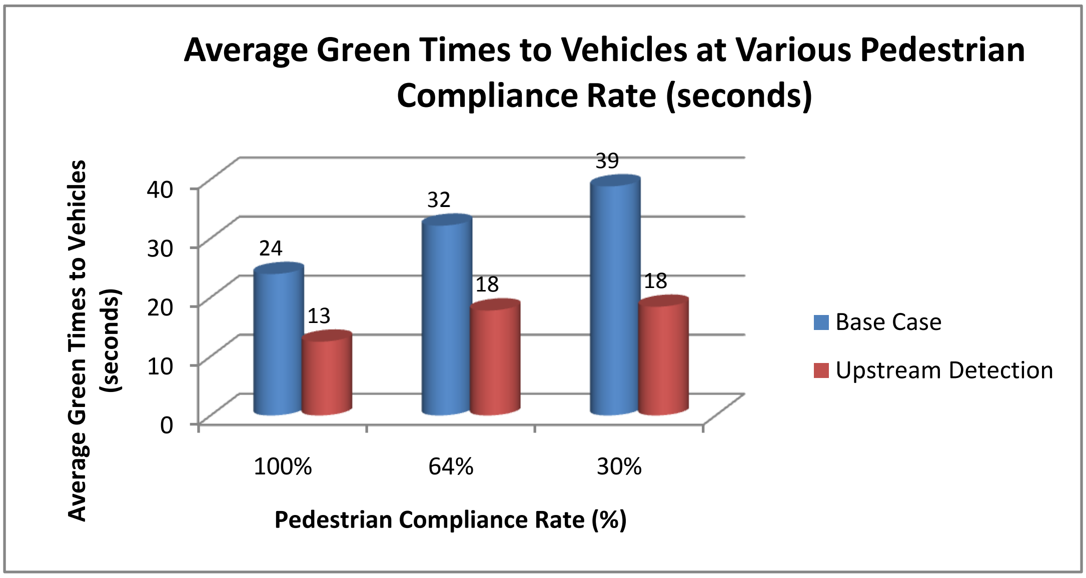


Figure 5.14 Average Green Times to Vehicles: Base Case versus Upstream Detection

As expected, simulation results in Figure 5.14 show that frequent signal changes in Upstream Detection reduced the effective green time to vehicles. As pedestrian compliance reduced, there was an increase in average green time to vehicles for both Base Case and Upstream Detection as there was less demand from pedestrians. However, at 64% and 30 % pedestrian compliance rates for upstream detection strategy, the number of signal cycles was same hence the same average green times to vehicles (18 seconds) as indicated in Figure 5.14 above.

The changes in the number of signal cycles and effective vehicle green time have implications in vehicle delay and pedestrian delay. Figure 5.15 and Figure 5.16 show the results on vehicle delay and pedestrian delay respectively when pedestrian compliance varies at 100%, 64% and 30%.

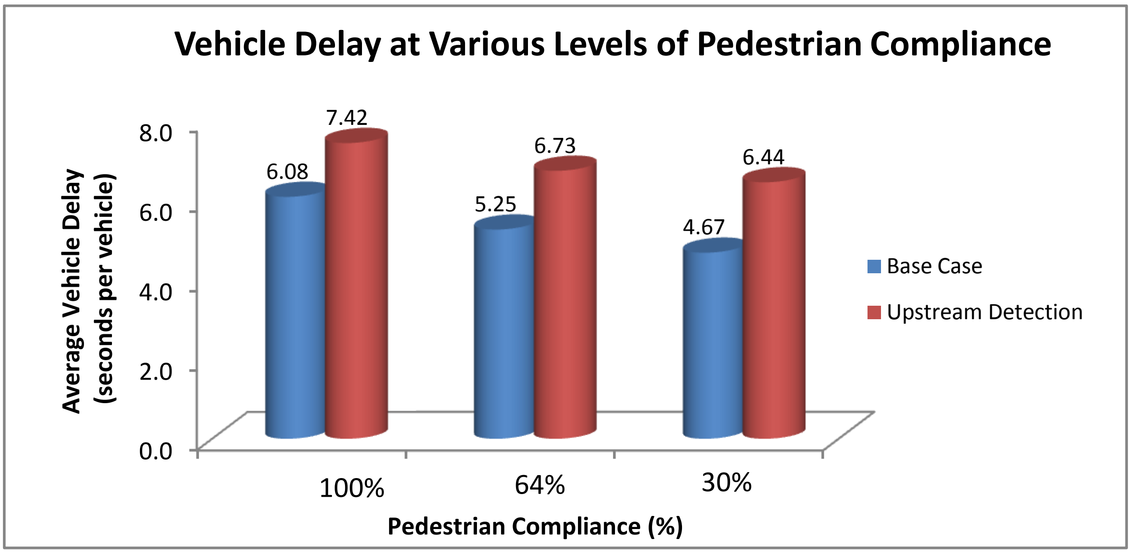


Figure 5.15 Vehicle Delay: Base Case versus Upstream Detection

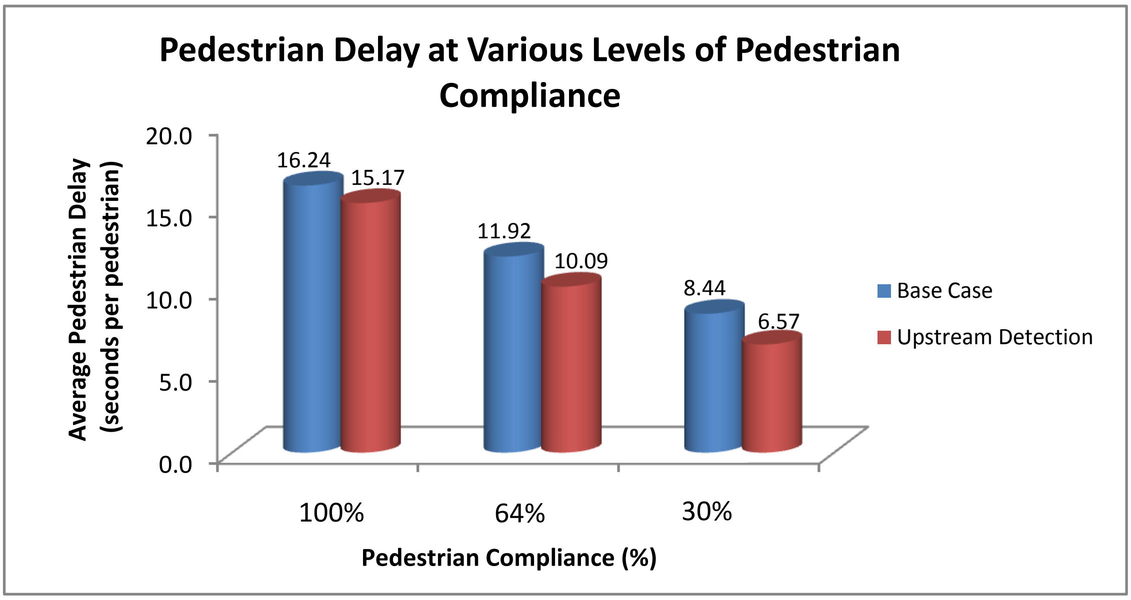


Figure 5.16 Pedestrian Delay: Base Case versus Upstream Detection

In Figure 5.15 and Figure 5.16, for both base case and upstream detection, as pedestrian compliance rates reduced from 100% to only 30% compliance rates, as expected there is a reduction in vehicle delay and pedestrian delay. This occurred because more pedestrians were taking the opportunity to gap-cross hence the reduced demand from pedestrians for the green man. However, at all levels of pedestrian compliance, upstream detection caused an increase in vehicle delay and a reduction in pedestrian delay as a consequence of more frequent changes in signal cycles and less average green times to vehicles in upstream detection strategy compared to base case.

5.4 Economic Evaluations

The performance of upstream detection was compared to base case. The comparisons between these two signal controls were quantified in term of total person delay and total delay costs to assess the overall benefits and economic benefits of the upstream detection strategy. The simulation results of vehicle delay, pedestrian delay and the throughput of vehicles and pedestrians that completed their journey at the simulated crossing enabling the calculation of total person delay. These values were then input into an economic evaluation to determine the monetary benefits of upstream detection strategy. The difference in total person delay and total delay costs between base case and upstream detection shows whether there is a benefit or disbenefit as a result of this form of upstream detection implementation. A reduction in either total person delay or total delay costs shows a benefit from upstream detection implementation. The evaluations of total person delay and total delay costs were conducted for twelve vehicle and pedestrian flow combinations.

5.4.1 Total Person Delay

The total person delay was first calculated using average delay time per person, occupancy rates and the number of vehicle completing their journey in the simulation period. Equation 5.1 below shows the calculation of total person delay (as described in Chapter 2).

Total person delay = $D_v O_v N_v + D_p N_p$ Equation 5.1

Where subscript v = mode of transport

subscript p = pedestrian

D = average delay per person

O = vehicle occupancy (D x O = average delay per vehicle)

N = number of vehicles/pedestrians completing their journey in the simulation period

The standard vehicle occupancy rates from the Department for Transport (2011b) were used and are shown in Table 5.2 below (see Chapter 2 for detailed explanations).

Table 5.2 Average Vehicle Occupancies for Various Modes of Transport

Mode of Transport	Average Vehicle Occupancies
Car	1.58
Bus	13.20
HGV	1.0
Pedestrians	1.0

The total person delay for twelve vehicle and pedestrian flow combinations for both base case and upstream detection strategy are shown in Table 5.3 below. The vehicle and pedestrian flows below are for both directions.

Table 5.3 Total Person Delay for Twelve Traffic Flow Combinations: Base Case and Upstream Detection

Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Total Person Delay (person seconds/hour) Upstream Detection	Base Case	Changes
100	100	812.7*	987.0	-174
	300	2570.5*	2850.3	-280
	500	4675.0*	5088.8	-414
300	100	1951.0	1932.7	18
	300	4531.0*	4537.9	-7
	500	6867.7*	6947.2	-79
700	100	4022.0	2874.5	1148
	300	7694.4	7209.3	485
	500	11224.6	10946.3	278
1408	100	8498.7	6808.6	1690
	300	18173.5	16791.2	1382
	500	25367.0	24815.3	552

*reduction

The total person delays in table above were calculated as below (for 300 veh/h-100 ped/h case):

Total person delay = $D_v O_v N_v + D_p N_p$ Equation 5.1

= 4.44 seconds/vehicle*2990 + 6.27 seconds/pedestrian*996

= 13265 + 6245

= 19509 seconds/10 hours

= 1951 seconds/hour

As seen in Table 5.3 after the implementation of upstream detection, there is a reduction in total person delay at five vehicle and pedestrian flow combinations: 100 veh/h-100 ped/h, 100 veh/h-300 ped/h,100 veh/h-500 ped/h, 300 veh/h-300 ped/h and 300 veh/h – 500 ped/h. There is a high increase in total person delay at 1408 veh/h – 100 ped/h followed by 1408 veh/h – 300 ped/h and 700 veh/h – 100 ped/h. Figure 5.17 below shows the percentage changes in total person delay after the implementation of upstream detection strategy.

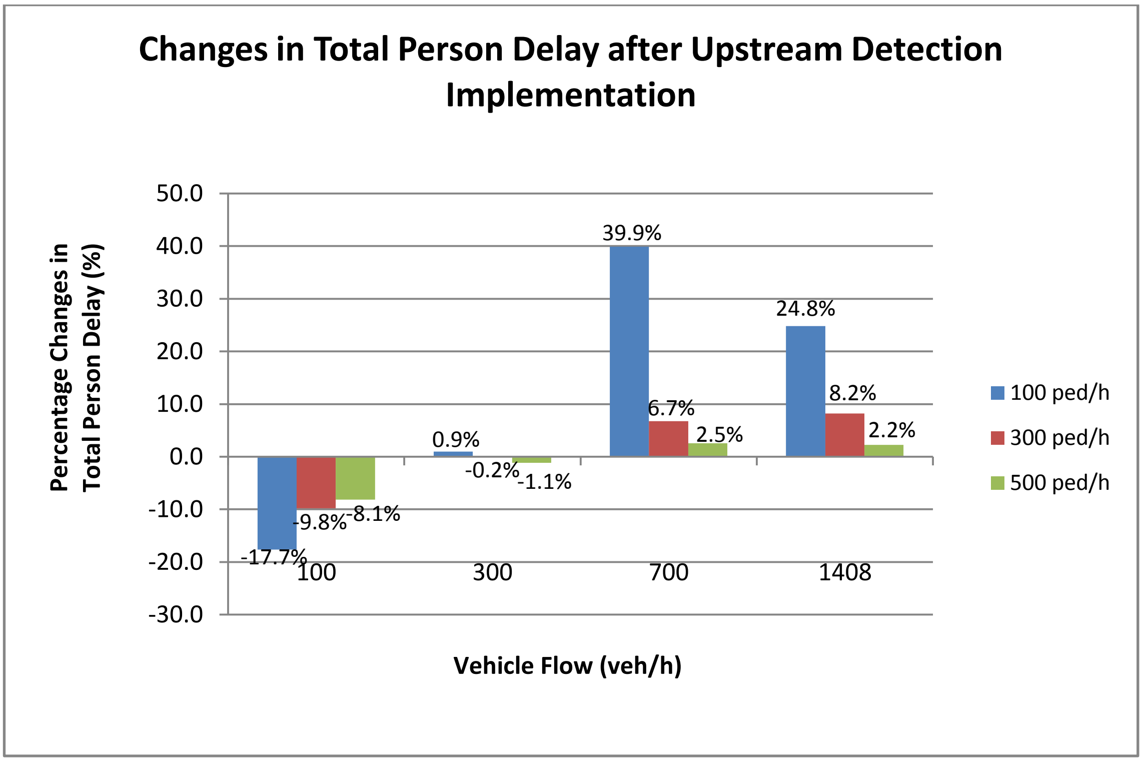


Figure 5.17 The Changes in Total Person Delay After Upstream Detection Implementation

It is shown in Figure 5.17 above that the only overall benefit of upstream detection occurs at low vehicle flows (100 veh/h and 300veh/h). At these two vehicle flows, upstream detection caused a reduction in total person delay by 0.2% to 17.7%. The results in Figure 5.17 for 700 veh/h – 100 ped/h is so much higher than for 1408 veh/h – 100 ped/h because it used percentage differences rather than absolute differences.

5.4.2 Total Delay Costs

(i) Standard Value of Time

The total person delay was then converted into economic evaluation using equation 5.2 below. The standard values of time per vehicle from the Department for Transport (2011b) were used and are shown in Table 5.4 below.

Total Delay Costs = $D_v O_v N_v V_v + D_p N_p V_p$ Equation 5.2

Where V = values of time per vehicle

D x O x N = total person delay

Table 5.4 Values of Time for Various Modes of Transport (Source: Department for Transport, 2011b)

Mode of transport	Values of Times per vehicle (£ per hour per vehicle)
Car	£10.46
Bus	£71.62
HGV	£10.18
Pedestrians	£9.38

Table 5.5 below shows the total delay costs for Upstream Detection and Base Case scenario for twelve vehicle flow and pedestrian flow combinations. The vehicle flow consists of 95% car, 3% HGV and 2% bus.

Table 5.5 Total Delay Costs for Twelve Traffic Flow Combinations: Base Case and Upstream Detection

		Total Delay Costs (£/hour)		
Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Upstream Detection	Base Case	Changes
100	100	2.3*	2.7	-0.4
	300	7.0*	7.7	-1
	500	12.5*	13.6	-1
300	100	5.9	5.6	0.3
	300	13.1	12.8	0.3
	500	19.4	19.3	0.1
700	100	12.5	8.4	4
	300	23.0	20.8	2
	500	32.8	31.2	2
1408	100	26.8	20.6	6
	300	55.9	50.2	6
	500	76.6	73.3	3

*reduction

The total delay costs above were calculated as in Table 5.6 below.

Table 5.6 The calculation of total delay costs for Upstream Detection at 300 veh/h – 100ped/h

Scenario: Upstream Detection at 300 veh/h – 100 ped/h	
Vehicle Total Delay Costs	Pedestrian Total Delay Costs
= 4.44 seconds/vehicle * 2990 *(0.95*£10.46 + 0.03*£10.18 + 0.02*£71.62) = 4.44/3600 * 2990 * (£11.67) = £43.04 /10 hours	= 6.27 seconds/pedestrian * 996 * £9.38 = 6.27/3600 * 996 * £9.38 = £16.27/10 hours
Total Delay Costs	= £43.04 + £16.27 (for 10 hours) = £59.31/10 hours =£5.9/hour

The implementation of upstream detection caused a reduction in total delay costs at three vehicle and pedestrian flow combinations: 100 veh/h-100 ped/h, 100 veh/h-300 ped/h and 100 veh/h-500 ped/h. Figure 5.18 below shows the percentage changes in total person costs after the implementation of upstream detection strategy.

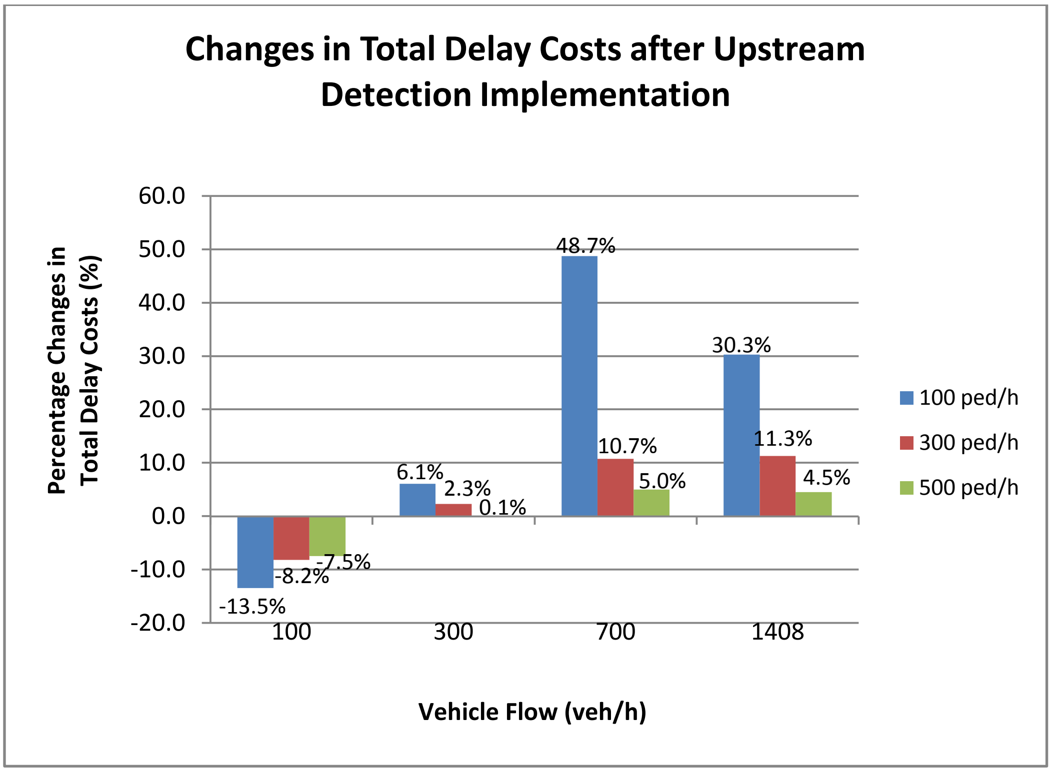


Figure 5.18 The Changes in Total Delay Costs After Upstream Detection Implementation

As shown in Figure 5.18, Upstream Detection resulted in a total delay costs saving at a lower vehicle flow, 100veh/h. At 100 veh/h, the implementation of Upstream Detection caused a total delay costs saving by 7.5% to 13.5%. At higher vehicle flow: 700 veh/h and 1408 veh/h, Upstream Detection caused an increase in total delay costs by 4.5% to 48.7%.

Overall, upstream Detection brought benefit to pedestrians by reducing their delay with increasing delay to vehicles. However, an economic assessment revealed that Upstream Detection caused a benefit at a lower vehicle flow in which it caused a total person delay saving by 8.1% to 17.7% and total delay costs saving by 7.5% to 13.5%. As vehicle flow increased, there was a disbenefit incurred by road users in which it caused an increase in total person delay and total delay costs. This was expected as vehicles have higher occupancy compared to pedestrians. Therefore, a benefit to pedestrians alone might cause a disbenefit to road users in general.

(ii) Relative Value of Time

Rather than being based on assumptions about the standard values of time as in the above section, adjusting the weightings applied to pedestrian and vehicle travel time savings would provide an understanding of the strategic importance to be attached to pedestrians if the improvements were to be supported. Table 5.7 below shows typical weighting factor from previous studies.

Table 5.7 Relative Values of time for various modes

Mode	Values of time per person
Car	1.0
HGV (Fowkes, 2001)	4.0
Bus (Haight, 1994)	0.5
Pedestrian (Mackie et al., 2003b; Wardman, 2004; Bhattacharya and Virkler, 2005; Ishaque, 2006)	0 to 4

The value of time used for evaluation purpose is an equity value, which is £4.46 per hour person, 2002 prices and values (Department for Transport, 2011b). The user cost computed by assigning different weighting factors to pedestrian and vehicles as shown in Equation 5.3 below (Bhattacharya and Virkler, 2005). See Chapter 2 for further details.

Total Delay Costs = $D_v O_v N_v T_v W_v + D_p N_p T_p W_p$ Equation 5.3

Where subscript v = vehicles

subscript p = pedestrian

D = average delay time per person

O = vehicle occupancy (D x O = average delay per vehicle)

N = number of vehicles or pedestrians completing their journey in the simulation period

D x O x N = total person delay

T = values of time, £4.46 per hour per person

W = weighting factors (shown in Table 5.7)

Table 5.8 below shows the total delay costs for the simulated road crossing with pedestrian weighting factor varies from 1 to 4.

Table 5.8 Total Delay Costs for various pedestrian weighting factors

Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Total Delay Costs (£/hour): Pedestrian weighting factor= 1		
		Upstream Detection	Base Case	Changes
100	100	1.33	1.44	-0.1
	300	3.69	3.94	-0.3
	500	6.32	6.76	-0.4
300	100	3.65	3.20	0.5
	300	7.52	7.17	0.4
	500	10.64	10.44	0.2
700	100	7.96	5.12	2.8
	300	13.89	12.34	1.6
	500	19.09	18.14	0.9
1408	100	17.32	13.21	4.1
	300	34.92	31.63	3.3
	500	46.77	45.33	1.4

Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Total Delay Costs (£/hour): Pedestrian weighting factor= 2		
		Upstream Detection	Base Case	Changes
100	100	1.91	2.37	-0.5
	300	6.20	6.93	-0.7
	500	11.41	12.46	-1.1
300	100	4.42	4.52	-0.1
	300	10.59	10.73	-0.1
	500	16.30	16.60	-0.3
700	100	8.97	6.60	2.4
	300	17.61	16.73	0.9
	500	26.08	25.60	0.5
1408	100	18.79	15.28	3.5
	300	40.89	37.99	2.9
	500	57.74	56.63	1.1

Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Total Delay Costs (£/hour): Pedestrian weighting factor= 3		
		Upstream Detection	Base Case	Changes
100	100	2.49	3.31	-0.8
	300	8.72	9.91	-1.2
	500	16.50	18.16	-1.7
300	100	5.20	5.84	-0.6
	300	13.66	14.28	-0.6
	500	21.96	22.76	-0.8
700	100	9.99	8.08	1.9
	300	21.33	21.12	0.2
	500	33.08	33.06	0.0
1408	100	20.27	17.35	2.9
	300	46.86	44.35	2.5
	500	68.71	67.92	0.8

Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Total Delay Costs (£/hour): Pedestrian weighting factor= 4		
		Upstream Detection	Base Case	Changes
100	100	3.07	4.24	-1.2
	300	11.23	12.90	-1.7
	500	21.59	23.87	-2.3
300	100	5.97	7.15	-1.2
	300	16.74	17.84	-1.1
	500	27.62	28.92	-1.3
700	100	11.00	9.55	1.5
	300	25.05	25.51	-0.5
	500	40.07	40.52	-0.5
1408	100	21.74	19.43	2.3
	300	52.83	50.71	2.1
	500	79.68	79.22	0.5

The total delay costs using different pedestrian weighting factor was calculated as in Table 5.9 below.

Table 5.9 The calculation of total delay costs for Upstream Detection at 300 veh/h – 100ped/h

Scenario: Upstream Detection (Pedestrian weighting factor=1) at 300 veh/h – 100 ped/h	
Vehicle Total Delay Costs	Pedestrian Total Delay Costs
= 4.44 seconds/vehicle * 2990 * (0.95*1.58*£4.46 *1+ 0.03*1*£4.46 *4+ 0.02*13.2*£4.46 *0.5) = £28.83 /10 hours	= 6.27 seconds/pedestrian * 996 * £4.46 * 1 = £7.74/10 hours
Total Delay Costs	= £28.83 + £7.74 (for 10 hours) = £36.6/10 hours =£3.7/hour

As can be seen in Table 5.9, when the pedestrian weighting factor increases, the changes in the total delay costs between Upstream Detection and Base Case becomes lesser. As pedestrian weighting factor increases, the total delay costs favour the Upstream Detection strategy at lower vehicle flow (100 veh/h and 300 veh/h). This trend can be seen in Figure 5.19 below.

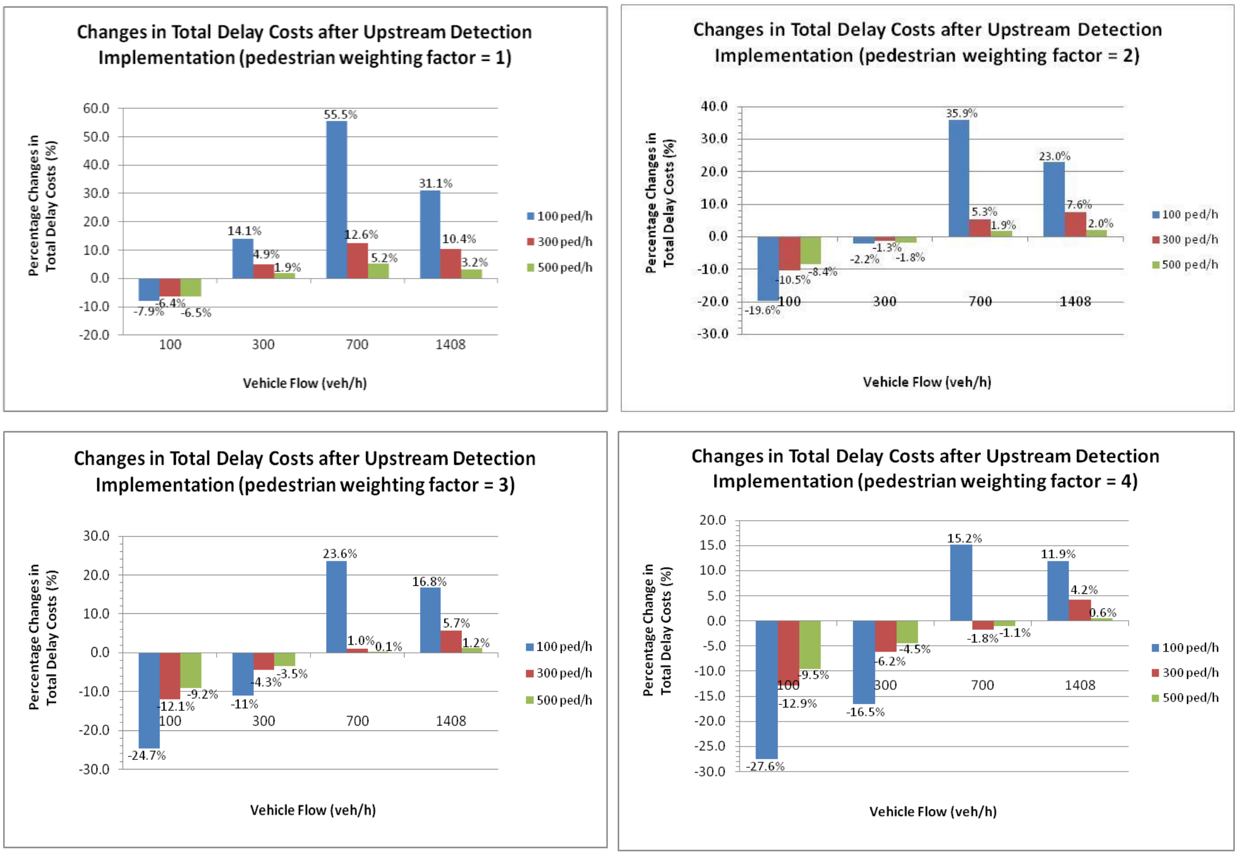


Figure 5.19 Changes in Total Delay Costs after Upstream Detection implementation for various pedestrian weighting factors

Figure 5.19 shows the implications of different pedestrian weighting factors in the Upstream Detection strategy. When travel time values for both car and pedestrian are equal, the implementation of Upstream Detection reduced the total delay costs to road users at low traffic flow combination (at 100 veh/h). This is expected for vehicles with a higher occupancy compared to pedestrians. However, there is a clear economic benefit when considering Upstream Detection when the pedestrian relative value of time is twice and above the car value. The benefit was clear at lower vehicle flow (100 - 300 veh/h). As the relative value of time to pedestrian increases to 4, there is an economic benefit in the Upstream Detection at 700 veh/h – 300 ped/h and 700 veh/h – 500 ped/h.

5.5 Summary

The Upstream Detection strategy was tested under three different scenarios: different locations of Upstream Detection, twelve traffic flow combinations and three levels of pedestrian compliance rate. It was assumed that pedestrian walking speed was in the range of 1.9 km/h and 7.2 km/h based on validated road network. Initially, Upstream Detection was located 3 metres upstream of the crossing.

In the first scenario, the best distance of Upstream Detection was determined from three locations tested - 3 meters, 5 meters and 10 meters in advanced of the crossing. The performance of Upstream Detection under different location of Upstream Detection was examined through delay experienced by vehicles and pedestrians. Simulation results showed that the best overall detector location was 5 meters upstream of the crossing.

In the second scenario, twelve traffic flow combinations were modelled to assess the performance of the Upstream Detection strategy over the Base Case strategy under various traffic flow levels. An extra detector was installed 5 meters upstream from the crossing. At lower pedestrian flow, there was a noticeable increase in vehicle delay and a reduction in pedestrian delay as a consequence of frequent signal cycle changes with the Upstream Detection strategy. As pedestrian flow increased to 500 ped/h, the change in vehicle delay and pedestrian delay became smaller. The positive impacts of Upstream Detection were apparent at a lower pedestrian flow. At low pedestrian demand and low vehicle volume, most of demands were served instantly by Upstream Detection hence the bigger change in pedestrian delay and vehicle delay. At low vehicle flow, the requirements on current traffic conditions such as minimum green to vehicle phase and gap-out event, were easily satisfied thus it provided earlier initiation of pedestrian demand by the activation of Upstream Detection. It caused frequent signal cycle number and large changes in vehicle delay and pedestrian delay compared to Base Case. As vehicle flow increased, it became difficult to satisfy three requirements on current traffic conditions: no vehicle demand and gap-out event event hence the small impact of Upstream Detection in vehicle delay and pedestrian delay.

Then, in the third scenario, the performance of Upstream Detection over Base Case was analysed on three different levels of pedestrian compliance behaviour: 100%, 64% and 30% compliance rate. It was observed that as pedestrian compliance reduced, the vehicle delay and pedestrian delay reduced. Lower pedestrian compliance caused less disruption to signal control, therefore, vehicle traffic could move on the road with less disruption from pedestrian demand hence the reduction of vehicle delay. It caused a reduction in pedestrian delay as well as they do not wait for the green time indication. It might be argued that there would be more benefit to all road users if no one complied to signal control, however, this would have safety implications on road users especially pedestrians.

Upstream Detection reduced the effective green time available to vehicles with possible implications for vehicle delay. It resulted in higher delay to vehicle compared to Base Case. On the other hand, it gave frequent pedestrian phase with the implications in pedestrian delay reductions.

There is a trade-off between pedestrian delay and vehicle delay at the signalised crossing. A reduction in pedestrian delay caused an increase in vehicle delay, therefore economic evaluations were conducted to determine the overall impact of Upstream Detection to the road crossing. It was shown in Figure 5.17, Figure 5.18 and Figure 5.19 that the implementation of Upstream Detection has a clear benefit at lower vehicle flow (100 veh/h for both directions) where flows of people in vehicles exceed flows of pedestrians. There was a small positive impact in travel time saving at 300 veh/h (150 veh/h for one direction) at all levels of pedestrian flow (lower:50 ped/h in one direction, medium:150 ped/h in one direction, and higher:250 ped/h in one direction). However, at a higher vehicle flow, it caused a larger increase in the total delay time.

The total delay costs were then assessed by using two different methods:
a) value of time per vehicle taken from Department for Transport (2011b) and
b) different pedestrian weighting factor (1, 2, 3, and 4). Using the standard value of time per vehicle from DfT (2011b), the implementation of Upstream Detection resulted in a reduction in total delay costs at low vehicle flow only (100 veh/h). Therefore, the results showed that there was an economic benefit

of implementing Upstream Detection to the road crossing only at low vehicle flow where the vehicle users were less than pedestrian flows. This result was similar to the analysis when the pedestrian value of time was valued as equal to car. However, by adjusting the pedestrian weighting factor to twice and more from the car value, there was a clear economic benefit of Upstream Detection at the road crossing at lower vehicle flow (100 veh/h and 300 veh/h for both directions) at all level of pedestrian flows. The benefit of Upstream Detection is higher as the pedestrian weighting factor is higher. Overall, it is clear that this form of upstream pedestrian detection is likely to provide benefits at lower vehicle flows and higher pedestrian flows. Effects of upstream pedestrian detection can be summarised in Table 5.10 below.

Table 5.10 Potential Effects of Upstream Detection

Pedestrian flow / Vehicle Flow	100 peds/hr	300 peds/hr	500 peds/hr
100 vehs/hr	√√	√√	√√
300 vehs/hr	√	√	√
700 vehs/hr	xx	x	x
1408 vehs/hr	xx	x	x

Key:

√ : possible benefit

√√ : probable benefit

x : possible disbenefit

xx : probable disbenefit

A note of caution with these results is that they are very much dependent on assumptions on pedestrian behaviour –in particular the use of the upstream detector and the availability/use of both pedestrian detectors. The logic modelled has resulted in significantly more pedestrian calls in a lower vehicle and pedestrian flow when an upstream detector is installed in addition to a kerbside push button. Unsurprisingly this has resulted in more frequent appearances of the 'green man', lower average delays to pedestrians and increased delay to vehicles. Further work would be valuable here to explore alternative pedestrian behaviours – which might be eventually validated through field trials.

6 Volumetric Detection

6.1 Introduction

This chapter describes further considerations undertaken to model the enhanced Puffin control to reflect volumetric pedestrian detection. The chapter covers all of the stages involved in this application, including model specification/development, implementation and assessment across a range of scenarios.

There are various ways in which knowledge of pedestrian volumes could be used to influence the signal control strategy, such as pedestrian priority (similar to bus priority) (Hounsell et al., 2001), and estimating pedestrian delay in real-time and carrying out an on-line signal optimisation process to achieve minimum total person delay/cost (Kirkham, 2006).

Pedestrian counting detectors have been available since 2002 (e.g. Crabtree (2002)) initially using low resolution infrared array technology. Although the study showed promising benefits with the ability to count the number of pedestrians wanting to cross the road, making it possible to allow a better balance between the movement of pedestrians and motorised traffic, the system was not sufficiently accurate and sensitive to the current pedestrian volume. Inaccuracies in counting pedestrian volumes using above-ground detection are likely for a number of reasons. For example, where pedestrians are very close to each other (in a group), they may be detected as a single pedestrian and misdetection of objects with a similar size and shape to a pedestrian (Bertozzi et al., 2007). More generally, pedestrians are not constrained to specific paths in the same way as vehicles, so counting will inevitably be less accurate. However, new algorithms/methods are emerging for pedestrian counting, so it is valid to consider the potential benefits which could be gained once accurate pedestrian volumetric counts are available.

Many optimisation techniques have been utilised for signal control, such as analytical models (Jiang et al., 2011), computer-based models (Li et al., 2004), genetic algorithms (Kim and Courage, 2003; Park and Kamarajugadda, 2007), fuzzy logic models (Schmocker et al., 2008) and neural networks. Kim and Courage (2003) used a hybrid genetic algorithm for setting the maximum green time based on the average green times of traffic actuated phases. Jiang et al. (2011) optimised the maximum green time based on the multiplication of the average value of maximum green time under each case and each individual probability. The authors concluded that the junction control delay increased with the maximum green time. However, such real time applications have been limited by their computational complexity and complex input requirements. Therefore, this study has investigated the off-line optimisation of maximum green setting under various traffic flow conditions. This simple approach is expected to illustrate how estimates of pedestrian volumes (currently unknown) coupled with traffic volume measurements (currently available) should influence maximum green time settings in standard Puffin control in a range of scenarios.

As in the Upstream Detection strategy, one aim of Volumetric Detection was to reduce the pedestrian delay at signalised pedestrian crossings – this time by changing the Maximum Green setting based on the number of pedestrians and vehicles on the road network. This represented a relatively simple control strategy in that it could easily be implemented on street within the existing Puffin logic. A range of objectives can be envisaged here, depending on the degree of priority (if any) which is given to pedestrians, according to policy. For this illustrative modelling, it was decided to explore the best maximum green settings from those tested which could give either (i) minimum person delay to all road users (pedestrians and vehicle occupants) or (ii) minimum overall travel cost for all road users, based on journey times and values of time for the different categories of road user.

Simulation results and a discussion on the performance of volumetric detection are described in the section that follows the methodology. The performance of Volumetric Detection strategy is compared from two aspects: efficiency (vehicle delay and pedestrian delay) and economic benefits. The final section summarises this research and proposes recommendations.

6.2 Methodology

Volumetric Detection as considered in this research is an offline traffic signal optimisation based on known/estimated traffic and pedestrian volumes. Volumetric Detection was modelled using the Base Case model with changes in maximum green settings. Maximum Green time limits the time that a vehicle phase can hold the green after a call of the conflicting phase is received (in this case, the conflicting phase being a pedestrian demand). It is a pre-specified value set in the signal controller, although a range of maximum green times can also be used, typically to reflect different traffic flows at different times of day (Department for Transport, 1995b).

Volumetric detection was evaluated here using the VISSIM case study signalised crossing (see Figure 6.1). Initially, the maximum green setting was pre-specified at 8 different maximum green settings. The impacts of these maximum green settings on vehicle delay and pedestrian delay were analysed to quantify the system performance. These results were then converted to total person delay and total delay costs to determine the effect of various maximum green settings on all road users. Then, the optimal maximum green setting was determined based on the lowest total person delay and the lowest total delay costs to road users. Then, economic evaluations were conducted to compare the performance of Volumetric Detection and the Base Case.

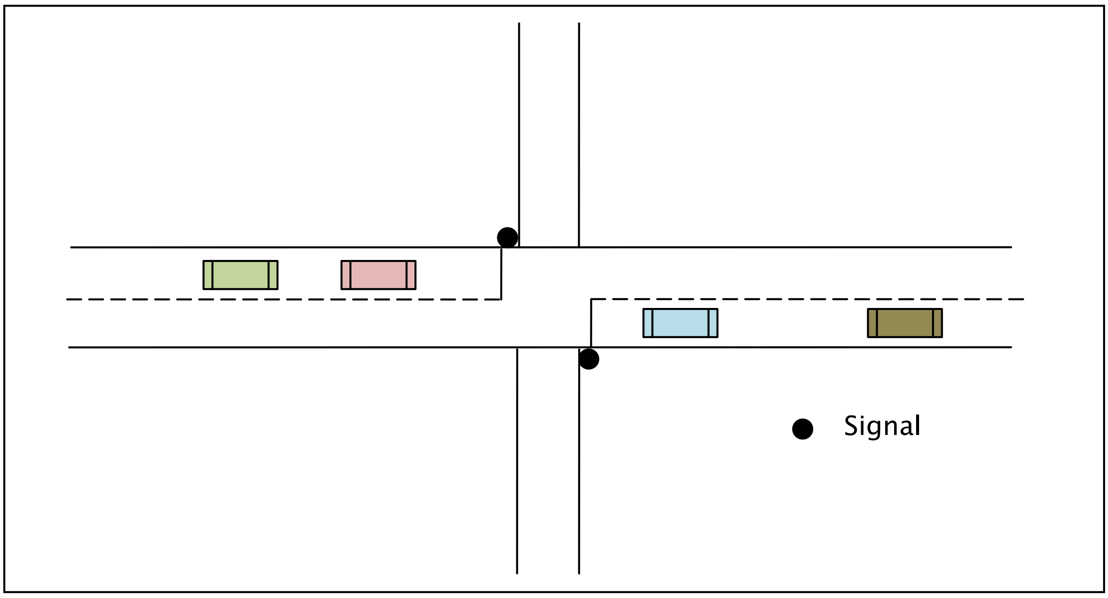


Figure 6.1 Puffin crossing in VISSIM

Using the crossing illustrated in Chapter 5, three kinds of vehicles were adopted to represent a general traffic composition of 95% cars, 3% HGV and 2% bus. Pedestrian walking speed in the simulated Puffin crossing ranging from 1.9 km/h to 7.2 km/h. Pedestrian compliance levels were assumed the same as the Market Street network, giving an average 64% compliance rate. Pedestrians were categorised into three types:

(a) Obey signal indication (whether he/she press the push button or not. He/she always follow the signal indications)
(b) Press the button but do not necessarily obey the signal indication (gap-cross when there is an opportunity)
(c) Do not press the push button and do not obey signal indication (gap-cross when there is an opportunity)

6.3 Simulation Scenarios

The simulation tests were conducted under various traffic demand and pedestrian flow scenarios, giving twelve traffic flow/pedestrian combinations as shown in Table 6.1 below. As before, these vehicle flow and pedestrian flow are for both directions.

Table 6.1 Various Traffic Flow Combinations

Pedestrian Flow (ped/h)	Vehicle Flow (veh/h)				
	100	300	700	1400	2000
100	√	√	√	√	√
300	√	√	√	√	√
500	√	√	√	√	√

These combinations represented wide-ranging traffic patterns and provided a reliable platform for evaluating the system performance. The simulation scenarios are illustrated in Figure 6.2 below.

Signal Control Scenario	Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Maximum Green Settings	Number of Simulation Runs
Volumetric Detection	100	100	10 s 20 s 22 s 24 s 26 s 28 s 30 s 40 s	80
		300	Same as above	80
		500	Same as above	80
	300	100	Same as above	80
		300	Same as above	80
		500	Same as above	80
	700	100	Same as above	80
		300	Same as above	80
		500	Same as above	80
	1400	100	Same as above	80
		300	Same as above	80
		500	Same as above	80
	2000	100	Same as above	80
		300	Same as above	80
		500	Same as above	80
Free Flow Traffic	100	No Pedestrian	-	10
	300	No Pedestrian	-	10
	700	No Pedestrian	-	10
	1400	No Pedestrian	-	10
	2000	No Pedestrian	-	10
	No Vehicle	100	-	10
	No Vehicle	300	-	10
	No Vehicle	500	-	10
TOTAL =				1280

Figure 6.2 The Overview of Simulation Scenario

As shown in Figure 6.2 above, there are two signal control scenarios to be simulated: Volumetric Detection and free flow traffic conditions. For each traffic flow combination, eight maximum green settings were simulated in the Volumetric Detection plan: 10 sec, 20 sec, 22 sec, 24 sec, 26 sec, 28 sec, 30 sec and 40 sec. In free flow traffic conditions, there are two traffic scenarios: Free flow vehicle traffic and free flow pedestrian traffic. In free flow vehicle traffic, pedestrians were taken out from the pedestrian crossing so that vehicles were expected to have smooth movement on the road without disturbances from the changes of signal indications. Similarly for free flow pedestrian traffic, vehicles were taken out from the pedestrian crossing so that pedestrians were expected to receive all green indications to allow smooth movement on the pedestrian crossing.

Free flow vehicle traffic and free flow pedestrian traffic were simulated to measure vehicle delay and pedestrian delay due to signal control. Vehicle delay measurements were determined by subtracting the free flow vehicle travel time from vehicle traffic time with signal operation. Pedestrian delay measurements were determined by subtracting the free flow pedestrian travel time from pedestrian travel time with signal operation.

The simulation time period was specified as 10 hours to account for the stochastic nature of traffic flow. For every test scenario, 10 simulation runs with a different random seed each were conducted. This resulted in 1280 simulation runs to evaluate the Volumetric Detection strategy.

6.3.1 Case 1: Various Maximum Green settings

Eight maximum green settings for fifteen vehicle and pedestrian flow combinations were simulated on the Puffin crossing: 10 seconds, 20 seconds, 22 seconds, 24 seconds, 26 seconds, 28 seconds, 30 seconds and 40 seconds. The impact of these maximum green settings was then examined.

The immediate impact of any change in maximum green settings should be evident in corresponding changes in the number of signal cycles per time period. Figure 6.3 shows the number of signal cycles for different combinations of vehicle and pedestrian flows at maximum green 10 and maximum green 40.

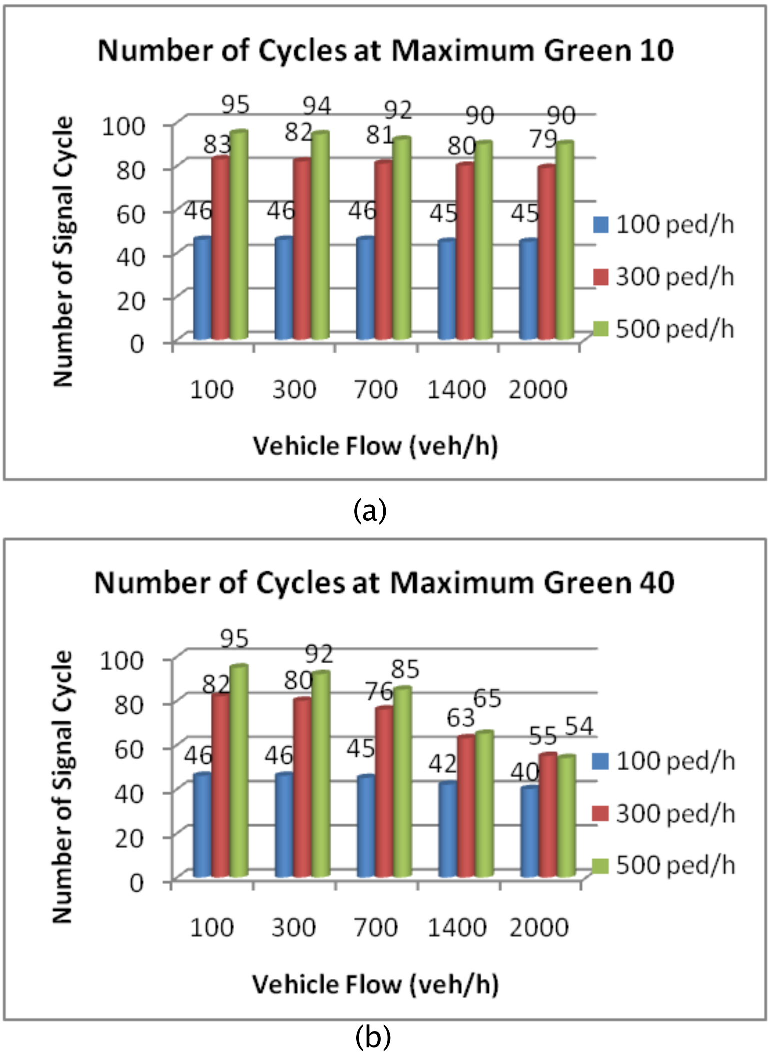


Figure 6.3 Number of Cycles for Fifteen Traffic Flow Combinations at Maximum Green 10 and Maximum Green 40

It is shown in Figure 6.3 above that for any specific vehicle flow, generally as pedestrian flow increased, there was an increase degree of saturation[a] hence the increase in the number of signal cycles (see Table 6.2).

---

[a]Degree of Saturation (DoS) = Flow/Capacity

$$DoS = \frac{qC}{gS}$$

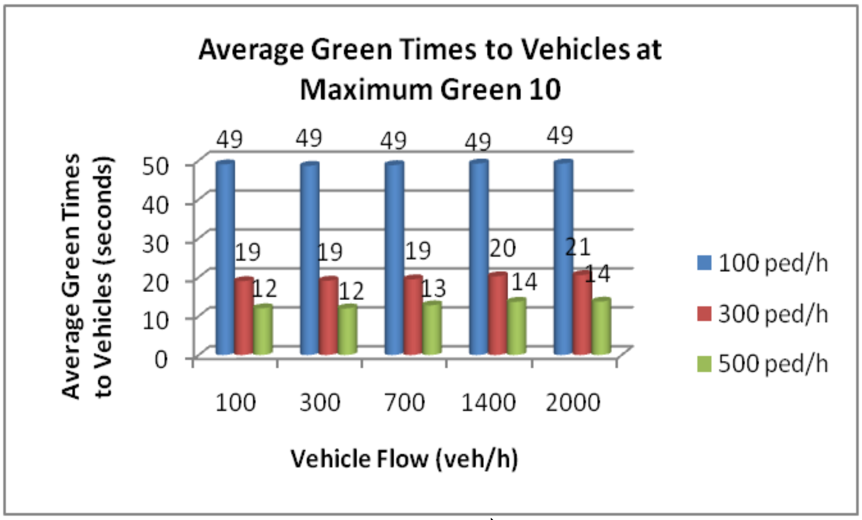
Where q = traffic flow
C = cycle time
g = effective green time
S = saturation flow

Table 6.2 Degree of Saturation (DoS) for Maximum Green 40

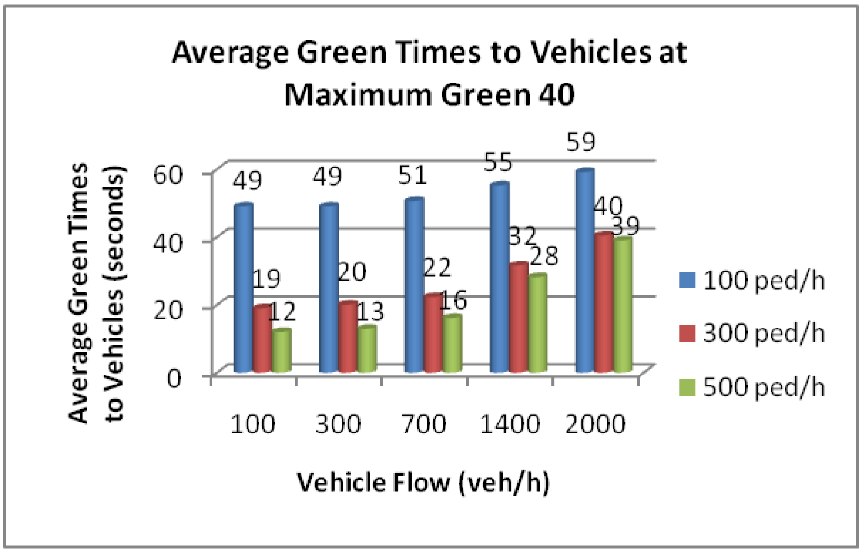
	Degree of Saturation (DoS) for Maximum Green 40		
Pedestrian Flow (ped/h) / Vehicle Flow (veh/h)	100	300	500
100	0.03	0.05	0.05
300	0.1	0.2	0.2
700	0.3	0.4	0.5
1400	0.5	0.6	0.7
2000	0.8	0.8	0.9

This is expected, as higher pedestrian demand means more frequent pedestrian calls (on the ‘push button’) and therefore more frequent stage changes. For one particular vehicle and pedestrian flow combination, degree of saturation reduced as maximum green setting increased from 10 seconds to 40 seconds hence the reduction in signal cycle changes as shown in Figure 6.3 above. Similarly, for any particular pedestrian flow, as vehicle demand increased, the number of signal cycles decreased, as there was less opportunity for ‘gap changing’. This is most noticeable where the maximum vehicle green is 40 secs; in this case there is greater scope for green time variability than where the maximum green time is 10 secs. With a maximum vehicle green of only 10 seconds, this green time is needed nearly every cycle to satisfy vehicle demand, so the number of cycles is then relatively insensitive to vehicle and pedestrian flows.

It is also useful to analyse how the average green time for vehicles varies with variations in vehicle and pedestrian flows (noting here that the green man duration for pedestrians is fixed). Figure 6.4 illustrates these relationships.



(a)



(b)

Figure 6.4 Average Vehicle Green Times for Fifteen Traffic Flow Combinations at Maximum Green 10 and Maximum Green 40

It is shown in Figure 6.4 that for one particular vehicle flow, the lower the pedestrian flow, the longer the average green time is for vehicles. This is expected, as there are fewer pedestrian calls. Note here that the average green time for vehicles can exceed the maximum green time substantially, because the maximum vehicle green time only applies ***after*** a pedestrian demand has been registered. As pedestrian flow increased, there was a reduction in average vehicle green times to cater the increasing pedestrian demand. Also, for any particular pedestrian flow, there was an increase in average vehicle green times as vehicle flow increased: This was particularly apparent for the higher maximum green time of 40 seconds.

Changes in the number of cycles and average vehicle green times for various vehicle and pedestrian flow combinations at various maximum green settings have an impact on vehicle delay and pedestrian delay. Figure 6.5 shows average vehicle delay per vehicle for fifteen vehicle and pedestrian flow combinations at eight different maximum green settings.

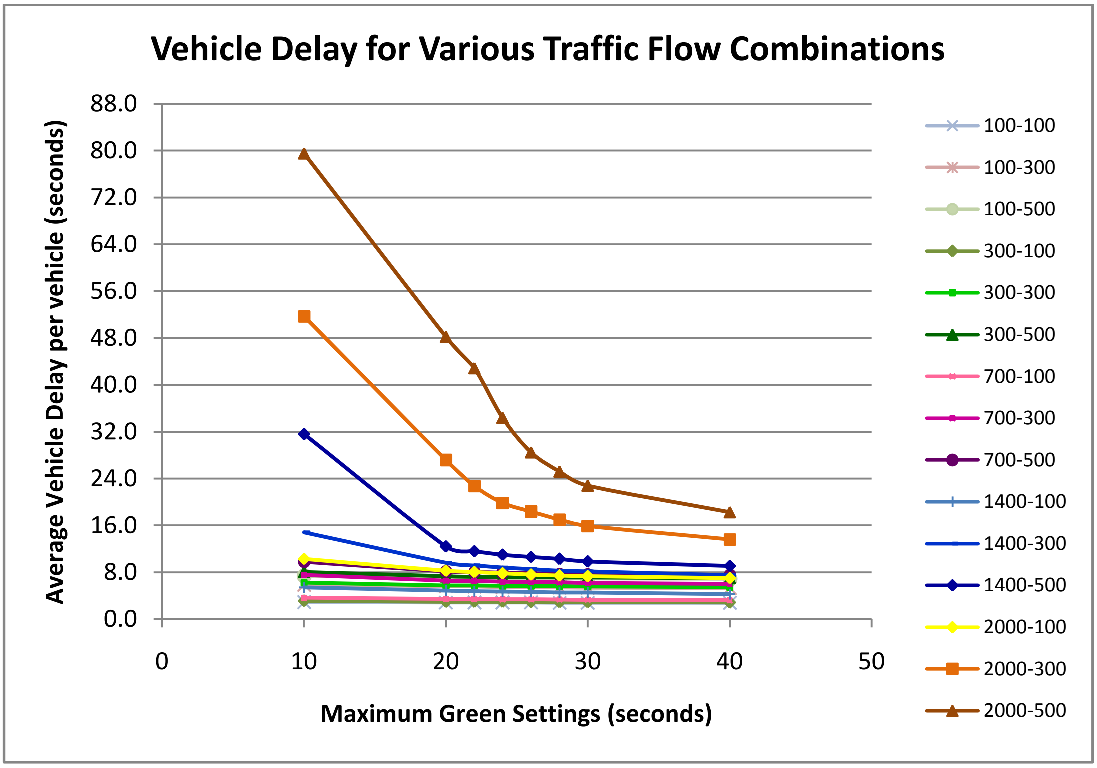


Figure 6.5 Average Vehicle Delay per vehicle for Various Traffic Flow Combinations at Eight Different Maximum Green Settings

It is seen in Figure 6.5 that the relationship between vehicle delay and maximum green setting depended on the vehicle and pedestrian volumes. At low volumes, a 10 seconds maximum green was evidently sufficient, as the relationship was effectively ‘flat’. However, as vehicle and pedestrian flows increased then it was clear that maximum green times set too low could cause much higher vehicle delays. As maximum green increased from 10 seconds to 40 seconds, there was a reduction in average vehicle delay per vehicle. The reduction was higher and most apparent at four vehicle and pedestrian flow combinations: 1400 veh/h-300 ped/h, 1400 veh/h-500 ped/h, 2000 veh/h- 300 ped/h and 2000 veh/h-500 ped/h. At eight maximum green settings for fifteen vehicle and pedestrian flow combinations, as pedestrian flow increased, there was an increase in average vehicle delay per vehicle as there were more disruptions to vehicle movement on the pedestrian crossing as a consequence of increasing pedestrian demand from the signal control. As maximum green setting increased, vehicles received a longer average vehicle green time as can be seen in Figure 6.4, resulting in a reduction in average delay per vehicle.

Figure 6.6 shows the results of average pedestrian delay per pedestrian for fifteen vehicle and pedestrian flow combinations at eight maximum green settings.

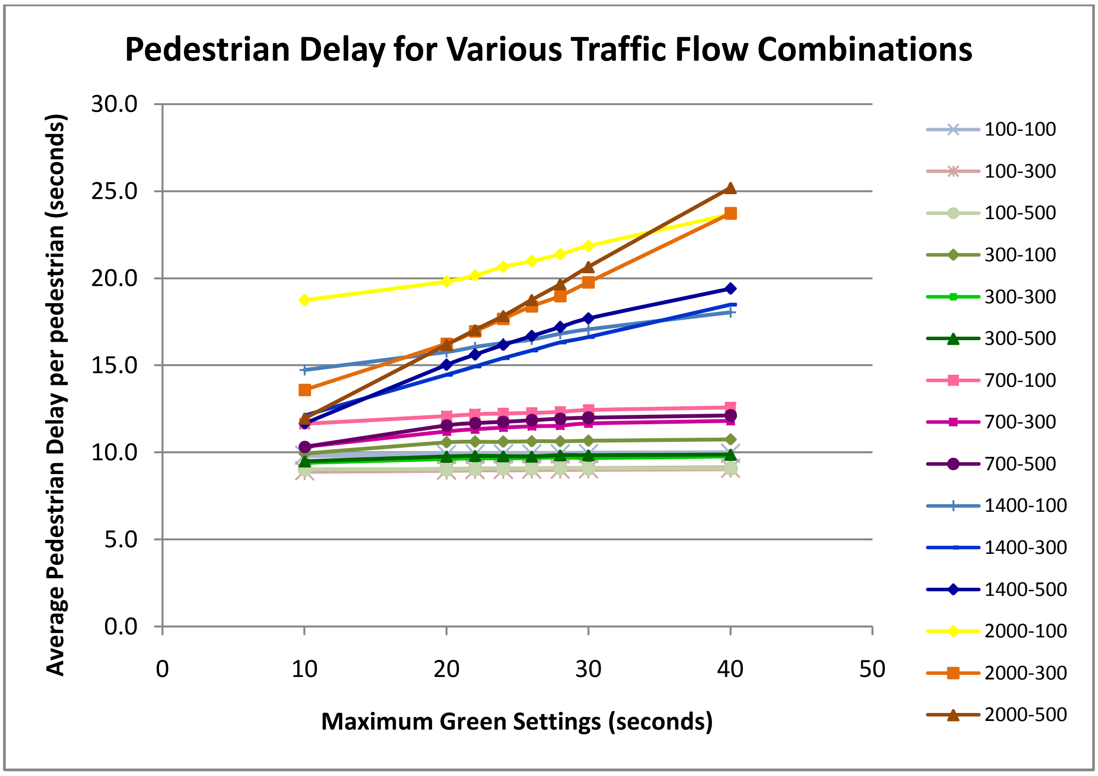


Figure 6.6 Average Pedestrian Delay per pedestrian

It is shown in Figure 6.6 that an increase in maximum green settings from 10 seconds to 40 seconds caused an increase in average delay per pedestrian. This was due to the vehicles receiving longer average green times hence pedestrians had to wait for a longer period before the pedestrian phase was given. This was particularly noticeable at high vehicle volumes. At eight maximum green settings for fifteen vehicle and pedestrian flow combinations, as pedestrian flow increased, as expected there was a reduction in average pedestrian delay per pedestrian. As pedestrian demand increased, pedestrians started to take precedence that caused frequent changes in signal cycles (see Figure 6.3). Therefore, pedestrians did not have to wait longer hence the reduction in average delay per pedestrian. However, a different result occurred at a higher vehicle flow (1400 veh/h and 2000 veh/h) in which an increase in pedestrian flow caused an increase in average pedestrian delay at some maximum green settings. At these two vehicle flows: 1400 veh/h and 2000 veh/h, as maximum green setting increased, an increase in pedestrian flow caused a saturated pedestrian condition on the crossing. This caused a significant increase and a gradual increase in average pedestrian delay respectively at a higher pedestrian flow and at a lower pedestrian flow (100 ped/h) and caused some of the lines are crossing each other.

For 100 ped/h, as vehicle flow increased from 100 veh/h to 2000 veh/h, there was approximately double increase in average delay per pedestrian. Then as maximum green increased from 10 seconds to 40 seconds, there was a slight increase in average pedestrian delay for both traffic flow combinations: 100 veh/h – 100 ped/h and 2000 veh/h – 100 ped/h. As vehicle flow increased from 100 veh/h to 2000 veh/h, crossing during the red phase becomes more difficult for those non-comply pedestrians. Therefore, the opportunity of gap-crossing behaviour decreased and pedestrians had little choice but to wait for 'Walk' signal indication. Besides that, as vehicle flow increased, vehicles received longer average green times (see Figure 6.4), hence forced pedestrians to wait longer before pedestrian phase was given.

At lower maximum green setting 10 seconds for 2000 veh/h, as pedestrian flow increased from 100 ped/h to 300 ped/h, there was a great reduction in average delay per pedestrian. However, the reduction occurred at a lesser rate as maximum green increased from 10 seconds to 40 seconds. Then as pedestrian flow increased to 500 ped/h, there was a steep increase in average pedestrian delay at eight different maximum green settings. The average pedestrian delay for 2000 veh/h – 500 ped/h started to cross the average pedestrian delay for 2000 veh/h – 100 ped/h and 2000 veh/h – 300 ped/h at maximum green 35 and maximum green 20 respectively. At higher vehicle flow, 2000 veh/h, vehicles dominated the road. Therefore, as maximum green increased, the average pedestrian delay continued to increase regardless of the increase in pedestrian demand.

In general, as maximum green settings increased for one particular vehicle and pedestrian flow combination, there was less signal cycle changes occurred as a result of longer average green times to vehicles. As a consequence, it reduced the average delay per vehicle but in the meantime it caused an increase in average delay per pedestrian.

A key objective here is to study and find the best maximum green time settings to use in different circumstances, taking account of both vehicle and pedestrian delays. With this objective, Figure 6.7, Figure 6.8 and Figure 6.9 illustrates the combination of average delay per vehicle and average delay per pedestrian for fifteen vehicle and pedestrian flow combinations at eight different maximum green settings.

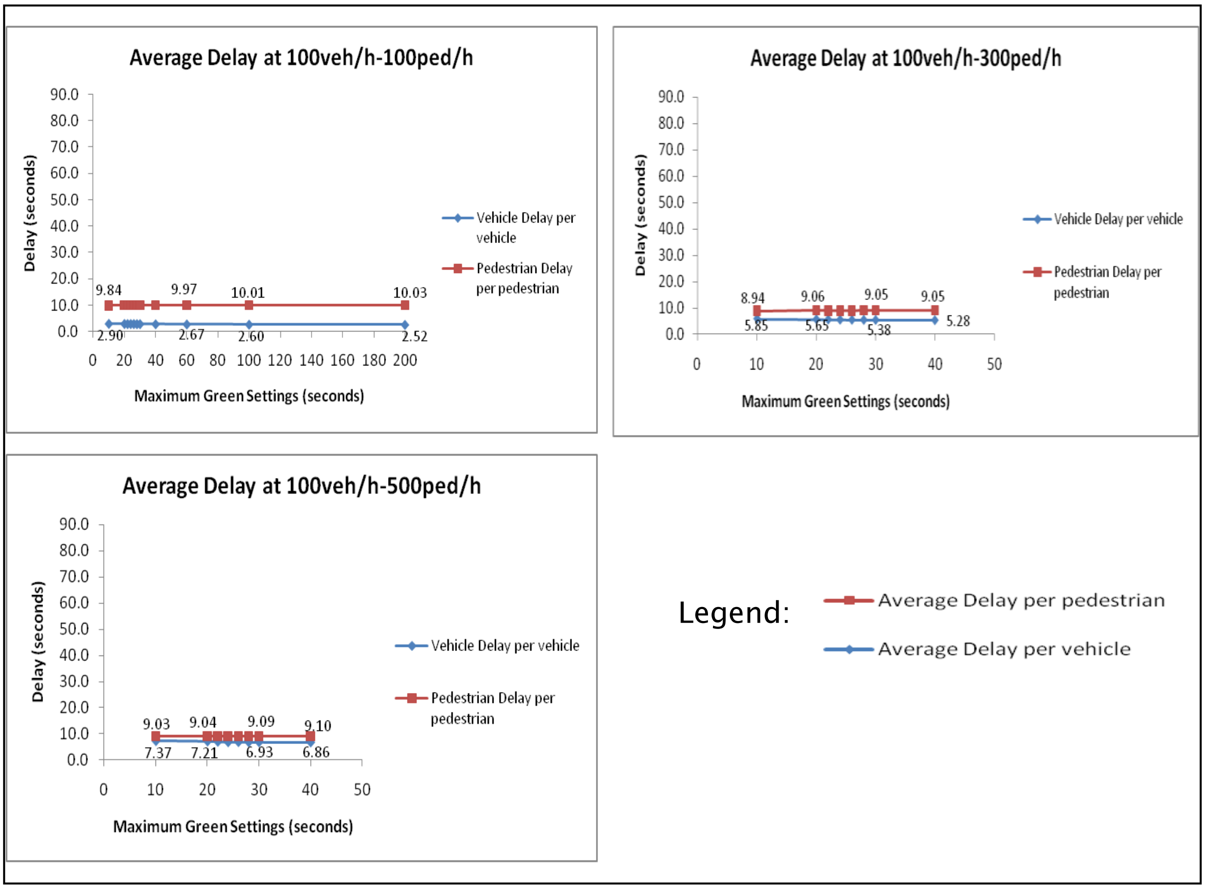


Figure 6.7 Average Delay for 100 veh/h at Eight Maximum Green Settings

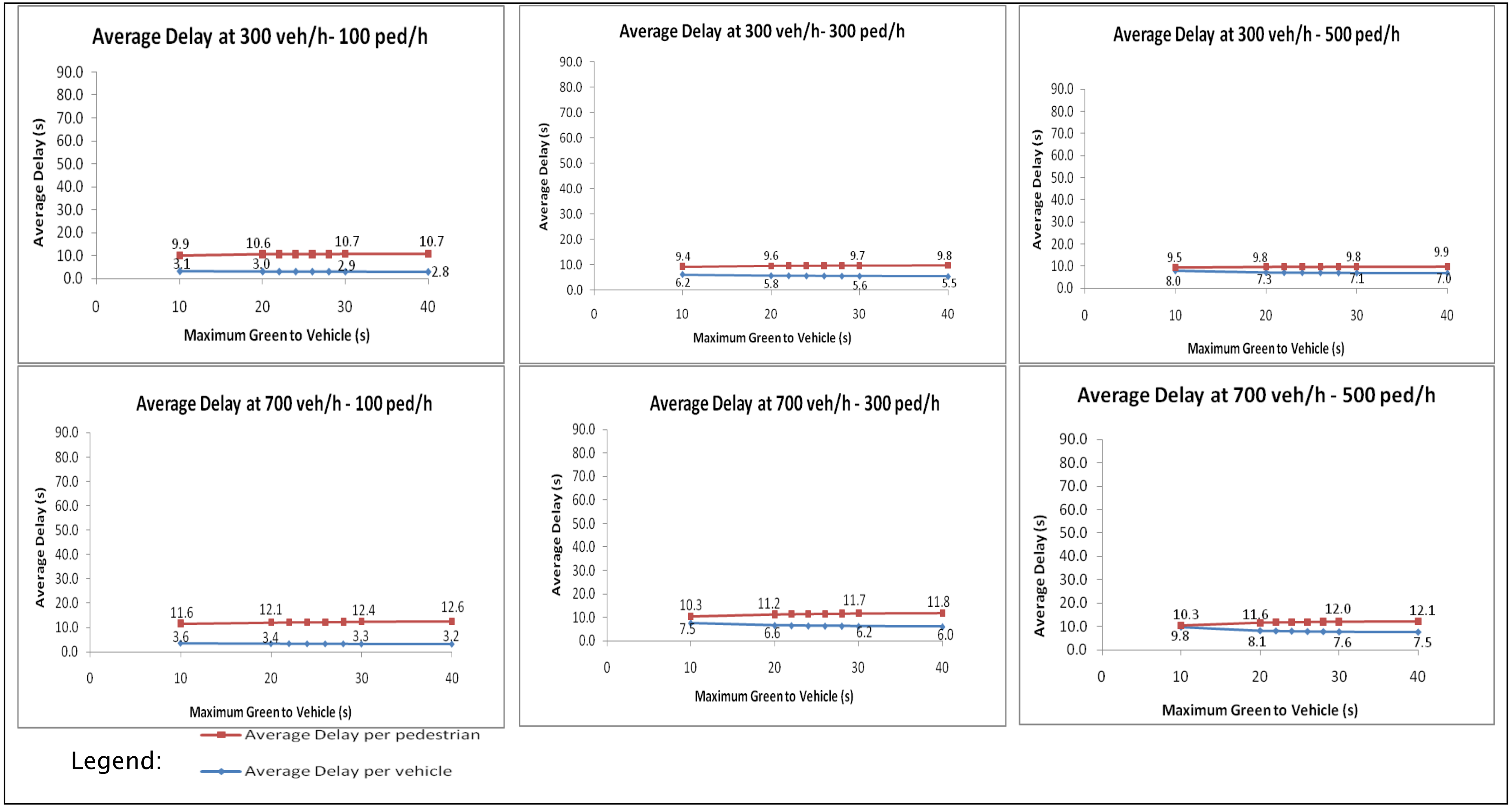


Figure 6.8 Average Delay for Six Traffic Flow Combinations at Eight Maximum Green Settings: 300 veh/h and 700 veh/h

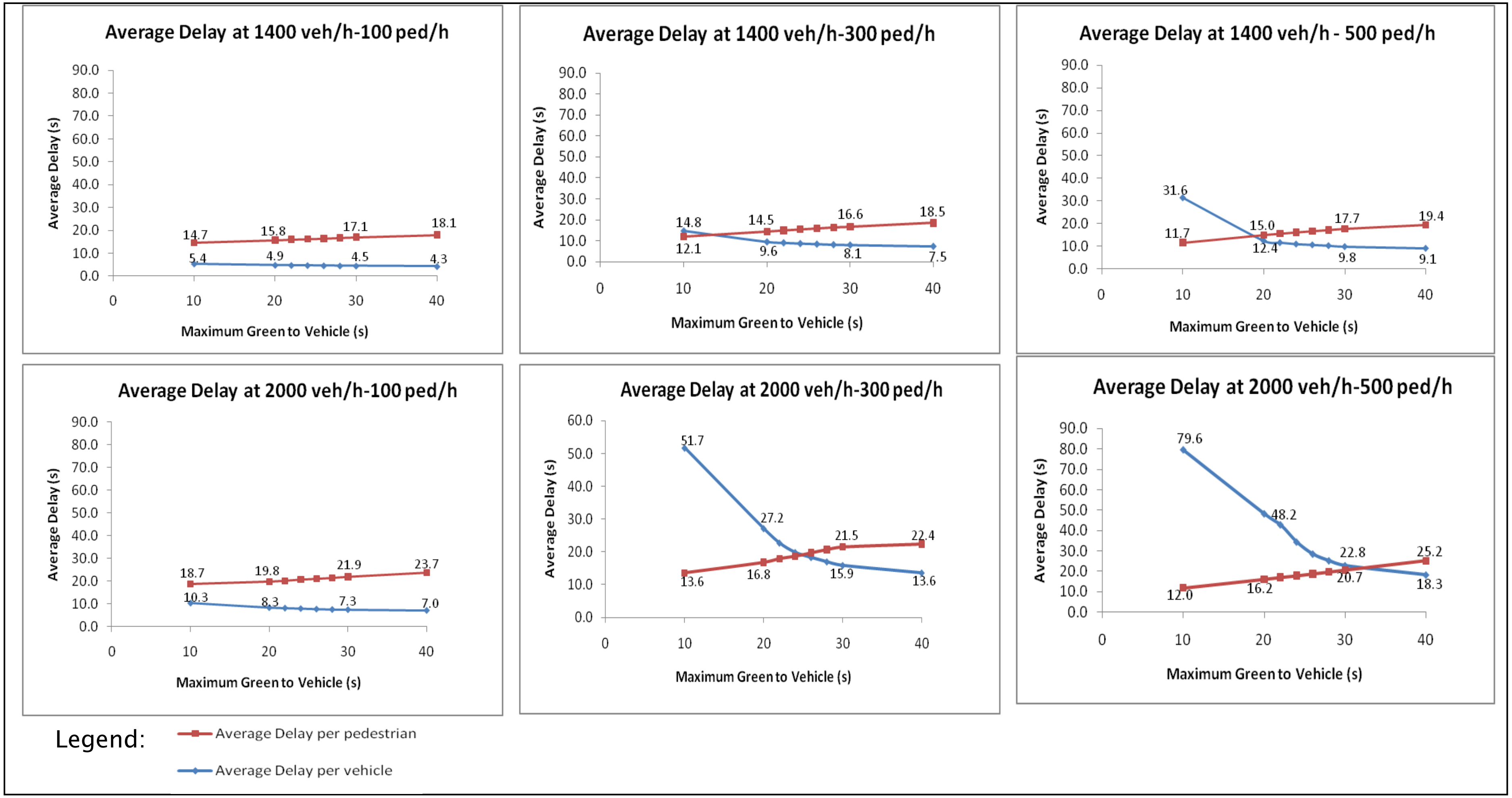


Figure 6.9 Average Delay for Six Traffic Flow Combinations at Eight Maximum Green Settings: 1400 veh/h and 2000 veh/h

Generally, as seen in Figure 6.7, Figure 6.8and Figure 6.9, an increase in maximum green setting for fifteen traffic flow combinations caused a reduction in average delay per vehicle and an increase in average delay per pedestrian. However, the changes in delay time for both vehicle and pedestrian as maximum green setting increased were small at lower vehicle flows (100 veh/h). The changes in average delay per vehicle and average delay per pedestrian increased as vehicle flow and/or pedestrian flow increased. Changes are particularly noticeable at higher vehicle and pedestrian flow combinations: 2000 veh/h – 500 ped/h. In some cases, the flows were sufficiently high to cause significant vehicle queuing and delay – particularly at lower settings of maximum vehicle green. In such cases, delays to vehicles could exceed the delays to pedestrians.

Results in Figure 6.7, Figure 6.8 and Figure 6.9 were then further analysed to determine the best maximum green time required to give (i) minimum delay to all road users (vehicle occupants and pedestrians combined) and (ii) minimum total cost of delay for all road users. These analyses and results are shown in the following sections.

6.3.2 Case 2: 'Optimal' Maximum Green settings

The average delay per vehicle and average delay per pedestrian at eight maximum green settings for fifteen traffic flow combinations were converted into total delay person and total delay costs. Then the best maximum green from those tested for fifteen vehicle and pedestrian flow combinations was determined based on the lowest total person delay and the lowest total delay costs.

6.3.2.1 Total Person Delay

The analysis of average delay per vehicle and average delay per pedestrian were converted into total person delay. This is to examine the impact of volumetric detection strategy on all road users at the pedestrian crossing.

Equation 6.1 shows the calculation of total person delay (as described in Chapter 2).

Total person delay = $D_v O_v N_v + D_p N_p$ Equation 6.1

Where subscript v= mode of transport

subscript p = pedestrian

D = average delay time per person

O = vehicle occupancy

N = number of vehicles or pedestrians completing their journey in the simulation period

The standard vehicle occupancy rates from the Department for Transport (2011b) were used and are shown in Table 6.3 below (see Chapter 2 for detail explanations).

Table 6.3 Average Vehicle Occupancies (Department for Transport, 2011b)

Mode of Transport	Average Vehicle Occupancies
Car	1.58
Bus	13.20
HGV	1.0
Pedestrians	1.0

Figure 6.10, Figure 6.11 and Figure 6.12 show the total person delay (person seconds per hour) at eight different maximum green settings for fifteen vehicle and pedestrian flow combinations.

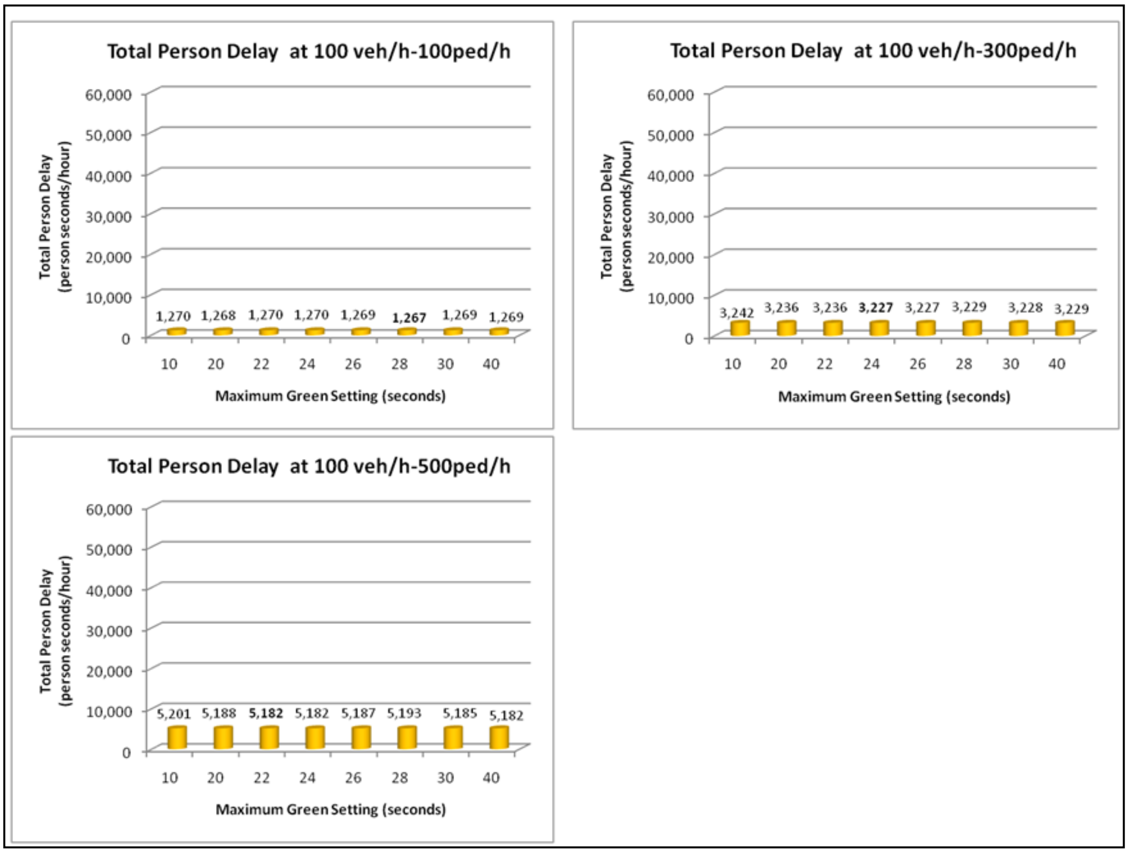


Figure 6.10 Total Person Delay for 100 veh/h at Eight Maximum Green Setting

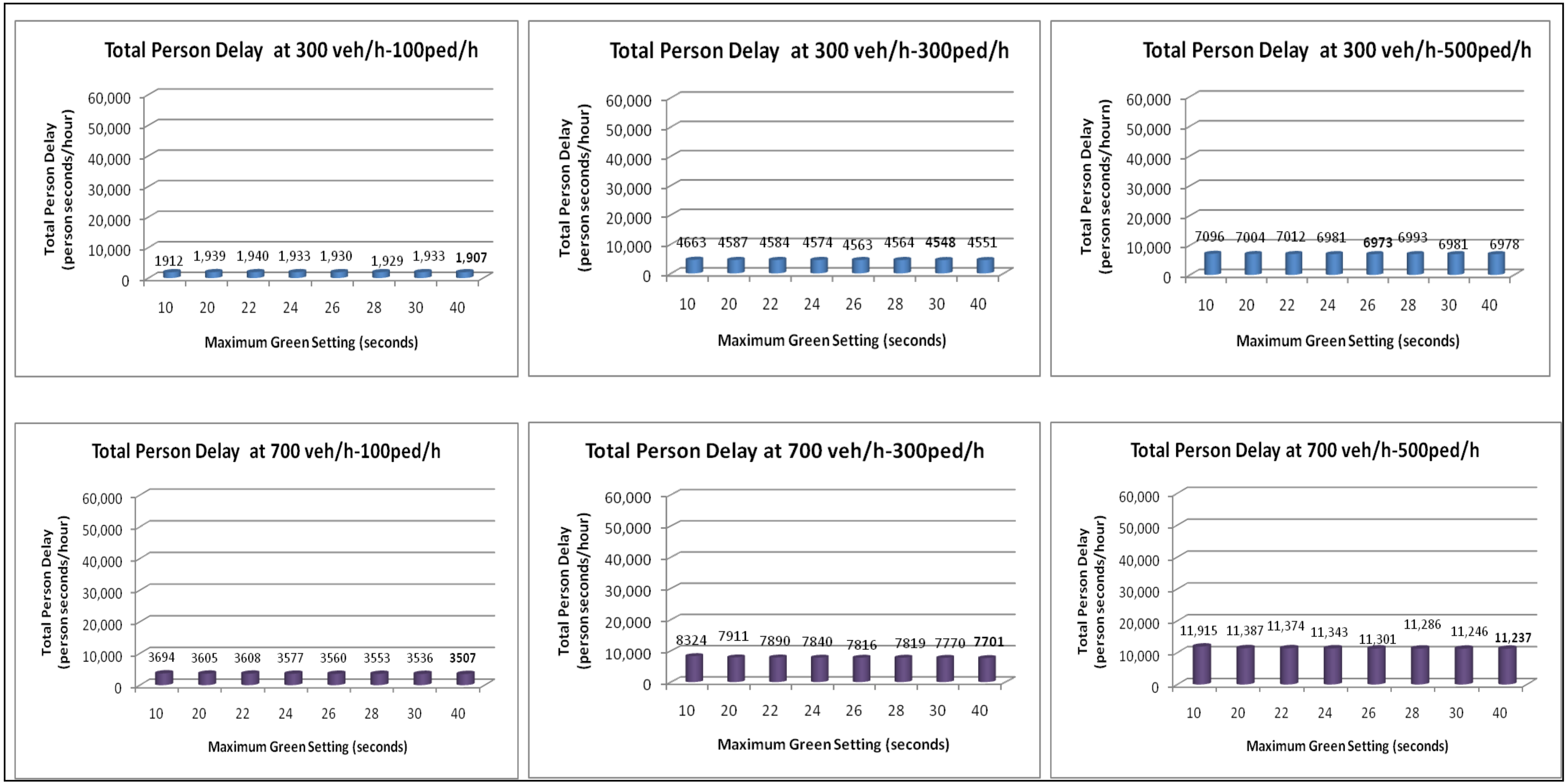


Figure 6.11 Total Person Delay for Six Traffic Flow Combinations at Eight Maximum Green Settings: 300 veh/h and 700 veh/h

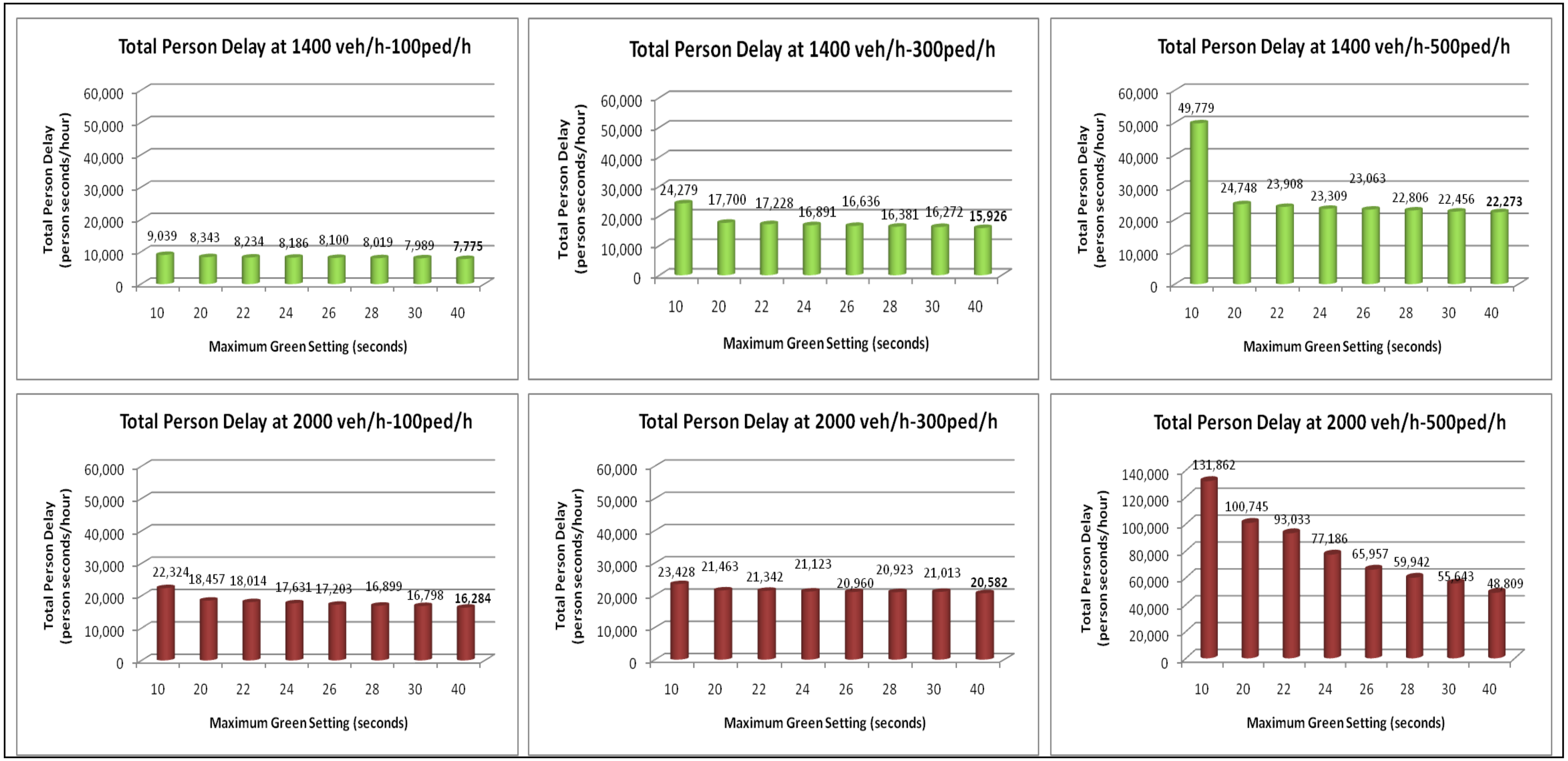


Figure 6.12 Total Person Delay for Six Traffic Flow Combinations at Eight Maximum Green Settings: 1400 veh/h and 2000 veh/h

As shown in Figure 6.10, Figure 6.11 and Figure 6.12, different maximum green settings for fifteen vehicle and pedestrian flow combinations produced different total person delays at the pedestrian crossing. The general trend in these figures is that total person delay decreases with increasing maximum green. It should be noted here that the ratio of the number of vehicle occupants to the number of pedestrians varied in these scenarios between 1.1 (with 300 veh/h and 500 ped/h) to 35.9 (with 2000 veh/h and 100 ped/h). In most cases, the number of vehicle occupants exceeded the number of pedestrians substantially, except at 100 veh/h. The results overall are therefore much more sensitive to vehicle delays. These tend to be lower with higher maximum green settings, as higher settings can cope with random cycle-to-cycle variations in flow, as occur on street and in VISSIM, and higher vehicle flow levels. It is also relevant to note that, at low vehicle flows, the signals should 'gap change' anyway in response to a pedestrian demand, so that having a high maximum vehicle green time is then irrelevant.

Figure 6.13 below shows the best maximum green setting from those tested for fifteen traffic flow combinations based on the lowest total person delay in Figure 6.10, Figure 6.11 and Figure 6.12.

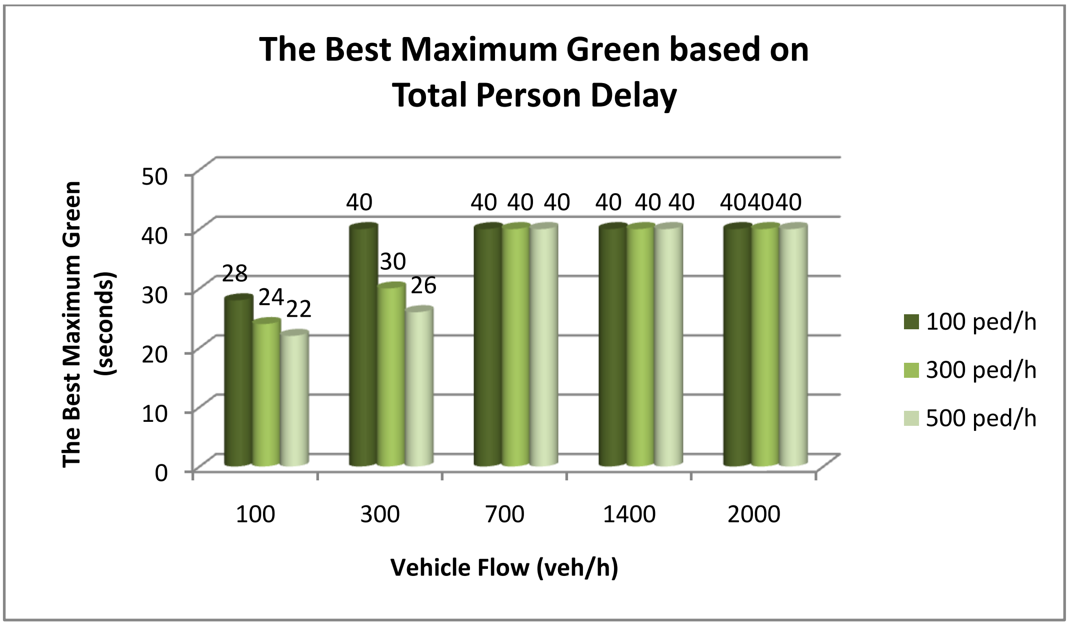


Figure 6.13 The Best Maximum Green from those tested based on Total Person Delay

It is seen in Figure 6.13 that at the lowest vehicle flow (100 veh/h and 300 veh/h), as expected the best maximum green settings reduced with the increase in pedestrian flow. Started from 700 veh/h, the best maximum green setting is 40 seconds, which produced the lowest total person delay to all road users, regardless of the increase in pedestrian flow. These results were expected as vehicle occupancies are normally higher than pedestrians, therefore, the higher maximum green setting brings the lowest total person delay hence bring benefit to all road users.

6.3.2.2 Total Delay Costs

(i) Standard Value of Time

The results of total person delay were then converted into monetary values to assess the best maximum green setting based on economic perspective. This can be important as the values of time recommended for vehicle occupants and pedestrians are different. Equation 6.2 shows the calculation of total delay costs (as described in Chapter 2).

Total delay costs = $D_v O_v N_v V_v + D_p N_p V_p$ Equation 6.2

Where subscript v = mode of transport

subscript p = pedestrian

D = average delay time per person

O = vehicle occupancy

N= number of vehicles or pedestrians completing their journey in the simulation period

V = value of times per person

D x O x N = total person delay

The standard values of time per person for various vehicle types and pedestrians from the Department for Transport (2011b) were used and are shown in Table 6.4 below (see Chapter 2 for detail explanations).

Table 6.4 Values of Time for Various Modes of Transport (Department for Transport, 2011b)

Mode of transport	Values of Times per vehicle (£ per hour per vehicle)
Car	£10.46
Bus	£71.62
HGV	£10.18
Pedestrians	£9.38

Figure 6.14, Figure 6.15 and Figure 6.16 below shows the total delay costs for Volumetric Detection scenario for fifteen vehicle flow and pedestrian flow combinations. The vehicle flow consists of 95% car, 3% HGV and 2% bus.

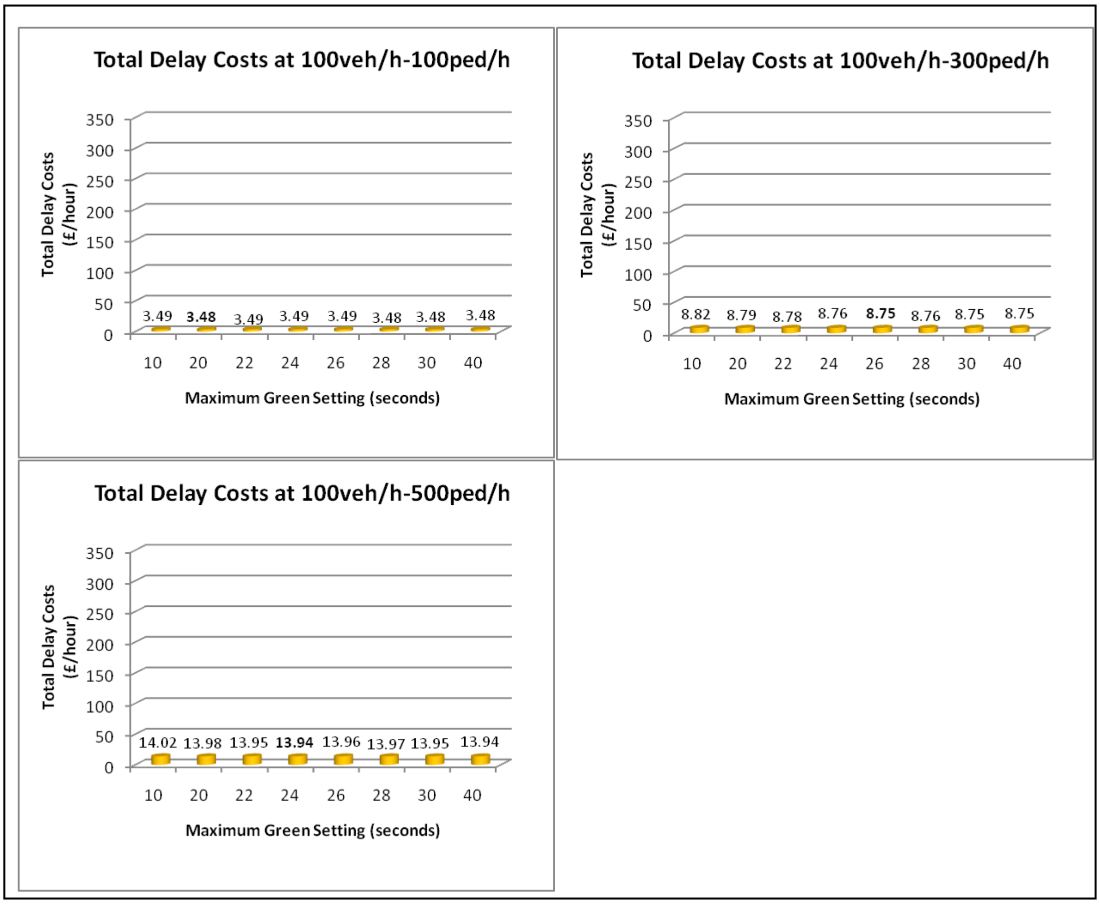


Figure 6.14 Total Delay Costs for 100 veh/h at Eight Maximum Green Settings

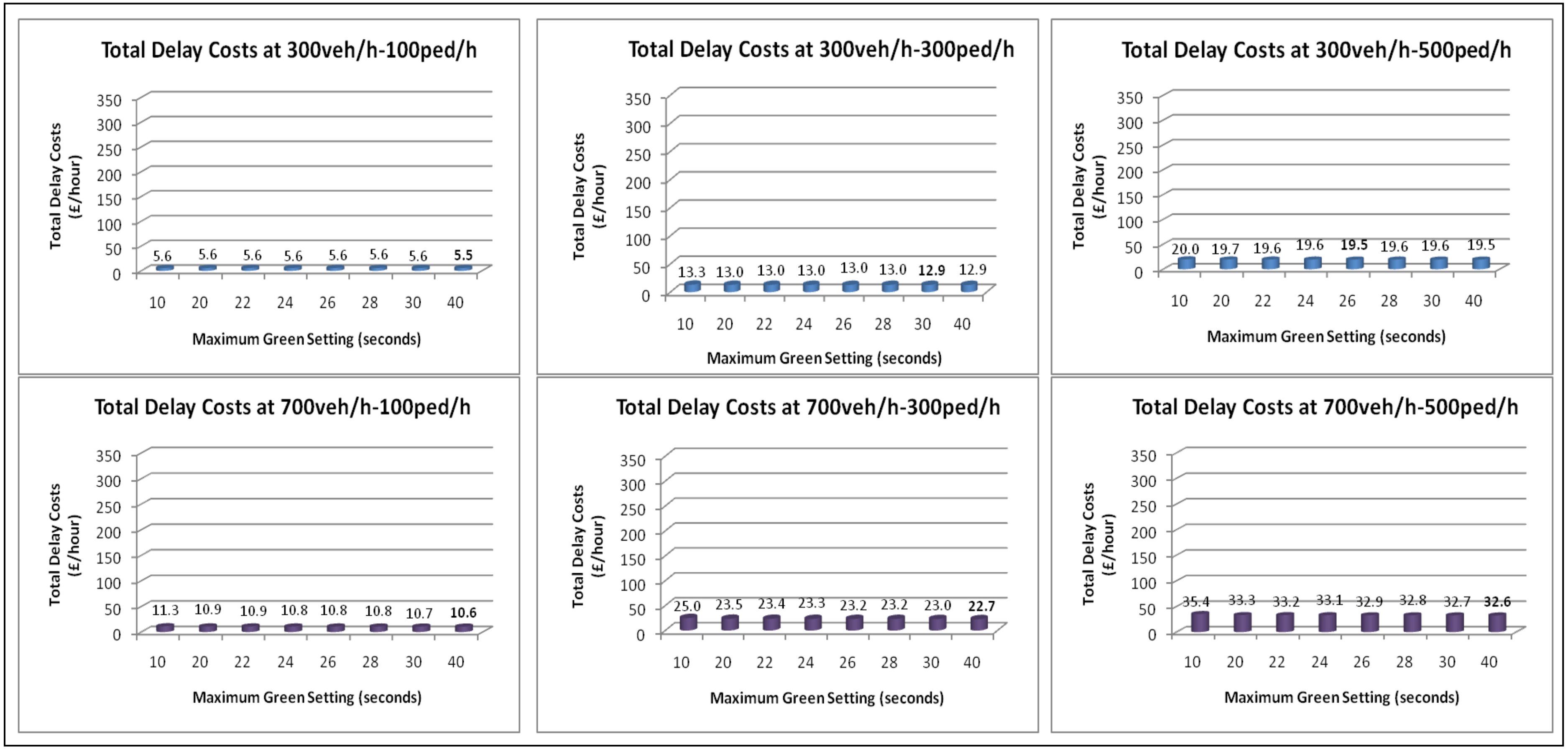


Figure 6.15 Total Delay Costs for Six Traffic Flow Combinations at Eight Maximum Green Settings: 300 veh/h and 700 veh/h

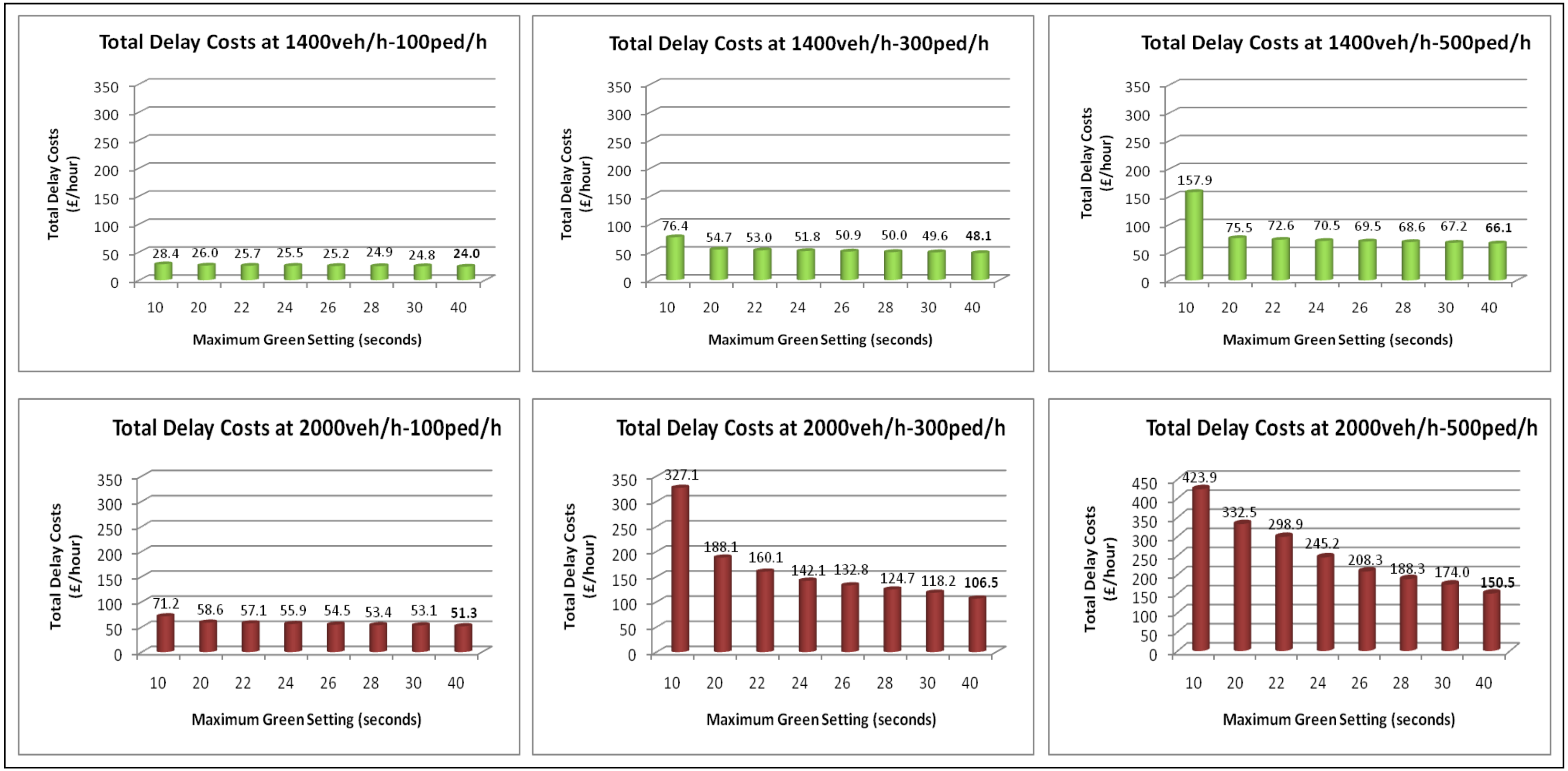


Figure 6.16 Total Delay Costs for Six Traffic Flow Combinations at Eight Maximum Green Settings: 1400 veh/h and 2000 veh/h

Figure 6.14, Figure 6.15 and Figure 6.16 show the fluctuating trend of total delay costs results at eight maximum green settings for fifteen vehicle and pedestrian flow combinations. The best maximum green setting from those tested was determined based on the maximum green setting that produced the lowest costs to the whole road users. Figure 6.17 below shows the best maximum green setting from those tested based on the lowest costs for fifteen traffic flow combinations.

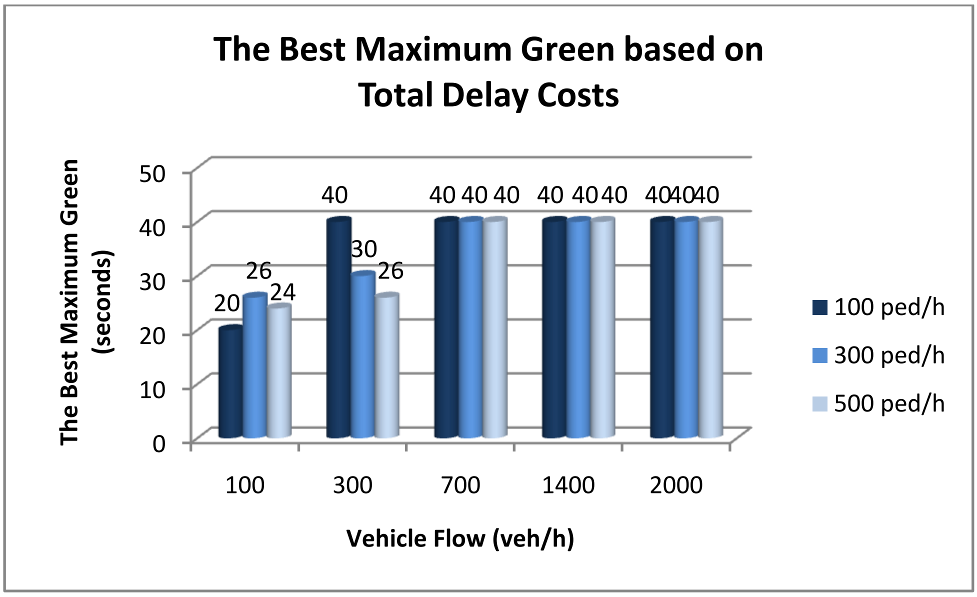


Figure 6.17 The Best Maximum Green from those tested based on Total Delay Costs

Figure 6.17 shows the fluctuating trend of the best maximum green setting from those tested based on total delay costs. These results were due to the variations in value of times retrieved from Department of Transport (2011b) as shown in Table 6.4. The value of times shown in Table 6.4 were based on the assumptions that majority of vehicle occupants (13.1% of car occupants, 100% of bus occupants and 100% of HGV occupants) travel in working time while only 1.7% of pedestrians travel in working time.

(ii) Relative Value of Time

Rather than using assumptions about the relative values of time as in above section, adjusting the weightings applied to the pedestrian and vehicle travel time savings would provide an understanding of the strategic importance to be attached to pedestrians if the improvements were to be supported. Table 6.5 below shows the weighting factor from previous studies.

Table 6.5 Relative Values of time for various modes

Mode	Values of time per person
Car	1.0
HGV (Fowkes, 2001)	4.0
Bus (Haight, 1994)	0.5
Pedestrian (Mackie et al., 2003b; Wardman, 2004; Bhattacharya and Virkler, 2005; Ishaque, 2006)	0 to 4

The value of time used for evaluation purpose is an equity value, which is £4.46 per hour person, 2002 prices and values (Department for Transport, 2011b). The user cost was computed by assigning different weighting factors to pedestrian and vehicles as shown in Equation 6.3 below (Bhattacharya and Virkler, 2005). See Chapter 2 for further details.

Total Delay Costs = $D_v O_v N_v T_v W_v + D_p N_p T_p W_p$ Equation 6.3

Where subscript v = vehicles

subscript p = pedestrian

D = average delay time per person

O = vehicle occupancy (D x O = average delay per vehicle)

N = number of vehicles or pedestrians completing their journey in the simulation period

$D \times O \times N$ = total person delay

T = values of time, £4.46 per hour per person

W = weighting factors (shown in Table 6.5)

Figure 6.18 below shows the best maximum green setting from those tested based on total delay costs (relative value of time) with pedestrian weighting factor varies from 1 to 4.

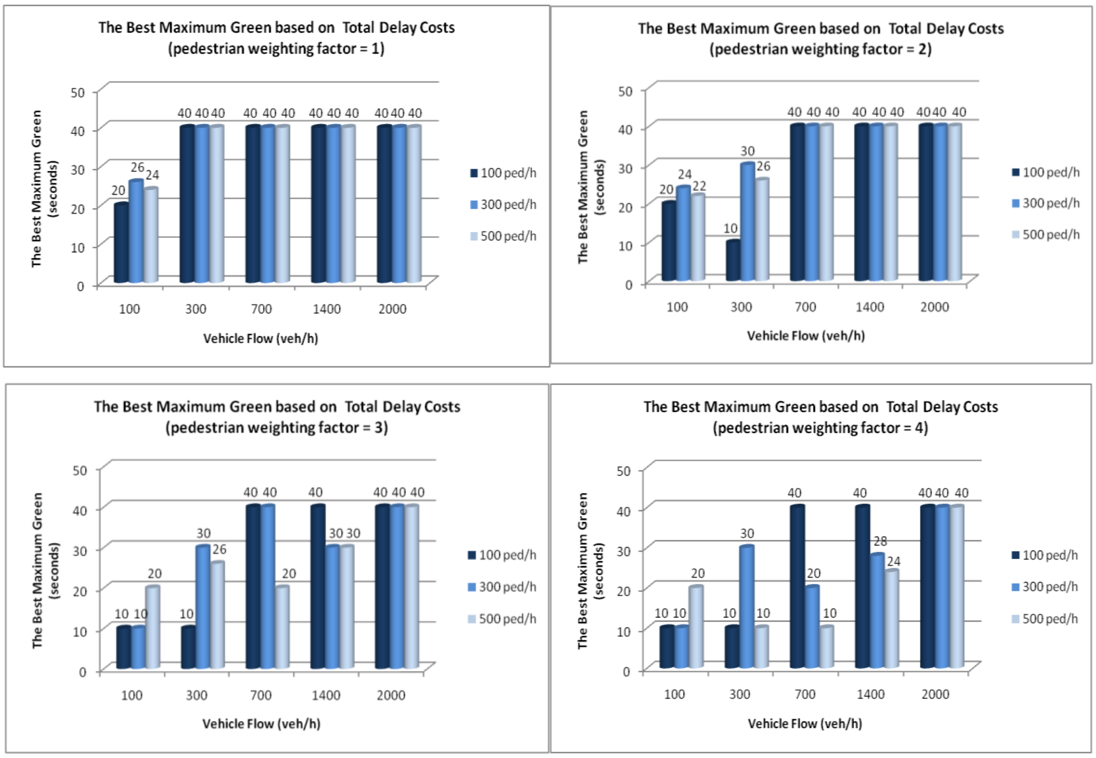


Figure 6.18 The Best Maximum Green from those tested based on Total Delay Costs (for various pedestrian weighting factor: 1, 2, 3, 4)

Figure 6.18 shows the implication of having different weighting factors in the best maximum green setting. When travel times value for both car and pedestrian are equal, the best maximum green setting was 40 seconds for most traffic flow combinations. This 40 seconds maximum green setting favour vehicles due to higher occupancy in vehicle compared to pedestrian. However, at 100 veh/h where the vehicle user is lower than pedestrian flow, the best maximum green setting respectively for 100 ped/h, 300 ped/h and 500 ped/h.

When the pedestrian weighting factor changed to twice and more the car value, the lowest total delay costs was achieved at a lower maximum green setting. When the pedestrian weighting factor is twice the car value, it starts to affect the best maximum green setting at 300 veh/h (where the vehicle user is higher than pedestrian flow). Then, as pedestrian weighting factor valued at three or four times the car value, it affected the best maximum green setting at a much higher vehicle flow (1400 veh/h). In this scenario (1400 veh/h), 40 seconds maximum green was not always the best maximum green setting at all levels of pedestrian flow. At 1400 veh/h, as pedestrian has much higher value compare to car, an increase in pedestrian flow caused a reduction in the best maximum green setting.

6.4 Economic Evaluations

The previous sections have illustrated the importance of the maximum green setting at a Vehicle-Actuated controlled Puffin. The ‘optimum’ value depends on the relative levels of both the vehicle and pedestrian flows – and on the ‘optimisation’ criterion being used (minimum overall delay, minimum overall delay cost, ‘priority’ to pedestrians, etc). However, without a knowledge of pedestrian volumes, a number of Local Authorities are known to set a fixed maximum green according to the range of values given in the DfT Puffin guidelines. The maximum green time is normally be set between 10 seconds and 30 seconds (Department for Transport, 1995b). Typically maximum green more than 30 seconds should be avoided to minimise pedestrian delay (Transportation Research Board, 2000; Department for Transport, 2006a).

The following analyses have therefore been undertaken to illustrate the level of disbenefits which can occur when maximum green is fixed irrespective of traffic and pedestrian volumes. This is termed the 'Base Case' below, in which a maximum green value of 20 seconds has been used in all scenarios.
The comparisons between these two signal control plans: Base Case and Volumetric Detection were made on total person delay and total delay costs. The difference in total person delay and total delay costs between base case (20 seconds maximum green) and volumetric detection (the best maximum green) shows whether there is a benefit or disbenefit as a result of implementing a maximum green dependent on vehicle/pedestrian volumes (termed volumetric detection here). A reduction in either total person delay or total delay costs means there was a benefit from the volumetric detection plan. The evaluations were conducted for fifteen vehicle and pedestrian flow combinations.

6.4.1 Total Person Delay

Equation 6.1 below shows the calculation of total person delay (as described in Chapter 2).

Total person delay = $D_v O_v N_v + D_p N_p$ Equation 6.1

Where subscript v = mode of transport

subscript p = pedestrian

D = average delay per person

O = vehicle occupancy (D x O = average delay per vehicle)

N = number of vehicles/pedestrians completing their journey in the simulation period

The total person delay for fifteen vehicle and pedestrian flow combinations for both base case and volumetric detection strategy are shown in Table 6.6 below.

Table 6.6 Total Person Delay for Twelve Traffic Flow Combinations: Base Case and Volumetric Detection

		Volumetric Detection		Base Case (20 secs)	
Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	MaxGreen (seconds)	Total Person Delay (person seconds/hour)	Total Person Delay (person seconds/hour)	Changes
100	100	28	1267*	1268	-1
	300	24	3227*	3236	-9
	500	22	5182*	5188	-6
300	100	40	1911*	1938	-27
	300	30	4547	4583	-36
	500	26	6974*	7008	-34
700	100	40	3507*	3603	-97
	300		7698*	7911	-213
	500		11239*	11383	-144
1400	100	40	7768*	8336	-568
	300		15920*	17703	-1783
	500		22260*	24753	-2493
2000	100	40	16287*	18454	-2167
	300		34219*	58939	-24720
	500		48842*	104092	-55250

*reduction

As seen in Table 6.6 above, changing the maximum green setting based on the vehicle flow and pedestrian flow conditions brings a reduction in total person delay for all fifteen vehicle and pedestrian flow combinations. Figure 6.19

below shows the percentage changes in total person delay for fifteen vehicle and pedestrian flow combinations after the implementation of the volumetric detection plan and its associated changes in maximum green times.

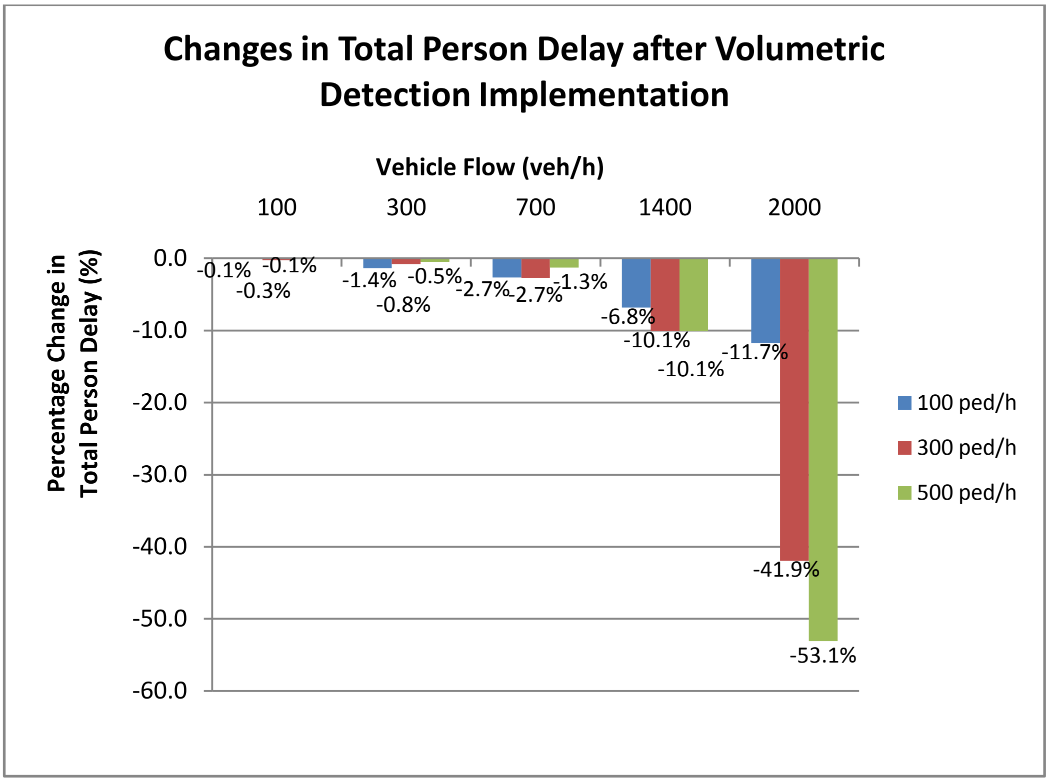


Figure 6.19 The Change in Total Person Delay after Volumetric Detection Plan

It is seen in Figure 6.19 that there is a reduction or saving in total person delay following the volumetric detection plan. The saving ranged between 0.1% and 53.1% for fifteen traffic flow combinations. Implementing volumetric detection with a higher maximum green time has reduced the total person delay by 53.1% at higher traffic flow combinations (2000 veh/h-500 ped/h: total traffic flows on both directions). Higher vehicle flow, 2000 veh/h forms the majority of road users due to higher vehicle occupancies hence the great saving in total person delay at the best maximum green 40 seconds compared to 20 seconds conventional maximum green.

6.4.2 Total Delay Costs

(i) Standard Value of Time

A similar analysis was conducted for total delay costs using the standard values of time per vehicle from the Department for Transport (2011b), shown in Table 6.7 below.

Table 6.7 Values of Time for Various Modes of Transport (Source: Department for Transport, 2011b)

Mode of transport	Values of Times per vehicle (£ per hour per vehicle)
Car	£10.46
Bus	£71.62
HGV	£10.18
Pedestrians	£9.38

The total person delay was converted into economic evaluation using equation 6.2 below.

Total Delay Costs = $D_v O_v N_v V_v + D_p N_p V_p$ Equation 6.2

Where V = values of time per vehicle

$D \times O \times N$ = total person delay

Table 6.8 below shows the total delay costs for volumetric detection and base case scenario for fifteen vehicle flow and pedestrian flow combinations (the traffic flow shown in the table are for both directions). The vehicle flow consists of 95% car, 3% HGV and 2% bus.

Table 6.8 Total Delay Costs for Twelve Traffic Flow Combinations: Base Case and Volumetric Detection

Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	Volumetric Detection: MaxGreen (seconds)	Volumetric Detection: Total Delay Costs (£/hour)	Base Case (20 secs): Total Delay Costs (£/hour)	Base Case (20 secs): Changes
100	100	20	3.48	3.48	0.00
	300	26	8.75*	8.79	-0.04
	500	24	13.94*	13.98	-0.03
300	100	40	5.5*	5.6	-0.1
	300	30	12.9*	13.0	-0.1
	500	26	19.5*	19.7	-0.2
700	100	40	10.6*	10.9	-0.3
	300		22.7*	23.5	-1
	500		32.6*	33.3	-1
1400	100	40	24.0*	26.0	-2
	300		48.1*	54.7	-7
	500		66.1*	75.5	-9
2000	100	40	51.3*	58.6	-7
	300		106.5*	188.1	-82
	500		150.5*	332.5	-182

*reduction

The implementation of volumetric detection caused a reduction in total delay costs at all vehicle and pedestrian flow combinations. Figure 6.20 below shows the percentage changes in total person costs after the implementation of volumetric detection strategy.

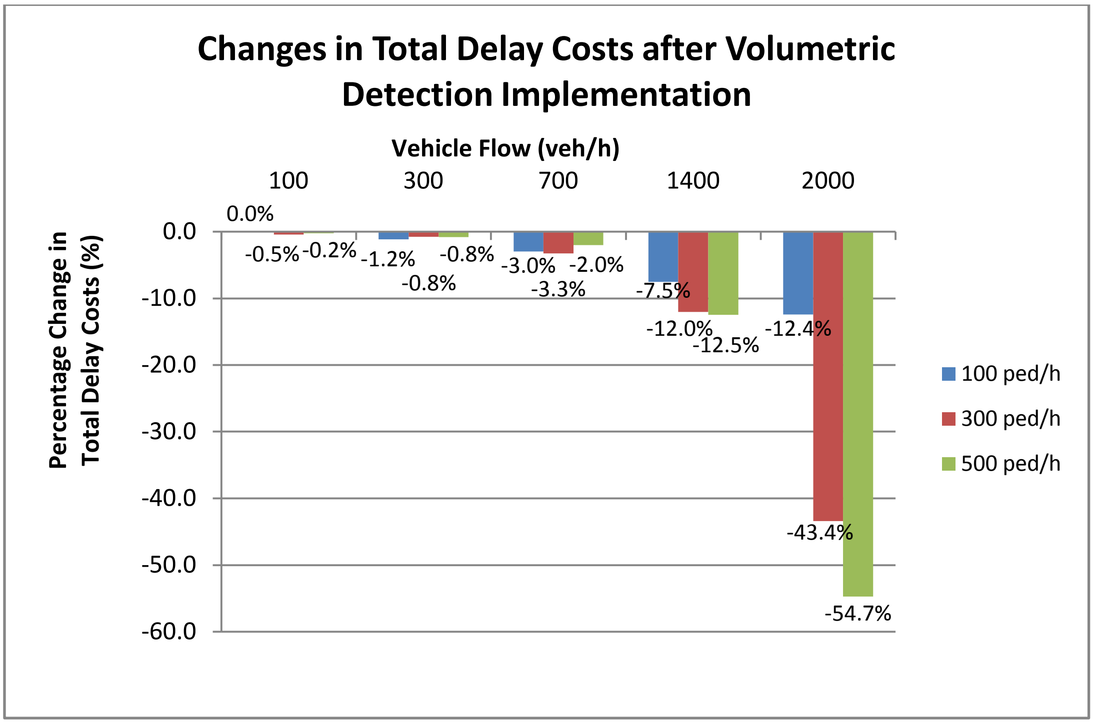


Figure 6.20 The Changes in Total Delay Cost after Volumetric Detection Plan

Figure 6.20 above shows that, from an economic perspective, volumetric detection brings benefit for all fifteen traffic flow combinations. The reduction in total delay costs ranged from 0.2% to 54.7% following the implementation of volumetric detection. Significant saving in delay costs occurred at a higher traffic flow combinations (2000 veh/h – 500 ped/h: traffic flows on both directions) at the best maximum green setting, 40 seconds.

(ii) Relative Value of Time

Then, adjusting the weightings applied to pedestrian and vehicle travel time savings would provide an understanding of the strategic importance to be attached to pedestrians if the improvements were to be supported. Therefore, the total delay costs were calculated by assigning different weighting factors to vehicle and pedestrian. Table 6.9 below shows the weighting factor from previous studies.

Table 6.9 Relative Values of time for various modes

Mode	Values of time per person
Car	1.0
HGV (Fowkes, 2001)	4.0
Bus (Haight, 1994)	0.5
Pedestrian (Mackie et al., 2003b; Wardman, 2004; Bhattacharya and Virkler, 2005; Ishaque, 2006)	0 to 4

The value of time used for evaluation purpose is an equity value, which is £4.46 per hour person, 2002 prices and values (Department for Transport, 2011b). The user cost computed by assigning different weighting factors to pedestrian and vehicles as shown in Equation 6.3 below (Bhattacharya and Virkler, 2005). See Chapter 2 for further details.

Total Delay Costs = $D_v O_v N_v T_v W_v + D_p N_p T_p W_p$ Equation 6.3

Where subscript *v* = vehicles

subscript *p* = pedestrian

D = average delay time per person

O = vehicle occupancy (*D* x *O* = average delay per vehicle)

N = number of vehicles or pedestrians completing their journey in the simulation period

D x *O* x *N* = total person delay

T = values of time, £4.46 per hour per person

W = weighting factors (shown in Table 6.9)

Table 6.10 below shows the total delay costs for volumetric detection and base case plan at the simulated road crossing with pedestrian weighting factor varies from 1 to 4.

Table 6.10 Total Delay Costs for various pedestrian weighting factor

		Pedestrian Weighting Factor = 1			
		Volumetric Detection		Base Case (20 secs)	
Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	MaxGreen (seconds)	Total Delay Costs (£/hour)	Total Delay Costs (£/hour)	Changes
100	100	20	1.83	1.83	0.00
	300	26	4.50	4.53	-0.03
	500	24	7.06	7.10	-0.04
300	100	40	3.16	3.22	-0.06
	300		7.16	7.28	-0.12
	500		10.59	10.71	-0.12
700	100	40	6.44	6.69	-0.25
	300		13.43	14.05	-0.62
	500		18.80	19.37	-0.57
1400	100	40	15.17	16.61	-1.44
	300		29.41	34.39	-4.98
	500		39.35	46.77	-7.42
2000	100	40	33.12	38.17	-5.05
	300		67.63	123.29	-55.66
	500		94.32	218.24	-123.92

		Pedestrian Weighting Factor = 2			
		Volumetric Detection		Base Case (20 secs)	
Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	MaxGreen (seconds)	Total Delay Costs (£/hour)	Total Delay Costs (£/hour)	Changes
100	100	20	3.05	3.05	0.00
	300	24	7.83	7.84	-0.01
	500	22	12.62	12.63	-0.01
300	100	10	4.45	4.53	-0.08
	300	30	10.75	10.82	-0.07
	500	26	16.62	16.69	-0.07
700	100	40	7.99	8.18	-0.19
	300		17.78	18.18	-0.40
	500		26.22	26.45	-0.23
1400	100	40	17.40	18.56	-1.16
	300		36.22	39.71	-3.49
	500		51.23	55.97	-4.74
2000	100	40	36.04	40.62	-4.58
	300		76.37	221.61	-145.24
	500		109.75	287.69	-177.94

		Pedestrian Weighting Factor = 3			
		Volumetric Detection		Base Case (20 secs)	
Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	MaxGreen (seconds)	Total Delay Costs (£/hour)	Total Delay Costs (£/hour)	Changes
100	100	10	4.27	4.27	0.00
	300	10	11.15	11.16	-0.01
	500	20	18.17	18.17	0.00
300	100	10	5.68	5.83	-0.15
	300	30	14.32	14.37	-0.05
	500	26	22.60	22.67	-0.07
700	100	40	9.54	9.68	-0.14
	300	40	22.13	22.31	-0.18
	500	20	33.52	33.52	0.00
1400	100	40	19.63	20.51	-0.88
	300	30	42.93	45.04	-2.11
	500	30	62.23	65.17	-2.94
2000	100	40	38.96	43.06	-4.10
	300		85.12	135.27	-50.15
	500		125.18	238.07	-112.89

		Pedestrian Weighting Factor = 4			
		Volumetric Detection		Base Case (20 secs)	
Vehicle Flow (veh/h)	Pedestrian Flow (ped/h)	MaxGreen (seconds)	Total Delay Costs (£/hour)	Total Delay Costs (£/hour)	Changes
100	100	10	5.49	5.49	0.00
	300	10	14.44	14.47	-0.03
	500	20	23.71	23.71	0.00
300	100	10	6.90	7.14	-0.24
	300	30	17.88	17.92	-0.04
	500	26	28.48	28.64	-0.16
700	100	40	11.10	11.17	-0.07
	300	20	26.44	26.44	0.00
	500	10	40.06	40.60	-0.54
1400	100	40	21.85	22.45	-0.60
	300	28	49.03	50.36	-1.33
	500	24	72.83	74.37	-1.54
2000	100	40	41.88	45.51	-3.63
	300		93.86	141.26	-47.40
	500		140.61	247.98	-107.37

As can be seen in Table 6.10, when the pedestrian weighting factor increases, the total delay costs favour the Volumetric Detection strategy at a higher vehicle flow (where the people in vehicle are more than pedestrian flows). This trend can be seen in Figure 6.21 below.

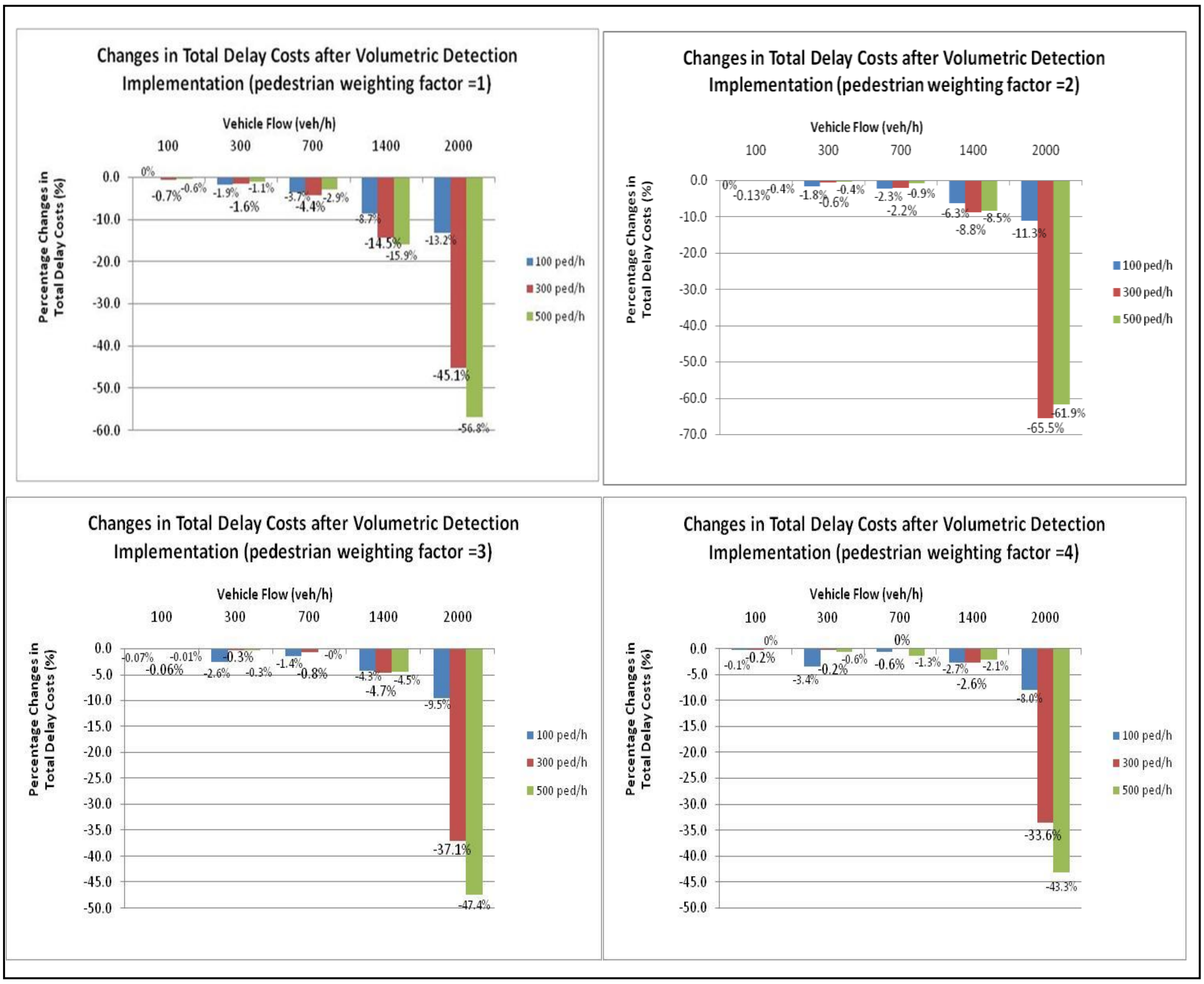


Figure 6.21 Changes in Total Delay Costs after Upstream Detection implementation for various pedestrian weighting factor

Figure 6.21 shows the implications of having different pedestrian weighting factors in Volumetric Detection strategy. The implementation of Volumetric Detection caused a reduction in total delay costs to road users at all traffic flow combinations especially at a higher vehicle flow (2000 veh/h). There is a clear benefit of implementing Volumetric Detection regardless of the pedestrian weighting factors.

6.5 Summary

Various maximum green settings under different traffic flow combinations were simulated and analysed in VISSIM microsimulation model. The lowest total person delay and total delay costs were the determinant of the best maximum green settings from those tested. Vehicle occupancies and monetary values of various modes of transport including pedestrians are derived from Department of Transport (2011).

As maximum green increased for fifteen traffic flow combinations, vehicles received longer average green time hence less changes in signal cycles. This caused a reduction in the average vehicle delay and in the meantime it caused an increase in average pedestrian delay. Even though the volumetric detection plan caused an increase in average pedestrian delay (Figure 6.8 and Figure 6.9), overall, volumetric detection caused saving in total person delay and costs compared to the base case (Table 6.6, Table 6.8 and Table 6.10). The savings were greater at a higher traffic flow combinations (2000 veh/h – 500 ped/h).

The decision to set the maximum green time depends on the transport policy whether it was based on minimum total person delay or minimum total delay costs. Furthermore the minimum delay for vehicles or pedestrians as in Figure 6.7, Figure 6.8 and Figure 6.9 may not yield the minimum user costs to the road network as shown in Figure 6.13, Figure 6.17 and Figure 6.18, confirming that the optimal signal control plan should balance delays to the motorised and non-motorised mode of transport. The results in Figure 6.13, Figure 6.17 and Figure 6.19 show that at higher vehicle flow 2000 veh/h, the higher maximum green setting imposed the best benefit to the road users on the road network. This was unsurprising as vehicles formed the majority of road users due to its level of vehicle occupancy. The best maximum green setting minimised both the total delay time and costs to all road users. The effect of Volumetric Detection is summarised in Table 6.11 below.

Table 6.11 Potential Effects of Volumetric Detection

Pedestrian flow / Vehicle Flow	100 peds/hr	300 peds/hr	500 peds/hr
100 vehs/hr	√	√	√
300 vehs/hr	√	√	√
700 vehs/hr	√	√	√
1400 vehs/hr	√√	√√	√√
2000 vehs/hr	√√	√√	√√

Key:

√ : possible benefit

√√ : probable benefit

x : possible disbenefit

xx : probable disbenefit

It should be noted here that these results mainly illustrate the importance of reflecting actual vehicle **and** pedestrian volumes when setting maximum green time values. The scale of the disbenefits in not doing so suggests that further research and development into pedestrian volumetric detection should be very worthwhile.

7 Conclusions and Future Work

7.1 Conclusions

This research has taken the Puffin crossing as the 'state-of-the-art' signal controlled crossing for pedestrians and has explored possible improved control strategies through the development and application of a Puffin simulation model, using VISSIM. In particular, two new strategies - Upstream pedestrian detection and volumetric pedestrian detection have been evaluated using VISSIM. The conclusions of the study are now presented with respect to the objectives as listed in Chapter 1.

(i) Objective 1: *To identify and understand the current facilities available in the UK for pedestrians crossings*.

There are two main types of pedestrian signalised crossings in Britain: Pelican crossings and Puffin crossings. Pelican crossings do not have any pedestrian detection technologies except for the push buttons. Flashing amber is displayed to vehicles during the clearance period to allow drivers to proceed if the crossing is clear from pedestrians.

On the other hand, Puffin crossings have three different aspects of pedestrian detection - the push button, kerbside detection and on-crossing detection. Kerbside detections and on-crossing detections employ several detection technologies, mainly microwave detection or infrared detectors to sense pedestrian presence. Puffin crossings are recommended by the Department for Transport for new signal controlled pedestrian facilities in the UK. Given this, and the opportunities provided by the new Puffin detection facilities for new control strategies, this research has focussed on the Puffin crossing as the 'base case'.

(ii) Objective 2: *To examine and develop potential new detection and control strategies for improving pedestrian facilities at signalised crossings*.

Upstream pedestrian Detection and Volumetric pedestrian Detection were identified as potential enhancements at Puffin crossings.. The idea of this strategy was to give an earlier detection of pedestrians (i.e. upstream of the crossing) as happens with vehicle detection. With this method, the pedestrian phase can be initiated as early as possible upon receiving the demand from upstream detection. Upstream Detection was modelled in the VISSIM microsimulation model by locating additional push button detection further upstream from the crossing and using enhanced pedestrian behaviour logic.

Volumetric pedestrian Detection was explored by analysing how maximum vehicle green settings in Puffin controller should ideally be varied according to vehicle **and** pedestrian volumes – making a reasonable assumption that technological advances will enable pedestrian volumes to be measured in the near future. Best Maximum Green settings were determined from VISSIM modelling based on both the lowest total person delay and total delay costs on the road network.

(iii) Objective 3: *To develop the required analytical/modelling approaches to enable the new detection and control strategies to be evaluated.*

Microsimulation models provide a real representation of individual traffic on a simulated road network. A critical appraisal carried out in this research indicated that the VISSIM microsimulation model had the modelling capabilities required for this study, particularly having the most advanced facilities for pedestrian behaviour modelling at the time various models were being critically reviewed. VISSIM was therefore selected and new logic written within it to enable specific modelling of a Puffin crossing. The VISSIM model was calibrated and validated based on real Puffin crossing data to ensure the model represented the real situation.

(iv) Objective 4: *To explore the impacts of the new strategies on pedestrians and all other road users in a range of scenarios*.

Three signal control plans were successfully modelled in VISSIM microsimulation model – current operations (the Base Case), Upstream pedestrian detection and Volumetric pedestrian detection, where vehicle maximum green was related to the levels of vehicle and pedestrian flows.. The impact of implementing Upstream Detection and Volumetric Detection was examined by two key measures of effectiveness - vehicle delay and pedestrian delay, which were then combined to indicate total person delay (all road users) and total delay cost.

In conclusion, the Upstream Detection strategy had a positive impact compared to the Base Case strategy, but only in specific combinations of vehicle and pedestrian flows. Simulation results showed that the Upstream Detection strategy reduced pedestrian delay, but at the expense of increased vehicle delay. This occurred because of the increased numbers of pedestrian calls resulting from the two push button locations. Overall, Upstream Detection reduced the total person delay to all road users at a lower vehicle flows, 100 veh/h and 300 veh/h. At higher vehicle flows, Upstream Detection almost always resulted in a reduction in higher total delay costs (vehicles and pedestrians). However, this result has a degree of uncertainty in that a pedestrian behaviour logic has had to be assumed which cannot yet be validated (because the strategy does not exist). Also, if policy favours pedestrians over vehicles more than assumed here, then the upstream detection strategy would become beneficial over a wider range of vehicle flows.

The 'volumetric detection' highlighted the importance of considering both vehicle **and** pedestrian flows when setting maximum vehicle. The economic assessment showed that the Volumetric Detection brought about savings in total person delay and total delay costs at all vehicle and pedestrian flow combinations – although in some cases of higher maximum green times vehicle delays reduced at the expense of higher pedestrian delays, which might be considered undesirable.,. This was relative to an assumed 'base case' with a fixed maximum green time of 20 secs. It is only likely to be in cases where the number of pedestrians exceed the number of vehicle occupants significantly, that Volumetric Detection would be helpful in reducing overall delay **and** delay to pedestrians.

Whilst the base case may not be entirely realistic, the results still show the importance of developing pedestrian volumetric detection and acting on the data this would give.

(v) Objective 5: *To develop recommendations*.

Results from this research have opened up new paths for further work, with a wide range of opportunities including further application or even further development of the model. This is explained in the next section.

7.2 Recommendations for Future research and development

Limitations of resources and time have caused some constraint in the scope of this research. With this in mind, the following recommendations are made for further research and development:

1. To develop a trial of upstream pedestrian detection at a site where benefits would be expected (e.g. where vehicle flows are low). This would illustrate its potential in a real environment and provide useful pedestrian behaviour data to improve the existing behaviour logic in models.

2. To develop an above-ground volumetric detector for pedestrians and to test it in trials, potentially of the 'variable maximum green' strategy suggested here, in the first instance.

3. To extend the research into volumetric detection (particularly) to study how a knowledge of pedestrian volumes could lead to an improved control strategy rather than just a modification of the existing strategy as researched here.

4. To consider a 'pedestrian priority' strategy (similar to 'bus priority') such as pedestrian green extension up to the pedestrian maximum green as long as there is confirmed demand of pedestrians on the kerbside

5. To expand the research to consider pedestrian facilities at signalised junctions, as well as signalised stand-alone crossings, including the range of control strategies used in practice in addition to vehicle actuation.

Appendices

Appendix A Puffin Logic

```
PROGRAM puffin;

/* CONSTANT */
  MaxGreen1:=30;
  MaxGreen3:=18;

/* ARRAYS */

/* SUBROUTINES */

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */

/* EXPRESSIONS */
Veh11 := Detection(11) > 0;
Veh12 := Detection(12) > 0;
Ped21 := Detection(21) > 0; /* push button detection */
Ped22 := Detection(22) > 0; /* push button detection */
        /*Ped31 := Detection(31) > 0;*/ /* upstream detection */
        /*Ped32 := Detection(32) > 0;*/ /* upstream detection */
Ped24 := Occupancy(24) > 2; /* kerbside detection */
Ped25 := Occupancy(25) > 2; /* kerbside detection */
Ped27 := Detection(27) > 0; /* on-crossing detection */
Ped28 := Detection(28) > 0; /* on-crossing detection */
        Min_Green_Stage1 := T_green(1) >= T_green_min(1); /* Period 1 */
        Min_Green_Stage2 := T_green(2) >= T_green_min(2); /* Period 4 */
        Min_Green_Stage3 := T_green(3) >= T_green_min(3); /* Period 5 and
Period 6*/
/* MAIN PROGRAM */

IF Stage_active(1) THEN
 IF Ped21 or Ped22 THEN
  PedDemand:=1;
```

```
  End;
  IF Veh11 or Veh12 THEN
      green2:=T_green(1)+1; /*VISSIM uses 1 second less than actual so needed
to be added*/
      green1:=green2+4;
  End;


PedDemand :=PedDemand=1;
MaxLengthStage1 := T_green(1) >= MaxGreen1;
GapOut :=T_green(1) >= green1;

  IF PedDemand THEN
   IF Ped24 or Ped25 THEN
     IF Min_Green_Stage1 THEN
      IF MaxLengthStage1 or GapOut THEN
Interstage(1,2);
      End;
     End;
    End;
  End;
End;


IF Stage_active(2) THEN
PedDemand:=0;
GapOut:=0;
  green2:=0;
  green1:=T_green_min(1);
  IF Min_Green_Stage2 THEN
Interstage (2,3);
  END;
End;
```

```
MaxLengthStage3 := T_green(3) >= MaxGreen3;

IF Stage_active(3) THEN
  IF Min_Green_Stage3 THEN
    IF (not Ped27 and not Ped28) or MaxLengthStage3 THEN
Interstage(3,1);
    END;
  END;
END
PROG_ENDE: .
/*-----------------------------------------------------------------*/
```

Glossary

1. Signal aspect
   The indication given by a signal in a signal head such as red, red/amber (standardised at 2 s), green and amber (standardised at 3s) (Salter and Hounsell, 1996; Department for Transport, 2006b; Department for Transport, 2006c).

2. Amber period (A)

   This is part of the transition from ‘green’ to ‘red’, in which amber indication is shown to traffic. It is timed to allow a vehicle that cannot safely stop on the green signal termination to enter the intersection legally (Roess et al., 2004).

3. All Red period (*ar*)

   This is part of the transition from ‘green’ to ‘red’ for a given set of movements. During the All Red period, all movements are shown red signal indication to allow a vehicle that legally enters the intersection on amber to safely cross the intersection before conflicting flows are released (Roess et al., 2004).

4. Actual green time

   Actual green time also known as display green time, which is the period between the commencement of green indication to the commencement of amber indication (Salter and Hounsell, 1996).During a green interval, the movements permitted have a ‘green’ light, while all other movements have a ‘red’ light.

5. Red period (*R*)

Movements not permitted to move have a red signal indication during the signal cycle. In general, the red interval overlaps the green intervals for all other movements in the intersection (Roess et al., 2004).

6. Effective green time

Effective green time is the amount of time that vehicles are moving (at a rate of one vehicle every *h* seconds) (Roess et al., 2004).

7. Minimum green time

According to Department of Transport(2006c), the minimum green is fixed, starting at the commencement of the green signal and not affected by demands. The shortest minimum green time is 7s but can be greater depending on site condition (Department for Transport, 2006c).

8. Intergreen period

The period between the end of green indication on one phase and commencement of green on the next phase (Salter and Hounsell, 1996). It provides a convenient time for right-turning vehicles to proceed after waiting in the centre of intersection.

9. Cycle

A signal cycle is the total time to complete one sequence of signal indications around an intersection (Homburger et al., 1996; Department for Transport, 2006c).

10. Phase

A set of movements which can take place simultaneously or the sequence of signal indications received by such a set of (Salter and Hounsell, 1996).

11. Stage

Part of the cycle during which a particular set of phases receive green and is defined by numbers (Salter and Hounsell, 1996).

12. Interstage period

The period between the end of one stage and the start of the next stage (Department for Transport, 2006c)

13. Capacity

When referring to a highway link or junction, capacity is defined as the maximum numbers of vehicle or passenger car units (PCU) that can be carried or accommodated in a highway link or junction (Slinn et al., 2005).

14. Saturation flow (*S*)

Saturation flow is the maximum flow, expressed in vehicle per hour (veh/h) or equivalent passenger car unit per hour (pcu/h), that can be discharged from a traffic lane when there is a continuous green indication and a continuous queue on the approach (Salter and Hounsell, 1996). It is also known as discharge rate.

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