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FACULTY OF ENGINEERING AND THE ENVIRONMENT

Transportation Research Group

Exploring New Bus Priority Strategies at Isolated Vehicle Actuated Junctions

by

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ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Doctor of Philosophy

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Bus priority in various forms has become an important application in towns and cities around the world, as Local Authorities seek to improve the efficiency and sustainability of their transport systems by promoting the use of public transport with its high passenger carrying capability. Segregating buses from general traffic, using busways, bus lanes, etc is increasingly being supplemented with priority at traffic signals, where signal timings respond to the approach of a bus to give it priority signalling through the junction. This was first trialled in UK on a significant scale in the 1980's in an area of south east London containing isolated traffic signals operating under the UK's 'D-system' of Vehicle Actuation (VA). There followed a period of some 20 years where equivalent priority strategies were developed, tested and implemented in the more difficult environment of Urban Traffic Control. These strategies have kept pace with the significant advances in technologies over this period, such as in detection, communications, processing and optimisation. However, this has not been the case with bus priority at isolated VA junctions, where strategies developed in London some 30 years ago still prevail – and even in large cities a significant number of signal controlled junctions operate in this way. This then suggested a research gap which has been taken up in this research – the exploration and development of new strategies for bus priority at isolated VA junctions.

Taking existing strategies as the 'base case', their effectiveness was first explored through theoretical and mathematical analysis. This led to the first new output from this research – more comprehensive predictive equations for bus priority benefits (delay savings) than existed, covering a range of operational conditions. The limitations of the mathematical approach were identified, so research then progressed to the development of microscopic simulation modelling (VISSIM) for junction modelling and for exploring new strategies. This involved four variants of junction design and scenarios reflecting differences in levels of congestion, bus flows, signal timings, etc. New and improved strategies were then developed through modelling, including (i) re-optimising parameter values for the existing priority methods, (ii) improved bus detector locations taking advantage of new Automatic Vehicle Location technologies and (iii) new strategies for bus priority, including a 'stronger' strategy termed 'always green bus' and 'differential priority', where the level of priority given to a bus depended on its performance (eg regularity) at that time. Strategies were also developed to minimise the impacts on general traffic through various forms of compensation, with total person delay then being used as an evaluation criterion.

The research has concluded with a series of recommendations for improved implementation of bus priority at isolated VA controlled junctions, taking advantage of the new technologies which are widely available and used within most bus fleets in the UK.

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List of other Publications

Ahmed, B. et al (2015) *Investigating bus priority parameters for isolated vehicle actuated junctions*, UTSG Annual Conference, London, January 2015.

Ahmed, B. (2014) *Exploring new bus priority methods at isolated vehicle actuated junctions*, Transportation Research Procedia, Vol. 4 (2014), pp. 391-406.

Ahmed, B. (2014) *Exploring new bus priority methods at isolated vehicle actuated junctions*, International Scientific Conference on Mobility and Transport, Sustainable Mobility in Metropolitan Regions, TUM, Germany.

Ahmed, B. (2013) *Exploring new strategies for differential bus priority at traffic signals to improve regularity*, UTSG Annual Conference, Oxford, January 2013.

Ahmed, B. (2012) *Modelling differential bus priority at traffic signals: potential and challenges*, UTSG Annual Conference, Aberdeen, January 2012.

DECLARATION OF AUTHORSHIP

I, Bashir Ahmed, declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

Exploring New Bus Priority Strategies at Isolated Vehicle Actuated Junctions

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. 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;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
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   [Ahmed, B. et al (2016) Investigating bus priority parameters for isolated vehicle actuated junctions, Transportation Planning and Technology, Vol. 39, No. 1, pp. 45-58.

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Signed: ....

Date: ....

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Definitions and Abbreviations

Abbreviations

AGB	Always Green Bus
AIMSUN	Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks
API	Application Programming Interface
AVL	Automatic Vehicle Location
BJYT	Bus Journey Time
DETR	Department of the Environment, Transport and the Regions
DfT	Department for Transport
DTO	Directorate of Traffic Operations
ERed	Effective Red
Ex	Extension
Ex&Re	Extension & Recall
GPRS	General Packet Radio Service
GPS	Global Positioning System
HGV	Heavy Goods Vehicle
iBus	London's new AVL system for detecting/locating buses
IHT	Institution of Highways and Transportation
MaxR	Priority Maximum Red
MGV	Medium Goods Vehicle
MOVA	Microprocessor Optimised Vehicle Actuation
PARAMICS	PARAllel MICroscopic Simulation
PC	Protected Compensation
PTV	Planung Transport Verkehr (PTV) AG
PVE	Priority Extension Time
PVI	Priority Inhibit Time
PVM	Priority Maximum Time
PVMin	Priority Minimum Time
SCOOT	Split Cycle Offset Optimisation Technique
SIMBOL	Simulation Model for Bus Priority at Traffic Signal
SPRINT	Selective PRIority Network Technique
SVD	Selective Vehicle Detection

TfL	Transport for London
TRL	Transport Research Laboratory Ltd.
TRG	Transport Research Group (University of Southampton)
UTC	Urban Traffic Control
VA	Vehicle Actuated
VAP	Vehicle Actuated Programming (used in VISSIM)
VISSIM	Verkehr In Städten – SIMulation (meaning: Traffic In Towns – SIMulation)
VisVAP	Vehicle Actuated Programming Tool (used in VISSIM)

Definitions

Acceleration Delay

The time needed by a stationary or slow vehicle to accelerate to drive at the desired speed is the acceleration delay.

Always Green Bus

Always Green Bus is a new method developed in this research which ensures a green signal for priority buses before arrival at the signal stop line.

Compensation

Compensation is the method of repaying the time lost to non-priority stages due to bus priority. After bus priority, the non-priority stages which are shortened or omitted during the priority call are given extra green in addition to their normal maximum green.

Deceleration Delay

This is the delay when a vehicle has to decelerate to slow down or stop due to red signal.

Differential Priority

Differential priority is the strategy where different levels of priority are awarded to buses at traffic signals according to their adherence to schedule/frequency.

Effective Green

The effective green is the duration within the signal green of the priority approach when detected buses require an extension. This green period is also called ‘extension time’.

Effective Red

The effective red is the duration within the total signal red of the priority approach when detected buses require a recall. This red period is also called ‘recall time’.

Exit Detector

An Exit detector is a bus detector located just after the signal stop line along the priority bus route to cancel priority green when the priority bus has crossed the stop line.

Extension

A green extension is the extension of the green phase of the bus route upon detection of a bus before the normal green period ends.

Inhibit

The method which prevents bus priority calls in consecutive signal cycles, is called inhibit.

Priority Compensation Time

This is the amount of extra green required to repay non-priority stages after the time lost due to a previous bus priority.

Priority Conflict

Priority conflict is the situation when buses arrive at different arms of a junction during same signal stage and priority to one arm’s buses will restrict allocation of priority to other arms at the same time.

Priority Detector Distance

This is the distance between the signal stop line and priority detector location’ which is sited upstream of the signal stop line.

Priority Extension Time

Priority extension time is the length of time a signal controller holds the priority phase at right of way when a priority bus is detected.

Priority Inhibit Time

Priority inhibit time is the period during which a bus priority call is not allowed.

Priority Maximum Time

Priority maximum time is the allowable maximum green extension in response to a bus priority request.

Priority Minimum Time

Priority minimum time is the required minimum duration to hold the green for a priority bus to allow it to cross the signal stop line when signal at the priority approach turns to green due to a recall.

Protected Compensation

Protected compensation ensures that no further bus priority can be granted until non-priority stages have been fully compensated following a priority action.

Queue Clearance Delay

It is the additional delay due to stationary vehicles in front of a priority bus waiting in the signal queue.

Queue Clearance Rate

Queue clearance rate is the average time required by each vehicle of a red signal queue to cross the stop line.

Queue Clearance Time

Queue clearance time is the time required by the last vehicle of a red signal queue to cross the stop line, typically measured from just before the signal changes to green from red.

Queue Occupancy

Queue occupancy is the average number of vehicles that can queue up in a certain distance from the stop line during the red signal.

Recall

A recall is allocating the green phase of the bus route as soon as possible upon detection of a bus during the red signal.

Stand Still Distance

The average headway of the queuing vehicles during red signal is called stand still distance.

Chapter 1: Introduction

1.1 Background

Buses are the main form of public transport in most towns and cities in many countries, including the U.K (Hounsell and McLeod 1999). With their large carrying capacity, buses make effective use of limited road space, and can therefore make a substantial contribution to reducing traffic congestion (Cheney 1992). However, buses themselves are often affected by congestion, leading to a decrease in speed and an increase in bus travel time variability and service irregularity. Providing priority to buses plays an important role to protect bus services from the effects of traffic congestion and to improve route frequencies, speeds and reliability (IHT 1997), thus improving levels of service for bus passengers and encouraging modal change (Polyviou 2010). It can be regarded that bus priority measures have a major role in supporting balanced and integrated transport strategies seeking to improve the quality of public transport (Yu 2008). 'Keeping buses moving' (DETR 1997) details a number of bus priority measures that can be considered to assist buses. These measures vary in scale and impact from a simple exemption from a manoeuvre prohibited to other traffic, to area-wide measures such as priority in traffic control systems (IHT 1987).

Among these methods, bus priority at traffic signals is the most relevant where opportunities for segregated systems are not available and/or where numerous traffic signals exist. To provide bus priority at signalised junctions buses are detected on priority approaches some distance from the stop line. Depending on the signal status at the time of detection, normal signal timings are overridden by the implemented priority methods. These methods alter signal timings in favour of approaching buses. In usual practice this is achieved by either extending the green period for an approaching bus or recalling the green stage, if the signals are currently red for the bus. After bus priority, the signal runs according to its normal timings. These forms of bus priority have been implemented in many cities in USA, UK, Japan, France, Denmark, Sweden, Switzerland, Finland, Germany, Australia, Austria, Italy, New Zealand (Gardner et al. 2009).

Bus priority at isolated Vehicle Actuated (VA) junctions started in London in the 1970's, but the first major evaluation trial occurred in the SELKENT area of London in 1987-88

(University of Southampton 1988). The success of the trial led to the expansion of bus priority to a further 300 VA controlled junctions in the outer areas of London. At most of the junctions the priority detectors were sited some 60m-80m upstream of the stop-line (University of Southampton 1988) from the consideration of bus journey time variability. At present, bus priority is installed (TRG 2011) at 509 pedestrian signals and 1389 signalised junctions (844 junctions operated within the SCOOT Urban Traffic Control (UTC) system and 545 VA junctions) in London.

Achievable benefits to buses and negative impacts to general traffics by bus priority largely dependent on implemented priority methods, priority parameters considered, policy objectives, junction types, and network characteristics. In this research existing bus priority methods and parameters for isolated VA junctions have been considered for improvement and new essential parameters included to improve the performance of bus priority methods. New advanced bus priority methods beneficial for buses as well as for general traffic have been explored.

1.2 Aim and Objectives

The main aim of this research has been to develop improved methods of providing bus priority at isolated traffic signals operating under vehicle actuated (VA) control, as practised in the UK.

The detailed objectives are as follows:

1. To critically review how bus priority operates at traffic signals in the UK and around the world
2. To identify the requirements for new research into bus priority at traffic signals and select one or more scenario for in-depth research
3. To develop potential improvements to current bus priority operations for the chosen scenario(s), taking advantage of new technologies and good practice from other systems around the world.
4. To evaluate and compare the performance of existing and improved bus priority methods and parameters, using both field data and simulation modelling
5. To develop recommendations for practitioners installing and operating bus priority within the scope of scenarios addressed within this research.

1.3 Methodology

During the early stages of this research a detailed review of the literature was carried out focusing on design and optimisation of bus priority at isolated junctions. The review covered existing bus priority methods and traditional priority parameters to identify research gaps for potential improvement in the context of the iBus priority architecture and isolated VA signal controller. A new improved theoretical procedure was developed for the prediction of bus priority benefits and dis benefits. The results derived from the theoretical procedure were used as a guideline to understand achievable performance by the priority methods and also to validate simulation models' outputs. The microscopic simulation tool VISSIM 5.40 was then used to develop realistic micro- simulation models. Both the theoretical analysis and simulation models were been developed using field data and site observations. Three types of junctions: a cross junction, a T-junction, and a pedestrian crossing were then selected for models developments and data collection considering peak and inter peak hours. This enabled the performance of existing and newly developed bus priority methods to be evaluated, compared, and interpreted considering delay savings to buses and impacts on general traffic. This study also includes a general discussion covering practical issues and knowledge gained from field observations, modelling exercises, assumptions and limitations, field characteristics and their impact on the performance of the priority methods. Finally conclusions include recommendations and the scope of future studies. The research methodology is illustrated by the flowchart in Figure 1.1 below.

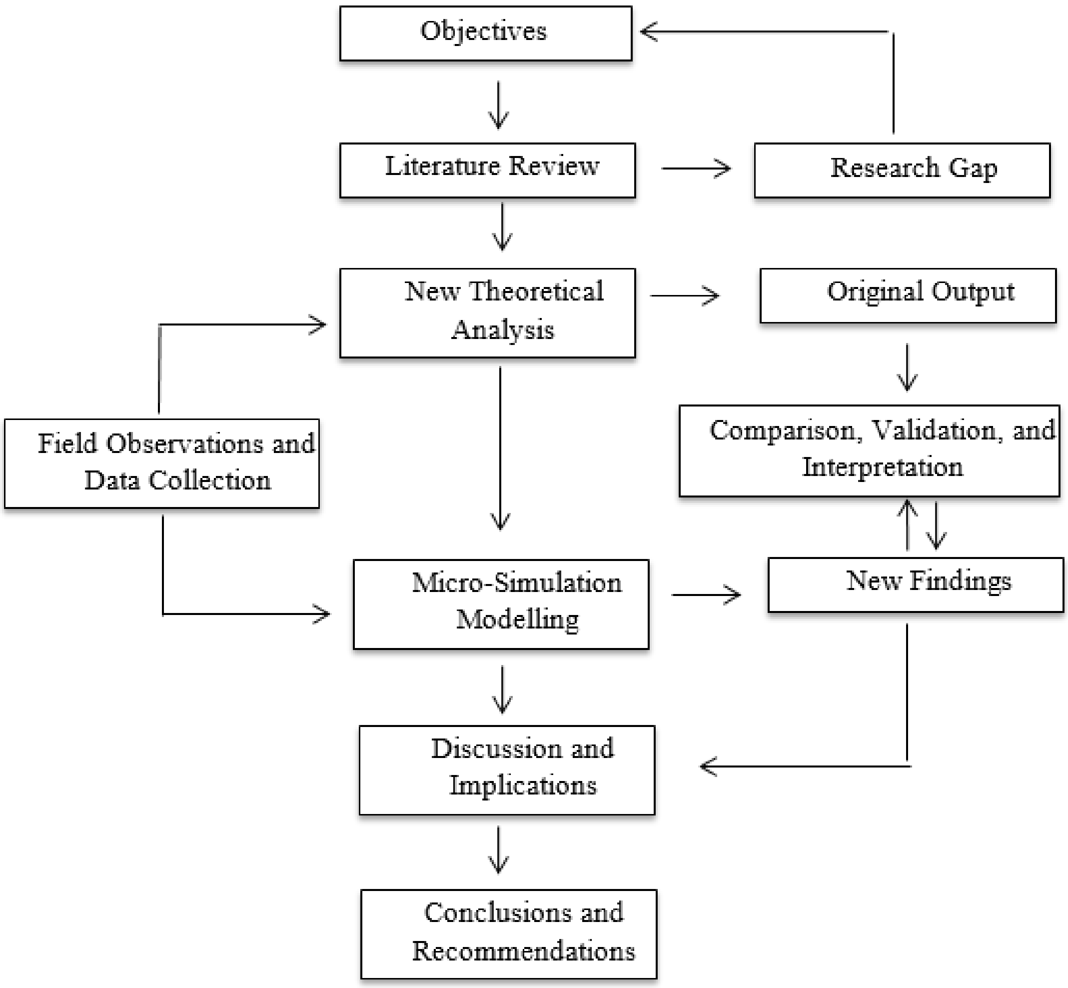


Figure 1.1: Research methodology flowchart

Chapter 2: Bus Priority at Traffic Signals

2.1 Introduction

Before implementing bus priority at signalised junctions, the appropriate bus priority type and bus detection method needs to be chosen carefully. Options available for siting the detectors and types of detection also need to be understood because these parameters control the efficiency of the bus priority system. Bus priority methods also need to be selected according to policy objectives, public transport organisational issues and types of traffic signal controller and so on. For the development of new bus priority methods and also for improving the existing methods, in depth understanding and awareness of the capabilities and limitations of the signal controllers is required. Alternative system architectures for bus priority at traffic signals also need to be considered and understood. These are amongst some of the issues reviewed in the following Sections.

2.2 Priority types

Bus priority options available in signalised junctions can be grouped as passive priority and active priority mainly considering the use or not of a detection system to determine the presence of buses.

2.2.1 Passive priority

Passive systems are those where signal timings are weighted, or re-optimised, to take account of streams of traffic containing significant bus flows. This is a straight forward form of priority at traffic signals. It gives more green time to the approach having higher bus flow than it would have done otherwise (Gardner et al. 2009). In effect, optimisation of signal timings is then based on minimising person delay (taking account of all vehicle occupants) rather than the usual criterion of minimum vehicle delay.

2.2.2 Active priority

With 'active' priority the traffic signal is responsive to the arrival of each bus detected up stream of the stop line on the approach through some form of active detection of the bus and communication of the priority requirement to the traffic signal controller. Buses can be given active priority by implementing different strategies depending on the priority objectives and the availability of the infrastructure to support the implementation (Gardner et al. 2009). The following strategies have been identified by PRISCILLA study (Gardner et al. 2009):

<u>Priority to All Buses</u>

All buses are given priority irrespective of whether they are late, early or on time. This strategy is called "maximum speed" strategy, as the aim is to increase the running speed of all buses (PRISCILLA 2002). However, it should be noted that where bus flows are high, priority to a large number of buses can delay other buses in the conflicting approaches, and so maximum speed is not necessarily achieved. This is one of the simplest strategies to implement, as the only information required about an individual bus is its expected arrival time at the traffic signal stop line. The strength of this strategy can be varied by assigning the level of priority to be awarded (e.g. full priority, traffic signal extensions only, or priority constrained by traffic considerations). It is possible that full priority to all buses can lead to high delays to general traffic, particularly where bus flows are high and the priority leads to a large number of traffic signal recalls being introduced.

<u>Differential Bus Priority</u>

Priority can be allocated to the eligible buses fulfilling pre-defined criteria designed to serve particular priority objectives *(details in Section 2.9).* 'Priority to late buses only' is the most common strategy. Eligibility to get priority is mainly checked by the following approaches:

Schedule Based Approach: Only buses that are behind their schedule receive priority. A Schedule based approach is suitable for low frequency services (eg less than 5 buses per hour). This strategy seeks to maximise the punctuality of buses, but not all buses are awarded priority so speed improvements may be limited. This priority strategy has been reported as being better than giving priority to all buses, since it provides a good balance between travel time savings and passenger waiting time savings and reduces the impact on general traffic (PRISCILLA 2002).

Headway Based Approach: This strategy provides priority to buses on the basis of their headway deviation (e.g. buses whose headway to the bus in front exceeds the scheduled headway are eligible for priority). Such a strategy aims to improve bus regularity and passenger waiting time savings at bus stops rather than bus speeds and is appropriate where buses operate to a high service frequency (e.g. an average headway of 12 minutes or less), where passengers tend to arrive at bus stops randomly (PRISCILLA 2002).

2.3 Bus detection and location methods

The first requirement for bus priority at traffic signals is a means of bus location/detection that identifies a bus on the priority approach of a traffic signal (Gardner et al. 2009). The following general categories summarise the options for this process.

<u>Methods where Only the Infrastructure is Equipped</u>

These methods provide bus detection with no need for on-bus equipment. This involves detecting buses using methods such as the ‘long loop’, ‘signature processing’ loops or above-ground systems, including video image processing (Gardner et al. 2009).

<u>Methods where Only the Bus is Equipped</u>

These methods allow buses to be detected solely from equipment on board of the bus. The main example here is the Global Positioning System (GPS) which provides continuous vehicle positioning to an accuracy of typically 5-10metres (PRISCILLA 2002). Appropriate on board software can then locate the bus relative to the traffic signals. Bus location on a fixed route can also be estimated using an odometer; however, potential cumulative errors make this approach rarely used in its own right.

<u>Methods where the Infrastructure and the Bus are Equipped</u>

These methods detect buses on the basis of communication between on-bus equipment and the related field infrastructure. For example (Gardner et al. 2009):

On-Bus and Local Infrastructure: This involves the use of bus transponders or ‘tags’ and communication with inductive loop or beacon detectors on the approach to each equipped junction. This provides reliable detection (of equipped buses only) at specific locations.

On-Bus and Central Infrastructure: This involves the use of on-board equipment for bus detection (e.g. the Global Positioning System, GPS) and, usually, radio-based communications between the bus and the control centre(s). Radio communications can vary from dedicated channels with ‘polling’, where the location of the bus is interrogated at regular intervals (e.g. every 30 seconds) to systems using GPRS technology and ‘exception reporting’ (e.g. the bus only communicates with the control centre(s) if it departs from its timetable/frequency by more than a pre-set amount). This latter option, which is popular at present, reduces communication costs but requires greater ‘intelligence’ on each bus (Hounsell et al. 2004).

2.4 Detector locations

It has been conventional in the UK to detect buses at only one location upstream of the traffic signals. This has occurred because, until GPS became available, detection required dedicated infrastructure, such as an inductive loop or a roadside beacon. Cost considerations then constrained choice to a single detector. However, the introduction of GPS-based priority systems has removed the need for new infrastructure, because detection is ‘virtual’ (i.e. based on the bus’s arrival at a predefined location, specified by its latitude and longitude co-ordinates). This has opened up the prospects of having multiple bus detection points and has led to research into this topic. For example, various bus detector locations were considered in an earlier study (Hounsell et al. 2004). Options assessed were:

- Use of a detector downstream of bus stops
- Use of a detector upstream of bus stops
- Use of an exit detector near the stop line to cancel priority actions, and hence save any time which might be wasted by retaining a green signal after the bus has left the junction
- Use of a secondary detector downstream of bus stops, in addition to primary detection upstream, to re-assess the priority requirements.
- Different combinations of these detectors.

Research (Hounsell et al. 2004) using simulation modelling showed that bus priority is most beneficial when combination of detectors (upstream detection along with a secondary detector and an exit detector) are implemented. This arrangement is particularly beneficial where the bus stop is close to the traffic signals (<50m), where the bus priority benefits from detection downstream of the stop are likely to be low.

2.5 Detection types

There are two main categories of detection (DfT 2004), namely SVD (Selective Vehicle Detection) and AVL (Automatic Vehicle Location).

Selective Vehicle Detection (SVD)

SVD detects vehicles as they pass a fixed point of a road network and can use infrastructure such as a ‘long loop’ or video image processing (Moon 2007). It normally requires communication between on-board vehicle systems and roadside equipment such as a bus transponder with inductive loop. In the SVD system bus location information is only available where the detectors are placed. It is an effective way of providing priority to all detected buses but it cannot allocate different levels of priority to particular buses such as only to late-running buses (DfT 2004).

Automatic Vehicle Location (AVL)

AVL is a system which provides ‘continuous’ real-time information on vehicle location, usually involving on-board location equipment and two-way communication with a control centre. The progress of vehicles (buses in this case) can then be tracked and compared with the timetable or with the bus in front (the headway) and this information can then be used for requesting priority for those buses which need it *(details in Section 2.9.1).*

2.6 Bus priority methods

Bus priority methods are the ways of providing priority to buses at traffic signals. These are:

Extension

A green extension involves the extension of the green phase of the bus route upon detection of a bus before the normal green period ends. In most cases, the green time for the priority approach is held or extended until the bus clears the intersection or when the pre-specified maximum green extension (or max-timer) is reached. A max-timer is usually used to set the maximum extension limit of the green phase, which is needed to control the disruption of other general traffic and to terminate any excessively long bus priority calls (Khasnabis and Rudraraju 1997).

Recall

This method applies if a bus is detected when the traffic signal is on red, causing the green signal to be recalled as soon as possible. It involves the shortening of either all or some selected non-bus phases. However, when designing the maximum length of an early green, special attention should be paid to the minimum green restriction, the clearance safety of the other phases (including vehicle and pedestrian phases), and the excessive delay of the truncated approaches. A recall generally causes more disruption to other traffic than a green extension because it causes more interference to the traffic signal settings (McLeod 1998).

Rolling Horizon Methods

These methods use bus location information further upstream from the junction (e.g. up to a 120 second bus journey time in UTOPIA (PRISCILLA 2002)) and use gradual adaptation of the relevant green stage occurrence and duration to match the predicted arrival time of the bus (PRISCILLA 2002). This has the advantage of a less abrupt impact on signal timings, which could compromise efficient signal co-ordination, but is more dependent on accurate journey time prediction (which naturally deteriorates the further the bus is from the junction).

Stage Re-ordering

The categories of bus priority methods described above are normally implemented without affecting the normal stage/phase structure. An alternative, and stronger form of priority often used in tram priority systems, is to allocate a specific stage to the bus/tram when it is detected. This stage is then inserted into the sequence at the next opportunity. This can mean effectively ‘skipping’ or delaying other stages, and may allow a repeated green of a bus/tram stage, if the bus/tram is detected in the inter-green period immediately after a bus/tram stage has just terminated. Common strategies for stage re-ordering are:

Stage Skipping: This strategy also provides an early green phase to the bus route upon detection of a bus during the red phase. This allows one or more non-bus stages to be omitted from the normal stage sequence when a bus is detected, so that the bus stage can be recalled as quickly as possible. Al-Sahili and Taylor (1996) reported that phase skipping would cause highest vehicular delay because it brought the highest disturbance to the system. In many countries, including the United Kingdom, stage skipping is not common practice (unless it is designated as a demand-dependent stage) and its implications on safety need to be carefully considered (Gardner et al. 2009).

Special Bus Phase: A special bus phase involves the insertion of a short bus phase into the normal phase sequence (Sunkari et al. 1995). This strategy is applicable to a signal timing plan with more than two phases.

Green Wave

This refers to an interventionist priority system where a special plan is initiated in the UTC system to provide a sequence of green signals for the selected priority vehicle(s). This is often implemented for emergency vehicles (particularly ambulances and fire appliances) responding to emergency calls. The long priority green periods (and long red periods to some traffic streams) can be justified by the importance of the vehicle and the infrequency of the event; such action can seldom be justified for public transport (PRISCILLA 2002).

Compensation, Inhibition and Recovery

Where bus priority is implemented as an 'override' to the normal traffic control, it is necessary to consider the traffic control operations immediately after the priority has been awarded. This may include the use of a compensation to non-priority stages if needed (e.g. repaying the time lost due to priority), and/or a 'recovery' mechanism to enable the signals to return to their underlying co-ordinated control in an efficient manner (PRISCILLA 2002) and/or to inhibit priority calls in consecutive cycles, to minimise negative impacts on non-priority traffic (Hounsell et al. 2004).

2.7 Traffic signal control systems

The type of traffic signal control system influences the type of bus priority methods which can be implemented. A variety of traffic signal control systems are operational in different cities around the world. These can be grouped into the following categories (Gardner et al. 2009):

2.7.1 Isolated systems

Signal controlled junctions that are located and operated independently are called isolated junctions. This form of control is used when traffic arrivals at the junction are largely unaffected by any neighbouring traffic signals and usually found in suburban/rural areas where traffic signal density is lower or in smaller towns. An isolated system can be fixed time or vehicle actuated. These are described below:

Fixed Time

With fixed time control, signal timings ('plans') are calculated off-line, and implemented using the traffic controller at the site. There may be just one fixed time plan operational for 24 hours or, more usually, a number of plans can be developed for varying traffic conditions at different times of day.

Vehicle Actuated

Vehicle actuated (VA) systems rely on traffic detectors on junction approaches to detect vehicles, to allocate green times to different traffic movements according the traffic detected. With its traffic responsive capability, VA is the most common form of control for isolated junctions in the UK (Gardner et al. 2009) and is known as 'D-system VA'. In this system, a vehicle approaching a red or amber signal registers a demand for a green. This demand is stored in the controller, which serves permitted stages in cyclic order omitting any stages for which no demand has been received. Once a green signal is displayed, the duration may be extended by vehicles detected moving towards the signal. If vehicles continue to extend the green period and a demand exists for another stage, the green signal will be terminated on expiry of a pre-set maximum period. On expiry of the last extension and with no more vehicles detected, the controller will answer a demand for another stage. This description is UK-specific, but it is expected that similar systems exist elsewhere. The VA system can give priority to buses detected on the approach by extending the current green period or by recalling the priority stage for the buses early. A 'priority recall' may be implemented by curtailing the non-priority stages to their minimum values. Non-priority stages curtailed to give priority may be compensated by increasing its normal maximum value by a compensation period. An inhibit facility can also be provided which prevents bus priority actions in consecutive signal cycles. This ensures that compensation can be given to non-priority stages.

Bus priority at VA junctions started in London in the 1970's with the first major evaluation trial occurring in the SELKENT area of London in 1987-88 (University of Southampton 1988). The success of the trial led to the expansion of bus priority at 300 more VA controlled junctions in the outer areas of London. The SELKENT bus priority scheme involved installation of bus detectors at some 56 signal controlled junctions and equipping 900 buses with transponders to activate the system. Most of the detectors were sited at 70m upstream of the stop line from the consideration of journey time variability and enough warning time. The system was capable of giving priority to the buses detected on the approach by extension or recall. The priority recall was implemented by curtailing the non-priority stages to their minimum values. Stage skipping was not allowed in this system, unless there was no demand for the stage. Any non-priority stage curtailed to give priority to buses was compensated by increasing its normal maximum value by a compensation period. An inhibit facility was also provided at some sites with high bus flows, to prevent bus priority occurring in consecutive signal cycles, which could disrupt non-priority signal stages significantly. Field trials undertaken at 10 junctions showed that overall bus delay savings was (Gardner et al. 2009) 9 sec/bus (32%). The trial demonstrated that bus priority at VA controlled junctions can give significant benefits to buses. The average bus delay saving of 9 sec/bus/junction was somewhat higher than that typically achieved at co-ordinated systems in London, where the needs of network stability can constrain the amount of bus priority given.

An advanced form of VA controller for isolated intersections used in the UK (Vincent 1999) is MOVA (Microprocessor Optimised Vehicle Actuation). It analyses lane-by-lane detector data and controls the signal timings to optimise delay and stops or capacity (if any approach becomes oversaturated). Bus priority can be implemented within MOVA (Crabtree and Vincent 1998) using Selective Vehicle Detectors (SVDs) to distinguish buses from most other vehicles. It gives priority to the buses detected on the priority approach by extending the current green period or by demanding the priority stage for the buses. The priority stage demand may be implemented by truncating the non-priority stages to their minimum values (stage truncations) or by skipping all those stages on-route to the priority stage (stage skipping). It is understood that a more advanced form of bus priority is also feasible within MOVA, involving integration of the bus detection into the optimisation algorithm, rather than using an override.

2.7.2 Co-ordinated systems

When signal controlled junctions are more closely located, and traffic interactions occur, co-ordinated control is often implemented. Operations at a junction are then influenced by operations at one or more neighbouring junctions, with all junctions then co-ordinated using an Urban Traffic Control (UTC) system. UTC systems are implemented in most medium and large towns and cities around the world, particularly in central areas where junction density is highest. Co-ordinated UTC systems can be traffic responsive or fixed time. These are described below:

Fixed Time UTC

With fixed time control, signal timings ('plans') are calculated off-line, often using software such as TRANSYT, and implemented via the UTC system. BUS TRANSYT can optimise signal co-ordination to take account of bus performance (PRISCILLA 2002). SPRINT (Selective PRIority Network Technique) was developed in the UK to give priority to buses at traffic signals controlled by a fixed time UTC system (Hounsell et al. 1997). The system gives priority to the buses detected on the priority approach by extending the current green period or recalling the next green period earlier. Extensions get preference over recalls. The priority implementation is constrained by maximum cycle, maximum move from the base, target degree of saturations and inhibit period.

Traffic Responsive UTC

Traffic responsive systems rely on traffic detectors on junction approaches to provide data that is used to calculate optimum signal settings in real time. The improved traffic performance that has been demonstrated with traffic responsive control has led to the development of a number of systems, such as SCOOT, SCATS, UTOPIA, PRODYN and BALANCE (Hounsell et al. 1996). Among them SCOOT is most common in the UK. Over 170 towns and cities in the UK now use SCOOT (DfT 2004).

SCOOT (Split Cycle Offset Optimisation Technique) is an adaptive Urban Traffic Control (UTC) system that responds automatically to fluctuations in traffic demand obtained from the on-street detectors (DETR 1999). Bus SCOOT is a facility incorporated into SCOOT to give priority to buses. To use Bus SCOOT implementation of devices/ systems for letting SCOOT know where the buses are e.g. loops, detectors or AVL systems are required. Bus priority can be provided in SCOOT by extending the current stage for a bus to allow it clear the junction, or shortening intervening stages to return more quickly to the bus stage (DETR 2000). The amount of priority given to buses can be restricted depending on the saturation of the junction as modelled by SCOOT and the target degrees of saturation for extensions and recalls. These are the degrees of saturation to which the non-priority stages can be run in the case of a priority extension or recall respectively. Normally, the amount of priority is decided by the SCOOT optimiser at the UTC centre and communicated to the local traffic controller. However, in the case of priority extensions, there is a facility to decide it locally within the limit set by the central control. In recent developments, SCOOT also has facility to give different levels of priority to buses based on their performance against the predefined criteria. For example, no priority for buses running on time, moderate priority for late buses, high priority for very late buses. The recent version of SCOOT also has facility to give priority by skipping non-bus stages.

2.8 Priority architectures

Bus priority at traffic signals can be achieved with an increasingly large range of system architectures. The location of intelligence within the system architecture is a major component which influences the performance of bus priority. The 'intelligence' termed here is the component that determines the priority requirement of a bus based on predefined criteria using bus location information (Hounsell and Shrestha 2005). Bus priority system architectures according to the location of intelligence in the system can be categorised as four types described below (Jones 1998).

Fully Centralised Architecture: Here the traffic control and priority functions are operated and integrated at the central level.
Centralised UTC and Decentralised Priority: This may be preferred, for example, where the benefits from bus priority might be adversely affected by data transmission delays if centralised priority were implemented.
Decentralised UTC and Centralised Priority: This may be appropriate where wide area priority requirements take precedence over local control.
Fully Decentralised Architecture: Here the traffic control and priority functions are operated and integrated at the local level.

A review of bus priority techniques and applications at traffic signals in Europe has been carried out within PRISCILLA project (Hounsell and Wall 2002) showed that AVL is in widespread use in different forms, with a range of system architectures/designs (PRISCILLA 2002). A comparison of the effectiveness of these different bus priority architectures on the basis of their important aspects and options available showed that (Hounsell and Shrestha 2005) iBus architecture is efficient in terms of the intelligence location and the way of communication *(iBus architecture is described in Section 2.9.1.1)*.

2.9 Differential priority

Differential priority is the strategy where different levels of priority are awarded to buses at traffic signals according to their adherence to schedule/frequency (Hounsell et al. 2008b). For example, higher level of priority to be given to late buses and a lower level or no priority to the buses which are early or on time (Shrestha 2003 and Zhang 2011). The objective of this form of differential priority is to produce greater punctuality or regularity in the service and reducing any extra delays to non-priority traffic caused by bus priority (Hounsell et al. 2008a). Differential priority in some form is reported to be implemented in many European cities including Cardiff (Hill 2000), Leicester (Gillam and Wright 2000), Twente (Witbreuk and Zoontjes 2004), Toulouse (PRISCILLA 2002) and Eidenhoven (Furth and Muller 2000). Most of these systems have implemented a differential priority system giving priority to late buses only.

2.9.1 Automatic vehicle location (AVL)

Implementation of differential priority method requires the use of an Automatic Vehicle Location (AVL) system (TRG 2010). AVL refers to the use of systems to locate and track vehicles in real time (Lobo 1998). The locational information of buses in a route obtained from AVL can be utilised to give priority according to individual requirement of buses (e.g. the calculation of the headway between buses at any point in time and priority requirements for each bus using a priority criterion defined). It provides a platform to implement differential bus priority system in which the relative positions of buses are used to check their eligibility for getting priority at an approaching traffic signal. Once the priority requirement for a bus is ascertained, the priority information is used to give priority to the bus at the downstream traffic signal(s). There are various AVL systems available, among them iBUS used in London is a modern flexible satellite-based AVL system.

2.9.1.1 iBus Architecture

To implement differential priority method requires the use of an AVL system that continuously provides the location information of buses in a network and intelligence to calculate the priority requirement of the buses (e.g. in terms of lateness). iBus has both of these facilities available. A simple representation of bus priority at traffic signals using iBus in London is given in Figure 2.1 below (Hounsell et al. 2008a).

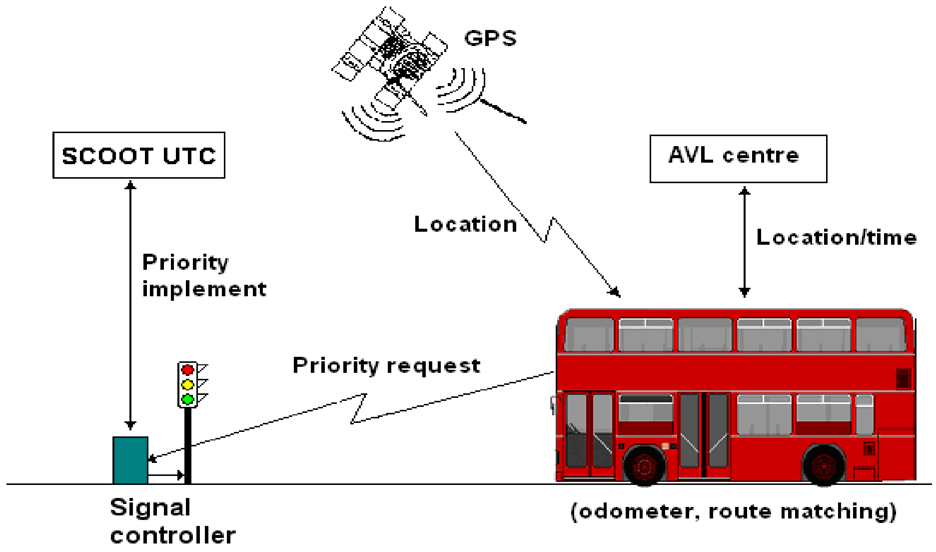


Figure 2.1: Simple representation of bus priority at traffic signals using iBus

The AVL centre transmits the priority level to the bus and the bus passes this message to the traffic controller at the time of detection. Radio communications are used for transmissions. This type of architecture has been in use in parts of London (Hounsell and McLeod 1999) using a beacon-based system. This system is now being replaced by a comprehensive GPS-based AVL system known as iBus. In this priority architecture, each bus receives its location every second from its on board GPS unit and is continuously monitored by the control centre. The monitoring is done by polling buses in 30-60 second intervals in addition to the information of arrival time at a bus stop that each bus sends when departing from a bus stop. The control centre uses the location information to update locations of the buses in its system and to calculate the headway and the headway deviation of the bus. The headway deviation hence calculated is passed to the bus in a coded format. When a bus arrives near a traffic signal, the bus is detected at a predefined location on the approach and the priority is triggered. The detection is carried out by comparing the location of the bus with the pre-defined location of the detection point(s) on the route, stored in the on-board computer. These detection points are also known as virtual detectors (as they have no physical presence). When priority is triggered, the bus sends the deviation to the bus processor (in the signal controller) in a coded format when sending priority requests.

The bus processor receives the deviation after decoding the priority message from the bus. Then it decides the priority level based on the deviation and the priority strategy implemented. The priority level sets the parameter for the traffic control system to calculate the amount of the priority time available to the detected bus at the traffic signal (Hounsell et al. 2008a). The priority level is then passed to the signal controller. The traffic signal controller (liaising with the central system) decides the type and amount of priority given to the approaching bus. This depends on the signal status, junction saturation and the priority level assigned. The working of differential priority in iBus is shown below in the functional diagram (Hounsell et al. 2008b).

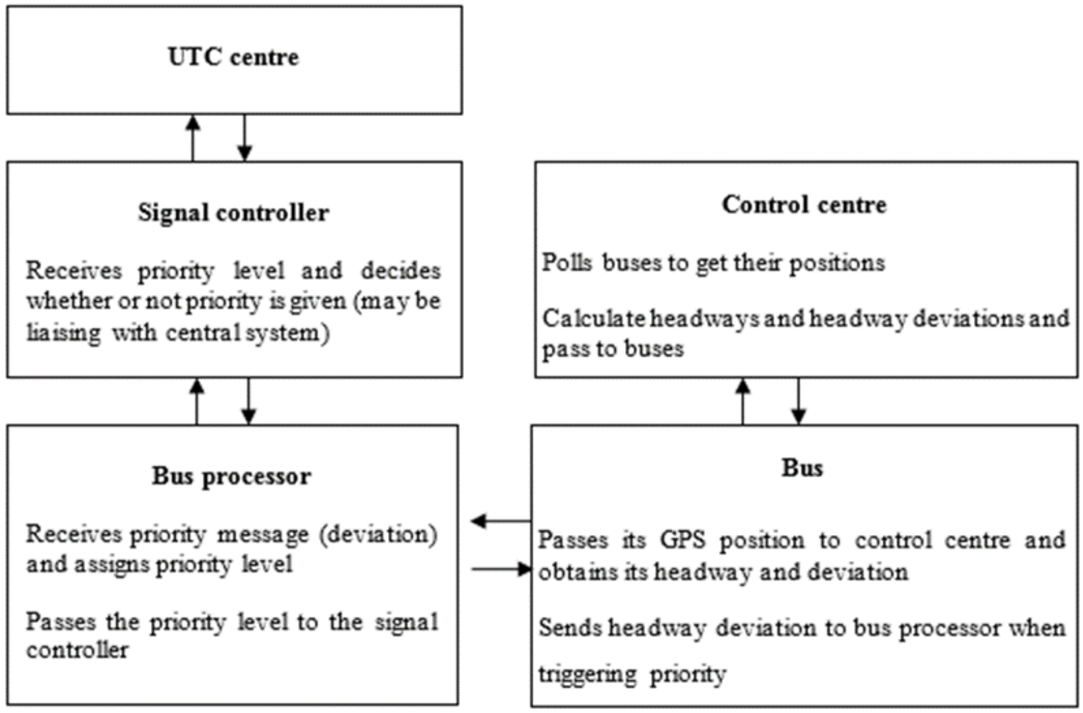


Figure 2.2: Functional diagram of main components of differential priority in iBus

In this iBus priority architecture, there is intelligence at the control centre (to calculate the deviation of buses) as well as in the local bus processor (to assign the level of priority). This allows various types of differential priority strategies to be implemented taking account of individual buses as well as the wider network.

2.9.2 Differential priority strategies

The differential priority strategy is the method of targeting buses for priority. These strategies alter the number of buses eligible for priority and the amount and type of priority they can get (depending on the priority level assigned). The proportion of buses getting different priority levels changes the outcome of the bus priority.

Various strategies for differential priority that can be implemented in iBus were considered by TRG and TRL study (TRG 1997 and Maxwell et al. 2003). Among them recommended best strategies from the study to achieve the set objective are given in the Table 2.1 below.

Table 2.1: Best strategy recommended (Maxwell et al. 2003; Ma et al. 2007)

Objective	**Best Strategy**
Reduce overall bus delay	Provide similar priority to all buses
Improve regularisation	Provide high priority to late buses and no priority to others
Maximise economic benefit	Provide high priority to late buses and extensions only to others

Table 2.1 above illustrates that overall delay savings to buses are maximum when all buses are provided same level of priority.

To target buses for differential priority bus lateness need to be calculated first. Lateness can be defined (Table 2.2) in the following ways (Ahmed 2012). Table 2.2 below illustrates various definitions of lateness. According to definition D1 lateness can be calculated by comparing actual headway of a bus with its scheduled headway.

Table 2.2: Lateness calculation

Lateness calculation	**Definition**
Selective Vehicle Detection	
D0	Difference between actual arrival time and scheduled arrival time
Differential Bus Priority	
D1	Difference between actual headway and scheduled headway
D2	Difference between actual headway and headway of the following bus
D3	Difference between actual headway and average headway in the corridor
D4	Compare lateness by definition 1, 2 & 3. Select the higher value.

Priority conditions are also required to be fulfilled before providing priority to late buses. Priority condition controls the eligibility of late buses to get priority. Priority eligibility can be checked in the following ways (Ahmed 2009; Ahmed 2012; Hounsell and Shrestha 2009).

According to the priority condition S1 in Table 2.3 below, a bus is eligible for priority only if it is late compared to the scheduled headway.

Table 2.3: Priority conditions

Strategy Nr	Strategy	Conditions
Improving Journey Times		
S0	Scheduled arrival time based	Actual arrival time> scheduled arrival time
Improving Regularity		
S1	Scheduled headway based	Actual headway> scheduled headway
S2	Bus behind headway based	Actual headway> headway of the following bus
S3	Scheduled & bus behind headway based	Actual headway> scheduled headway & headway of the following bus
S4	Average headway based	Actual headway> average headway of the corridor
S5	Scheduled & average headway based	Actual headway> scheduled headway & average headway of the corridor
S6	Bus behind & average headway based	Actual headway> headway of the following bus & average headway of the corridor
S7	Scheduled, bus behind & average headway based	Actual headway> scheduled headway & headway of the following bus & average headway of the corridor

Which method of lateness calculation and which priority condition need to be considered for differential priority depends on priority objectives (Ahmed 2012; Ahmed 2013).

2.10 Priority objectives

Different levels of priority can be given according to requirements (e.g. lateness) in more advanced forms of bus priority at traffic signals. The priority strategy selected controls the number of buses eligible for priority (depending on the lateness criteria) and the amount of priority they can get (depending on the priority level assigned). This changes the outcome of the bus priority in terms of bus delay savings, regularity benefits, impacts on other traffic and total economic benefits (Gardner et al. 2009). Hence, a priority strategy can be implemented targeting one of the following objectives:

<u>Bus Journey Time Savings</u>

Bus priority at traffic signals can be targeted to improve journey time of buses through a junction. Shorter journey time could give competitive edge to buses in comparison to general traffic and encourage modal change. If this is the only criteria, then giving *the* same levels of priority to all buses will give the best results.

<u>Bus Regularity and Punctuality</u>

Bus regularity and punctuality are the main factors in passenger perception (DfT 2005 and TfL 2007) of bus service performance. Punctuality is the measure showing the percentages of buses on time taking account of the accepted tolerance. This is used in low frequency timetabled services. Regularity is the measure showing the variation in headways (the interval between consecutive buses travelling on a route) in comparison to the scheduled headway. This is used in high frequency headway-based services. These measures affect passenger waiting times at bus stops. Targeting late buses or the buses with higher headways will give the best results if this is the only criteria.

<u>Total Economic Benefit</u>

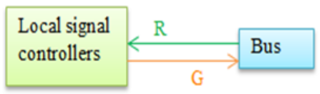
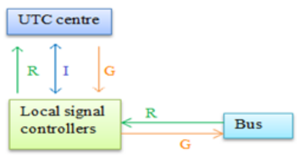
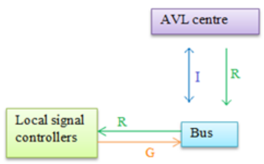
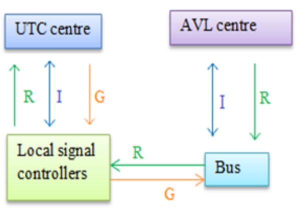
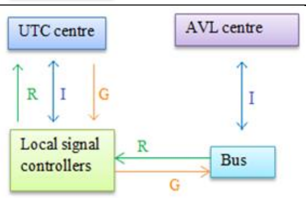
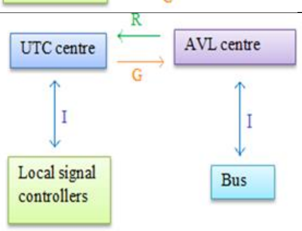
Total economic benefit is another potential objective function for bus priority at traffic signals. This is calculated on the basis of the performance of buses and all other traffic at a junction, including the effects of passengers waiting for buses. This criterion takes account of general traffic in addition to the benefits to the buses when calculating total economic benefits.

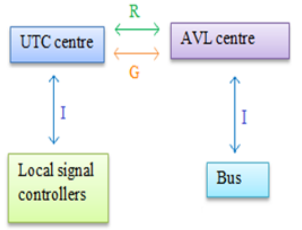
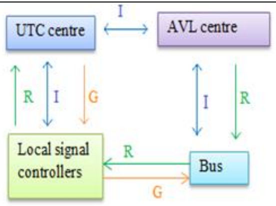
2.11 Bus priority at traffic signals: worldwide context

2.11.1 System architecture

The Table 2.4 below provides an illustrative summary of the main system architectures currently being used around the world. They are categories based on location of intelligence, priority request method, and location of priority control.

Table 2.4: System architecture around the world (PRISCILLA 2002, Traffic Safety and Operation Lab 2012)

Category	Architecture (R=priority request; G=priority grant; I=information transmission)	Priority Options			Applications /Cities
		Intelligence	Request	Decision	
A1		Local	Decentralised	Local	Geneva, Switzerland Malmo, Sweden Nantes, France Prague, Czech Republic
A2		Local	Decentralised	Central	Glasgow, UK
A3		Central	Decentralised	Local	Aalborg, Denmark Brighton and Hove, UK Helsinki, Finland
A4		Central	Decentralised/ Centralised	Central	London, UK
A5		Local	Decentralised/ Centralised	Central	Zurich, Switzerland Japan (41 of 47 cities)
A6		Central	Centralised	Central	Cardiff, UK Gothenburg, Sweden Southampton, UK Turin, Italy

Category	Architecture (R=priority request; G=priority grant; I=information transmission)	Priority Options			Applications /Cities
		Intelligence	Request	Decision	
A7		Central	Centralised	Central	Toulouse, France
A8		Central	Decentralised	Central	Genoa, Italy

2.11.2 Comparisons of system architecture

The Table below illustrates the advantages and disadvantages of available system architectures.

Table 2.5: Comparisons of system architectures (Traffic Safety and Operation Lab 2012)

Comparisons of System Architectures: Aspect	
Intelligence	
Local: Simple and efficient method Less communication requirements More suitable for timetable services	*Central:* Possibility of network based bus priority (e.g. dynamic priority) Compatible with multi-purpose use of the data More suitable for headway based services
Priority request	
Decentralised: More accurate priority request Applicable to both UTC controlled as well as isolated junctions Needs extra infrastructure and communications	*Centralised:* Needs less infrastructure Applicable to signals under UTC system and central level 'intelligence' only.
Priority decision	
Local controller: Controller instant implementation gives higher potential delay savings Often more complex to implement on signals under a UTC system	*Central UTC:* UTC takes account of signal coordination and hence less impact to the general traffic Applicable to the signals under a UTC system only.

2.11.3 Applications

Bus priority at traffic signals has been found more than 105 cities around the world (Traffic Safety and Operation Lab 2012). The Table 2.6 below shows the priority strategies considered in the cities around the world and corresponding network size.

Table 2.6: Applications around the world (Traffic Safety and Operation Lab 2012)

City	Country	Priority strategies	Network configuration	Year
Arlington Heights	USA	GE, RC	12 nodes	1985
Bay Area	USA	Passive priority, GE RC, based on schedule adherence	> 75 nodes	
Burlington	USA	GE, RC	80 nodes	1993
Calgary	USA	GE, RC	67 nodes	2000
Charlotte	USA	GE, RC	17 nodes	1985
Chicago	USA	Passive priority, Conditional priority, GE, RC	84 nodes	2003
Glendale	USA	GE, RC	17 nodes	2001
Houston	USA	GE, RC	1563 nodes	2004
Los Angeles	USA	Bus regularity based on headway, priority to buses with more than 1.5 scheduled headways behind its leader	26 corridors, 1000 nodes (25% in the city), more than 900 buses	1990
Minneapolis	USA	Based on delay with respect to its schedule time, its number of passengers, location and speed.	22 nodes	2004
New York City	USA	GE , RC	20 nodes	2007
Oakland	USA	GE, RC	62 nodes, 1 corridor	2003
Orlando	USA	GE, RC	19 nodes	1997
Ottawa	Canada	GE, RC, special phase, unconditional priority to all buses	40 nodes	1990s
Philadelphia	USA	GE	61 nodes	2002
Pittsburgh	USA	special phase	5 nodes	
Port Townsend	USA	special phase	2 nodes	
Portland	USA	Passive priority, Active priority, GE, RC, based on person delay and schedule adherence	370 nodes	1987
Richland	USA	GE, RC	31 nodes	1995
Sacramento	USA	GE, RC	600 nodes	
Salt Lake City	USA	GE, RC	12 nodes	
San Mateo County	USA	GE, RC, and special phase	77 nodes	1990
Seattle	USA	GE, RC	26 nodes, 3 corridors	1999
St. Cloud	USA	GE, RC	89 nodes	

City	Country	Priority strategies	Network configuration	Year
Tacoma	USA	GE, RC	110 nodes, 6 corridors, 245 buses	2002
Toronto	Canada	GE, RC, and special phase; queue jump lanes	338 nodes on 8 street-car routes and 4 bus routes	1989
Vancouver	Canada	Passive priority, Active priority, GE, RC, special phase, bus lateness	2 corridors, 59 on B-line and 4 on Willingdon, 28 buses	2001
Washington	USA	GE, RC		
King County	USA	GE, RC, Based on traffic conditions	3 corridors, 28 nodes and 1400 buses	
Aalborg	Denmark	Priority to buses lateness>=3min	51 nodes	1996
Brighton and Hove	UK	GE, RC, Priority to late buses	8 SCOOT nodes	1997
Cardiff	UK	Priority to buses with lateness and passengers loading	46 SCOOT nodes,191 buses	1999
Genoa	Italy	Improving speed (test) , improving punctuality (test),	>84 nodes	1992
Glasgow	UK	bus lateness and passenger loading	500 buses, SCOOT system	
Gothenburg	Sweden	special phase		
Helsinki	Finland	GE, RC, Special phase; priority to bus lateness		1999
London	UK	GE, RC, Compensation (trial), Stage skipping (trial)	3200 nodes and 8000 buses	1970
Nantes	France	GE, Priority to all detected buses	31km bus lanes, 1 bus-only street	
Prague	Czech Republic	Priority to late buses	10km bus lane, 65 nodes and 352 buses	
Southampton	UK	GE, Priority to all buses		
Toulouse	France	Bus adherence		1999
Turin	Italy	Bus adherence		2000
Vienna	Austria	Priority to all buses with GE	23.3km bus lanes, 1.3 bus-only street and 185 nodes	
Zurich	Switzerland	Priority to all buses		
41 cities(total 47 cities in Japan)	Japan	Predict bus arrival time, Recommend a desired bus speed	bus lane	

City	Country	Priority strategies	Network configuration	Year
Auckland	New Zealand	GE , RC	174 nodes	2003
Brisbane	Australia	Priority to late buses, GE, RC		
Sydney	Australia	Priority to late buses, GE, RC		
Bangalore	India	GE, RC		

Note: GE= Extension, RC= Recall

Table 2.7 below summarises the benefits of bus priority for a range of cities around the world. It shows some variation in the benefit criteria and also some degree of variability in the levels of benefit between different cities. It should be noted that these benefits are often affected by the policy adopted rather than the capability of the system. For example, in London, the policy is to provide bus priority with minimal impact on other traffic. Given the high levels of bus flow and congestion in London, this means that priority has had to be constrained.

Table 2.7: Priority benefits and impacts around the world (Gardner et al. 2009)

Priority benefits and impacts					
City	**Delay savings**	**Travel time**	**Variability**	**Patronage**	**General traffic**
Aalborg	5.8 sec/bus/jun	4% reduction in average			
Brighton		Reduced	Reduced		
Cardiff		3-4% reduction	Improved schedule adherence		1-2% increase
Genoa		7-10% reduction			
Glasgow			Reduced considerably	Increased	
Gothenburg		13-15% decrease			5-10% savings
Helsinki		11% reduction		11% increase	
London	9 sec/bus/jun at isolated and 3-5 sec/bus/jun at SCOOT junctions				
Malmo			Headway reduced from		

Priority benefits and impacts					
City	**Delay savings**	**Travel time**	**Variability**	**Patronage**	**General traffic**
			10 min to 7.5 min.		
Prague		2% reduction			
Southampton	9.5 sec/jun				Increased 3.8 sec/jun
Stockholm		10% savings			
Stuttgart		Speed increased from 9 to 10.1 miles/hr		10% increase	
Suceava				10-12% increase	
Tallinn		Speed increase by 2km/hr			
Toulouse		5-24% decrease			
Turin		12% reduction			
Zurich				42% increase	
Japan		5% reduction			
Auckland	11 sec/bus/jun				
Sydney		up to 21% reduction	Up to 49% reduction		
Portland			Improved reliability		Very little effect
King County	25-34%	reduced by 5.5-8%	Reduced by 35-40%		Minimal effect
Los Angeles		reduced by 6-8%		Increased by 1-13%	Typically 1 sec/veh/jun

2.12 Chapter summary

This Chapter has provided a state-of-the-art review of bus priority at traffic signals, covering the UK in some detail and summarising systems and their effectiveness elsewhere in the world. It is clear that bus and tram priority at traffic signals is well established in many towns and cities worldwide and that, where effectiveness has been reported, benefits to buses/trams and been worthwhile, with a typical payback period of 1-3 years, mainly through reduced passenger delays. This review has also highlighted some of the factors affecting system performance (eg detector location, bus flows, traffic congestion, etc).

It is clear from this review that bus priority of this type can be introduced with minimal effects on general traffic, provided an appropriate, efficient control strategy is implemented. A range of system architectures have been identified (centralised, de-centralised, distributed intelligence, etc), dependent mainly on the characteristics of the existing traffic control system (isolated, co-ordinated, fixed-time, traffic responsive, etc) and public transport organisation/operations. There is no clear indication of the relative effectiveness of different architectures – and research on this topic would seem to be needed. However, this would require an order of magnitude increase in detail and data related to the systems concerned – and obtaining this data could be problematic.

Turning to the situation in the UK, bus priority in UTC (particularly SCOOT) has been extensively researched in the 1990’s and 2000’s, and the need for further research is not evident at this point. In contrast, the bus priority methodology for isolated VA junctions was developed in the 1970’s and 1980’s and only evaluated in detail in one trial (the SELKENT study). Since then, D-system VA has remained the predominant method of isolated signal control in the UK, and new bus priority installations have largely used the priority methods developed over 30 years ago. Given the advances in detection, communications and data processing/control, it is clearly timely to critically review this methodology with a view to proposing improvements. This is the focus of the next Chapter, where the associated research gaps are identified.

Chapter 3: Research Gaps

3.1 Introduction

It was concluded from the literature review in Chapter 2 that the most promising area of research into bus priority at traffic signals would be to focus on priority at isolated vehicle actuated traffic signals in the UK. To follow up on this conclusion it has been necessary to undertake a detailed review of the current operating parameters in this form of priority and to identify specific aspects where new research would be worthwhile – termed ‘research gaps’ in the remainder of this Chapter. These are described in the following Sections.

3.2 Priority parameters

To provide bus priority at isolated VA junctions buses are detected on priority approaches some distance from the stop line. Depending on the signal status at the time of detection, normal signal timings are overridden by the implemented priority methods. For example, if a bus is detected during green, the duration of green is held at least for the duration of the expected bus travel time from the detection point to the stop line, subject to a maximum green time. If a bus is detected during red, the duration of red is reduced based on minimum time constraints of non- priority stages. After bus priority, the signal runs according to its normal timings. The effectiveness of these priority methods is largely controlled by the priority parameters used. One of the research objectives is to improve bus priority parameters used in practice and also to explore new parameters to improve performance of bus priority methods. The main bus priority parameters are as set out in the following Sections.

3.2.1 Detector location

Present practice: Detector distance from signal stop line is one of the most influencing parameter for priority extensions. The guidelines for detector siting are therefore based on the needs of green extensions. Such optimal siting for green extensions may not be optimal for recalls. Earlier detection of buses can increase the benefit of bus extension provision and in the case of priority recalls minimise the delays to the buses by starting shortening of non-priority stages earlier. Although an increase in detection distance from the stop line increases the theoretical effectiveness of bus priority, the prediction accuracy of the bus arrival time at the stop line is likely to reduce. This could degrade the performance of the bus priority to some degree. Hence the optimum detector distance is a compromise between the need for detection as soon as possible and the need for accurate journey time prediction (TRG 2007).

The ideal detector distance for a junction depends on the site-specific characteristics that include bus speed, the journey time variability and the value of priority maximum time (PVM) used. Table 3.1 below illustrates that with the increase of speed limit of a link, the ideal detection distance also increases. It also illustrates that in a link where journey time variability is high due to pedestrian movements, parking and loading activities, the ideal detector distance is shorter compared to links where journey times is predictable. Furthermore, the ideal location may be constrained by various other field factors such as the link length, the presence of a bus stop (TRG 2005, Hyder 2005, and York 1993) and a pedestrian crossing.

In this research, links without bus stops are considered. This applies to the situations where there is either no bus stop on the link or the bus stop is well upstream of the 'normal' bus detector location. Ideal detector distances for different link type without bus stops and free flow speeds are given in Table 3.1 (TRG 2007, Siemens 2007) below.

Table 3.1: Ideal detector distance for different link type without bus stops

Link type description	Speed limit (mph)	Average free flow speed (m/s)	Ideal detector distance (m)
30 mph link with some interference from pedestrian or parking/loading activities	30	7	70
30 mph link with no noticeable interference from pedestrian or parking/loading activities	30	9	90
40 mph link	40	13	130

The detector distances for different link types given in Table 3.1 are based on the recommended bus journey time (BJYT) values of 10 seconds for priority extension time (PVE) of 13 seconds. Here, BJYT is the average bus journey time taken to travel the detector distance in free flow speed and PVE is defined in the Sub-Section below. Table 3.1 also shows general agreement with the guidelines that advise placing the detector at a location giving a bus journey time of 10 to 15 seconds to the stop line (DfT 2000). Bus detectors should be normally located downstream of any ‘unpredictable’ elements, such as pedestrian crossings or bus stops, as the time spent at such elements is highly variable.

Research gaps: Recommended guidelines for detector location advice to site detectors typically 70m – 130m upstream of the stop line (see Table 3.1 above). This recommendation is based on the consideration to increase prediction accuracy of the bus arrival time at the stop line. Because with the increase of detection distance, journey time variability increases. This also increases the risk of unnecessary green for some buses which actually crossed the stop line but priority is still running because of high journey time variability consideration which will increase unnecessary dis-benefit to non-priority traffics. This variability issue could be dealt with by using an exit detector in the vicinity of the stop line, so that the green time is terminated when a bus crosses the exit detector. Because of the availability of virtual detectors (Hounsell et al. 2008a), exit detectors can be implemented without any additional infrastructure cost. This opens the window to detect buses further upstream of the stop line and to test the performance of the bus priority methods with increases in detection distance.

Detector distances used in present practice are based on the requirement of the extension but they are not necessarily optimal for recall. If detector is placed at the usual location (70m to 130m from stop line), during peak hours it is likely that due to the red signal buses may be subject to a traffic queue which extends upstream of the detector. In this case, a priority call may not be triggered immediately because of the queuing vehicles in front of the bus delaying it from reaching the detector. This is illustrated in Figure 3.1

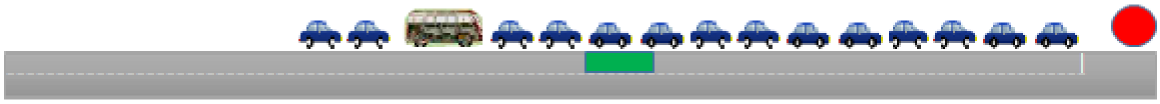


Figure 3.1: Limitations when bus detector is located close to the junction

Bus priority benefits from recalls might therefore be improved by relating the detector location to the average queue length during red. Traffic queues usually vary from junction to junction and also vary with peak, off peak and inter peak hours. So detection distance should ideally be junction specific, and also vary by time of day. Performance of the bus priority methods considering average queue length, various junction types, and time of day need to be explored.

Earlier detection of buses could increase the benefit to buses of bus extension provision because more buses will be provided with a green extension compared to traditional detection. However, a longer detection distance will necessitate a longer extension period (and longer overall green time) compared to a shorter detector distance. Extensions usually have less disbenefits to non-priority traffic than recalls, as stages are lengthened rather than being truncated. Figures 3.2-3.5 below illustrate the reason, with an example of a green time for the priority approach of 40 sec, and detection distance travel times varying from 10 to 25 seconds.

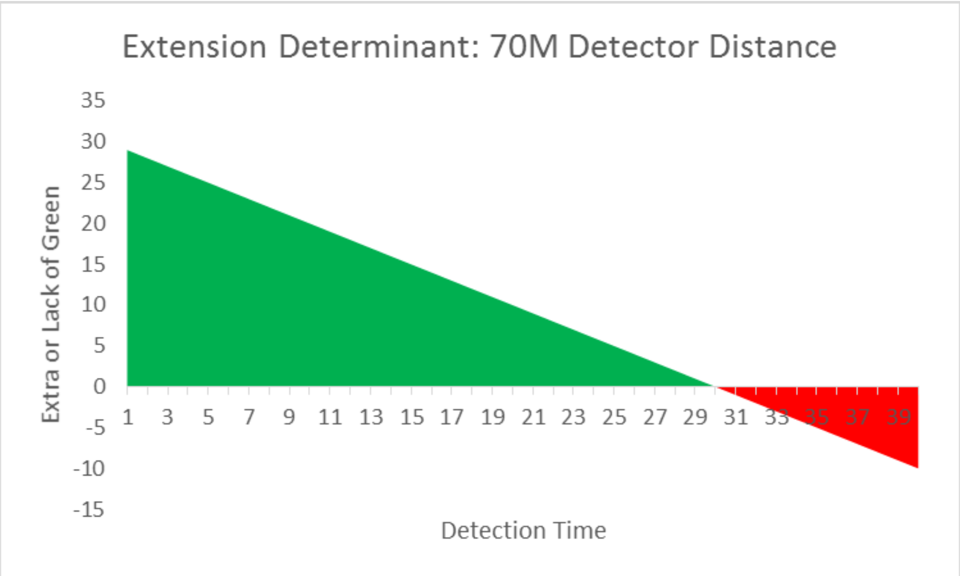


Figure 3.2: Buses needed short extension due to short detection distance

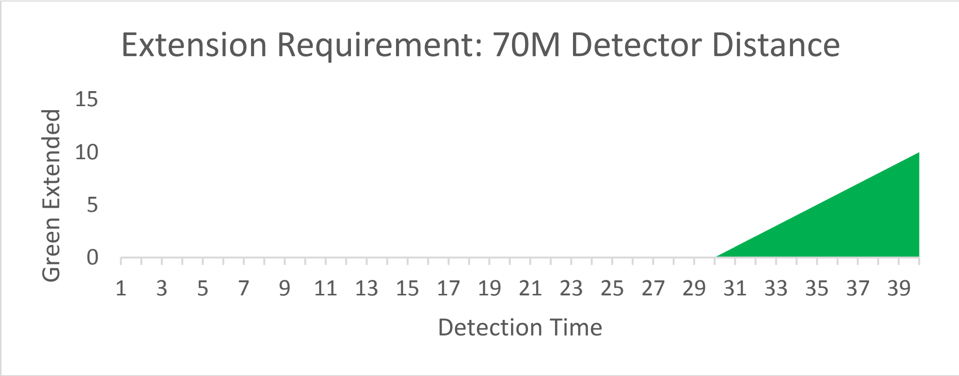


Figure 3.3: Buses provided short extension due to short detection distance

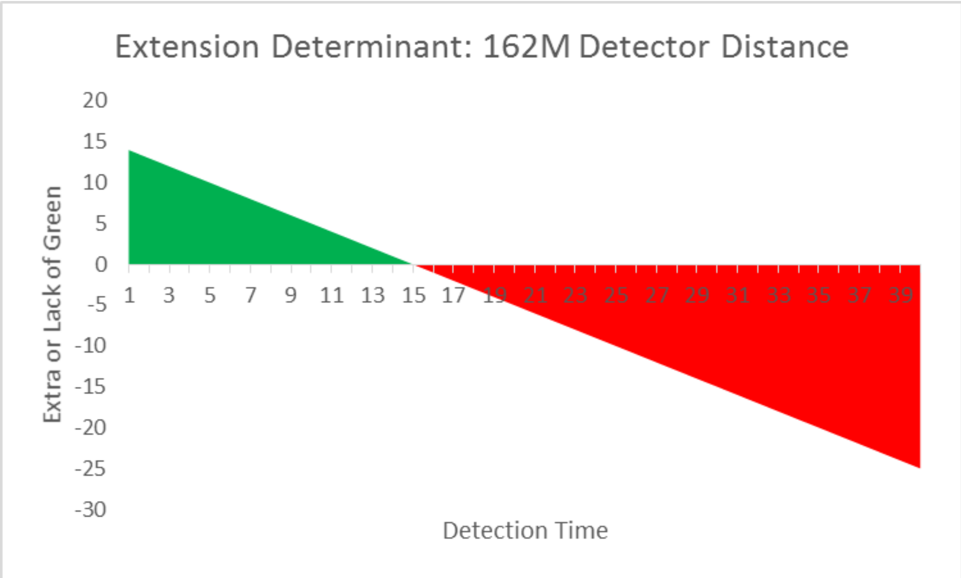


Figure 3.4: Buses needed longer extension due to longer detection distance

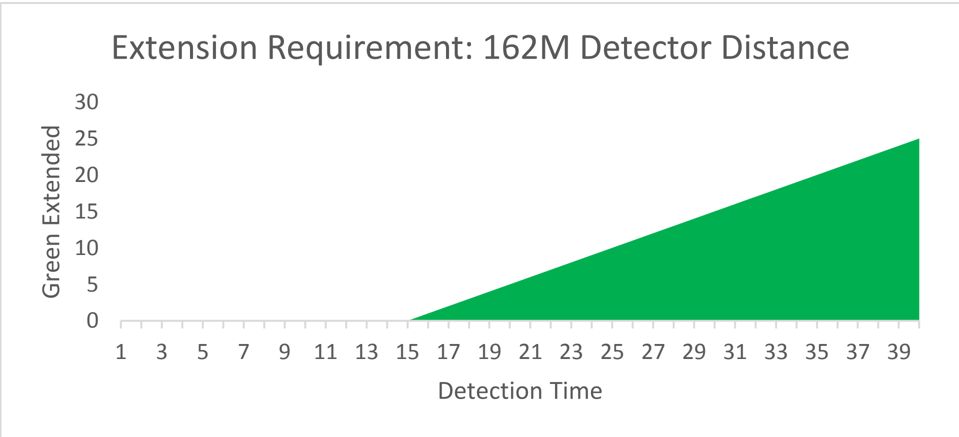


Figure 3.5: Buses provided longer extension due to longer detection distance

Figures 3.2 and 3.3 illustrate that at a 70m detection distance buses require an extension if detected in the 30th second of green or later. Figures 3.4 and 3.5 show that at 162m detection distance buses require an extension if detected in the 15th second of green or later. So the duration of the extension requirement (effective green) increases with the increase of detection distance which also increases the probability of the number of buses getting an extension. It also increases the maximum amount of extension if a bus is detected in the last second of green.

If we detect buses early, less buses will require recall. Fewer recalls mean less dis benefits to non-priority traffic. Again, benefits from each recall could be higher if detected early compared to traditional detection because the signal will get more time to prepare and respond to the approaching bus before it arrives at the stop line. That means less waiting and higher bus delay savings. Figures 3.6 & 3.7 illustrates the reasons. These Figures apply to a non-priority green time of 30 sec, two inter green times 7 sec each, a total maximum red period for priority approach of 44 sec, and a detector to stop line travel time of 25 secs for longer detection and 10 secs for shorter detection. Figure 3.6 illustrates that at the 70m detection distance buses require a recall if detected at or before the 34th second of red. Figure 3.7 shows that at a 162m detection distance buses require a recall if detected at or before the 19th second of red. That means with the increase of detection distance the duration of the recall requirement (effective red) decreases, so reducing the probability of buses getting a recall. It also reduces the maximum amount of waiting time without a recall when buses are detected in the first second of red.

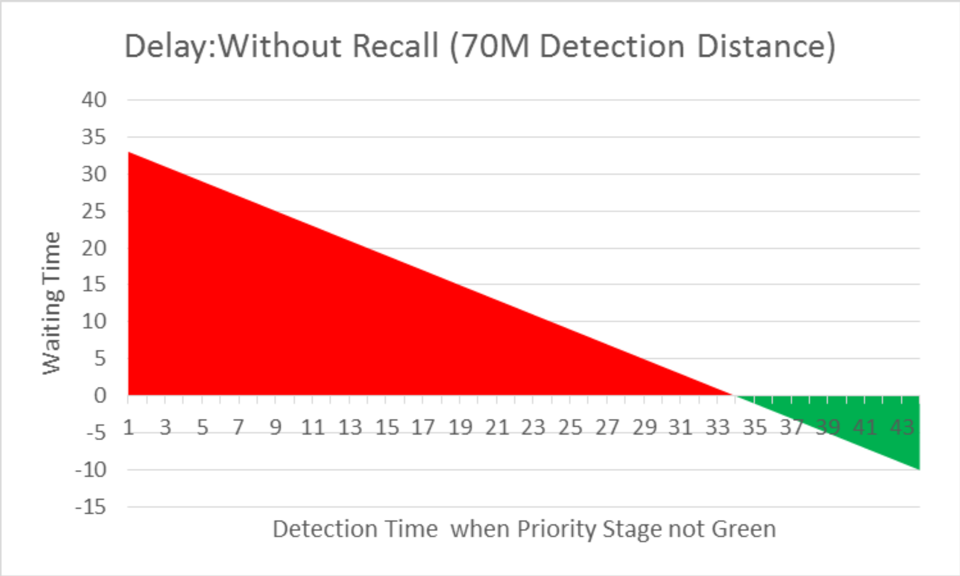


Figure 3.6: More buses needed recall due to short detection distance

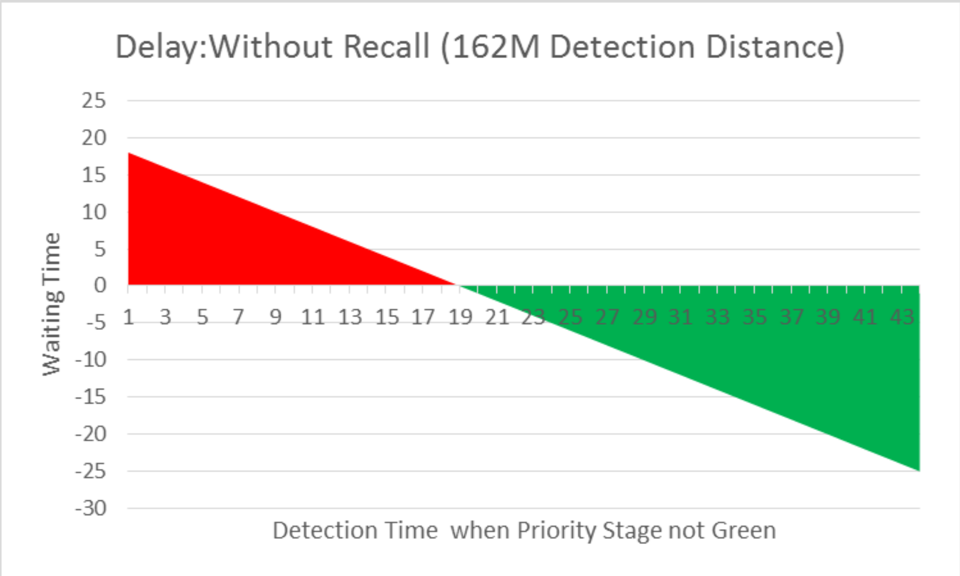


Figure 3.7: Less buses needed recall due to longer detection distance

The Figures 3.2 to 3.7 above illustrate that by detecting buses early, more buses can be targeted for extension and less buses require a recall. That means dis benefits to non-priority arms can be reduced. Benefits can be improved by considering junction queue lengths, inter green time and minimum green time constraints when siting detectors. New research is therefore warranted to understand the impact of early detection in a range of scenarios.

3.2.2 Priority maximum time (PVM)

Present practice: The priority maximum time parameter, PVM specifies a further maximum running period which commences at the expiry of the normal maximum running period if a priority extension timer is running. PVM is a user-defined parameter which sets a maximum adjustment to the extension green time in a cycle. A typical value of 15 seconds is used at VA junctions in London (TRG 2007). If this parameter is set low for operational reasons, there is no benefit in siting detector to give a higher journey time, as extensions equal to this higher journey time will not be permitted. Hence, it is recommended to site a detector such that detector to stop line journey time does not exceed the PVM value (TRG 2007).

Higher values of PVM allow greater opportunities for extensions but it should not be set so high that it would cause unacceptable delay to non-priority traffic (Khasnabis and Rudraraju 1997) or other problems such as exit blocking. The higher value increases delay savings from priority extensions but can worsen the impact on non-priority stages at congested junctions.

Hence, a PVM value of 20 seconds is recommended (TRG 2007) unless a junction is congested. At congested junctions, PVM may be set to a lower value provided that it is greater than or equal to PVE. It is to be noted that if PVE is set to 13 seconds (as in current practice), the higher value of PVM will only be used by buses arriving during the extended green period. However, a higher value of PVM would allow a higher value for PVE (and greater detector distance) which should anyway produce higher bus priority delay savings.

Table 3.2: Recommended PVM values

Junction Type	PVM (Sec)
Not Congested	20
Congested	< 20

Research gap: According to the research gap discussed in the previous Sub Section 3.2.1, if average queue length, inter green time, and minimum green time constraints are considered while siting priority detectors then new values for priority maximum time need to be explored, because recommended values are based on the traditional shorter detection distance. PVM value should be junction specific and dependent on time of the day because queue length varies from junction to junction, and during peak, inter peak, off peak hours.

3.2.3 Priority extension time (PVE)

Present practice: Priority extension time, PVE, is the length of time a VA controller holds the priority phase at right of way when a bus is detected. This depends on the detector distance and should be equal to the expected bus travel time between the bus detector and the traffic signal stop line. This may be calculated from the average free-flow bus travel time between the bus detector and the traffic signal stop line (BJYT) plus some extra time to cover variations in the journey time. The extra time equal to 30% of BJYT is appropriate for links without bus stops and that of 50% of BJYT for detection at bus stops (TRG 2006).

Table 3.3: Recommended PVE

Link Type	PVE (Sec)
Without bus stops	BJYT + 30% of BJYT
With bus stops	BJYT + 50% of BJYT

Research gap: Guidelines for adding 30% of extra BJYT time with BJYT is based on detection close to the junction. But for early detection, journey time variability will be higher. So a higher percentage of extra BJYT needs to be considered. This higher extra BJYT will incur unnecessary additional delay to non-priority arms especially for faster buses than average unless the waste of unnecessary priority green can be avoided by using an exit detector.

3.2.4 Priority minimum time (PVMin)

Present practice: When a priority recall is activated, the green phase may be terminated at the end of the phase minimum if an opposing phase is recalled by a bus. To give the bus sufficient time to clear the stop line, a priority minimum green period may be required which is longer than the normal minimum green. For practical purposes it is recommended to use a priority minimum time of 10-20 seconds depending on the junction circumstances. A priority minimum time of 10 seconds may be used at a junction during off-peak periods when the junction is not congested (TRG 2007). A priority minimum time of up to 20 seconds may be used during peak periods when the junction can be congested (TRG 2007).

Table 3.4: Recommended priority minimum time

Junction Type	Priority Minimum Time (Sec)
Not Congested	10
Congested	Up to 20

Research gap: The current recommendation for setting PVMin is based on current recommendations for detector location, which does not consider the junction queue condition. However, the priority minimum time should arguably take account of bus journey time and variations in the queuing vehicles in front of it. If queue lengths vary by time of day, the priority minimum time may also need to be varied. Priority minimum time should also arguably be junction specific, because queue length varies from junction to junction. For example, at a junction having on average 15 cars waiting in the queue during red, the last vehicle (which could be a bus) will need around 30 seconds at least to cross the stop line, assuming an average discharge rate of 2 sec/car. Increasing the PVMin may have a negative impact to buses on opposite arms, so this would need to be explored – noting that any such impacts might be mitigated if an exit detector is used. There are clear research gaps here worthy of exploration.

3.3 New strategies

In addition to identifying research gaps and requirements related to the current operation of bus priority in D-system VA, some new potential strategies have been identified in this research, as described in the following Sections.

3.3.1 Effective red for recall (ERed)

Present practice: Buses detected during the whole red period are considered for priority.

Research gap: Present practice, outlined above, would seem to be sub-optimum because buses detected during the end of the red period and during the inter green time from the non priority stage to priority stage, donot needed recall. This is also dependent on the travel time from detection point to stop line. When a bus is detected during red, at the time of detection if the estimated travel time from detection point to stop line is greater than the remaining red period then the bus will automatically get green before it arrives at the stop line, so a recall is not required. The effective red period can therefore be defined as the duration of the red period when detected buses require a recall. The higher the detection distance the shorter will be the effective red period. Buses detected during the effective red period will gain from the recall. If buses are provided a recall during the whole red period, as in current practice, the buses detected outside the effective red period will not get any benefit as they do not need priority but due to the unnecessary recall, traffic on the non priority arm(s) will be disbenefited. Figures 3.8 & 3.9 below illustrate the importance of effective red period for a case where the non-priority green time is 30 sec, there are two inter green times of 7 sec each, the total maximum red period for the priority approach is 44 sec, the detector to stop line travel time t = 25 sec for longer detection or t =10 sec for shorter detection.

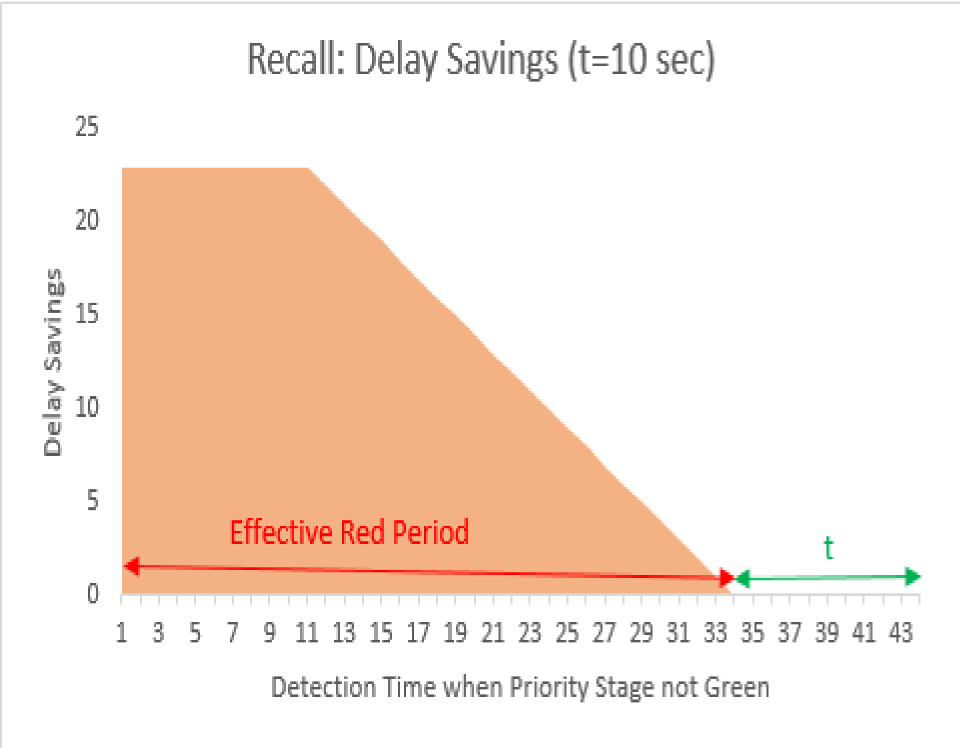


Figure 3.8: Effective red period and delay savings for t =10 sec

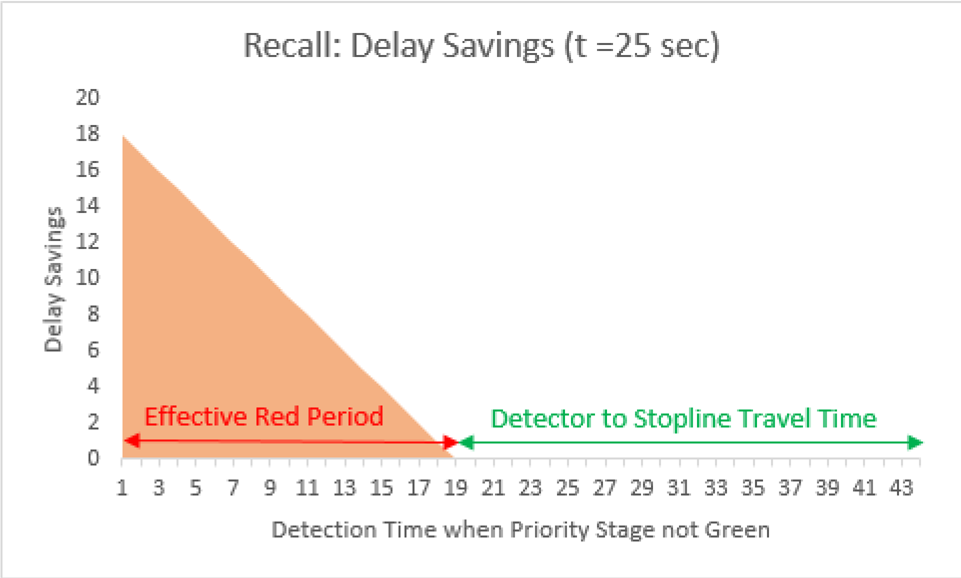


Figure 3.9: Effective red period and delay savings for t =25 sec

Figure 3.8 illustrates that at a 70m detection distance when the detector to stop line travel time is 10 seconds, buses require a recall if detected at or before the 34th second of red. Figure 3.9 shows that at a 162m detection distance when the detector to stop line travel time is 25 seconds, buses require a recall if detected at or before the 19th second of red. So the effective red periods for 70m and 162m detection distance are the first 34 seconds and 19 seconds of total red of the priority approach respectively. That means with the increase of detection distance the duration of effective red decreases which reduces the number of buses getting a recall. The effective red can be calculated by using the following formulae:

Effective red = Maximum red period of the priority approach in a signal cycle – detector to stop line bus travel time.

3.3.2 Priority compensation time

Present practice: Compensation is an extension of the normal maximum running periods which may be introduced, following a priority recall, in nominated signal phases associated with each bus priority phase. These signal phases are the phases that may have terminated earlier than normal due to a recall. Compensation time ensures that the time lost by non-priority traffic is repaid, if required. It should be noted that compensation time may be curtailed by a priority recall and may therefore not work effectively unless a priority inhibition is implemented. Methods (TfL 2001) to calculate required average compensation time(s) are described in TfL's user guide for "Bus Priority-Selective Vehicle Detection in London (U/2706/TO/382)". These methods are appropriate for simple junctions with 2 or 3 signal stages.

Research gap: In current practice, the average green time lost by non priority arms due to each recall is provided to those arms after priority as an additional green time (compensation) if required. But instead of providing compensation based on the average lost green time it may be better to provide the actual lost green lost time. Compensation time is usually protected by implementing inhibit timer, which prevents bus priority being provided in consecutive cycles. However implementation of an inhibit timer has a negative impact on buses, as some buses will be excluded from priority. An alternative operational mode developed in this research is as follows: Instead of an inhibit timer, compensation could be protected by considering compensation requirement parameters. If required and compensation is running, no bus will be considered for priority at that time but will be allocated priority after compensation is completed, if still needed. This could reduce the additional delay to buses due to the inhibit timer. Compensation may not be required in a junction having high conflicting bus flow with active priority in all of its arms. In that situation, green time lost due to a priority recall is likely to be repaid automatically by conflicting priority in the approach which lost green before. The performance of bus priority methods with and without compensation considering conflicting priority therefore needs to be explored.

3.3.3 Priority inhibit time (PVI)

Present practice: The priority inhibit time is a period during which a priority recall from a particular priority unit is inhibited. However, priority extensions are still serviced and the effect of inhibition lasts for one signal cycle only. Without inhibit timers the compensation timers for phases cut short in a previous cycle could be cancelled by a new priority recall. This can cause problems at congested sites with high bus flows where the signal phase with high bus flows may be recalled in consecutive cycles, causing additional delays for traffic on non-priority phases. The use of inhibition at such sites prevents priority recalls being granted in consecutive cycles and, when used with the compensation facility, ensures that the time lost by non-priority traffic phases is immediately repaid if required. However, at sites with low bus flows, the chance of buses recalling priority in consecutive cycles is low and hence this is less of a problem.

The inhibit timer starts as soon as its priority phase gains right of way due to a priority recall, meaning that phases are curtailed or demands skipped in order for the priority phase to gain right of way. When the phase that had the priority recall subsequently reappears, its inhibit timer terminates whatever value remains. The inhibit timer will also cancel when it reaches its set value. Therefore the set value must be high enough to ensure that at least a complete cycle of the method of control runs before the inhibit timer expires. To achieve this, each inhibit timer should be set to 180 seconds (TRG 2007). Note that the inhibit will be effective for the duration of the inhibit timer, or the duration of the cycle, whichever value is least. In many situations, more than one priority unit must be inhibited as a result of a priority recall. This can happen when other opposing phases with priority units which (if activated) would cause the phase that was cut short to be terminated early again, but this time whilst its compensation period is running. Arguably, these priority units should be inhibited too.

Research gap: Further research (TRG 2007) is required to specify the site characteristics to warrant the use of priority inhibit time and to give a more detailed methodology for using it. Inhibit should be dependent on the requirement of non-priority arms. Instead of using whole cycle duration or 180 sec to terminate inhibit timer as recommended previously, it should take account of whether compensation is required (if there is traffic demand) and if required whether compensation is provided. If compensation is not required, the inhibit timer should be stopped immediately. If compensation is required, inhibit timer also should be stopped immediately after providing compensation. This strategy will provide similar dis benefits for non-priority arms but more benefits for buses. Again, bus priority benefits and dis benefits with inhibit when conflicting priority is running in the junction need to be explored. Because, due to inhibit of priority recall in one arm, buses running in the other arms where green is protected by the inhibit will be benefitted.

3.3.4 Always green bus

Present practice: Extensions and recalls are the widely used bus priority methods. Stronger bus priority methods such as ‘stage skipping’ is not generally practiced in the UK because of safety concerns from safety aspects.

Research gap: According to the research gap discussed in the previous Sub Section 3.2.1, it is expected that bus priority benefit will be higher if detected further upstream taking account of junction queue length, minimum green times, and intergreen times. For example: If a detector can be sited in a location which gives detector to signal stop line bus journey time at least equals to or greater than the sum of the intergreen times, minimum green of non prioirty arms, and queue clearance time, then theoretically it is possible that a bus will not need to stop due to signal if detected during red and if recall is provided. Because, before arrival to the signal stop line, when buses arrive at the end of the queue, signal will turn to green and traffic queue will start to clear. Figure 3.10 below illustrates the strategy. It is a stronger priority strategy which may also have additional delay to non priority traffic. The performance of this method needs to be explored.

D1 = distance between the detector and end of the traffic queue = (Inter green times + Minimum green times)* Average bus speed.

D2 = Average queue length.

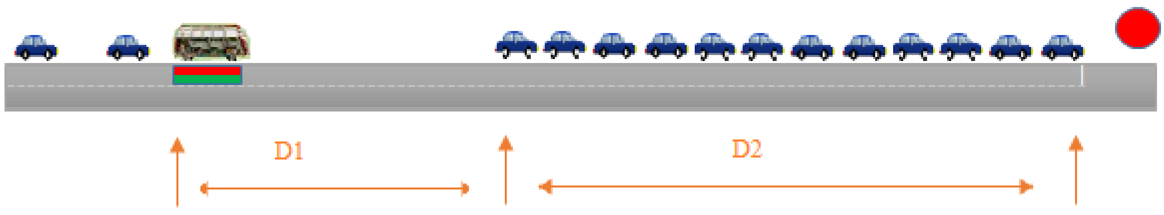


Figure 3.10: Strategy for siting a detector for always green bus

3.3.5 Multiple detectors

Present practice: A single bus detector is used to detect buses for priority.

Research gap: Due to the availability of virtual detectors it is now possible to implement multiple detection without any new infrastructure. Research gap discussed in the previous Sections 3.2.1, it is understood that optimal siting for extension may not be optimal for recall. So, instead of using a single detector, two detectors would be beneficial. One for extension and other is for recall. Again, to avoid the negative impact due to increase of journey time variability with detector distance, exit detectors just after the signal stop line will be beneficial. This exit detectors may cancel the priority when buses are detected or hold the priority until detected. The performance of bus priority methods considering multiple detectors and exit detectors need to be explored.

3.3.6 Differential priority

Present practice: Priority is given to all detected buses in most cases.

Research gap: Stronger priority methods such as 'always green bus' will provide higher delay savings to buses compared to traditional methods with addition delay to non-priority traffic. Usual bus priority methods also have high dis-benefits especially when the junction is congested and buses are detected early. So, when bus priority incurs high dis-benefit to non-priority traffic, priority could be provided targeting late buses only. This will alleviate the negative impact.

3.4 Priority conflict

Present practice: Bus priority at junctions where there can be conflicting priority calls operate on a 'first come, first served principle', but with priority extensions taking precedence over priority recalls. The performance of this algorithm has not been assessed previously to any great extent.

Research gap: In busy city centres, it is common that bus services run through conflicting arms of a junction. In that situation, bus priority on more than one or all signal stages may be required. If that junction has a high bus flow, it is likely that buses will arrive on different arms (same signal stage) at the same time. If this happens, priority on one arm will have a negative impact on buses arriving at the same stage on conflicting arms. For example: if a bus arrives first during green of a junction approach, it will be provided extension if needed. But if another bus arrives during red at the same stage in another approach, that bus will not be provided an immediate recall; instead it has to wait longer due to priority extension of the first bus. Again, if a bus arrives first in a junction approach during red, it will be provided with a recall but if another bus arrives during green on other junction approach of the same stage it will not get extenson even if needed instead green will be cut due to the recall for the first bus. So when buses run through conflicting arms of a junction at the same stage, priority on one arm will have negative impact on buses of conflicting arms. If bus flow is high, the performance of the priority methods is likely to be reduced. Research could be valuable here to explore the performance of bus priority methods considering priority conflicts.

3.5 Signalised pedestrian crossing

Present practice: Priority to buses at signalised pedestrian crossings is provided only by a green extension.

Research gap: Signalised pedestrian crossings are very common in places of high bus passenger generation. These pedestrian crossings also delay buses especially where pedestrian demand is high. Present practice is generally not to offer bus priority at pedestrian crossings, but where priority is provided it is by a traditional green extension. A recall is not allowed because of safety concerns for pedestrians if their crossing times are cut short. The result is that buses often have to stop at pedestrian crossings, an undesirable feature of their operations. New research seeking improved provision for buses at pedestrian crossings would therefore seem to be justified.

3.6 Evaluation of bus priority: theoretical approach

Present practice: Evaluation of bus priority using a theoretical technique would be valuable to understand the expected performance of priority methods and also for the validation of the micro-simulation models. However, the existing formulae to calculate bus priority benefits are based on several assumptions for simplicity and provide a rough guide (Vincent et al. 1978). Also some important parameters are not considered in the formulae.

Research gap: The performance of the priority methods might be able to be calculated more accurately by deriving new formulae and graphical procedures considering important new parameters which were not considered before. For example: additional delay due to acceleration, additional delay due to queuing traffic during red, effective red period for priority, and travel time between the detector to the stop line. These observations suggest a good case for further research in to theoretical approaches.

3.7 Chapter summary

Table 3.5 summarises the research gaps discussed in this Chapter. It also highlights the research gaps considered for detailed and limited study in the next Chapters with reasons for these selections also highlighted.

Table 3.5: Research gaps summary

Research Gaps	Study Type	Main Reason
Priority parameter : detector location	Detailed	Main parameter controls priority benefits
Priority parameter: priority maximum time	Detailed	Control detector location
Priority parameter : priority extension time	Limited	Dependent on detector location
Priority parameter : priority minimum time	Detailed	Controls benefits from recall
Priority parameter : effective red	Detailed	Controls performance of recall
Priority parameter : queue length	Detailed	Controls performance of recall
Priority compensation time	Limited	Repaid considering actual loss
Priority inhibit time	Detailed	Reduce priority dis benefits
Priority conflict	Detailed	Can reduce priority benefits
Signalised pedestrian crossing	Detailed	To explore bus friendly crossing
Always green bus	Detailed	New and stronger priority
Multiple detectors	Limited	Availability of virtual detectors
Differential priority	Limited	To reduce the dis benefits of stronger methods
Theoretical evaluation	Detailed	To predict priority performance more accurately

It has been illustrated in this Chapter that performance of bus priority methods can be increased by improving currently operating parameters (detector location, priority maximum time, priority extension time, priority minimum time) and also by considering new parameters (effective red, and queue length). To address the identified research gaps following studies have been carried out in the next Chapters. These are: By using micro-simulation modelling in depth research has been carried out to understand the impact of these parameters on priority benefits. Detailed study also has been carried out to explore better compensation strategies for non-priority traffics. Performance of priority methods also have been evaluated considering priority conflict. Micro simulation models have been developed to test the performance of priority methods on isolated vehicle actuated junctions and pedestrian crossing. New strategy ‘always green bus’ has been considered for in depth evaluation to understand wider impact as it is a stronger method. Exits detectors have been modelled to understand their impact on priority performance and operational efficiency. To reduce the dis benefits of stronger priority methods, differential priority has been modelled targeting late buses only for priority. To predict the performance of priority methods more accurately new theoretical techniques have been developed.

Chapter 4: Evaluation of Bus Priority at Traffic Signals: Theoretical Methods

4.1 Introduction

Evaluation of bus priority at traffic signals is necessary to understand the potential benefits and possible negative impact. The main benefit to buses is junction delay savings, while potential dis benefits to non-priority traffic can be additional delay to them. This Chapter describes derivation of formulae to calculate bus delay savings and additional delay to non-priority arms by traditional and proposed bus priority methods for various junction types. Delay savings to buses by traditional methods using theoretical techniques are also available in the TRRL Laboratory Report 814 &1089 (Vincent et al. 1978 and Cooper 1983). These are based on several assumptions for simplicity but will provide a yardstick for comparison with the formulae developed in this research. The formulae derived in this research include essential new factors such as additional delay due to acceleration, additional delay due to queuing traffic during red, effective red period for priority, and travel time between detector to stop line. The theoretical techniques described to estimate the impact on non-priority traffic in this Chapter will provide minimum impact because of several simplified assumptions. Procedure to estimate delay to non-priority traffic using Websters formula (Webster and Cobbe 1966) has also been illustrated in previous studies (TRG 1987). But, again, that procedure provides approximate estimations only because during the calculation of green lost time by non priority arms the impact of bus detection time and effective red period were not considered. In the graphical procedure illustrated in this Chapter, average green lost time is estimated more accurately. The proposed theoretical methods are ‘validated’ here by comparing results with the micro-simulation models, existing analytical methods, and SELKENT scheme’s findings.

4.2 Signal and junction details

The following parameters have been used in this Chapter for the derivation of formulae.

Detector distance = S meters.

Detector to stop line travel time = $t+2$ sec.

Green time for priority stage = $g1$ sec .

Intergreen 1-2 = $ig12$ sec

Minimum green for stage1 = $g1m$ sec

Cycle time = C sec

Average queue length on priority approach during red = Q cars

Time taken per car to start to move after red = Qr sec

Average delay due to queue clearance = Dq sec

Delay due to acceleration = Da sec

Bus flow per hour on priority stage = F

Two Signal Stages (additional details)

Green time for non priority stage1 = $g2$ sec.

Intergreen 2-1 = $ig21$ sec

Minimum green for stage2 = $g2m$ sec

Two Signal Stages and One Pedestrian Stage (additional details)

Green time for non priority stage1 = $g2$ sec.

Green time for pedestrian stage = ped sec.

Minimum green for stage2 = $g2m$ sec

Intergreen 2-3 = $ig23$ sec

Intergreen 3-1 = $ig31$ sec

Three Signal Stages (additional details)

Green time for non priority stage1 = $g2$ sec.

Green time for non priority stage2 = $g3$ sec.

Minimum green for stage2 = $g2m$ sec

Minimum green for stage3 = $g3m$ sec

Intergreen 2-3 = $ig23$ sec

Intergreen 3-1 = $ig31$ sec

Three Signal Stages and One Pedestrian Stage (additional details)

Green time for non priority stage1 = $g2$ sec.

Green time for non priority stage2 = $g3$ sec.

Green time for pedestrian stage = ped sec.

Minimum green for stage2 = $g2m$ sec

Minimum green for stage3 = *g3m* sec

Intergreen 2-3 = *ig23* sec

Intergreen 3-4 = *ig34* sec

Intergreen 4-1 = *ig41* sec

4.3 Green Extensions

4.3.1 Steps to calculate average delay savings by each extension

If a bus is detected when the priority stage is green then an extension may be required. Buses fail to cross the stop line if detected during the last t secs of green. So an extension is needed during the last t secs.

The definition of delay (used for derivation): Travel time to cross the section between detection point to stop line. It includes the remaining red when the bus arrives at the stop line and the additional delay due to stopping. These additional delays are acceleration delay and the delay to clear queuing traffic. Table 4.1 below shows the steps to calculate delay savings with various detection times.

Table 4.1: Delay savings with various detection time (extension)

Bus Detection Time	Delay: without Extension	Delay: with Extension	Delay Savings
Scenario 1: Bus detected last sec of green	*t+ (c-g1 -t) + Dq + Da*	*t*	*(c-g1-t) + Dq +Da*
Scenario 2: Bus detected (g1-t) sec of green	*t + (c-g1) + Dq +Da*	*t*	*(c-g1) + Dq +Da*
Scenario 3: Bus detected g1-t -1 sec of green (remaining green >t)	*t*	*t*	*0*
Scenario 4: Bus detected 1st sec of green (remaining green >t)	*t*	*t*	*0*

When a bus is detected at g1 seconds of green (Scenario1 of Table 4.1) in Figure 4.1, then, without an extension, the time required to cross the section between the detection point and the stop line is the travel time (t) within the section, remaining red when arriving at the stop line (C-g1-t), the delay due to queue clearance (Dq), and acceleration delay (Da). However, when an extension is provided the time required to cross the section between the detection point and the stop line is only the travel time (t) within the section because the bus will not see any red signal (so, no delay due to red) and there is no acceleration delay (because of no stopping), and there is no queue clearance delay (because of no queue). That means the delay savings generated by an extension compared to without an extension is [(C-g1-t)+Dq+Da] which is the sum of the remaining red at the stop line (without an extension), the delay due to the queue and the acceleration (without extension).

Similarly, when a bus is detected at g1-t second of green (Scenario2 of Table 4.1) in Figure 4.1, then, without an extension, the time required to cross the section between the detection point and the stop line is the travel time (t) within the section, the remaining red when the bus arrives at the stop line (C-g1), the delay due to queue clearance (Dq), and the acceleration delay (Da). However, when an extension is provided the time required to cross the section between the detection point and the stop line is only the travel time (t) within the section for the same reasons described in Scenario 1. That means that the savings generated by an extension compared to without an extension is [(C-g1)+Dq+Da] which is the sum of the remaining red at the stop line (without extension), the delay due to the queue and the acceleration (without extension).

However, if a bus is detected at any time less than g1-t (Scenario3 and 4 of Table 4.1) in Figure 4.1, then the bus will arrive at the stop line during green with or without an extension. In both cases, the time required to cross the section between the detection point and the stop line is the bus travel time (t) within the section. Therefore, in this scenario an extension would not produce any benefit and is not therefore required.

Delay savings from an extension have been plotted graphically in Figure 4.1 by using the phase diagram of the priority approach, and by using the amount of delay saved (Table 4.1) due to an extension when detected in Scenarios1, 2, 3 and 4. This graphical plot has been used to estimate average delay savings from each extension and also to estimate delay savings when the bus detection time with respect to the phase diagram is known.

Figure 4.1 illustrates delay savings from extensions according to the time of detection. Average queue clearance delay savings are considered for simplicity.

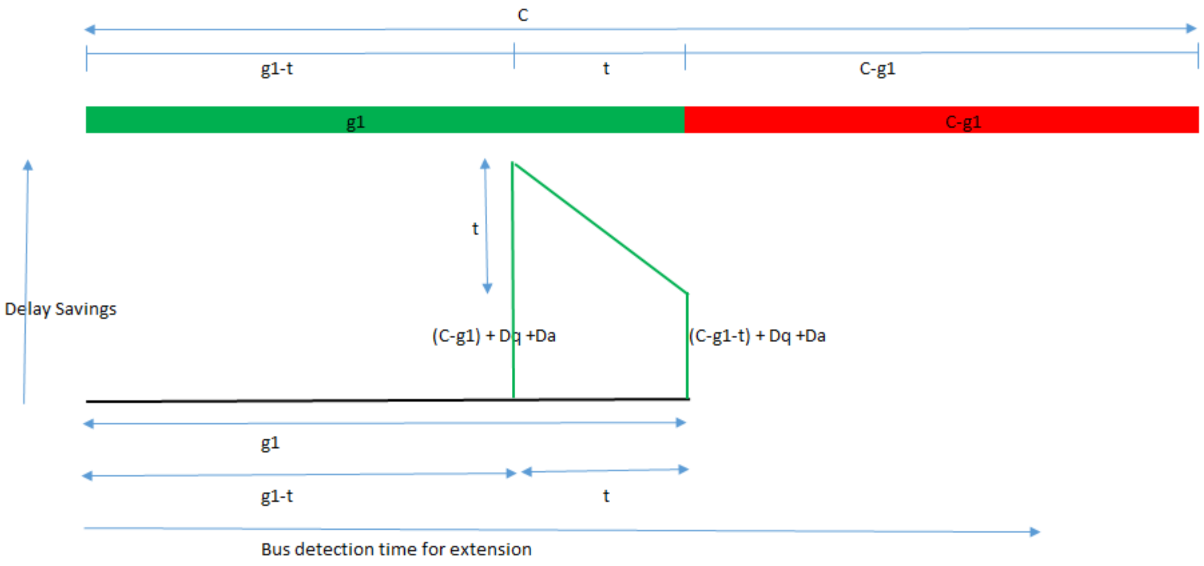


Figure 4.1: Delay savings by extension with time of detection

A bus will benefit from an extension if detected during the last t secs of green. Benefits will be highest if detected at (g1-t) sec. Benefits will be lowest if detected at the last sec of green. Average benefits will be = (c-g1-t) + Dq +Da + 1/2*t = c-g1-1/2*t + Dq +Da.

The bar charts in Figures 4.2 to 4.4 illustrate junction delay and savings with and without extensions for a junction with 40 sec green for the priority approach, 74 sec cycle time, 10 sec travel time from detector to stop line, and queue length during red in the priority approach 15 cars (assumed 7 sec queue clearance delay), and 2 sec acceleration delay (assumed).

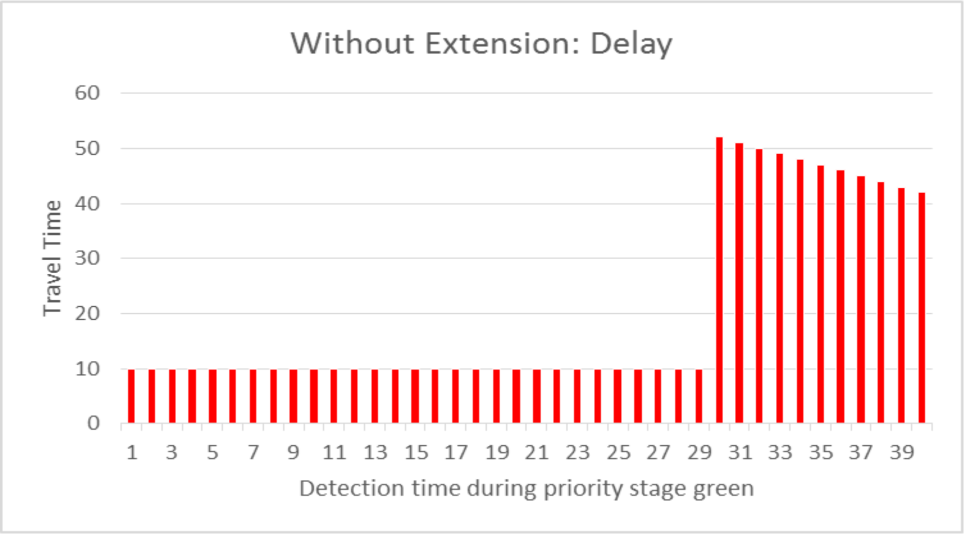


Figure 4.2: Delay without extension

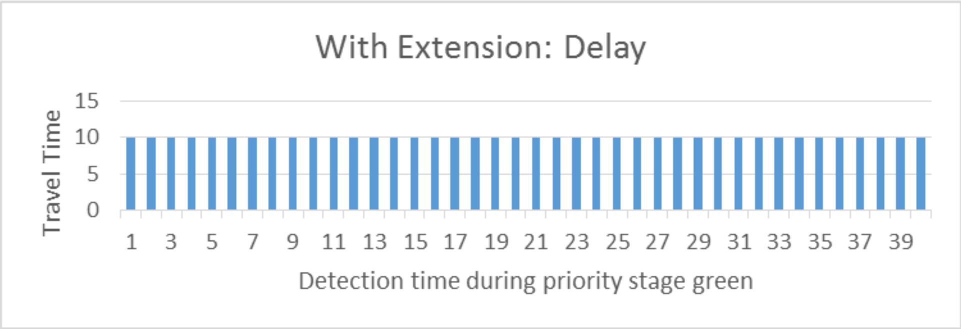


Figure 4.3: Delay with extension

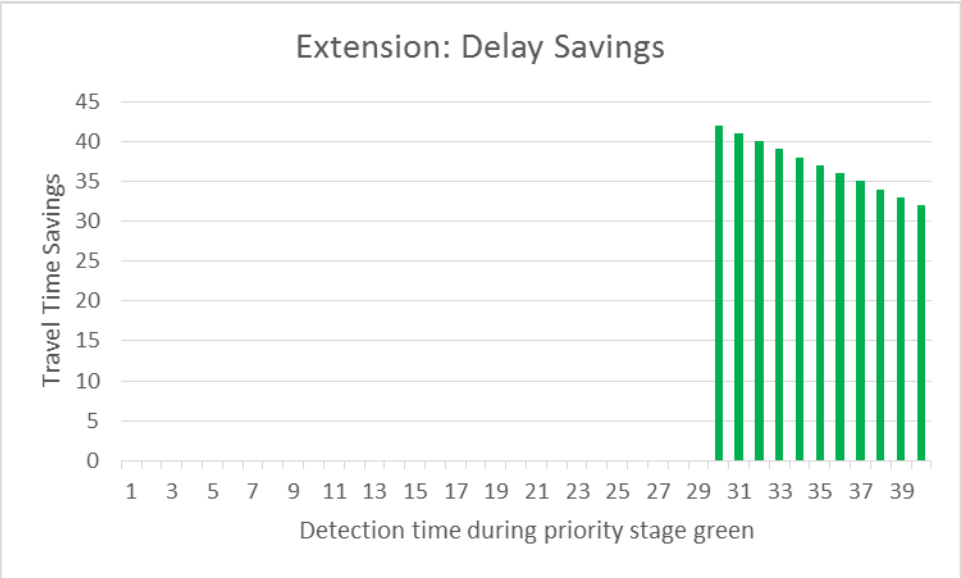


Figure 4.4: Delay savings by extension

Figures 4.2 and 4.3 have been plotted by using the steps described in Table 4.1. Figure 4.4 has been plotted by subtracting 4.3 from 4.2 which provides delay savings due to an extension with the time of bus detection for a junction having the characteristics described above.

4.3.2 Derivation of formulae to calculate average benefits

Without priority, buses fail to cross the stop line if detected during the last t sec of green considering 2 sec of amber as effectively green. So priority is needed during this period.

So effective green for extension *(Ge) = t* sec. That time period can also be called *time for extension.*

Average delay due to signal queue *(Dq) = 1/2*Q*Qr* sec

Average delay savings due to each extension *(Be) = C-g1-t/2+Da+Dq* sec

Bus flow per cycle on priority stage *(f) = F*C/3600*

Assumption: Poission distribution of bus arrivals; buses arrive at traffic signals randomly and independently, bus arrival is uniform.

The probability of no bus arrival during cycle time *(Po) = Poi(f)*

The probability of one or more bus arrivals during cycle time *(P1) = 1-Po*

The probability of bus detection during effective green for extension *(Pe) = t/C*

Average benefits per cycle *(Bc) = Pe*P1*Be* sec/cycle

Average benefit *(B) = 3600/C*Bc*1/F* sec/bus

Benefits derived from the theoretical calculation provide the maximum benefits achievable. In reality benefits will be less because not all detected buses during the effective green for extensions will get an extension because of the maximum extension time constraints.

4.3.3 Steps to calculate dis benefits by each extension to non priority arms

Two Stages: Dis benefits to non-priority arm 1

Assume an extension is provided in the last t seconds of g1. So the average extension time is *t/2* sec.

Other assumptions:

- Cars arrives at the stop line uniformly
- It is obvious that due to priority queue will increase at the non priority arms. But delay due to this increase has not been considered. Additional delay when some of the queuing traffic fail to clear the stop line after priority when signal turns to green for them due to long queue build-up is not considered. It is assumed that after bus priority all queuing traffic during red will be able to clear the junction when signal turns to green for them.

Car detected just before stop line

Table 4.2 below shows the delay increase to non-priority traffic with various arrival times at the stop line.

Table 4.2: Delay increase to non-priority traffic with various arrival times at the stop line

Arrival time at stop line	Without Extension: Delay	With Extension: Delay	Delay Increase
Scenario1: 1st Second of ig21	*ig21+g1+ig12*	*ig21+g1+t/2+ig12*	*t/2*
Scenario2: Last Second of ig21	*g1+ig12*	*g1+t/2+ig12*	*t/2*
Scenario3: Last Second of g1	*ig12*	*t/2+ig12*	*t/2*
Scenario4: g1+t/2 second	*ig12-t/2*	*ig12*	*t/2*
Scenario5: Last Second of ig12	*0*	*t/2*	*t/2*
Scenario6: ig12+t/2 second	*0*	*0*	*0*

A car arriving at the stop line during the first second of the red signal (Scenario1 in Table 4.2) as illustrated in the phase diagram (Figure 4.5) for the non priority arm, has to wait to get a green signal. Without an extension the waiting time is the remaining red which is the inter green time from stage 2 to stage 1 (ig21), the duration of green of the priority stage (g1), and the inter green time from stage 1 to stage 2 (ig12) in this case. But with an extension on the priority approach the waiting time of that car increases because the remaining red is extended which is the inter green time from stage 2 to stage 1 (ig21), the duration of extended green of the priority stage (g1+t/2), and the inter green time from stage 1 to stage 2 (ig12). So for this particular car the delay increase is due to the extension on priority approach and is t/2 seconds.

A car arriving at the stop line during the last second of inter green of ig21 (Scenario2 of Table 4.2) as illustrated in the phase diagram (Figure 4.5) of the non priority arm, has to wait less to get a green signal as the inter green ig21 has already passed. Without an extension the waiting time is the remaining red which is the duration of green for the priority stage (g1), and inter green time from stage 1 to stage 2 (ig12). However, with an extension on the priority approach, the waiting time of that car increases because the remaining red is extended by the duration of the extended green of the priority stage (g1+t/2), and the inter green time from stage 1 to stage 2 (ig12). So for this particular scenario the car delay increase due to the extension on the priority approach is t/2 seconds.

However, when a car arrives at the non priority arm stop line during the last second of green g1 of priority approach (Scenario3 of Table 4.2), the car has much less delay. Because the inter green time ig21 and green time g1 have already passed. Without an extension the remaining red is the duration of inter green time from stage 1 to stage 2 (ig12). But with an extension the remaining red is extended which is the duration of average extension (t/2), and the inter green time from stage 1 to stage 2 (ig12). So for this particular scenario the car delay increase due to the extension on the priority approach is t/2 seconds.

Again, a car detected at the non priority arm stop line during the last second of inter green of ig12 (Scenario5 of Table 4.2), does not need to wait without extension as red period has already passed. Without an extension the remaining red is zero. But with an extension the remaining red is the average duration of an extension (t/2). So for this particular scenario, the car delay increase due to the extension on the priority approach is also t/2 seconds.

Finally, a car detected at the non priority arm stop line during the last second of extended red (Scenario6 of Table 4.2), does not need to wait with or without extension. This is because without an extension the car arrived at the stop line during green of the non priority arm. But with an extension the extended red has just finished. So for this particular scenario and for all car arrivals after that in a signal cycle, there is no delay increase due to the extension at priority approach.

By using the amount of car delay increase in each scenario of Table 4.2 and by using the phase diagram of the non priority arm, the car delay increase due to extension with car arrival time at the non priority arm stop line has been plotted (Figure 4.5). This graphical plot has been used to estimate the average delay increase at the non priority arm by each extension and to estimate the exact delay increase for traffic due to an extension when traffic arrival time at the stop line is known.

The scenarios of Table 4.2 are illustrated in Figure 4.5 below, which shows graphically the delay increase by extension to non priority arm1 of a two stage signal control junction.

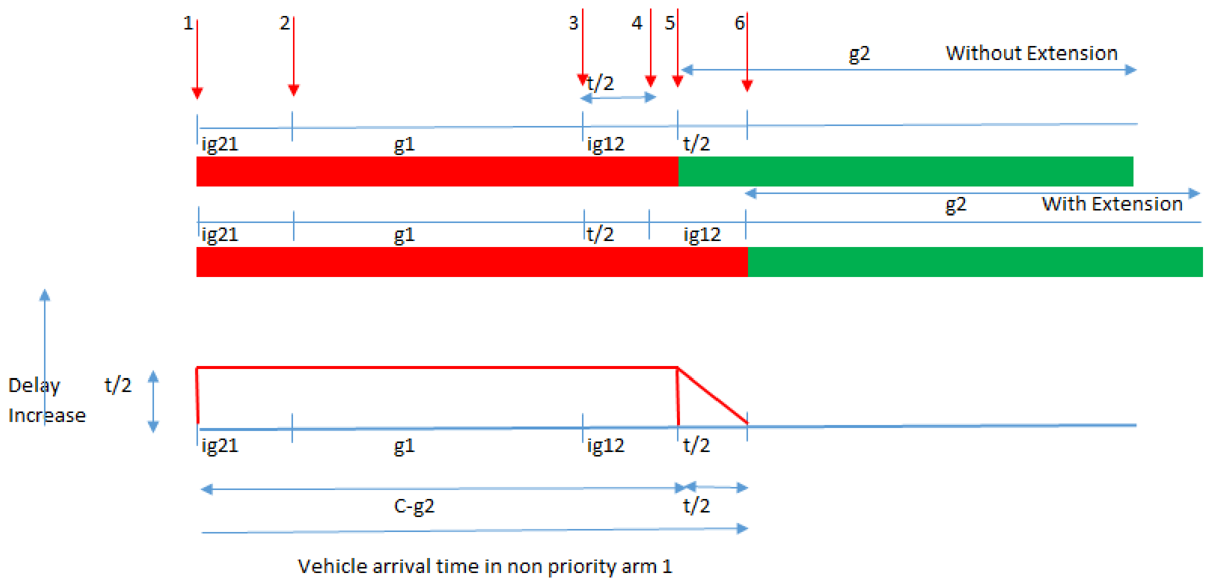


Figure 4.5: Delay increase due to green extension to non priority arm1 (two stage)

Using the procedure described above, the delay increase to non priority arms for other junctions such as junctions having 1) two traffic stages and one pedestrian stage, 2) three traffic stages, 3) three traffic stages and one pedestrian stage, have been plotted. Those graphs of delay increase show the same trend as shown in Figure 4.5 above. So the graph for delay increase to non priority arms can be generalised as follows:

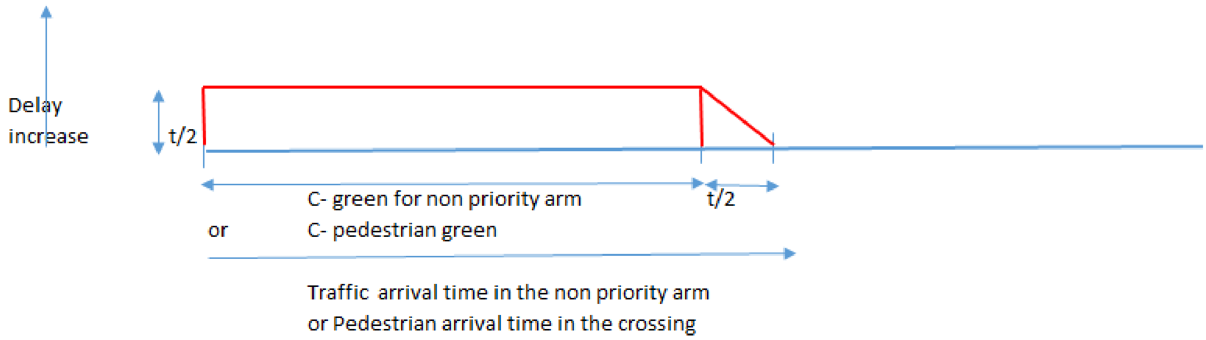


Figure 4.6: Delay increase to non priority arms by extension

4.3.4 Derivation of formulae to calculate average dis benefits to a non priority arm

Delay increase to non priority arm during *(R1) = C- green for non priority arm + t/2* sec

Average delay increase by each extension = *De* sec

Traffic flows on non priority arm = *Fc1* vehicles/hr

During duration R1 vehicle arrivals *(N1) = Fc1*R1/3600* Nr

Total delay increase by each extension in one cycle *(Dt) = De*N1* sec

Number of cycles with an extension *(Ce) = Pe*P1*3600/C* Nr

Calculation of *Pe and P1* is described in the previous Sub Section (4.3.2).

Average delay increase *(D) = Ce*Dt/Fc1* sec/vehicle

The delay increase due to an extension derived by this theoretical method could be less than actual because in reality a long queue may build up on non priority arms because of the extension and not all queuing vehicles will be able to cross the stop line when the signal turns to green for them. For those who missed the green signal after an extension, their delay will be much higher (average delay by extension +cycle length).

Tables 4.3, & 4.4 below show benefits and dis benefits due to an extension for a two stage junction calculated by the theoretical methods developed here.

<u>Notes:</u> [g1/C= Priority Green/Cycle Time; t+2 = Detector to stop line travel time; B = Benefits to buses; NT = Dis benefits to non priority traffic; + = Delay savings; - = Delay increase]

Table 4.3: Benefits and dis benefits by extension (100m detection distance)

Two Stage Junction (T-Junction without Pedestrian Crossing), Extension, Detection 100m, g1/C = 0.6										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
12	4.38	0.14	3.92	0.26	3.18	0.41	2.63	0.51	2.21	0.58

Table 4.4: Benefits and dis benefits by extension (with detection distance)

Two Stage Junction (T-Junction without Pedestrian Crossing), Extension, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.2		.3		.4		.5		.6		.7	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
6	3.99	0.03	3.49	0.04	3.03	0.05	2.54	0.06	2.13	0.06	1.60	0.07
12	7.63	0.13	6.64	0.16	5.72	0.20	4.75	0.23	3.92	0.26	2.87	0.29
18	10.95	0.31	9.46	0.38	8.08	0.45	6.63	0.52	5.38	0.59	3.80	0.66
24	13.92	0.57	11.95	0.70	10.09	0.83	8.18	0.95	6.49	1.07	4.40	1.20
30	16.56	0.93	14.10	1.12	11.77	1.32	9.39	1.51	7.27	1.70	4.67	1.91

Benefits and dis benefits due to green extensions for other junction types calculated by the theoretical methods are given in the appendix A.

4.4 Recall

4.4.1 Steps to calculate average delay savings by each recall

If a bus is detected when the priority stage is not green a recall may be required.
Delay here is defined as the waiting time before crossing the stop line.
Table 4.5 below describes the methods to estimate delay savings by recall.

Table 4.5: Methods to estimate delay savings by recall.

Bus Detection Time	Without Recall: Delay *(Dw)*	With Recall: Delay *(Dr)*	Delay Savings *(Sr)* *Sr = Dw-Dr*
	Remaining red when detected – detector to stop line travel time + Dq +Da	Remaining red after recall – detector to stop line travel time + Dq +Da	Delay without recall- delay with recall

Delay savings by each recall is dependent on the location of priority detector. Considering various detector siting location (different *t*), delay saving by recall for different junction types are illustrated below. When buses are detected early (the detector is sited relatively far from the stop line), it is likely that due to the early green because of the recall the queue discharge will start early. There will be additional delay savings due to this early queue discharge, but for simplicity this is not considered.

Two Stage Junctions

Tables 4.6, 4.7, & 4.8 below illustrate the steps to calculate bus delay savings due to a recall with the time of bus detection for different travel times from detector to stop line.

Table 4.6: Bus delay savings due to a green recall with time of detection (t <= ig21)

Bus Detection Time	Without Recall: Delay	With Recall: Delay	Delay Savings
Scenario 1: Bus detected during ig12	*ig12 + g2 + ig21 + Dq +Da -t*	*ig12 + g2m +ig21 +Dq +Da - t*	*g2-g2m*
Scenario 2: Bus detected 1st second of g2	*g2 + ig21 + Dq +Da -t*	*g2m +ig21 +Dq +Da -t*	*g2-g2m*
Scenario 3: Bus detected g2m second of g2	*g2 - g2m + ig21 + Dq +Da -t*	*ig21 +Dq +Da -t*	*g2-g2m*
Scenario 4: Bus detected last second of g2	*ig21 + Dq +Da -t*	*ig21 +Dq +Da -t*	*0*
Scenario5: Bus detected during ig21	*ig21 + Dq +Da -t*	*ig21 +Dq +Da -t*	*0*

Table 4.7: Bus delay savings due to a green recall with time of detection (ig12+g2m+ig21> t > ig21)

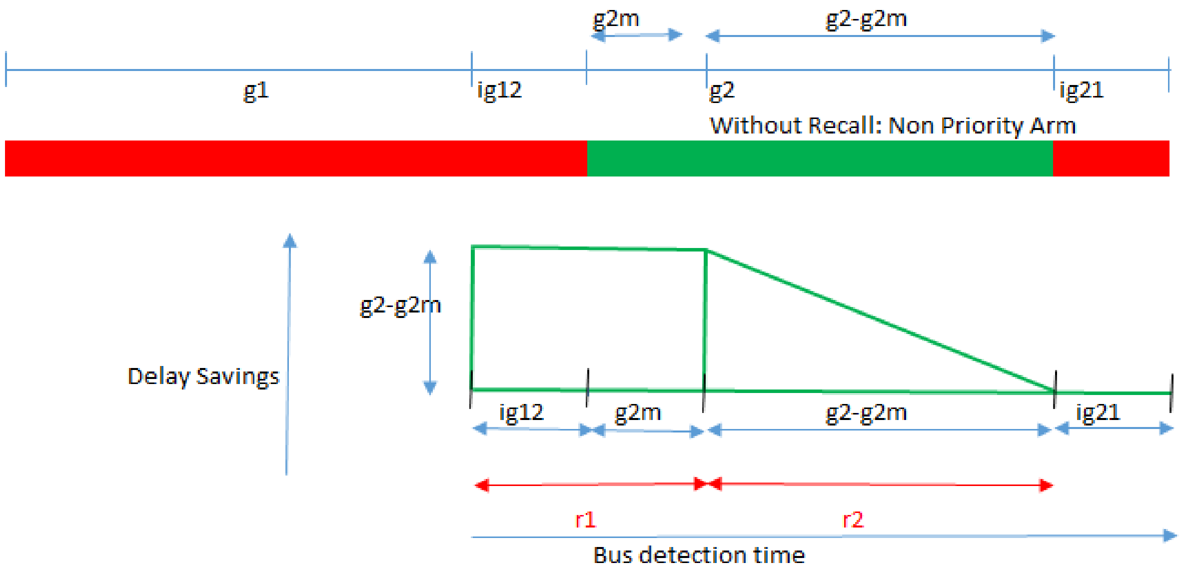
Bus Detection Time	Without Recall: Delay	With Recall: Delay	Delay Savings
Scenario 1: Bus detected during ig12	*ig12 + g2 + ig21 + Dq +Da -t*	*ig12 + g2m +ig21 +Dq +Da - t*	*g2-g2m*
Scenario 2: Bus detected 1st second of g2	*g2 + ig21 + Dq +Da -t*	*g2m +ig21 +Dq +Da -t*	*g2-g2m*
Scenario 3: Bus detected ig12+g2m+ig21-t	*(ig12+g2+ig21) –(ig12+g2m+ig21-t)+ Dq +Da -t*	*(ig12+g2m+ig21) –(ig12+g2m+ig21-t)+ Dq +Da -t*	*g2-g2m*
Scenario 4: Bus detected C-g1-t	*Dq +Da*	*Dq +Da*	*0*
Scenario5: Bus detected after C-g1-t	*Dq +Da*	*Dq +Da*	*0*

Table 4.8: Bus delay savings due to a green recall with time of detection (t >= ig12+g2m+ig21)

Bus Detection Time	Without Recall: Delay	With Recall: Delay	Delay Savings
Scenario 1: Bus detected during ig12	*ig12 + g2 + ig21 + Dq +Da -t*	*Dq +Da*	*ig12 + g2 + ig21 -t = C-g1-t*
Scenario 2: Bus detected at (ig12+g2+ig21-t)	*Dq +Da*	*Dq +Da*	*0*
Scenario 3: Bus detected after (ig12+g2+ig21-t)	*Dq +Da*	*Dq +Da*	*0*

Figures 4.7, 4.8 & 4.9 below illustrate delay savings due to a green recall with time of detection for different detector sittings.

Figure 4.7 below illustrates the bus delay saving due to each recall with time of detection (t <= ig21).



Effective red period = r1+r2 = C-g1-ig21 (when t <= ig21)

Figure 4.7: Bus delay saving due to each recall with time of detection (t <= ig21)

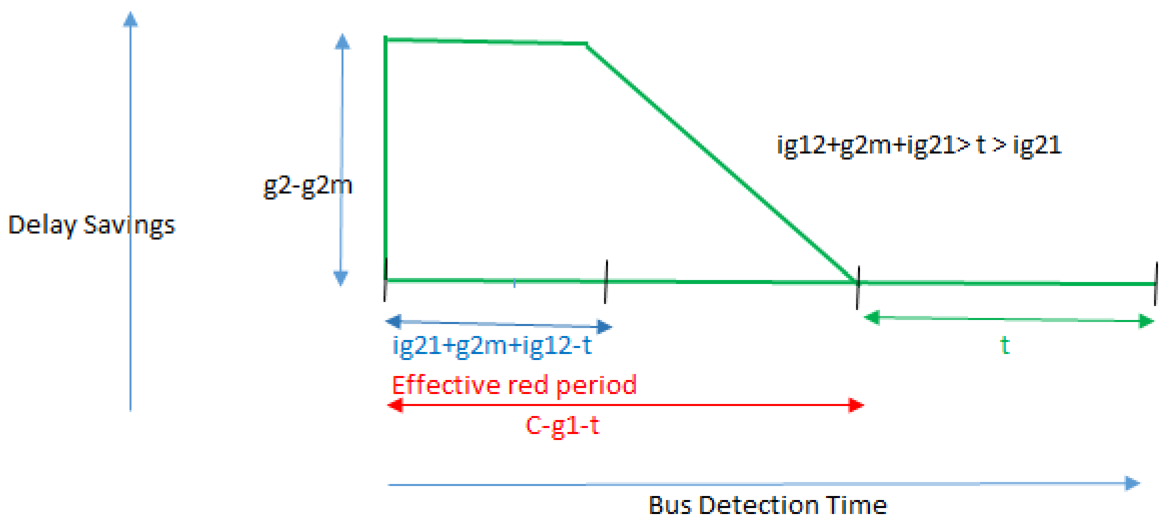


Figure 4.8: Bus delay saving due to each recall with time of detection (ig12+g2m+ig21>t > ig21)

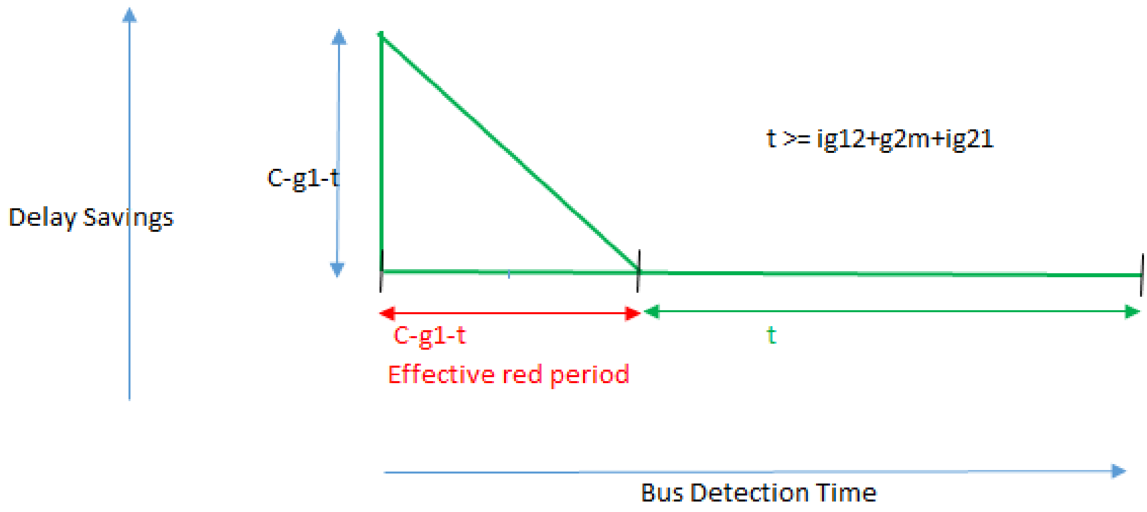


Figure 4.9: Bus delay saving due to each recall with time of detection (t >= ig12+g2m+ ig21)

Figures 4.10, 4.11 & 4.12 bellow describe delay to buses with and without a recall with time of detection and then illustrates bus delay savings due to a recall. Signal details are: g1= 40 sec, g2 = 20 sec, ig12 = ig21 = 7 sec, g2m=7 sec, t =7 sec. These examples are for illustration only.

Figure 4.10 below illustrates the delay to buses without recall with time of detection.

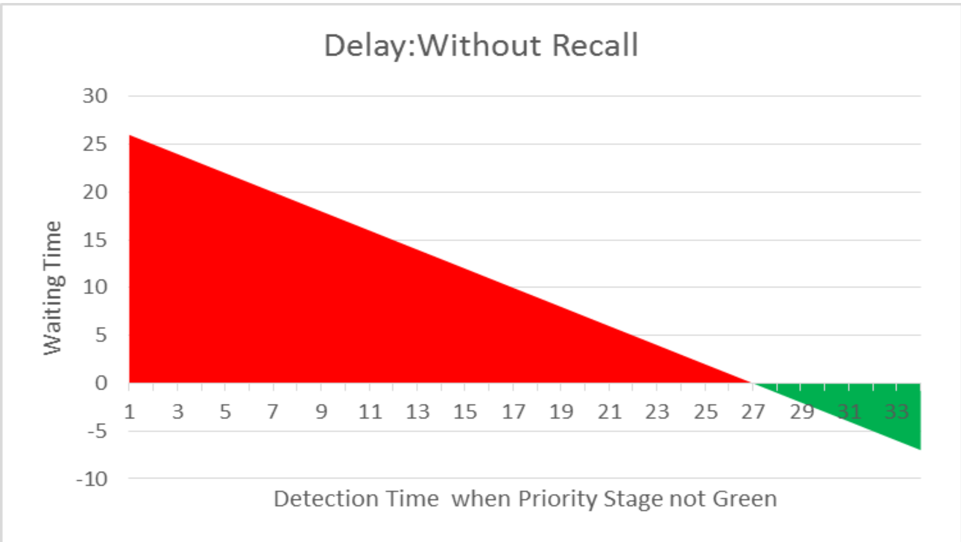


Figure 4.10: Delay to buses without recall with time of detection

Figure 4.11 below illustrates the delay to buses due to a recall with time of detection.

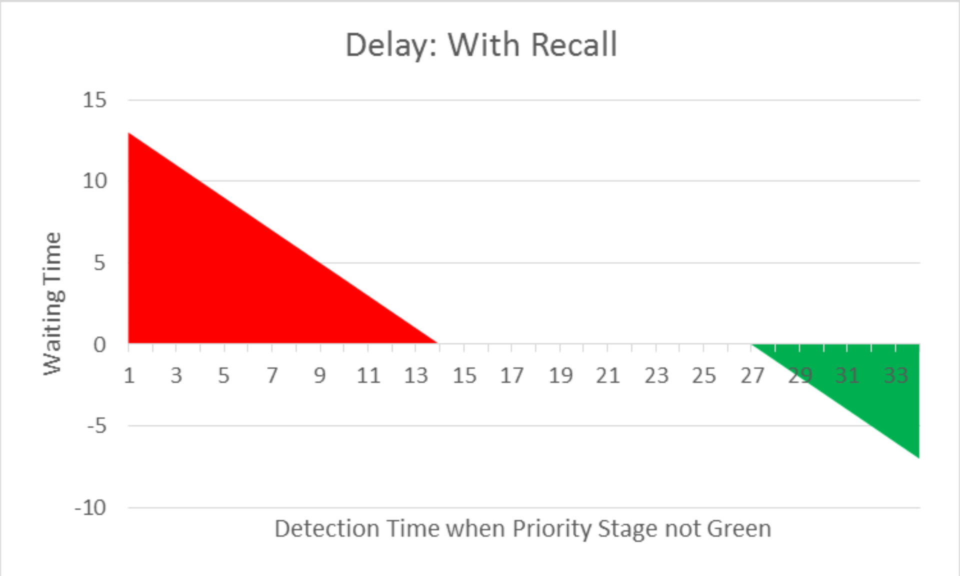


Figure 4.11: Delay to buses due to a recall with time of detection

Figure 4.12 below illustrates the delay savings to buses due to a recall with time of detection.

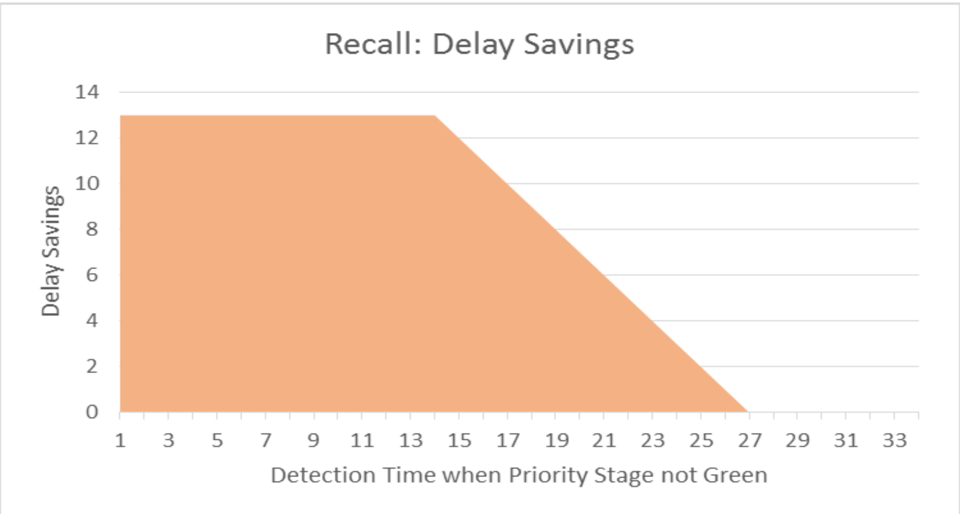


Figure 4.12: Delay savings to buses by recall with time of detection

Two Stage & One Pedestrian Stage Junction

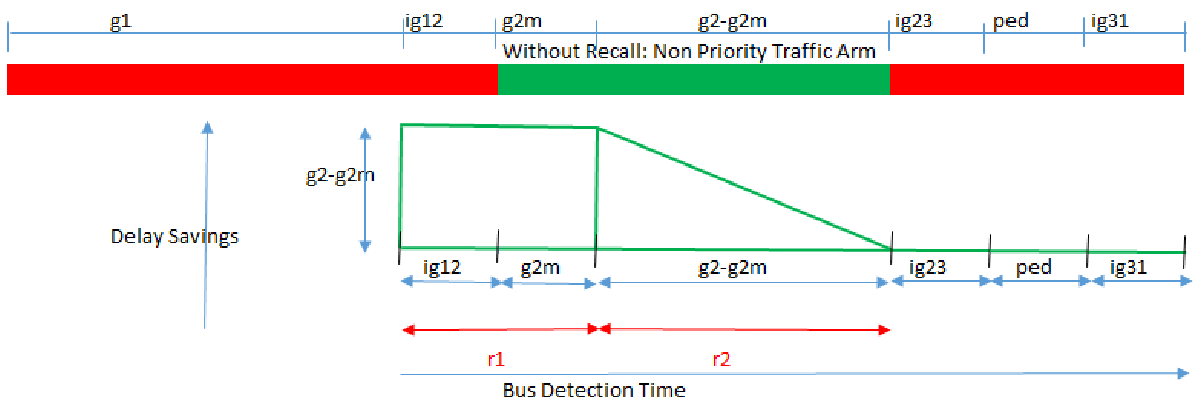
Table 4.9 below shows the steps to calculate the delay savings due to a recall with time of detection (when $t <= ig23+ped+ig31$) for a three stage junction which includes a pedestrian stage.

Table 4.9: Bus delay savings due to a recall with time of detection (t <= ig23+ped+ig31)

Bus Detection Time	Delay without Recall	Delay with Recall	Delay Savings
Scenario 1: Bus detected during ig12	*ig12 + g2 + ig23 + ped + ig31 + Dq +Da -t*	*ig12 + g2m +ig23 + ped + ig31 +Dq +Da -t*	*g2-g2m*
Scenario 2: Bus detected 1st second of g2	*g2 + ig23 + ped + ig31 + Dq +Da -t*	*g2m +ig23 +Ped + ig31 +Dq +Da -t*	*g2-g2m*
Scenario 3: Bus detected g2m second of g2	*g2 - g2m + ig23 + ped + ig31 + Dq +Da -t*	*ig23 + ped + ig31 +Dq +Da -t*	*g2-g2m*
Scenario 4: Bus detected last second of g2	*ig23 + ped + ig31 + Dq +Da -t*	*ig23 + ped + ig31 +Dq +Da -t*	*0*
Scenario5: Bus detected during ig23	*ig23 + ped + ig31 + Dq +Da -t*	*ig23 + ped + ig31 +Dq +Da -t*	*0*
Scenario6: Bus detected during ped stage	*ped + ig31 + Dq +Da -t*	*ped + ig31 +Dq +Da -t*	*0*
Scenario7: Bus detected during ig31	*ig31 + Dq +Da -t*	*ig31 +Dq +Da -t*	*0*

Bus delay savings due to a recall with time of detection for other detection distances can be estimated by following similar steps.

Figures 4.13, 4.14, 4.15 below illustrate bus delay savings due to each recall with time of detection for different detection distances.



Effective red period = r1+r2 = C-g1-ig23-ped-ig31 (When t <= ig23+ped+ig31)

Figure 4.13: Bus delay savings due to each recall with time of detection (t <= ig23+ped+ig31)

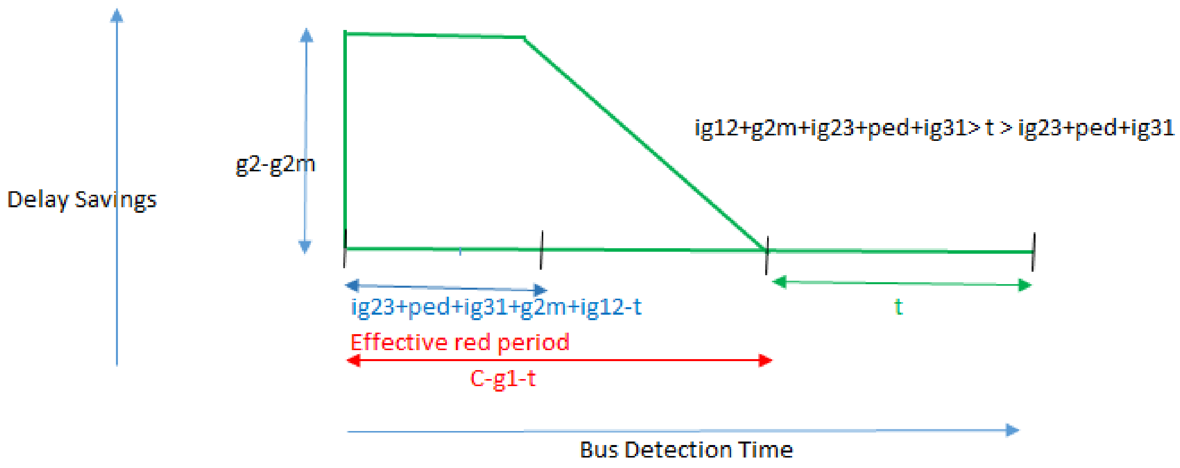


Figure 4.14: Bus delay savings due to each recall with time of detection (ig12+g2m+ig23+ped+ig31 > t > ig23+ped+ig31)

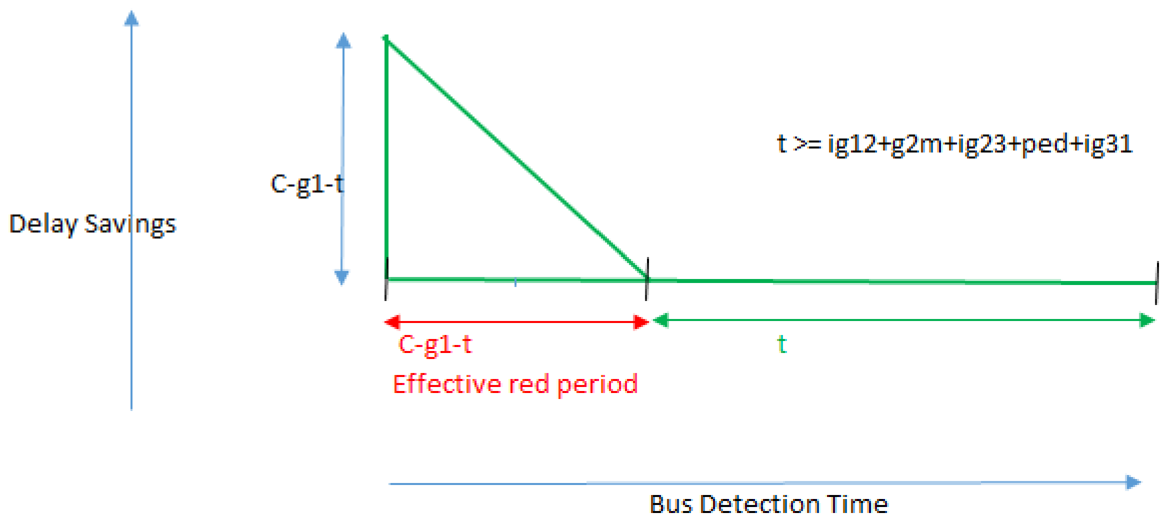


Figure 4.15: Bus delay saving due to each recall with time of detection (t >= ig12+g2m+ig23+ped+ig31)

Figures 4.16, 4.17, & 4.18 below describe the delay to buses with and without a recall with time of detection and then illustrates delay savings due to each recall. Signal details are: g1= 40 sec, g2 = 20 sec, ped = 7 sec, ig12 = ig23 =7 sec, ig31 =13 sec, g2m=7 sec, t =7 sec. This example is for illustration only.

Figure 4.16 below illustrates the delay to buses without recall with time of detection.

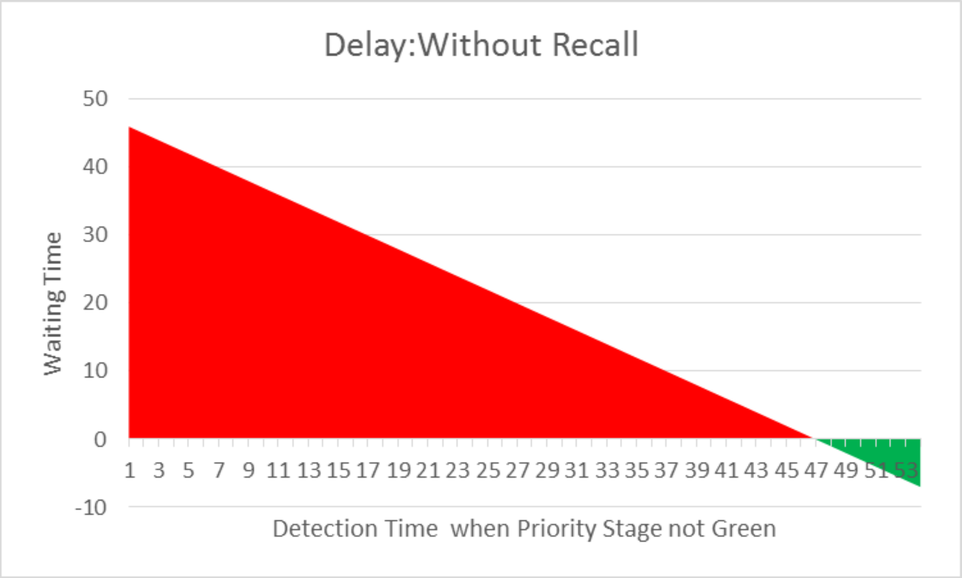


Figure 4.16: Delay to buses without recall with time of detection

Figure 4.17 below illustrates the delay to buses due to each recall with time of detection.

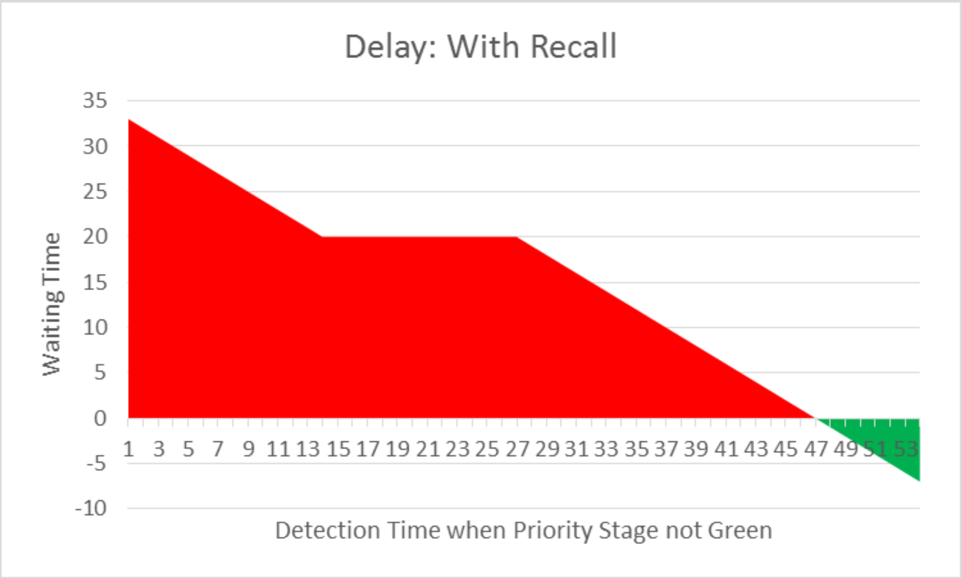


Figure 4.17: Delay to buses due to each recall with time of detection

Figure 4.18 below illustrates the delay savings to buses due to each recall with time of detection.

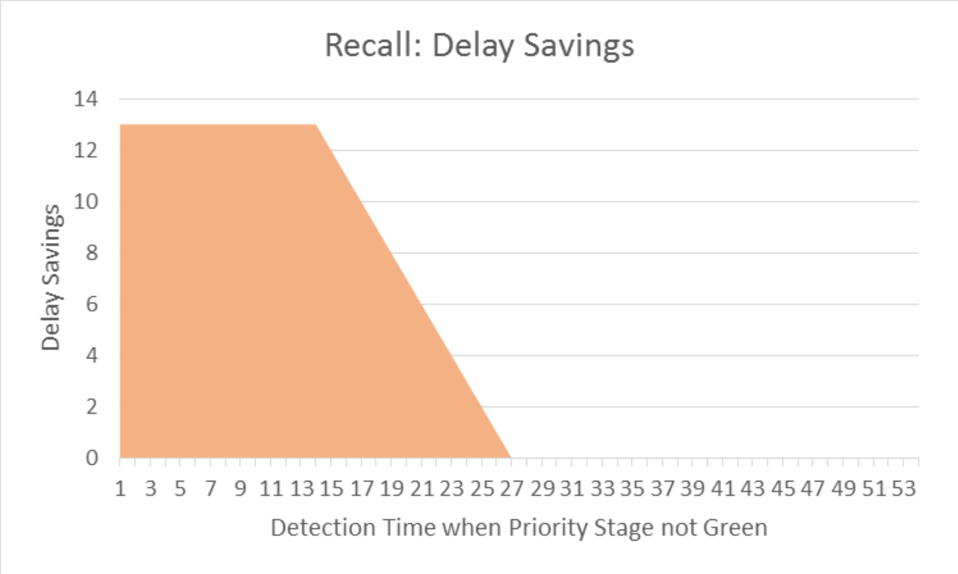


Figure 4.18: Delay savings to buses due to each recall with time of detection

Three Stage Junction

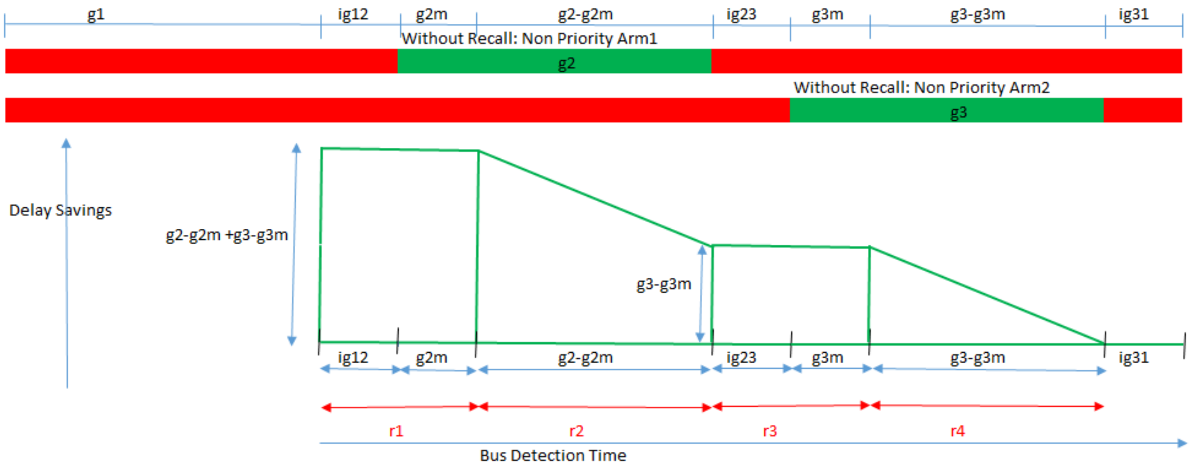
Table 4.10 below shows the steps to estimate the bus delay savings due to a recall with time of detection (ig31 >= t).

Table 4.10: Delay savings due to a recall with time of detection (ig31 >= t)

Bus Detection Time	Delay without Recall	Delay with Recall	Delay Savings
Scenario 1: Bus detected during ig12	*ig12 + g2 + ig23 + g3 + ig31 + Dq + Da -t*	*ig12 + g2m +ig23 + g3m + ig31 +Dq + Da -t*	*g2-g2m + g3 -g3m*
Scenario 2: Bus detected 1st second of g2	*g2 + ig23 + g3 + ig31 + Dq + Da -t*	*g2m +ig23 + g3m + ig31 +Dq + Da -t*	*g2-g2m + g3 -g3m*
Scenario 3: Bus detected g2m second of g2	*g2 -g2m + ig23 + g3 + ig31 + Dq + Da -t*	*ig23 + g3m + ig31 +Dq + Da -t*	*g2-g2m + g3 -g3m*
Scenario 4: Bus detected last second of g2	*ig23 + g3 + ig31 + Dq + Da -t*	*ig23 + g3m + ig31 +Dq + Da -t*	*g3 -g3m*
Scenario5: Bus detected during ig23	*ig23 + g3 + ig31 + Dq + Da -t*	*ig23 + g3m + ig31 +Dq + Da -t*	*g3 -g3m*
Scenario6: Bus detected 1st second of g3	*g3 + ig31 + Dq + Da -t*	*g3m + ig31 +Dq + Da -t*	*g3 -g3m*
Scenario7: Bus detected g3m second of g3	*g3 -g3m + ig31 + Dq + Da -t*	*ig31 +Dq + Da -t*	*g3 -g3m*
Scenario8: Bus detected last second of g3	*ig31 + Dq + Da -t*	*ig31 +Dq + Da -t*	*0*
Scenario9: Bus detected during ig31	*ig31 + Dq + Da -t*	*ig31 +Dq + Da -t*	*0*

For other detection distances, delay savings can be estimated following the above steps.

Figures 4.19, 4.20, 4.21, & 4.22 below illustrate bus delay saving due to each recall with time of detection.



Effective red period = r1+r2+r3+r4 = C-g1-ig31 (when ig31 >= t)

Figure 4.19: Bus delay savings due to each recall with time of detection (ig31 >= t)

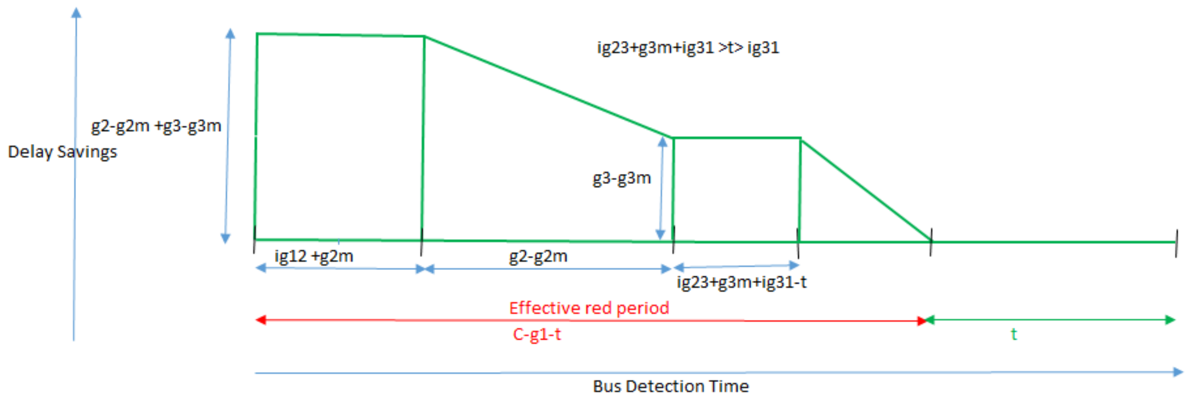


Figure 4.20: Bus delay savings due to each recall with time of detection (ig23+g3m+ig31>t>ig31)

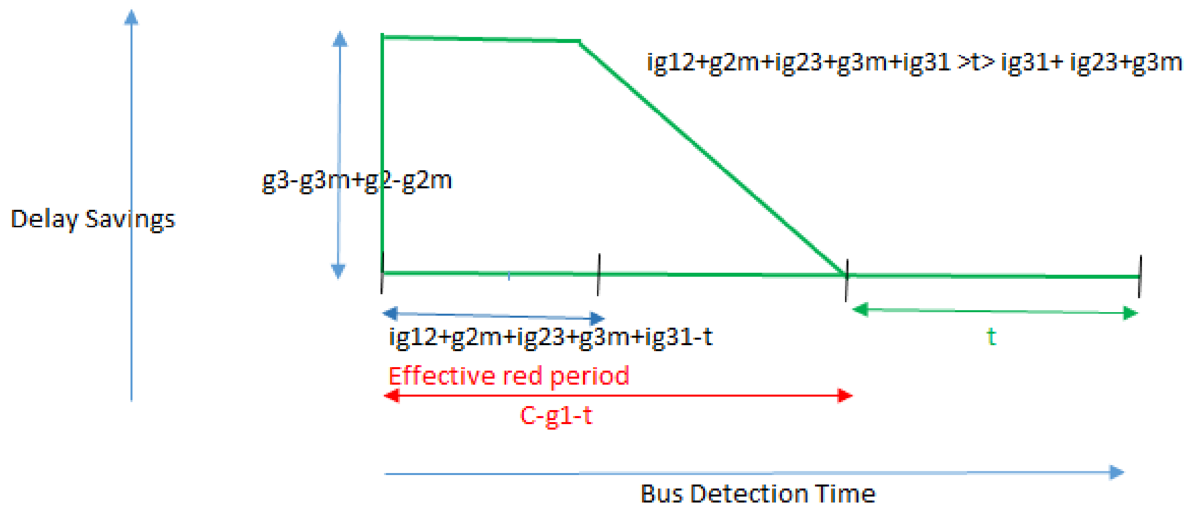


Figure 4.21: Bus delay savings due to each recall with time of detection (ig12+g2m+ig23+g3m+ig31 > t> ig31+ig23+ig3m)

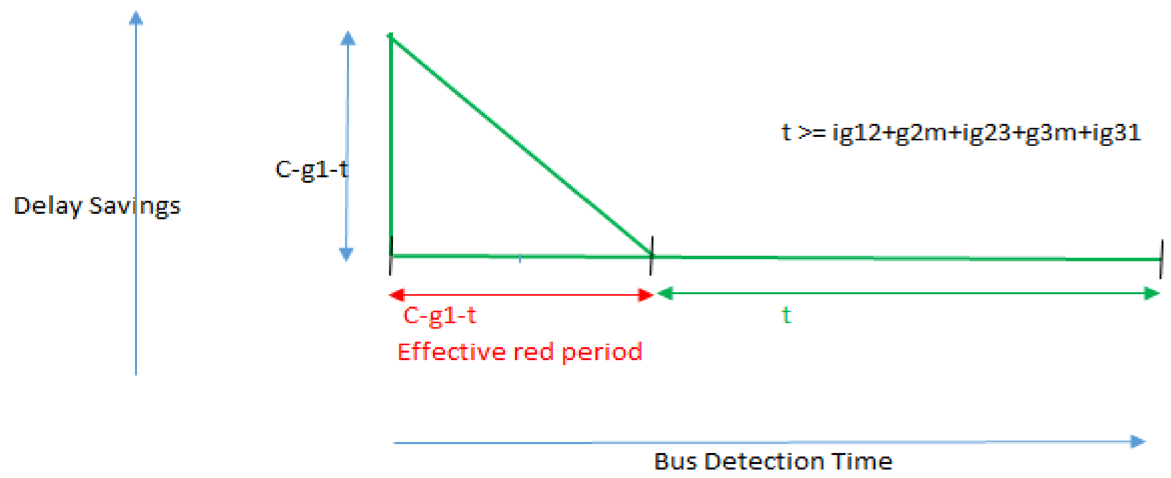


Figure 4.22: Bus delay savings due to each recall with time of detection (t > = ig12+g2m+ig23+g3m+ig31)

Figures 4.23, 4.24 & 4.25 below describe delay to buses with and without recall with time of detection and then illustrate delay savings due to each recall. Signal details are: g1= 40 sec, g2 = g3= 20 sec, ig12 = ig23= ig31 = 7 sec, g2m = g3m = 7 sec, t=7 sec. This example is for illustration only.

Figure 4.23 below illustrates the delay to buses without recall with time of detection.

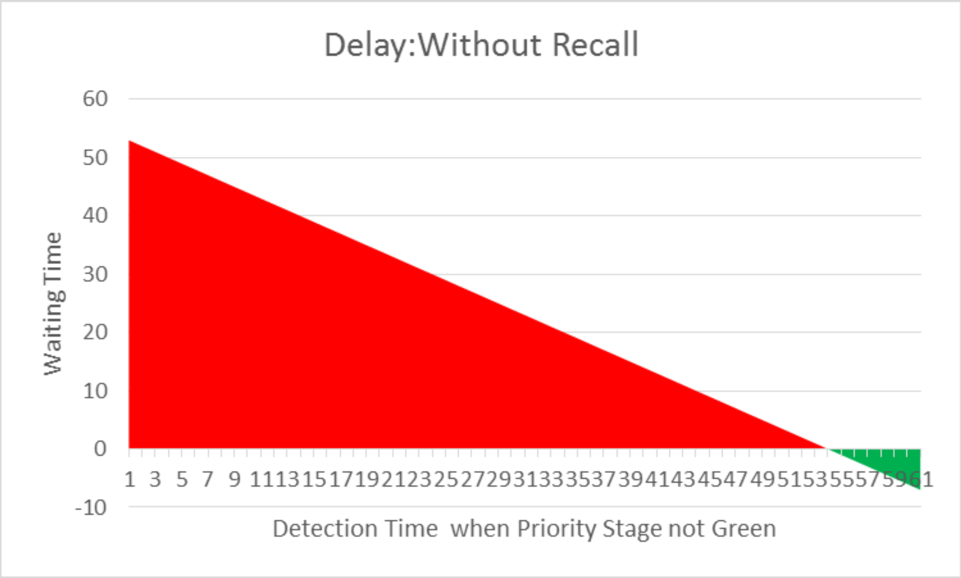


Figure 4.23: Delay to buses without recall with time of detection

Figure 4.24 below illustrates the delay to buses due to each recall with time of detection.

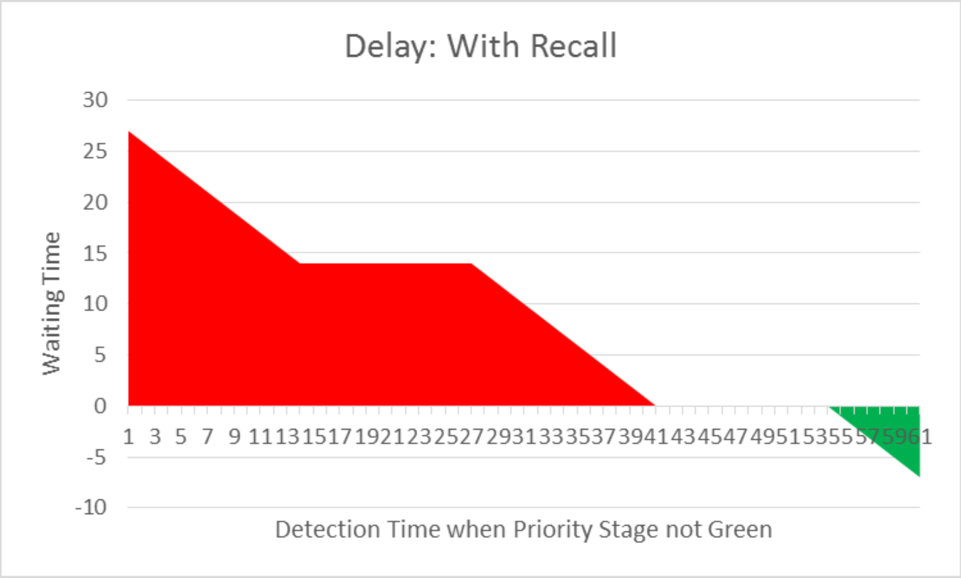


Figure 4.24: Delay to buses due to each recall with time of detection

Figure 4.25 below illustrates the delay savings to buses due to each recall with time of detection.

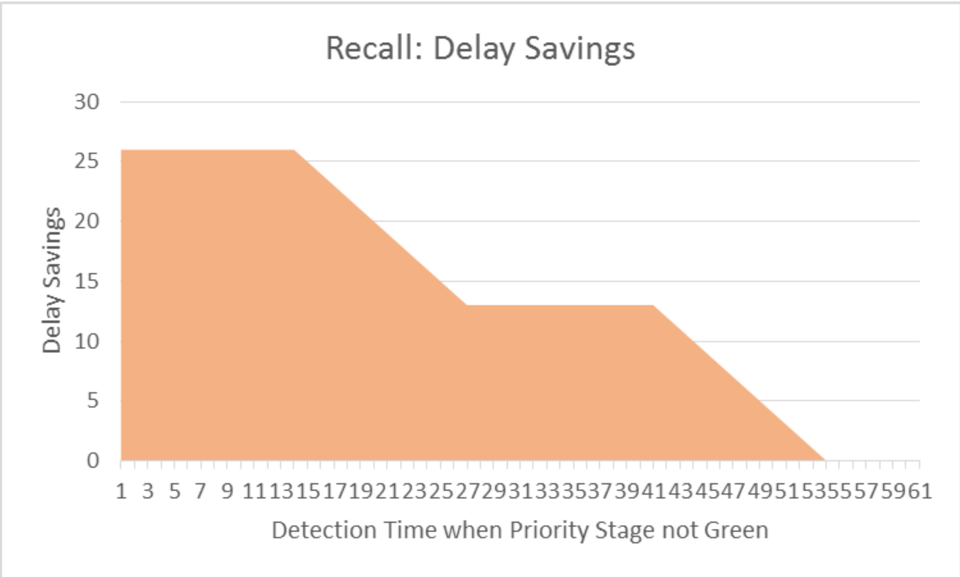


Figure 4.25: Delay savings to buses due to each recall with time of detection

Three Stage and One Pedestrian Stage Junction

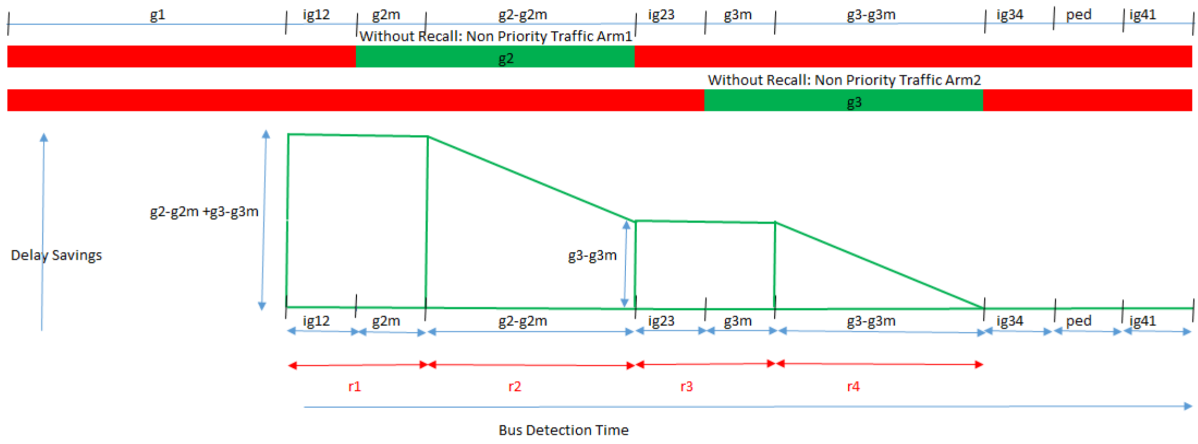
Table 4.11 below shows the steps to calculate the delay savings due to a recall with time of detection (when ig34+ped+ig41 >=t).

Table 4.11: Delay savings due to recall with time of detection (ig34+ped+ig41 >=t)

Bus Detection Time	Delay without Recall	Delay with Recall	Delay Savings
Scenario 1: Bus detected during ig12	*ig12 + g2 + ig23 + g3 + ig34 +ped + ig41 + Dq +Da -t*	*ig12 + g2m + ig23 + g3m + ig34 + ped + ig41 +Dq +Da -t*	*g2-g2m + g3 -g3m*
Scenario 2: Bus detected 1st second of g2	*g2 + ig23 + g3 + ig34 +ped + ig41 + Dq +Da -t*	*g2m + ig23 + g3m + ig34 + ped + ig41 +Dq +Da -t*	*g2-g2m + g3 -g3m*
Scenario 3: Bus detected g2m second of g2	*g2 -g2m + ig23 + g3 + ig34 +ped + ig41 + Dq +Da -t*	*ig23 + g3m + ig34 + ped + ig41 +Dq +Da -t*	*g2-g2m + g3 -g3m*
Scenario 4: Bus detected last second of g2	*ig23 + g3 + ig34 +ped + ig41 + Dq +Da -t*	*ig23 + g3m + ig34 + ped + ig41 +Dq +Da -t*	*g3 -g3m*
Scenario5: Bus detected during ig23	*ig23 + g3 + ig34 +ped + ig41 + Dq +Da -t*	*ig23 + g3m + ig34 + ped + ig41 +Dq +Da -t*	*g3 -g3m*
Scenario6: Bus detected 1st second of g3	*g3 + ig34 +ped + ig41 + Dq +Da -t*	*g3m + ig34 + ped + ig41 +Dq +Da -t*	*g3 -g3m*
Scenario7: Bus detected g3m second of g3	*g3 -g3m + ig34 +ped + ig41 + Dq +Da -t*	*ig34 + ped + ig41 +Dq +Da -t*	*g3 -g3m*
Scenario8: Bus detected last second of g3	*ig34 +ped + ig41 + Dq +Da -t*	*ig34 + ped + ig41 +Dq +Da -t*	*0*
Scenario9: Bus detected during ig34	*ig34 +ped + ig41 + Dq +Da -t*	*ig34 + ped + ig41 +Dq +Da -t*	*0*
Scenario10: Bus detected during ped stage	*ped + ig41 + Dq +Da -t*	*ped + ig41 +Dq +Da -t*	*0*
Scenario11: Bus detected during ig41	*ig41 + Dq +Da -t*	*ig41 +Dq +Da -t*	*0*

For other detection distances delay savings can be calculated following the steps above.

Figures 4.26, 4.27, 4.28, &4.29 below illustrate delay saving due to each recall with time of detection.



Effective red period = r1+r2+r3+r4 = C-g1-ig34-ped-ig41 (when ig34+ped+ig41 >=t)

Figure 4.26: Bus delay saving due to each recall with time of detection (ig34+ped+ig41 >=t)

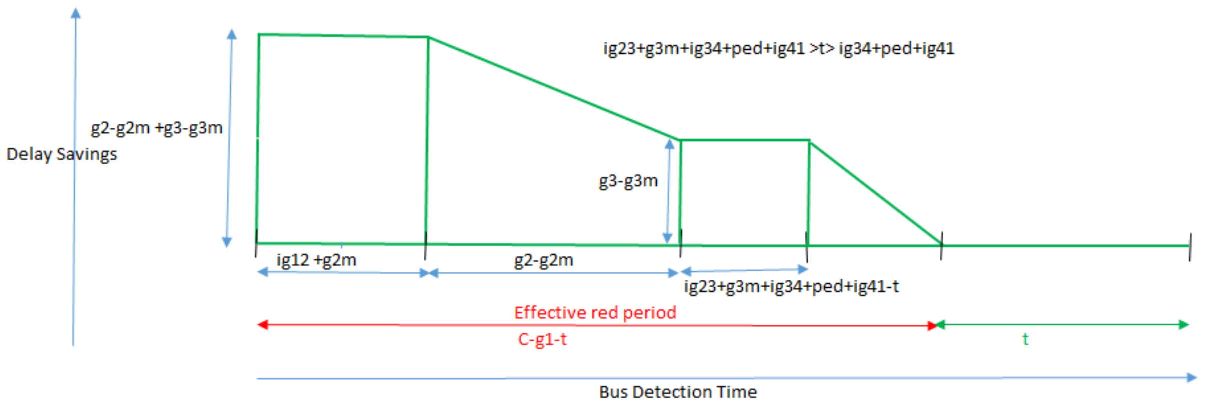


Figure 4.27: Bus delay saving due to each recall with time of detection (ig23+g3m+ig34+ped+ig41 >t > ig34+ped+ig41)

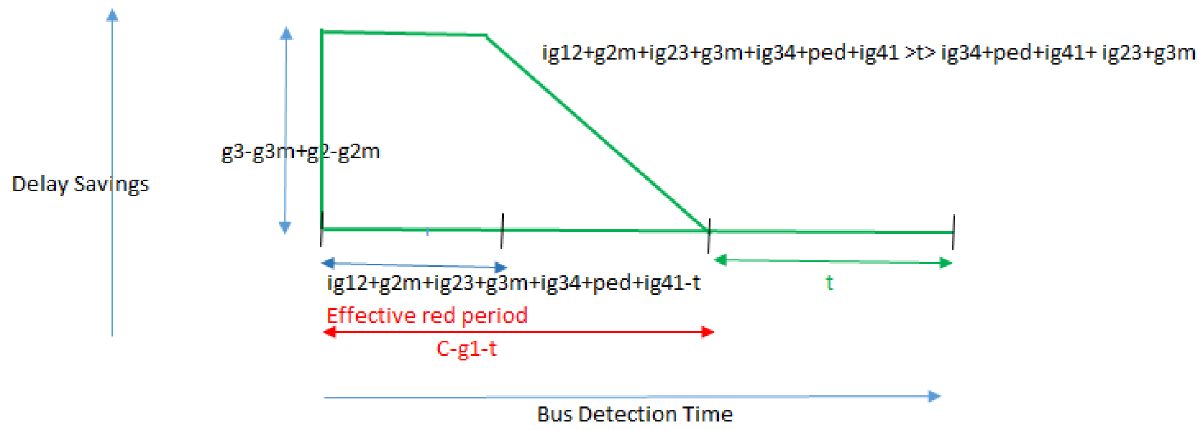


Figure 4.28: Bus delay saving by each recall with time of detection (ig12+g2m+ig23+g3m+ig34+ped+ig41 > t> ig34+ped+ig41+ig23+g3m)

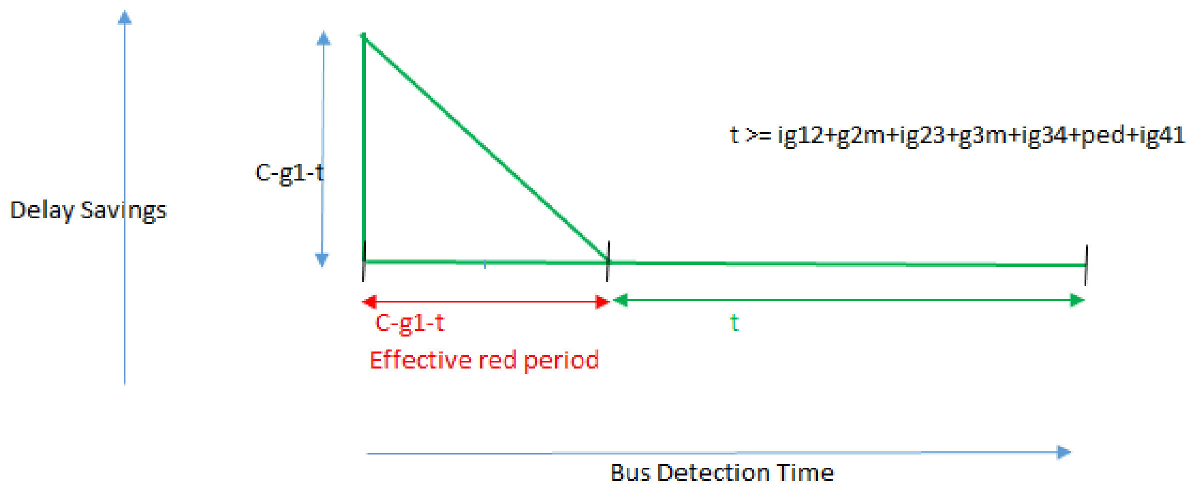


Figure 4.29: Bus delay saving due to each recall with time of detection (t>= ig12+g2m+ig23+g3m+ig34+ped+ig41)

Figures 4.30, 4.31, & 4.32 below describe delay to buses with and without recall with time of detection and then illustrates delay savings by recall. Signal details are: g1= 40 sec, g2 = g3= 20 sec, ped =7 sec, ig12 = ig23 = ig34 = 7 sec, ig41= 13 sec, g2m = g3m = 7 sec, t =7 sec.

Figure 4.30 below illustrates the delay to buses without recall with time of detection.

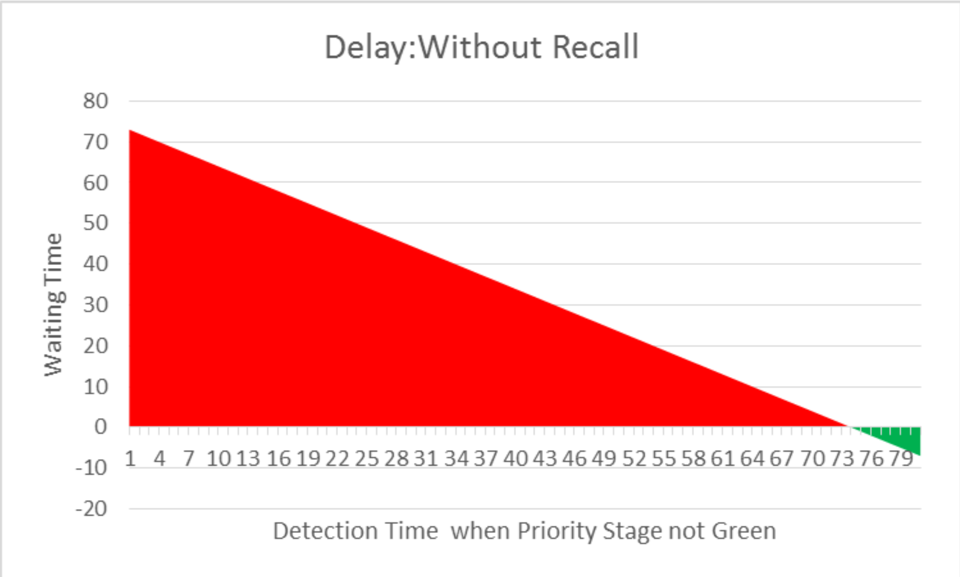


Figure 4.30: Delay to buses without recall with time of detection

Figure 4.31 below illustrates the delay to buses with recall with time of detection.

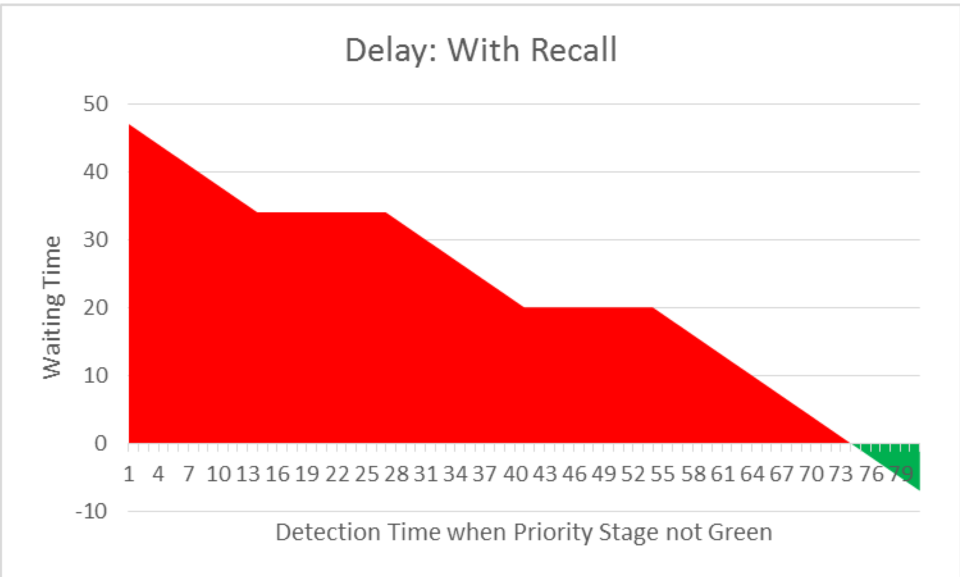


Figure 4.31: Delay to buses due to each recall with time of detection

Figure 4.32 below illustrates the delay savings to buses due to each recall with time of detection.

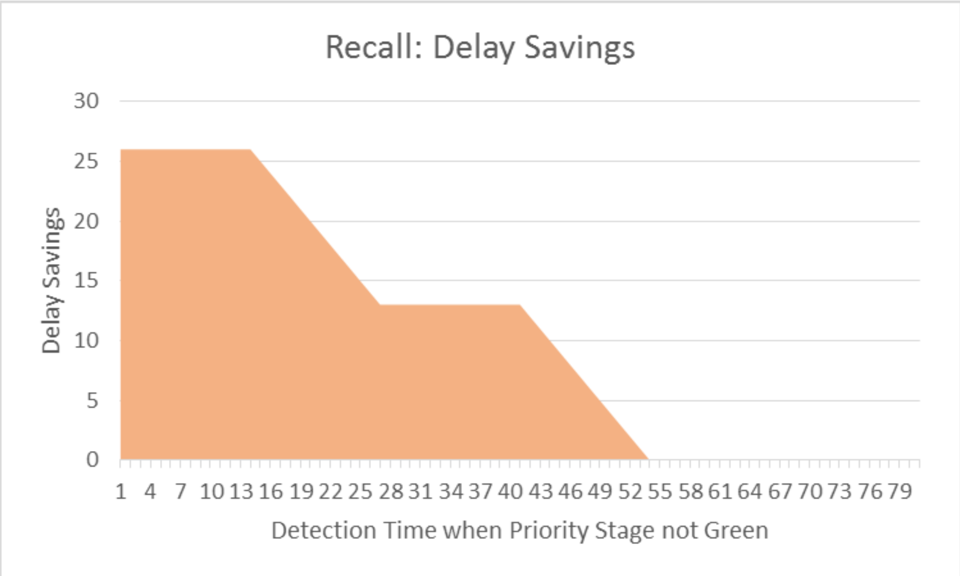


Figure 4.32: Delay savings to buses by recall with time of detection

4.4.2 Derivation of formulae to calculate average benefits

Total red period for recall = *Rt* sec.

This is the red period for priority approach without recall.

Effective red period for recall = *Re* sec

This is the red period when a detected bus will benefit if a recall is provided. If a recall is provided during the red period other than effective red, then there will be no benefits to buses. The effective red period for recall can be called *recall time*.

Average savings from each recall = *Br* sec.

Br is derived from the graphs of delay savings described in the previous Sub Section 4.4.1.

Bus flow during effective red on priority approach *(f) = F*Re/3600*

Assumption: Poission distribution of bus arrival, bus arrives at traffic signals randomly and independently, bus arrival is uniform.

Probability of no bus arrival during effective red *Po = Poi(f)*

Probability of one or more bus arrivals during effective red *P1 = 1-Po*

Average benefits per cycle *(Bc) = P1*Br* sec/cycle

Average benefit *(B) = 3600/C*Bc*1/F* sec/bus

4.4.3 Steps to calculate dis benefits to non priority arms

Two Stages Junction

Delay increase to non priority arm1

Figure 4.33 and Table 4.12 below describe the delay increase to the non priority arm due to recall on the priority approach. Scenarios considered in the Table and Figure below represent vehicle arrival time at the stop line. There is no delay increase before scenario 2.

Table 4.12: Delay increase to non priority arm due to recall

Vehicle arrival time at the stop line	Delay without Recall	Delay with Recall	Delay Increase
Scenario 1: First second of g2	0	0	0
Scenario 2: Last second of g2m	0	$ig21+g1+ig12+Dq+Da$	$ig21+g1+ig12+Dq+Da = C-g2+Dq+Da$
Scenario 3: Last second of ig21 (with recall)	0	$g1+ig12+Dq+Da$	$g1+ig12+Dq+Da$
Scenario 4: Last second of g2	0	$ig21+g1+ig12-(g2-g2m)+Dq+Da = C-g2-g2+g2m+Dq+Da$	$C-2g2+g2m+Dq+Da$
Scenario 4a: First second of ig21	$ig21+g1+ig12$	$ig21+g1+ig12-(g2-g2m)$	$-(g2-g2m)$
Scenario 5: Last second of ig12 (with recall)	$g2-g2m$	0	$-(g2-g2m)$
Scenario 6: Last second of ig12	0	0	0

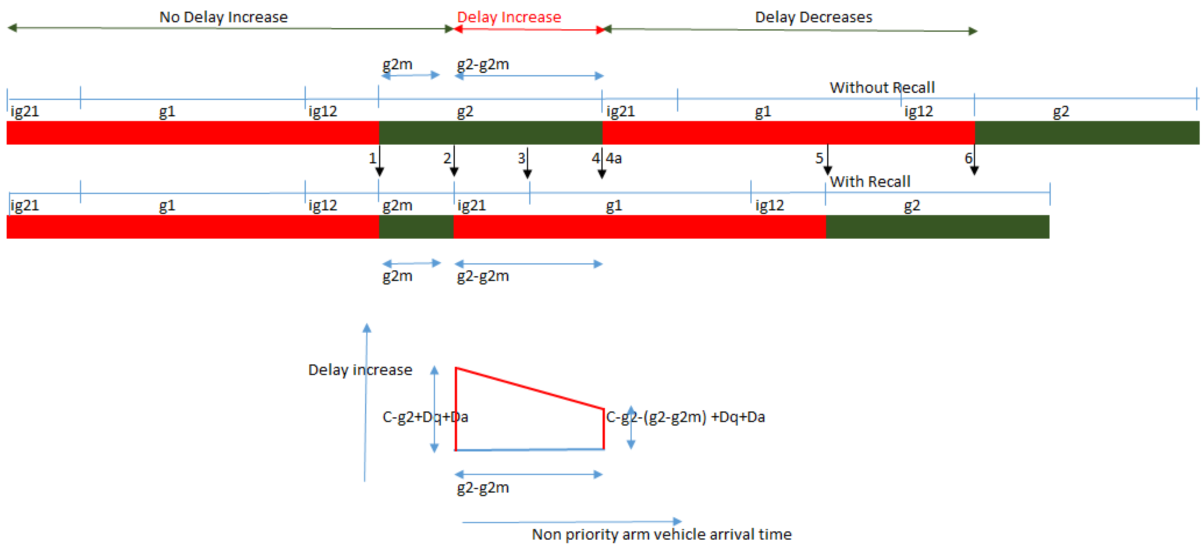


Figure 4.33: Delay increase to non priority arm due to recall

Vehicle arriving at the stop line after scenario 4a will have less delay than usual. This delay saving is not considered. Because it is assumed that due to green time reduction a longer queue will build up and in the next immediate green not all cars will be able to clear the junction. Delay due to deceleration is not needed to be considered because deceleration happens during red, and the red period is already considered in the calculation. However, it is necessary to consider Dq and Da, because a recall is stopping fast moving cars. Those cars end up in the queue, and during the next immediate green additional time needed to discharge that queue and to accelerate.

Two traffic stage junctions, and junctions having two traffic stages and one pedestrian stage both have same delay increase for the non priority arm. Pedestrians will benefit by a recall due to a shorter cycle length with no loss of pedestrian green.

Three Stage Junctions

By using the steps described in the Table 4.12 & Figure 4.33 delay increase to non priority arms for three traffic stage junctions can be plotted as shown below.

Delay Increase to Non Priority Arm1

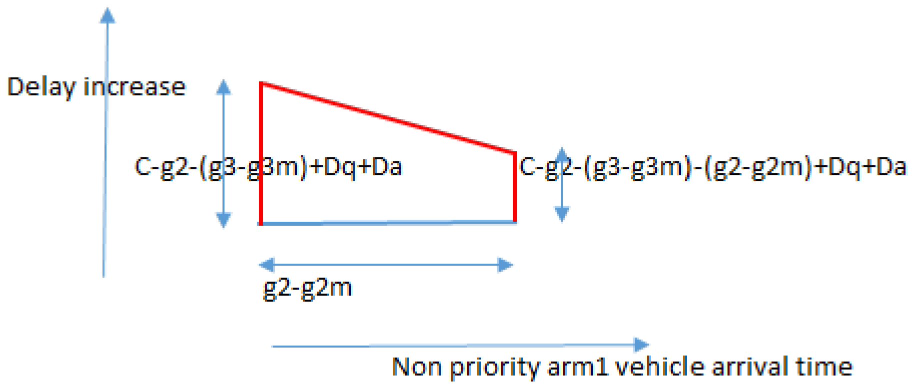


Figure 4.34: Delay increase to non priority arm1 due to recall

Delay Increase to Non Priority Arm2

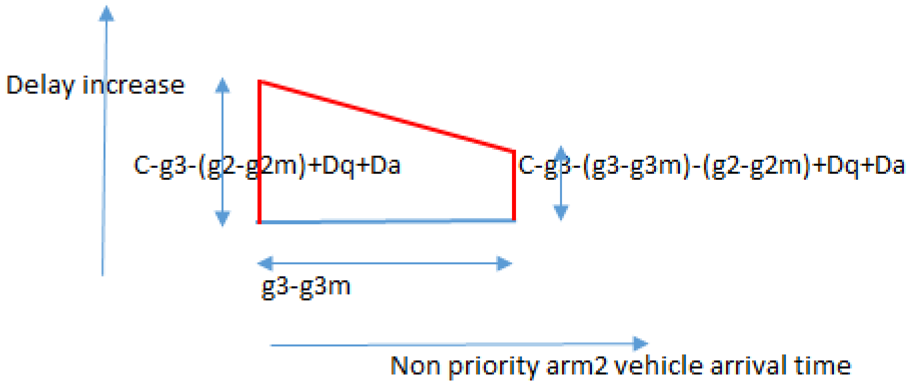


Figure 4.35: Delay increase to non priority arm2 due to recall

These delay increase graphs also valid for junction having three traffic stages and one pedestrian stage. Pedestrian will be benefited by recall due to short cycle length and due to no loss of pedestrian green.

Delay increase to non priority arm due to recall can be generalised as follows.

Condition 1: When bus detected for recall in the priority approach during minimum green or before start of minimum green of non priority arm.

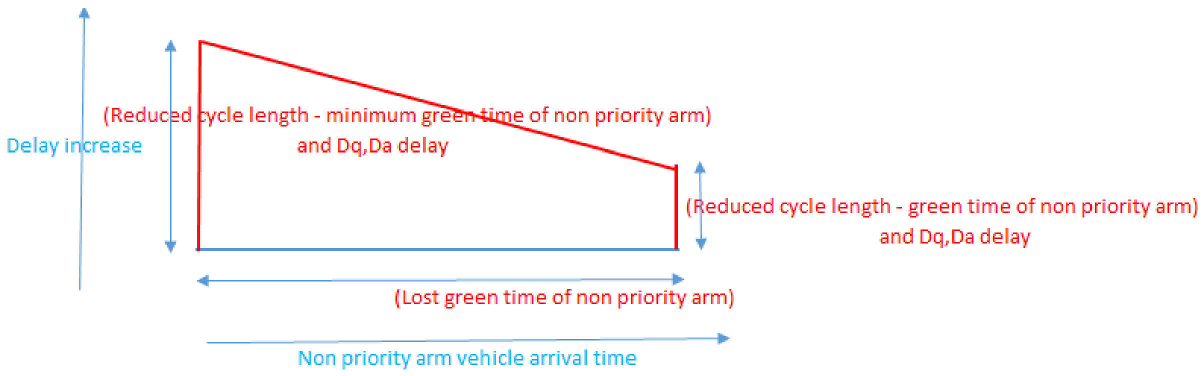


Figure 4.36: Delay increase to non priority arm due to recall (Condition 1)

Condition 2: When bus detected for a recall at priority approach after minimum green of non-priority arm.

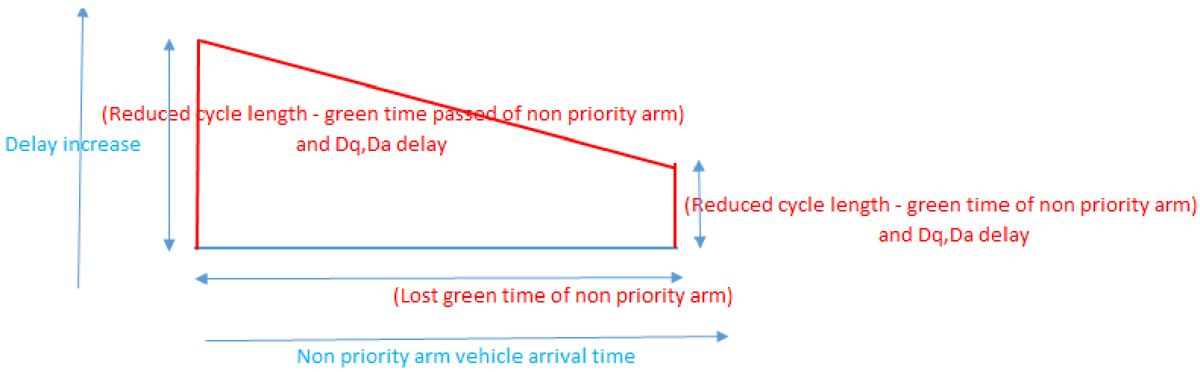


Figure 4.37: Delay increase to non priority arm due to recall (Condition 2)

4.4.4 Steps to calculate lost green time of non priority arm

Depending on the arrival of bus at the priority approach during red, the time lost due to each recall on the non priority arm varies.

Two Stage Junction

Figure 4.38 below illustrates the lost green time by each recall at a non priority arm of a two traffic stage junction.

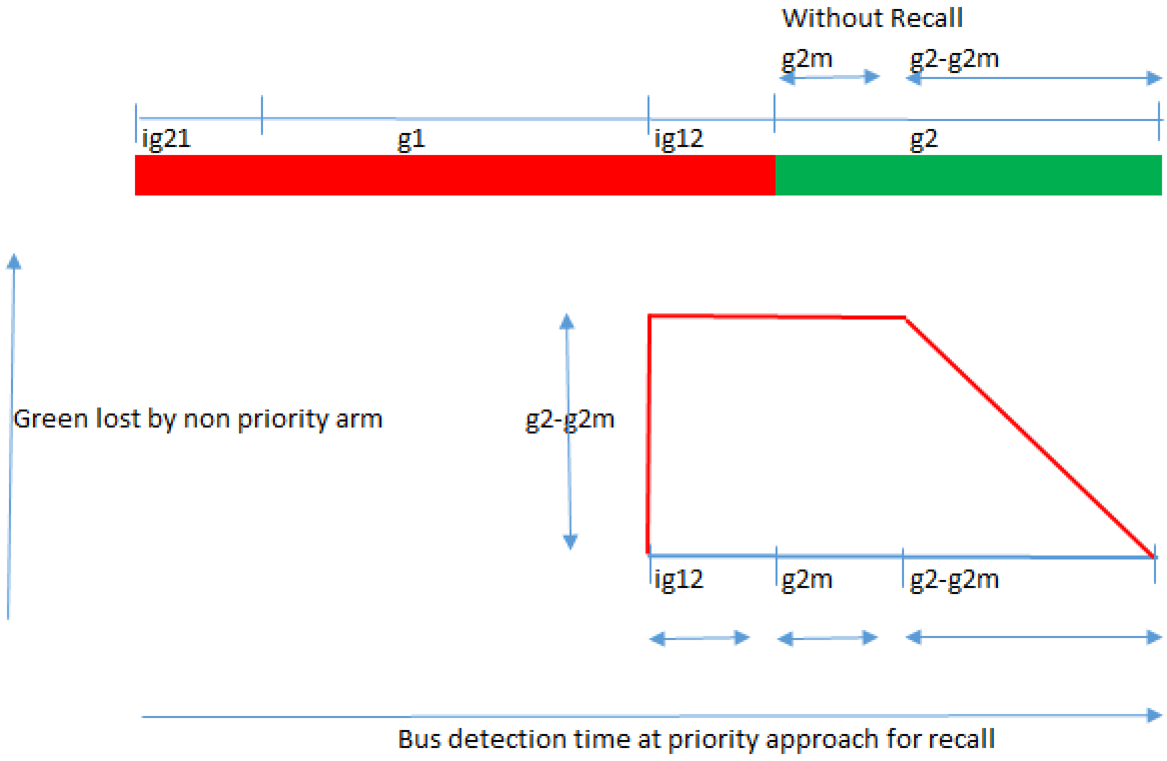


Figure 4.38: Lost green time due to each recall at non priority arm

Two Stages and Pedestrian Stage Junction

Figure 4.39 below illustrates the lost green time due to each recall at a non priority arm of a two traffic stage and one pedestrian stage junction.

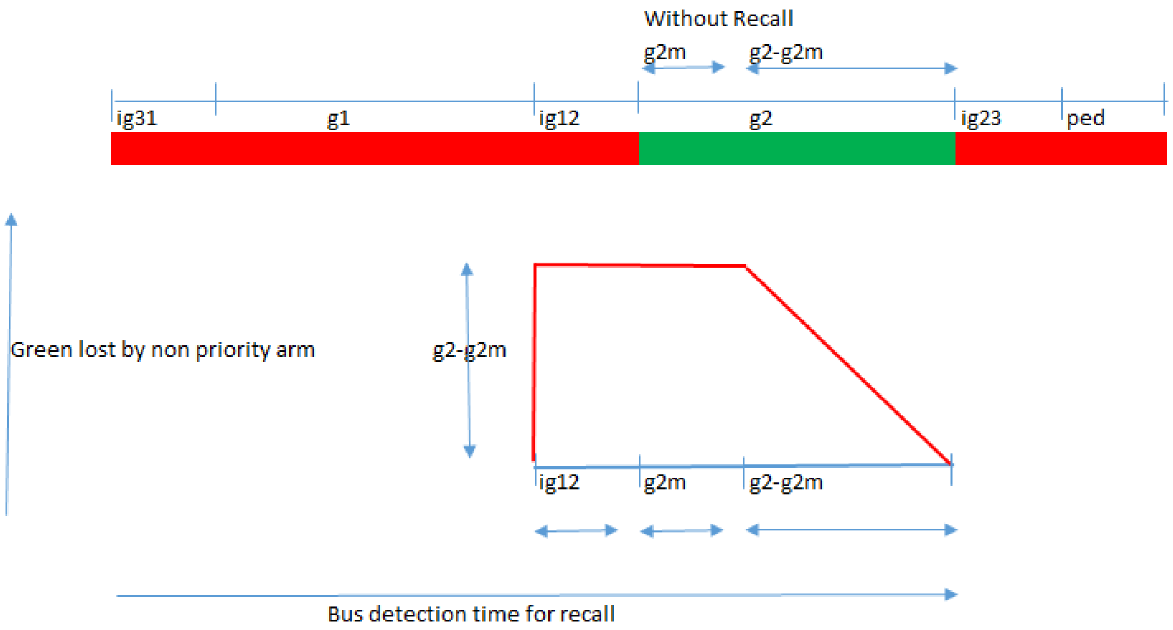


Figure 4.39: Lost green time on the non priority arm due to each recall

Three Stage Junction

Figure 4.40 below illustrates the lost green time due to each recall at non priority arm1 of a three traffic stage junction.

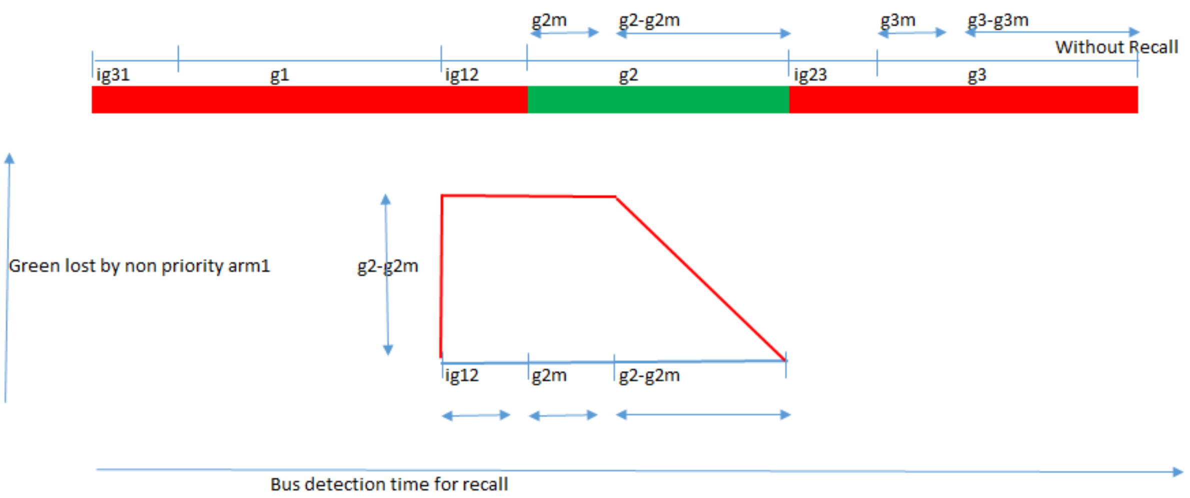


Figure 4.40: Lost green time due to each recall at non priority arm1

Figure 4.41 below illustrates the lost green time due to each recall at non priority arm2 of a three traffic stage junction.

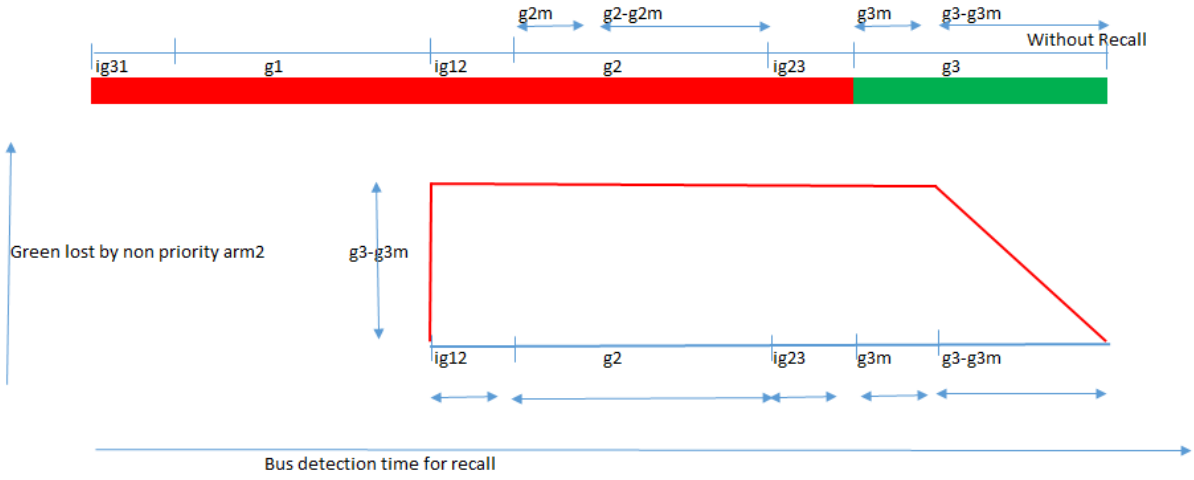


Figure 4.41: Lost green time due to each recall at non priority arm2

Three Stages and Pedestrian Stage Junction

Figure 4.42 below illustrates the lost green time due to each recall at non priority arm1 of a three traffic stage and one pedestrian stage junction.

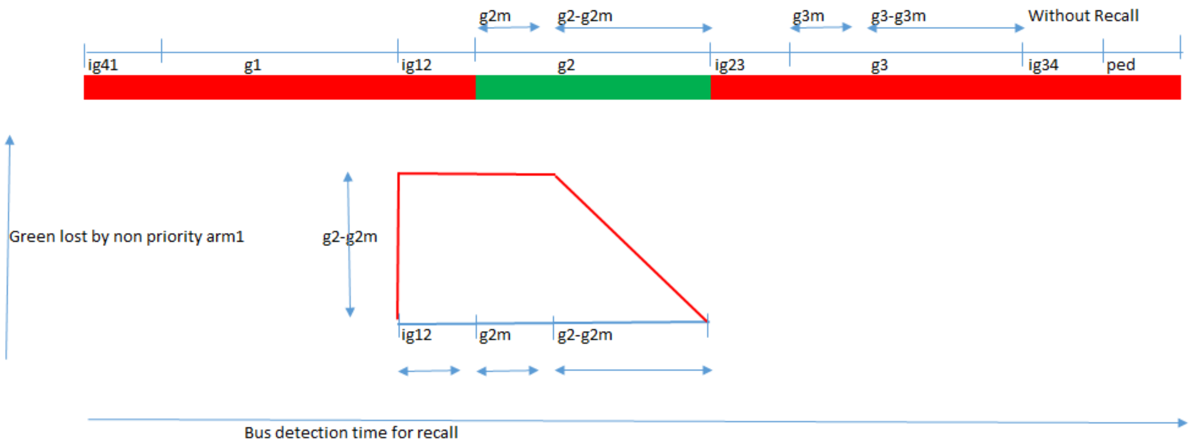


Figure 4.42: Lost green time due to each recall at non priority arm1

Figure 4.43 below illustrates the lost green time due to each recall at non priority arm2 of a three traffic stage and one pedestrian stage junction.

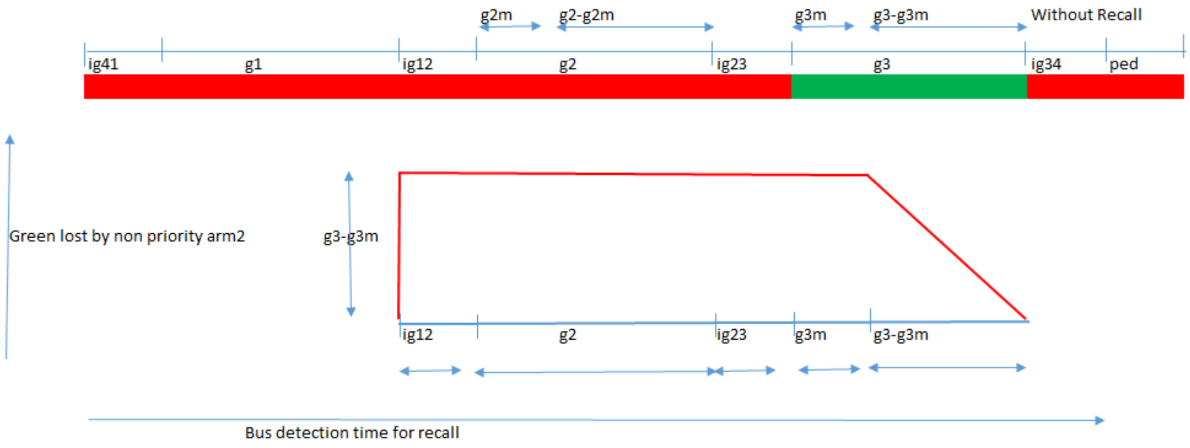


Figure 4.43: Lost green time due to each recall at non priority arm2

4.4.5 Derivation of formulae to calculate average dis benefits to non priority arm

Average time lost by non priority arm = *La* sec.

La can be calculated by using the graphs described above (Sub Section 4.4.4) depending on junction types.

Reduced cycle length *(Cr) = C-La* sec

Green time provided to non priority arm *(Gp) = normal green time -La* sec

Average delay increase to non priority arm = *Dia* sec

Dia can be calculated by using the graphs described above (Sub Section 4.4.3).

Traffic flows at non priority arm = *Fc* veh/hr

Traffic arrival during *La* at non priority arm *(N) = Fc*La/3600* Nr

Total delay by each recall in one cycle *(Dt) = N*Dia* sec

If non priority arms have traffic close or over it's signal capacity, there will be stationary vehicles waiting at the junction during green of non priority arms without recall. So due to the reduction in green time, the number of stationary vehicles (and the delay) will increase. In that situation *N* needs to be re calculated by considering the number of stationary vehicles which will fail to clear the junction *(La/time taken per stationary vehicle to clear the junction)* and adding new traffic arrivals during *La*.

Nr of cycles with recall *(Cre) = P1*3600/C* Nr

Calculation of *P1* is discussed in the previous Sub Sections (4.3.2).

Delay Increase to a non priority arm *(D) = Cre*Dt/Fc* sec/veh

Delay increase to non priority arms due to recalls derived by the described methods will be minimum dis benefits. In reality delay will be higher, because due to a recall, especially in peak hours, the traffic queue will build upon the non priority arms. Not all queuing traffic will be able to clear the junction in the next immediate green for them after recall. For those who fail to clear the junction, delay is much higher.

Table 4.13 and 4.14 below shows the benefits to buses and dis benefits to non priority arms due to a recall for a two traffic stage junction. Table 4.15 shows the green time loss because of each recall for a two traffic stage junction. These values are calculated by the theoretical methods described in this Chapter.

Notes: [g1/C= Priority Green/Cycle Time; t+2 = Detector to stop line travel time; B = Benefits to buses; NT = Dis benefits to non priority traffic; + = Delay savings; - = Delay increase]

Table 4.13: Benefits to buses and dis benefits to non priority arms by recall (100m detection distance)

Two Traffic Stage Junction (T-Junction without Pedestrian Crossing), Recall without Inhibit, Detection 100m, g1/C = 0.6										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
12	2.44	0.48	2.37	0.93	2.23	1.74	2.10	2.46	1.98	3.10

Table 4.14: Benefits to buses and dis benefits to non priority arms by recall (with detection distance)

Two Traffic Stage Junction (T-Junction without Pedestrian Crossing), Recall without Inhibit, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.2		.3		.4		.5		.6		.7	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
6	17.44	2.28	13.01	2.51	8.93	2.24	5.64	1.77	3.05	1.11	0.75	0.33
12	15.35	2.12	11.25	2.30	7.52	2.01	4.60	1.54	2.37	0.93	0.54	0.25
18	12.76	1.92	9.06	2.04	5.77	1.73	3.31	1.27	1.53	0.70	0.27	0.14
24	10.10	1.72	6.83	1.78	3.98	1.44	1.99	0.98	0.69	0.46	0.02	0.04
30	7.66	1.51	4.82	1.51	2.45	1.14	0.95	0.68	0.15	0.21	0	0

Table 4.15: Non priority arm green time loss due to each recall

g1/C	Two Traffic Stage Junction (T-Junction without Pedestrian Crossing), Recall
	Average Green Loss by Each Recall (Sec): Non Priority Arms
	Arm1
	-
0.2	28.66
0.3	24.38
0.4	19.44
0.5	14.88
0.6	9.98
0.7	3.58

Average green loss of non priority arms by each recall is independent of t +2 (detector to stop line travel time) and F (bus flow).

For other junction types, the benefits and dis benefits due to recalls, and the average green loss by non priority arms due to recalls have been calculated by theoretical methods and are shown in the appendix A.

4.5 Inhibit

4.5.1 Derivation of formulae to calculate average benefits

This is where priority is limited to one cycle at a time (eg priority in consecutive cycles is not permitted).

The probability of a bus arrival during effective red for any cycle = *P1*

The calculation of *P1* is described in the previous Sub Section (4.3.2).

The probability of a bus arrival during the next immediate cycle during effective red

*Pinh = P1*P1*

(As events are independent of each other)

During inhibit buses will not get a recall

The probability of a recall *(Pr) = P1-Pinh*

Average benefits per cycle *(Bc) = Pr*Br* sec/cycle

Average benefit *(B) = 3600/C*Bc*1/F* sec/bus

4.5.2 Derivation of formulae to calculate average disbenefits

Nr of cycles with recall *(Cre) = Pr*3600/C* Nr

Delay increase of the non priority arm *(D) = Cre*Dt/Fc* sec/car

Dt and Fc has been described in the Sub Section 4.4.5.

The benefit to buses and dis benefits to non priority arms due to inhibit is shown in Table 4.16 and 4.17 below for a two traffic stages junction.

<u>Notes:</u> [g1/C= Priority Green/Cycle Time; t+2 = Detector to stop line travel time; B = Benefits to buses; NT = Dis benefits to non priority traffic; + = Delay savings; - = Delay increase]

Table 4.16: Benefit to buses and dis benefits to non priority arms due to recalls with inhibit (100m detection distance)

Two Traffic Stage Junction (T-Junction without Pedestrian Crossing), Recall with Inhibit, Detection 100m, g1/C = 0.6										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
12	2.29	0.45	2.08	0.82	1.72	1.35	1.43	1.68	1.19	1.86

Table 4.17: Benefit to buses and dis benefits to non priority arms due to recalls with inhibit (with detection distance)

Two Traffic Stage Junction (T-Junction without Pedestrian Crossing), Recall with Inhibit, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.2		.3		.4		.5		.6		.7	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
6	12.43	1.62	9.69	1.87	6.99	1.75	4.62	1.45	2.61	0.95	0.68	0.30
12	11.24	1.55	8.61	1.76	6.05	1.62	3.87	1.30	2.08	0.82	0.50	0.23
18	9.66	1.46	7.18	1.62	4.80	1.44	2.88	1.10	1.39	0.63	0.26	0.14
24	7.91	1.35	5.59	1.46	3.43	1.24	1.79	0.88	0.65	0.43	0.02	0.04
30	6.20	1.22	4.08	1.28	2.18	1.01	0.88	0.63	0.14	0.21	0	0

Benefits and dis benefits due to recalls with inhibit for other junction types also shown in the appendix A.

4.6 Priority conflict: buses running on conflicting arms

Bus priority benefits by extension and recall will be less if buses run on conflicting arms of a junction because buses arriving on conflicting arms simultaneously cannot both get priority at the same time.

4.6.1 Derivation of formulae to calculate average benefits

Two Stage Junction: Buses Running On Both Arms

Cycle time = C

Arm1

Average delay savings by each extension = $Abe1$

Average delay savings by each recall = $Abr1$

Effective green for extension = $Ge1$

Effective red period for recall = $Re1$

Bus flow per hour on arm1= $F1$

Arm2

Bus flow per hour on arm2 = $F2$

Average delay increase by each extension of arm2 to arm1 = $Ade2\_1$

Average delay increase by each recall of arm2 to arm1 = *Adr2_1*

Effective green for extension = *Ge2*

Effective red period for recall = *Re2*

Values for all the parameters described above are known or can be found using the methods described in the previous Sections of this Chapter.

Calculation : Benefit at Arm1

Arm1

Bus flow during effective green for extension *(f1e1) = F1*Ge1/3600*

Bus flow during effective red for recall *(f1r1) = F1*Re1/3600*

Probability of one or more bus arrival during Ge1 = *Pe1*

Probability of one or more bus arrival during Re1 = *Pr1*

Arm2

Bus flow during Ge1 *(f2e1) = F2*Ge1/3600*

Bus flow during Re1 *(f2r1) = F2*Re1/3600*

Probability of one or more bus arrival during Ge1 = *Pe1_2*

Probability of one or more bus arrival during Re1 = *Pr1_2*

These probabilities can be found using the methods described in the previous Sub Sections (4.3.2).

Conflict

Conflict happen when buses arrive on the opposite arms at the same time.

Probability of bus arrival on arm1 &2 during Ge1 *(Pe1_1&2) = Pe1*Pe1_2*

Probability of bus arrival on arm1 &2 during Re1 *(Pr1_1&2) = Pr1*Pr1_2*

Assumption: During conflict half of the bus will not get priority

Probability of extension for arm1 considering conflict *(Pe1_c) = Pe1 - 1/2*Pe1_1&2*

Probability of recall for arm1 considering conflict *(Pr1_c) = Pr1 - 1/2*Pr1_1&2*

Benefit by extension for arm1 *(Be1) = Pe1_c*3600/C*Abe1*1/F1* sec/bus

Benefit by recall for arm1 *(Br1) = Pr1_c*3600/C*Abr1*1/F1* sec/bus

Total benefit by extension and recall *(B1) = Be1+Br1* sec/bus

Calculation: Dis Benefits to Buses at Arm1

Arm2

Bus flow during effective green for extension *(f2e2) = F2*Ge2/3600*

Bus flow during effective red for recall *(f2r2) = F2*Re2/3600*

Probability of one or more bus arrival during Ge2 = *Pe2*

Probability of one or more bus arrival during Re2 = *Pr2*

<u>*Arm1*</u>

Bus flow during Ge2 *(f1e2) = F1*Ge2/3600*

Bus flow during Re2 *(f1r2) = F1*Re2/3600*

Probability of one or more bus arrival during Ge2 = *Pe2_1*

Probability of one or more bus arrival during Re2 = *Pr2_1*

<u>*Conflict*</u>

Probability of bus arrival on arm1 &2 during Ge2 *(Pe2_1&2) = Pe2*Pe2_1*

Probability of bus arrival on arm1 &2 during Re2 *(Pr2_1&2) = Pr2*Pr2_1*

Assumption: During conflict half of the buses of arm1 will get dis benefits

Probability of dis benefits for arm1 *(Pe2_d1) = 1/2*Pe2_1&2*

Probability of dis benefits for arm1 *(Pr2_d1) = 1/2*Pr2_1&2*

Dis benefits by extension e2 to arm1 *(De2_1) = Pe2_d1*3600/C*Ade2_1*1/F1* sec/bus

Dis benefit by recall r2 to arm1 *(Dr2_1) = Pr2_d1*3600/C*Adr2_1*1/F1* sec/bus

Total dis benefit by extension & recall of arm2 to arm1 *(D2_1) = De2_1+Dr2_1* sec/bus

Total benefit *(B) = B1-D2_1* sec/bus

Finally, if bus priority incurs disbenefits to non priority traffics of opposite arms when there is no conflict in the junction, then dis benefits of arm1 due to priority at arm2 need to be considered in the total benefit calculation.

Table 4.18 shows benefits to buses for a two traffic stage junction when buses run in all conflicting approaches. The values are calculated by the methods described in this Section.

Table 4.18: Benefit to buses with conflicting priority (two traffic stages)

T Junction without Pedestrian Crossing: Two Traffic Stage				
Extension & Recall with Conflict; Peak Flow; One Way Bus Flow; Detector Distance 100m				
Bus Frequency (Buses/Hr) on each conflicting arm				
5	10	20	30	40
Benefit: Bus (Scc/Bus)				
5.79	4.3	1.73	-0.4	-2.14

The method described above is applicable for any junction type with and without pedestrian crossing. Benefits to buses with conflicting priority request for other junction types are shown in the Appendix A.

Three Stage Junction: Buses Running On All Arms

For example: the method described above can be applied for three stage junctions with bus services on all approaches. During calculation priority conflicts and dis benefits to arm1 due to arm2 and arm3 need to be included. Priority conflict between arm1 and arm2, and between arm1 and arm3 can be found by the methods described above. Bus dis benefits to arm1 due to arm2 and arm3 during conflict can be found by using the method described above.

4.7 Always green bus

4.7.1 Extension for always green bus

Benefits to buses and dis benefits to non priority arms by extension for always green bus can be calculated by the methods described in the previous Section 4.3.
Table 4.20 and 4.21 below shows benefits and dis benefits due to extensions for always green bus of a two traffic stages junction.

4.7.2 Recall for always green bus

4.7.2.1 Steps to calculate average delay savings by each recall for always green bus

Bus detected when priority stage is not green. Recall required.
Delay is the waiting time due to signal to cross the stop line.

Two Stage Junction

The Table 4.19 below shows the steps to calculate delay savings by recall for always green bus with time of bus detection in two traffic stage junction.

Table 4.19: Delay savings due to recalls for always green bus with time of bus detection (two traffic stage junction)

Bus Detection	Without Recall: Delay	With Recall: Delay	Delay Savings
Scenario 1: Bus detected during ig12	*ig12 + g2 + ig21 + Dq +Da -t*	*0*	*ig12 + g2 + ig21 + Dq +Da –t = C-g1-t+Dq+Da*
Scenario 2: Bus detected 1st second of g2	*g2 + ig21 + Dq +Da -t*	*0*	*g2 + ig21 + Dq +Da -t*
Scenario 3: Bus detected g2m second of g2	*g2 - g2m + ig21 + Dq +Da -t*	*0*	*g2 - g2m + ig21 + Dq +Da -t*
Scenario 4: Bus detected at q. (Xq = t-ig21)	*Dq+Da*	*0*	*Dq+Da*
Scenario 5: Bus detected at p. (Xp = t-ig21-Dq-Da)	*0*	*0*	*0*
Scenario 6: Bus detected last second of g2	*0*	*0*	*0*
Scenario7: Bus detected during ig21	*0*	*0*	*0*

Figure 4.44 below illustrates the bus delay saving by each recall for always green bus with time of bus detection in two traffic stage junction.

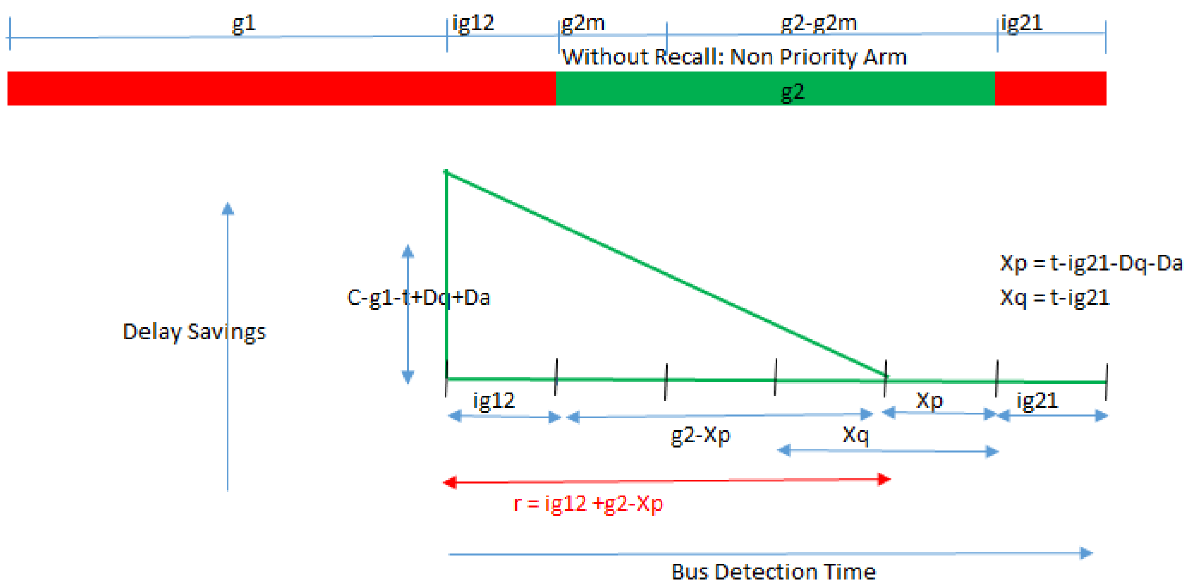


Figure 4.44: Bus delay saving due to each recall for always green bus with time of bus detection (two traffic stage junction)

A green recall will be effective if buses are detected during *r* red periods. Average savings by each recall can also be found from the graph 4.44.

Figures 4.45, 4.46, & 4.47 below describe delay to buses with and without recall for always green bus with time of detection and then illustrates delay savings in two traffic stage junction. Signal details are: g1= 40 sec, g2 = 30 sec, ig12 = ig21 = 7 sec, g2m =7 sec, t =21 sec. Dq and Da not considered for simplicity. This example is for illustration only.

Figure 4.45 below illustrates the delay to buses without recall for always green bus with time of detection (two traffic stage junction).

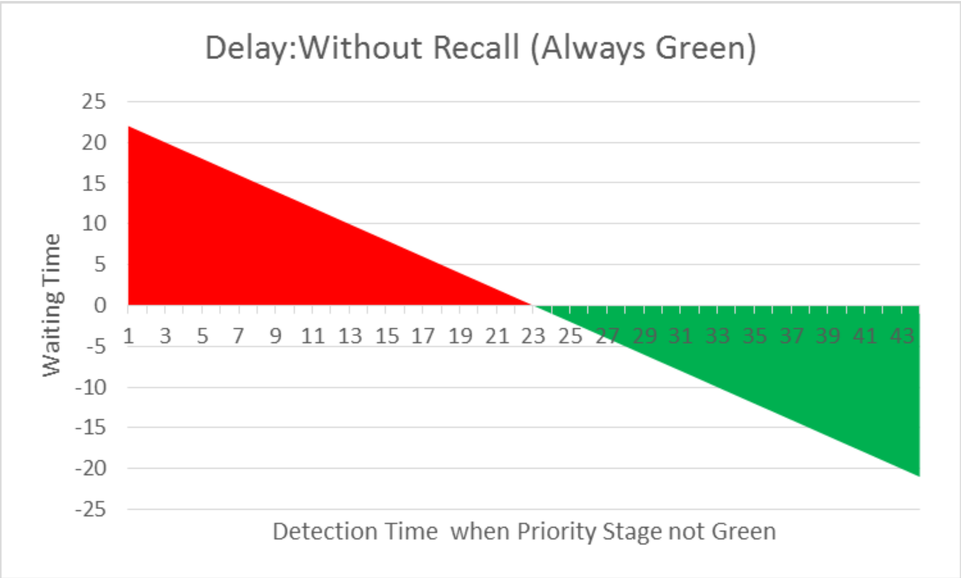


Figure 4.45: Delay to buses without recall for always green bus with time of detection (two traffic stage junction)

This graph provides evidence that during recall for always green bus, because of the long detection distance, the probability of getting green at the stop line will increase even though buses are detected during red. That means that the probability of a recall will be low. So there will be less recall by always green bus method. So impact on the non priority arm will be less compare to traditional recall.

Figure 4.46 below illustrates the delay to buses with recall for always green bus with time of detection in two traffic stage junction.

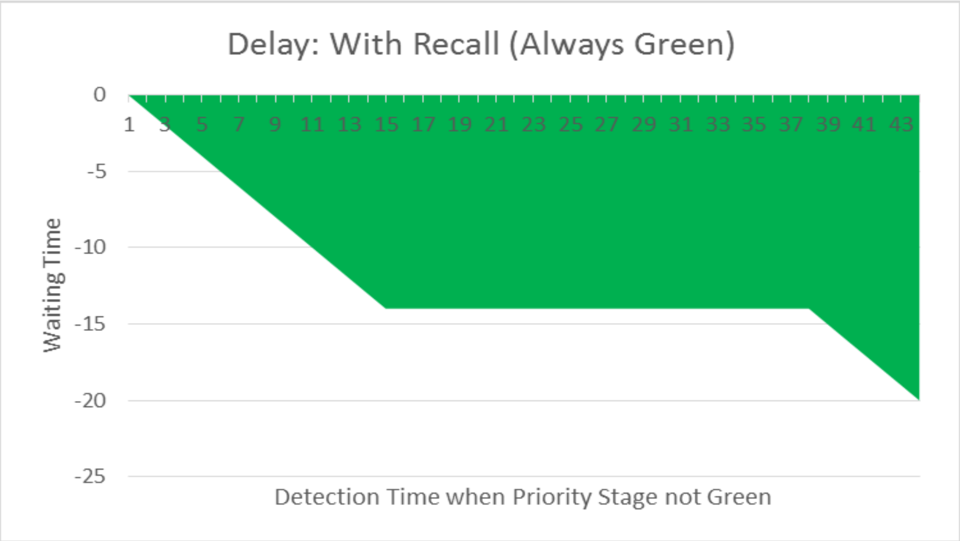


Figure 4.46: Delay to buses with recall for always green bus with time of detection (two traffic stage junction)

Figure 4.46 illustrates that, by recall for always green bus will always get green when they arrive at the stop line, so there will be no waiting theoretically.

Figure 4.47 below illustrates the delay savings due to a recall for always green bus with time of detection in two traffic stage junction.

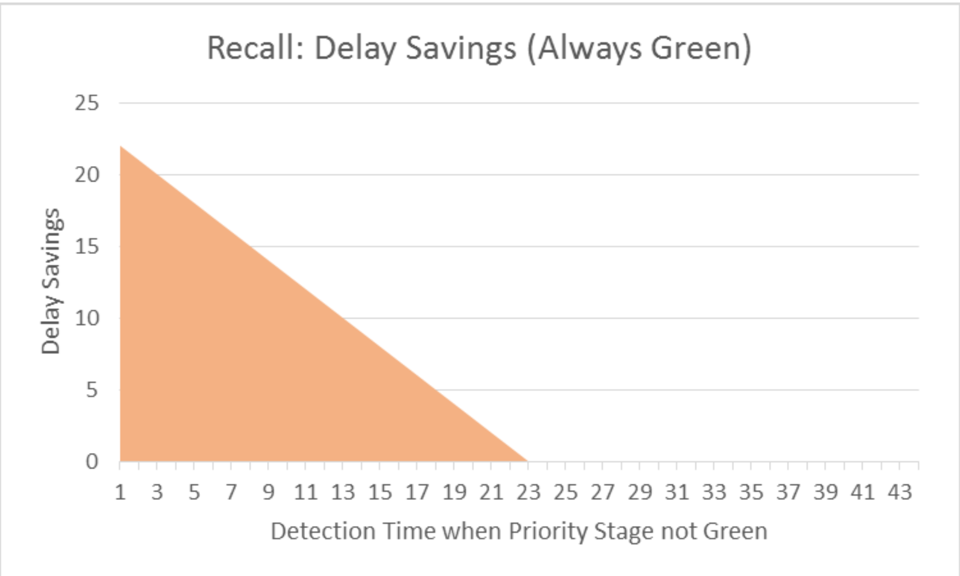


Figure 4.47: Delay savings to buses by recall for always green bus with time of detection (two traffic stage junction)

Figure 4.47 provides evidence that by recall for always green bus, the duration of recall requirement will be less compared to the traditional method. So there will be less recalls but the average benefit by each recall will be high compared to the traditional method because buses always get green at the stop line. So detected buses never wait theoretically.

4.7.2.2 Derivation of formulae to calculate average benefits by each recall for always green bus

Two Stage Junction

Effective red period for recall = *Re* sec

Re = ig12+g2-Xp

Xp = t-ig21-Dq-Da

This is the red period when a detected bus will get benefit if a recall is provided. If a recall is provided during the red period other than effective red, then there will be no benefits to buses. The effective red period for recall can be called *recall time.*

Average savings from each recall = *Br* sec.

Br can be derived from the graph of delay savings described in the previous Section 4.7.2.1.

Bus flow during effective red on priority approach *(f) = F*Re/3600*

Assumption: Poission distribution of bus arrival, bus arrives at traffic signals randomly and independently, bus arrival is uniform.

The probability of no bus arrival during effective red *Po = Poi(f)*

The probability of one or more bus arrivals during effective red *P1 = 1-Po*

Average benefits per cycle *(Bc) = P1*Br* sec/cycle

Average benefit *(B) = 3600/C*Bc*1/F* sec/bus

4.7.2.3 Steps to calculate lost green time to non-priority arms by recall for always green bus

Two Stage Junction

The methods developed in the previous Sections 4.4.3 & 4.4.4 can be used to find out the impact on non-priority arms. The following graph (Figure 4.48) needs to be used to find out the average loss of green by recall for always green bus in two traffic stage junction.

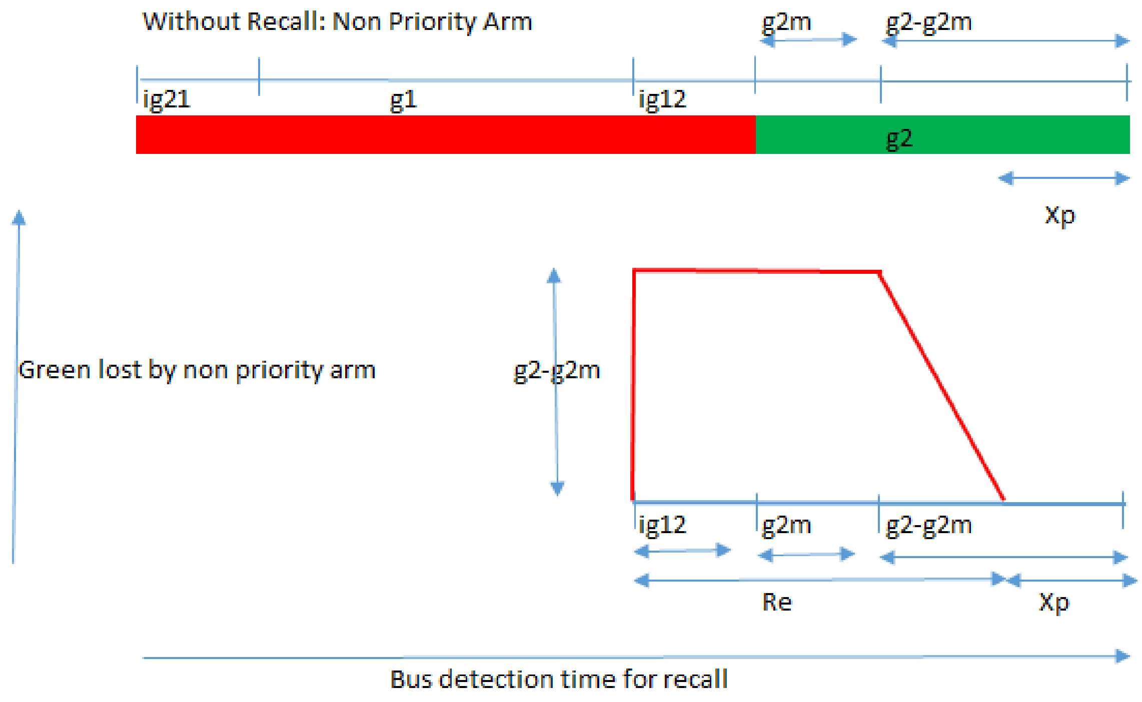


Figure 4.48: Green loss by non priority arm due to recall for always green bus (two traffic stage junction)

It is expected that the always green bus method will provide higher bus delay savings and less negative impact to non priority arm compared to traditional methods. Because, this strategy results in more extensions and less recalls being provided. Also, buses do not need to stop due to the traffic signal - theoretically. Buses can avoid acceleration delay, delay due to signal queue discharge time, and also waiting time for minimum green constraints and inter green time.

Table 4.20 and 4.21 below shows benefits to buses and dis benefits to non priority arms by always green bus in two traffic stage junction. These values are calculated by the methods described in this Section.

Similarly for other junction types benefits and dis benefits by always green bus method has been calculated and provided in Appendix A.

<u>Notes:</u> [g1/C= Priority Green/Cycle Time; t+2 = Detector to stop line travel time; B = Benefits to buses; NT = Dis benefits to non priority traffic; + = Delay savings; - = Delay increase]

Table 4.20: Benefits to buses and dis benefits to non priority arms by always green bus (two traffic stage junction, with different bus frequency)

Two Traffic Stage: T-Junction without Pedestrian Crossing, Always Green Bus, Detection 226m, g1/C = 0.6										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
27	Extension									
	7.74	0.76	6.92	1.36	5.62	2.21	4.65	2.74	3.90	3.07
	Recall without Inhibit									
	0.37	0.17	0.37	0.34	0.36	0.66	0.35	0.97	0.34	1.26
	Recall with Inhibit									
	0.36	0.17	0.35	0.32	0.33	0.60	0.31	0.84	0.29	1.05

Table 4.21: Benefits to buses and dis benefits to non priority arms by always green bus (two traffic stage junction, with different priority approach green)

Two Traffic Stage: T-Junction without Pedestrian Crossing, Always Green Bus, Detection 226m, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.2		.3		.4		.5		.6		.7	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
27	Extension											
	15.28	0.74	13.07	0.89	10.98	1.06	8.82	1.21	6.92	1.36	4.58	1.53
	Recall without Inhibit											
	8.84	1.62	5.78	1.65	3.17	1.29	1.42	0.83	0.37	0.34	0	0
	Recall with Inhibit											
	7.04	1.29	4.82	1.37	2.78	1.13	1.30	0.76	0.35	0.32	0	0

4.8 Validation of Theoretical Methods

Table 4.22 below illustrates the comparison of the priority benefits for different junction types for extensions and recalls between the formulae published by TRL and proposed theoretical technique in this study. As expected, benefits derived from the TRL procedure for extensions are much less compare to the proposed analytical method. This is because in TRL derivations only the red period of a cycle is considered as savings from extensions for simplicity whereas there are also other savings from extensions such as acceleration delay savings and queue clearance delay savings. Thus benefits from extensions have been underestimated in the TRL technique. As expected benefits from recalls are less when derived by the proposed analytical method compared to the TRL technique. This is because, in the TRL derivation minimum green time constraints for non priority arms and the effective red period have not been considered and thus benefits from recalls have been over estimated. But in the proposed analytical method all these factors have been considered to estimate benefits by recall more accurately. The TRL analytical method also does not cover four stage junctions (in the Table 4.22 cross junction with pedestrian crossing). It also does not provide a method to estimate the priority disbenefits to non priority arms.

Table 4.22: Comparison of the results of proposed Theoretical Methods and TRL Analytical Method

Comparison of Proposed Theoretical Method and TRL Analytical Method						
10 Bus per Hour; One Way; Peak Flow						
Junction Type	g1/C	Detector Location (m)	Bus Delay Savings: (Sec/Junction/Bus)			
			Extension		Recall	
			Proposed Theoretical Method	TRL Analytical Method	Proposed Theoretical Method	TRL Analytical Method
Cross Junction with Pedestrian Crossing	0.3	150	11.92	n/a	7.41	n/a
Cross Junction without Pedestrian Crossing	0.4	100	7.24	5.5 (Cooper 1983)	8.17	10.20 (Cooper 1983)
T Junction with Pedestrian Crossing	0.5	150	9.28	7 (Cooper 1983)	2.56	4.76 (Cooper 1983)
T Junction without Pedestrian Crossing	0.6	100	4.38	3 (Vincent et al. 1978)	2.44	3.53 (Vincent et al. 1978)

Derived average priority benefits and disbenefits considering all the four junction types have also been compared between the proposed analytical method, micro simulation models, and results from the SELKENT scheme during peak and inter peak traffic conditions. Table 4.23 below validates the results of the three methods because they are similar. In this comparison, junctions with two traffic stages, three traffic stages, two traffic stages with an all red pedestrian stage and three traffic stages with an all red pedestrian stage have been considered.

Table 4.23: Comparison of the results of proposed Analytical Procedures, SELKENT Scheme, and Micro Simulation Models

Comparison of Proposed Analytical Procedures, SELKENT Scheme, and Micro Simulation Results						
Average of All Junction Types, Extension and Recall						
Traffic Condition	Delay Savings: (Sec/Junction/Vehicle Type)					
	Priority Bus (Sec)			Non Priority Traffic (Sec)		
	Proposed Analytical Methods	SELKENT Scheme (University of Southampton 1988)	Micro-Simulation	Proposed Analytical Methods	SELKENT Scheme (University of Southampton 1988)	Micro-Simulation
Peak	13	11	11	-3	-3	-4 (Cross junction with pedestrian crossing not considered)
Inter Peak	10	8	9	-1	0	-2

Comparison of the results derived from the proposed theoretical methods and micro simulation outputs considering the same parameters for priority extensions and recalls together are presented in Table 4.24 below. This Table illustrates that the analytical procedure and micro simulation provide similar output. For each junction type, derived benefits for buses from the analytical method are higher compared to micro-simulation results because in reality not all buses which are provided priority will be benefitted. For example, a priority bus will not get benefits even though priority is provided if the estimated detector to stop line travel time is lower than the actual travel time or if the estimated queue clearance time is lower than the actual queue clearance time. In the micro simulation model, these real world junction conditions are reflected, thus producing less benefit. So, the analytical procedure will provide maximum achievable benefits to buses. In Table 4.24

below, the difference between micro simulation results and analytical results are higher in the cross junction compared to the T junction. This is because bus journey time is less predictable in this junction due to busy bus stops, higher pedestrian activity and higher congestion levels. Less predictable bus journey time means that a higher percentage of buses will fail to cross the stop line even after priority is provided. That is reflected in the simulation results.

Disbenefits to non priority arms derived from analytical methods are much lower than micro-simulation results because in the analytical methods it is assumed that after bus priority, all queuing traffic in the non priority arms will be able to clear the junction in the next immediate stage. This assumption is most realistic when the junction degree of saturation is relatively low, as typically in inter peak hours and off peak hours. But in reality, during peak hours a junction can run close to or over its capacity. In that situation, non priority arms are likely to have long traffic queues during the red period. Bus priority will make this queue even longer. When the non priority arms become oversaturated many cars waiting at the end of the queue fail to cross the stop line in the next immediate cycle. Those who have failed to cross have to wait an additional cycle, and so overall delay will be higher, as reflected in the micro simulation. The T Junction without pedestrian crossing is a less busy junction (Chapter 7 Table 7.2, Chapter 5 Table 5.18) and both methods then provide the same dis benefit at this junction. Again, the cross junction with pedestrian crossing is running close to its capacity and is a very busy junction (Chapter 7 Table 7.1 , Chapter 5 Table 5.16) . On the non priority arms, some of the queuing traffic during red usually fails to cross the stop line in one go when the signal turns to green for them at this junction. Bus priority makes the queue length worse at these arms and increase the disbenefits many fold because after bus priority some of the non priority queuing traffic has to wait two or three additional cycle to cross the stop line. If in the meantime another priority is provided, the situation on those arms becomes worse, and it may take some time to recover the non priority arm's capacity. This reality has been reflected at this junction in the micro simulation output. But in the analytical methods, for simplicity, during dis-benefits calculation junction capacity and saturation level has not been considered assuming just after bus priority all queuing traffic in the non priority arms will be able to cross the stop line when the signal turns to green from them. Thus disbenefits derived from this analytical technique will be a rough estimation and will give the minimum disbenefits to non priority arms.

Table 4.24: Comparison of the results of proposed Theoretical Methods and Micro Simulation Models

Comparison of Proposed Theoretical Method and Micro Simulation Results					
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow					
Junction Type	Detector Location (m)	Delay Savings: (Sec/Junction/Vehicle Type)			
		Priority Bus (Sec)		Non Priority Arms Car (Sec)	
		Proposed Theoretical Method	Micro-Simulation	Proposed Theoretical Method	Micro-Simulation
Cross Junction with Pedestrian Crossing	150	19	14	-10	-345
Cross Junction without Pedestrian Crossing	100	15	10	-1	-6
T Junction with Pedestrian Crossing	150	12	12	-1	-7
T Junction without Pedestrian Crossing	100	7	5	-1	-1

4.9 The Need for Micro Simulation Models

It has been established (Table 4.22) that analytical procedures illustrated in this Chapter estimate bus priority benefits and disbenefits more accurately compared to previous analytical methods. However, analytical methods have limitations because of many simplifications and assumptions required to make the methods workable. For example, the previous Section illustrated how analytical methods can easily over-estimate the benefits to buses and under-estimate the negative impacts on non-priority traffic.

Analytical methods developed to date are also inflexible in a number of other respects. For example, detector location and queue length on a priority approach have an impact on bus priority benefits: Recall benefits are higher when buses are detected just at the end of the queue length. So if detectors are sited before or after the queue length (Ahmed et al. 2015) benefits reduce (Chapter 7, Table 7.22 to 7.29). However, analytical methods fail to show the impact of queue length and bus detection (Table A16, A19, A22, A25) on priority benefits because, in the analytical method, all buses are detected at the predefined location for priority and counted for benefits. In reality, when the queue length is longer than the predefined detector location, buses arriving at the end of the queue will not be detected, so priority will not be provided. In the field queue length varies from junction to junction and with time of the day. At the same time, queue pattern also depends on traffic arrival pattern, which varies every moment. These queue variations can only be realistically replicated by using micro simulation models.

Bus priority benefits and disbenefits also depend largely on many other junction characteristics. For example: junction delay (Chapter 7, Table 7.53 to 7.55), junction layout, junction types (Chapter 7, Table 7.57 to 7.60), one way or two way bus flow (Chapter7, Table 7.65 to 7.68), pedestrian movements in the junction and traffic arrival patterns. Analytical methods do not consider these factors. In the analytical technique, fixed time signals (for vehicle actuated signal maximum stage green) have been considered but in reality green time and cycle length vary with traffic demand. So, once again, this suggests the need for micro simulation modelling.

Nevertheless, analytical methods do have a role in providing a pre assessment of priority impacts before deciding whether to do more detailed and expensive modelling exercises. Analytical procedures can be used to get a generic idea of the priority benefits and disbenefits, but to estimate the impacts of bus priority more accurately and to understand junction and network specific priority impacts before implementation, micro simulation models are necessary.

4.10 Chapter summary

Calculation procedures of delay savings to buses and negative impact to non priority arms for traditional, and proposed bus priority methods considering different junction types have been illustrated in this Chapter theoretically by using graphs and formulae incorporated within analytical techniques. Derivation methods to estimate the performance of bus priority with inhibit and priority conflicts also have been illustrated. These procedures provide more accurate estimation of bus priority benefits and dis benefits compared to existing analytical methods, because various essential new bus priority parameters have been included in the derivation and existing parameters also have been improved. Proposed theoretical methods also have been validated by comparing the results with the existing analytical method, results from the SELKENT bus priority scheme in London, and micro-simulation models. It is concluded that the analytical techniques can be used to get an estimate of maximum achievable benefits and minimum disbenefits due to priority. However, these techniques cannot reflect the wide range of operational features which vary in practice, and this can only be done by using an appropriate micro simulation approach. In the next Chapters, different type of junction with different network conditions are used as case studies to illustrate the application of micro-simulation and illustrate the impacts of various design and operational features associated with bus priority.

Chapter 5: Data Collection, Analysis and Application

5.1 Introduction

Southampton is the main city in central southern England and the third largest city in the South East outside London. It is an important national, regional and local transport hub. At present congestion occurs during peak times at key junctions and areas in the network. It is expected that over the next twenty years demand for travel will rise by seven million trips a year within the city (SCC 2015). Most of these new trips and some existing ones will need to be accommodated on public transport because of limited road space. At present around a quarter of peak period trips and a fifth of off-peak trips in the city are made by public transport (SCC 2015). There are 7 operators providing a total of 38 services in the Southampton bus network. Together they carry around 20 million journeys a year or 85% of all public transport trips to work in the city (SCC 2015). But only three commercial operators provide the majority of services, and most major routes have a good frequency of service during the day. In addition to services entirely within the city boundaries, Southampton City Centre is linked with nearby towns and districts along six main corridors, known as the Western approach, Shirley Corridor, Avenue Corridor, Bevois Valley Corridor, Northam Corridor, and Itchen Bridge. However, buses have only a 12% share of the city's work trips and so more needs to be done to encourage motorists to travel to work by bus and assist in reducing peak time congestion. Southampton City Council has a challenging goal to increase bus patronage by 50% over the next 20 years (SCC 2015). To achieve this, one of the bus priority schemes is to improve reliability and punctuality of buses along the main corridors by improving traffic signals.

To develop realistic base models for further analysis of bus priority at traffic signals, suitable sites with in the main corridors in Southampton were selected considering different junction types. The following Sections outline the data requirements and the data collection processes which led to the establishment of a reliable database for the simulation model development and further analysis.

5.2 Data Requirements

The data requirements for this research were identified as:

- Traffic flow data for each arm of each junction type
- Pedestrian flow data at each pedestrian crossing of each junction type
- The variation of flow during peak and inter peak hours
- Traffic composition data
- Signal details for each junction type
- Queue details on each arm of each junction type
- The variation of queues during peak and inter peak hours
- Data to establish the relationship between the number of queuing vehicles for a given traffic composition with link length
- Data to estimate the required time per queuing vehicle to cross the stop line when signal changes from red to green
- Data to estimate the delay per queuing vehicle
- Junction delay data to buses for each junction type
- Travel time data within the chosen network
- Bus stops dwell time data
- Link speed for each junction type
- Bus services and frequency data through each junction type

These identified data items were collected from the chosen sites for respective junction types, as described below.

5.3 Site Selection

To understand the performance of bus priority parameters and methods on different junction types and characteristics one signalised cross junction, one signalised T-junction, and one signalised pedestrian crossing from Southampton were chosen for the required data collection to develop realistic base models based on those junctions. The plan was to survey and fully analyses these junctions first and then to review the need for further data collection.

Figure 5.1 below illustrates the chosen junctions.

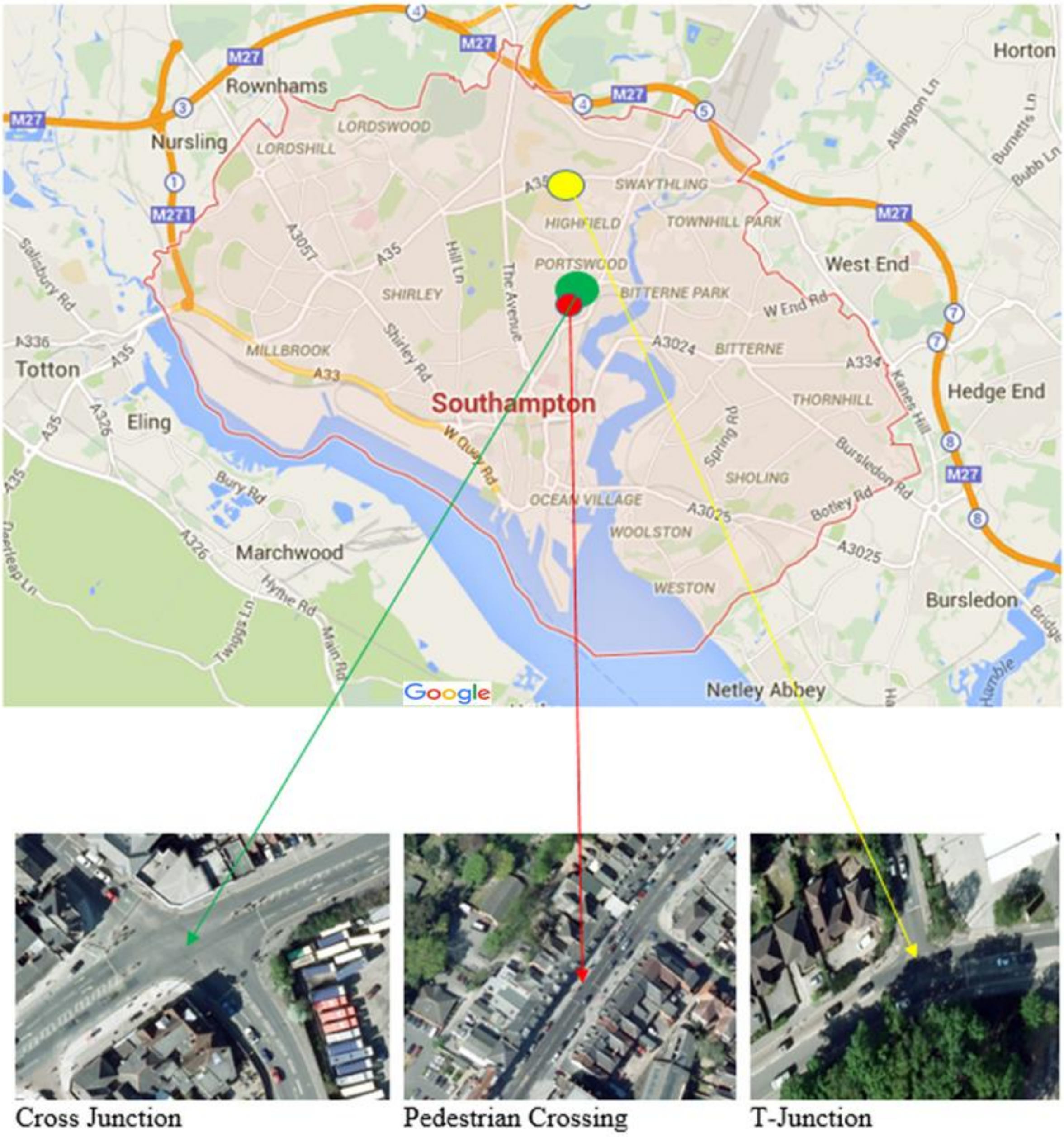


Figure 5.1: Location of sites *(Source: Map data ©2013 Google)*

Cross Junction

For the development of the cross junction base model, the junction between Highfield Lane, St. Denys Road and Portswood Road was selected. Figure 5.2 below illustrates this junction.

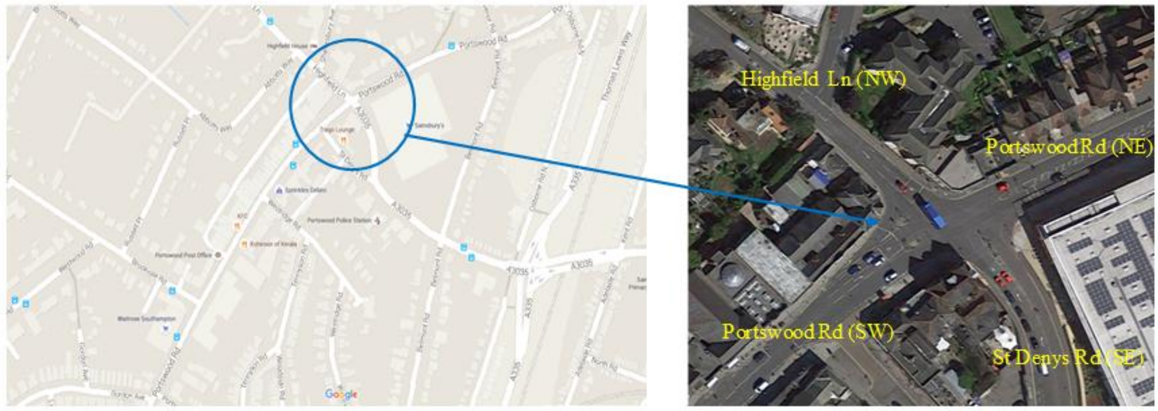


Figure 5.2: Cross junction: Portswood junction (*Source: Map data ©2015 Google*)

This is a four-arm signalised junction. The south-west arm of the junction has two lanes and a left turn flare. Other arms have two lanes. Right turning from the north-east arm of Portswood Rood to Highfield Lane is not allowed. But in the upstream of the junction all arms are only single lane.

This junction is chosen for cross junction base model development because all approaches have bus routes. Bus frequency and passenger activity with in the area is high. This is a busy junction during peak and inter-peak hours. Bus service details for this junction is provided in Appendix B.

T Junction

For the development of a T- junction base model, the junction of Glen Eyre Road and Burgess Road was selected, as illustrated in Figure 5.3.

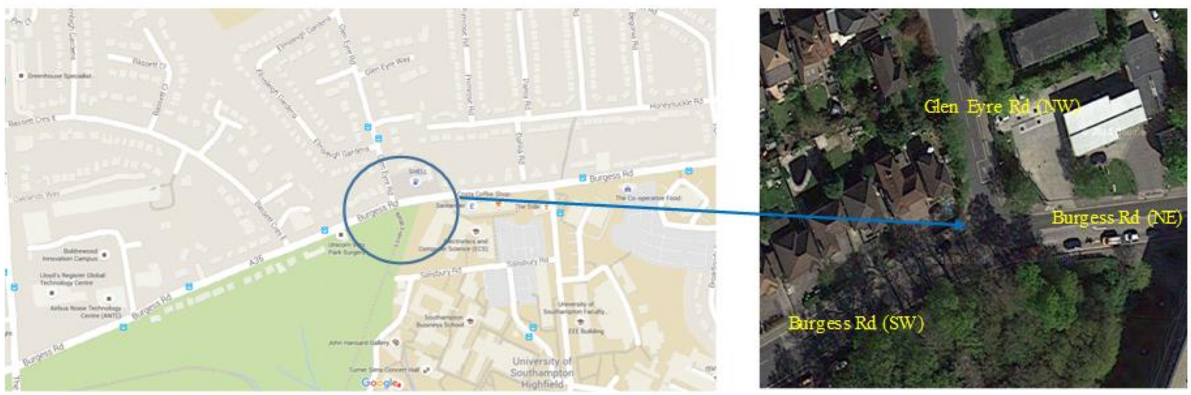


Figure 5.3: T junction: Burgess Road vs Glen Eyre Road *(Source: Map data ©2015 Google)*

This is a three arm signalised junction. At the junction approach the north-east arm of Burgess Road has two lanes and all other approaches have one lane. But in the upstream of the junction all arms are only single lane.

This junction was chosen for the T-junction base model development because all approaches have bus routes. Bus frequency is modest and pedestrian activity varies significantly by time of day, being predominantly comprised of students. Bus service details for this junction is provided in Appendix B.

Pedestrian Crossing

For the development of the pedestrian crossing base model a pedestrian crossing on Portswood Road in Portswood was selected. Figure 5.4 below illustrates the pedestrian crossing within the network. Both arms of the crossing are single lane.

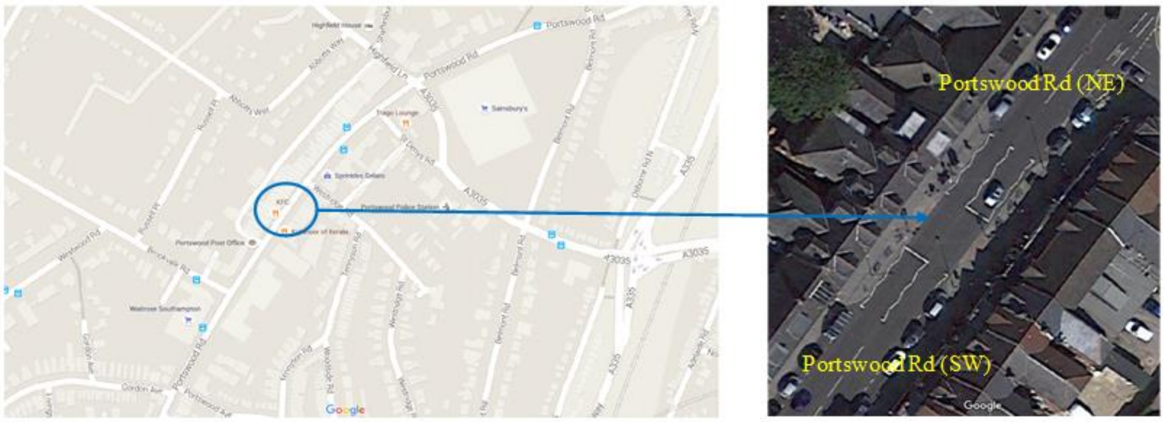


Figure 5.4: Pedestrian crossing: Portswood road *(Source: Map data ©2015 Google)*

This crossing was chosen for the pedestrian crossing base model development because pedestrian activity is high in this shopping district and there are six bus services running through this crossing in both directions. Among them two services are high frequency service. Bus service details for this crossing is provided in Appendix B.

5.4 Links Description

All links of the selected junctions and pedestrian crossing are on 30mph speed limit zone. All the carriageways of cross junction, T-junction, and pedestrian crossing are single carriageway with one lane each direction. But at junction approaches additional lanes are added to increase the junction capacity. Arm descriptions of each junction approach of the selected junctions have been described in the Tables 5.1, 5.2, and 5.3 below.

Table 5.1: Cross junction approach description

Cross Junction		
Junction Arm	Lane Nr	Description
Portswood Rd (SW)	3	1 left turning lane, 1 straight ahead lane, 1 right turning lane
Portswood Rd (NE)	2	1 left turning lane, 1 straight ahead lane
Highfield Ln (NW)	2	1 straight ahead /left turning lane, 1 right turning lane
St Denys Rd (SE)	2	1 straight ahead /left turning lane, 1 right turning lane

Table 5.2: Pedestrian crossing approach description

Pedestrian Crossing		
Crossing Arm	Lane Nr	Description
Portswood Rd (SW)	1	1 straight ahead lane
Portswood Rd (NE)	1	1 straight ahead lane

Table 5.3: T Junction approach description

T Junction		
Junction Arm	Lane Nr	Description
Burgess Rd (SW)	1	1 left turning/ straight ahead lane
Burgess Rd (NE)	2	1 right turning lane, 1 straight ahead lane
Glen Eyre Rd (NW)	1	1 right /left turning lane

5.5 Data Collection Methods

5.5.1 Traffic Flow Data

Cross Junction

Flow data was collected by field surveys at each junction. For the cross junction the survey was carried out on 04.03.13 from 8.00 am to 7.00pm. It was observed in the field that this junction has similar flows in the morning and afternoon hours but higher flow in the evening hours. Average flow data during the busy period was used in the base model for evening peak. Similarly average flow data during the normal period (8am to 3pm) has been used in the base model for morning and inter peak. It is also observed that for a short duration the junction became very congested and the congested scenario has been modelled in the base model considering the highest observed flow of the day in each arm of the junction. Observed average traffic flow in each arm of the junction for normal, busy, and congested condition is presented in Table 5.5 below. During flow counts turning movements were also recorded and the average turning ratio from each arm is also presented in Table 5.5 below. Observed pedestrian flow data was also collected and is presented in the same Table.

Table 5.4: Junction condition by time of the day (Cross junction & Pedestrian crossing)

Cross Junction & Pedestrian Crossing		
	Duration	Junction Condition
Morning & Inter Peak	08.00-15.00	Normal
Evening Peak	15.00-19.00	Busy
Extreme Peak: (considering highest flow of the day in each arm of the junction)		Congested

Table 5.5: Cross junction flow data

Cross Junction						
Junction Arm	Flow (Vehicles/hr)			Turning Percentage		
	Morning & Inter Peak	Evening Peak	Extreme Scenario	Straight	Left	Right
Portswood Rd (SW)	477	582	621	61%	25%	14%
Portswood Rd (NE)	366	384	483	84%	16%	
Highfield Ln (NW)	330	356	432	45%	21%	34%
St Denys Rd (SE)	333	338	406	55%	30%	15%
Pedestrian Flow in each direction (Pedestrian/hr)						
Pedestrian Crossing (on St Denys Rd)	199	409	513	n/a	n/a	n/a

Flow data for each hour from 8am to 7pm is provided in the Appendix B.

Pedestrian Crossing

The chosen pedestrian crossing for the base model development is on the South West arm of Portswood road at the cross junction. As there is no other junction between the cross junction and the selected pedestrian crossing, traffic flow data was not required to be collected because it can be calculated from the collected flow data for the cross junction. Only pedestrian flow data was collected by field survey on 12.03.13 for morning and inter peak (8.00am to 2pm), and evening peak (3pm to 7pm). It was observed that pedestrian flow is similar throughout the day. Observed average traffic flow and pedestrian flow in each arm of the crossing for normal, busy, and congested condition is presented in Table 5.6 below.

Table 5.6: Pedestrian crossing flow data

Pedestrian Crossing			
Junction Arm	Flow (Vehicle/hr)		
	Morning & Inter Peak	Evening Peak	Extreme Scenario
Portswood Rd (SW)	477	582	621
Portswood Rd (NE)	520	545	674
Pedestrian Flow in each direction (Pedestrian/hr)			
	135	154	174

Pedestrian flow data for each hour from 8am to 7pm is provided in the Appendix B.

T-Junction

Flow data for the T-junction was collected by field survey on 18.03.13 from 7.00 am to 7.00pm. It was observed in the field that this junction has similar flows in the morning and evening peak hours but less flow in the afternoon hours. During morning (7am to 10am) and evening (4pm to 7pm) peak the junction is busy and during the inter peak from 10am to 4pm the junction is not busy. Average flow data during the busy period was used in the base model for the morning and evening peak. Similarly average flow data for the less busy period was used in the base model for the inter peak. It was also observed that for a short duration the junction become very congested and the congested scenario was modelled in the base model considering the highest observed flow of the day in each arm of the junction. Observed average traffic flow in each arm of the junction for normal, busy, and congested condition is presented in Table 5.8 below. During flow counts turning movements were also recorded and the average turning ratio from each arm is also presented in the Table 5.8 below. Pedestrian flow data for each hour for the whole day has not been collected because it was observed that this flow was similar throughout the day. Pedestrian flow data was collected in the morning (8am to 10am), afternoon (12pm to 2pm), and evening (4pm to 6pm) hours and average pedestrian flow is presented in Table 5.8 below.

Table 5.7: T-junction condition with time of the day

T-Junction		
	Duration	Junction Condition
Morning Peak	7am -10am	Busy
Evening Peak	4pm -7pm	Busy
Inter Peak	10am -4pm	Normal
Extreme Peak: (considering highest flow of the day in each arm of the junction)		Congested

Table 5.8: T-junction flow data

T- Junction						
Junction Arm	Flow (Vehicle/hr)			Turning Percentage		
	Morning & Evening Peak	Inter Peak	Extreme Scenario	Straight	Left	Right
Burgess Rd (SW)	745	529	840	90%	10%	
Burgess Rd (NE)	733	602	828	88%		12%
Glen Eyre Rd (NW)	285	127	486		72%	28%
Pedestrian Flow in each direction (Pedestrian/hr)						
Pedestrian Crossing (on Burgess Road)	190	190	190	n/a	n/a	n/a

Flow data for each hours from 7am to 7pm is provided in the appendix B.

5.5.2 Traffic Composition Data

During traffic flow data collection traffic composition data also collected. It was observed that traffic composition at the selected sites was similar. While counting traffic flow, the numbers of cars, taxis, heavy good vehicles, medium good vehicles (large van), motor cycles, and cycles data was recorded. Small vans were considered as cars because of their similar length to a car. Results are given in Table 5.9 below.

Table 5.9: Traffic composition data

Traffic Composition	
Vehicle Type	Ratio
Car	0.806
Taxi	0.046
Medium Good Vehicle (MGV)	0.035
Heavy Good Vehicle (HGV)	0.004
Motor Bike	0.032
Cycle	0.077

5.5.3 Traffic Signal Data

Traffic signal details for each junction were collected by field survey. Base models signal controllers were developed based on collected signal data during peak hours because signal controllers are vehicle actuated. In the vehicle actuated junction signal controller provides maximum stage green during peak hours due to high demand of traffic in each approach.

Cross Junction

The cross junction data was collected on 04.03.13 from 3pm to 7pm (whole evening peak) and from 11am to 12am (inter peak). Observed green times for each stage are presented in the Appendix B. It was found that during evening peak hours the signal stages run up to their maximum green most of the time. Figure 5.5 below illustrates the signal stage diagrams of the cross junction. Tables 5.10 and 5.11 below illustrate signal details as observed in the field.

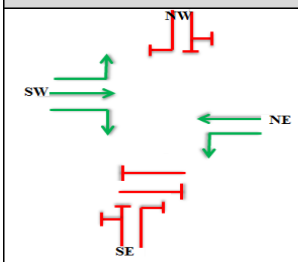
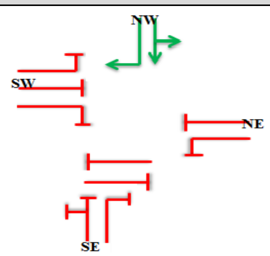
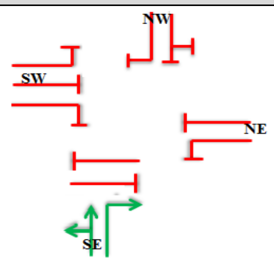
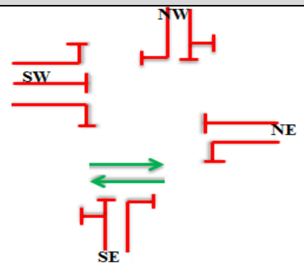
Cross Junction *(Source: Map data ©2013 Google)*			
Stage 1	Stage 2	Stage 3	Stage 4
			

Figure 5.5: Cross junction stage diagra

Table 5.10: Cross junction signal stage details

Cross Junction: Signal Stage Details				
Junction Arm	Symbol	Nr	Minimum Green (Sec)	Maximum Green (Sec)
Portswood Rd (SW +NE)	S1	1	7	35
Highfield Ln (NW)	S2	2	7	20
St Denys Rd (SE)	S3	3	7	20
Pedestrian Green	S4	4	7	7

Table 5.11: Cross junction signal details

Cross Junction: Signal Details												
Max Cycle Time (Sec)	117											
Inter Green (Sec)	1-2	1-3	1-4	2-1	2-3	2-4	3-1	3-2	3-4	4-1	4-2	4-3
	9	9	7	7	7	7	7	7	6	13	13	13
Amber (Sec)	3	3	3	3	3	3	3	3	3	0	0	0
Red/Amber (Sec)	2	2	0	2	2	0	2	2	0	2	2	2

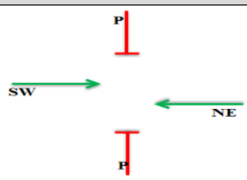
Pedestrian Crossing

The pedestrian crossing data was collected on 12.03.13 from 4pm to 5pm (evening peak) and from 12am to 1pm (inter peak). Observed green times for each stage are presented in the Appendix B. Data collection for a longer duration was not carried out because it was found that this pedestrian crossing has similar pedestrian and traffic demand throughout the day. The length of the pedestrian stage is dependent on the required time by the pedestrian to cross the crossing. For the slowest pedestrian maximum time is allocated (6sec green and 11 see clearance time). Again, for the fast pedestrian allocated time is minimum (6see green + 4sec clearance). In the developed pedestrian crossing, pedestrian behaviour has not been considered, so to ensure pedestrians safety all pedestrian are provided highest clearance time of 11 sec as observed in the field. Figure 5.6 below illustrates the signal stage diagrams. Tables 5.12 and 5.13 below illustrate signal details as observed in the field.

Pedestrian Crossing

(Source: Map data ©2013 Google)

Stage 1



Stage 2

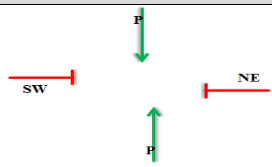


Figure 5.6: Pedestrian crossing stage diagram

Table 5.12: Pedestrian crossing signal stage details

Pedestrian Crossing: Signal Stage Details				
Junction Arm	Symbol	Nr	Minimum Green (Sec)	Maximum Green (Sec)
Portswood Rd (SW +NE)	S1	1	7	35
Pedestrian Green	S2	2	6	6

Table 5.13: Pedestrian crossing signal details

Pedestrian Crossing: Signal Details		
Max Cycle Time (Sec)	60	
Inter Green (Sec)	1-2	2-1
	6	13
Amber (Sec)	3	0
Red/Amber (Sec)	0	2

T Junction

The T junction data was collected on 18.03.13 from 8am to10am (morning peak), 12am to 2pm (inter peak) and 4pm to 6pm (evening peak). Observed green times for each stage are presented in the Appendix B. It has been found that during peak hours signal stages run up to their maximum green most of the time. The Figure 5.7 below illustrates the signal stage diagrams for the T junction. Tables 5.14 and 5.15 below illustrate signal details as observed in the field.

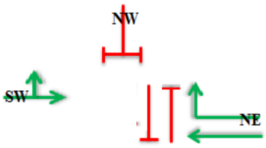
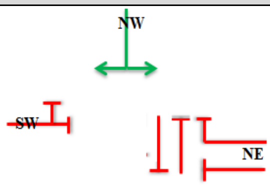
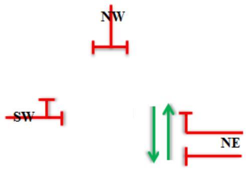
T-Junction *(Source: Map data ©2013 Google)*	Stage 1	Stage 2	Stage3
			

Figure 5.7: T-junction signal stage diagram

Table 5.14: T junction signal stage details

T Junction: Signal Stage Details				
Junction Arm	Symbol	Nr	Minimum Green (Sec)	Maximum Green (Sec)
Burgess Rd (SW + NE)	S1	1	7	50
Glen Eyre Rd (NW)	S2	2	7	20
Pedestrian Green	S3	3	7	7

Table 5.15: T junction signal details

T Junction: Signal Details						
Max Cycle Time (Sec)	105					
Inter Green (Sec)	1-2	1-3	2-1	2-3	3-1	3-2
	8	6	7	7	13	13
Amber (Sec)	3	3	3	3	0	0
Red/Amber (Sec)	2	0	2	0	2	2

5.5.4 Junction Queue Data

Junction queue information is required to validate the base models. Junction queue is a new priority parameter considered in this research. Other priority parameters also influenced by junction queue length.

Cross Junction

The number of queuing traffic due to signal red at each arm of the junction was collected on 05.03.13 from 3pm to 7 pm (whole evening peak: busy condition) and from 10am to 2pm (inter peak: normal condition). Data is presented in the Appendix B. It was found that except for Portswood Road (NE) arm all other arms have long queuing traffic of this junction during evening peak (busy) hours. In Portswood Road (SW) arm of the junction the queue condition become worse due to parking activities, pedestrian movement, and two uncoordinated pedestrian crossings located close to the junction on that link. It was also observed that evening peak exit blocking occurs on St Denys Road (SE) arm of the junction due to another very busy and major junction (Thomas Lewis Way vs St Denys Rd) located close to Portswood Junction. Table 5.16 below summarises the queue data for cross junction.

Table 5.16: Cross junction queue data

Cross Junction: Queue Due to Red						
Condition	Busy			Normal		
Junction Arm	Average (Nr)	Maximum (Nr)	Mode (Nr)	Average (Nr)	Maximum (Nr)	Mode (Nr)
Portswood Rd (SW)	16	30	21	9	20	9
Portswood Rd (NE)	8	19	8	7	14	6
Highfield Ln (NW)	13	25	13	8	16	6
St Denys Rd (SE)	12	27	10	10	20	11

Pedestrian Crossing

The number of queuing traffic due to signal red at each arm of the crossing was collected on 12.03.13 from 3pm to 5 pm (evening peak: busy condition) and from 11am to 1pm (inter peak: normal condition). Data is presented in the Appendix B. It has been found that long traffic queues usually do not build up during red signal. But in Portswood Road (SW) arm of the crossing queue conditions sometimes become worse due to parking activities, pedestrian movement, and due to Portswood Junction signal located close to the crossing on that link. Table 5.17 below summarises the queue data for the pedestrian crossing.

Table 5.17: Pedestrian crossing queue data

Pedestrian Crossing: Queue Due to Red						
Condition	Busy			Normal		
Junction Arm	Average (Nr)	Maximum (Nr)	Mode (Nr)	Average (Nr)	Maximum (Nr)	Mode (Nr)
Portswood Rd (SW)	5	15	3	3	10	2
Portswood Rd (NE)	4	11	3	4	11	2

T Junction

The number of queuing traffic due to signal red on each arm of the junction was collected on 19.03.13 from 7am to 10am (whole morning peak), from 12am to 2pm (inter peak), and 4 pm to 7 pm (whole evening peak). Data is presented in the Appendix B. It was found that this junction is under saturated most of the time even in the peak hours. Long traffic queue due to red in the major road (both arms of Burgess Road) has been observed during peak hours. In the Burgess Road (SW) arm of the junction queue conditions became worse due to exit blocking on Burgess Road (NE) arm because of another busy and major junction (Burgess Road vs University Road) located nearby. Table 5.18 below summarises the queue data for T junction.

Table 5.18: T junction queue data

T Junction: Queue Due to Red									
Condition	Busy						Normal		
	Morning Peak			Evening Peak			Inter Peak		
Junction Arm	Avg (Nr)	Max (Nr)	Mode (Nr)	Avg (Nr)	Max (Nr)	Mode (Nr)	Avg (Nr)	Max (Nr)	Mode (Nr)
Burgess Rd (SW)	12	30	13	12	31	13	7	17	4
Burgess Rd (NE)	7	21	10	8	20	7	5	14	2
Glen Eyre Rd (NW)	7	18	7	4	14	3	2	7	2

5.5.5 Queue Occupancy Data

It was observed in the field that the number of stationary vehicles queuing in front of a bus during the red signal is one of the major parameter to influence the signal delay. To site bus detectors upstream of the queue length, queue occupancy data is required. Queue occupancy data describes the number of vehicles that can queue up in a certain distance during red. This number is dependent on vehicle composition, driver behaviour, average gap between vehicles (standstill distance), etc. Queue occupancy data was collected for the cross junction and the T-junction on 06.03.13 and 20.03.13 respectively by field survey. All together 52 observations were made. Data is presented in the Appendix B. For the pedestrian crossing, this has not been done because at this crossing queue length is not long enough. Table 5.19 below describes the relationship between the number of queuing vehicles with length of link required to accommodate that number for both junctions.

Table 5.19: Relationship between number of queuing vehicles with queue length

Relationship between queuing vehicles number with queue length		
	Link Length (m)	Average Number of Queuing Vehicles (Nr)
Cross Junction	100	17
T-Junction	100	17

5.5.6 Queue Clearance Time

Queue clearance time is the time required by the last vehicle of signal queue to cross the stop line when signal changes to green from red. Queue clearance rate is the average time required by each queuing vehicle of signal queue to cross the stop line when signal changes to green from red. It was observed in the field that during busy hours in both cross junction and T-junction, most of the green time is utilised to clear the junction queue. Stationary vehicles waiting for green in the queue need longer travel time to cross the stop line due to extra time to react with front vehicle movements (to get ready and start to move), and then to accelerate. So, queue clearance time is much higher than the free flow travel time considering same link length. The higher the number of queuing vehicles, the longer green period is required to clear the queue due to the waste of green by each drivers reaction time. If required queue clearance time is higher than the provided green, then not all queuing vehicles will be able to cross the stop line in one go. Understanding this parameter during bus priority implementation is very important because it controls the minimum amount of priority green required during recall and priority conflict if a bus joins the queue after a certain number of vehicles in front. The amount of clearance time required by different numbers of queuing vehicles during red was collected in the sites for both junctions on 06.03.13 and 20.03.13. For the pedestrian crossing, this has not been done because at this crossing queue length is not long enough. It was observed that the higher the number the longer period is required. But queue clearance rate (time required by each vehicle) is the same. Queue clearance rate derived from observed data is been presented in Table 5.20 below.

Table 5.20: Queue clearance rate

Queue Clearance Rate		
Cross Junction	Average Queue Clearance Time	2.1 sec/vehicle
T-Junction	Average Queue Clearance Time	2.1 sec/vehicle

That means, if 20 vehicles queue up during red then the time required to cross the stop line by the last vehicle when signal changes from red to green is (20*2.1) 42 sec. So 42 sec green time need to be provided to clear the queue in one go. All together 160 sample data was collected and is presented in the Appendix B.

5.5.7 Signal Delay Data

Signal delay data is very important to validate the models and also to understand the relationship of junction delay with priority performances. Delay data due to the signal aspect was collected from 06.05.13 to 24.05.13 for the selected junctions and pedestrian crossing. Data was collected randomly by travelling through the junctions and pedestrian crossing by bus. Data was also collected by observation at the sites. Arrival time for each bus was recorded when it slows down (start to decelerate) and stop due to the signal. Again departure time for that bus was also recorded when it started to move (start to accelerate) and speed up. From the time difference delay was calculated. If buses arrive at the signal during green and do not need to stop, their delay due to the signal is considered as zero. Buses on the major road only considered for data collections. It was observed that, during peak hours due to long traffic queue buses often fail to clear the junction at first occurrence when signal changes from red to green. For those buses additional delay is the whole cycle length. Average delay to buses running on the major road by the cross junction, T-junction, and pedestrian crossing is presented in the Tables 5.21, 5.22, and 5.23 below. These Tables also describe the percentage of buses that has to stop due to signal during different junction conditions.

Table 5.21: Cross junction signal delay

Signal Delay: Cross Junction			
Junction Condition	Average Delay (Sec/Bus)	Stopped	No Delay
Inter Peak and Morning Peak	37	74%	26%
Evening Peak	42	76%	24%

Table 5.22: Pedestrian crossing signal delay

Signal Delay: Pedestrian Crossing			
Junction Condition	Average Delay (Sec/Bus)	Stopped	No Delay
Inter Peak and Morning Peak	10	56%	44%
Evening Peak	12	61%	39%

Table 5.23: T junction signal delay

Signal Delay: T-Junction			
Junction Condition	Average Delay (Sec/Bus)	Stopped	No Delay
Inter Peak	16	56%	44%
Morning and Evening Peak	29	71%	29%

For the cross junction 125 sample data (66 inter peak and morning peak, 59 evening peak) has been collected. These data are presented in the Appendix B. For the T junction 105 sample data (50 inter peak, 55 morning and evening peak) were collected. These data are presented in the Appendix B. For the pedestrian crossing 108 sample data (54 morning and inter peak, 54 evening peak) was collected. These data are also presented in the Appendix B.

Delay due to acceleration and deceleration has been included within the signal delay data. Because acceleration and deceleration happen at the junction due to signal when buses required to stop. But these parameters depend on bus type, engine type, bus drivers attitude, and many other factors. To replicate the filed acceleration and deceleration of buses at the modelled junctions these data also should be collected separately in the further studies. But in this research recommended acceleration and deceleration profiles by TFL DTO modelling guidelines (TfL 2010) have been used for models development.

5.5.8 Journey Time Delay Data

Bus journey time data was collected from 06.05.13 to 24.05.13 for six services within the Southampton network. Data was collected randomly while travelling by the selected buses during peak and inter peak hours. For each journey, beginning bus stop to end bus stop travel time data, delay due to each signalised junction and pedestrian crossing with in the route, and bus dwell time at each bus stop within the route was recorded. For each service major bus stops where scheduled departure time table available have been selected as beginning and end bus stops. From scheduled time table of the beginning and end bus stops, scheduled travel time of each service has been calculated. During each journey, network traffic conditions, drivers driving behaviours, occurrence of incidents have been recorded. For each journey, return trip has been made by the same service and all the data described have been recorded. In Table 5.24 below for each selected service length of trip, beginning and end bus stop details, total number of signalised junctions, pedestrian crossings, and bus stops covered within the trip have been described.

Table 5.24: Trip details

Trip Details						
Bus Service	Trip Length (Km)	Beginning Bus Stop	End Bus Stop	Total Nr of Signalised Junctions	Total Nr of Signalised Pedestrian Crossings	Total Nr of Bus Stops
U2	3.3	University Interchange	New College	5	3	8
U6	3.7	Swaythling Macdonald	RSH	9	7	13
B1	4.2	Hilton Hotel	New College	3	6	12
B2	3.6	Swaythling Macdonald	New College	7	5	12
F5	3.6	Swaythling Macdonald	New College	7	5	12
F7	2.3	Belmont Road	RSH	7	7	9

In total data was been collected for 107 trips. 46 trips during inter peak hours and 61 trips during peak hours.

Journey time delay was calculated by comparing actual travel time with the scheduled travel time. Delay due to signalised junctions was calculated by adding each junction delay within the journey. Delay due to pedestrian crossings was calculated in the same way. It was observed that 48% of buses were on time (less than 1 minute late or early), 45% buses were more than 1 minute late, and 7% buses were more than 1 minute early. It was also observed that 7% of buses are more than 5 minute late and 6% of buses are more than 2 minutes early. During inter peak hours more buses were on time compare to peak hours. During peak hours more buses were late compared to inter peak hours. Table 5.25 below illustrates the performance of buses to maintain their scheduled travel time. The purpose of this analysis is to understand whether bus priority required or not. If needed, when it is required most. As most of the buses are on time during inter peak hours, and most of the buses are late during peak hours providing priority during peak hours will be more beneficial to buses. Again, it has been observed that, a high percentage of buses are on time and few number of buses are also early. So targeting late buses only for priority in this network will be justified to avoid unnecessary negative impact to general traffics. Because, if priority is provided to on time or early buses, these buses will arrive at the bus stops more earlier than scheduled. To match the scheduled departure time, buses will wait at the bus stops. That means the priority provided to early or on time buses by doing harm to non priority traffic will be wasted at the bus stops.

Table 5.25: Percentage of buses on time, late, and early compare to scheduled travel time

Percentage of Buses On Time, Late, and Early compare to Scheduled Travel Time			
Network Condition	On time	More than 1 minute late	More than 1 minute early
Inter Peak	54%	35%	11%
Peak	43%	52%	5%

It was observed that on average buses were more late during peak hours compared to inter peak hours as shown in the Table 5.26 below. Travel time delay for each trip was calculated by comparing actual travel time with scheduled travel time. Then the average of the travel time delay was calculated considering all trips for a network condition. This information is very important to replicate the bus delay profile in the modelled junctions considering peak and inter peak hours.

Table 5.26: Travel time delay with time of the day

Network Condition	Average Travel Time Delay (Sec/Bus)
Inter Peak	55
Peak	102

It was also observed that on average buses are delayed more by the signalised junctions during peak hours compared to inter peak hours as shown in Table 5.27 below. For each trip total waiting time at all signalised junctions was calculated by adding waiting times at each junction for that trip. Then average waiting time at the junctions was calculated by considering all trips for a network condition. In the same way average waiting time at the pedestrian crossing has been calculated. These information is necessary to understand the impact of signalised junctions and pedestrian crossings on bus delay considering network conditions. The Table below illustrates that priority is needed at the signalised junctions most during peak hours. Again, at pedestrian crossings total average delay to buses is less, so priority may not be required there.

Table 5.27: Waiting time at junctions & pedestrian crossings

Delay: Waiting Time at Junctions & Pedestrian Crossings		
Network Condition	Average Delay (Sec/Bus)	
	By Signalised Junctions	By Signalised Pedestrian Crossings
Inter Peak	126	19
Peak	167	15

It was also observed that on average a higher percentage of travel time is wasted by the signalised junctions during peak hours compared to inter peak hours as shown in the Table

5.28 below. The percentage of wasted travel time due to signalised junctions for each journey was calculated as follows:

Total junction delay by all junctions with in a trip/ Scheduled journey time

Then average percentage of wasted travel time due to signalised junctions has been calculated considering all trips for a network condition.

The percentage of wasted travel time due to signalised pedestrian crossings for each journey was calculated as follows:

Total pedestrian crossing delay by all pedestrian crossings with in a trip/ Scheduled journey time

Then the average percentage of wasted travel time due to signalised pedestrian crossings was calculated considering all trips for a network condition.

Table 5.28: Percentage of wasted travel time with time of the day

Waste of Travel Time: Waiting Time at Junctions & Pedestrian Crossings		
Network Condition	Percentage of wasted travel time	
	By Signalised Junctions	By Signalised Pedestrian Crossings
Inter Peak	17%	3%
Peak	23%	2%

These information is necessary to understand when and where buses waste their travel time most. The Table above illustrates that high percentage of bus travel time is wasted at signalised junctions, so priority is required there. But at signalised pedestrian crossing waste of travel time is less, so priority is not necessary.

Detailed data for each journey is provided in the Appendix B.

5.5.9 Bus Stops Dwell Time Data

Bus stops dwell time data is required to model the bus stops realistically as they are in the field. Buses are stopped at a bus stop in the model to load and unload passengers based on the dwell time distribution defined for that bus stop. If the distribution does not reflect the field situation, it is not possible to realistically model bus travel times, arrival at and departure from bus stops as observed in the field. When a bus stop is located close to a junction and priority detector is sited upstream of the bus stop, in that situation it is very important to understand the dwell time distribution of that bus stop before implementing priority. While collecting bus journey time data from 06.05.13 to 24.05.13 within the Southampton network dwell time data for all bus stops within each journey was collected. It was observed that most of the bus stops are request bus stop where dwell time is less. In the request bus stops passengers demand is very less, and when buses stop at those bus stops due to passengers request, their dwell time is predictable. For request bus stops altogether 1216 sample dwell time data were collected. Within the surveyed bus routes Portswood Broadway and University Interchange are the two major bus stops. In both bus stops passenger demand is very high and dwell time is difficult to predict. It has been observed that at the University Interchange buses are scheduled for longer dwell time because of driver changeovers and administrative activities happening there. It was also observed that because of the long scheduled dwell time, many buses wait (bus holding) to match the scheduled departure time. For Portswood Broadway altogether 425 and for University Interchange altogether 470 sample bus dwell time data were collected. Bus dwell time distribution of the request bus stops, Portswood Broadway, and University Interchange are presented in Table 5.29 below. Detail of dwell time data are available in the Appendix B.

Table 5.29: Bus dwell time distribution

Bus Dwell Time Distribution [N (Mean, Standard Deviation)] in Sec			
Bus Stop	Request Stop	Portswood Broadway	University Interchange
	N (12,15)	N (42,31)	N (138,90)

5.5.10 Speed Data

Speed data is required to realistically model speed profiles reflecting field speeds. In this research recommended speed profiles by TFL DTO modelling guidelines (TfL 2010) have been used for models development. These profiles are then calibrated based on observed speed for each selected junction. Finally, modelled speed profiles for each junction have been validated by comparing with the observed speeds. Link speed data for cross junction and T-junction at each site has been collected on 06.03.13 and 20.03.13 respectively. For the pedestrian crossing speed data was not collected because this crossing is on a link of the cross junction, so at the pedestrian crossing, the speed distribution will be same as the cross junction. It was observed in the field that at the T-junction vehicles drive faster than at the cross junction because of less interaction with parking vehicles and pedestrians. At the cross junction vehicle speed data is similar throughout the whole day because of similar interaction with pedestrian and parking vehicles. But at the T-junction vehicles drive faster during inter peak hours than peak because the junction is less busy during inter peak. Average link speed derived from collected data for the junctions is described in Table 5.30 below. All together 37 and 34 sample data have been collected for the cross junction and T-junction respectively. Data is presented in the Appendix B.

Table 5.30: Average link speed

Average Link Speed (m/s)		
Junction Type	Peak	Inter Peak
Cross Junction	7.59	7.71
Pedestrian Crossing	7.59	7.71
T-Junction	8.47	9.87

5.6 Chapter summary

In this Chapter selected sites for realistic base models development have been described and the required data for the base models development, validations and scenarios development have been identified. The data required for bus priority parameters and methods development and evaluation have been identified, collected (DfT 2014a) and analysed to provide the basis for developing the microscopic simulation models in the next Chapter.

Chapter 6: The Models

6.1 Introduction

To develop the required models based on the chosen sites and the observed data by using micro-simulation, it is necessary first to identify the best tool suitable for this research purpose. This Chapter therefore starts with a comparison of the contenders for this model and continues with a description of how the selected model was developed and validated for this research.

6.2 Modelling Tool Selection

6.2.1 Model Attributes

This Section identifies the key features that must be considered to model bus priority at traffic signals to achieve the research objectives. The main requirements of such a model are:

Bus: Bus generation profile

Bus stop: Dwell time, bus stop detectors, real time bus arrival time & delay

Traffic signals: Traffic responsive signal controller (isolated VA for this research), signal detectors, signal delay

Priority detectors: Bus detectors, exit detectors

Priority methods: Green extension, green recall, green cut, stage skipping, compensation & inhabitation, differential priority

AVL system: Detecting buses real time, headway and lateness calculation

Real world traffic scenarios: Different junction types, peak hour scenario, inter peak hour scenario, congestion

Evaluation: Impact on bus journey time, impact of general traffic

These key components have been used to compare micro-simulation tools to select the best one suitable for this research purpose.

6.2.2 Comparison of VISSIM, AIMSUN, PARAMICS & SIMBOL

Microscopic traffic simulation tools have gained significant popularity and are widely used both in industry and research mainly because of the ability of these tools to reflect the dynamic nature of the transportation system in a stochastic fashion. VISSIM, AIMSUN, and PARAMICS are the most popular commercial software for micro simulation having comparative capabilities (Papageorgiou et al. 2009). SIMBOL is a non-commercial micro simulation tool used by TRG for modelling bus priority on a corridor basis.

VISSIM is a time step and behaviour based microscopic traffic simulation model developed at the University of Karlsruhe, Karlsruhe, Germany, in the early 1970s. PTV Transworld AG, a German company, began the commercial distribution of VISSIM from 1993 and continues to maintain the software up to this date. It is composed of two main components: A traffic simulator and signal state generator (Bloomberg and Dale 2000). The model consists of a psycho-physical car following model for longitudinal vehicle movement and a rule-based lane changing algorithm for lateral movements. VISSIM is especially renowned for its signal control module, which by using a vehicle actuated programming language can model almost any traffic control logic (Papageorgiou et al. 2009). Further, VISSIM scores high on its ability to model public transportation systems (Papageorgiou et al. 2009).

AIMSUN, which is short for Advanced Interactive Microscopic Simulator for Urban and Non- Urban Networks, was developed by the Department of Statistics and Operational Research, Universitat Poletecnica de Catalunya, Barcelona, Spain (Xiao et al. 2005). This microscopic traffic simulation software is capable of reproducing various real traffic networks and conditions on a computer platform. The driver behaviour models inside AIMSUN such as the car-following model (Gibbs model), lane changing model and gap-acceptance model provide the behaviour of each single vehicle for the entire simulation period (TSS 2006).

PARAMICS is a widely used microscopic traffic simulation tool initially developed at the University of Edinburgh in the early 1990’s and was introduced commercially in 1997 by SAIS Limited and Quadstone Limited in the UK. PARAMICS, which stands for Parallel Microscopic Simulation comprises various modules which include a modeller, a processor, an analyser, a monitor, a converter and an estimator. PARAMICS is renowned for its visualisation graphics and for its ability to model quite a diverse range of traffic scenarios (Papageorgiou et al 2009).

SIMBOL stands for SImulation Model for Bus priOrity at traffic signals. It was developed by TRG to model bus priority at traffic signals which enables a range of different bus priority strategies and logics to be modelled taking account of characteristics of buses, bus stops, passengers, AVL systems and traffic signals (Shrestha 2002).

Each package has strengths and weaknesses that make it suitable for certain applications, depending on the type of transportation improvement or planning analysis being considered. There limitations and capabilities should be understood prior to selecting one for the valuation of bus priority at traffic signals.

Table 6.1: Comparison of VISSIM, AIMSUN, PARAMICS & SIMBOL to model bus priority at traffic signals (PTV AG 2008; TSS 2010; SIAS Limited 2010; Shrestha 2002)

Model Components	Microscopic Traffic Simulation Software			
	VISSIM	**AIMSUN**	**PARAMICS**	**SIMBOL**
Bus				
Bus Generation Profile	Yes	Yes	Yes	Yes
Bus Stop				
Dwell Time	Yes	Yes	Yes	Yes
Detectors	Yes	Yes	Yes	Yes
Bus Arrival Time	Yes	Yes	Yes	No
Delay	Yes	Yes	Yes	No
Traffic Signals				
VA Signal Controller	Yes	Yes	Yes	No
Signal Detectors	Yes	Yes	Yes	Yes
Signal Delay	Yes	Yes	Yes	Yes
Priority Detectors				
Bus Detectors	Yes	Yes	Yes	Yes
Exit Detectors	Yes	Yes	Yes	Yes
Priority Methods				
Green Extension	Yes	Yes	Yes	Yes
Green Recall	Yes	Yes	Yes	Yes
Green Cut	Yes	Yes	Yes	Yes
Stage Skipping	Yes	Yes	Yes	No

Model Components	Microscopic Traffic Simulation Software			
	VISSIM	**AIMSUN**	**PARAMICS**	**SIMBOL**
Compensation	Yes	Yes	Yes	No
Inhabitation	Yes	Yes	Yes	No
Differential Priority	Yes	Yes	Yes	Yes
AVL System				
Real Time Bus Detection	Yes	Yes	Yes	Yes
Headway and Lateness Calculation	Yes	Yes	Yes	Yes
Real World Traffic Scenarios				
Different Junction Types	Yes	Yes	Yes	Yes
Peak Hour Scenario	Yes	Yes	Yes	Yes
Inter Peak Hour Scenario	Yes	Yes	Yes	Yes
Congestion	Yes	Yes	Yes	Yes
Evaluation				
Impact on Bus Journey Time	Yes	Yes	Yes	Yes
Impact of General Traffic	Yes	Yes	Yes	Yes

Table 6.1 gives a comparison of the 4 models according to the simulation requirements of this research. This Table shows that SIMBOL is unable to model a number of features, so was rejected at an early stage. On the face of it, the other three models can model all aspects, so deeper research was undertaken to understand *how* these models represent the features required.

All three tools can model buses and bus stops. VISSIM and AIMSUN have more control on bus generation than PARAMICS because in VISSIM and AIMSUN time headway can be used but in PARAMICS buses are generated based on a distribution.

AIMSUN and VISSIM are preferable to model bus stops than PARAMICS because of the ability to model various bus stop features and modelling simplicity. Dwell time can be calculated by using passenger arrival rate or normal distribution in PARAMICS but in AIMSUN only the normal distribution method is available. VISSIM can model dwell time using a normal distribution, an empirical distribution or boarding and alighting rate.

VISSIM, AIMSUN and PARAMICS are all capable of modelling VA Traffic Signals Controller and priority methods. In VISSIM, a VAP language (similar to C) and a flowchart editor VisVAP is used to model user defined traffic signal control and priority methods, and a COM interface is used for this purpose. But in PARAMICS and AIMSUN an application programming interface (API) is used. To model an AVL system and various real world traffic scenarios requires an interface for coding, which is available in VISSIM, AIMSUN, and PARAMICS, even though this can be time consuming. All three tools can produce the required outputs for evaluation purposes but to evaluate network performance VISSIM is arguably the best (Boxill and Yu 2000; Kolmakova et al. 2006). Modelling output should closely match with the real world traffic scenario and there is some evidence that VISSIM and AIMSUN can produce more reliable output than PARAMICS considering deviation from real world (Choa et al. 2003; Manstetten et al. 1997).

The discussion above indicates that VISSIM and AIMSUN are more suitable than PARAMICS for this research purpose. Furthermore, there is evidence that VISSIM is better than AIMSUN at modelling bus stops (Boxill and Yu 2000; Thorrignac 2008 ; Barrios et al. 2001), bus stop information provision (Kolmakova et al. 2006), bus service operations (Boxill and Yu 2000 ; Papageorgiou et al. 2009; Thorrignac 2008; Ahmed 2005; Barrios et al. 2001; Ratrout and Rahman 2009; Kolmakova et al. 2006) and bus signal priority (Papageorgiou et al. 2009; Thorrignac 2008; Barrios et al. 2001; Ratrout and Rahman 2009; Kolmakova et al. 2006). According to Thorrignac (2008) VISSIM can model precisely detailed operations of buses, bus priority methods at traffic signals and the wider effects of bus priority strategies on all users and even on the society and environment.

User friendly tools can also save model development time. According to Bloomberg and Dale (2000), Thorrignac (2008), Boxill and Yu (2000), Ratrout and Rahman (2009), Kotusevski and Hawick (2009) VISSIM is more user friendly than AIMSUN. Visual display can be used for model verification and finding errors. VISSIM has better visual display capabilities than AIMSUN (Barrios et al. 2001; Thorrignac 2008; Choa et al. 2003 ; Ratrout and Rahman 2009). Again VISSIM is more powerful to model transport system complexity than AIMSUN (Kolmakova et al. 2006). The discussion above and previous research suggest that VISSIM is the most suitable for this research purpose and VISSIM 5.40 was therefore selected for model development. Considering the above model requirements three base models have been developed. These are base models for the cross junction, the T- junction, and the pedestrian crossing.

6.3 Base Models Development

By using google maps and some field measurements of geometric layouts for each selected junction and pedestrian crossing, base models for cross junction, T-junction and pedestrian crossing were developed. The geometric layout and scales of the base models are realistic because they are developed according to their layout and scales in the field. Figures 6.1, 6.2, & 6.3 below illustrate the developed models.

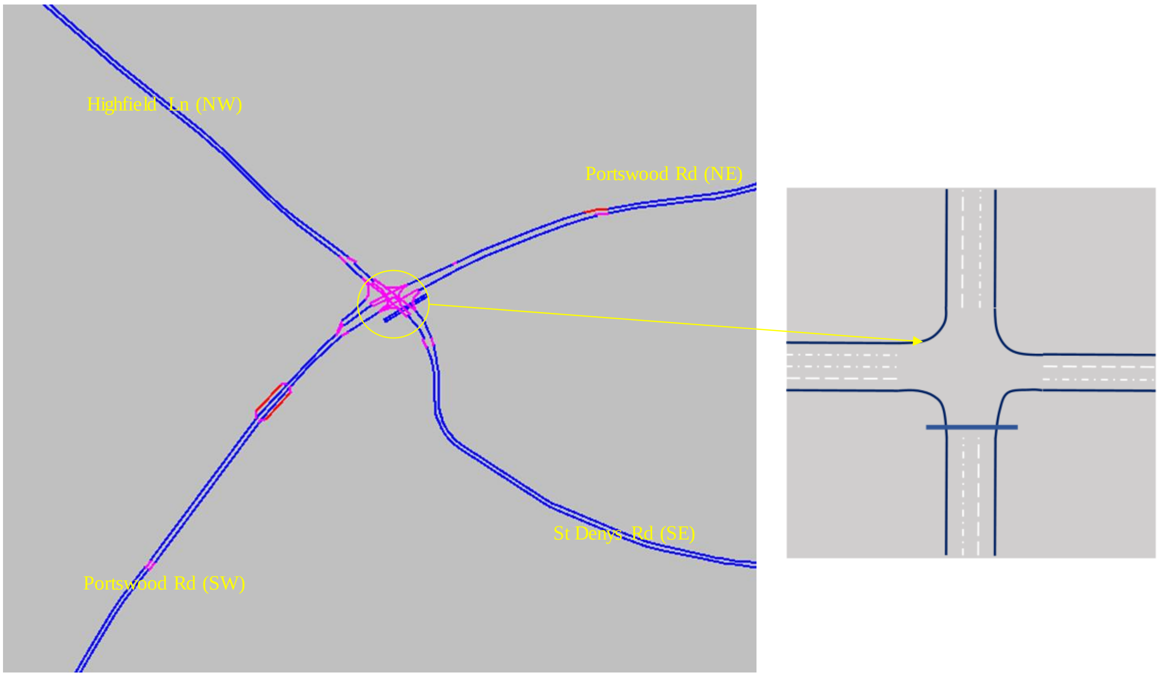


Figure 6.1: Cross junction

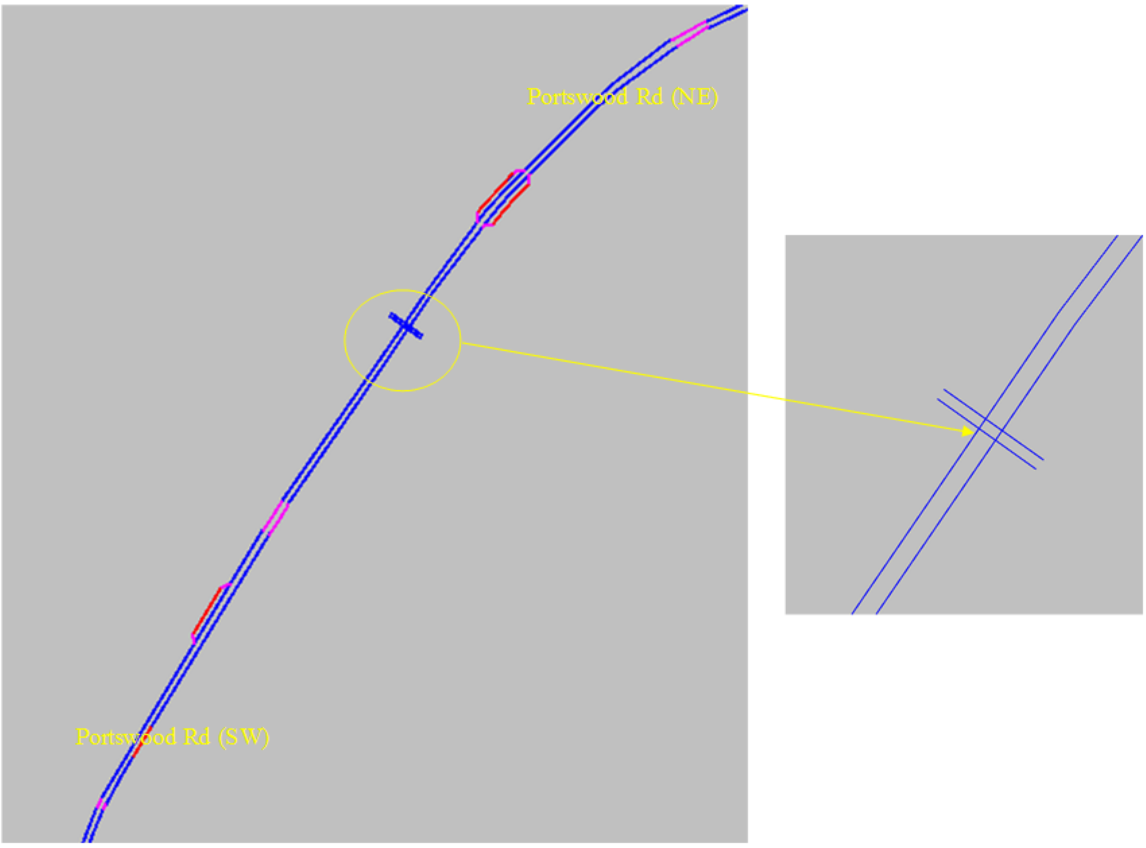


Figure 6.2: Pedestrian crossing

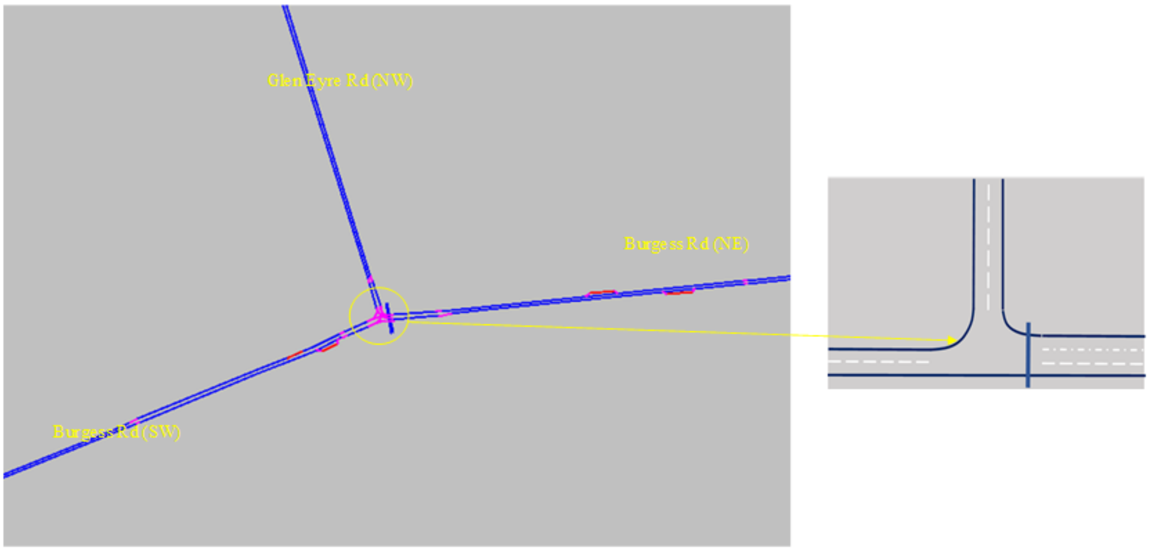


Figure 6.3: T junction

It was observed in the field that in each junction and pedestrian crossing, there are on street parking activities, pedestrian movements without crossing, and also bus stops located closed to the junction. In the base models these issues has not been considered. Traffic inputs for each base model were provided by following exact collected traffic flow data considering network conditions and average turning proportions as observed throughout the day were modelled for the respective junction and pedestrian crossing. Traffic flow data and turning proportions for the observed network conditions were illustrated in Section 5.5.1 of Chapter 5. Signal details for each junction and pedestrian crossing have been modelled as observed in the field respectively. Signal data for each junction and pedestrian crossing has been used for respective signal controller development as presented in Section 5.5.3 of Chapter 5.

One high frequency bus service running through the major road in each junction and pedestrian crossing has been modelled for implementation simplicity. A range of bus frequencies have been considered, as described in Chapter 7. The distribution of bus headways has been modelled based on field data described in Section 5.5.8 in Chapter 5. Buses were generated at fixed time intervals but by using a dummy bus stop at the beginning of each bus route the fixed time headway has been modified according to the field. Because buses cannot maintain their scheduled headway in the field for various reasons, they may run early, on time, or late. In the dummy bus stop dwell time distribution (Table 6.2) has been modelled based on the observed distribution of the adherence of the actual travel time with the scheduled travel time considering network conditions. VISSIM models generate buses at fixed time intervals at the beginning of each route. The objective to model a dummy bus stop at the beginning of each route is to stop buses based on field observed lateness profile. Thus bus headway distribution and lateness profiles have been modelled realistically as they are in the field.

Table 6.2: Distribution of the deviation from scheduled travel time

Dummy Bus Stops	
Network Condition	Dwell Time Distribution
Peak Hours	N (102,119)
Inter Peak Hours	N (55,78)

A maximum 30 mph speed limit has been modelled on all links of each junction and pedestrian crossing according to the field value. Vehicle composition has been modelled based on field data as illustrated in Section 5.5.2 of Chapter 5. To record the travel time through the junctions and pedestrian crossings travel time sections through each of the traffic routes and bus routes have been modelled. Each of these sections for traffic and buses are 1100m long and the junction or pedestrian crossing are located at the middle of the section. Long travel time sections have been modelled to track the journey from well upstream of the junction and bus stops (during scenario development) to include bus stops activity, and to truly capture acceleration, deceleration, and delay at the bus stops and junction stop lines for accurate average speed and journey time. The travel time section also had to be sufficiently long to truly capture the impact of a long junction queue on travel time. To measure pedestrian delay due to the signal controller, travel time sections for pedestrians through the crossings have been modelled.

6.4 Model Inputs

Many inputs are built in. For example: vehicle acceleration and deceleration, driving behaviour, and the car following model are defined by VISSIM. User defined inputs in each model are traffic flows, pedestrian flows, vehicle composition, routing decisions, distribution of speed, bus service frequencies, dwell time distributions, on board passengers, signal controller details, average headway of queuing vehicles, and distraction. These inputs have been modelled based on observed data described in Chapter 5.

6.5 Signal Controller Development

VISSIM does not have a built in VA signal controller nor built in bus priority methods. But it has VAP and VisVAP interfaces which give the user flexibility to design and build new control strategies – in this case a VA signal controller and bus priority. In those interfaces various built in VAP- Functions and Commands are available which have been used in this research to develop isolated VA signal controller and various bus priority methods. For example: Interstage (<from_stage>, <to_stage>) is a built in VAP function which is used to tell the controller to run the inter stage. Similarly, Detection (<no>) is used to tell the controller to check whether a vehicle or a bus has been detected by the detector.

By using VAP and VisVAP interfaces, VAP functions, and VAP programming elements the signal controller's main interface has been developed. The working methodology of the main interface has been illustrated in Sub-Sections 6.5.1 and 6.5.2.2 (Figures 6.4, 6.8 and 6.9) and VAP code for the main interface is provided in Appendix C. This main interface has been coded to interact with other modules of the controller dynamically to allow the user to test various bus priority methods. These interactions were illustrated in Sub-Section 6.5.2 (Figure 6.8) and VAP code for the interactions is provided in Appendix C. The interactions are: to take the inputs, to run the general VA signal controller when a priority bus is not detected or when bus priority is not active, to run various bus priority methods according to user preference when a priority bus has been detected, to run various compensation methods according to user preference, and also to record and produce controller outputs. Descriptions of signal controller's required inputs have been provided in the Sub-Section 6.5.2.1. The working logic of the VA signal controller without any bus priority and it's interaction with the main interface has been described in the Sub-Sections 6.5.1.1 and 6.5.2.3 (Figure 6.5). VAP code for this general signal controller module has been provided in Appendix C (VAP Code S1). By using a respective flow chart described in Sub-Section 6.5.2.4 bus priority methods: extension (Figure 6.12), recall (Figure 6.14), extension and recall (Figure 6.15), cut and recall (Figure 6.17), and always green bus (Figure 6.19) have been developed. VAP code for each of the methods is provided in Appendix C (VAP Code S2- S6). Sub-Section 6.5.2.5 describes various compensation methods for non priority traffic (Figure 6.21). This flow chart has been used to develop various compensation methods and VAP code for each of the compensation method is provided in Appendix C (VAP Code S7- S10). The coding for differential bus priority method (VAP Code S11) and exit detection (VAP Code S12) have been illustrated in Appendix C. Coding for the T Junction with Pedestrian Crossing is presented as a sample in the Appendix C. Because, more than 300 pages needed to present coding for all modelled junctions. Finally controller outputs have been described in the Sub-Section 6.5.2.6.

6.5.1 Signal Controller's Basic Working Methodology

To provide bus priority at VA junctions by various priority methods buses are detected on priority approaches some distance from the stop line. Depending on priority conditions (eligibility), and the signal status at the time of detection, normal signal timings are overridden by the implemented priority methods. For example, if a bus is detected during green, the duration of green is held at least for the duration of the expected bus travel time from the detection point to the stop line, subject to a maximum green time. If a bus is detected during red, the duration of red is reduced based on minimum time constraints of non priority stages. After bus priority, the signal runs according to its normal timings. If bus priority is implemented with compensation then additional green time is provided to non priority stages depending on compensation conditions (eligibility) before going back to normal settings. The flowchart below (Figure 6.4) describes the basic methodology to implement bus priority at VA junctions.

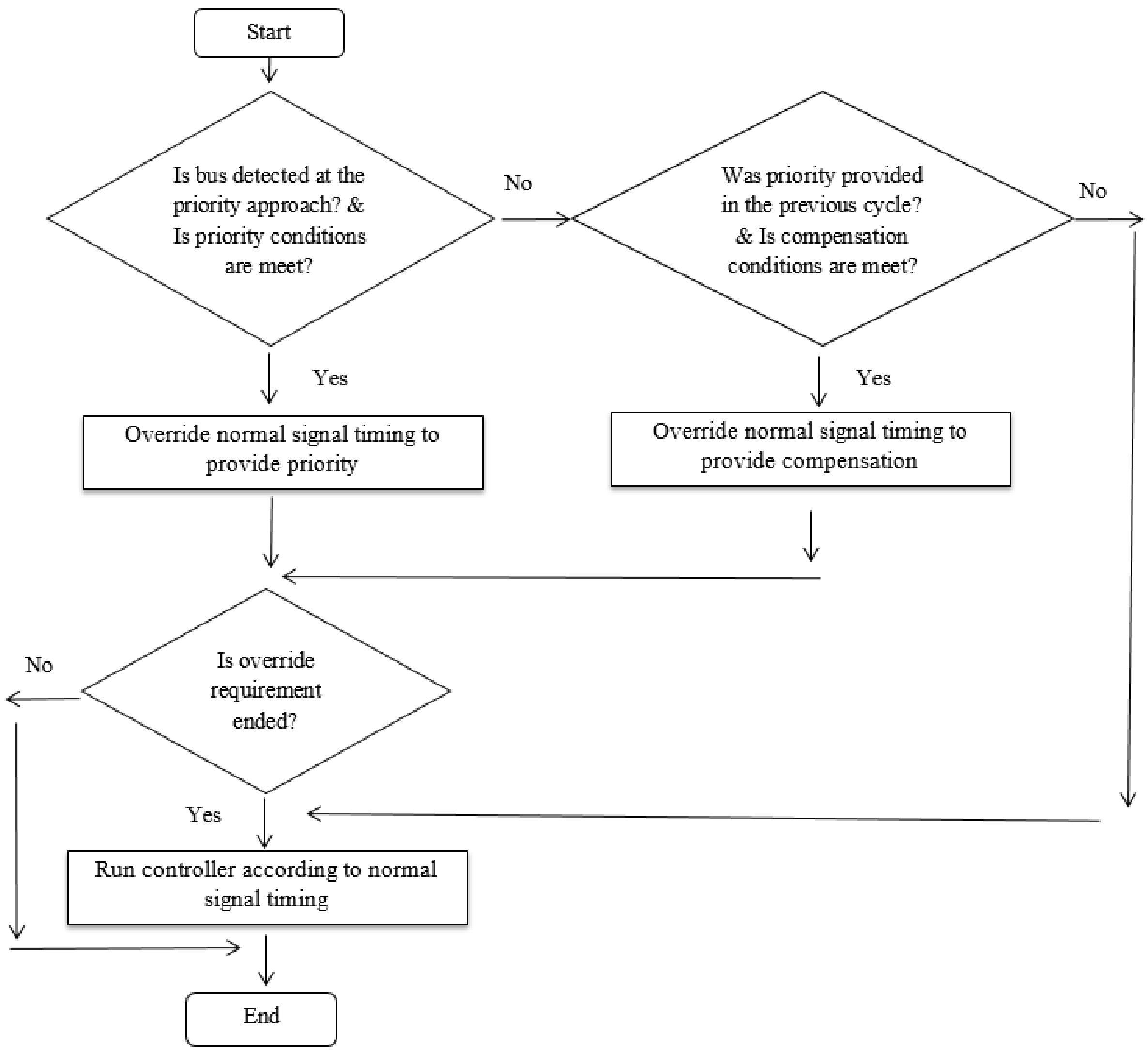


Figure 6.4: Signal controller's basic working methodology

Normal signal settings without the influence of priority methods and compensation are described below.

6.5.1.1 Isolated Vehicle Actuated (VA) Controller (Normal Setting)

Isolated vehicle actuated controller has been implemented in the base models. Vehicle actuated systems rely on traffic detectors on junction approaches to detect vehicles, to allocate green times to different traffic movements according the traffic detected. With its traffic responsive capability, VA is the most common form of control for isolated junctions in the UK (Gardner et al. 2009). The most common form of vehicle actuated strategy still in use in the UK is known as (Salter and Hounsell 1996) D-system VA (vehicle actuation).

With this system, a series of buried loops are placed on the approaches with the initial detector some 40 metres distant from the stop line (Figure 6.6). The method of control may be summarised as follows, for stage based control (Figure 6.5) when priority or compensation is not required.

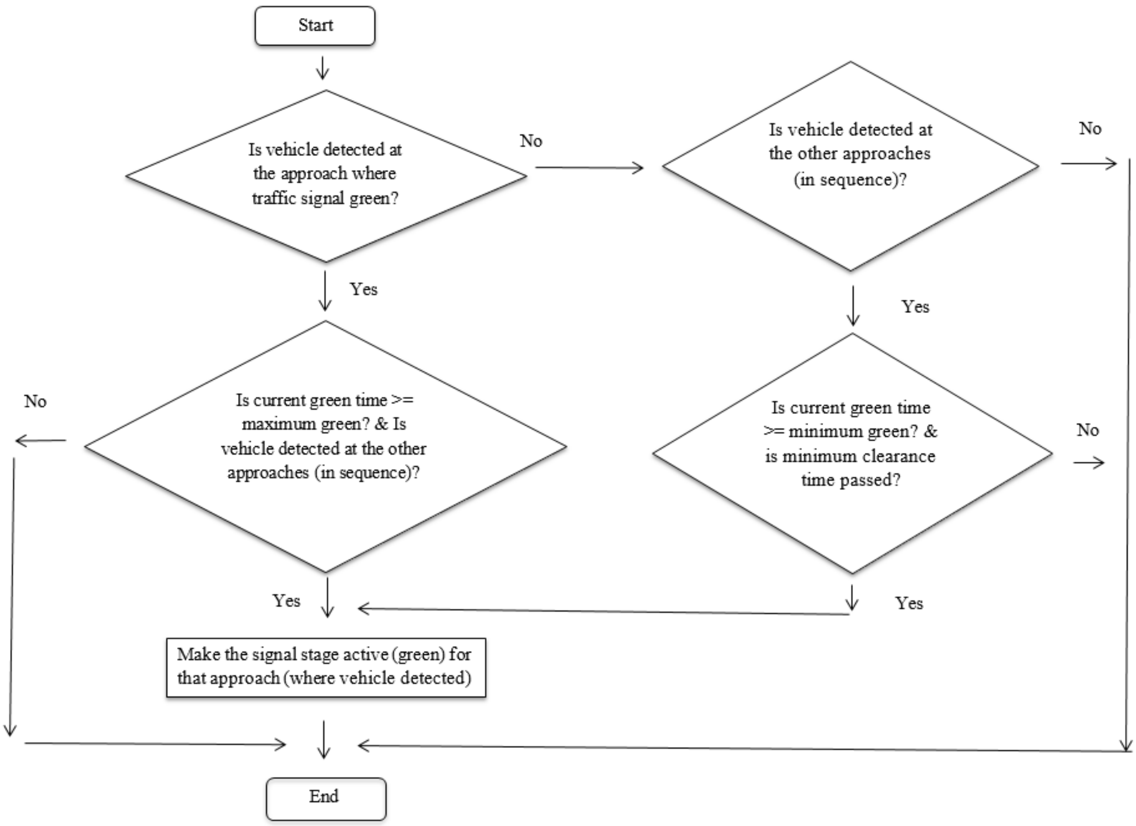


Figure 6.5: Isolated VA signal controller (normal setting)

A vehicle detected on an approach during the display of the green indication will normally extend the period of green so that the vehicle can cross the stop line before the expiry of green. Usually there are three loops on an approach (Figure 6.6), each one of which extends the green time by 1.5 seconds. When a vehicle is detected approaching a red or amber signal indication, the demand for the green signal is stored in the controller which serves stages in cyclic order and omits any stages for which a demand has not been received. The demand for the green stage is satisfied when the previous stage that showed a green indication has exceeded its minimum green period and there has not been a demand for a green extension on the running stage, or the last vehicle extension on the running stage has elapsed and there has not been a further demand. Alternatively, the demand for the green stage is satisfied if, after the demand is entered in the controller, the running stage runs to a further period of time known as the maximum green time. This would occur if there were continuous demands for green on the running stage. Figure 6.6 below illustrates the location (Cooper 1983) of D-system detectors to detect vehicles in each junction approach.

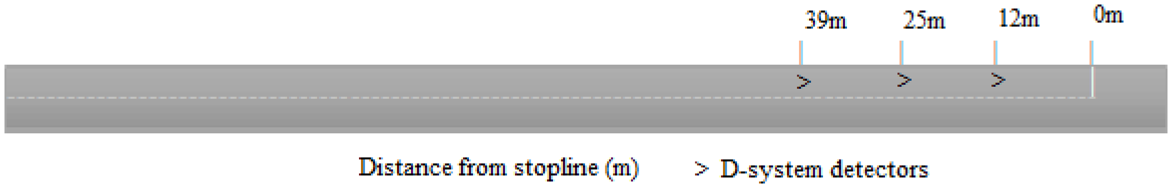


Figure 6.6: Location of D-system detectors

D- system detectors were modelled at the junction approaches to detect all vehicles as shown in the Figure 6.6 above while isolated D-system VA signal control was developed as shown in the Figure 6.5 above.

At pedestrian crossings, instead of three detectors, one pedestrian detector 0m away from kerb was modelled (Figure 6.7) in each pedestrian crossing approach. This simulates a pedestrian pressing the push button to request a crossing signal (the ‘green man’). Vehicle stages were developed following the methodology described in Figure 6.5 above. However, the methodology for a pedestrian stage is different. If there is pedestrian demand and the vehicle stage is running, the pedestrian stage will be active when vehicle demand has been fulfilled (minimum green provided, minimum clearance time provided, maximum green reached or exceeded) according to the principles described above. During a pedestrian stage a fixed amount of pedestrian green only is provided. While the pedestrian stage is running and there is further demand from pedestrian, unlike a vehicle stage, pedestrian green will not be extended. Demand will be stored in the controller and this demand will be fulfilled after dealing with the vehicle demands.

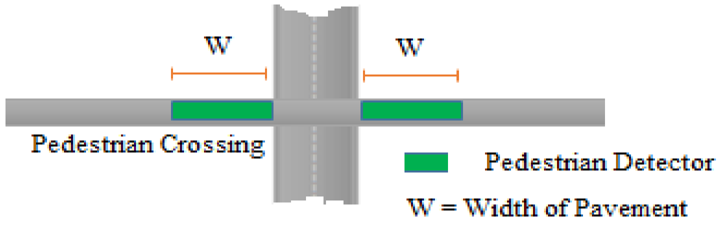


Figure 6.7: Location of pedestrian detectors

6.5.2 Implementation of Bus Priority Methods in the Signal Controller

To develop an isolated vehicle actuated signal controller capable to provide bus priority by various methods, VISSIM VAP and VisVAP interfaces were used. Each base model has a main module (function) and several sub modules (sub functions) which interact with each other to establish the controller. Figure 6.8 below illustrates various interactions within the controller in a simple way.

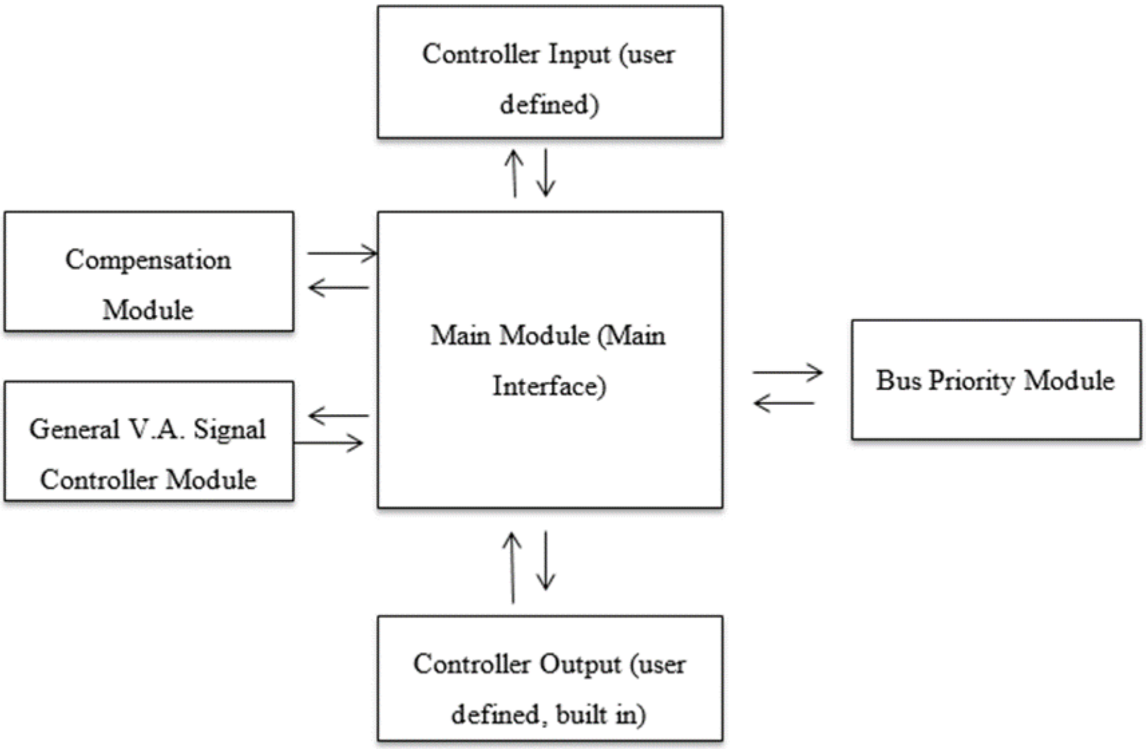


Figure 6.8: Interaction within the controller

6.5.2.1 Controller Input

The developed signal controller requires many user defined inputs. The general V.A. Signal controller module requires the following inputs: maximum stage duration, minimum stage duration, minimum green extension time for detected vehicles, duration of amber, duration of red& amber, vehicle junction clearance time. These inputs were modelled based on the field data described in Section 5.5.3 in Chapter 5. For the bus priority module the required inputs are: estimated bus travel time from detector to stop line, maximum extension, maximum red period of each stage, and minimum clearance time for bus during recall. These inputs were based on existing bus priority parameters (at other sites) and suggested parameters. These inputs were modelled to explore the performance of bus priority methods with the change of parameters.

6.5.2.2 Main Module

The main module is the interface of the controller. The general signal controller module, bus priority modules and compensation module interact with each other through the main module. The main module also controls whether general the signal module, the bus priority module or the compensation module will be active in each call of the signal controller. The flowchart below (Figure 6.9) illustrates the working procedures of the main module.

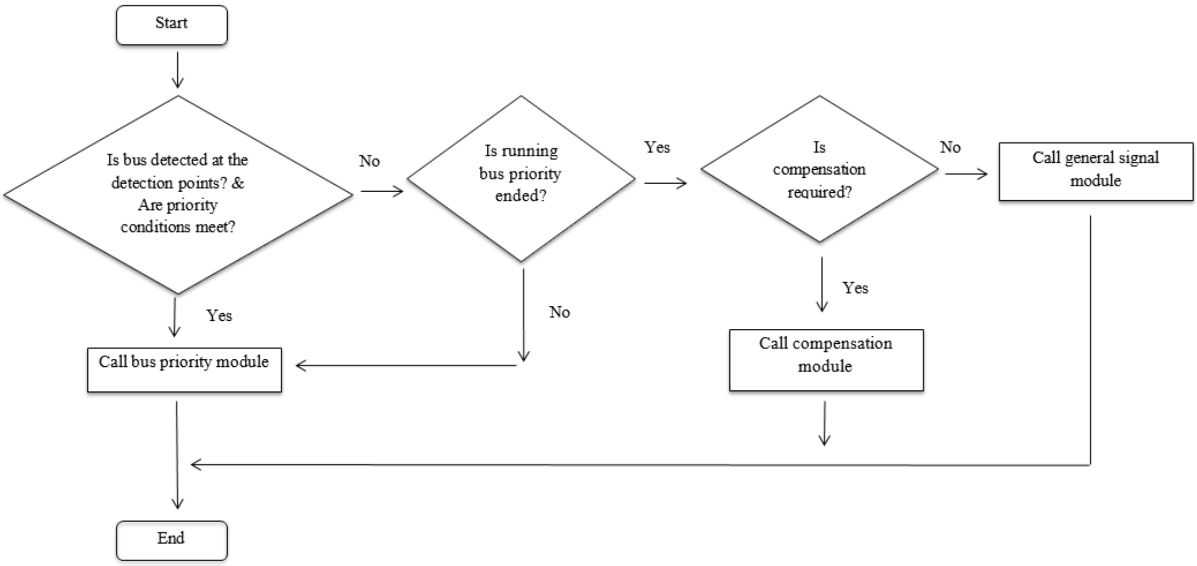


Figure 6.9: Main module

In this module whether a bus is detected or not is firstly checked. If detected and priority conditions are met then the bus priority module is called. Once a bus priority module has been called it allows the module to complete priority. Implemented priority conditions are described in Table 6.3 below. Which conditions need to be meet is determined by the bus priority methods and parameters considered.

Table 6.3: Priority conditions for main module

Priority Conditions	Descriptions
Condition1 (need to be meet by all priority methods except extension)	If bus priority is already running, priority request from other buses during that time will not be granted. So when a bus is considered for priority, other buses will not be detected by priority detectors until priority to the considered bus has been ended. Exception: During extension period other buses in the same priority stage are also considered for further extension.
Condition2 (need to be meet by all priority methods with protected compensation)	If compensation of non-priority stages are required due to previous bus priority and if compensation is protected then priority request from detected bus will not be granted until compensation is provided. If compensation is protected and compensation module is running, then also priority request from detected bus will not be granted until compensation ended. But if compensation is not protected, then priority request from a detected bus will be granted instantly even if compensation is required or compensation module is running as long as other conditions are fulfilled.
Condition3 (need to be meet by recall & always green bus method when parameter effective red has been considered)	Effective red for recall consideration. Buses detected during effective red for recall has been granted recall. So a detected bus will get recall if remaining red period at the time of detection is greater than estimated travel time from detection point to stop line.

If a bus is not detected or priority conditions are not meet and if bus priority is not running then the process checks whether compensations are required due to previous bus priority. If compensation of any non priority stage is required, then the compensation module is called. Otherwise the general V.A. signal controller module is called.

6.5.2.3 General Signal Controller Module

The flow diagram of the general signal controller module was given in Section 6.5.1.1 at Figure 6.5. VAP code for this module has been provided in Appendix C.

Here, when called by the main module, whether a vehicle is detected at the approach where signal stage is active is firstly checked. If it is detected, then it will check whether maximum green time is reached and whether vehicle is detected at the other approaches. If any of the condition is false, the stage will remain active. But if both conditions are true then signal stage of the other approach will be active. During this change, stage sequence will be considered. But if vehicle is not detected during the first check, it will then check for vehicle detection at the other approaches. If no vehicle detected current signal stage will remain active. But if detected, it will then check whether minimum green time of the current stage reached and whether minimum clearance time provided. If any of the condition is false current signal stage will remain active. But if both conditions are fulfilled, then signal stage of the other approach in sequence will be active.

6.5.2.4 Bus Priority Modules

Five bus priority modules have been implemented in the controller to provide bus priority by five bus priority methods. These are:

Extension

A green extension involves the extension of the green phase of the bus route upon detection of a bus before the normal green period ends. The green time for the priority approach is held or extended based on estimated travel time from detection point to stop line and pre-specified maximum green extension (or max-timer). Figure 6.11 below illustrates the extension method for a three stage junction (Figure 6.10). The implementation and logic of this method is described in Figure 6.12. VAP code for this module has been provided in Appendix C.

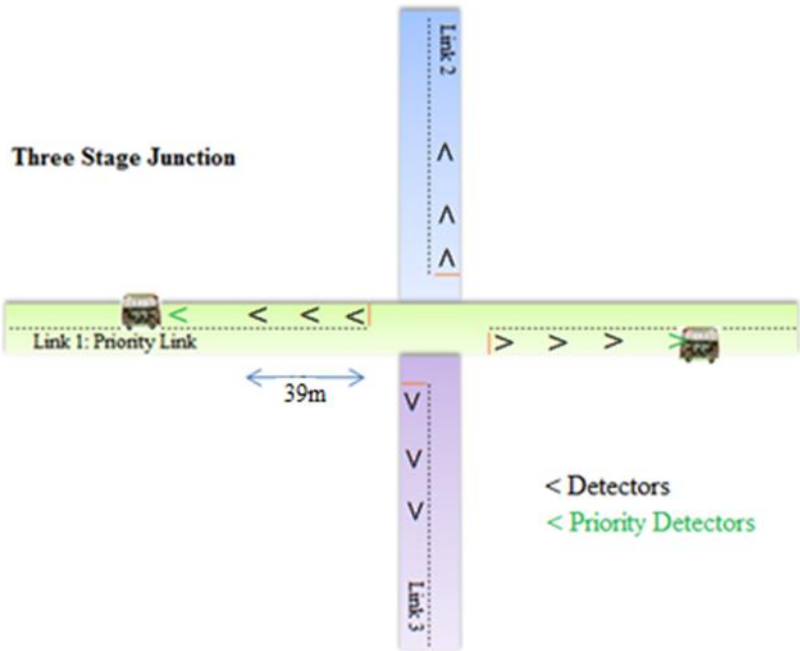


Figure 6.10: Typical three stage cross junction

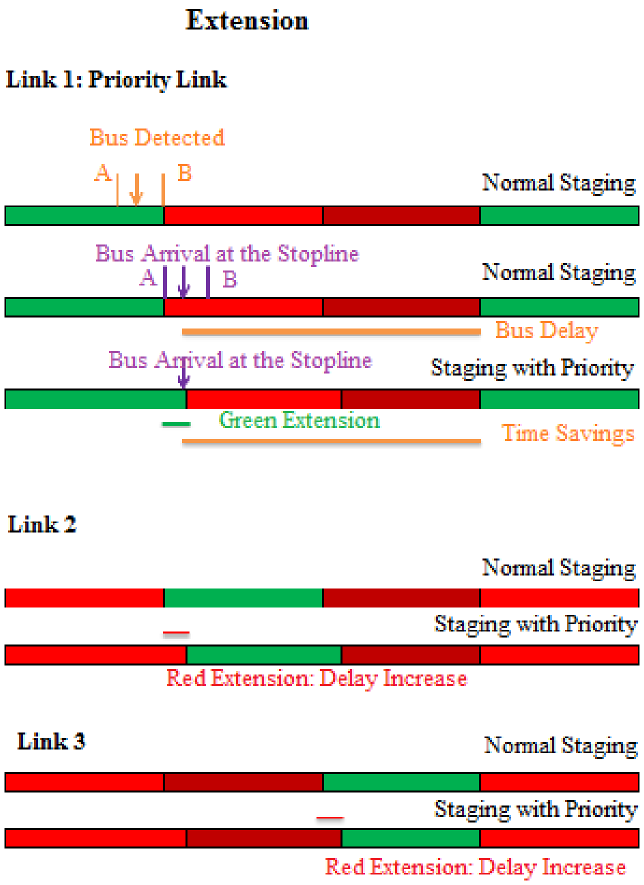


Figure 6.11: Phase diagram without and with extension

This module has been developed to provide bus priority by the method of extension. The flowchart (Figure 6.12) below illustrates the working procedures of this module.

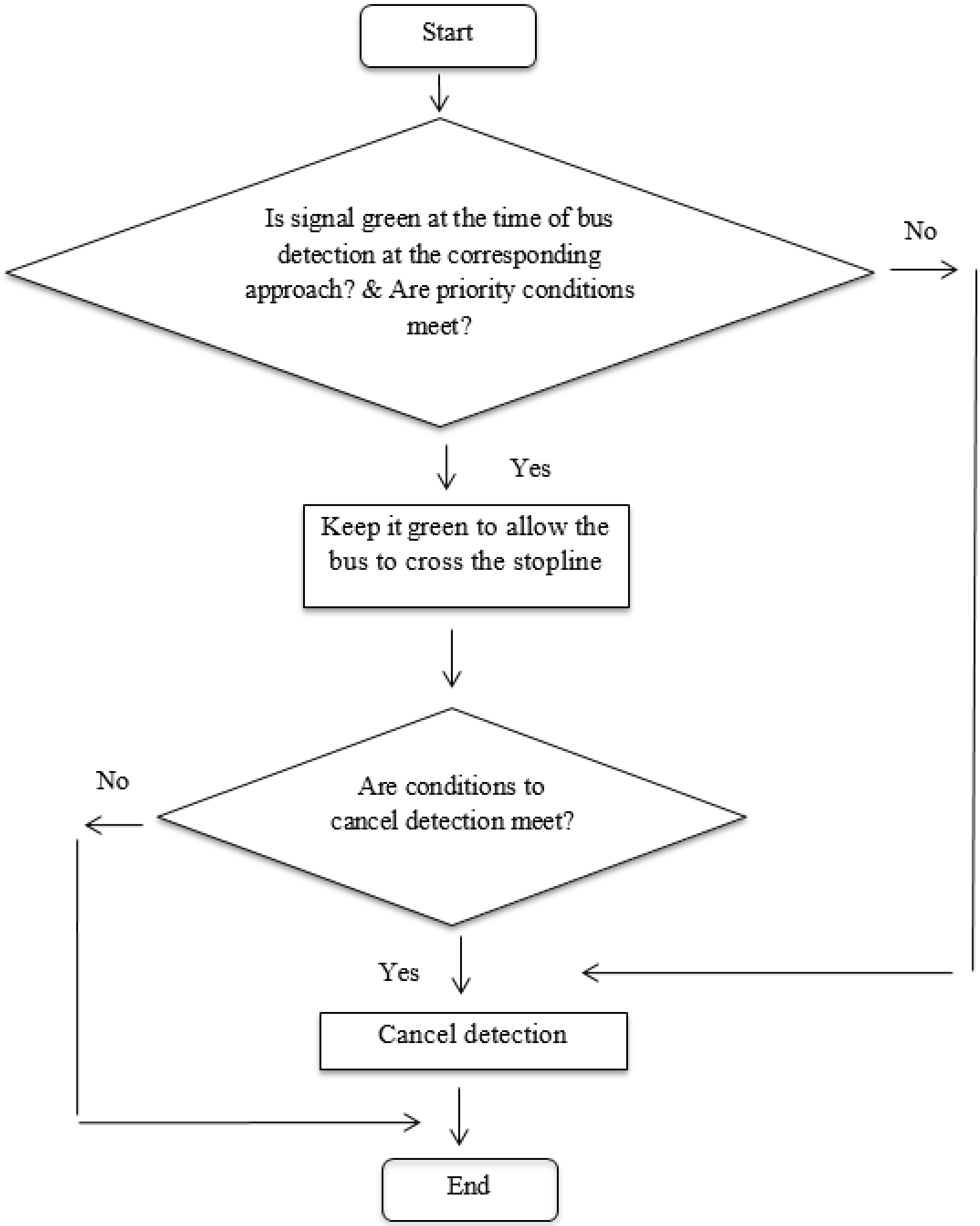


Figure 6.12: Bus priority module for extension

When called by the main module, it first checks whether the signal is green on the approach which has bus detection. It also checks whether conditions for an extension are meet. Extension conditions are described in Table 6.4 below.

Table 6.4: Conditions for extension

Extension conditions	
Condition1	Maximum extension not reached
Condition2	Bus is not detected at the exit detector

Which conditions are needed to be fulfilled depends on the implemented strategies and the parameters considered.

If the signal is not green, or conditions are not met then bus detection will be cancelled to provide no priority. Otherwise green will be kept to allow the bus to cross the stop line. That means green time will be extended if needed. After that bus detection will be cancelled if conditions for cancellation are met. Cancellation conditions are described in Table 6.5 below.

Table 6.5: Conditions to cancel extension

Cancellation Conditions	
Condition1	Green is kept for PVE time or more
Condition2	Bus is detected at the exit detector
Condition3	Maximum extension reached

Which conditions are needed to be fulfilled depends on implemented strategies and parameters considered.

The amount of extension provided depends on estimated travel time from the detection point to stop line and elapsed green time when detected. If the estimated bus travel time is equal to or less than remaining green time at the time of bus detection, an extension is not needed. But if the estimated bus travel time is higher than the remaining green time at the time of detection, an extension is necessary. The amount of extension required is the time difference between the estimated travel time and the remaining green time considering that the signal will run up to its maximum green without priority. If a bus is detected at the last second of green the maximum extension will be needed. But if a bus is detected at the start of green, extension may not be necessary. The Priority extension time has been calculated using the relation below.

Priority extension time (PVE) = Average bus journey time from detector to stop line (t seconds) + 30% extra (0.3t seconds) to cover journey time variations (TRG 2007).

Recall

This strategy provides an early green phase to the bus route upon detection of a bus during the red phase. It involves the shortening of either all or some selected non-bus phases. Shortening of a pedestrian phase is not allowed and minimum green time constraints for non-priority phases are considered. Figure 6.13 below illustrates the recall method for a three stage junction (Figure 6.10). The implementation and logic of this method is described in the Figure 6.14. VAP code for this module has been provided in Appendix C.

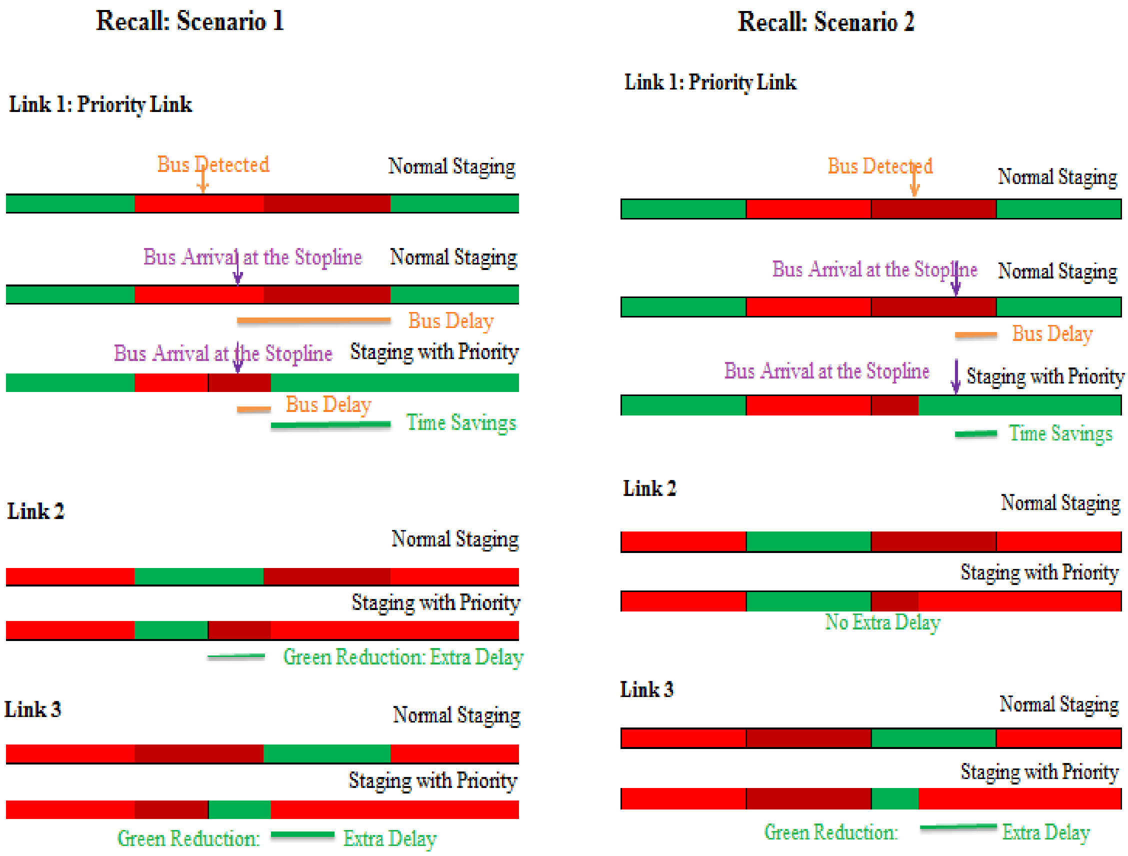


Figure 6.13: Phase diagram without and with recall

The flowchart below (Figure 6.14) illustrates the working procedures of the recall module to provide priority by the method of recall.

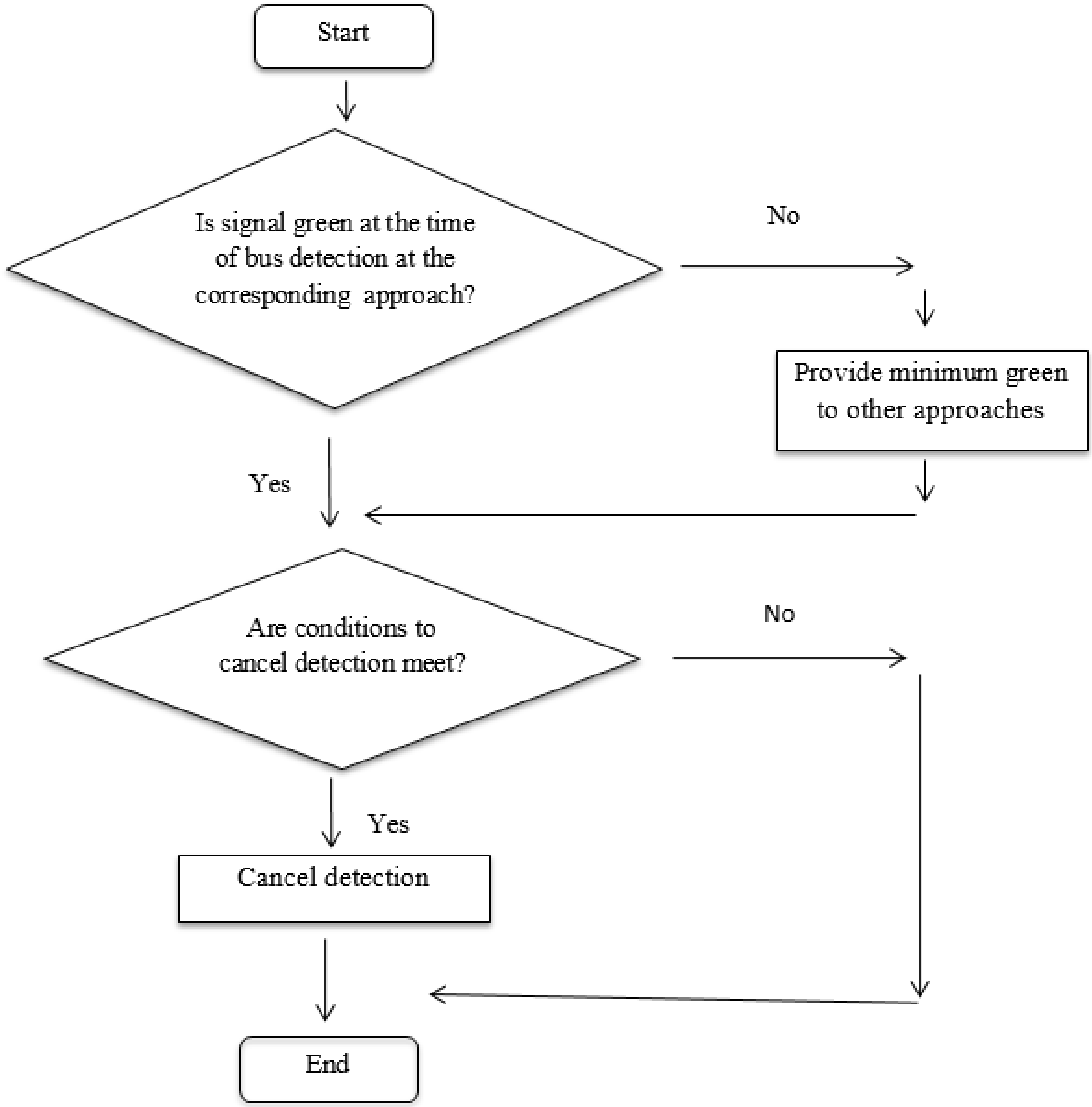


Figure 6.14: Bus priority module for recall

When called by the main module, it first checks whether the signal is green at the approach of bus detection. If green and cancellation conditions are met then detection will be cancelled. Cancellation conditions are described in Table 6.6 below.

Table 6.6: Conditions to cancel recall

Cancellation Conditions	
Condition1	Previous recall ended
Condition2	Minimum priority green for recall provided
Condition3	Bus detected at the exit detector

Which conditions are needed to be fulfilled depends on implemented strategies and parameters considered.

If bus is detected during red, minimum green time will be provided to non-priority approaches. After that bus detection will be cancelled if cancellation conditions are met, as described in Table 6.6 above.

Extension with Recall

The flowchart (Figure 6.15) below illustrates the working procedures of the module to provide priority by the method of extension and recall together. VAP code for this module has been provided in Appendix C.

When called by the main module, it first checks whether the signal is green on the approach with bus detection and whether conditions for extensions are met. Conditions for extension are described in the extension module in Table 6.4. If true, green will be kept to allow the bus to cross the stop line. That means green time will be extended if needed. After that bus detection will be cancelled if cancellation conditions are met. Cancellation conditions are described in Table 6.7 below.

If the signal is red on the approach with bus detection, the recall condition is met. Then only minimum green time will be provided to the other approaches to bring the green of the bus detected approach as soon as possible. After the recall, detection will be cancelled if cancellation conditions are met.

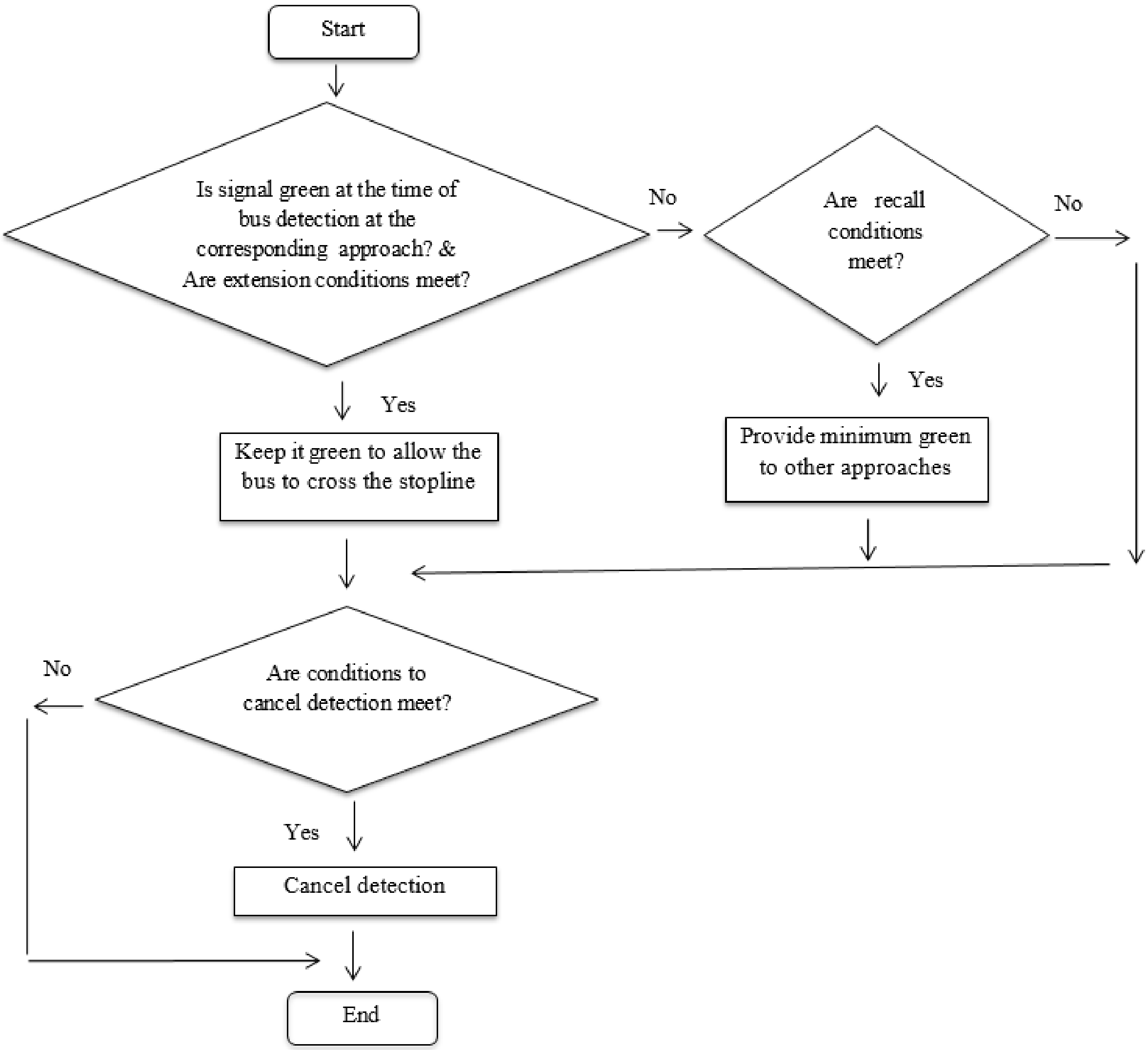


Figure 6.15: Bus priority module for extension & recall (together)

If both extension and recall conditions are not met then detection will be cancelled when cancellation conditions are met. Cancellation conditions are described in Table 6.7 below.

Table 6.7: Conditions to cancel extension with recall

Cancellation Conditions		
Condition1	Extension	Green is kept for PVE time or more
Condition2	Extension/ Recall	Bus is detected at the exit detector
Condition3	Extension	Maximum extension reached
Condition4	Recall	Minimum priority green for recall provided

Which conditions are needed to be fulfilled depends on the implemented strategies and parameters considered.

Cut and Recall

This new strategy provides an early green phase to the bus route upon detection of a bus during the green phase. The current green phase of the priority approach is terminated at the time of detection if it is expected that normal green will end before arrival of bus at the stop line. After green cut it involves the shortening of either all or some selected non-bus phases. Shortening of a pedestrian phase is not allowed and minimum green time constraints for non-priority phases are considered. It is expected that the amount of green time cut from priority approach will reduce the impact on non-priority arms by providing their stages early. Again, buses will get next green early because of cut and recall. Figure 6.16 below illustrates cut with recall method for a three stage junction (Figure 6.10). The implementation and logic of this method is described in Figure 6.17. VAP code for this module has been provided in Appendix C.

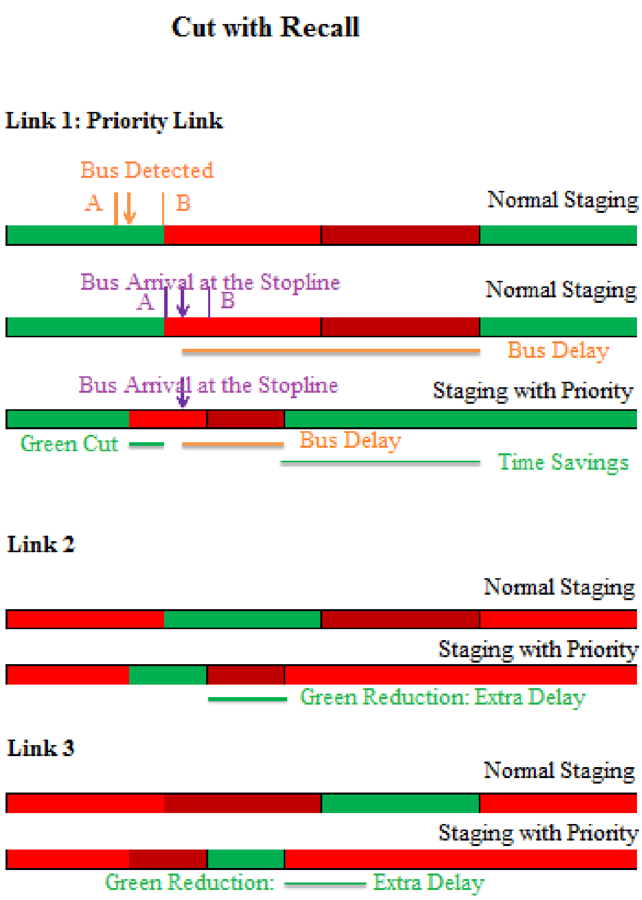


Figure 6.16: Phase diagram without and with cut

The flowchart (Figure 6.17) below illustrates the working procedures of the module to provide priority by the method of cut and recall.

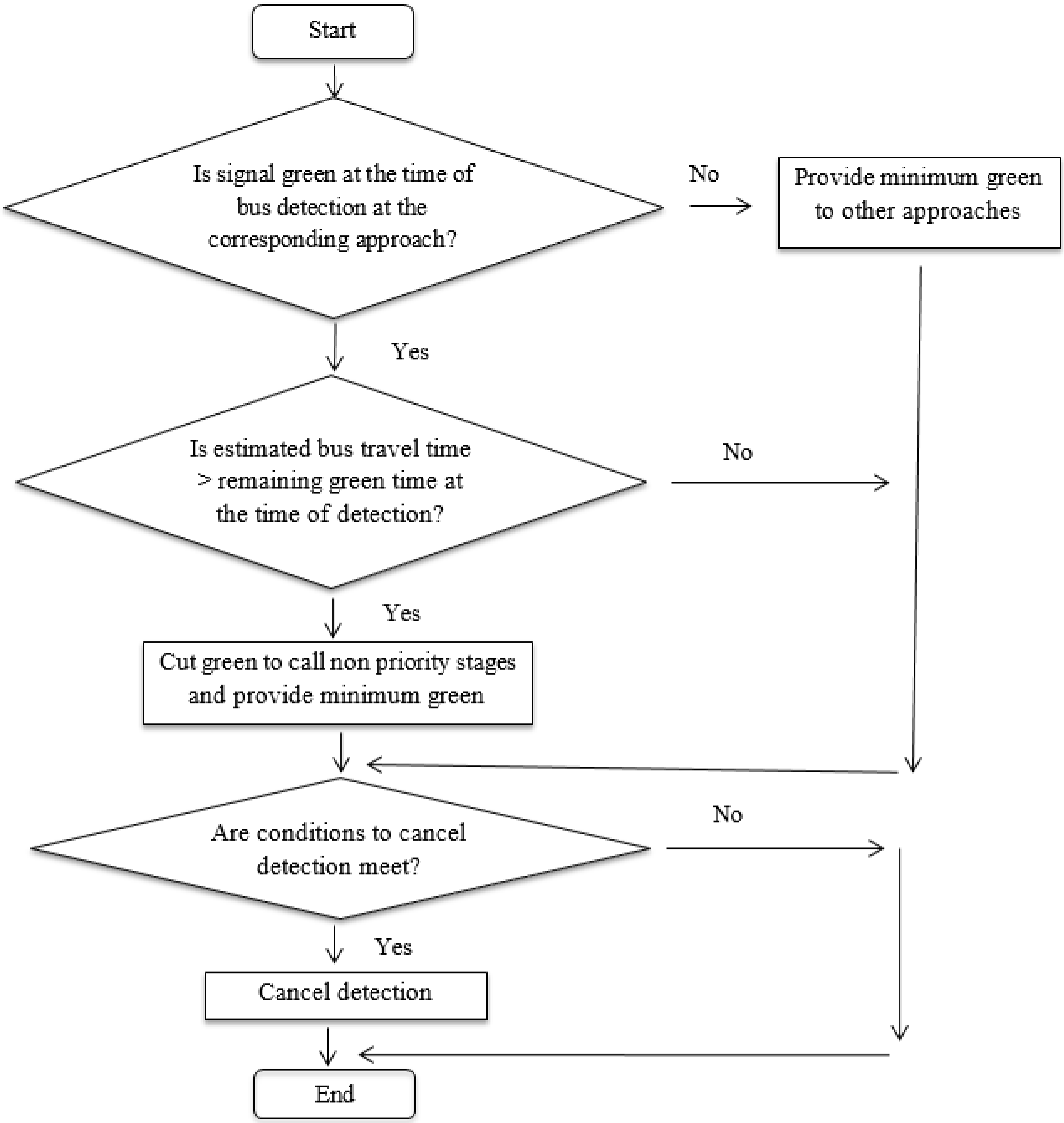


Figure 6.17: Bus priority module for cut & recall

When called by the main module, it first checks whether the signal is green on the approach with bus detection. If green and remaining green time is equal to or higher than the estimated bus travel time then detection will be cancelled. Otherwise green for that approach will be cut (making sure minimum green time is provided, and there is demand in other approaches) and minimum green time will be provided to non-priority approaches. After that bus detection will be cancelled when cancellation conditions are met. Cancellation conditions are described in the Table 6.8 below.

Table 6.8: Conditions to cancel cut with recall

Cancellation Conditions	
Condition1	During no cut, green is kept for PVE time or more
Condition2	Bus is detected at the exit detector
Condition3	Minimum priority green for recall provided

If the signal is not green on the approach with bus detection, only minimum green time will be provided to the other approaches so that green on the bus detected approach is recalled as soon as possible. After the recall has occurred, detection will be cancelled when cancellation conditions are met.

'Always Green Bus'

This new strategy involves detecting buses early and adjusts the signal timing, so that a detected bus will always get green when it arrives close to the stop line. The distance of the detector from the stop line depends on the length of traffic queue, the duration of non-priority stages (for pedestrians) or minimum green time constrains (for traffic) and inter green times. To implement this method, bus travel time from detection point to the end of signal queue/stop-line (when there is no queue) should be equal to or greater than minimum green time plus inter green time for non-priority arms (traffic) or pedestrian stage length plus inter green time. Figure 6.18 below illustrates the 'always green bus' method for a three stage junction (Figure 6.10). The implementation and logic of this method is described in Figure 6.19. VAP code for this module has been provided in Appendix C.

Figure 6.18: Phase diagram without and with 'always green bus'

By this priority method eligible buses can avoid stopping at a signalised junction or pedestrian crossing theoretically. To implement this strategy, siting detector upstream of the stop line considering bus speed, junction queue length, inter green time, minimum green time of non priority stages, and duration of pedestrian stage is crucial.

The flowchart (Figure 6.19) below illustrates the procedures of the 'always green bus' method.

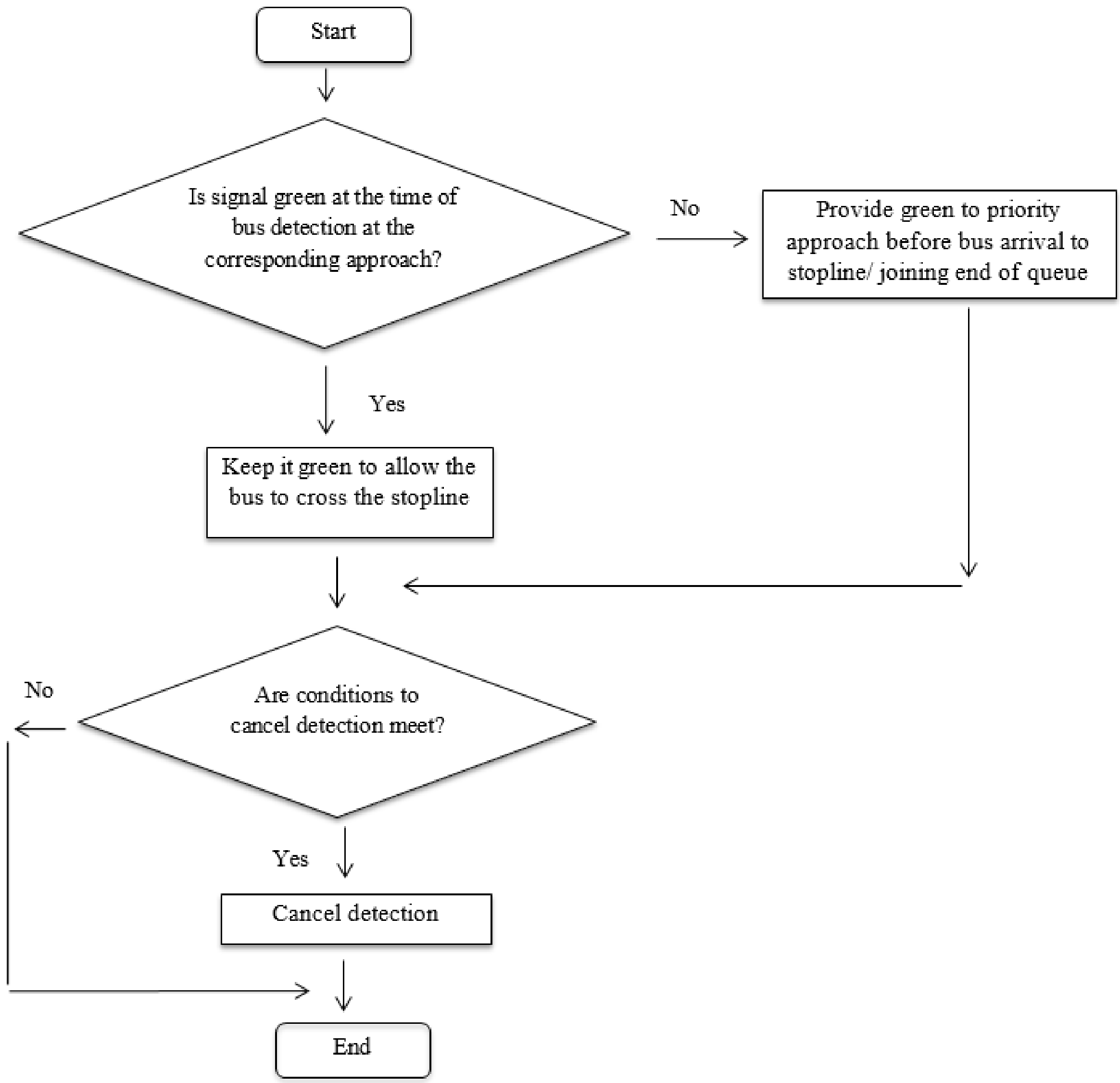


Figure 6.19: Bus priority module for 'always green bus'

When called by the main module, it firstly check the signal status of the priority approach. If the priority stage is green, it will hold the green to allow the detected bus to cross the stop line without stopping. Then detection will be cancelled when cancellation conditions are met. If the priority stage is not green when the module is called, it will adjust the signal timing of non priority stages to provide green to priority stage such that the detected bus will always get green before arrival to the stop line or at the end of the junction queue. This signal adjustment is done by cutting non priority greens if necessary but ensuring their minimum green times. But for pedestrian stage, green cut is not allowed due to pedestrian safety. Table 6.9 below describe the cancellation conditions.

Table 6.9: Conditions to cancel 'always green bus' method

Cancellation Conditions	
Condition1	Green is hold for PVE time or more
Condition2	Bus is detected at the exit detector
Condition3	Queue clearance time is provided during detection at red

6.5.2.5 Stage Compensation Module

This strategy involves repaying the time lost due to priority to non-priority stages. After bus priority, those non-priority stages which are shortened or omitted during a priority call are given extra green in addition to their normal maximum green if needed. Four types of compensation strategies have been developed. These are: unprotected compensation, protected compensation by need, protection by usual inhibit, and protection by improved inhibit.

Unprotected compensation: Compensation is provided if no bus is detected after bus priority. Even if during unprotected compensation a bus is detected, compensation is cancelled. This compensation is not guaranteed.

Protected compensation by need: After bus priority no bus will be detected until the compensation requirement is fulfilled. At the same time if there is no need for compensation, compensation will not be provided and buses will be considered for priority. This is guaranteed compensation, because buses will not get priority until non priority stages are compensated *(Chapter 3 Section 3.3.2)*.

Protection by usual inhibit: Buses are ignored for a certain period of time after bus priority without checking compensation requirement. So when the timer stops, buses are detected and compensation is cancelled even if requirements are not fulfilled. It is a not guaranteed compensation in current practice. Because the inhibit timer runs up to first bus detection, if more than one bus is detected in the cycle just after the priority cycle, non-priority stages will not get compensation *(Chapter 3 Section 3.3.3)*.

Protection by improved inhibit: Usual inhibit method has been improved by considering the requirement of the non priority arms. In the improved inhibit the timers terminates when there is no need for compensation to detect buses. If there is need for compensation, buses are ignored for a fixed period of time after bus priority. This is guaranteed compensation, because buses will not get priority for a fixed period of time until non priority stages are compensated *(Chapter 3 Section 3.3.3)*.

Figure 6.20 below illustrates the compensation method for a three stage junction (Figure 6.10). The implementation and logic of this method is described in Figure 6.21. VAP code for this module has been provided in Appendix C.

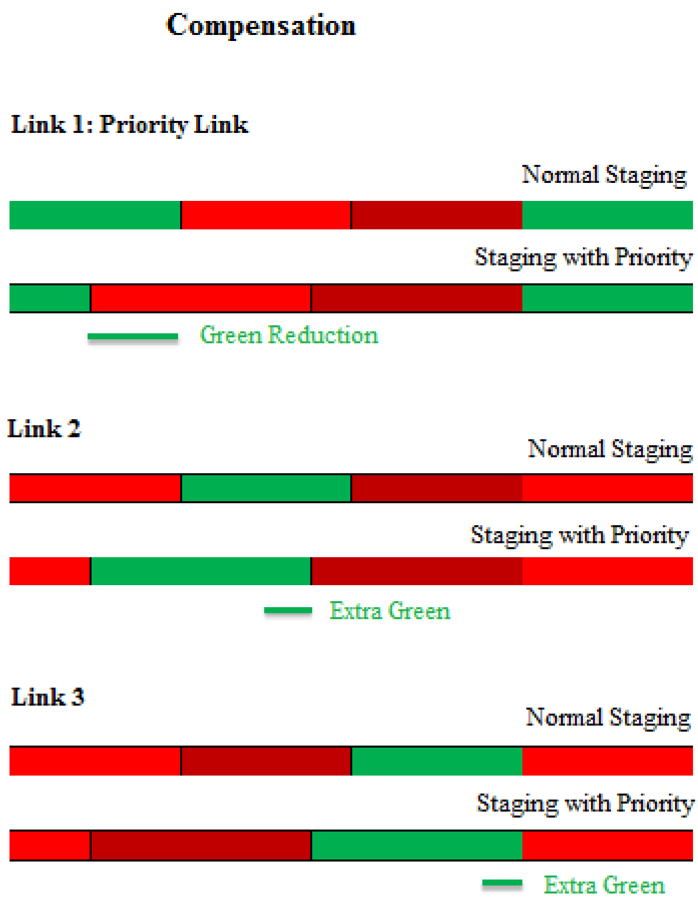


Figure 6.20: Phase diagram without and with compensation

This module provides compensation to non-priority arms if their green time is cut due to bus priority. The amount of green time cut is repaid by compensation module in the next cycle after bus priority.

The flowchart (Figure 6.21) below describes the functionalities of this module. When called by the main module, it will first check whether a vehicle is detected at the approach where compensation needed. If there is no detection, it will cancel compensation requirement. If detected, it will call general V.A. signal controller to increase the maximum stage green duration by adding the lost green time due to the bus priority just ended.

Compensated maximum green for non priority stage = Normal maximum green of that stage + amount of green cut from that stage due to bus priority.

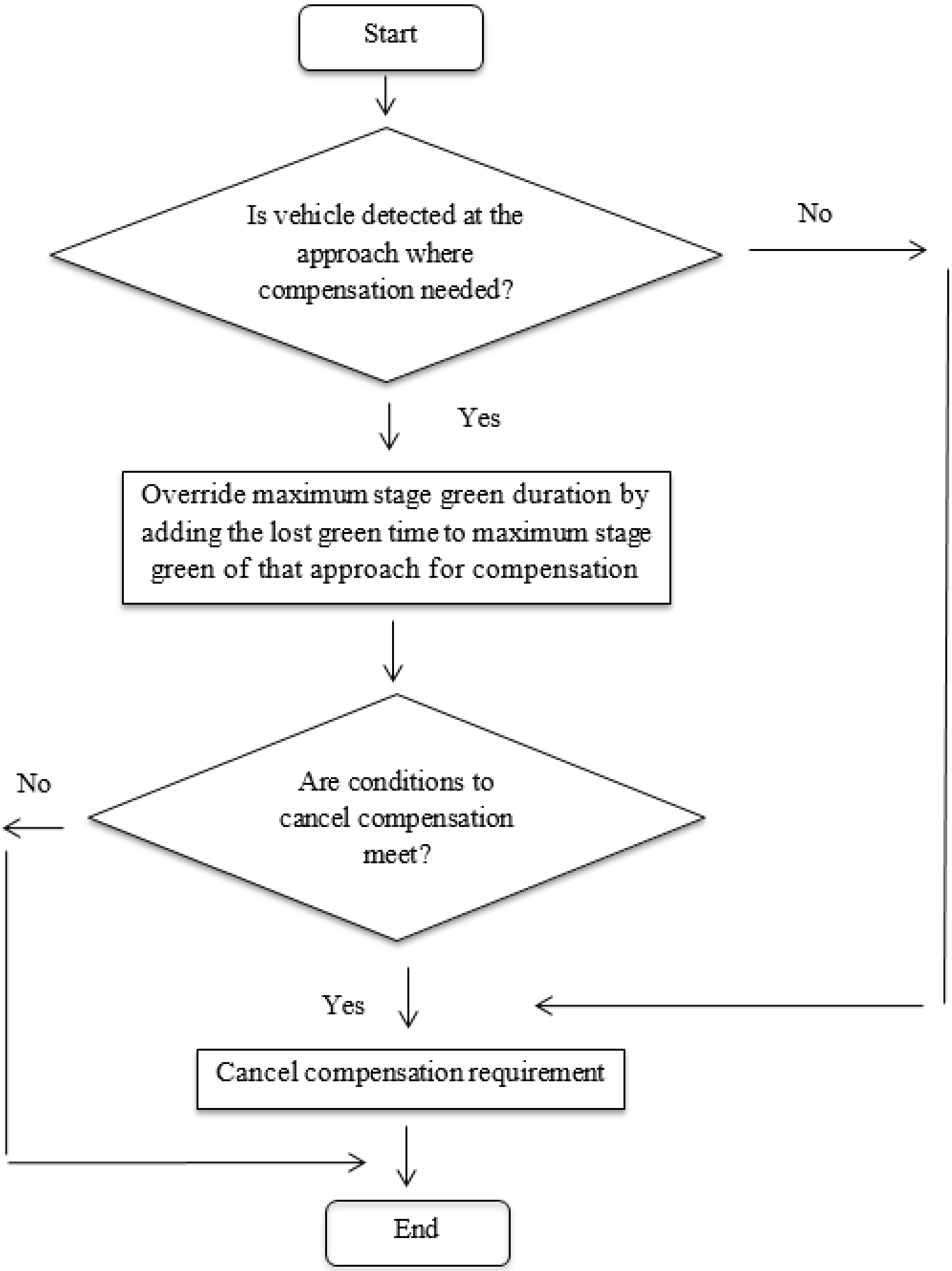


Figure 6.21: Stage compensation module

The general V.A. signal controller will be active with a new compensated maximum green for non priority stages where required. Compensation requirement will be cancelled when cancellation conditions are met. Compensation cancellation conditions are described in

Table 6.10 below. When the compensation requirement is cancelled, the general V.A. signal controller runs according to normal maximum stage duration.

Table 6.10: Conditions to cancel compensation

Compensation Cancellation Conditions		
Condition Nr	Compensation Type	Description of Conditions
Condition1	Protected/Unprotected/Inhibit	Lost green time is repaid
Condition2	Unprotected	Bus detected at priority approach
Condition3	Inhibit	Inhibit timer ended

6.5.2.6 Controller Outputs

In-built controller outputs have been used to model the signal controller. These are a visual display of the controller, recording of the signal status in each second in text files, recording of the vehicles and bus detection in each second in the text file. A text (*.LSA) file describes the change of signal stages by providing information such as time of stage change, duration of stage green, beginning and end of the green time, duration of stage red, beginning and end of the red time, red/amber duration, beginning and end of the red/amber time, amber duration, beginning and end of the amber time. A text (*.LZV) file provides average green time of each stage, average red time of each stage, and distribution of signal times. Also another text (*.LDP) file provides information of vehicle, pedestrian, and bus detection in each stage with time and signal status at that time. These outputs files have been provided in the Appendix C for illustration.

6.6 Travel Time Sections

To record travel time through the cross junction and T junction, six travel time sections, and for pedestrian crossing four travel time sections, 1100 m long each have been modelled. They are designed in such a way that the signal stop line is located at the middle of the travel time section. Two of the travel time sections record bus travel time and the rest record car travel times for each junction/pedestrian crossing. To capture the pedestrian travel time two travel time sections through the pedestrian crossing one in each direction have been modelled for each junction/pedestrian crossing. Pedestrian travel time sections are short, and their length depends on the width of the road and pavement. During modelling travel time sections well upstream of a bus stop are selected to include bus stops activity, and to truly capture acceleration, deceleration, delay at bus stops and junction stop lines for accurate average speed and journey time. Longer travel time sections are modelled because it has been observed that during peak hours particularly during congested situation long traffic queues can develop due to the traffic signal. To capture the impact of these queues a long travel time section is require. Journey time sections are modelled from each arm of the junction to opposite arm in each direction. Each section begins from a point well upstream of the signal stop line where change in acceleration, deceleration does not happen and speeds are steady. Each section ends to a point well downstream of the signal stop line where change in acceleration, deceleration does not happen and speeds are steady. Thus the sections will truly capture the change of acceleration, deceleration, speed, delay, and journey time.

6.7 Model Outputs

In the built controller, outputs described in Section 6.5.2.6 and user defined travel time outputs (*.RSZ file) have been used for performance evaluation of the methods and parameters. Sample travel time outputs have been provided in the Appendix C for illustration. For verification and validation of the model outputs such as junction delay, queue length, average speed, mean green time, saturation flow, and delay due to signal queue are used. For analysis of the benefits and dis-benefits of the modelled strategies and parameters the following user defined outputs have been used. These are:

Bus journey time savings: Time saved due to priority by each bus to travel from beginning to end point of the travel time sections through the junction or crossing.

Car journey time savings: Car delay improvement due to priority by each car to travel from beginning to end point of the travel time sections through the junction or crossing.

Pedestrian delay: Delay to pedestrian due to priority at the pedestrian crossing.

6.8 Realistic Models Development

Developed models have been verified, calibrated, and validated to ensure that the existing traffic conditions has been realistically (Islington Council 2010) replicated in the base models. The base models have been developed to represent realistic and typical junctions and pedestrian crossing. The base model for the cross junction has been adopted from the Portswood junction but it does not fully represent the Portswood junction because of various modelling assumptions and simplifications. For the same reasons the modelled T-junction and pedestrian crossing does not represent Burgess Road vs Gelen Eyre Road junction and Portswood pedestrian crossing respectively. The attempt to verify, calibrate, and validate the base models is to understand whether the base models are functioning as expected and to test whether the results are realistic.

6.8.1 Models Verification

Models have been verified by using visual and text outputs. VISSIM has interfaces to visualised signal time tables, signal changes, detector records, vehicle speed, and travel times during simulation run. It helps to verify whether the models are working as expected. Bus generations, dwell time, bus stops activity, bus priority at the signal, inter peak, peak and congested condition, junction performance were all checked visually to ensure that the real world scenario is represented realistically. For example: in the field observations were made to understand the behaviour of queuing traffic during the red signal. Such behaviour included length of the queue, vehicle occupancy in a certain queue length, headway between stationary vehicles, and queue clearance time. By simulating the models at the running speed of 1 simulation/sec, the observations done in the field also has been done several times in the models to understand whether those observed behaviour realistically modelled. To understand whether the models are working as expected, text outputs also has been checked and analysed to find out signal status, changes, and detector's detection second by second. This helped to verify whether the controller was working as expected.

6.8.2 Model Calibration

6.8.2.1 Queue Occupancy

The developed base models were calibrated to realistically represent the number of queuing vehicles during red in a certain link length. The occupancy of the number of stationary vehicles in a certain link length is controlled by the parameter 'average stand still' distance for a given traffic composition. This parameter actually controls the average headway of the queuing vehicles. VISSIM uses 2 meters as default average stand still distance (average gap between queuing vehicles). But it was found that this default value does not represent the observed values at the sites. The number of vehicles that can occupy in a certain length in the queue condition is much less if default parameter is used. So this parameter has been calibrated by trial and error method to match the field situation. It has been found that an average stand still distance of 1.3 meters perfectly matched the field occupancy of queuing vehicles in a certain length as shown in the Table 6.11 below. So 1.3m has been used in the models as the average stand still distance.

Table 6.11: Number of queuing vehicles in a certain link length calibration

Relationship between number of queuing vehicles with queue length			
	Average Stand Still Distance (m)	Link Length (m)	Average Number of Queuing Vehicles (Nr)
Observed	n/a	100	17
VISSIM Default	2	100	15
Calibrated (Modelled)	1.3	100	17

6.8.2.2 Queue Clearance Time

The time required by the last vehicle in the queue to cross the stop line when the signal changes to green from red is dependent on the number of vehicles waiting in the queue in front, drivers reaction time, acceleration time, and average gap between queuing vehicles. Modelling queue clearance time according to the field situation is very important because it controls the signal delay and also some bus priority parameters. So, when the parameter average stand still distance (average gap between queuing vehicles) has been calibrated by trial and error method, the average queue clearance time in the models also has been compared with sites observed value. It has been found that calibrated stand still distance provides 2.1 sec/vehicle queue clearance rate in the models which is also the observed value in the fields as shown in the Table 6.12 below.

Table 6.12: Average queue clearance time calibration

Queue Clearance Rate	
	Average Queue Clearance Time (Sec/vehicle)
Observed	2.1
Calibrated (Modelled)	2.1

6.8.3 Validation

6.8.3.1 Signal Green Time Validation

Observed average green times of each stage at each junction have been compared with the modelled average green time. Tables 6.13, 6.14, and 6.15 below illustrate that the average green time of each stage of each model is realistic.

Table 6.13: Observed and modelled average green time comparison (Cross junction)

Cross Junction: Signal Stage Validation								
			Evening Peak			Morning & Inter Peak		
Junction Arm	Symbol	Nr	Observed Average Green (Sec)	Modelled Average Green (Sec)	Percentage of Variation (%)	Observed Average Green (Sec)	Modelled Average Green (Sec)	Percentage of Variation (%)
Portswood Rd (SW +NE)	S1	1	33.8	32.9	-3%	26.4	29.9	13%
Highfield Ln (NW)	S2	2	19.4	19.5	1%	18.7	18	-4%
St Denys Rd (SE)	S3	3	19.6	19.3	-2%	18.4	19	3%
Pedestrian Green	S4	4	7	7	0%	7	7	0%

Table 6.14: Observed and modelled average green time comparison (Pedestrian crossing)

Pedestrian Crossing: Signal Stage Validation								
			Evening Peak			Morning & Inter Peak		
Junction Arm	Symbol	Nr	Observed Average Green (Sec)	Modelled Average Green (Sec)	Percentage of Variation (%)	Observed Average Green (Sec)	Modelled Average Green (Sec)	Percentage of Variation (%)
Portswood Rd (SW +NE)	S1	1	28.1	27.4	-2%	26.4	25.1	-5%
Pedestrian Green	S2	2	6	6	0%	6	6	0%

Table 6.15: Observed and modelled average green time comparison (T junction)

T Junction: Signal Stage Validation								
			Peak			Inter Peak		
Junction Arm	Symbol	Nr	Observed Average Green (Sec)	Modelled Average Green (Sec)	Percentage of Variation (%)	Observed Average Green (Sec)	Modelled Average Green (Sec)	Percentage of Variation (%)
Burgess Rd (SW + NE)	S1	1	44.1	48.8	11%	36.1	34.6	-4%
Glen Eyre Rd (NW)	S2	2	17.1	18	5%	11.1	10.4	-6%
Pedestrian Green	S3	3	7	7	0%	7	7	0%

6.8.3.2 Junction Queue Validation

Observed average and maximum queuing vehicles number due to red signal on each arm of each junction have been compared against modelled averages and maximum respectively for each junction condition. Tables 6.16, 6.17 and 6.18 below illustrate that observed traffic queues have been realistically modelled.

Table 6.16: Observed and modelled traffic queue comparison (Cross junction)

Cross Junction: Queue Validation								
Condition	Evening Peak				Morning & Interpeak			
Junction Arm	Observed Average (Nr)	Modelled Average (Nr)	Observed Maximum (Nr)	Modelled Maximum (Nr)	Observed Average (Nr)	Modelled Average (Nr)	Observed Maximum (Nr)	Modelled Maximum (Nr)
Portswood Rd (SW)	16	14	30	28	9	7	20	18
Portswood Rd (NE)	8	7	19	17	7	8	14	13
Highfield Ln (NW)	13	13	25	27	8	9	16	19
St Denys Rd (SE)	12	13	27	29	10	10	20	19

Table 6.17: Observed and modelled traffic queue comparison (Pedestrian crossing)

Pedestrian Crossing: Queue Validation								
Condition	Evening Peak				Morning & Interpeak			
Junction Arm	Observed Average (Nr)	Modelled Average (Nr)	Observed Maximum (Nr)	Modelled Maximum (Nr)	Observed Average (Nr)	Modelled Average (Nr)	Observed Maximum (Nr)	Modelled Maximum (Nr)
Portswood Rd (SW)	5	5	15	12	3	3	10	12
Portswood Rd (NE)	4	4	11	10	4	4	11	12

Table 6.18: Observed and modelled traffic queue comparison (T junction)

T Junction: Queue Validation								
Condition	Peak				Inter Peak			
Junction Arm	Observed Average (Nr)	Modelled Average (Nr)	Observed Maximum (Nr)	Modelled Maximum (Nr)	Observed Average (Nr)	Modelled Average (Nr)	Observed Maximum (Nr)	Modelled Maximum (Nr)
Burgess Rd (SW)	12	14	31	30	7	7	17	15
Burgess Rd (NE)	8	9	21	22	5	6	14	13
GlenEyre Rd (NW)	6	7	16	17	2	3	7	7

6.8.3.3 Link Speed Validation

The average observed link speeds of each junction type have been compared with the modelled average link speeds considering junction conditions. Table 6.19 below illustrates that observed link speed has been realistically modelled. Because according to TFL DTO modelling guidelines (TfL 2010) modelled journey time should be within 15% of observed values. Travel time is dependent on link speed. As link speed has been realistically modelled, so modelled travel time are also realistic.

Table 6.19: Average link speed comparison

Link Speed Validation						
	Observed Average Link Speed (m/s)	Modelled Average Link Speed (m/s)	Percentage of Variation (%)	Observed Average Link Speed (m/s)	Modelled Average Link Speed (m/s)	Percentage of Variation (%)
Junction Condition/ Type	Evening Peak			Morning & Inter Peak		
Cross Junction	7.59	7.63	1%	7.71	7.69	0%
Pedestrian Crossing	7.59	7.52	-1%	7.71	7.58	-2%
Junction Condition/ Type	Peak			Inter Peak		
T Junction	8.47	8.40	-1%	9.87	9.76	-1%

6.8.3.4 Signal Delay Validation

Observed average signal delay to buses through each junction on the major road has been compared with the modelled average. Table 6.20 below illustrates that modelled signal delay to buses are realistic.

It was expected to get higher signal delay in the base models compared to field because in the pedestrian stage pedestrian behaviour has not been considered. So for pedestrian safety, in the models pedestrian stage runs up to its maximum regardless of fast or slow pedestrian movement. But in practice, pedestrian stage length is variable. Maximum duration is provided for slowest pedestrian, and for fastest pedestrian minimum stage duration is provided. When a pedestrian stage run shorter than maximum, signal delay will be less which is reflected in the Table 6.20.

According to TFL DTO modelling guidelines (TfL 2010) modelled journey time should be within 15% of observed values. Travel time through a junction is dependent on signal delay and link speed. As, signal delay and link speed has been realistically modelled, so modelled travel time through the junction are also realistic.

Table 6.20: Observed and modelled signal delay comparison

Signal Delay Validation: Through Major Road						
	Observed Average Signal Delay (Sec/Bus)	Modelled Average Signal Delay (Sec/Bus)	Percentage of Variation (%)	Observed Average Signal Delay (Sec/Bus)	Modelled Average Signal Delay (Sec/Bus)	Percentage of Variation (%)
Junction Condition/ Type	Evening Peak			Morning & Inter Peak		
Cross Junction	41.5	45.1	9%	36.8	40.1	9%
Pedestrian Crossing	11.8	13.2	12%	10.4	12.3	18%
Junction Condition/ Type	Peak			Inter Peak		
T Junction	29.2	32.7	12%	16.1	18.2	13%

6.9 Chapter summary

In this Chapter model requirements for implementing bus priority at traffic signals have been identified. Considering these requirements, VISSIM 5.40 has been selected for the model development by comparing the most popular micro simulation tools. Then base models have been developed using observed data described in Chapter 5. This Chapter has also illustrated the methodology and implementation of isolated VA signal controller logic, D-system detectors, and various bus priority methods used in the models. Required inputs and models' outputs also have been explained. Finally the models have been calibrated, verified, and validated as realistic. These realistic models have been used as base for various scenarios development and for the evaluation of the bus priority parameters and methods in the next Chapter.

Chapter 7: Scenarios Development, Results and Interpretation

7.1 Introduction

Previous Chapters have (i) described the existing and new bus priority parameters, methods and strategies proposed for testing and evaluation (ii) described the proposed evaluation methodologies, including the use of VISSIM and have (iii) illustrated the junctions where testing and evaluation is to take place, including issues of calibration and validation. This Chapter now continues with a full description and interpretation of the tests undertaken, leading to a variety of recommendations for practice.

7.2 Junction Descriptions

The validated base models – the cross junction with pedestrian crossing, T-junction with pedestrian crossing, and pedestrian crossing - have been used for scenario development and for evaluating the performance of existing and new priority parameters and methods. From the base model of a junction with pedestrian crossings another two models have been developed without pedestrian crossings. These are cross junction without pedestrian crossing and T-junction without pedestrian crossing. Signal details (without pedestrian stage), traffic flows, vehicles compositions, speed profiles, and all other model parameters have been kept unchanged. These two new base models without pedestrian crossings provide a scenario with a lower traffic degree of saturation, to ensure that this situation is evaluated. Tables 7.1 to 7.9 below illustrate the degree of saturation, delay, and queue details in each modelled base junction to describe how busy each junction is. The Tables below illustrate that the modelled cross junction with pedestrian crossing is a relatively busy junction. Particularly, it's two non priority arms (Highfield Ln and St Denys Rd) run close to their capacity. Delay on those arms are high. The required average queue clearance times in each cycle on those arms are much higher than the corresponding maximum stage green. The cross junction without a pedestrian crossing and the T-junction with pedestrian crossing are normal busy junctions.

The T junction without pedestrian crossing and the pedestrian crossing are comparatively quiet junctions.

Table 7.1: Degree of saturation without priority: Cross junction

Degree of Saturation: Cross Junction			
Junction Arms	Conditions	Cross Junction with Pedestrian Crossing	Cross Junction without Pedestrian Crossing
Portswood Rd (SW)	Evening Peak	0.86	0.72
Portswood Rd (NE)	Evening Peak	0.59	0.50
Highfield Ln (NW	Evening Peak	0.96	0.81
St Denys Rd (SE)	Evening Peak	0.92	0.77

Table 7.2: Degree of saturation without priority: T junction

Degree of Saturation: T Junction			
Junction Arms	Conditions	T Junction with Pedestrian Crossing	T Junction without Pedestrian Crossing
Burgess Rd (SW)	Morning& Evening Peak	0.78	0.63
Burgess Rd (NE)	Morning& Evening Peak	0.79	0.64
GlenEyre Rd (NW)	Morning& Evening Peak	0.69	0.56

Table 7.3: Degree of saturation without priority: Pedestrian crossing

Degree of Saturation: Pedestrian Crossing		
Junction Arms	Conditions	Pedestrian Crossing
Portswood Rd (SW)	Evening Peak	0.49
Portswood Rd (NE)	Evening Peak	0.45

Table 7.4: Junction delay without priority: Cross junction

Junction Delay: Cross Junction (Sec/Veh); Without Priority			
Junction Arms	Conditions	Cross Junction with Pedestrian Crossing	Cross Junction without Pedestrian Crossing
Portswood Rd (SW) & (NE)	Evening Peak	45	26
Highfield Ln (NW)	Evening Peak	148	40
St Denys Rd (SE)	Evening Peak	138	37
Pedestrian Crossing	Evening Peak	40	n/a

Table 7.5: Junction delay without priority: T junction

Junction Delay: T Junction (Sec/Veh); Without Priority			
Junction Arms	Conditions	T Junction with Pedestrian Crossing	T Junction without Pedestrian Crossing
Burgess Rd (SW) & (NE)	Morning& Evening Peak	33	12
GlenEyre Rd (NW)	Morning& Evening Peak	50	30
Pedestrian Crossing	Morning& Evening Peak	34	n/a

Table 7.6: Junction delay without priority: Pedestrian crossing

Junction Delay: Pedestrian Crossing (Sec/Veh); Without Priority		
Junction Arms	Conditions	Pedestrian Crossing
Portswood Rd (SW) & (NE)	Evening Peak	13
Pedestrian	Evening Peak	11

Table 7.7: Queue details without priority: Cross junction

Queue Length: Cross Junction							
Junction Arms	Conditions	Cross Junction with Pedestrian Crossing			Cross Junction without Pedestrian Crossing		
		Vehicle Nr (Nr)	Length (m)	Clearance Time (Sec)	Vehicle Nr (Nr)	Length (m)	Clearance Time (Sec)
Portswood Rd (SW)	Evening Peak	14	82	29	7	41	15
Portswood Rd (NE)	Evening Peak	7	41	15	5	29	11
Highfield Ln (NW	Evening Peak	13	77	27	6	35	13
St Denys Rd (SE)	Evening Peak	13	77	27	7	41	15

Table 7.8: Queue details without priority: T junction

Queue Length: T Junction							
Junction Arms	Conditions	T Junction with Pedestrian Crossing			T Junction without Pedestrian Crossing		
		Vehicle Nr (Nr)	Length (m)	Clearance Time (Sec)	Vehicle Nr (Nr)	Length (m)	Clearance Time (Sec)
Burgess Rd (SW)	Morning& Evening Peak	14	82	29	7	41	15
Burgess Rd (NE)	Morning& Evening Peak	9	53	19	6	35	13
GlenEyre Rd (NW)	Morning& Evening Peak	7	41	15	4	24	8

Table 7.9: Queue details without priority: Pedestrian crossing

Queue Length: Pedestrian Crossing				
Junction Arms	Conditions	Pedestrian Crossing		
		Vehicle Nr (Nr)	Length (m)	Clearance Time (Sec)
Portswood Rd (SW)	Evening Peak	5	29	11
Portswood Rd (NE)	Evening Peak	4	24	8

7.3 Priority Extension Time (PVE) Calculation

Tables 7.10 to 7.12 below illustrate implemented priority extension times for different detection distances in the cross junction, T-junction, and pedestrian crossing models. Calculation is based on the method described in Chapter 3 Section 3.2.3. Each priority extension time has been modelled for the corresponding bus detection location. Some of the priority extension times and corresponding detection distances are high and the higher values may not be practical at some junctions. However, these higher priority extensions with higher detector siting distances have been included at this stage as they may allow stronger/higher levels of priority to be considered.

Table 7.10: Priority extension time (PVE) calculation: Cross junction

Priority Extension Time (PVE) Calculation				
Cross Junction: Evening Peak				
Detector Distance (S) (m)	Average Speed (V) (m/s)	Average Bus Journey Time (T= S/V) (Sec)	Journey Time Variability t= 0.3T (Sec)	Priority Extension Time (PVE = T+t) (Sec)
50	7.63	7	2	9
100		13	4	17
150		20	6	26
200		26	8	34
250		33	10	43
324		42	13	55
365		48	14	62

Table 7.11: Priority extension time (PVE) calculation: T junction

Priority Extension Time (PVE) Calculation				
T Junction: Morning and Evening Peak				
Detector Distance (S) (m)	Average Speed (V) (m/s)	Average Bus Journey Time (T= S/V) (Sec)	Journey Time Variability t= 0.3T (Sec)	Priority Extension Time (PVE = T+t) (Sec)
50	8.4	6	2	8
100		12	3	15
150		18	5	23
200		24	7	31
226		27	8	35
250		30	9	39
267		32	10	42

Table 7.12: Priority extension time (PVE) calculation: Pedestrian crossing

Priority Extension Time (PVE) Calculation				
Pedestrian Crossing: Evening Peak				
Detector Distance (S) (m)	Average Speed (V) (m/s)	Average Bus Journey Time (T= S/V) (Sec)	Journey Time Variability t= 0.3T (Sec)	Priority Extension Time (PVE = T+t) (Sec)
100	7.52	13	4	17
217		29	9	38

7.4 Detector Distance for 'Always Green Bus'

For the 'Always Green Bus' priority method, the detector distance has been calculated as follows *(detail methodology in Chapter 3 Section 3.3.4)*:

Detection distance (m) = (minimum green + inter green time) of non priority stages * average bus speed + average queue length during red.

Table 7.13 below shows detector distances to provide always green for buses for the modelled junction types.

Table 7.13: Calculation of detector distances: 'always green bus' method

Calculation of Detector Distances: Always Green Bus							
Junction Types	Traffic Condition	Inter Greens (Sec)	Minimum Greens (Sec)	Minimum Greens + Inter Greens (C) (Sec)	Average Speed (V) (m/s)	Average Queue Length(Q) (m)	Detector Distance (D= C*V+Q) (m)
Cross Junction with Pedestrian Crossing	Evening Peak	9,7,7	7,7	37	7.63	82	365
Cross Junction without Pedestrian Crossing	Evening Peak	9,7,7	7,7	37	7.63	41	324
T Junction with Pedestrian Crossing	Morning and Evening Peak	8,7	7	22	8.4	82	267
T Junction without Pedestrian Crossing	Morning and Evening Peak	8,7	7	22	8.4	41	226
Pedestrian Crossing	Evening Peak	6,13	6	25	7.52	29	217

At the cross junction and T- junction with pedestrian crossings during the 'always green bus' method, the pedestrian stage has been skipped if a bus is detected during other non priority stages. This is to reduce the detection distance for 'always green bus' method. So, in the calculation in the Table 7.13 above in such junction types minimum pedestrian stage and inter green time due to pedestrian stage are not considered. Stage skipping is not a preferable strategy in the UK. So, pedestrian safety aspect of 'always green bus' method in the junction with pedestrian crossing should be explored during further studies.

7.5 Priority Parameters Test

7.5.1 Impact of Detector Distance on Extension

To investigate the impact of detector location on extension detectors have been sited at five different locations from the stop line on the priority approach. These are 50m, 100m, 150m, 200m and 250m upstream from signal stop line. Investigations have been performed on four selected junction types of different characteristics described on Section 7.2. Peak hour flows have been modelled. 10 buses per hour in each direction have been modelled in the major road.

With the increase of detector distance delay savings to buses increase in all selected junction types. Negative impact on non priority traffic is also increase. This result is also expected and reasons for this expectation is described in Chapter 3 on Section 3.2.1.

The Tables 7.14 to 7.17 below illustrates delay savings to buses and impact on general traffic by extension with different detection distances.

Table 7.14: Impact of detector distance on extension: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Extension; Peak Flow; 10 Bus per hr each direction; Both Way; Major Road				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
50	-8	-2	0	0
100	-6	-9	0	7
150	-11	-14	-1	11
200	-60	-98	-2	14
250	-149	-197	-2	16

Table 7.15: Impact of detector distance on extension: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Extension; Peak Flow; 10 Bus per hr each direction; Both Way; Major Road			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
50	1	0	0
100	0	0	3
150	-1	-2	5
200	-2	-5	9
250	-4	-7	10

Table 7.16: Impact of detector distance on extension: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Extension; Peak Flow; 10 Bus per hr each direction; Both Way; Major Road				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
50	1	0	0	1
100	0	-1	0	5
150	-2	-5	-2	8
200	-4	-8	-1	10
250	-5	-10	-3	12

Table 7.17: Impact of detector distance on extension: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Extension; Peak Flow; 10 Bus per hr each direction; Both Way; Major Road			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
50	0	0	1
100	0	-1	4
150	0	-1	5
200	-1	-2	6
250	-2	-4	7

It is clear from the Tables 7.14 to 7.17 above that by detecting buses early, the performance of extensions can be improved in all junction types. Negative impact on non priority traffic is very high on the cross junction with pedestrian crossing because it's non priority arms are running close to the saturation level without priority. Delay on those arms are also high without priority. Queuing traffic during red without priority fails to clear the junction completely due to required queue clearance time being much higher than maximum stage green. Extension with early detection is making the situation even worse particularly in the non priority arms of this junction.

7.5.2 Impact of Priority Maximum Time (PVM) on Extension

To explore the impact of priority maximum time parameter on the performance of extensions, five PVM values have been considered. These are extension time 12 sec (for T Junction 11sec), 20 sec, 30sec, 40 sec, and 50sec. These values have been implemented in the priority extension method on the selected junction types. PVM is effective when bus frequency is very high because, during the priority extension of one bus if another or more bus is detected, PVM controls the eligibility of the later buses for extension (detailed description in Chapter 3 Section 3.2.2). This has been modelled by increasing bus flow in each direction to 40 buses per hour.

The Tables 7.18 to 7.21 below illustrates the impact of increase of PVM on the performance of extension on different junction types.

Table 7.18: Impact of PVM on extension: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Extension; 70m Detection Distance; Bus Flow 80/hr (Both Way Total)				
	Delay Savings: (Sec/Junction/Vehicle Type)			
PVM (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
12	-63	-109	-2	22
20	-67	-125	-3	26
30	-73	-128	-3	27
40	-79	-144	-3	27
50	-79	-144	-3	27

Table 7.19: Impact of PVM on extension: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Extension; 70m Detection Distance; Bus Flow 80/hr (Both Way Total)			
	Delay Savings: (Sec/Junction/Vehicle Type)		
PVM (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
12	-1	-2	4
20	-1	-2	5
30	-1	-2	6
40	-2	-3	6
50	-2	-3	6

Table 7.20: Impact of PVM on extension: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Extension; 70m Detection Distance; Bus Flow 80/hr (Both Way Total)				
	Delay Savings: (Sec/Junction/Vehicle Type)			
PVM (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
11	-1	-3	-3	6
20	-1	-3	-3	6
30	-1	-3	-3	6
40	-1	-3	-3	6
50	-1	-3	-3	6

Table 7.21: Impact of PVM on extension: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Extension; 70m Detection Distance; Bus Flow 80/hr (Both Way Total)			
	Delay Savings: (Sec/Junction/Vehicle Type)		
PVM (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
11	-1	-2	2
20	-1	-2	2
30	-1	-2	2
40	-1	-2	2
50	-1	-2	2

Tables 7.18 to 7.21 above illustrate that with the increase of PVM values, benefits or disbenefits by extension do not change that much. Because, only very few buses take advantage of the PVM and by increasing the PVM that number does not increase that much. But a higher value of PVM allows the detector siting distance to be increased. As higher PVM values do not increase the negative impact on general traffic but allow the detection distance to be increased, higher PVM values have been used in the rest of this Chapter.

7.5.3 Impact of Detector Location on Recall

To investigate the impact of detector distance on the performance of green recalls, detectors have been sited on five different locations from the stop line on the priority approaches in the models. These are 50m, 100m, 150m, 200m and 250m from the stop line. On each of the selected junction types peak flows have been modelled. Also to test the performance of recalls when the traffic queue is long during red on priority approaches, peak flows have been increased on priority approaches such that a 140m long queue builds up during red.

Signal details have been kept the same as in the base models. Priority on the major road has been considered. With a one way bus service of 10 buses per hour modelled.

Tables 7.22 to 7.29 below illustrate that delay savings by recall are higher if detectors are sited at the location where junction queue ends on the priority approach. If detectors are sited at a location shorter or higher than average queue length then delay savings reduces (Ahmed et at. 2015). Because, if the detector is very close to the stop line, buses may arrive during red at the end of queuing cars upstream of the detector. So buses may not be detected and therefore not get priority. This explains why a recall with shorter detection distance than the average queue length is less beneficial. On the other hand, if a detector is sited too far from the stop line, buses detected during green may be stopped at red period if signal changes occur before crossing the stop line.

A recall is only provided if a bus is detected during red. Some cases were observed on the models where a bus was detected during green, so a recall would not be provided when actually the bus needs a recall because the detector is so far away that signal will change to red before the bus arrives at the stop line. So when buses are detected very far from the stop line the number of buses provided with a recall can be less than the number of buses needing a recall. This explains why a recall with longer detection distance than average queue length is less beneficial *(details on Chapter 3 on Section 3.2.1)*.

The scale of the savings depends on junction type, junction delay, and proportion of red on priority arms. Negative impact on the cross junction with pedestrian crossing is very high for the reasons described in Section 7.5.1.

Table 7.22: Impact of detector location on recall: Cross junction with pedestrian crossing (average queue 140m)

Junction Type: Cross Junction with Pedestrian Crossing				
Priority Method: Recall; Average Queue 140m; Peak Flow Increased				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
50	-64	-115	1	18
100	-139	-319	1	37
150	-233	-436	-2	45
200	-218	-411	-2	42
250	-168	-341	-2	35

Table 7.23: Impact of detector location on recall: Cross junction with pedestrian crossing (average queue 82m)

Junction Type: Cross Junction with Pedestrian Crossing				
Priority Method: Recall; Average Queue 82m; Peak Flow				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
50	-95	-194	1	15
100	-148	-273	1	19
150	-118	-201	1	15
200	-61	-129	1	14
250	-55	-130	1	10

Table 7.24: Impact of detector location on recall: Cross junction without pedestrian crossing (average queue 140m)

Junction Type: Cross Junction without Pedestrian Crossing			
Priority Method: Recall; Average Queue 140m; Peak Flow Increased			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
50	-4	-6	4
100	-5	-10	5
150	-6	-13	10
200	-5	-11	9
250	-5	-10	8

Table 7.25: Impact of detector location on recall: Cross junction without pedestrian crossing (average queue 41m)

Junction Type: Cross Junction without Pedestrian Crossing			
Priority Method: Recall; Average Queue 41m; Peak Flow			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
50	-6	-9	7
100	-6	-9	6
150	-5	-7	6
200	-5	-5	5
250	-5	-5	4

Table 7.26: Impact of detector location on recall: T junction with pedestrian crossing (average queue 140m)

Junction Type: T Junction with Pedestrian Crossing				
Priority Method: Recall; Average Queue 140m; Peak Flow Increased				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
50	-2	-5	1	6
100	-2	-5	1	7
150	-2	-5	0	8
200	-2	-4	0	7
250	-2	-4	0	6

Table 7.27: Impact of detector location on recall: T junction with pedestrian crossing (average queue 82m)

Junction Type: T Junction with Pedestrian Crossing				
Priority Method: Recall; Average Queue 82m; Peak Flow				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
50	-4	-7	1	3
100	-6	-11	0	5
150	-6	-11	0	5
200	-5	-9	0	4
250	-4	-6	0	3

Table 7.28: Impact of detector location on recall: T junction without pedestrian crossing (average queue 140m)

Junction Type: T Junction without Pedestrian Crossing			
Priority Method: Recall; Average Queue 140m; Peak Flow Increased			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
50	-1	-2	2
100	-1	-3	3
150	-1	-3	4
200	-1	-2	4
250	-1	-2	2

Table 7.29: Impact of detector location on recall: T junction without pedestrian crossing (average queue 41m)

Junction Type: T Junction without Pedestrian Crossing			
Priority Method: Recall; Average Queue 41m; Peak Flow			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
50	0	-1	2
100	0	-1	2
150	-1	-1	1
200	-1	-1	1
250	-1	-1	1

7.5.4 Priority Minimum Time

7.5.4.1 Priority Without Conflict

Priority minimum time is the minimum time required for a priority bus after recall to cross the stop line *(details in Chapter 3 on Section 3.2.4)*. The longer the traffic queue in front of the priority bus the higher should be the priority minimum time. To understand the impact of priority minimum time on the performance of recals, five priority minimum times have been modelled. These are 10sec, 20sec, 30sec, 40sec, and 50sec. Again, some of these times are higher than would typically be used in practice, but have been included here to improve trend identification.

These priority minimum times have been tested on the selected four junction types considering peak condition. Flows at priority approaches have been increased to increase the junction queue at the priority approaches to 140m. To clear the 140m long queue after red, a 50 sec minimum green time was required. One way bus service with frequency of 10 buses per hour has been modelled. In these analyses, detectors are sited 150 meters from the stop line with buses running one way only on the major road with a frequency of 10 buses/hr.

Tables 7.30 to 7.31 below illustrate that with 50sec minimum priority time, benefits from recalls are at their highest particularly for the cross junction. At this junction the priority stage runs up to a maximum 35sec without a priority minimum constraint. As queuing traffic is longer, it is likely that a bus may get held up at the end of the traffic queue, and 35sec green period is not enough to clear the bus from the junction. That bus will fail to cross the stop line, meaning that the recall has been wasted, but causes unnecessary delay to non priority arms. This is reflected in Tables 7.30 and 7.31 for the cross junction.

Table 7.30: Priority minimum time for non conflicting priority: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Priority Method: Recall; Average Queue 140m; Peak Flow Increased				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Minimum Time (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
10	-115	-275	1	27
20	-115	-275	1	27
30	-137	-276	1	28
40	-202	-390	0	31
50	-233	-436	-2	45

Table 7.31: Priority minimum time for non conflicting priority: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Priority Method: Recall; Average Queue 140m; Peak Flow Increased			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Minimum Time (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
10	-4	-7	6
20	-4	-8	6
30	-4	-8	7
40	-4	-9	8
50	-6	-13	10

Table 7.32: Priority minimum time for non conflicting priority: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Priority Method: Recall; Average Queue 140m; Peak Flow Increased				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Minimum Time (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
10	-2	-5	0	8
20	-2	-5	0	8
30	-2	-5	0	8
40	-2	-5	0	8
50	-2	-5	0	8

Table 7.33: Priority minimum time for non conflicting priority: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Priority Method: Recall; Average Queue 140m; Peak Flow Increased			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Minimum Time (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
10	-1	-3	4
20	-1	-3	4
30	-1	-3	4
40	-1	-3	4
50	-1	-3	4

The bus priority minimum time parameter has no influence on the benefits of a recall at the T junction. Because, at this junction the priority stage runs up to the maximum 50sec without the priority minimum time constraint and so queuing traffic after recall is likely to clear the junction without this parameter. This is reflected in the Tables 7.32 and 7.33 for the junction. These Tables above also illustrate that priority minimum time parameter is fully dependent on junction queue length and maximum green time of the priority stage on a junction without conflicting bus flow.

7.5.4.2 Priority with Conflict

The Priority minimum time parameter is very influential when in a junction priority buses run through more than one conflicting approach during same signal stage. In that situation a priority conflict likely to occur. For example, if a priority recall is provided to a bus, priority green needs to be held for a certain amount of time to allow the bus to clear the junction. That depends on the travel time from the detection point to the stop line and is influenced by the average queue length. If another priority bus is detected during that period on another conflicting priority approach while conflicting phase is red, that bus will be allocated a recall instantly if the priority minimum time constraint is not implemented. That means without the priority minimum time parameter, during conflicting recalls, priority green for the first bus may be cancelled by the conflicting second bus on another priority approach. This will delay the first bus and also will waste the first recall time which has a negative impact on general traffic. To avoid this situation, a recall is not allowed to any buses until priority minimum time associated with the previous recall has finished.

Priority minimum time is dependent on travel time from the detection point to the stop line and also on length of traffic queue during red. If priority minimum time is implemented without considering these issues, priority benefits to buses will reduce, because buses will fail to cross the stop line during the conflict period even though priority is provided to them. That is reflected in Tables 7.34 to 7.37 below. These Tables illustrate that the higher the priority minimum time, the higher will be the benefits to buses. But disbenefits to general traffic can also increase with the increase of priority minimum time, so priority minimum time constraint should be just enough to allow the bus to clear the junction after priority recall.

The Priority minimum time parameter has been modelled in the selected four junction types. Five priority minimum time have been considered. These are 10sec, 20 sec, 30sec, 40sec and 50sec.

Peak hour condition has been modelled. To increase the queue length, peak flows have been increased. Detectors have been sited at 150m distance from the stop line at junction with pedestrian crossings. At junctions without pedestrian crossings, detectors have been sited at 100m distance.

Two conflicting bus services, 20 buses per hour each, have been modelled. On the cross junction, Portswood Road (SW) and Highfield Lane (NW) have been modelled as priority arms. On T-junction, Burgess Road (SW) and Glen Eyre Road (NW) have been modelled as priority arms. Only one way bus flow for each service has been modelled. Benefits to buses on Highfield Lane (NW) at cross junction, and at T-junction on Glen Eyre Road (NW) are presented.

Tables 7.34 to 7.37 below illustrate that with the increase of priority minimum time benefits to buses increase with recalls during conflicting priority. The reasons are explained above in Section 7.5.4.2. The reasons for higher disbenefits at cross junction with pedestrian crossings have been described in the Section 7.5.1. With the increase of priority minimum time disbenefits to general traffic increase because of longer holding of priority green at one approach has higher negative impact on other approaches.

Table 7.34: Priority minimum time for conflicting priority: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing			
Priority Method: Recall; Peak Flow Increased; Conflicting Priority; Detector Distance 150m			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Minimum Time (Sec)	All Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
10	-27	4	59
20	-77	4	67
30	-113	2	90
40	-138	-2	93
50	-166	-6	97

Table 7.35: Priority minimum time for conflicting priority: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing		
Priority Method: Recall; Peak Flow Increased; Conflicting Priority; Detector Distance 100m		
	Delay Savings: (Sec/Junction/Vehicle Type)	
Priority Minimum Time (Sec)	All Arms Car (Sec)	Priority Bus (Sec)
10	-1	22
20	-3	22
30	-7	30
40	-10	33
50	-12	33

Table 7.36: Priority minimum time for conflicting priority: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing			
Priority Method: Recall; Peak Flow Increased; Conflicting Priority; Detector Distance 150m			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Minimum Time (Sec)	All Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
10	-3	5	57
20	-5	5	81
30	-9	4	111
40	-9	1	116
50	-10	-1	120

Table 7.37: Priority minimum time for conflicting priority: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing		
Priority Method: Recall; Peak Flow Increased; Conflicting Priority ; Detector Distance 100m		
	Delay Savings: (Sec/Junction/Vehicle Type)	
Priority Minimum Time (Sec)	All Arms Car (Sec)	Priority Bus (Sec)
10	-1	13
20	-1	20
30	-2	28
40	-2	29
50	-3	29

7.5.5 Effective Red Period

The performance of recall taking account of effective red period while allocating priority has been evaluated on the selected four junction types. One way bus flow on major road with 40 buses per hour have been modelled. This higher bus flow has been modelled to increase the probability of utilizing the effective red parameter. Peak hour traffic flows at major road priority approaches on junction with pedestrian crossing have been reduced to decrease the queue length on the priority approaches. On other junctions (without pedestrian crossing) peak hour traffic flows have been used. Detectors are sited at 150m distance from the stop line. Longer detector distance has been modelled to capture the impact of effective red period realistically.

Tables 7.38 to 7.41 below show the comparison of usual recall with effective recall in terms of reducing delay to general traffic and bus delay savings. As expected, the performance of both recall strategies to improve bus delay savings is the same. But ‘effective recall’ has much less negative impact on general traffic compared to traditional recall. The reasons for this outcome have been described in Section 3.3.1.

Table 7.38: Comparison of traditional recall and effective recall: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Usual Recall vs Effective Recall; Peak Flow Reduced; Detector Distance 150m				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Recall Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
Usual Recall	-337	-612	-5	17
Effective Recall	-251	-500	-5	17

Table 7.39: Comparison of traditional recall and effective recall: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Usual Recall vs Effective Recall; Peak Flow; Detector Distance 150m			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Recall Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
Usual Recall	-22	-46	12
Effective Recall	-17	-37	12

Table 7.40: Comparison of traditional recall and effective recall: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Usual Recall vs Effective Recall; Peak Flow Reduced; Detector Distance 150m				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Recall Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
Usual Recall	-16	-28	0	8
Effective Recall	-11	-21	0	8

Table 7.41: Comparison of traditional recall and effective recall: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Usual Recall vs Effective Recall; Peak Flow; Detector Distance 150m			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Recall Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
Usual Recall	-4	-8	3
Effective Recall	-2	-5	3

Table 7.42: Delay savings by effective recall compare to recall in practice

Delay Savings By Effective Recall compare to Recall in Practice				
40 Buses per hour (One Way); Major Road; Detector Distance 150m				
	Delay Savings (Percentage)			
Junction Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
Cross Junction with Pedestrian Crossing	26%	18%	0%	0%
Cross Junction without Pedestrian Crossing	22%	21%	n/a	0%
T Junction with Pedestrian Crossing	31%	25%	0%	0%
T Junction without Pedestrian Crossing	39%	35%	n/a	0%

Table 7.42 above illustrates that effective red parameter reduces high percentage of delay increase on non priority arms compare to traditional recall. But the reduction percentage varies with junction type. Because, the delay savings to non priority arms by effective recall compare to traditional recall is dependent on the duration of the red period on priority approaches and junction characteristics. It is also dependent on the travel time from the detector to stop line. Higher travel time means less delay to non priority arms because with the increase of travel time from detector to stop line, the duration of effective red period reduces. Shorter effective red period means less number of buses require recall. Again, for a fixed detection point in different junction types, effective red period increase with the increase of maximum red duration at priority approaches. A longer effective red period means that a higher number of buses will require a priority recall compared to a shorter effective red period. So, when the effective red period is longer, the reduction in the negative impact to non priority arms will be less compared to shorter effective red. That is reflected in Table 7.42 above.

7.6 Selecting Values for Parameters

It has been established in this evaluation *(Section 7.5)* that it is more beneficial to detect buses early compared to traditional practice and to consider the queue condition of the priority approaches when siting detectors. It is more beneficial to buses when the PVM value large enough to accommodate that detector to stop line travel time. So, PVM and priority minimum time parameters should consider the priority approach queue conditions. In the rest of the Chapter different priority methods have been evaluated by considering many realistic scenarios. For these evaluations the priority parameters tested in Section 7.5 have been implemented in the base models. Values of the parameters have been determined based on the parameter performance test results described in the previous Sub Sections. Parameter values have also been determined by considering junction characteristics described in Sections 7.2, 7.3 and 7.4.

Tables 7.43 and 7.44 below illustrate the priority parameters implemented in the models for the selected junction types. The basis of parameter values presented in these Tables is described below:

Detector distance (S) has been determined based on queue condition of the priority approaches and considering benefits and dis benefits of early detection. Priority extension time (PVE) has been implemented based on the methods described in the Sections 7.3 and 7.4. Priority maximum red (MaxR) is the maximum red period of the priority approach in a normal cycle (without priority). A higher value for priority maximum time (PVM) has been implemented *(from Section 7.5.2)* because of no direct disbenefit to the non priority traffic due to this higher PVM. If PVE exceeds PVM (likely for the 'always green bus' method), the value for PVM has been reset equal to PVE. Methodologies for determining priority minimum time (PVMin) for conflicting priority and non conflicting priority are different. For non conflicting bus flow, the priority minimum time (PVMin) equals the average queue clearance time (Qt) of the priority approaches.

PVmin = Qt

But, if PVE exceeds the value of Qt, the priority minimum time(PVmin) has been reset equal to PVE.

PVmin = PVE (if PVE > Qt)

For conflicting bus flow, the priority minimum time (PVMin) equals the average queue clearance time (Qt) of the priority approaches plus detector to end of queue travel time (Dt).

PVmin = Qt+ Dt

But, if PVE exceeds the sum of (Qt +Dt), the priority minimum time(PVmin) has been reset equal to PVE.

PVmin = PVE (if PVE > Qt +Dt)

Effective red period has been considered in all recall methods. Effective red period (ERed) equals the priority maximum red (MaxR) minus detector to stop line travel time (DSt).

ERed = MaxR - DSt

Table 7.43: Implemented priority parameter: Extension and recall

Priority Parameters: Extension and Recall; Peak Condition							
Junction Types	Detector Distance (m)	Priority Extension Time (Sec) (PVE)	Priority Maximum Red (Sec) (MaxR)	Priority Maximum Time (Sec) (PVM)	Priority Minimum Time (Sec)(PVmin)		Effective Red Period (Sec) (ERed)
					No Priority Conflict	Priority Conflict	
Cross Junction with Pedestrian Crossing	150	26	82	50	29	38	62
Cross Junction without Pedestrian Crossing	100	17	63	50	17	23	50
T Junction with Pedestrian Crossing	150	23	55	50	29	37	37
T Junction without Pedestrian Crossing	100	15	35	50	15	22	23
Pedestrian Crossing	100	17	25	50	n/a	n/a	n/a

Table 7.44: Implemented priority parameter: Always green bus

Priority Parameters: Always Green Bus; Peak Condition							
Junction Types	Detector Distance (m)	Priority Extension Time (Sec) (PVE)	Priority Maximum Red (Sec) (MaxR)	Priority Maximum Time (Sec) (PVM)	Priority Minimum Time (Sec)(PVMin)		Effective Red Period (Sec) (ERed)
					No Priority Conflict	Priority Conflict	
Cross Junction with Pedestrian Crossing	365	62	82	62	62	66	34
Cross Junction without Pedestrian Crossing	324	55	63	55	55	55	21
T Junction with Pedestrian Crossing	267	42	55	50	42	51	23
T Junction without Pedestrian Crossing	226	35	35	50	35	37	8
Pedestrian Crossing	217	38	25	50	38	n/a	0

7.7 Scenarios Development and Bus Priority Impact

Scenarios have been developed by implementing priority parameters described in Table 7.43 and 7.44 for ‘extension and recall’ and the ‘always green bus’ method respectively. A bus frequency of 10 buses per hour on the major road in each direction (both ways) and peak hour conditions have been modelled. If the modelled parameters, bus frequency, direction of bus flow, and traffic condition are different from above, they are described in the respective Sub Section of the scenario.

7.7.1 Performance of Extension and Recall with Detector Distance

Performance of the extension and recall priority methods together have been evaluated on different detection distances. These are 50m, 100m, 150m, 200m, and 250m from the stop line.

As expected, Tables 7.45 to 7.48 below illustrate that bus priority benefits by extension and recall together increase with the increase of detection distance for all junction types. The reasons for this expectation have been described in Chapter 3 in Section 3.2.1. With the increase of detection distance, disbenefits to non priority traffic also increases. The negative impact on non priority traffic is very high at the cross junction with pedestrian crossing. Because all arms of this junction are major arms with high traffic flows, particularly the non priority arms are running close to their saturation level without priority. Queuing traffic during red without priority fail to clear off the junction completely due to required queue clearance time much higher than maximum stage green. Bus priority to all buses is making the situation even worse particularly in the non priority arms of this junction.

Table 7.45: Performance of extension and recall with detection distance: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Extension & Recall; Peak Flow; 10 Bus per hr each direction; Both Way; Major Road				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
50	-163	-363	2	12
100	-192	-397	1	16
150	-348	-610	-2	19
200	-369	-649	-2	23
250	-383	-662	-4	27

Table 7.46: Performance of extension and recall with detection distance: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Extension & Recall; Peak Flow; 10 Bus per hr each direction; Both Way; Major Road			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
50	-5	-11	7
100	-5	-12	10
150	-7	-16	14
200	-9	-20	16
250	-10	-22	17

Table 7.47: Performance of extension and recall with detection distance: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Extension & Recall; Peak Flow; 10 Bus per hr each direction; Both Way; Major Road				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
50	-8	-16	0	6
100	-11	-19	-1	10
150	-11	-20	-1	12
200	-18	-34	-2	13
250	-20	-32	-3	13

Table 7.48: Performance of extension and recall with detection distance: T-junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Extension & Recall; Peak Flow; 10 Bus per hr each direction; Both Way; Major Road			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Detector Distance (m)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
50	-1	-3	3
100	-1	-3	6
150	-2	-4	7
200	-2	-6	8
250	-2	-6	8

7.7.2 Performance of Extension and Recall during Priority Conflict

The performance of extension and recall together have been tested considering different bus flows on conflicting priority arms of the modelled junctions types. For the cross junction three conflicting arms were considered. These are Portswood Road (major arm), Highfield Lane (major arm), St Denys Rd (major arm). For the T-Junction two conflicting arms were considered. These are Burgess Road (major arm) and Glen Eyre Rd (minor arm). On each farm bus frequencies of 5, 10, 20, 30, and 40 buses per hour have been modelled for the peak hour condition.

Tables 7.49 to 7.52 below illustrate that, when buses run through conflicting priority arms of a junction, priority to one arm has negative impact on the buses of another arms. With the increase of bus flows, conflict increases as does the negative impact on buses and general traffic. During conflicting priority, buses on the arms where delays are higher without priority (due to less green time), will get advantage considering the same flow in the conflicting arms. This is because, on those arms, the duration of the maximum red period is higher compared to the other arm, so buses on those arms will require a higher number of recalls causing a higher negative impact to other arm buses and improving benefits of their own buses. As the duration of the maximum red period is much lower at the major arm of a junction, buses require fewer recalls, causing less negative impact to minor road buses. For the same reason, buses on the minor road will get benefits causing a higher negative impact on major road buses when bus flows are same in both major and minor roads of a junction. So buses on the major road are disadvantaged overall, as reflected in the Tables below. At the same time, general traffic on the major road also get disbenefits. When buses run through the conflicting arms of a junction priority to one arm has negative impact on other arms. This is due to the increase of red or cut of green in the other arms to provide priority on their conflicting arm. Again, when buses arrive in the conflicting arms during same stage, priority to one arm restricts the allocation of priority to other arms at the same time. This has a high negative impact on restricted arms. When buses run through the conflicting arms of a junction and priority is implemented, normal signal timings will be highly disturbed particularly with the increase of bus frequency. The higher will be disturbance, the higher will be the dis benefits to general traffic.

Table 7.49: Performance of extension and recall during priority conflict: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing						
Extension & Recall with Conflict; Peak Flow; One Way Bus Flow; Detector Distance 150m						
	Delay Savings: (Sec/Junction/Vehicle Type)					
Bus Frequency (Nr)	All Arms Car (Sec)	Highfield Ln & St Denys Rd Car (Sec)	Pedestrian Crossing (Sec)	Portswood Rd Priority Bus (Sec)	Highfield Ln Priority Bus (Sec)	St Denys Rd Priority Bus (Sec)
5	3	28	-2	-30	68	62
10	-18	20	-3	-91	38	57
20	-71	34	-5	-346	34	68
30	-42	120	-6	-378	91	180
40	-83	41	-7	-350	74	43

Table 7.50: Performance of extension and recall during priority conflict: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing					
Extension & Recall with Conflict; Peak Flow; One Way Bus Flow; Detector Distance 100m					
	Delay Savings: (Sec/Junction/Vehicle Type)				
Bus Frequency (Nr)	All Arms Car (Sec)	Highfield Ln & St Denys Rd Car (Sec)	Portswood Rd Priority Bus (Sec)	Highfield Ln Priority Bus (Sec)	St Denys Rd Priority Bus (Sec)
5	-3	-1	13	15	15
10	-8	-4	1	10	14
20	-11	-3	-17	9	9
30	-19	-4	-41	12	4
40	-26	-7	-53	8	2

Table 7.51: Performance of extension and recall during priority conflict: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing					
Extension & Recall with Conflict; Peak Flow; One Way Bus Flow; Detector Distance 150m					
	Delay Savings: (Sec/Junction/Vehicle Type)				
Bus Frequency (Nr)	All Arms Car (Sec)	Minor Arms Car (Sec)	Pedestrian Crossing (Sec)	Major Arm Priority Bus (Sec)	Minor Arm Priority Bus (Sec)
5	-4	1	-1	5	32
10	-9	5	-2	-31	31
20	-30	3	-1	-97	27
30	-42	12	-2	-177	36
40	-46	13	-3	-154	31

Table 7.52: Performance of extension and recall during priority conflict: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing				
Extension & Recall with Conflict; Peak Flow; One Way Bus Flow; Detector Distance 100m				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Bus Frequency (Nr)	All Arms Car (Sec)	Minor Arms Car (Sec)	Major Arm Priority Bus (Sec)	Minor Arm Priority Bus (Sec)
5	0	1	4	26
10	0	3	1	22
20	-1	3	0	23
30	-1	6	-3	27
40	-1	6	-2	25

7.7.3 Relationship of Extension and Recall with Junction Delay

To explore the relationship of the priority performance with junction delay at priority approaches, four traffic conditions have been modelled on each of the four junction types considered. These are congestion, peak, inter peak, and off peak conditions with buses on the major road in both direction with a frequency of 10 buses per hour (each direction).

Tables 7.53 to 7.56 below illustrate that performance of the bus priority methods depends on the junction delay. The higher the delay on the priority approach without priority, the larger will be the savings to the buses due to priority. When the delay is higher at the priority approaches (usually major arms), the non priority arms delay (usually minor arms) will also be higher in the 'no priority' situation. Priority to the priority arms buses will make the non priority arms traffic condition worse. So, when junction delay is higher, signal becomes more sensitive to any changes due to priority, which increases the delay to non priority traffic.

Table 7.53: Relationship of extension and recall with junction delay: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing					
Extension and Recall vs Delay; 10 Bus per hr each way, Major Road, Both Direction					
	Delay Savings: (Sec/Junction/Vehicle Type)				
Junction Conditions	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)	Delay without Priority (Sec)
Congestion	-417	-756	-2	32	60
Peak	-348	-610	-2	19	45
InterPeak	-144	-342	-1	18	40
OffPeak	-2	-5	-2	12	29

Table 7.54: Relationship of extension and recall with junction delay: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing				
Extension and Recall vs Delay; 10 Bus per hr each way, Major Road, Both Direction				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Junction Conditions	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)	Delay without Priority (Sec)
Congestion	-138	-279	20	35
Peak	-5	-12	10	26
InterPeak	-3	-7	10	25
OffPeak	-1	-4	8	18

Table 7.55: Relationship of extension and recall with junction delay: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing					
Extension and Recall vs Delay; 10 Bus per hr each way, Major Road, Both Direction					
	Delay Savings: (Sec/Junction/Vehicle Type)				
Junction Conditions	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)	Delay without Priority (Sec)
Congestion	-36	-84	0	47	87
Peak	-11	-20	-1	12	33
InterPeak	-2	-5	-2	9	18
OffPeak	-1	-2	-2	8	16

Table 7.56: Relationship of extension and recall with junction delay: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing				
Extension and Recall vs Delay; 10 Bus per hr each way, Major Road, Both Direction				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Junction Conditions	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)	Delay without Priority (Sec)
Congestion	-18	-37	7	16
Peak	-1	-3	6	12
InterPeak	-1	-1	3	7
OffPeak	-1	-1	3	6

7.7.4 Relationship of Extension and Recall with Junction Types

The performance of the extension and recall together has been tested on different junction types. Tests have been done on the four base models by changing traffic flows and signal details suitable for each junction type. For each base model three junction types have been developed. These are Major-Major, Major-Minor, and Minor-Major junctions. Major arms mean with higher traffic flow, and minor arms mean relatively lower traffic flow on that arm. First part of the junction type name is the priority arm. For example, at Minor-Major junction type minor arm is the priority arm.

Tables 7.57 to 7.60 below illustrate that bus delay savings are higher by the priority method when buses run on the minor road because delay is higher on the minor road without priority. However, providing priority on the minor road has a higher negative impact on the major road traffic depending on how busy the major road is. Again, at Major-Minor junction, when buses run on the major road, priority benefits to buses are much lower because the 'without priority' delay is less. At the same time, disbenefits to non priority arms are also reduced because traffic flows on those arms are lower.

At a Major-Major junction, bus priority impacts depend on the junction saturation level. As all the arms are major arms, they are likely to be busy due to higher flows and the junction is then more sensitive to the signal changes due to priority. But higher benefits to buses can be achieved by implementing priority at Major –Major junction when priority arm has higher delay due to other major arms traffic demand without priority. That is reflected in Table 7.59 for the T-junction with pedestrian crossing Major-Major junction type. It is clear from Tables 7.57 to 7.60 below that achievable benefits to buses and dis benefits to general traffic are totally dependent on the types of junctions, types of priority approach, traffic flows, and signal details considering other conditions and parameters are the same. Even though, performance of bus priority on the considered scenarios of junction type are presented in the same Table of corresponding base model, they are not comparable because of the difference in signal details and traffic flows. The intention to present them in the same Table is to illustrate how priority performance varies with the change of junction characteristics within the same base model.

Table 7.57: Performance of extension and recall with junction types: Cross junction with pedestrian crossing

Cross Junction with Pedestrian Crossing				
Extension and Recall vs Junction Types; 10 Bus per hr each way; Both Direction				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Junction Types	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
Major-Major	-348	-610	-2	19
Major-Minor	-13	-28	-4	13
Minor-Major	-12	-28	-5	26

Table 7.58: Performance of extension and recall with junction types: Cross junction without pedestrian crossing

Cross Junction without Pedestrian Crossing			
Extension and Recall vs Junction Types; 10 Bus per hr each way; Both Direction			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Junction Types	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
Major-Major	-5	-12	10
Major-Minor	-2	-5	8
Minor-Major	-3	-8	14

Table 7.59: Performance of extension and recall with junction types: T junction with pedestrian crossing

T Junction with Pedestrian Crossing				
Extension and Recall vs Junction Types; 10 Bus per hr each way; Both Direction				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Junction Types	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
Major-Major	-16	-101	0	128
Major-Minor	-11	-20	-1	12
Minor-Major	-107	-185	-4	30

Table 7.60: Performance of extension and recall with junction types: T junction without pedestrian crossing

T Junction without Pedestrian Crossing			
Extension and Recall vs Junction Types; 10 Bus per hr each way; Both Direction			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Junction Types	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
Major-Major	-23	-47	12
Major-Minor	-1	-3	6
Minor-Major	-5	-11	20

7.7.5 Performance of Extension and Recall with Bus Frequency

Five bus frequencies were modelled on each junction type. These are 5, 10, 20, 30, and 40 buses per hour in each direction on the major road in the peak period.

Tables 7.61 to 7.64 below illustrate that with the increase of bus flows priority benefits to buses increase but not in a proportionate rate. This is because not all buses can be given extension due to priority maximum time constraints and only one bus can be given recall at a time. The reason for the increase of average priority benefits to buses with the increase of bus flows is that, when buses run more frequently, due to priority request from one bus, other buses arriving at the priority approach during priority stage benefit automatically. With the increase of bus frequency, the probability of arrival at the priority approach during priority stage increases. With the increase of bus frequency average green time of the priority approach also increases due to frequent priority calls. Delay will be less when average green time is longer. When buses run more frequently, providing priority to all buses was found to generate more disbenefits to general traffic compared to benefits to buses. This is because, with many priority calls, the traffic signal loses its normal staging and dis benefits to non priority arms due to frequent priority calls becomes difficult to recover. When a junction is very busy, running close to or over capacity, disbenefits can be worse due to priority calls from high frequency buses.

Table 7.61: Performance of extension and recall with bus frequency: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Extension and Recall vs Bus Frequency; Both Way Bus, Major Road, Peak Flow, Detection 150m				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Bus Frequency (Nr)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
5	-254	-457	-1	19
10	-348	-610	-2	19
20	-422	-756	-2	29
30	-478	-853	-5	35
40	-487	-856	-4	50

Table 7.62: Performance of extension and recall with bus frequency: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Extension and Recall vs Bus Frequency; Both Way Bus, Major Road, Peak Flow, Detection 100m			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Bus Frequency (Nr)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
5	-2	-5	10
10	-5	-12	10
20	-15	-32	15
30	-63	-129	16
40	-130	-265	16

Table 7.63: Performance of extension and recall with bus frequency: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Extension and Recall vs Bus Frequency; Both Way Bus, Major Road, Peak Flow, Detection 150m				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Bus Frequency (Nr)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
5	-2	-4	-1	12
10	-11	-20	-1	12
20	-27	-47	-2	13
30	-68	-119	-3	17
40	-431	-726	-6	19

Table 7.64: Performance of extension and recall with bus frequency: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Extension and Recall vs Bus Frequency; Both Way Bus, Major Road, Peak Flow, Detection 100m			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Bus Frequency (Nr)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
5	0	-1	3
10	-1	-3	6
20	-3	-6	6
30	-4	-10	7
40	-6	-14	7

7.7.6 Performance of Extension and Recall with One Way and Both Way Bus Flow

The performance of extension and recall together was also evaluated on four junction types considering one way and two way bus flows.

Tables 7.65 to 7.68 below illustrate that delay savings to buses with one way and two way bus flows are similar. But when priority is considered for both ways, delay to non priority arms increases compare to one way flow. This is, because delay savings to buses is expressed as average savings to buses and by considering priority for both way buses have very little impact on average priority benefits. The only addition benefit is when buses arrive at the priority approaches during two way flow at the same priority stage. However, when priority is considered for two way flow then the number of priority calls almost doubles compared to priority to one way buses. So the impact on non priority arms also increases considerably.

Table 7.65: Performance of extension and recall with one way and both way bus flow: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Extension and Recall vs Bus Direction, 10 Bus per Hour, Peak Flow, 150m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Bus Direction	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
One Way	-180	-345	-1	14
Both Way	-348	-610	-2	19

Table 7.66: Performance of extension and recall with one way and both way bus flow: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Extension and Recall vs Bus Direction, 10 Bus per Hour, Peak Flow, 100m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Bus Direction	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
One Way	-3	-6	10
Both Way	-5	-12	10

Table 7.67: Performance of extension and recall with one way and both way bus flow: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Extension and Recall vs Bus Direction, 10 Bus per Hour, Peak Flow, 150m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Bus Direction	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
One Way	-3	-7	0	12
Both Way	-11	-20	-1	12

Table 7.68: Performance of extension and recall with one way and both way bus flow: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Extension and Recall vs Bus Direction, 10 Bus per Hour, Peak Flow, 100m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Bus Direction	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
One Way	0	-1	5
Both Way	-1	-3	6

7.7.7 Cut & Recall

The performance of the cut and recall priority method was been evaluated on the selected four junction types.

The Tables below illustrates that cut and recall method produces less benefits to buses and more dis benefits to non priority traffics compare to extension and recall method. In this method extension is not provided to those buses which require an extension, instead of extending green at the priority approach, green has been cut at the time of detection. Minimum green at non priority approaches was provided and cycle length reduced to provide green to the detected buses early. In this method all buses who required priority are targeted for recall. A high number of recalls means higher delay to non priority traffic. As recall reduces the delay to pedestrian at pedestrian crossings, this method performed better for pedestrians. Buses have to wait for a short time to cross the stop line compared to an extension; this increases the overall delay to buses compare to the extension and recall method. The intention of this priority method is to explore whether dis benefits to non priority arms can be reduced due to shorter priority cycle length. But disbenefits actually increased due to the higher number of priority recalls. This method reduces the green time on all approaches, resulting in higher delays.

Table 7.69: Performance of cut and recall: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Cut and Recall; 10 Bus per Hour; Both Way, Major Road, Peak Flow, Detection 150m				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
Extension & Recall	-348	-610	-2	19
Cut & Recall	-355	-611	-1	11

Table 7.70: Performance of cut and recall: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Cut and Recall; 10 Bus per Hour; Both Way, Major Road, Peak Flow, Detection 100m			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
Extension & Recall	-5	-12	10
Cut & Recall	-8	-19	6

Table 7.71: Performance of cut and recall: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Cut and Recall; 10 Bus per Hour; Both Way, Major Road, Peak Flow, Detection 150m				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
Extension & Recall	-11	-20	-1	12
Cut & Recall	-23	-28	0	4

Table 7.72: Performance of cut and recall: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Cut and Recall; 10 Bus per Hour; Both Way, Major Road, Peak Flow, Detection 100m			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
Extension & Recall	-1	-3	6
Cut & Recall	-2	-4	2

7.7.8 Always Green Bus

The performance of the 'Always Green Bus' method has been evaluated on four junction types considering two way bus flows on the major road in peak hours.

The Table 7.73 below illustrates that delay savings to buses are much higher in each junction type compare to the traditional extension and recall method together (detecting closer to the stop line (70m) without considering queue length, minimum green time and inter green time constraints). This is expected, because in this method, buses are detected early compared to usual practice. The siting location of detectors are on the basis of a longer extension such that priority buses do not need to stop at the traffic signal *(details in Chapter 3, Section 3.3.4)*. In this method buses are detected early and the signal timing is adjusted such that the detected bus will always arrive at the stop line during green period. However, this method also has higher negative impacts on non priority arms compared to the traditional method because of longer duration of green holding at the priority approaches. In the Table AGB means Always Green Bus method and ER means Extension and Recall together (70m detection).

Table 7.73: Comparison of the performance of always green bus with extension and recall at 70m detection

Always Green Bus vs Extension and Recall (70m)								
10 Bus per Hour, Both Direction, Peak Flow,								
	Delay Savings: (Sec/Junction/Vehicle Type)							
	AGB	ER	AGB	ER	AGB	ER	AGB	ER
Junction Types	All Arms Car (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)	Priority Bus (Sec)
Cross Junction with Pedestrian Crossing	-374	-190	-638	-387	-23	2	30	14
Cross Junction without Pedestrian Crossing	-14	-5	-29	-12	n/a	n/a	16	8
T Junction with Pedestrian Crossing	-10	-8	-20	-16	-12	0	20	7
T Junction without Pedestrian Crossing	-2	-1	-4	-3	n/a	n/a	8	4

7.7.9 Compensation Methods

Four compensation strategies were implemented in each junction type with the extension and recall method. These are: unprotected compensation, protected compensation by need, protection by inhibit, and protection by improved inhibit. Higher bus frequency of 20 buses per hour in each direction (both way) in the major road has been modelled. Higher bus frequency has been considered to truly capture the need of compensation at non priority arms.

Tables 7.74 to 7.77 below illustrate that using compensation methods the negative impacts on non priority arms can be reduced substantially. The performance of the compensation method depends on the type of protection provided to non priority arms. As shown in the Tables below, unprotected compensation is the least effective in protecting non-priority traffic. Because, compensation is provided if no bus is detected after bus priority. Even if during unprotected compensation a bus is detected, compensation is cancelled. Providing compensation by protecting it according to the need of the non priority traffic performs better compared to other compensation strategies as shown in the Tables below. Because, after bus priority no bus will be detected until the compensation requirement is fulfilled. At the same time if there is no need for compensation, compensation will not be provided and buses will be considered for priority. Protecting compensation by usual inhibit performs modestly to reduce delay to non priority arms. Because, after bus priority for a certain period of time subsequent buses are ignored for priority while compensation is provided. So when the timer stops, buses are detected and compensation is cancelled even if requirements are not fulfilled. That's why protection by inhibit shows higher negative impact to non priority arms compare to protection by need in the busy junctions (junctions with pedestrian crossings, Tables 7.74 and 7.76). Again, protection by usual inhibit is also not effective for buses. This is because buses are ignored for a certain period of time after bus priority even if the compensation is not needed. This explains why benefits to buses are less compared to other compensation methods in less busy junctions (junctions without pedestrian crossings, Table 7.75 and 7.77). However, this usual compensation method can be improved by considering the requirement of the non priority arms. In the improved inhibit the timers terminates when there is no need for compensation to detect buses. If there is need for compensation, buses are ignored for a fixed period of time after bus priority. This improved inhibit performs much better than inhibit in practice and also close to 'protected compensation by need' compensation method.

Table 7.74: Performance of compensation methods: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Extension and Recall with Compensation; 20 Bus per Hour; Both Way; Peak Flow, 150m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Type of Compensation	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
No Compensation	-422	-756	-2	29
Unprotected Compensation	-354	-636	-7	24
Protected Compensation by Need	-307	-537	-8	19
Protection by Inhibit	-319	-548	-7	20
Protection by Improved Inhibit	-310	-539	-7	19

Table 7.75: Performance of compensation methods: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Extension and Recall with Compensation; 20 Bus per Hour; Both Way; Peak Flow, 100m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Type of Compensation	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
No Compensation	-15	-32	15
Unprotected Compensation	-10	-21	13
Protected Compensation by Need	-5	-11	10
Protection by Inhibit	-5	-10	7
Protection by Improved Inhibit	-5	-11	10

Table 7.76: Performance of compensation methods: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Extension and Recall with Compensation; 20 Bus per Hour; Both Way; Peak Flow, 150m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Type of Compensation	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
No Compensation	-27	-47	-2	13
Unprotected Compensation	-15	-27	-2	12
Protected Compensation by Need	-9	-18	-2	12
Protection by Inhibit	-11	-21	-3	13
Protection by Improved Inhibit	-9	-18	-2	12

Table 7.77: Performance of compensation methods: T-junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Extension and Recall with Compensation; 20 Bus per Hour; Both Way; Peak Flow, 100m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Type of Compensation	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
No Compensation	-3	-6	6
Unprotected Compensation	-2	-5	6
Protected Compensation by Need	-2	-4	5
Protection by Inhibit	-2	-3	4
Protection by Improved Inhibit	-2	-4	5

7.7.10 Performance of Extension and Recall while Protected Compensation on with Bus Frequency

As protected compensation has been shown to be the best compensation method *(Section 7.7.9)*, it has been considered for further testing. Five bus frequencies have been modelled on each junction type. These are 5, 10, 20, 30, and 40 buses per hour in each direction (both way).

Tables 7.78 to 7.81 below illustrate that with the increase of bus frequency extra delay to non priority arms reduces with protected compensation in operation. This is expected because higher bus frequency means more buses will ask for priority causing higher delays to non priority arms. So protecting the non priority arms during higher bus flow will not allow higher number of buses to all get priority, which will reduce the extra delay to non priority arms due to priority. Benefits to buses will also be reduced due to protected compensation compare to without compensation because fewer buses are awarded priority. When bus frequency is low (5 buses per hr), protected compensation has no impact on benefits to buses and also reduces the delay to non priority arms. This is because, after bus priority, non priority arms gain from the compensation provided and as bus frequency is low it is not likely that next bus will be detected during compensation period.

Tables 7.78 to 7.81 below also illustrate that the performance of protected compensation varies with the junction types. When the junction is busy, bus priority has higher negative impact on non priority arms, so protected compensation will save more delay to non priority arms compare to less busy junction. Table 7.78 below illustrates that even after implementation of protected compensation, delay to non priority arms is still high. This is because the non priority arms at the cross junction with pedestrian crossing are running close to the saturation level without priority and bus priority makes the situation at these arms worse. These arms are so sensitive to any signal changes that, repaying their lost time due to priority by compensation cannot actually recover their negative impact fully. Non priority arms of this junction have high delay without priority. Maximum stage green time at non priority approaches of this junction is not enough to clear the queue during red fully even without priority. So, bus priority has very high effect on the performance of these arms.

[In the Tables PC means Protected Compensation.]

Table 7.78: Performance of extension and recall while protected compensation on with bus frequency: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing								
Extension and Recall vs Bus Frequency; Both Way Bus, Major Road, Peak Flow, Detection 150m								
	Delay Savings: (Sec/Junction/Vehicle Type); PC = Protected Compensation							
	Without PC	With PC	Without PC	With PC	Without PC	With PC	Without PC	With PC
Bus Frequency (Nr)	All Arms Car (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)	Priority Bus (Sec)
5	-254	-89	-457	-136	-1	-3	19	19
10	-348	-207	-610	-340	-2	-4	19	15
20	-422	-307	-756	-537	-2	-8	29	19
30	-478	-360	-853	-609	-5	-9	35	24
40	-487	-383	-856	-624	-4	-9	50	36

Table 7.79: Performance of extension and recall while protected compensation on with bus frequency: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing						
Extension and Recall vs Bus Frequency; Both Way Bus, Major Road, Peak Flow, Detection 100m						
	Delay Savings: (Sec/Junction/Vehicle Type); PC = Protected Compensation					
	Without PC	With PC	Without PC	With PC	Without PC	With PC
Bus Frequency (Nr)	All Arms Car (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)	Priority Bus (Sec)
5	-2	-1	-5	-3	10	10
10	-5	-3	-12	-7	10	8
20	-15	-5	-32	-11	15	10
30	-63	-5	-129	-11	16	11
40	-130	-6	-265	-13	16	12

Table 7.80: Performance of extension and recall while protected compensation on with bus frequency: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing								
Extension and Recall vs Bus Frequency; Both Way Bus, Major Road, Peak Flow, Detection 150m								
	Delay Savings: (Sec/Junction/Vehicle Type); PC = Protected Compensation							
	Without PC	With PC	Without PC	With PC	Without PC	With PC	Without PC	With PC
Bus Frequency (Nr)	All Arms Car (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Pedestrian Crossing (Sec	Priority Bus (Sec)	Priority Bus (Sec)
5	-2	-1	-4	-2	-1	-2	12	12
10	-11	-6	-20	-10	-1	-2	12	9
20	-27	-9	-47	-18	-2	-2	13	12
30	-68	-12	-119	-24	-3	-4	17	15
40	-431	-19	-726	-36	-6	-6	19	15

Table 7.81: Performance of extension and recall while protected compensation on with bus frequency: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing						
Extension and Recall vs Bus Frequency; Both Way Bus, Major Road, Peak Flow, Detection 100m						
	Delay Savings: (Sec/Junction/Vehicle Type); PC = Protected Compensation					
	Without PC	With PC	Without PC	With PC	Without PC	With PC
Bus Frequency (Nr)	All Arms Car (Sec)	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)	Priority Bus (Sec)
5	0	0	-1	-1	3	3
10	-1	0	-3	-1	6	5
20	-3	-2	-6	-4	6	5
30	-4	-2	-10	-6	7	6
40	-6	-3	-14	-8	7	6

7.7.11 Performance of Always Green Bus with Protected Compensation

Performance of Always Green Bus method with protected compensation has been evaluated on four junction types considering both way bus flows.

Tables 7.82 to 7.85 below illustrate that by protected compensation negative impact on non priority arms due to always green bus method can also be reduced. But as it is a stronger bus priority method, compensation is not as effective as in extension and recall method to reduce non priority arms delay. When junction is busy, reduction by compensation is higher compare to less busy junctions as reflected in the Tables below. But when non priority arms run close to or over the capacity, the reduction of delay by compensation is less. That is reflected in the Table 7.82 below in cross junction with pedestrian crossing. Reasons for the unacceptable delay have been described in the Section 7.7.10. As expected, due to protected compensation priority benefits to buses will be reduced because buses are not detected when compensation is required and delayed by the compensation.

Table 7.82: Performance of always green bus with protected compensation: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Always Green Bus; 10 Bus per Hour; Both Way; Peak Flow; 365m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
Without Protected Compensation	-374	-638	-23	30
With Protected Compensation	-267	-460	-21	23

Table 7.83: Performance of always green bus with protected compensation: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Always Green Bus; 10 Bus per Hour; Both Way; Peak Flow; 324m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
Without Protected Compensation	-14	-29	16
With Protected Compensation	-9	-18	13

Table 7.84: Performance of always green bus with protected compensation: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Always Green Bus; 10 Bus per Hour; Both Way; Peak Flow; 267m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
Without Protected Compensation	-10	-20	-12	20
With Protected Compensation	-4	-11	-12	17

Table 7.85: Performance of always green bus with protected compensation: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Always Green Bus; 10 Bus per Hour; Both Way; Peak Flow; 226m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Type	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
Without Protected Compensation	-2	-4	8
With Protected Compensation	-1	-2	7

7.7.12 Differential Priority

Differential bus priority has been implemented on each junction type. Differential bus priority strategies have been considered to explore whether these can supplement other bus priority strategies particularly stronger methods by reducing disbenefits to non-priority traffic. Priority has been provided considering four lateness condition. Lateness has been defined by comparing actual headway with the scheduled headway. In condition 1 all buses have been provided priority. In condition 2 only buses with a headway of 2 minutes or more above the scheduled headway have been considered for priority. In condition 3 only buses with a headway of 4 minutes or more above the scheduled headway have been considered for priority. In condition 4 only buses with a headway of 5 minutes or more above the scheduled headway have been considered for priority. The buses have been delayed based on observed *(Chapter 5, Section 5.5.8)* distribution. For implementation simplicity only one directional bus service has been modelled.

7.7.12.1 Priority to Late Buses: Extension and Recall

Differential bus priority has been implemented with green extensions and recalls.

Tables 7.86 to 7.89 below illustrate that by providing priority according to the lateness of buses substantially reduces disbenefits to non priority arms. The higher the threshold of the lateness to be eligible for priority the lower is the negative impact on non priority traffic. Table 7.86 below also illustrates that differential priority is more beneficial when implemented in the busy junctions (cross junction with pedestrian crossing). Average delay savings to buses also decreases with the increase of lateness threshold of differential priority, because less buses are given priority. Only buses which are late more than or equals to the defined lateness threshold will be benefitted. Table 7.89 below also illustrates that, for a less busy junction differential priority may not be needed because without differential priority impacts on non priority arms are not high.

Differential priority improves bus regularity and reduces passengers waiting time at the bus stops. These benefits are not quantified here because they are beyond this research scope. The intention to implement basic differential priority in the modelled junction types is to explore whether higher disbenefits can be minimised by targeting 'late' buses only for priority, particularly in the busy junctions. (Note that here, and following, 'late' buses refer to those buses with a higher than scheduled headway). At the same time, targeting late buses only for priority is arguably a smarter strategy because priority is provided according to need. If priority is provided to on time or early buses, buses will arrive at the bus stops earlier than expected and to match the scheduled departure time, bus drivers will often wait at one or more bus stops. That means the priority provided to early or on time buses will be wasted at the bus stops, whilst still causing unnecessary delay to non-priority traffic. Also delaying buses at bus stops causes additional delay to on board passengers.

Table 7.86: Performance of extension and recall considering differential priority: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow; 150m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Condition	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
All Bus	-180	-345	-1	14
=> 2mins Late	-34	-54	-1	8
=> 4mins Late	-8	-15	0	2
=> 5mins Late	0	-1	0	1

Table 7.87: Performance of extension and recall considering differential priority: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow; 100m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Condition	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
All Bus	-3	-6	10
=> 2mins Late	-1	-1	1
=> 4mins Late	0	0	0
=> 5mins Late	0	0	0

Table 7.88: Performance of extension and recall considering differential priority: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow; 150m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Condition	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
All Bus	-3	-7	0	12
=> 2mins Late	-2	-5	0	5
=> 4mins Late	0	0	0	3
=> 5mins Late	0	0	0	1

Table 7.89: Performance of extension and recall considering differential priority: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow; 100m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Condition	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
All Bus	0	-1	5
=> 2mins Late	0	-1	1
=> 4mins Late	0	0	0
=> 5mins Late	0	0	0

7.7.12.2 Priority to Late Buses: Always Green Bus

Differential bus priority has been implemented with the ‘always green bus’ method.

Tables 7.90 to 7.93 below illustrate that by providing priority according to the lateness of buses substantially reduces disbenefits to non priority arms. The higher the threshold of the lateness to be eligible to get priority the lower is the negative impact on non priority traffic. Table 7.90 below also illustrates that differential priority is more beneficial when implemented in the busy junctions (cross junction with pedestrian crossing). Average priority benefits to buses also decrease with the increase of lateness threshold of differential priority. The reasons are described in the Section 7.7.12.1. Table 7.93 below also illustrates that, for a less busy junction differential priority may not be needed because without differential priority impact on non priority arms are not high. The intention for implementing differential priority with the ‘Always Green Bus’ method is to explore whether higher disbenefits due to this stronger method can be minimised by targeting buses based on their lateness, particularly in the busy junctions.

Table 7.90: Performance of always green bus considering differential priority: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing				
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 365m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Condition	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
All Bus	-223	-380	-10	29
=> 2mins Late	-6	-17	-5	8
=> 4mins Late	-2	-10	-2	5
=> 5mins Late	0	0	0	1

Table 7.91: Performance of always green bus considering differential priority: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing			
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 324m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Condition	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
All Bus	-5	-10	18
=> 2mins Late	-3	-5	3
=> 4mins Late	-1	-1	1
=> 5mins Late	0	0	0

Table 7.92: Performance of always green bus considering differential priority: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing				
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 267m Detection				
	Delay Savings: (Sec/Junction/Vehicle Type)			
Priority Condition	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Pedestrian Crossing (Sec)	Priority Bus (Sec)
All Bus	-3	-8	-6	20
=> 2mins Late	-1	-3	-4	9
=> 4mins Late	0	0	-1	4
=> 5mins Late	0	-1	0	2

Table 7.93: Performance of always green bus considering differential priority: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing			
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 226m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Condition	All Arms Car (Sec)	Non Priority Arms Car (Sec)	Priority Bus (Sec)
All Bus	-2	-3	8
=> 2mins Late	0	-1	2
=> 4mins Late	0	0	1
=> 5mins Late	0	0	0

7.7.13 Pedestrian Crossing

Implementation of bus priority at a signal controlled pedestrian crossing required careful consideration of the potential delay increase to pedestrians and potential safety effects for pedestrians. Bus priority is rarely provided at pedestrian crossings due to the limited benefits available, but where it is provided this is by providing priority extensions only to buses. In this Section other bus priority methods are explored to see if they can offer minimum impact on pedestrian but higher benefits to buses.

7.7.13.1 Extension and Always Green Bus Methods at Pedestrian Crossing

Extension and 'Always Green Bus' priority methods have been implemented on the pedestrian crossing base model. Table 7.94 illustrates that, as expected, this strategy saves more delay to buses compared to extension only, but it also has a higher negative impact on pedestrians. The reasons for the higher benefits and dis benefits have been described in Section 7.7.8.

Table 7.94: Performance of extension and always green bus method at pedestrian crossing

Junction Type: Pedestrian Crossing			
10 Bus per Hour; Both Way; Peak Flow; Detection: Extension 100m, Always Green Bus 217m			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Type	All Arms Car (Sec)	Non Priority Arms Pedestrian (Sec)	Priority Bus (Sec)
Extension	0	0	2
Always Green Bus	1	-3	6

7.7.13.2 Priority to Late Buses: Always Green Bus at Pedestrian Crossing

Table 7.95 below shows that the negative impact to pedestrians can be reduced or avoided at pedestrian crossing by providing priority to late buses only. Average overall delay savings to buses also reduce, whilst benefits to the targeted buses (late buses only) remain the same. Table 7.95 below illustrates that by providing priority to buses which are 2 minutes or more late has no negative impact on pedestrians. The reasons for the improved performance have been described in the previous Section 7.7.12.

Table 7.95: Performance of always green bus considering differential priority at pedestrian crossing

Junction Type: Pedestrian Crossing			
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 217m Detection			
	Delay Savings: (Sec/Junction/Vehicle Type)		
Priority Condition	All Arms Car (Sec)	Non Priority Arms Pedestrian (Sec)	Priority Bus (Sec)
All Bus	0	-1	5
=> 2mins Late	0	0	1
=> 4mins Late	0	0	0
=> 5mins Late	0	0	0

7.7.14 Exit Detector

Exit detectors have been implemented in the models to explore whether these can be used to supplement bus priority methods by reducing dis benefits particularly at busy junctions where bus priority negative impact is high and also at pedestrian crossings. Two types of exit detectors have been modelled just after the stop line to control priority after it has been granted. These are:

Weak Exit Detection: This cancels priority when a priority bus is detected at the exit detector if this occurs before the priority would normally end. It is weak in terms of priority benefit because, if a bus travel time is longer than the priority time then priority will be cancelled by the signal controller before detection. It is likely to happen for slower buses or during congestion periods.

Strong Exit Detection: This holds priority until a priority bus is detected up to a maximum holding period. It is strong in terms of priority benefits because, it makes sure all buses cross the stop line before cancelling priority except in extreme cases when the holding period is exceeded. For implementation simplicity, maximum holding period has been modelled as maximum priority extension time and priority minimum time.

7.7.14.1 Exit Detector: Extension and Recall

The performance of exit detection under conventional priority operations (green extension and recall) has been evaluated on four junction types considering one way bus flows.

Tables 7.96 to 7.99 below illustrate that stronger exit detection provides more benefits to buses compared to weak exit detection, as expected. This is because of higher priority extension time and higher priority minimum time compare to weak exit detections. The Tables also illustrate that exit detectors reduce negative impact on non-priority arms. The overall impact on non priority traffic on all arms also reduced in all junctions except the T junction with pedestrian crossing, where priority arms' traffic flows are very high compared to non priority arms and, due to the cancellation of priority by the exit detection on the priority arm more general traffic lost extra green time. Priority benefits to buses with or without exit detection is same. Because, the number of buses getting priority with or without exit detectors remain same. Because, it does not control the eligibility to get priority. But buses are likely to have higher benefits with strong exit detection because green is held until they exit when otherwise priority might be curtailed before the bus crosses the stop line particularly when it is difficult to predict the bus arrival time at stop line due to network uncertainty. Network uncertainty has not been modelled in this research. Exit detectors reduce delays to non priority arms. Because, it does not allow unnecessary holding of green at the priority approaches.

The Table 7.100 below illustrates the reduction of negative impact to non priority arms by exit detectors when priority is provided by extension and recall method. It shows that performance of exit detectors varies with junction types. With the increase of junction saturation level performance of exit detector also increases. Because, the higher the saturation level of a junction, particularly non priority arms, the more sensitive they are to green losses due to priority. Exit detectors effectively control unnecessary green losses. The Table also shows that exit detectors can successfully control the allocation of unnecessary priority green.

Table 7.96: Performance of extension and recall considering exit detector: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing								
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow; 150m Detection								
	Delay Savings: (Sec/Junction/Vehicle Type)							
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Car (Sec)		Pedestrian Crossing (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	-180	-75	-345	-172	-1	0	14	14
Strong Exit Detection	-286	-84	-499	-185	-2	-1	22	22

Table 7.97: Performance of extension and recall considering exit detector: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing						
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow; 100m Detection						
	Delay Savings: (Sec/Junction/Vehicle Type)					
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Car (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	-3	-1	-6	-2	10	10
Strong Exit Detection	-6	-1	-13	-2	13	13

Table 7.98: Performance of extension and recall considering exit detector: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing								
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow; 150m Detection								
	Delay Savings: (Sec/Junction/Vehicle Type)							
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Car (Sec)		Pedestrian Crossing (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	-3	-4	-7	-2	0	0	12	12
Strong Exit Detection	-10	-11	-19	-9	-2	-1	14	14

Table 7.99: Performance of extension and recall considering exit detector: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing						
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow; 100m Detection						
	Delay Savings: (Sec/Junction/Vehicle Type)					
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Car (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	0	0	-1	0	5	5
Strong Exit Detection	-1	0	-2	-1	6	6

Table 7.100: Savings by exit detectors: Extension and recall

Savings by Exit Detectors				
Extension and Recall; 10 Bus per Hour; One Way; Peak Flow				
Junction Type	Non Priority Arms Delay Reduction (Sec/Junction/Vehicle Type)		Unnecessary Priority Green Reduction (Sec/Junction/Cycle)	
	Weak Exit Detector	Strong Exit Detector	Weak Exit Detector	Strong Exit Detector
Cross Junction with Pedestrian Crossing	173	314	3	6
Cross Junction without Pedestrian Crossing	4	11	1	5
T Junction with Pedestrian Crossing	5	10	1	3
T Junction without Pedestrian Crossing	1	1	1	2

7.7.14.2 Exit Detector: Always Green Bus

The performance of Always Green Bus method with exit detectors has been evaluated on four junction types considering one way bus flows.

Tables 7.101 to 7.104 below illustrate that stronger exit detection provides more benefits to buses compared to weak exit detection. The Tables also illustrates that exit detectors reduce negative impact on non-priority arms largely. The overall impact on non priority traffic on all arms also reduces in all junctions except T junction with pedestrian crossing. This is because at the T Junction with pedestrian crossings, priority arms have higher traffic flows compared to non priority arms and due to cancelling of priority more general traffic lost extra green time. Priority benefits to buses with or without exit detection is same, while exit detectors reduce delays to non priority arms significantly. All the reasons have described in the Section 7.7.14.1.

Table 7.105 below illustrates the reduction of negative impact to non priority arms by exit detectors when priority is provided by the 'Always Green Bus' method. It also shows that performance of exit detectors varies with junction type. With the increase of junction degree of saturation, the performance of exit detection also increases. The reasons have described in the Section 7.7.14.1. The Table also shows that exit detectors can successfully control the allocation of unnecessary priority green.

Table 7.101: Performance of always green bus considering exit detector: Cross junction with pedestrian crossing

Junction Type: Cross Junction with Pedestrian Crossing								
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 365m Detection								
	Delay Savings: (Sec/Junction/Vehicle Type)							
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Car (Sec)		Pedestrian Crossing (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	-223	-39	-380	-79	-10	-8	29	29
Strong Exit Detection	-312	-45	-531	-92	-16	-9	33	33

Table 7.102: Performance of always green bus considering exit detector: Cross junction without pedestrian crossing

Junction Type: Cross Junction without Pedestrian Crossing						
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 324m Detection						
	Delay Savings: (Sec/Junction/Vehicle Type)					
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Car (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	-5	-2	-10	-6	18	18
Strong Exit Detection	-7	-2	-12	-6	20	20

Table 7.103: Performance of always green bus considering exit detector: T junction with pedestrian crossing

Junction Type: T Junction with Pedestrian Crossing								
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 267m Detection								
	Delay Savings: (Sec/Junction/Vehicle Type)							
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Car (Sec)		Pedestrian Crossing (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	-3	-4	-8	-4	-6	-4	20	20
Strong Exit Detection	-5	-6	-12	-5	-7	-5	25	25

Table 7.104: Performance of always green bus considering exit detector: T junction without pedestrian crossing

Junction Type: T Junction without Pedestrian Crossing						
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 226m Detection						
	Delay Savings: (Sec/Junction/Vehicle Type)					
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Car (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	-2	-2	-3	-1	8	8
Strong Exit Detection	-3	-3	-5	-2	10	10

Table 7.105: Savings by exit detectors: Always green bus

Savings by Exit Detectors				
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow				
Junction Type	Non Priority Arms Delay Reduction (Sec/Junction/Vehicle Type)		Unnecessary Priority Green Reduction (Sec/Junction/Cycle)	
	Weak Exit Detector	Strong Exit Detector	Weak Exit Detector	Strong Exit Detector
Cross Junction with Pedestrian Crossing	301	439	3	8
Cross Junction without Pedestrian Crossing	4	6	2	7
T Junction with Pedestrian Crossing	4	7	2	6
T Junction without Pedestrian Crossing	2	3	1	4

7.7.14.3 Exit Detector: Pedestrian Crossing

Extension and 'Always Green Bus' priority methods have been evaluated with exit detectors on a pedestrian crossing. For implementation simplicity only one directional bus service has been modelled. This test has been considered to explore whether bus priorities at pedestrian crossings can be supplemented by exit detectors to minimise pedestrian delay.

Tables 7.106 and 7.107 below illustrate that at the pedestrian crossing exit detectors can minimise pedestrian delay considering a bus frequency of 10 buses per hour. So exit detectors can supplement bus priority strategies to increase pedestrian safety by minimising delay. But the outcome may vary with the increase of pedestrian and bus frequency. Again, with and without exit detectors benefits to buses remain unchanged. Benefits to buses increases with stronger exit detection method compare to weak exit detection. The reasons have described in the Section 7.7.14.1.

Table 7.108 below illustrates the reduction of negative impact to pedestrians by exit detectors when priority is provided by Extension and Always Green Bus method respectively. It shows that delay savings to pedestrians at pedestrian crossing are less by exit detectors as there were less delay without it. The Table also shows that exit detectors can successfully control the allocation of unnecessary priority green.

Table 7.106: Performance of extension considering exit detector: Pedestrian crossing

Junction Type: Pedestrian Crossing						
Extension; 10 Bus per Hour; One Way; Peak Flow; 100m Detection						
	Delay Savings: (Sec/Junction/Vehicle Type)					
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Pedestrian (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	0	0	0	0	1	1
Strong Exit Detection	0	0	-1	0	2	2

Table 7.107: Performance of always green bus considering exit detector: Pedestrian crossing

Junction Type: Pedestrian Crossing						
Always Green Bus; 10 Bus per Hour; One Way; Peak Flow; 217m Detection						
	Delay Savings: (Sec/Junction/Vehicle Type)					
Priority Cancel Condition	All Arms Car (Sec)		Non Priority Arms Pedestrian (Sec)		Priority Bus (Sec)	
	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector	Without Exit Detector	With Exit Detector
Weak Exit Detection	0	0	-1	0	5	5
Strong Exit Detection	1	0	-2	0	6	6

Table 7.108: Savings by exit detectors: Pedestrian crossing

Savings by Exit Detectors: Pedestrian Crossing				
10 Bus per Hour; One Way; Peak Flow				
Priority Type	Pedestrian Delay Reduction (Sec/Junction/Pedestrian)		Unnecessary Priority Green Reduction (Sec/Junction/Cycle)	
	Weak Exit Detector	Strong Exit Detector	Weak Exit Detector	Strong Exit Detector
Extension	0	1	0	1
Always Green Bus	1	2	2	4

7.8 Chapter summary

The conclusions of this Chapter can be categorised as follows:

7.8.1 Priority Parameters

Delay savings to buses could be increased by detecting buses early *(Section 7.5.1)*. But early detection could increase the delay to non priority arms traffic.

Higher PVM values have no or less direct negative impact on non priority traffic depending on bus frequency and junction characteristics *(Section 7.5.2)*. But higher PVM values allow to site detectors further upstream compare to traditional practice and thus increase performance of extension indirectly.

Recall performs best when detectors are sited at the end of average queue lengths of the priority arms *(Section 7.5.3)*.

Junction queue clearance time and detector to stop line bus travel time influence priority minimum time parameter. This consideration increases the performance of recall *(Section 7.5.4)*. Higher priority minimum time could also increase the delay on other arms.

Enhanced priority parameter ‘effective red period’ for recall reduces negative impact on non priority arms significantly *(Section 7.5.5)*.

New parameter for compensation ‘need of the non priority arms traffic’ protects the non priority arms when required from excessive bus priority delay and also effective for buses *(Section 7.7.9)*.

7.8.2 Priority Strategies

Performance of bus priority strategies varies with junction characteristics, junction types, signal characteristics, junction saturation level, time of the day, and many other factors *(Table 7.109)*. Priority impacts in a particular junction may vary significantly from the overall priority impacts on a network consisting many junctions. The Table below illustrates that delay to buses could be reduced significantly by implementation of bus priority. However, it could cause unacceptable delay to non priority traffic *(Table 7.109)* in some scenarios. When non priority arms run close to or over the capacity, bus priority could do more harms than benefits.

Table 7.109: Summary of bus priority impact (Junction delay savings)

Delay Savings: (Sec/Junction/Vehicle Type)													
	PB	ND	AD	PB	ND	AD		PB	ND	AD	PB	ND	AD
	Ex&Re_N			AGB_N				Ex&Re_BF			Ex&Re_S		
CJ_P	17	-478	-264	30	-509	-299	Min	19	-457	-254	12	-5	-2
							Max	50	-856	-487	32	-756	-417
CJ_WP	10	-9	-4	17	-20	-10	Min	10	-5	-2	8	-4	-1
							Max	16	-265	-130	20	-279	-138
TJ_P	12	-14	-7	20	-14	-7	Min	12	-4	-2	8	-2	-1
							Max	19	-726	-431	128	-185	-107
TJ_WP	6	-2	-1	8	-4	-2	Min	3	-1	0	3	-1	0
							Max	7	-14	-6	20	-47	-23

[PB = Priority Bus Delay Savings, ND = Non Priority Arms Traffic Delay Savings, AD = Overall All Arms Non Priority Traffic Delay Savings

CJ_P = Cross Junction with Pedestrian Crossing, CJ_WP = Cross Junction without Pedestrian Crossing

TJ_P = T Junction with Pedestrian Crossing, TJ_WP = T Junction without Pedestrian Crossing

Ped = Pedestrian Crossing

Ex&Re_N = Extension & Recall; Peak Flow; 10 Buses per hr each direction; Major Road

AGB_N = Always Green Bus ; Peak Flow; 10 Buses per hr each direction; Major Road

Ex&Re_BF = Extension & Recall; Peak Flow; 5 -40 Buses per hr each direction; Major Road

Ex&Re_S = Extension & Recall; 10 Buses per hr each direction; All Scenarios

+ = Delay Savings, - = Delay Increase: Delay Savings/Increase Compare to No Bus Priority]

Overall person delay savings by bus priority could be less. In the busy junctions particularly where non priority arms are busy and in junctions with pedestrian crossings where pedestrian activity is high, bus priority could increase overall delay per person *(Table 7.110)*.

Table 7.110: Summary of bus priority impact (Person delay savings)

Average Person Delay Savings (Sec/Junction/Person)					
	Ex&Re_N	AGB_N		Ex&Re_BF	Ex&Re_S
CJ_P	-160.49	-183.00	Min	-153.76	0.63
			Max	-293.10	-252.99
CJ_WP	-0.94	-4.10	Min	0.62	0.97
			Max	-98.08	-103.46
TJ_P	-2.82	-2.17	Min	0.72	0.78
			Max	-302.31	-52.32
TJ_WP	0.46	0.08	Min	0.63	0.63
			Max	-3.29	-14.03
Ped	0.51	1.93	-	-	-

+ = Delay Savings, - = Delay Increase: Delay Savings/Increase Compare to No Bus Priority

Interpretation and calculation method of Table 7.110 has been presented in Appendix B.

Delay savings to buses increase with the increase of detection distance for extension and recall together *(Section 7.7.1)*. But with the increase of detection distance, delay to non priority arms traffic also increases.

Benefits to buses due to priority is higher in a junction where delay is higher without priority (normal signal setting). But when junction delay is higher during normal conditions, priority increases delay to non priority traffic significantly *(Section 7.7.3)*.

Bus priority performance is largely dependent on the type of junction and type of priority approach *(Section 7.7.4)*. When priority is implemented in the minor arm of a junction whose other arms are major, priority benefits to buses and dis benefits to general traffic are higher. Junctions where all the arms are major, could also delay general traffic significantly due to bus priority. But dis benefits due to priority is much lower when priority is provided in the busy major arm of a junction where other arms are minor.

Average delay savings to buses increase with the increase of bus flows. But delay to non priority traffic also increases *(Section 7.7.5)*.

Average priority benefits is slightly higher when priority is considered for both direction of a bus route compare to one directional bus route considering same bus flows in each direction. But dis benefits could be double in two directional priority compare to one directional priority *(Section 7.7.6)*.

When buses run through conflicting arms of a junction, particularly when the conflicting arms bus frequencies are high, priority to one arm could delay the buses on other conflicting arms *(Section 7.7.2)*. Implementation of bus priority in all the conflicting arms having high frequency bus flows, could cause significant delay to buses and general traffic. But when bus frequency is low, additional negative impact due to conflicts is not high.

New priority method (cut and recall) which involves cutting green at the priority approach instead of extending green to target all buses for recall reduces priority benefits to buses compare to traditional methods and also increase delay to general traffics *(Section 7.7.7).*

Always green bus method performs much better to reduce delay to buses compare to traditional methods. However, this method could increase delay to non priority arms traffic compare to traditional methods *(Section 7.7.8).* So , bus detection strategy considering queue length, minimum green time, inter green time, and average bus travel time from detection point to end of the queue to adjust signal timing for priority buses to allow them to cross the junction without stopping performs much better than traditional detection.

Compensation methods reduce the negative impact due to bus priority on non priority arms traffic substantially *(Table 7.111).* Due to compensation delay savings to buses also could be reduced. Again, performance of compensation method depends on the type of strategies considered *(Section 7.7.9).*

Table 7.111: Performance summary of compensation strategies

Delay Savings: (Sec/Junction/Vehicle Type)									
	PB	ND	PB	ND		PB	ND	PB	ND
	Ex&Re_N_PC		AGB_N_PC			Ex&Re_BF_PC		Ex&Re_CT	
CJ_P	-4	270	-7	178	Min	0	219	-5	120
					Max	-14	321	-10	219
CJ_WP	-2	5	-3	11	Min	0	2	-2	11
					Max	-5	252	-8	22
TJ_P	-3	10	-3	9	Min	0	2	0	20
					Max	-4	690	-1	29
TJ_WP	-1	2	-1	2	Min	0	0	0	1
					Max	-1	6	-2	3

[Ex&Re_N_PC = Extension & Recall with Protected Compensation (by need); Peak Flow; 10 Buses per hr each direction; Major Road

AGB_N_PC = Always Green Bus with Protected Compensation (by need) ; Peak Flow; 10 Buses per hr each direction; Major Road

Ex&Re_BF_PC = Extension & Recall with Protected Compensation (by need); Peak Flow; 5 -40 Buses per hr each direction; Major Road

Ex&Re_CT = Extension & Recall with Compensation; Peak Flow; 20 Buses per hr each direction; Major Road; All Compensation Type

+ = Delay Savings, - = Delay Increase: Delay Savings/Increase Compare to Bus Priority with No Compensation]

Unprotected compensation method reduces less delay compare to protected compensations and not suitable where bus frequency is high. Again, traditional inhibit method could be ineffective for priority buses as well as for non priority arms traffics. It could reduce less delay to non priority traffic and also could increase bus delay compare to advanced strategies. Proposed advanced inhibit method performs much better compare to inhibit in practice due to the consideration of the non priority arms compensation requirements. But proposed and advanced 'protection by need' compensation method is the best compensation strategy for delay savings at non priority arms and also beneficial for priority buses. Again, performance of protected compensation increases with the increase of bus flows and junction saturation level *(Section 7.7.10)*. But when bus frequency is low protected compensation strategies are not required, unprotected compensation serves the purpose.

Protected compensation reduces delay to non priority arms when implemented with 'always green bus' method *(Section 7.7.11)*. However, performance of 'always green bus' is likely to be reduced.

Targeting late buses only for priority substantially reduces dis benefits to non priority arms due to priority *(Table 7.112 and Section 7.7.12)*. Higher dis benefits due to stronger bus priority method 'always green bus' also could be reduced substantially by targeting late buses only for priority, particularly in the busy junction with high bus flows.

Table 7.112: Performance summary of priority to late buses and exit detection strategies

	Non Priority Arms Traffic Delay Savings: (Sec/Junction/Vehicle Type)			
	Ex&Re_N_L	AGB_N_L	Ex&Re_N_E	AGB_N_E
CJ_P	291	363	244	370
CJ_WP	5	5	8	5
TJ_P	2	5	8	6
TJ_WP	0	2	1	3

[Ex&Re_N_L = Extension & Recall for Late Bus Only (=> 2mins Late); Peak Flow; 10 Buses per hr; Major Road

AGB_N_L = Always Green for Late Bus Only (=> 2mins Late) ; Peak Flow; 10 Buses per hr; Major Road

Ex&Re_N_E = Extension & Recall with Exit Detection; Peak Flow; 10 Buses per hr; Major Road

AGB_N_E = Always Green Bus with Exit Detection ; Peak Flow; 10 Buses per hr; Major Road

+ = Delay Savings, - = Delay Increase: Delay Savings/Increase Compare to Bus Priority for All Buses without Exit Detector]

Exit detectors effectively control unnecessary holding of green at the priority approaches due to priority. Cancelling priority at right time by exit detectors are beneficial for buses and non priority arms traffic both. But traffic at non priority arms get the most benefits due to significant delay reduction *(Table 7.112)*. Again, performance of exit detectors depend on the strength of the cancel strategy implemented, junction and network characteristics, and time of the day. With the increase of junction saturation level, particularly in non priority arms, performance of exit detectors increase *(Section 7.7.14)*.

At pedestrian crossings continuous bus priority may not be required because delay to buses due to pedestrian crossing is generally less. Again, delay savings to buses by extension at the crossings is also very less with minimum delay increase to pedestrian. Priority by 'always green bus' method saves much higher delay to buses compare to the method used in practice (extension). But due to the increase of pedestrian delay and considering safety aspects, stronger priority methods may not be acceptable when all buses are targeted. By providing priority to late buses only and/ or by implementing exit detectors average delay to the pedestrian could be minimised *(Table 7.113 and Section 7.7.13)*.

Table 7.113: Summary of bus priority impact at pedestrian crossings

Pedestrian Crossing					
Delay Savings: (Sec/Crossing/Vehicle Type)					
	PB	ND	AD	ND	ND
	All Bus			Late Bus (=> 2mins Late)	Exit Detector
Ex_N	2	0	0	0	0
AGB_N	6	-2	1	0	0

[PB = Priority Bus Delay Savings, ND = Pedestrian Delay Savings, AD = Overall All Non Priority Traffic Delay Savings

Ex_N = Extension; Peak Flow; 10 Buses per hr each direction

AGB_N = Always Green Bus ; Peak Flow; 10 Buses per hr each direction

+ = Delay Savings, - = Delay Increase: Delay Savings/Increase Compare to No Bus Priority]

Chapter 8: Discussion

8.1 Limitations

8.1.1 Site conditions

It is inevitable that a study such as this, involving real world traffic scenarios, will have some limitations. The plan in the research was to focus on 'normal'/typical junction layouts and traffic situations, where results and trends are least likely to be affected by site-specific peculiarities or abnormal conditions. This has meant that some site conditions have not been addressed. These include:

- *Exit blocking.* This is evident when/if the normal rate of traffic discharge across the stop line is reduced because of congestion (or exit blocking) downstream. There can be a range of reasons for this undesirable situation, but, if it occurs, it should be taken account of in the bus priority strategy. There may be a variety of ways of doing this, but there derivation and testing has been considered to be beyond the scope of this study. Results in this study therefore only apply to non-exit blocked situations.

- *Bus stops close to the stop-line.* If a bus stop is located between the bus detector and the stop line variable bus stop dwell time can make the bus journey too unpredictable to enable efficient bus priority to be achieved. The assumption in this research has been that, should this occur, the bus stop could be moved either upstream of the bus detector or downstream on to the junction exit.

- *Short links.* It has been assumed in this research that the road link is always longer than the bus detection distance and/or any traffic queuing caused by bus priority operations. Results therefore do not apply where short links occur and these assumptions are broken.

- *Traffic incidents.* Traffic incidents such as accidents, roadworks, vehicle breakdowns, etc can cause abnormal traffic conditions which may well affect the efficiency of operational bus priority strategies. It has been considered beyond the scope of this research to develop bus priority strategies specifically for these unusual events.

8.1.2 Modelling Limitations

The analytical modelling developed here has been a step forward over existing methods, but even so a range of simplifying assumptions have been required to make it workable. These include assumed constancy in traffic flows, bus flows, saturation flows, journey times and conditions where capacity exceeds demand (i.e. no congestion). These simplifications are useful when comparing alternative strategies, but can tend to result in an overestimation of actual benefits.

The VISSIM microscopic simulation model as used also contains some modelling limitations in this context. These include:

- The assumption of a single bus route travelling through the junctions. This assumption was made for simplicity. In reality, a number of bus services run through the junctions, with differences in some characteristics.
- The assumption that buses are correctly located and that there is no error in the location calculation. In reality, there is likely to be some locational error due to (for example) variations in GPS detection accuracy. Whilst this could be represented to some extent in VISSIM, there is evident that the effect of this on bus priority benefits is modest at most.
- Assumptions about bus driver behaviour – particularly concerning their desired speed which, in VISSIM is determined by sampling from a normal distribution of speeds to represent typical variability. In practice, the latest in-cab driver support systems will inform the driver of his/her 'performance' in real-time, for example relating to whether or not the bus is on schedule or has a good spacing with other buses in front or behind. This information could, in practice, encourage the bus driver to speed up or slow down in a non-random fashion. At this time, the occurrence of this speed re-adjustment and its extent is not well known/understood, so it could not be incorporated in to the modelling.
- Assumptions about junctions suitable for detector siting at any distance. It is not always possible to detect buses early or to implement stronger bus priority methods due to many practical issues. These constraints include: when the link length of a

priority approach is shorter than desired detection distance or when there is a bus stops and or a pedestrian crossing within the desired detection distance or in a junction where network uncertainty is high due to pedestrian movements, parking and loading activities. Junctions having those characteristics were observed at the cross junction with pedestrian crossing at the site in Portswood. Providing priority by detecting buses up stream of these features requires journey time uncertainty to be considered (not modelled in such details), meaning longer green time at the priority approaches causing unacceptable delays for other approaches of the junction and also could cause exit blocking. But those impacts could be avoided by detecting buses down stream of the constraints or by using a combination of detectors such as upstream and down stream of the constraints with exit detectors. Further research is required to explore the better detection methodologies considering these practical constraints in the models. But if a junction having those constrains is in need of bus priority particularly by early detection, it is much more beneficial from bus priority implementation point of view and also to avoid addition priority dis benefits, to shift those constrains down stream of the junction if possible.

8.2 Future Possibilities

It has been evident during this research that a number of opportunities are arising to potentially make the bus priority applications being considered here even more efficient. For illustration, two possibilities are discussed briefly here:

1. *Passenger counting.* With the appropriate new technology, it is possible now to obtain real-time measures for passenger counting (boarding and alighting), to obtain passenger loading figures and for numbers of passengers waiting a bus stops. In the context of bus priority, this information could be useful in influencing the priority strategy used. For example, there may be an economic case for giving higher priority to a full bus and/or to one where high volumes of passengers are waiting downstream. This is recommended as a useful avenue for possible further research.

2. *Mobile applications.* Many, if not most, passengers will now have a ‘Smart’ phone. Amongst other things, these devices may allow users to track bus movements in real-

time so that users can make better decisions about which bus to catch, where to catch it and when to arrive at the bus stop. This may affect perceived regularity and excess waiting time at stops – criteria which are used for performance monitoring. Little is known about this activity at present, so it is again proposed as an area for future research.

Chapter 9: Achievements, Conclusions and recommendations

9.1 Achievements

The main achievements of this research can be summarised as follows:

1. The development of an advanced analytical procedure for predicting the delay savings for buses through providing priority of different types at isolated signal controlled junctions. This extends previous work by TRL (Vincent et al. 1978 and Cooper 1983) and others to include different bus detection times/locations, acceleration delay, queue clearance delay, minimum green time constraints, effective red periods, ‘inhibit’ operations and priority conflicts (where bus priority is operational on more than one stage).

2. The compilation of a substantial database of traffic, bus and traffic signal operations at selected junctions in Southampton, to support model development and testing.

3. The development and application of the VISSIM microscopic simulation model to investigate existing bus priority parameters and strategies at isolated signal controlled junctions and new strategies developed during the course of this research. This involved new coding and extensive sensitivity testing.

9.2 Conclusions

The conclusions of this research can be categorised as follows:

9.2.1 Advanced Analytical Technique

The proposed advanced analytical methods for bus priority evaluation can estimate priority benefits and dis benefits more accurately compared to existing analytical methods. This is because the proposed method includes new additional parameters such as impact of bus detection time, acceleration delay, queue clearance delay, minimum green time constraints of non priority arms, effective red periods, and travel time between detector to stop line.

The proposed analytical procedures can be used to estimate the maximum achievable benefits and unavoidable minimum disbenefits of bus priority for a particular scenario. But due to various limitations, analytical techniques and presented impacts by using these techniques can be used as a rough guideline to understand priority impact. For more accurate junction and network specific evaluation, micro-simulation is more appropriate

9.2.2 Priority Parameters

Benefits to buses from green extensions can be increased by detecting buses early and implementing longer green times (PVM) where necessary.

The performance of recalls is highest when detectors are sited at the end of the average queue lengths of the priority arms as long as queue lengths are not too short.

The Priority minimum time parameter is dependent on junction queue clearance time and detector to stop line bus travel time. This consideration increases the performance of recall.

Bus detection strategy considering queue length, minimum green time, inter green time, and average bus travel time from detection point to end of the queue performs much better than traditional detection. Because it allows to adjust signal timing for priority buses before arrival at the stop line.

Implementation of effective red period parameter can reduce negative impact on non-priority arms significantly due to recall.

Compensation parameter ‘need of the non priority arms traffics’ can protect the non priority arms when required from excessive bus priority delay and also effective for buses.

9.2.3 Priority Strategies

Overall Conclusions

By implementing extension and recall alone, an average 11 sec/junction/bus delay was saved when bus frequency was 10 buses per hour during peak conditions. However, this could generate extra delay for non-priority traffic of up to 8 sec/bus/junction, suggesting that compensation facilities should be provided for this traffic.

But performance of bus priority strategies varies with junction characteristics, junction types, signal characteristics, junction saturation level, time of the day, and many other factors. Considering those factors delay savings to buses were found to vary from 3 sec/junction/bus to 128 sec/junction/bus for bus frequency of 10 buses per hour. Delay increase to non priority arms traffic were found to vary from 1 sec/junction/vehicle to 279 sec/junction/vehicle. But these very high and very low priority impacts were found from scenario specific evaluations, may not represent field situations.

Priority benefits and dis benefits in a particular junction may vary significantly from an overall priority impacts on a network consists of many junctions. Before implementation of bus priority, junction specific evaluation is recommended. Because, it was found that bus priority could cause unacceptable delay to non priority traffic. Further study is also recommended to establish the guideline of acceptable delay on non priority traffics. It is also recommended to assess the priority impact of a junction on neighbourhood junctions. Because, when all impacts are considered, bus priority could cause more harm than benefits if implemented blindly. It is also recommended not to provide bus priority, when a junction runs close to or over it’s capacity because during that condition priority could do unrecoverable disturbance of the signals. In the modelled scenario of that condition, up to 756 sec/junction/vehicle delay increase at non priority arms traffic was observed considering bus frequency of 10 buses per hour.

Detailed Conclusions

Person Delay

Overall person delay savings by bus priority could be less. In the modelled junctions 0.08 to 1.93 sec/junction/person delay was saved due to bus priority. However, in the busy junctions particularly where non priority arms were busy and in junctions with pedestrian crossings where pedestrian flows were high, bus priority increased overall delay per person.

Optimum Detection

Delay savings to buses increase with the increase of detection distance when extension and recall priority methods are implemented combined. But, delay to non priority arm's traffic also increase. So optimal detector siting place is a trade of between achievable delay savings to buses and acceptable delay increase to non priority traffics. Again, the increase of negative impact is dependent on junction and network characteristics, time of the day. So, optimal detector location is site specific and varies time of the day to minimise negative impact as much as possible.

Junction Characteristics

Benefits to buses due to priority increases in a junction with the increase of delay. However, when junction delay is higher during normal conditions, priority can increase the delay to non priority traffic significantly.

Bus priority performance is largely dependent on the type of junction and type of priority approach. When priority is implemented in the minor arm of a junction whose other arms are major, priority benefits to buses and dis benefits to general traffic are higher. Junctions where all the arms are major, can also delay general traffic significantly due to bus priority. But dis benefits due to priority are much lower when priority is provided in the busy major arm of a junction where other arms are minor.

Bus Frequency

Average delay savings to buses increase with the increase of bus flows. Delay savings were increased from 3 sec/junction/bus to 50 sec/junction/bus with the increase of bus frequency from 5 buses per hour to 40 buses per hour in each direction (both ways). However, with the increase of bus flows delay to non priority traffics also increase. When bus frequency is very high in a junction, providing priority to all buses is not recommended because it could increase unacceptable delay to non priority arms traffic. Up to 726 sec/junction/vehicle delay increase to non priority arms traffic was found in the modelled high frequency scenario considering 40 buses per hour in each direction (both ways). These very high benefits and dis benefits were scenario specific impacts, may not realistically represent field situations.

Priority Direction

Average priority benefits are slightly higher when priority is considered for both direction of a bus route compare to one directional bus route considering same bus flows in each direction. But dis benefits could be double in two directional priority compare to one directional priority.

Conflicting Priority

When buses run through conflicting arms of a junction, particularly when the conflicting arms' bus frequencies are high, priority to one arm can delay buses on the other conflicting arms. It is recommended not to implement priority in all conflicting arms having high frequency bus flows, because normal signal timing could be highly disturbed incurring significant delay to buses and general traffic. Before implementation of priority in a junction having conflicting bus flows, it is recommended to do junction specific impact evaluation considering probability of conflicts, number of conflicting arms, junction and network characteristics, and also time of the day. But when bus frequency is low, additional negative impact due to conflicts is not significant.

Always Green Bus

Always green bus method performs much better to reduce delay to buses compare to traditional methods. However, it could increase delay to non priority arms traffic compare to traditional methods. This method saved an average delay of 19 sec/junction/bus considering bus frequency of 10 buses per hour. But, average delay to non priority arms traffic were increased to 12 sec/ junction/vehicle due to it. It was found that 'always green bus' method saved 69% more delay to buses compare to traditional methods, while non priority arms traffic suffered 51% more delay increase. It is recommended to do junction specific evaluation before implementation of this stronger priority.

Compensation Types

Compensation methods reduce the negative impact on non priority arms traffic substantially. Depending on the type of compensation, 1 to 29 sec/junction/vehicle non priority arms delay were reduced compare to without compensation extension and recall strategy considering 20 buses per hour in each direction (both ways). However, delay savings to buses were also decreased up to 10 sec/junction/bus.

Unprotected compensation method reduces less delay to non priority arms traffic compare to protected compensations and not suitable where bus frequency is high. Again, traditional inhibit method could be ineffective for priority buses as well as for non priority arms traffic. It could reduce less delay to non priority arms traffic and also could increase bus delay compare to advanced strategies. Proposed improved inhibit method performs much better compare to inhibit in practice due to the consideration of the non priority arms compensation requirements. But proposed advanced new strategy ‘protection by need’ compensation method is the best compensation strategy for delay savings at non priority arms and also beneficial for priority buses. This new strategy saved delay at non priority arms up to 10 sec/junction/vehicle compare to without compensation extension and recall when 10 buses per hour run in each direction (both ways). However, delay savings to buses also decreased up to 4 sec/junction/bus.

<u>Bus Frequency and Compensation</u>

Protected compensation is recommended when bus frequency is high and junction is busy particularly non priority arms. Performance of protected compensation increases with the increase of bus flows and junction saturation level. It was found that, with the increase of bus flow from 5 to 40 buses per hour in each direction (both ways) delay at non priority arms traffic due to extension and recall were reduced from 0 to 690 sec/junction/vehicle respectively by protected compensation. However, benefits to buses by extension and recall were also reduced up to 14 sec/junction/bus. It should be noted that these higher values of delay reduction are scenario specific, may not realistically represent field situations.

<u>Always Green Bus and Compensation</u>

Protected compensation reduces delay to non priority arms when implemented with ‘always green bus’ method. But performance of ‘always green bus’ is likely to be reduced. When implemented with ‘always green bus’ strategy, protected compensation reduced delay at non priority arms up to 11 sec/junction/vehicle considering 10 buses per hour in each direction (both ways). However, delay savings to buses also reduced up to 7 sec/junction/bus. As always green bus method is a stronger priority method, it is recommended to implement protected compensation with it.

<u>Priority to Late Buses</u>

Targeting late buses only for priority reduce dis benefits to non priority arms traffic substantially. Providing priority to late buses only is recommended, because it effectively reduces priority dis benefits particularly where bus flows is high and junction is busy. Higher dis benefits due to stronger bus priority method ‘always green bus’ also reduce substantially by targeting late buses only for priority. It was found, when priority was provided to only 2 minutes or more late buses considering bus flows of 10 buses per hour, up to 5 sec/junction/vehicle delay at non priority arms was reduced compare to providing priority to all buses.

Exit Detection

Exit detectors effectively control unnecessary holding of green at the priority approaches due to priority. Exit detectors are recommended, because cancelling priority at right time by exit detectors are beneficial for buses and non priority arms traffic both. However, traffic at non priority arms get the most benefits due to significant delay reduction. By implementing exit detectors, up to 11 sec/junction/vehicle delay at non priority arms was reduced compare to priority without exit detectors considering bus frequency of 10 per hour. However, performance of exit detectors depend on the strength of the cancel strategy implemented, junction and network characteristics, and time of the day. With the increase of junction saturation level, particularly in non priority arms, performance of exit detectors increase.

Pedestrian Crossings

At pedestrian crossings bus priority is not recommended because delay to buses due to pedestrian crossing is generally less. However, delay savings to buses by extension (used in practice) at the crossings is also very less. Considering bus frequency of 10 buses per hour by extension at pedestrian crossing, only 2 sec/crossing/bus delay were saved with no average delay increase to pedestrian. But 'always green bus' method saved bus delay of 6 sec/crossing/bus while increasing pedestrian delay of 2 sec/crossing/pedestrian.

Priority by 'always green bus' method saves much higher delay to buses compare to the method used in practice (extension). But due to the increase of pedestrian delay and considering safety aspects, stronger priority methods may not be acceptable when all buses are targeted. By providing priority to late buses only and by implementing exit detectors average delay increase to the pedestrian could be avoided. By targeting 2 minutes or more late buses for stronger priority and/ or implementing exit detectors, delay increase to pedestrian were avoided considering bus frequency of 10 per hour.

9.3 Recommendations for further research

This study has illustrated fundamental findings of bus priority impacts covering a wide range of realistic scenarios. Further studies should focus on developing decision support tools for practitioners and policy makers to help in decision making considering all possible scenarios.

This research has largely taken the existing vehicle actuated control method to explore potential improvements to its bus priority facilities. With advances in technology, real-time control and V2I systems (vehicle to infrastructure), there are opportunities to explore more advanced and sophisticated bus priority strategies, taking advantage also of the ‘virtual detector’ capabilities of satellite detection.

The practical issues, limitations, and future possibilities described in the previous Chapter 8 should be considered in the models for further studies.
Due to the availability of virtual detectors, instead of siting single optimal detector for extension and recall, two detectors could be more beneficial. One is optimal for extension and other is optimal for recall.

The parameter queue length could be made dynamic by measuring queue length at the priority approach real time instead of using average queue length based on historical data.

Further studies also recommended to explore the optimal location of priority exit detectors.

In individual junction modelling, it is not possible to capture wider impact of bus priority, for example: exit blocking. Further studies should consider at least a corridor/ network having multiple junctions to understand the wider impact of bus priority. Corridor or network based study is also required to explore the performance of differential bus priority.

Enhanced priority parameters and strategies should be explored considering coordinated signals, particularly SCOOT for the UK.

Evaluation of bus priority strategies also should consider environmental impact during further studies.

Appendices

Appendix A

Table A1 - A54

Appendix B

Table B1 – B35

Appendix C

Sample VAP Code S1 – S12

Sample Output O1 – O4

Appendix A

Theoretical Methods: Parameters and Signal Details Considered

Table A1: Parameters considered in the theoretical methods for T Junction (two traffic stage, two traffic stage and one pedestrian stage)

T Junction : two traffic stage, two traffic stage and one pedestrian stage		
Detection Distance (m)	Average Speed (m/s)	Detector to Stop-line Average Bus Journey Time (t+2) (sec)
50	8.4	6
100	8.4	12
150	8.4	18
200	8.4	24
250	8.4	30

Table A2: Parameters considered in the theoretical methods for Cross Junction (three traffic stage, three traffic stage and one pedestrian stage)

Cross Junction: three traffic stage, three traffic stage and one pedestrian stage		
Detection Distance (m)	Average Speed (m/s)	Detector to Stop-line Average Bus Journey Time (t+2) (sec)
50	7.63	7
100	7.63	13
150	7.63	20
200	7.63	26
250	7.63	33

Table A3: Signal Details considered in the theoretical methods for T Junction without Pedestrian Crossing (two traffic stage)

Two Traffic Stage: T Junction without Pedestrian Crossing					
Priority Arm Green/Cycle Time	Priority Arm Green (Sec)	Non Priority Arm Green (Sec)	Inter Green 1-2 (Sec)	Inter Green 2-1 (Sec)	Cycle Time (Sec)
g1/C	g1	g2	ig12	ig21	C
0.2	17	53	8	7	85
0.3	26	45	8	7	85
0.4	34	36	8	7	85
0.5	43	28	8	7	85
0.6	50	20	8	7	85
0.7	60	11	8	7	85

Appendix A

Table A4: Signal Details considered in the theoretical methods for T Junction with Pedestrian Crossing (two traffic stage and one pedestrian stage)

Two Traffic Stage and One Pedestrian Stage: T Junction with Pedestrian Crossing							
Priority Arm Green/Cycle Time	Priority Arm Green (Sec)	Non Priority Arm Green (Sec)	Pedestrian Green (Sec)	Inter Green 1-2 (Sec)	Inter Green 2-3 (Sec)	Inter Green 3-1 (Sec)	Cycle Time (Sec)
g1/C	g1	g2	ped	ig12	ig23	ig31	C
0.1	11	60	7	8	7	13	105
0.2	21	49	7	8	7	13	105
0.3	32	39	7	8	7	13	105
0.4	42	28	7	8	7	13	105
0.5	50	20	7	8	7	13	105
0.6	63	7	7	8	7	13	105

Table A5: Signal Details considered in the theoretical methods for Cross Junction without Pedestrian Crossing (three traffic stage)

Three Traffic Stage: Cross Junction without Pedestrian Crossing							
Priority Arm Green/Cycle Time	Priority Arm Green (Sec)	Non Priority Arm1 Green (Sec)	Non Priority Arm2 Green (Sec)	Inter Green 1-2 (Sec)	Inter Green 2-3 (Sec)	Inter Green 3-1 (Sec)	Cycle Time (Sec)
g1/C	g1	g2	g3	ig12	ig23	ig31	C
0.1	10	33	33	9	7	7	98
0.2	20	28	28	9	7	7	98
0.3	29	23	23	9	7	7	98
0.4	35	20	20	9	7	7	98
0.5	49	13	13	9	7	7	98
0.6	59	8	8	9	7	7	98

Table A6: Signal Details considered in the theoretical methods for Cross Junction with Pedestrian Crossing (three traffic stage and one pedestrian stage)

Three Traffic Stage and One Pedestrian Stage: Cross Junction with Pedestrian Crossing									
Priority Arm Green/Cycle Time	Priority Arm Green (Sec)	Non Priority Arm1 Green (Sec)	Non Priority Arm2 Green (Sec)	Pedestrian Green (Sec)	Inter Green 1-2 (Sec)	Inter Green 2-3 (Sec)	Inter Green 3-4 (Sec)	Inter Green 4-1 (Sec)	Cycle Time (Sec)
g1/C	g1	g2	g3	ped	ig12	ig23	ig34	ig41	C
0.1	12	32	32	7	9	7	6	13	117
0.2	23	26	26	7	9	7	6	13	117
0.3	35	20	20	7	9	7	6	13	117
0.4	47	14	14	7	9	7	6	13	117
0.5	59	8	8	7	9	7	6	13	117

<u>Notes:</u> [g1/C= Priority Green/Cycle Time; t+2 = Detector to stop line travel time; B = Benefits to buses; NT = Dis benefits to non priority traffic; P = Dis benefits to pedestrians; + = Delay savings; - = Delay increase]

Derived benefits and dis benefits by theoretical methods: Green extension

Two Traffic Stage Junction: T-Junction without Pedestrian Crossing

Table A7: Benefits to buses and dis benefits to non priority arms by extension (100m detection distance)

T-Junction without Pedestrian Crossing, Extension, Detection 100m, g1/C = 0.6										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
12	4.38	0.14	3.92	0.26	3.18	0.41	2.63	0.51	2.21	0.58

Table A8: Benefits to buses and dis benefits to non priority arms by extension (with detection distance)

T-Junction without Pedestrian Crossing, Extension, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.2		.3		.4		.5		.6		.7	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
6	3.99	0.03	3.49	0.04	3.03	0.05	2.54	0.06	2.13	0.06	1.60	0.07
12	7.63	0.13	6.64	0.16	5.72	0.20	4.75	0.23	3.92	0.26	2.87	0.29
18	10.95	0.31	9.46	0.38	8.08	0.45	6.63	0.52	5.38	0.59	3.80	0.66
24	13.92	0.57	11.95	0.70	10.09	0.83	8.18	0.95	6.49	1.07	4.40	1.20
30	16.56	0.93	14.10	1.12	11.77	1.32	9.39	1.51	7.27	1.70	4.67	1.91

Two Traffic Stage and One Pedestrian Stage Junction: T-Junction with Pedestrian Crossing

Table A9: Benefits to buses and dis benefits to non priority arms by extension (150m detection distance)

T-Junction with Pedestrian Crossing, Extension, Detection 150m, g1/C = 0.5															
t+2 (Sec)	F (Buses/Hr) Both Way Total														
	10			20			40			60			80		
	Benefit: Bus (Scc/Bus), Dis Benefits: Non Priority Traffic (Sec/Veh), and Pedestrian (Sec/Pedestrian)														
	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P
	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
18	9.28	0.33	0.38	7.23	0.58	0.67	5.64	0.91	1.04	4.51	1.09	1.24	3.70	1.19	1.36

Appendix A

Table A10: Benefits to buses and dis benefits to non priority arms by extension (with detection distance)

T-Junction with Pedestrian Crossing, Extension, F = 20 buses/hr (10+10) Both Way Total																		
t+2 (Sec)	g1/C (Priority Green/Cycle Time)																	
	.1			.2			.3			.4			.5			.6		
	Benefit: Bus (Scc/Bus), Dis Benefits: Non Priority Traffic (Sec/Veh), and Pedestrian (Sec/Pedestrian)																	
	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P
	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
6	4.35	0.03	0.07	3.93	0.04	0.07	3.45	0.05	0.07	3.02	0.06	0.07	2.67	0.06	0.07	2.24	0.07	0.07
12	8.44	0.14	0.29	7.59	0.17	0.29	6.65	0.20	0.29	5.78	0.23	0.29	5.08	0.25	0.29	4.22	0.28	0.29
18	12.28	0.32	0.66	11.0	0.39	0.67	9.59	0.46	0.66	8.27	0.53	0.67	7.23	0.58	0.67	5.94	0.65	0.67
24	15.86	0.59	1.20	14.15	0.72	1.20	12.27	0.83	1.20	10.51	0.96	1.20	9.13	1.05	1.20	7.39	1.17	1.20
30	19.19	0.95	1.90	17.04	1.15	1.90	14.69	1.33	1.90	12.49	1.52	1.90	10.76	1.67	1.90	8.59	1.85	1.90

Three Traffic Stage Junction: Cross-Junction without Pedestrian Crossing

Table A11: Benefits to buses and dis benefits to non priority arms by extension (100m detection distance)

Cross-Junction without Pedestrian Crossing, Extension, Detection 100m, g1/C = 0.4										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
13	7.24	0.17	6.38	0.30	5.04	0.47	4.07	0.58	3.37	0.63

Table A12: Benefits to buses and dis benefits to non priority arms by extension (with detection distance)

Cross-Junction without Pedestrian Crossing, Extension, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.1		.2		.3		.4		.5		.6	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
7	4.97	0.07	4.42	0.08	3.93	0.08	3.60	0.09	2.83	0.09	2.50	0.10
13	8.92	0.25	7.91	0.27	6.99	0.29	6.38	0.30	4.95	0.33	4.33	0.34
20	13.18	0.61	11.63	0.66	10.21	0.70	9.26	0.73	7.06	0.79	6.11	0.81
26	16.53	1.06	14.51	1.13	12.65	1.20	11.43	1.25	8.56	1.35	7.33	1.40
33	20.09	1.75	17.52	1.86	15.15	1.98	13.59	2.05	9.96	2.22	8.40	2.29

Three Traffic Stage and One Pedestrian Stage Junction: Cross-Junction with Pedestrian Crossing

Table A13: Benefits to buses and dis benefits to non priority arms by extension (150m detection distance)

Cross-Junction with Pedestrian Crossing, Extension, Detection 150m, g1/C = 0.3															
t+2 (Sec)	F (Buses/Hr) Both Way Total														
	10			20			40			60			80		
	Benefit: Bus (Scc/Bus), Dis Benefits: Non Priority Traffic (Sec/Veh), and Pedestrian (Sec/Pedestrian)														
	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P
	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
20	11.92	0.89	0.47	10.27	1.53	0.80	7.82	2.33	1.22	6.14	2.74	1.44	4.97	2.96	1.56

Table A14: Benefits to buses and dis benefits to non priority arms by extension (with detection distance)

Cross-Junction with Pedestrian Crossing, Extension, F = 20 buses/hr (10+10) Both Way Total															
t+2 (Sec)	g1/C (Priority Green/Cycle Time)														
	.1			.2			.3			.4			.5		
	Benefit: Bus (Scc/Bus), Dis Benefits: Non Priority Traffic (Sec/Veh), and Pedestrian (Sec/Pedestrian)														
	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P
	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
7	4.88	0.17	0.10	4.41	0.18	0.10	3.88	0.18	0.10	3.35	0.19	0.10	3.0	0.19	0.10
13	8.82	0.60	0.33	7.94	0.62	0.33	6.96	0.64	0.33	5.98	0.66	0.33	5.33	0.67	0.33
20	13.14	1.44	0.80	11.78	1.49	0.80	10.27	1.53	0.80	8.76	1.57	0.80	7.76	1.60	0.80
26	16.60	2.46	1.37	14.82	2.53	1.37	12.86	2.60	1.37	10.90	2.67	1.37	9.59	2.72	1.37
33	20.35	3.99	2.24	18.08	4.11	2.25	15.60	4.23	2.25	13.11	4.34	2.25	11.45	4.42	2.25

Derived benefits and dis benefits by theoretical methods: Recall

Without Inhibit

Two Traffic Stage Junction: T-Junction without Pedestrian Crossing

Table A15: Benefits to buses and dis benefits to non priority arms by recall (100m detection distance)

T-Junction without Pedestrian Crossing, Recall without Inhibit, Detection 100m, g1/C = 0.6										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
12	2.44	0.48	2.37	0.93	2.23	1.74	2.10	2.46	1.98	3.10

Table A16: Benefits to buses and dis benefits to non priority arms by recall (with detection distance)

T-Junction without Pedestrian Crossing, Recall without Inhibit, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.2		.3		.4		.5		.6		.7	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
6	17.44	2.28	13.01	2.51	8.93	2.24	5.64	1.77	3.05	1.11	0.75	0.33
12	15.35	2.12	11.25	2.30	7.52	2.01	4.60	1.54	2.37	0.93	0.54	0.25
18	12.76	1.92	9.06	2.04	5.77	1.73	3.31	1.27	1.53	0.70	0.27	0.14
24	10.10	1.72	6.83	1.78	3.98	1.44	1.99	0.98	0.69	0.46	0.02	0.04
30	7.66	1.51	4.82	1.51	2.45	1.14	0.95	0.68	0.15	0.21	0	0

Table A17: Non priority arm green time loss due to each recall

g1/C	T-Junction without Pedestrian Crossing, Recall
	Average Green Loss by Each Recall (Sec): Non Priority Arms
	Arm1
	-
0.2	28.66
0.3	24.38
0.4	19.44
0.5	14.88
0.6	9.98
0.7	3.58

Two Traffic Stage and One Pedestrian Stage Junction: T-Junction with Pedestrian Crossing

Table A18: Benefits to buses and dis benefits to non priority arms by recall (150m detection distance)

T-Junction with Pedestrian Crossing, Recall without Inhibit, Detection 150m, g1/C = 0.5										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
18	2.56	0.64	2.47	1.23	2.29	2.28	2.13	3.18	1.98	3.95

Table A19: Benefits to buses and dis benefits to non priority arms by recall (with detection distance)

T-Junction with Pedestrian Crossing, Recall without Inhibit, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.1		.2		.3		.4		.5		.6	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
6	17.28	3.79	12.34	3.60	8.24	3.03	4.62	2.04	2.47	1.23	0.45	0.26
12	17.28	3.79	12.34	3.60	8.24	3.03	4.62	2.04	2.47	1.23	0.45	0.26
18	17.28	3.79	12.34	3.60	8.24	3.03	4.62	2.04	2.47	1.23	0.45	0.26
24	17.28	3.79	12.34	3.60	8.24	3.03	4.62	2.04	2.47	1.23	0.45	0.26
30	16.16	3.66	11.40	3.43	7.50	2.86	4.11	1.88	2.14	1.11	0.37	0.22

Table A20: Non priority arm green time loss due to each recall

g1/C	T-Junction with Pedestrian Crossing, Recall
	Average Green Loss by Each Recall (Sec): Non Priority Arms
	Arm1
	-
0.1	32.35
0.2	26.53
0.3	21.11
0.4	14.88
0.5	9.98
0.6	2.75

Three Traffic Stage Junction: Cross-Junction without Pedestrian Crossing

Table A21: Benefits to buses and dis benefits to non priority arms by recall (100m detection distance)

Cross-Junction without Pedestrian Crossing, Recall without Inhibit, Detection 100m, g1/C = 0.4										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
13	8.17	0.94	7.64	1.81	6.72	3.18	5.94	4.21	5.29	5.00

Table A22: Benefits to buses and dis benefits to non priority arms by recall (with detection distance)

Cross-Junction without Pedestrian Crossing, Recall without Inhibit, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.1		.2		.3		.4		.5		.6	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
7	20.67	3.10	15.39	2.87	10.77	2.37	8.21	1.99	3.17	0.95	1.44	0.47
13	19.71	2.92	14.56	2.67	10.10	2.17	7.64	1.81	2.89	0.82	1.30	0.40
20	18.54	2.69	13.56	2.43	9.29	1.94	6.96	1.58	2.54	0.68	1.12	0.31
26	16.40	2.50	11.76	2.22	7.84	1.73	5.76	1.38	1.95	0.54	0.82	0.23
33	13.54	2.26	9.36	1.96	5.92	1.47	4.15	1.14	1.17	0.39	0.42	0.14

Table A23: Non priority arms green time loss due to each recall

g1/C	Cross-Junction without Pedestrian Crossing, Recall	
	Average Green Loss by Each Recall (Sec): Non Priority Arms	
	Arm1	Arm2
	-	-
0.1	17.95	21.88
0.2	15.04	17.94
0.3	12.00	13.94
0.4	10.09	11.49
0.5	5.18	5.57
0.6	2.76	2.88

Three Traffic Stage and One Pedestrian Stage Junction: Cross-Junction with Pedestrian Crossing

Table A24: Benefits to buses and dis benefits to non priority arms by recall (150m detection distance)

Cross-Junction with Pedestrian Crossing, Recall without Inhibit, Detection 150m, g1/C = 0.3										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
20	7.41	8.90	6.88	16.52	5.96	28.62	5.20	37.48	4.58	43.98

Table A25: Benefits to buses and dis benefits to non priority arms by recall (with detection distance)

Cross-Junction with Pedestrian Crossing, Recall without Inhibit, F = 20 buses/hr (10+10) Both Way Total										
t+2 (Sec)	g1/C (Priority Green/Cycle Time)									
	.1		.2		.3		.4		.5	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
7	16.42	38.12	11.36	26.70	6.88	16.52	3.18	7.83	1.21	3.02
13	16.42	38.12	11.36	26.70	6.88	16.52	3.18	7.83	1.21	3.02
20	16.42	38.12	11.36	26.70	6.88	16.52	3.18	7.83	1.21	3.02
26	16.42	38.12	11.36	26.70	6.88	16.52	3.18	7.83	1.21	3.02
33	15.50	35.42	10.61	24.39	6.32	14.72	2.87	6.71	1.07	2.48

Table A26: Non priority arms green time loss due to each recall

g1/C	Cross-Junction with Pedestrian Crossing, Recall	
	Average Green Loss by Each Recall (Sec): Non Priority Arms	
	Arm1	Arm2
	-	-
0.1	17.38	21.09
0.2	13.84	16.35
0.3	10.09	11.49
0.4	5.93	6.44
0.5	2.76	2.88

Derived benefits and dis benefits by theoretical methods: Recall with Inhibit

Two Traffic Stage Junction: T-Junction without Pedestrian Crossing

Table A27: Benefits to buses and dis benefits to non priority arms by recall (100m detection distance)

T-Junction without Pedestrian Crossing, Recall with Inhibit, Detection 100m, g1/C = 0.6										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
12	2.29	0.45	2.08	0.82	1.72	1.35	1.43	1.68	1.19	1.86

Table A28: Benefits to buses and dis benefits to non priority arms by recall (with detection distance)

T-Junction without Pedestrian Crossing, Recall with Inhibit, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.2		.3		.4		.5		.6		.7	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
6	12.43	1.62	9.69	1.87	6.99	1.75	4.62	1.45	2.61	0.95	0.68	0.30
12	11.24	1.55	8.61	1.76	6.05	1.62	3.87	1.30	2.08	0.82	0.50	0.23
18	9.66	1.46	7.18	1.62	4.80	1.44	2.88	1.10	1.39	0.63	0.26	0.14
24	7.91	1.35	5.59	1.46	3.43	1.24	1.79	0.88	0.65	0.43	0.02	0.04
30	6.20	1.22	4.08	1.28	2.18	1.01	0.88	0.63	0.14	0.21	0	0

Two Traffic Stage and One Pedestrian Stage Junction: T-Junction with Pedestrian Crossing

Table A29: Benefits to buses and dis benefits to non priority arms by recall (150m detection distance)

T-Junction with Pedestrian Crossing, Recall with Inhibit, Detection 150m, g1/C = 0.5										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
18	2.37	0.59	2.11	1.05	1.68	1.67	1.33	1.99	1.06	2.12

Table A30: Benefits to buses and dis benefits to non priority arms by recall (with detection distance)

T-Junction with Pedestrian Crossing, Recall with Inhibit, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.1		.2		.3		.4		.5		.6	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
6	11.84	2.60	8.99	2.62	6.34	2.33	3.78	1.67	2.11	1.05	0.41	0.23
12	11.84	2.60	8.99	2.62	6.34	2.33	3.78	1.67	2.11	1.05	0.41	0.23
18	11.84	2.60	8.99	2.62	6.34	2.33	3.78	1.67	2.11	1.05	0.41	0.23
24	11.84	2.60	8.99	2.62	6.34	2.33	3.78	1.67	2.11	1.05	0.41	0.23
30	11.26	2.55	8.45	2.54	5.87	2.24	3.42	1.57	1.86	0.96	0.34	0.20

Three Traffic Stage Junction: Cross-Junction without Pedestrian Crossing

Table A31: Benefits to buses and dis benefits to non priority arms by recall (100m detection distance)

Cross-Junction without Pedestrian Crossing, Recall with Inhibit, Detection 100m, g1/C = 0.4										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
13	7.11	0.84	5.79	1.37	3.85	1.82	2.58	1.83	1.74	1.65

Table A32: Benefits to buses and dis benefits to non priority arms by recall (with detection distance)

Cross-Junction without Pedestrian Crossing, Recall with Inhibit, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.1		.2		.3		.4		.5		.6	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
7	13.11	1.96	10.31	1.92	7.63	1.68	6.01	1.46	2.51	0.75	1.18	0.38
13	12.92	1.91	10.09	1.85	7.40	1.59	5.79	1.37	2.36	0.67	1.10	0.34
20	12.64	1.84	9.77	1.75	7.08	1.48	5.48	1.25	2.17	0.58	0.99	0.27
26	11.56	1.76	8.76	1.65	6.18	1.36	4.69	1.13	1.72	0.48	0.74	0.21
33	9.92	1.66	7.25	1.52	4.85	1.21	3.52	0.97	1.07	0.35	0.39	0.13

Three Traffic Stage and One Pedestrian Stage Junction: Cross-Junction with Pedestrian Crossing

Table A33: Benefits to buses and dis benefits to non priority arms by recall (150m detection distance)

Cross-Junction with Pedestrian Crossing, Recall with Inhibit, Detection 150m, g1/C = 0.3										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
20	6.34	7.62	5.04	12.10	3.20	15.36	2.05	14.74	1.32	12.67

Table A34: Benefits to buses and dis benefits to non priority arms by recall (with detection distance)

Cross-Junction with Pedestrian Crossing, Recall with Inhibit, F = 20 buses/hr (10+10) Both Way Total										
t+2 (Sec)	g1/C (Priority Green/Cycle Time)									
	.1		.2		.3		.4		.5	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
7	10.53	24.44	7.79	18.30	5.04	12.10	2.49	6.13	0.99	2.47
13	10.53	24.44	7.79	18.30	5.04	12.10	2.49	6.13	0.99	2.47
20	10.53	24.44	7.79	18.30	5.04	12.10	2.49	6.13	0.99	2.47
26	10.53	24.44	7.79	18.30	5.04	12.10	2.49	6.13	0.99	2.47
33	10.33	23.61	7.56	17.38	4.82	11.21	2.33	5.46	0.91	2.11

Derived benefits and dis benefits by theoretical methods: Extension and Recall

Two Traffic Stage Junction: T-Junction without Pedestrian Crossing

Table A35: Benefits to buses and dis benefits to non priority arms by extension and recall (100m detection distance)

T-Junction without Pedestrian Crossing, Extension and recall , Detection 100m, g1/C = 0.6										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
12	6.82	0.62	6.29	1.19	5.41	2.15	4.73	2.97	4.19	3.68

Table A36: Benefits to buses and dis benefits to non priority arms by extension and recall (with detection distance)

T-Junction without Pedestrian Crossing, Extension and recall , F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.2		.3		.4		.5		.6		.7	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
6	21.43	2.31	16.5	2.55	11.96	2.29	8.18	1.83	5.18	1.17	2.35	0.4
12	22.98	2.25	17.89	2.46	13.24	2.21	9.35	1.77	6.29	1.19	3.41	0.54
18	23.71	2.23	18.52	2.42	13.85	2.18	9.94	1.79	6.91	1.29	4.07	0.8
24	24.02	2.29	18.78	2.48	14.07	2.27	10.17	1.93	7.18	1.53	4.42	1.24
30	24.22	2.44	18.92	2.63	14.22	2.46	10.34	2.19	7.42	1.91	4.67	1.91

Two Traffic Stage and One Pedestrian Stage Junction: T-Junction with Pedestrian Crossing

Table A37: Benefits to buses and dis benefits to non priority arms by extension and recall (150m detection distance)

T-Junction with Pedestrian Crossing, Extension and recall , Detection 150m, g1/C = 0.5															
t+2 (Sec)	F (Buses/Hr) Both Way Total														
	10			20			40			60			80		
	Benefit: Bus (Scc/Bus), Dis Benefits: Non Priority Traffic (Sec/Veh), and Pedestrian (Sec/Pedestrian)														
	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P
	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
18	11.84	0.97	0.38	9.7	1.81	0.67	7.93	3.19	1.04	6.64	4.27	1.24	5.68	5.14	1.36

Table A38: Benefits to buses and dis benefits to non priority arms by extension and recall (with detection distance)

T-Junction with Pedestrian Crossing, Extension and recall , F = 20 buses/hr (10+10) Both Way Total																		
t+2 (Sec)	g1/C (Priority Green/Cycle Time)																	
	.1			.2			.3			.4			.5			.6		
	Benefit: Bus (Scc/Bus), Dis Benefits: Non Priority Traffic (Sec/Veh), and Pedestrian (Sec/Pedestrian)																	
	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P
	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
6	21.63	3.82	0.07	16.27	3.64	0.07	11.69	3.08	0.07	7.64	2.1	0.07	5.14	1.29	0.07	2.69	0.33	0.07
12	25.72	3.93	0.29	19.93	3.77	0.29	14.89	3.23	0.29	10.4	2.27	0.29	7.55	1.48	0.29	4.67	0.54	0.29
18	29.56	4.11	0.66	23.34	3.99	0.67	17.83	3.49	0.66	12.89	2.57	0.67	9.7	1.81	0.67	6.39	0.91	0.67
24	33.14	4.38	1.2	26.49	4.32	1.2	20.51	3.86	1.2	15.13	3	1.2	11.6	2.28	1.2	7.84	1.43	1.2
30	35.35	4.61	1.9	28.44	4.58	1.9	22.19	4.19	1.9	16.6	3.4	1.9	12.9	2.78	1.9	8.96	2.07	1.9

Three Traffic Stage Junction: Cross-Junction without Pedestrian Crossing

Table A39: Benefits to buses and dis benefits to non priority arms by extension and recall (100m detection distance)

Cross-Junction without Pedestrian Crossing, Extension and recall , Detection 100m, g1/C = 0.4										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
13	15.41	1.11	14.02	2.11	11.76	3.65	10.01	4.79	8.66	5.63

Table A40: Benefits to buses and dis benefits to non priority arms by extension and recall (with detection distance)

Cross-Junction without Pedestrian Crossing, Extension and recall , F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.1		.2		.3		.4		.5		.6	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
7	25.64	3.17	19.81	2.95	14.7	2.45	11.81	2.08	6	1.04	3.94	0.57
13	28.63	3.17	22.47	2.94	17.09	2.46	14.02	2.11	7.84	1.15	5.63	0.74
20	31.72	3.3	25.19	3.09	19.5	2.64	16.22	2.31	9.6	1.47	7.23	1.12
26	32.93	3.56	26.27	3.35	20.49	2.93	17.19	2.63	10.51	1.89	8.15	1.63
33	33.63	4.01	26.88	3.82	21.07	3.45	17.74	3.19	11.13	2.61	8.82	2.43

Three Traffic Stage and One Pedestrian Stage Junction: Cross-Junction with Pedestrian Crossing

Table A41: Benefits to buses and dis benefits to non priority arms by extension and recall

(150m detection distance)

Cross-Junction with Pedestrian Crossing, Extension and recall , Detection 150m, g1/C = 0.3															
t+2 (Sec)	F (Buses/Hr) Both Way Total														
	10			20			40			60			80		
	Benefit: Bus (Scc/Bus), Dis Benefits: Non Priority Traffic (Sec/Veh), and Pedestrian (Sec/Pedestrian)														
	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P
	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
20	19.33	9.79	0.47	17.15	18.05	0.8	13.78	30.95	1.22	11.34	40.22	1.44	9.55	46.94	1.56

Table A42: Benefits to buses and dis benefits to non priority arms by extension and recall (with detection distance)

Cross-Junction with Pedestrian Crossing, Extension and recall , F = 20 buses/hr (10+10) Both Way Total															
t+2 (Sec)	g1/C (Priority Green/Cycle Time)														
	.1			.2			.3			.4			.5		
	Benefit: Bus (Scc/Bus), Dis Benefits: Non Priority Traffic (Sec/Veh), and Pedestrian (Sec/Pedestrian)														
	B	NT	P	B	NT	P	B	NT	P	B	NT	P	B	NT	P
	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
7	21.3	38.29	0.1	15.77	26.88	0.1	10.76	16.7	0.1	6.53	8.02	0.1	4.21	3.21	0.1
13	25.24	38.72	0.33	19.3	27.32	0.33	13.84	17.16	0.33	9.16	8.49	0.33	6.54	3.69	0.33
20	29.56	39.56	0.8	23.14	28.19	0.8	17.15	18.05	0.8	11.94	9.4	0.8	8.97	4.62	0.8
26	33.02	40.58	1.37	26.18	29.23	1.37	19.74	19.12	1.37	14.08	10.5	1.37	10.8	5.74	1.37
33	35.85	39.41	2.24	28.69	28.5	2.25	21.92	18.95	2.25	15.98	11.05	2.25	12.52	6.9	2.25

Derived benefits by theoretical methods: Extension and Recall with Conflict

Two Traffic Stage Junction: T-Junction without Pedestrian Crossing

Table A43: Benefits to buses by extension and recall with conflict (100m detection distance)

T Junction without Pedestrian Crossing: Two Traffic Stage				
Extension & Recall with Conflict; Peak Flow; One Way Bus Flow; Detector Distance 100m				
Bus Frequency (Buses/Hr) on each conflicting arm				
5	10	20	30	40
Benefit: Bus (Scc/Bus)				
5.79	4.3	1.73	-0.4	-2.14

Two Traffic Stage and One Pedestrian Stage Junction: T-Junction with Pedestrian Crossing

Table A44: Benefits to buses by extension and recall with conflict (150m detection distance)

T Junction with Pedestrian Crossing: Two Traffic Stage and One Pedestrian Stage				
Extension & Recall with Conflict; Peak Flow; One Way Bus Flow; Detector Distance 150m				
Bus Frequency (Buses/Hr) on each conflicting arm				
5	10	20	30	40
Benefit: Bus (Scc/Bus)				
9.12	6.36	1.68	-2.08	-5.09

Three Traffic Stage Junction: Cross-Junction without Pedestrian Crossing

Table A45: Benefits to buses by extension and recall with conflict (100m detection distance)

Cross Junction without Pedestrian Crossing: Three Traffic Stage				
Extension & Recall with Conflict; Peak Flow; One Way Bus Flow; Detector Distance 100m				
Bus Frequency (Buses/Hr) on each conflicting arm				
5	10	20	30	40
Benefit: Bus (Scc/Bus)				
10.98	5.67	-3.04	-9.78	-14.94

Three Traffic Stage and One Pedestrian Stage Junction: Cross-Junction with Pedestrian Crossing

Table A46: Benefits to buses by extension and recall with conflict (150m detection distance)

Cross Junction with Pedestrian Crossing: Three Traffic Stage and One Pedestrian Stage				
Extension & Recall with Conflict; Peak Flow; One Way Bus Flow; Detector Distance 150m				
Bus Frequency (Buses/Hr) on each conflicting arm				
5	10	20	30	40
Benefit: Bus (Scc/Bus)				
1.02	-17.54	-48.65	-73.24	-92.69

Derived benefits and dis benefits by theoretical methods: Always Green Bus

Two Traffic Stage Junction: T-Junction without Pedestrian Crossing

Table A47: Benefits to buses and dis benefits to non priority arms by always green bus (with different bus frequency)

T-Junction without Pedestrian Crossing, Always Green Bus, Detection 226m, g1/C = 0.6										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
27	Extension									
	7.74	0.76	6.92	1.36	5.62	2.21	4.65	2.74	3.90	3.07
	Recall without Inhibit									
	0.37	0.17	0.37	0.34	0.36	0.66	0.35	0.97	0.34	1.26
	Recall with Inhibit									
	0.36	0.17	0.35	0.32	0.33	0.60	0.31	0.84	0.29	1.05

Table A48: Benefits to buses and dis benefits to non priority arms by always green bus (with different priority approach green)

T-Junction without Pedestrian Crossing, Always Green Bus, Detection 226m, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.2		.3		.4		.5		.6		.7	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
27	Extension											
	15.28	0.74	13.07	0.89	10.98	1.06	8.82	1.21	6.92	1.36	4.58	1.53
	Recall without Inhibit											
	8.84	1.62	5.78	1.65	3.17	1.29	1.42	0.83	0.37	0.34	0	0
	Recall with Inhibit											
	7.04	1.29	4.82	1.37	2.78	1.13	1.30	0.76	0.35	0.32	0	0

Two Traffic Stage and One Pedestrian Stage Junction: T-Junction with Pedestrian Crossing

Table A49: Benefits to buses and dis benefits to non priority arms by always green bus (with different bus frequency)

T-Junction with Pedestrian Crossing, Always Green Bus, Detection 267m, g1/C = 0.5										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
32	Extension									
	12.87	1.09	11.25	1.91	8.76	2.97	7.01	3.57	5.74	3.90
	Recall without Inhibit									
	1.98	0.53	1.92	1.02	1.80	1.92	1.70	2.72	1.60	3.41
	Recall with Inhibit									
	1.86	0.50	1.69	0.90	1.40	1.49	1.16	1.85	0.96	2.05

Table A50: Benefits to buses and dis benefits to non priority arms by always green bus (with different priority approach green)

T-Junction with Pedestrian Crossing, Always Green Bus, Detection 267m, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.1		.2		.3		.4		.5		.6	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
32	Extension											
	20.24	1.10	17.94	1.31	15.45	1.52	13.09	1.74	11.25	1.91	8.94	2.11
	Recall without Inhibit											
	15.40	3.56	10.77	3.32	7.00	2.74	3.77	1.78	1.92	1.02	0.32	0.19
	Recall with Inhibit											
	10.85	2.51	8.07	2.49	5.54	2.17	3.17	1.50	1.69	0.90	0.29	0.18

Three Traffic Stage Junction: Cross-Junction without Pedestrian Crossing

Table A51: Benefits to buses and dis benefits to non priority arms by always green bus (with different bus frequency)

Cross-Junction without Pedestrian Crossing, Always Green Bus, Detection 324m, g1/C = 0.4										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
42	Extension									
	17.95	1.94	15.81	3.41	12.49	5.39	10.10	6.54	8.35	7.21
	Recall without Inhibit									
	2.19	0.42	2.12	0.82	2.01	1.55	1.90	2.20	1.80	2.78
	Recall with Inhibit									
	2.06	0.40	1.89	0.73	1.59	1.23	1.34	1.55	1.13	1.74

Table A52: Benefits to buses and dis benefits to non priority arms by always green bus (with different priority approach green)

Cross-Junction without Pedestrian Crossing, Always Green Bus, Detection 324m, F = 20 buses/hr (10+10) Both Way Total												
t+2 (Sec)	g1/C (Priority Green/Cycle Time)											
	.1		.2		.3		.4		.5		.6	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)											
	B	NT	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-	+	-
42	Extension											
	24.10	2.91	20.84	3.10	17.80	3.30	15.81	3.41	11.19	3.68	9.20	3.80
	Recall without Inhibit											
	9.82	1.95	6.25	1.61	3.45	1.13	2.12	0.82	0.25	0.17	0.01	0.01
	Recall with Inhibit											
	7.56	1.50	5.09	1.31	2.97	0.97	1.89	0.73	0.24	0.17	0.01	0.01

Three Traffic Stage and One Pedestrian Stage Junction: Cross-Junction with Pedestrian Crossing

Table A53: Benefits to buses and dis benefits to non priority arms by always green bus (with different bus frequency)

Cross-Junction with Pedestrian Crossing, Always Green Bus, Detection 365m, g1/C = 0.3										
t+2 (Sec)	F (Buses/Hr) Both Way Total									
	10		20		40		60		80	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
48	Extension									
	23.71	5.28	20.42	9.09	15.54	13.84	12.22	16.31	9.89	17.61
	Recall without Inhibit									
	4.45	5.57	4.25	10.63	3.89	19.44	3.56	26.72	3.28	32.76
	Recall with Inhibit									
	4.05	5.07	3.52	8.80	2.66	13.32	2.02	15.16	1.54	15.39

Table A54: Benefits to buses and dis benefits to non priority arms by always green bus (with different priority approach green)

Cross-Junction with Pedestrian Crossing, Always Green Bus, Detection 365m, F = 20 buses/hr (10+10) Both Way Total										
t+2 (Sec)	g1/C (Priority Green/Cycle Time)									
	.1		.2		.3		.4		.5	
	Benefit: Bus (Scc/Bus) and Dis Benefits: Non Priority Traffic (Sec/Veh)									
	B	NT	B	NT	B	NT	B	NT	B	NT
	+	-	+	-	+	-	+	-	+	-
48	Extension									
	27.36	8.59	24.04	8.85	20.42	9.09	16.80	9.33	14.39	9.49
	Recall without Inhibit									
	11.95	29.27	7.74	19.14	4.25	10.63	1.69	4.15	0.54	1.25
	Recall with Inhibit									
	8.66	21.20	5.99	14.82	3.52	8.80	1.50	3.68	0.50	1.15

Appendix B

Flow Data

Table B1: Cross Junction- Portswood Rd (SW) Flow Data

Cross Junction, Portswood Rd (SW), Date: 04.03.13								
Time	Flows (Vehicle/hr)				Turning Percentage			
	Total	Straight	Left	Right	Straight	Left	Right	Total
08.00-09.00	419	246	111	62	59%	26%	15%	100%
09.00-10.00	480	277	135	68	58%	28%	14%	100%
10.00-11.00	499	314	117	68	63%	23%	14%	100%
11.00-12.00	412	252	86	74	61%	21%	18%	100%
12.00-13.00	492	295	117	80	60%	24%	16%	100%
13.00-14.00	560	375	135	49	67%	24%	9%	100%
15.00-16.00	621	363	182	76	58%	29%	12%	100%
16.00-17.00	603	363	170	70	60%	28%	12%	100%
17.00-18.00	557	352	117	88	63%	21%	16%	100%
18.00-19.00	545	305	152	88	56%	28%	16%	100%

Table B2: Cross Junction- Portswood Rd (NE) Flow Data

Cross Junction, Portswood Rd (NE), Date: 04.03.13								
Time	Flows (Vehicle/hr)				Turning Percentage			
	Total	Straight	Left	Right	Straight	Left	Right	Total
08.00-09.00	398	344	54	0	86%	14%	0%	100%
09.00-10.00	356	332	24	0	93%	7%	0%	100%
10.00-11.00	290	235	54	0	81%	19%	0%	100%
11.00-12.00	302	235	66	0	78%	22%	0%	100%
12.00-13.00	483	434	48	0	90%	10%	0%	100%
13.00-14.00	368	338	30	0	92%	8%	0%	100%
15.00-16.00	376	332	44	0	88%	12%	0%	100%
16.00-17.00	365	327	38	0	90%	10%	0%	100%
17.00-18.00	414	305	109	0	74%	26%	0%	100%
18.00-19.00	381	267	114	0	70%	30%	0%	100%

Table B3: Cross Junction- Highfield Ln (NW) Flow Data

Cross Junction, Highfield Ln (NW), Date: 04.03.13								
Time	Flows (Vehicle/hr)				Turning Percentage			
	Total	Straight	Left	Right	Straight	Left	Right	Total
08.00-09.00	306	120	78	108	39%	25%	35%	100%
09.00-10.00	306	138	66	102	45%	22%	33%	100%
10.00-11.00	324	198	36	90	61%	11%	28%	100%
11.00-12.00	330	192	60	78	58%	18%	24%	100%
12.00-13.00	360	104	88	168	29%	24%	47%	100%
13.00-14.00	354	114	84	156	32%	24%	44%	100%
15.00-16.00	331	156	46	129	47%	14%	39%	100%
16.00-17.00	432	179	87	165	41%	20%	38%	100%
17.00-18.00	285	111	82	92	39%	29%	32%	100%
18.00-19.00	377	199	86	92	53%	23%	24%	100%

Appendix B

Table B4: Cross Junction- St Denys Rd (SE) Flow Data

Cross Junction, St Denys Rd (SE), Date: 04.03.13								
Time	Flows (Vehicle/hr)				Turning Percentage			
	Total	Straight	Left	Right	Straight	Left	Right	Total
08.00-09.00	364	258	85	21	71%	23%	6%	100%
09.00-10.00	406	247	113	46	61%	28%	11%	100%
10.00-11.00	291	140	99	52	48%	34%	18%	100%
11.00-12.00	260	135	78	47	52%	30%	18%	100%
12.00-13.00	343	172	104	68	50%	30%	20%	100%
13.00-14.00	333	186	108	40	56%	32%	12%	100%
15.00-16.00	352	204	97	51	58%	28%	14%	100%
16.00-17.00	352	191	115	46	54%	33%	13%	100%
17.00-18.00	341	189	102	51	55%	30%	15%	100%
18.00-19.00	306	148	102	56	48%	33%	18%	100%

Table B5: Cross Junction- Pedestrian Crossing on St Denys Rd (SE), Flow Data

Cross Junction, Pedestrian Crossing on St Denys Rd (SE), Date: 04.03.13		
Time	Flows (Pedestrian/hr)	
	Total (both direction)	Each Direction
08.00-09.00	120	60
09.00-10.00	354	177
10.00-11.00	414	207
11.00-12.00	400	200
12.00-13.00	480	240
13.00-14.00	618	309
15.00-16.00	684	342
16.00-17.00	1026	513
17.00-18.00	918	459
18.00-19.00	642	321

Table B6: T Junction- Burgess Rd (SW) Flow Data

T Junction, Burgess Rd (SW), Date: 18.03.13								
Time	Flows (Vehicle/hr)				Turning Percentage			
	Total	Straight	Left	Right	Straight	Left	Right	Total
07.00-08.00	648	594	54	-	92%	8%	-	100%
08.00-09.00	840	666	174	-	79%	21%	-	100%
09.00-10.00	708	636	72	-	90%	10%	-	100%
10.00-11.00	444	414	30	-	93%	7%	-	100%
11.00-12.00	570	498	72	-	87%	13%	-	100%
12.00-13.00	504	486	18	-	96%	4%	-	100%
13.00-14.00	690	624	66	-	90%	10%	-	100%
15.00-16.00	438	396	42	-	90%	10%	-	100%
16.00-17.00	750	666	84	-	89%	11%	-	100%
17.00-18.00	714	612	102	-	86%	14%	-	100%
18.00-19.00	810	750	60	-	93%	7%	-	100%

Table B7: T Junction- Burgess Rd (NE) Flow Data

T Junction, Burgess Rd (NE), Date: 18.03.13								
Time	Flows (Vehicle/hr)				Turning Percentage			
	Total	Straight	Left	Right	Straight	Left	Right	Total
07.00-08.00	828	798	-	30	96%	-	4%	100%
08.00-09.00	696	606	-	90	87%	-	13%	100%
09.00-10.00	738	630	-	108	85%	-	15%	100%
10.00-11.00	654	600	-	54	92%	-	8%	100%
11.00-12.00	510	450	-	60	88%	-	12%	100%
12.00-13.00	570	498	-	72	87%	-	13%	100%
13.00-14.00	660	576	-	84	87%	-	13%	100%
15.00-16.00	618	528	-	90	85%	-	15%	100%
16.00-17.00	636	558	-	78	88%	-	12%	100%
17.00-18.00	714	612	-	102	86%	-	14%	100%
18.00-19.00	786	660	-	126	84%	-	16%	100%

Table B8: T Junction- Glen Eyre Rd (NW) Flow Data

T Junction, Glen Eyre Rd (NW), Date: 18.03.13								
Time	Flows (Vehicle/hr)				Turning Percentage			
	Total	Straight	Left	Right	Straight	Left	Right	Total
07.00-08.00	114	-	90	24	-	79%	21%	100%
08.00-09.00	486	-	306	180	-	63%	37%	100%
09.00-10.00	270	-	204	66	-	76%	24%	100%
10.00-11.00	108	-	90	18	-	83%	17%	100%
11.00-12.00	114	-	90	24	-	79%	21%	100%
12.00-13.00	102	-	78	24	-	76%	24%	100%
13.00-14.00	180	-	150	30	-	83%	17%	100%
15.00-16.00	132	-	90	42	-	68%	32%	100%
16.00-17.00	138	-	84	54	-	61%	39%	100%
17.00-18.00	366	-	258	108	-	70%	30%	100%
18.00-19.00	336	-	192	144	-	57%	43%	100%

Table B9: T Junction- Pedestrian Crossing on Burgess Rd (NE), Flow Data

T Junction, Pedestrian Crossing on Burgess Rd (NE), Date: 18.03.13		
Time	Flows (Pedestrian/hr)	
	Total (both direction)	Each Direction
08.00-09.00	375	188
09.00-10.00	370	185
12.00-13.00	382	191
13.00-14.00	391	196
16.00-17.00	386	193
17.00-18.00	379	190

Table B10: Pedestrian Crossing on Portswood Rd, Flow Data

Pedestrian Crossing on Portswood Rd , Date: 12.03.13		
Time	Flows (Pedestrian/hr)	
	Total (both direction)	Each Direction
08.00-09.00	156	78
09.00-10.00	204	102
10.00-11.00	270	135
11.00-12.00	282	141
12.00-13.00	306	153
13.00-14.00	288	144
15.00-16.00	348	174
16.00-17.00	316	158
17.00-18.00	300	150
18.00-19.00	270	135

Signal Data

Table B11: Cross Junction- Inter Peak Signal Stage Green

Cross Junction- Signal Stage Green, Inter Peak, Duration: 11am to12am, Date:04.03.13											
Portswood Rd (SW +NE)			Highfield Ln (NW)			St Denys Rd (SE)			Pedestrian Stage		
S1 (Sec)			S2 (Sec)			S3 (Sec)			S4 (Sec)		
25	30		20	20		20	20		18	17	
25	25		20	18		20	18		18	18	
25	25		20	18		20	18		18	18	
23	30		18	18		16	18		18	16	
25	35		18	18		18	18		18	18	
25	25		20	15		18	18		18	18	
25	20		17	15		19	20		18	15	
25	30		20	18		19	19		18	18	
20	25		20	20		18	18		18	18	
20	25		20	17		13	19		18	18	
25	35		20	20		18	18		18	17	
33	35		20	20		20	20		17	18	
25	30		15	20		16	20		17	18	
23			20			16			16		
25			20			20			18		

Table B12: Cross Junction- Evening Peak Signal Stage Green

Cross Junction- Signal Stage Green, Evening Peak, Duration: 3pm to 7pm, Date:04.03.13															
Portswood Rd (SW +NE)				Highfield Ln (NW)				St Denys Rd (SE)				Pedestrian Stage			
S1 (Sec)				S2 (Sec)				S3 (Sec)				S4 (Sec)			
35	35	30	30	20	15	20	20	20	20	20	20	18			
35	35	33	35	20	20	20	20	20	20	15	20	18			
35	35	35	35	20	20	20	20	20	20	20	20	18			
35	35	35	35	20	20	20	20	20	20	20	20	18			
35	35	35	35	20	20	20	20	20	20	20	20	18			
32	35	35	35	20	20	20	20	20	20	20	20	16			
30	35	35	35	20	20	20	20	20	20	20	20	18			
35	35	35	35	20	20	20	20	20	20	20	20	18			
33	35	35	35	20	20	20	18	20	20	20	20	18			
35	30	35	35	18	20	20	18	18	20	20	20	18			
35	35	35	35	18	20	20	18	18	20	20	20	18			
35	30	35	35	18	20	20	18	18	20	20	20	16			
33	35	30	35	18	20	20	18	20	20	20	20	16			
33	35	35	35	18	20	20	20	20	20	20	20	18			
33	35	30	35	20	20	20	20	20	20	15	20	18			
35	35	30	30	20	20	20	20	20	20	15	20	18			
35	35	35	30	20	20	20	18	20	20	15	20	18			
35	35	35	35	18	20	20	20	20	20	20	20	18			
35	35	35	30	20	20	20	20	20	20	20	20	18			
30	35	35	35	20	20	20	20	20	20	20	20	16			
35	35	35	30	20	20	20	18	20	20	20	20	18			
35	35	30	35	20	20	18	20	20	13	15	15	18			
30	35	33	35	18	20	20	20	20	20	20	20	18			
30	33	30	35	20	20	20	20	20	20	20	20	18			
35	35	30	35	20	20	20	20	20	20	18	20	18			
30	35	35		20	20	20		20	20	20		17			
30	30	30		20	20	20		20	20	20		15			
35	30	30		20	20	20		20	20	20		18			
35	35	35		20	20	20		20	20	20					
35	35	35		20	20	20		20	20	20					
35	35	35		20	20	16		20	20	20					
35	35	35		20	20	20		20	20	20					
30	35	35		20	20	16		15	15	20					
32	35	35		20	20	16		15	20	20					
30	35	35		20	18	18		20	20	20					
30	35	35		18	20	13		18	20	20					
35	35	35		18	20	15		20	20	20					
30	35	35		18	20	15		20	20	20					
30	35	35		18	20	20		20	20	20					
35	30	35		15	20	20		20	20	20					

Table B13: T Junction- Evening Peak Signal Stage Green

T Junction- Signal Stage Green, Evening Peak, Duration: 4pm-6pm, Date: 18.03.13														
Burgess Rd (SW + NE)					Glen Eyre Rd (NW)					Pedestrian Stage				
S1 (Sec)					S2 (Sec)					S3 (Sec)				
50	50	50	35	50	12	14	8	20	20	18	16			
30	50	34	50	50	12	12	16	20	20	18	16			
50	50	50	40	50	12	20	14	20	20	18	16			
46	50	40	30	40	12	12	10	20	20	18				
46	22	50	30	50	20	12	17	20	20	18				
50	46	50	50	50	8	12	20	20	20	16				
36	50	50	50	50	15	17	20	20	20	16				
34	50	37	40	50	15	20	10	20	20	16				
50	46	37	45	50	10	7	12	20	18	16				
50	50	50	37	34	7	14	20	20	18	16				
46	50	45	50	50	20	8	20	20	20	18				
50	50	20	50		7	20	20	20		18				
50	50	40	50		15	18	20	20		16				
30	50	37	50		15	16	10	20		18				
50	50	20	50		14	8	20	20		18				

Table B14: T Junction- Morning Peak Signal Stage Green

T Junction- Signal Stage Green, Morning Peak, Duration: 8am-10am, Date: 18.03.13														
Burgess Rd (SW + NE)					Glen Eyre Rd (NW)					Pedestrian Stage				
S1 (Sec)					S2 (Sec)					S3 (Sec)				
50	50	50	35	40	15	20	20	20	20	18	16			
50	35	25	50	50	15	20	18	12	7	16	18			
50	30	50	50	43	20	20	20	14	20	18	18			
35	45	35	40	50	20	20	20	10	20	16				
50	50	35	45	50	18	20	18	7	18	18				
50	35	40	35	42	20	20	20	7	20	15				
50	45	50	47	50	7	20	10	20	20	16				
50	50	50	50		20	20	20	18		16				
50	30	45	40		18	20	20	7		14				
50	50	25	50		8	20	20	20		16				
45	40	25	50		20	20	18	20		18				
50	35	27	50		16	20	20	18		17				
35	50	50	50		20	20	20	20		16				
50	25	40	43		20	20	20	10		18				
42	50	25	50		20	20	20	20		17				

Table B15: T Junction- Inter Peak Signal Stage Green

T Junction- Signal Stage Green, Inter Peak, Duration: 12.00-14.00, Date: 18.03.13														
Burgess Rd (SW + NE)					Glen Eyre Rd (NW)					Pedestrian Stage				
S1 (Sec)					S2 (Sec)					S3 (Sec)				
42	20	30	40	26	10	9	10	7	8	16				
30	40	50	40	26	20	9	10	7	16	18				
50	55	45	26	37	20	7	13	15	14	18				
30	60	22	45	26	10	14	9	15	10	18				
15	50	50	50	60	7	7	18	14	17	18				
25	12	50	26	50	7	10	10	7	12	17				
50	45	20	18	50	7	10	10	12	7	16				
25	50	45	30	50	10	10	9	20	10	16				
28	45	45	35	40	12	13	9	12	12	16				
35	20	40	25		12	13	12	12		16				
15	50	50	40		10	9	12	12		18				
35	12	43	23		12	10	12	17		18				
30	35	40	30		12	7	12	20		16				
30	13	13	50		10	7	12	7		17				
45	50	60	25		10	7	8	14		18				
10	20	55	50		12	7	8	8		16				
45	60	40	15		7	10	15	20		16				
50	30	20	26		10	12	15	9		18				
28	30	40	26		14	7	10	16		16				
30	40	37	50		7	10	7	8		18				

Table B16: Pedestrian Crossing Signal Details

Pedestrian Crossing Signal Details, Date: 12.03.13											
Inter Peak, Time: 12am to 1pm						Evening Peak, Time: 4pm to 5pm					
Cycle Time		Portswood Rd (SW +NE)		Pedestrian Stage		Cycle Time		Portswood Rd (SW +NE)		Pedestrian Stage	
C (sec)		S1 (sec)		S2 (sec)		C (sec)		S1 (sec)		S2 (sec)	
55	42	34	18	13	16	47	37	29	17	10	12
58	51	35	33	15	10	59	60	35	35	16	17
38	54	18	30	12	16	56	31	35	12	13	11
48	48	30	28	10	12	55	48	31	24	16	16
59	42	35	22	16	12	48	37	26	18	14	11
55	51	35	30	12	13	51	53	30	35	13	10
46	47	26	27	12	12	54	53	30	35	16	10
40	40	19	18	13	14	60	49	35	27	17	14
35	55	15	35	12	12	53	51	29	30	16	13
50	42	28	20	14	14	50	52	26	28	16	16
50	48	30	23	12	17	50	60	25	35	17	17
47	47	25	27	14	12	60	41	35	17	17	16
46	50	26	25	12	17	52	59	28	35	16	16
35		12		15		49		25		16	
60		35		17		41		20		13	

Queue Data

Table B17: Cross Junction- Evening Peak Queue Data

Cross Junction- Queue Length, Evening Peak, Duration: 3pm to7pm, Date: 05.03.13																			
Portswood Rd (SW)					Portswood Rd (NE)					Highfield Ln (NW)					St Denys Rd (SE)				
Q1 (Nr)					Q2 (Nr)					Q3 (Nr)					Q4 (Nr)				
23	16	25	8	9	11	8	9	9		10	9	16	12		10	8	16	12	
25	14	30	19	14	9	5	7	5		12	23	13	14		9	15	17	13	
23	14	25	12	4	7	16	3	11		21	20	4	8		7	20	17	11	
23	18	22	4	9	5	18	5	10		14	16	19	6		8	18	17	10	
25	11	14	11	12	5	7	10	5		12	21	8	8		7	16	19	7	
22	11	18	10	7	6	8	13	9		11	18	15	8		4	11	15	9	
20	21	18	8	11	3	9	6	4		10	25	4	7		2	10	10	7	
14	21	19	18	8	4	9	7	4		13	20	11	11		8	16	10	9	
21	24	15	11	16	10	11	12	6		11	20	4	4		10	19	11	10	
24	17	20	4	22	10	8	12	10		10	19	13	13		8	19	17	9	
24	16	25	15	11	8	13	8	5		7	17	2	2		9	14	13	8	
21	8	20	13	14	3	11	8	4		6	10	15	15		5	13	17	10	
18	20	21	22	21	6	8	11	15		2	8	6	6		10	10	16	15	
21	15	27	23	19	7	11	7	4		17	10	11	11		13	18	14	11	
17	17	22	18		5	16	9	7		19	17	5	5		10	15	16	5	
19	25	5	10		10	13	4	15		23	12	6	6		11	21	20	15	
15	24	19	6		5	9	6	8		18	8	10	10		11	23	22	15	
13	18	21	13		13	8	14	5		16	7	9	9		12	13	20	13	
16	17	16	7		8	4	14	8		24	9	20	20		8	13	22	12	
12	13	17	2		16	8	19	8		24	9	22	22		15	9	27	9	
20	10	21	10		10	18	14	10		23	15	16	16		19	9	22	12	
16	14	12	8		12	9	11	10		21	14	14	14		16	10	21	2	
22	21	6	16		4	9	7	6		19	14	12	12		17	9	14	7	
23	10	14	12		9	10	12	11		25	9	11	11		19	9	11	11	
21	17	16	23		11	11	8	3		18	8	6	6		16	11	10	11	
25	13	18	12		7	6	5	3		23	7	13	13		8	7	5	6	
14	14	17	23		10	6	7	8		17	10	10	10		7	6	7	5	
23	15	7	5		9	10	5	6		16	15	13	13		10	6	8	8	
22	15	20	7		6	8	6	1		13	20	17	17		17	8	8	14	
20	24	15	17		3	7	10	12		11	14	13	13		19	7	10	10	

Table B18: Cross Junction- Inter Peak Queue Data

Cross Junction- Queue Length, Inter Peak, Duration: 10am -2pm, Date: 05.03.13																				
Portswood Rd (SW)						Portswood Rd (NE)					Highfield Ln (NW)					St Denys Rd (SE)				
Q1 (Nr)						Q2 (Nr)					Q3 (Nr)					Q4 (Nr)				
9	4	13	19	12	9	6	5				4	11				10	12			
9	2	9	20	1	11	4	5				10	3				11	11			
5	1	7	18	6	13	5	3				11	2				11	14			
3	13	4	2	3	7	6	9				10	4				10	5			
8	8	9	14	16	8	7	14				8	11				12	8			
7	2	13	16	10	8	8	13				8	7				8	6			
13	14	12	8	9	3	4	11				7	2				2	5			
1	11	14	5	3	11	13	4				6	8				7	11			
6	8	2	20	20	10	10	6				3	12				11	11			
9	5	4	16	18	7	10	7				8	9				16	9			
10	10	17	17	7	8	12	6				4	10				16	7			
7	7	18	12	7	11	8	6				8	11				6	1			
4	11	6	6	9	3	8	6				7	12				7	15			
3	5	7	19	12	10	5	10				4	11				4	4			
6	8	9	17	8	4	10	5				6	5				7	8			
10	20	11	14	10	6	6	4				9	16				8	7			
8	14	4	14	13	7	7	10				13	7				7	19			
10	7	14	8	17	3	12	6				7	11				17	16			
5	10	8	11	20	8	12	5				4	14				16	17			
11	1	9	20	13	9	6	7				4	13				10	15			
3	12	6	19	7	9	6	5				2	10				8	13			
4	3	8	17	13	3	3	4				4	7				2	9			
9	11	6	7	17		8					8					4				
10	10	10	5	15		7					10					7				
7	10	11	7	17		5					6					18				
11	11	11	6	20		5					3					15				
5	15	5	16	1		8					7					14				
12	14	6	10	8		7					5					20				
6	17	15	5	9		5					5					11				
8	13	9	7	14		3					6					12				
3	10	10	14	14		4					11					11				
12	5	9	7	11		6					6					13				
1	7	10	13	7		5					6					13				
9	10	10	10	4		3					6					8				
1	15	9	3	15		10					8					3				
7	7	13	9	9		9					6					7				
2	5	6	15	8		4					7					3				
14	13	6	9	9		7					8					13				
4	9	2	8	9		11					14					11				
15	10	6	12	9		9					6					14				

Appendix B

Table B19: T Junction- Evening Peak Queue Data

T Junction- Queue Length, Evening Peak, Duration: 4pm to 7pm, Date: 19.03.13																	
Burgess Rd (SW)						Burgess Rd (NE)						Glen Eyre Rd (NW)					
Q1 (Nr)						Q2 (Nr)						Q3 (Nr)					
17	18	4	16	2	7	5	19	3	9	10	8	4	5	13	0	9	7
18	17	7	12	12	13	7	17	3	3	15	4	6	5	4	4	4	3
18	14	12	21	13	16	14	3	7	8	1	2	4	5	3	4	4	4
17	16	7	17	3	5	14	17	6	4	12	7	6	7	1	3	1	4
8	16	14	14	7	5	13	5	18	18	6	11	4	7	2	1	2	3
17	15	12	19	3	16	17	17	1	7	18	20	2	1	4	4	5	4
7	17	15	5	5	9	10	10	9	1	5	7	9	5	9	3	1	3
20	13	15	15	0	13	3	3	1	1	6	7	2	1	4	1	2	7
10	9	13	8	7	13	3	3	4	7	12	2	2	5	4	3	7	2
14	16	10	18	7	11	3	2	2	7	1	4	3	3	4	2	2	4
14	6	4	14	10	12	10	17	3	2	13	10	1	6	3	3	5	9
17	13	7	26	11	11	5	3	3	4	11	8	4	3	3	6	4	4
6	9	6	13	7	3	6	7	9	10	16	7	4	5	1	7	4	4
20	15	13	12	8	15	3	7	1	8	12	9	2	10	0	5	5	4
7	22	8	12	11		7	20	13	7	17		3	5	6	11	6	
14	9	20	11	11		18	17	17	3	8		5	2	2	1	3	
17	13	17	22	17		14	20	17	1	1		3	14	6	3	5	
15	14	5	24	12		8	16	8	6	5		0	2	8	3	10	
20	20	2	14	16		4	3	1	4	12		2	5	11	3	5	
5	10	15	4	7		4	10	5	7	8		2	8	2	3	2	
17	12	20	18	11		5	5	12	2	15		5	5	2	5	9	
10	12	26	6	8		5	7	8	0	4		2	7	3	3	2	
17	13	12	14	6		5	6	15	2	11		4	5	2	2	5	
10	15	23	5	13		5	5	20	8	7		4	3	0	2	8	
19	13	17	12	9		2	7	11	11	4		4	8	5	8	5	
16	6	13	4	12		4	6	7	12	2		8	4	4	11	7	
12	25	13	6	11		12	13	0	0	4		2	2	3	3	5	
14	4	5	10	13		3	7	2	6	2		3	3	2	2	3	
17	7	10	13	13		4	15	4	3	9		2	3	4	5	8	
18	9	9	4	6		8	6	2	8	3		9	5	3	3	4	
9	5	13	11	12		17	7	9	5	9		2	2	2	3	2	
7	13	12	10	6		7	1	3	8	10		5	1	1	14	3	
5	26	14	16	5		18	2	9	10	6		0	3	3	11	3	
22	2	15	7	9		7	9	10	11	8		1	4	2	3	5	
22	16	10	16	5		3	7	6	19	11		5	5	6	3	2	
18	6	20	17	13		2	13	8	3	4		2	4	10	3	7	
19	13	13	8	31		2	20	11	3	10		8	7	3	4	3	
12	13	22	15	13		4	2	4	5	4		7	3	10	2	4	
20	10	26	12	14		20	10	10	5	9		2	14	4	5	5	
13	17	22	13	13		2	8	4	5	3		5	4	7	4	4	

Table B20: T Junction- Inter Peak Queue Data

T Junction- Queue Length, Inter Peak, Duration: 12am to 2pm, Date: 19.03.13																	
Burgess Rd (SW)						Burgess Rd (NE)						Glen Eyre Rd (NW)					
Q1 (Nr)						Q2 (Nr)						Q3 (Nr)					
11	4	12				1	7	7				7	2	0			
3	7	2				4	1	2				0	0	3			
8	6	16				2	2	5				3	2	3			
4	0	1				11	7	2				2	0	2			
3	6	2				6	7	6				3	3	3			
4	1	2				7	0	10				2	2	2			
8	4	1				8	0	4				2	4	0			
6	9	6				5	1	7				1	0	1			
7	16	1				2	11	3				7	2	0			
5	6	5				0	10	6				2	6	0			
12	3	1				1	5	6				1	6	1			
7	8	7				2	14	1				0	2	3			
3	5	12				2	0	2				1	1	4			
0	7	10				2	2	12				2	0	2			
3	3	5				11	0	4				0	1	2			
10	4	17				2	1	10				1	1	3			
0	11	13				4	0	10				2	2	1			
6	15	11				0	3	8				2	4	4			
5	3	1				3	4	12				5	4	2			
9	12	16				0	3	13				4	3	4			
2	1	6				11	3	6				2	1	2			
2	7	4				0	6	0				2	1	2			
11	10	17				3	3	1				0	2	2			
6	0	5				10	2	9				1	3	2			
3	10	4				3	11	1				2	2	3			
7	1					0	4					1	1				
12	4					4	6					1	0				
4	8					4	6					4	3				
8	5					2	1					0	0				
4	14					0	9					3	3				
5	17					2	6					1	5				
15	17					5	2					1	2				
7	13					7	1					2	2				
7	2					3	7					0	0				
3	0					0	4					2	3				
4	7					1	10					1	0				
4	7					13	5					4	0				
1	3					8	1					1	3				
13	13					10	8					1	2				
2	5					1	2					1	2				

Appendix B

Table B21: T Junction- Morning Peak Queue Data

T Junction- Queue Length, Morning Peak, Duration: 7am to10am, Date: 19.03.13																	
Burgess Rd (SW)						Burgess Rd (NE)						Glen Eyre Rd (NW)					
Q1 (Nr)						Q2 (Nr)						Q3 (Nr)					
11	26	18	4			3	2	8	10			7	15	1	6		
7	30	9	7			7	7	1	2			7	10	10	8		
9	27	20	6			0	2	12	11			2	7	7	7		
5	25	10	11			8	12	3	5			2	16	3	6		
8	27	15	5			0	2	15	8			3	15	7	5		
5	13	20	11			2	1	1	10			0	16	7	1		
7	14	26	9			10	4	0	10			3	18	9	2		
11	10	29	11			4	3	2	4			5	17	11	4		
6	13	27	12			16	2	3	10			1	14	14	3		
4	14	26	11			4	5	5	4			3	7	11	1		
12	14	27	15			9	13	1	4			7	4	14	3		
2	10	13	9			10	14	3	10			3	7	14	0		
7	14	16	13			4	15	1	11			0	4	15	3		
12	7	29	1			10	9	12	13			7	8	15	4		
3	22	26	8			1	1	13	9			1	7	17	5		
7	16	21	15			11	9	4	7			3	2	15	9		
5	13	19	5			0	9	1	5			6	9	18	7		
4	13	19	3			9	16	0	7			1	5	17	4		
5	3	20	5			5	7	7	8			3	3	15	7		
7	3	22	17			12	10	5	8			4	3	14	5		
13	11	13	7			10	6	13	10			4	2	10	8		
1	12	12	5			13	18	13	4			11	5	10	7		
14	14	9	17			6	10	18	7			10	9	8	2		
9	15	7	12			10	9	6	5			11	6	10	8		
2	13	17	8			11	3	11	2			11	8	5	5		
8	13	15	4			10	10	13	8			11	6	9	7		
10	3	13				0	5	5				10	6	7			
9	12	7				5	7	12				9	6	4			
4	13	6				11	13	14				7	5	7			
0	9	6				13	13	16				9	14	5			
16	3	8				17	5	9				9	5	8			
8	8	4				0	5	1				3	7	7			
9	11	6				3	1	10				7	8	2			
17	9	11				17	1	9				8	9	8			
18	4	6				21	2	15				6	8	5			
7	1	2				15	1	7				7	4	3			
20	16	4				16	2	11				7	1	4			
10	8	8				10	4	6				12	6	2			
14	9	10				3	3	16				8	7	5			
20	18	11				2	2	10				14	7	8			

Table B22: Pedestrian Crossing- Evening Peak Queue Data

Pedestrian Crossing- Queue Length, Evening Peak, Duration: 3pm to 5pm, Date: 12.03.13													
Portswood Rd (SW)							Portswood Rd (NE)						
Q1 (Nr)							Q2 (Nr)						
5	1	3	3	1	4	8	5	3	7	2	2	2	4
2	5	14	7	3	1	15	3	2	5	10	2	2	9
3	6	3	3	7	4	3	8	5	6	1	4	1	0
9	6	3	4	1	2	15	3	3	3	6	5	7	5
3	3	15	4	2	0	0	2	2	2	0	3	4	3
2	10	9	3	8	6	15	0	2	9	1	3	1	11
4	6	1	5	8	4	1	0	3	7	0	3	1	1
1	12	9	3	1	0	15	2	0	0	4	6	3	0
3	1	3	2	0	5		6	4	0	5	6	2	
1	14	5	1	0	1		7	3	4	2	8	3	

Table B23: Pedestrian Crossing- Inter Peak Queue Data

Pedestrian Crossing- Queue Length, Inter Peak, Duration: 11am to 1pm, Date: 12.03.13													
Portswood Rd (SW)							Portswood Rd (NE)						
Q1 (Nr)							Q2 (Nr)						
3	4	4	9	3	3		1	2	6	5	10	0	
3	5	0	0	0	5		5	6	0	3	7	1	
5	10	4	0	2	1		7	3	1	5	4	1	
2	3	3	0	7	5		0	7	5	11	2	2	
4	2	2	3	5	0		5	1	5	1	2	5	
2	1	0	1	4	7		2	2	6	3	0	3	
2	0	10	1	0	5		2	6	9	5	3	4	
2	2	0	1	9	2		1	4	0	6	2	5	
3	1	10	0	2	1		1	4	9	8	3	3	
3	1	3	2	2			2	1	0	2	4		

Appendix B

Queue Occupancy Data

Table B24: Queue Occupancy Data

Queue Occupancy Data		
Link Length (m)	Nr of Queuing Vehicles (Nr)	
	Date: 20.03.13	Date: 06.03.13
	T Junction	Cross Junction
100	16	17
100	19	17
100	18	17
100	18	17
100	18	17
100	18	17
100	18	17
100	19	17
100	16	18
100	16	17
100	15	17
100	16	17
100	18	17
100	15	17
100	18	15
100	19	16
100	18	18
100	19	16
100	16	18
100	17	15
100	17	16
100	17	18
100	16	16
100	17	16
100	16	15
100	17	18
100	16	17

Queue Clearance Data

Table B25: Queue Clearance Time

Queue Clearance Time : Time required (T, sec) to cross the stop-line by last queuing vehicle (Q, nr)															
Date: 20.03.13								Date: 06.03.13							
T Junction								Cross Junction							
Q	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q	T
nr	sec	nr	sec	nr	sec	nr	sec	nr	sec	nr	sec	nr	sec	nr	sec
5	11	10	22	15	32	20	37	5	12	10	24	15	32	20	44
5	12	10	22	15	32	20	39	5	12	10	22	15	33	20	45
5	11	10	21	15	34	20	40	5	13	10	22	15	34	20	44
5	9	10	22	15	28	20	41	5	11	10	21	15	30	20	40
5	10	10	19	15	28	20	42	5	11	10	20	15	30	20	42
5	12	10	22	15	32	20	42	5	9	10	21	15	32	20	42
5	12	10	22	15	30	20	44	5	11	10	20	15	33	20	38
5	11	10	21	15	32	20	38	5	10	10	20	15	33	20	44
5	10	10	20	15	33	20	42	5	12	10	21	15	34	20	45
5	10	10	23	15	34	20	38	5	11	10	19	15	31	20	38
5	9	10	17	15	30	20	41	5	10	10	20	15	30	20	41
5	13	10	23	15	30	20	47	5	10	10	21	15	33	20	47
5	10	10	23	15	32	20	42	5	11	10	22	15	30	20	42
5	10	10	21	15	33	20	43	5	10	10	21	15	30	20	44
5	10	10	19	15	33	20	43	5	11	10	21	15	32	20	42
5	10	10	20					5	11	10	21				
5	10	10	19					5	9	10	20				
5	12	10	22					5	10	10	20				
5	12	10	23					5	11	10	19				
5	11	10	20					5	10	10	22				
5	10	10	22					5	11	10	23				
5	11	10	22					5	12	10	17				
5	10	10	19					5	9	10	23				
5	10	10	22					5	12	10	23				
5	10	10	20					5	12	10	17				

Signal Delay Data

Table B26: Cross Junction- Signal Delay

Cross Junction- Signal Delay, Date: 06.05.13 to 24.05.13															
Inter Peak and Morning Peak								Evening Peak							
(Sec)								(Sec)							
131	68	30	28	9	0	32		0	38	0	58	85	71		
72	0	40	25	0	52	53		50	69	55	33	59	41		
29	0	17	44	0	11	36		50	0	31	0	38	74		
0	42	0	27	38	80	86		59	66	68	29	20	0		
87	61	0	74	0	0	26		65	37	0	0	36	74		
0	73	0	25	53	38	0		0	69	99	71	0	18		
33	38	44	4	0	0			21	40	0	55	59	32		
85	0	64	36	6	49			59	100	36	47	55	33		
62	57	22	83	60	0			96	0	0	16	75	91		
56	101	97	66	31	46			20	84	0	0	69			

Appendix B

Table B27: T Junction- Signal Delay

T Junction- Signal Delay, Date: 06.05.13 to 24.05.13															
Inter Peak								Morning and Evening Peak							
(Sec)								(Sec)							
36	13	24	25	0				0	47	30	48	37	0		
23	42	0	0	37				50	32	0	33	43	28		
19	0	18	22	31				51	24	0	59	44	37		
0	30	0	23	32				53	0	0	0	47	0		
0	0	17	0	0				0	0	15	34	0	67		
0	0	0	0	0				134	19	0	44	0			
44	28	41	37	32				0	25	0	66	31			
17	0	0	0	32				54	28	30	52	43			
36	0	0	0	20				45	0	10	30	19			
36	40	0	14	38				56	41	20	57	22			

Table B28: Pedestrian Crossing- Signal Delay

Pedestrian Crossing - Signal Delay, Date: 06.05.13 to 24.05.13															
Inter Peak and Morning Peak								Evening Peak							
(Sec)								(Sec)							
13	0	16	0	0	16			10	20	18	0	0	8		
0	19	21	0	0	0			0	0	18	0	21	0		
0	21	0	26	6	14			0	21	10	17	23	0		
0	51	0	0	0	22			20	0	18	22	0	7		
14	43	15	0	8				0	0	0	0	14			
4	0	15	0	26				0	21	45	48	5			
0	16	0	0	23				40	0	23	0	16			
0	13	0	7	17				5	18	0	0	0			
17	5	0	38	0				23	18	18	14	0			
33	0	13	22	6				21	15	18	21	19			

Journey Time Delay Data

Table B29: Journey Time Delay Data

[BS = Bus Service, AT = Actual Travel Time, ST = Scheduled Travel Time, TD = Travel Time Delay, JD = Signalised Junctions Delay, PD = Signalised Pedestrian Crossings Delay, WSJ = Waste of Travel Time by Signalised Junctions, WSP = Waste of Travel Time by Signalised Pedestrian Crossing.]

Journey Time Delay Data, Date: 06.05.13 to 24.05.13															
Morning & Evening Peak								Inter Peak							
BS	AT	ST	TD	JD	PD	WSJ	WSP	BS	AT	ST	TD	JD	PD	WSJ	WSP
U6	898	840	58	89	10	11%	1%	U6	822	840	-18	33	14	4%	2%
U6	1010	840	170	209	30	25%	4%	U6	848	840	8	176	10	21%	1%
U6	825	840	-15	132	6	16%	1%	U6	878	840	38	169	20	20%	2%
U6	937	780	157	259	0	33%	0%	U6	939	840	99	242	5	29%	1%
U6	822	780	42	91	0	12%	0%	U6	857	840	17	100	0	12%	0%
U6	789	780	9	144	5	18%	1%	U6	850	840	10	114	0	14%	0%
U2	842	600	242	508	0	85%	0%	U6	853	780	73	61	39	8%	5%
U2	574	600	-26	143	5	24%	1%	U6	820	780	40	146	17	19%	2%
U2	840	1080	-240	168	15	16%	1%	U6	800	780	20	57	11	7%	1%
U2	768	1080	-312	77	0	7%	0%	U6	975	780	195	229	31	29%	4%
U6	980	840	140	274	0	33%	0%	U6	886	780	106	150	0	19%	0%
U6	1212	840	372	365	7	43%	1%	U2	696	600	96	177	0	30%	0%
U6	1064	840	224	300	0	36%	0%	U2	535	600	-65	149	0	25%	0%
U6	833	840	-7	129	11	15%	1%	U2	622	600	22	217	0	36%	0%
U6	890	840	50	211	10	25%	1%	U2	839	1080	-241	155	20	14%	2%
U6	780	840	-60	119	14	14%	2%	U2	710	1080	-370	80	0	7%	0%
U6	1150	840	310	264	17	31%	2%	U2	810	1080	-270	221	0	20%	0%
U6	880	780	100	146	25	19%	3%	F5	813	840	-27	142	21	17%	3%
U6	1130	780	350	232	35	30%	4%	F5	784	840	-56	60	42	7%	5%
U6	934	780	154	262	11	34%	1%	F5	883	840	43	157	21	19%	3%
U6	790	780	10	152	7	19%	1%	F5	718	840	-122	110	42	13%	5%
U6	813	780	33	122	15	16%	2%	F5	993	720	273	77	38	11%	5%
U6	934	780	154	292	13	37%	2%	F5	880	720	160	151	27	21%	4%
U6	903	780	123	143	0	18%	0%	F5	1045	720	325	221	40	31%	6%
U6	849	780	69	289	0	37%	0%	B2	805	840	-35	217	14	26%	2%
U2	742	600	142	253	0	42%	0%	B2	482	840	-358	91	13	11%	2%
U2	659	600	59	230	0	38%	0%	B2	862	840	22	124	42	15%	5%
U2	624	600	24	202	0	34%	0%	B2	580	840	-260	107	29	13%	3%
U2	660	1080	-420	126	14	12%	1%	B2	957	840	117	171	9	20%	1%
U2	1018	1080	-62	266	40	25%	4%	B2	696	840	-144	110	0	13%	0%
U2	880	1080	-200	224	0	21%	0%	B2	960	840	120	226	56	27%	7%
F5	841	840	1	94	21	11%	3%	B2	838	840	-2	143	14	17%	2%
F5	817	840	-23	199	0	24%	0%	B2	720	840	-120	161	23	19%	3%
F5	883	840	43	174	15	21%	2%	B2	803	840	-37	120	25	14%	3%
F5	1162	840	322	215	38	26%	5%	B1	676	600	76	183	22	31%	4%
F5	938	840	98	125	0	15%	0%	B1	550	600	-50	53	13	9%	2%
F5	909	840	69	144	27	17%	3%	B1	717	720	-3	12	14	2%	2%
B2	755	840	-85	163	28	19%	3%	B1	695	720	-25	68	27	9%	4%
B2	781	840	-59	146	10	17%	1%	B1	662	720	-58	80	0	11%	0%
B2	655	840	-185	82	14	10%	2%	F7	601	540	61	67	49	12%	9%
B2	956	840	116	187	54	22%	6%	F7	706	540	166	145	36	27%	7%
B2	919	840	79	254	34	30%	4%	F7	722	540	182	134	19	25%	4%
B2	844	840	4	187	17	22%	2%	F7	560	540	20	38	0	7%	0%
B1	719	600	119	96	11	16%	2%	F7	630	480	150	66	32	14%	7%
B1	700	600	100	61	10	10%	2%	F7	541	480	61	65	0	14%	0%
B1	920	600	320	119	12	20%	2%	F7	506	480	26	40	17	8%	4%
B1	790	600	190	157	37	26%	6%								
B1	941	600	341	167	0	28%	0%								
B1	675	720	-45	35	20	5%	3%								
B1	789	720	69	62	35	9%	5%								
B1	895	720	175	73	0	10%	0%								
B1	800	720	80	41	35	6%	5%								
F7	473	540	-67	43	10	8%	2%								

Journey Time Delay Data, Date: 06.05.13 to 24.05.13															
Morning & Evening Peak								Inter Peak							
BS	AT	ST	TD	JD	PD	WSJ	WSP	BS	AT	ST	TD	JD	PD	WSJ	WSP
F7	644	540	104	206	20	38%	4%								
F7	587	540	47	157	0	29%	0%								
F7	604	540	64	150	15	28%	3%								
F7	1107	540	567	163	55	30%	10%								
F7	587	540	47	107	34	20%	6%								
F7	623	540	83	89	21	16%	4%								
F7	716	540	176	47	14	9%	3%								
F7	583	540	43	46	44	9%	8%								

Bus Service Data

Table B30: Junctions Bus Service Details

Junctions Bus Service Details, Date: 06.05.13 to 24.05.13				
Cross Junction				
Bus Service	Service Provider	Frequency	Arm - Arm	Direction
F5	First Bus	Every 30 minutes	Portswood Rd (SW) - Portswood Rd (NE)	Sholing - Tulip Road
F7	First Bus	Every 7 minutes	Portswood Rd (SW) - St Denys Rd (SE)	Southampton City Centre - Townhill Park
B2	Blue Star	Every 20 minutes	Portswood Rd (SW) - Portswood Rd (NE)	Southampton City Centre - Fair Oak Square
B16	Blue Star	Every 15 minutes	Portswood Rd (SW) - St Denys Rd (SE)	Southampton City Centre - Townhill Park
U1	Unilink	Every 7 minutes	Portswood Rd (SW) - Highfield Ln (NW)	Southampton City Centre - Airport Parkway
U6	Unilink	Every 20 minutes	Portswood Rd (SW) - Portswood Rd (NE)	Southampton City Centre - General Hospital
Pedestrian Crossing				
F5	First Bus	Every 30 minutes	Portswood Rd (SW) - Portswood Rd (NE)	Sholing - Tulip Road
F7	First Bus	Every 7 minutes	Portswood Rd (SW) - Portswood Rd (NE)	Southampton City Centre - Townhill Park
B2	Blue Star	Every 20 minutes	Portswood Rd (SW) - Portswood Rd (NE)	Southampton City Centre - Fair Oak Square
B16	Blue Star	Every 15 minutes	Portswood Rd (SW) - Portswood Rd (NE)	Southampton City Centre - Townhill Park
U1	Unilink	Every 7 minutes	Portswood Rd (SW) - Portswood Rd (NE)	Southampton City Centre - Airport Parkway
U6	Unilink	Every 20 minutes	Portswood Rd (SW) - Portswood Rd (NE)	Southampton City Centre - General Hospital
T-Junction				
U2	Unilink	Every 10 minutes	Burgess Rd (SW) - Burgess Rd (NE) - Glen Eyre Rd (NW)	Southampton City Centre - Bencraft
U6	Unilink	Every 20 minutes	Burgess Rd (SW) - Burgess Rd (NE)	Southampton City Centre - General Hospital
U9	Unilink	Every 60 minutes	Burgess Rd (SW) - Burgess Rd (NE)	General Hospital - Townhill Park

Bus Stops Dwell Time Data

Table B31: Bus Stop Dwell Time- Portswood Broadway

Bus Stop Dwell Time- Portswood Broadway, Date: 06.05.13 to 24.05.13														
Dwell Time (Sec)														
27	37	35	17	51	26	20	107	41	16	24				
22	12	122	88	14	41	20	19	21	23	24				
96	25	65	20	49	76	30	20	24	25	27				
51	64	50	130	63	30	54	20	33	57	24				
49	34	34	34	85	82	25	18	30	46	117				
34	28	62	23	64	29	23	43	59	33	52				
45	15	45	61	20	49	53	79	35	36	18				
37	18	39	53	93	29	15	92	0	20	36				
57	33	41	93	16	31	19	150	13	36	18				
16	31	140	54	29	99	42	87	0	29	26				
19	0	70	30	60	17	42	36	14	87	60				
22	0	26	54	85	26	39	36	34	38	45				
22	27	37	68	39	97	75	60	19	21	36				
42	40	33	42	79	43	50	121	31	49	26				
31	16	27	58	42	17	26	96	97	69	11				
14	23	85	20	72	28	79	73	232	35	45				
26	0	75	66	18	77	44	87	75	56	23				
26	34	0	16	22	50	28	39	42	17	49				
34	13	34	43	29	51	21	77	34	13	31				
14	33	15	81	57	50	23	45	87	0	25				
0	16	20	33	59	49	43	27	60	49	60				
11	0	60	143	76	34	36	39	41	9	73				
18	14	34	88	51	31	51	20	69	13	20				
38	17	27	27	28	72	57	17	227	42	15				
19	23	107	62	28	86	70	0	66	48	34				
39	21	100	46	86	18	25	36	82	20					
20	18	53	27	36	0	25	64	11	30					
73	33	32	77	43	52	86	124	17	59					
35	16	18	31	104	36	14	13	49	33					
0	28	26	51	50	35	62	19	14	18					
13	18	47	0	24	58	42	69	34	19					
68	0	26	116	41	74	0	38	38	47					
0	32	30	44	24	41	0	25	85	52					
23	25	17	106	35	28	30	26	23	82					
33	19	19	15	57	40	64	27	55	16					
40	32	51	45	50	13	25	78	0	34					
33	22	54	27	19	65	63	17	72	36					
0	19	52	52	27	36	116	36	17	146					
19	21	35	32	20	34	34	127	42	68					
67	75	0	117	33	0	48	34	10	20					

Table B32: Bus Stop Dwell Time- University Interchange

Bus Stop Dwell Time- University Interchange, Date: 06.05.13 to 24.05.13														
Dwell Time (Sec)														
197	35	145	218	55	116	280	165	113	142	71	180			
259	58	208	181	162	76	26	87	67	212	181	131			
37	33	298	187	174	66	40	58	48	220	269	159			
174	39	196	171	57	61	52	180	47	250	375	218			
134	136	66	206	224	42	435	258	53	245	81	80			
126	35	248	199	41	69	154	244	104	109	253	223			
41	38	92	48	239	178	75	88	104	21	60	107			
42	138	435	220	48	193	48	170	117	32	170	464			
67	146	223	30	46	96	74	193	50	49	92	91			
35	111	156	73	81	61	176	202	180	38	55	187			
255	241	34	222	156	92	32	204	192	150	268	65			
207	208	55	221	59	28	285	109	44	104	47	157			
165	143	137	90	252	21	233	82	72	147	129	208			
110	235	140	65	49	47	230	221	149	386	44	234			
32	57	296	77	224	62	60	158	169	30	30	80			
239	29	36	166	300	59	264	128	237	154	43	33			
172	79	162	95	47	15	104	172	79	35	124	72			
218	54	203	183	175	10	102	132	56	104	35	111			
50	122	60	168	334	53	312	112	205	17	33	18			
128	177	80	257	156	298	72	258	30	114	145	0			
49	45	193	92	200	428	40	211	82	18	69	0			
125	136	80	51	128	50	258	54	94	195	210	75			
37	45	131	300	42	39	168	203	104	132	193	50			
66	245	50	215	313	446	166	191	266	326	165	48			
125	95	276	217	35	109	257	61	28	55	64	64			
46	134	43	159	33	183	142	170	173	33	23	45			
205	254	144	164	73	308	147	64	226	267	118	70			
43	140	153	100	93	0	292	178	71	282	31	60			
180	64	41	239	180	29	191	234	197	242	259	54			
228	206	100	218	84	17	188	190	40	23	273	64			
208	150	199	147	290	88	100	151	211	165	141				
76	273	97	91	137	48	282	257	106	62	91				
158	107	84	239	305	309	139	244	85	202	42				
176	138	236	192	32	84	168	167	226	60	176				
83	190	110	172	83	40	284	53	217	66	396				
37	60	142	200	61	547	238	108	53	126	82				
211	120	429	223	144	105	113	59	23	185	213				
184	107	94	46	191	104	192	32	179	199	107				
30	51	173	325	190	238	101	54	111	191	26				
146	148	162	220	158	52	64	152	50	87	30				

Table B33: Bus Stops Dwell Time- Request Stops

Bus Stops Dwell Time- Request Stops, Date: 06.05.13 to 24.05.13														
Dwell Time (Sec)														
21	0	0	46	12	20	0	23	0	0	19	22	17		
0	18	0	0	15	22	0	10	13	11	0	18	18		
17	0	0	0	29	0	0	25	14	0	0	0	0		
0	0	0	12	33	0	0	0	0	0	0	23	16		
0	0	17	0	0	0	0	0	0	11	0	13	0		
0	11	0	0	25	0	0	16	18	23	0	0	31		
0	0	13	18	16	19	38	11	10	0	0	18	23		
27	11	0	22	29	13	0	21	16	0	9	36	15		
0	0	10	12	0	26	0	18	18	0	16	0	16		
0	0	0	8	9	0	12	0	0	12	0	15	0		
0	14	28	14	14	17	0	8	0	36	25	0	22		
0	0	15	10	0	27	13	0	0	41	0	61	0		
0	0	0	0	10	0	14	20	30	0	0	0	0		
24	51	0	0	12	0	12	22	0	0	14	35	10		
13	12	0	0	12	16	24	82	0	24	34	17	30		
0	36	0	0	0	17	0	0	0	0	16	51	0		
23	47	0	0	35	99	0	22	12	7	21	0			
0	14	0	0	0	0	0	12	0	22	26	51			
19	0	0	0	0	11	14	57	0	15	0	0			
0	37	0	0	21	0	0	0	0	19	7	29			
0	0	0	0	22	22	0	14	0	0	16	0			
28	0	14	0	32	10	0	29	32	0	25	25			
0	55	76	0	41	0	0	0	0	50	87	23			
31	0	0	0	15	26	10	17	27	0	12	15			
0	18	0	43	14	9	9	0	0	0	11	25			
0	18	0	18	28	0	18	27	0	19	12	13			
15	0	18	15	0	0	0	43	12	0	0	12			
0	0	12	0	14	0	18	20	15	0	0	30			
0	17	15	49	0	29	14	21	0	0	23	0			
0	13	15	0	15	0	24	0	0	0	0	0			
12	0	25	25	0	64	15	0	23	0	12	0			
20	0	23	11	0	13	10	18	0	38	17	14			
17	0	0	0	0	23	0	0	0	10	18	82			
0	20	32	0	0	0	24	23	0	11	21	0			
43	27	86	0	0	16	0	19	0	21	30	0			
0	0	0	22	48	0	0	0	20	0	7	16			
0	0	26	17	0	0	20	36	0	10	32	32			
16	12	15	69	0	21	0	20	0	16	0	0			
14	37	44	0	10	0	0	0	0	0	39	74			
0	0	0	0	12	10	0	0	0	9	0	0			
0	13	21	56	38	0	0	15	8	19	0	0			
0	0	0	15	37	15	0	15	0	0	0	0			
26	0	28	0	0	25	0	14	0	0	18	0			
0	0	11	0	0	30	0	13	0	37	16	0			
18	0	0	0	0	22	0	23	0	0	0	17			
25	0	27	58	0	20	24	19	0	0	27	27			
0	28	0	45	0	19	12	12	17	16	0	17			
11	0	0	20	0	14	17	13	0	0	28	22			
46	14	10	34	0	0	17	45	0	20	20	12			
0	0	24	0	0	15	0	21	0	21	23	0			
33	0	0	13	30	6	0	0	0	0	0	17			
24	0	8	0	0	17	31	0	0	10	0	20			
13	10	15	0	0	0	0	0	0	0	15	0			
0	0	0	0	23	12	21	0	0	21	0	0			
0	0	12	11	18	20	0	20	0	11	23	0			
18	18	0	21	12	0	0	19	10	0	0	12			
20	10	0	0	12	27	0	24	16	0	0	0			
18	0	0	0	0	22	0	10	0	9	13	0			
0	0	23	0	14	18	0	13	0	0	0	28			
16	23	0	0	13	16	0	19	0	44	11	0			
0	0	12	0	21	0	15	70	0	0	17	20			
17	35	20	0	0	22	0	43	8	0	28	0			

Appendix B

Bus Stops Dwell Time- Request Stops, Date: 06.05.13 to 24.05.13														
Dwell Time (Sec)														
25	0	0	0	0	0	0	31	17	26	0	20			
15	17	0	0	0	0	14	0	12	0	0	25			
50	90	0	0	0	0	0	22	0	41	0	0			
13	23	30	0	0	22	27	11	0	0	12	0			
0	20	0	0	32	0	37	0	15	70	19	0			
15	28	24	0	0	26	32	0	19	37	23	20			
19	63	0	18	0	18	18	33	17	27	0	90			
0	0	0	0	0	26	0	13	0	0	11	0			
0	0	0	42	0	14	19	0	0	0	0	25			
22	11	0	33	0	10	19	13	0	13	25	36			
8	16	0	0	19	0	0	0	14	0	0	21			
20	0	0	0	85	15	0	0	22	19	0	11			
25	0	15	19	48	12	0	66	29	0	22	0			
28	0	9	0	38	0	11	0	0	0	14	13			
0	0	0	16	20	0	0	0	59	30	8	19			
14	0	15	16	0	41	0	0	0	0	0	15			
23	0	0	0	0	0	0	14	17	0	8	35			
27	0	77	9	21	20	0	0	0	0	26	13			
16	21	21	16	0	16	0	20	21	22	0	15			
9	23	16	16	0	55	0	36	0	65	0	25			
15	0	0	36	19	0	0	4	15	14	72	31			
14	0	0	9	0	0	20	0	14	18	0	0			
0	15	24	50	24	16	0	11	0	0	0	15			
23	0	0	10	13	26	8	0	34	0	0	0			
16	12	0	0	27	14	18	22	33	0	51	13			
20	0	18	16	31	16	0	0	13	0	16	27			
14	15	14	21	25	0	9	0	0	29	0	14			
9	0	21	0	0	0	0	13	21	0	8	13			
14	17	0	0	21	18	44	0	8	0	0	0			
0	11	0	18	18	0	14	0	32	14	0	14			
13	0	8	14	21	0	29	19	14	0	16	17			
0	0	16	16	0	0	0	35	0	17	0	16			
0	0	17	35	0	12	16	0	21	0	20	20			
0	0	0	14	19	23	0	0	0	15	0	16			
0	0	0	17	12	0	21	0	23	0	0	42			
34	0	0	22	43	0	81	0	14	0	7	0			
0	0	0	21	25	11	0	0	0	0	0	0			
0	0	0	0	16	10	17	0	27	0	0	0			

Speed Data

Table B34: Junctions Speed Data

Junctions Speed Data: Calculated from Travel Time Data			
50m Travel Time (Sec)			
T Junction, Date: 20.03.13		Cross Junction, Date: 06.03.13	
Inter Peak	Peak	Inter Peak	Peak
4.19	6.14	8.31	8.25
4.19	6.36	8.62	6.95
5.59	6.31	8.80	4.05
4.56	6.14	7.65	6.24
5.61	5.29	7.25	7.77
4.24	4.66	6.75	8.76
6.14	6.94	7.79	4.76
6.05	6.99	6.48	7.27
4.59	6.28	7.18	4.10
4.83	6.76	7.14	6.49
5.73	4.84	7.30	6.81
4.49	5.64	6.23	7.25
5.76	4.12	4.76	5.76
4.64	7.33	6.90	5.53
5.59	5.21	5.73	7.78
6.22	5.43	4.71	7.90
4.78		3.95	6.29
3.98		4.24	
		3.95	
		5.90	
Average Travel Time (Sec)			
5.06	**5.90**	**6.48**	**6.59**
Speed (m/s)			
9.87	**8.47**	**7.71**	**7.59**

Bus Occupancy Data

Table B35: Bus Occupancy Data

Bus Occupancy Data, Date: 06.05.13 to 24.05.13, Peak													
Service Name	F7		U2		U6			B1		B2		F5	
Occupancy (Nr)	15	19	31	67	30	21	92	16	40	17	42	15	34
	13	20	67	67	32	17	39	37	39	22	32	21	28
	33	30	67	39	28	92	20	33	37	49	30	25	
	17	11	23	55	25	23	92	30	42	43	38	16	
	15	33	31		33	32	25	28	43	53	29	19	
	26	15	30		43	35	15	22	23	50	37	11	
	14		43		24	22	15	45		31		17	
	55		40		27	37	92	43		28		10	
	42		29		27	19	41	36		26		18	
	25		44		15	33	92	35		35		23	
Average	**33.67**												

Average Person Delay Calculation

The average person delay is estimated combining delays of vehicles and their average vehicle occupancy, and also considering pedestrian delay in the pedestrian crossings. The average occupancy during weekday peak according to Web TAG 3.5.6 (DfT 2014b) for cars is 1.45. It has been observed (Table B35) that during peak hours average bus occupancy is

33.67 (passengers only). Using these values, the delay per person can be calculated using equation below:

Average Person Delay = [1.45* (delay/car)*total cars + 33.67*(delay/bus)*total buses + (delay/pedestrian)*total pedestrian] / total persons

Expectations

Cross Junction with pedestrian crossing could cause unacceptable person delay due to bus priority as it's pedestrian activity is very high and also non priority arms are very busy. And Cross Junction without pedestrian crossing could increase average person delay as it's non priority arms are very busy. Again, T Junction with pedestrian crossing also could increase average person delay as it's pedestrian activity is high. But T Junction without pedestrian crossing average person delay savings is expected as this junction is not busy. Also at pedestrian crossing average person delay savings is expected as delay to pedestrian due to bus priority is not high but with bus priority all cars also get benefits.

Appendix C

Signal Controller Development: T Junction with Pedestrian Crossing

Sample VAP Code

[Notes: In the Codes, for each scenario,

Main Interface is coded under MAIN PROGRAM

Isolated VA Signal Controller (general setting without bus priority) is coded under SUBROUTINE General_Stage

Bus Priority Method is coded under SUBROUTINE Bus_Stage

Compensation Method is coded under SUBROUTINE Compensation_Stage

Priority Cancel Method by Exit Detectors is coded under SUBROUTINE Cancel_Bus_Stage]

VAP Code S1: General Signal Controller Module

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\Debuged\ManyBuses_07.03.15\Two Stages +
Ped\Without Bus Priority\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
            END;


/* EXPRESSIONS */
            Veh_Detec_1 := Detection (1) > 0;
            Veh_Detec_2 := Detection (2) > 0;
            Ped_Detec := Detection (3) > 0;
            Min_Green_Stage1 := T_green (1) >= T_green_min (1);
            Min_Green_Stage2 := T_green (2) >= T_green_min (2);
```

```
            Min_Green_Stage3 := T_green (3) >= T_green_min (3);
            Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
            Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
            Gap_Out_1 := Headway (1) >= MIN_GAP;
            Gap_Out_2 := Headway (2) >= MIN_GAP;

/* General_Stage */

S00Z002:    IF Stage_active( 1 ) THEN
S01Z002:      IF Veh_Detec_1 THEN
S02Z002:        IF Max_Green_Stage1 AND Veh_Detec_2 THEN
S03Z002:          Interstage( 1,2)
                ELSE
S02Z003:          IF Max_Green_Stage1 AND Ped_Detec THEN
S03Z003:            Interstage( 1,3)
                  END
                END
              ELSE
S01Z005:        IF Max_Green_Stage1 AND Veh_Detec_2 THEN
S03Z005:          Interstage( 1,2)
                ELSE
S01Z006:          IF Max_Green_Stage1 AND Ped_Detec THEN
S03Z006:            Interstage( 1,3)
                  ELSE
S01Z007:            IF Veh_Detec_2 THEN
S02Z007:              IF Min_Green_Stage1 AND Gap_Out_1 THEN
S03Z007:                Interstage( 1,2)
                      END
                    ELSE
S01Z009:              IF Ped_Detec THEN
S02Z009:                IF Min_Green_Stage1 AND Gap_Out_1 THEN
S03Z009:                  Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
S00Z011:    IF Stage_active( 2 ) THEN
S01Z011:      IF Veh_Detec_2 THEN
S02Z011:        IF Max_Green_Stage2 AND Ped_Detec THEN
S03Z011:          Interstage( 2,3)
                ELSE
S02Z012:          IF Max_Green_Stage2 AND Veh_Detec_1 THEN
```

```
S03Z012:          Interstage( 2,1)
                END
              END
            ELSE
S01Z014:      IF Max_Green_Stage2 AND Ped_Detec THEN
S03Z014:        Interstage( 2,3)
              ELSE
S01Z015:        IF Max_Green_Stage2 AND Veh_Detec_1 THEN
S03Z015:          Interstage( 2,1)
                ELSE
S01Z016:          IF Ped_Detec THEN
S02Z016:            IF Min_Green_Stage2 AND Gap_Out_2 THEN
S03Z016:              Interstage( 2,3)
                    END
                  ELSE
S01Z018:            IF Veh_Detec_1 THEN
S02Z018:              IF Min_Green_Stage2 AND Gap_Out_2 THEN
S03Z018:                Interstage( 2,1)
                      END
                    END
                  END
                END
              END
            END
          END;
S00Z021:  IF Stage_active( 3 ) THEN
S02Z021:    IF Min_Green_Stage3 AND Veh_Detec_1 THEN
S03Z021:      Interstage( 3,1)
            ELSE
S02Z022:      IF Min_Green_Stage3 AND Veh_Detec_2 THEN
S03Z022:        Interstage( 3,2)
              ELSE
S02Z023:        IF Min_Green_Stage3 THEN
S03Z023:          Interstage( 3,1)
                END
              END
            END
          END
PROG_ENDE:  .
/*--------------------------------------------------------------------------------*/
```

Appendix C

VAP Code S2: Extension

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\Extension Only\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1);
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION
            END;
D01S00Z007: IF Stage_active (1) THEN
D01S01Z007:   IF T_green (1) < Absolute_Extension THEN
D01S02Z007:     IF T_green (1) >=Req_Extension THEN
D01S03Z007:       Detec_Stg_1:=0
                END
              ELSE
D01S03Z009:     Detec_Stg_1:=0; Interstage( 1,2)
              END
            ELSE
D01S00Z010:   Detec_Stg_1:=0
            END
D01PROG_ENDE: .
/*--------------------------------------------------------------------------*/


SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                  END
                END
              ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
                ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
```

```
                ELSE
D02S01Z007:       IF Veh_Detec_2 THEN
D02S02Z007:         IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:           Interstage( 1,2)
                    END
                  ELSE
D02S01Z009:         IF Ped_Detec THEN
D02S02Z009:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:             Interstage( 1,3)
                      END
                    END
                  END
                END
              END
            END
          END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
              ELSE
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
```

```
            END
          END;
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
D02PROG_ENDE: .
/*----------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
              G_EXTENSION := 23;
              MAX_EXTENSION := 50;
            END;

/* EXPRESSIONS */
            Veh_Detec_1 := Detection (1) > 0;
            Veh_Detec_2 := Detection (2) > 0;
            Ped_Detec := Detection (3) > 0;
            Min_Green_Stage1 := T_green (1) >= T_green_min (1);
            Min_Green_Stage2 := T_green (2) >= T_green_min (2);
            Min_Green_Stage3 := T_green (3) >= T_green_min (3);
            Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
            Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
            Gap_Out_1 := Headway (1) >= MIN_GAP;
            Gap_Out_2 := Headway (2) >= MIN_GAP;
```

```
/* MAIN PROGRAM */

S00Z002:    IF NOT Detec_Stg_1 THEN
S02Z002:      IF Presence (1001) THEN
S04Z002:        Detec_Stg_1:= 1
              END
            END;
S00Z005:    IF Detec_Stg_1 THEN
S04Z005:      GOSUB Bus_Stage
            ELSE
S00Z008:      GOSUB General_Stage
            END
PROG_ENDE:    .
/*------------------------------------------------------------------------------*/
```

VAP Code S3: Recall

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\Recall Only\T_Junction.vv */

VAP_FREQUENCY 1;



/* ARRAYS */

/* SUBROUTINES */

SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Stage_active (1) THEN
D01S02Z003:   IF NOT R THEN
D01S03Z003:     Detec_Stg_1:= 0
              ELSE
D01S02Z004:     IF T_green (1) >= MIN_RED THEN
D01S03Z004:       Detec_Stg_1:= 0; R:= 0
                END
              END
            END;
D01S00Z007: IF Stage_active (2) THEN
D01S02Z007:   IF T_green (2)>= T_green_min (2) THEN
D01S03Z007:     Interstage (2,3)
              END
            END;
D01S00Z010: IF Stage_active (3) THEN
D01S02Z010:   IF T_green (3)>= T_green_min (3) THEN
D01S03Z010:     R:= 1; Interstage (3,1)
              END
            END
```

```
D01PROG_ENDE: .
/*------------------------------------------------------------------------------*/

SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                  END
                END
              ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
                ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                  ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
              ELSE
```

```
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
D02PROG_ENDE: .
/*-----------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_RED_1 := 55;
              AVG_TRAVEL_TIME := 18;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
```

```
            MIN_RED := 29;
          END;

/* EXPRESSIONS */
          Veh_Detec_1 := Detection (1) > 0;
          Veh_Detec_2 := Detection (2) > 0;
          Ped_Detec := Detection (3) > 0;
          Min_Green_Stage1 := T_green (1) >= T_green_min (1);
          Min_Green_Stage2 := T_green (2) >= T_green_min (2);
          Min_Green_Stage3 := T_green (3) >= T_green_min (3);
          Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
          Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
          Gap_Out_1 := Headway (1) >= MIN_GAP;
          Gap_Out_2 := Headway (2) >= MIN_GAP;

/* MAIN PROGRAM */

S00Z002:  IF NOT Detec_Stg_1 THEN
S02Z002:    IF Presence (1001) THEN
S03Z002:      IF Stage_active (1) THEN
S04Z002:        Detec_Stg_1:= 1
              ELSE
S03Z003:        Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z004:        IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z004:          Detec_Stg_1:= 1
                END
              END
            END
          END;
S00Z007:  IF Detec_Stg_1 THEN
S04Z007:    GOSUB Bus_Stage
          ELSE
S00Z010:    GOSUB General_Stage
          END
PROG_ENDE:  .
/*-----------------------------------------------------------------------------*/
```

VAP Code S4: Extension with Recall

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\Extension & Recall\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1);
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION
            END;
D01S00Z006: IF Stage_active (1) THEN
D01S01Z006:   IF NOT R THEN
D01S02Z006:     IF T_green (1) < Absolute_Extension THEN
D01S03Z006:       IF T_green (1) >=Req_Extension THEN
D01S04Z006:         Detec_Stg_1:= 0
                  END
                ELSE
D01S04Z008:       Detec_Stg_1:=0; Interstage( 1,2)
                END
              ELSE
D01S01Z009:     IF Presence (1001) THEN
D01S04Z009:       R:= 0
                ELSE
D01S01Z010:       IF T_green (1) >= MIN_RED THEN
D01S04Z010:         Detec_Stg_1:= 0; R:= 0
                  END
                END
              END
            END;
D01S00Z013: IF Stage_active (2) THEN
D01S03Z013:   IF T_green (2)>= T_green_min (2) THEN
D01S04Z013:     Interstage (2,3)
              END
            END;
D01S00Z016: IF Stage_active (3) THEN
D01S03Z016:   IF T_green (3)>= T_green_min (3) THEN
D01S04Z016:     R:= 1; Interstage (3,1)
              END
            END
D01PROG_ENDE: .
```

```
/*------------------------------------------------------------------------------*/


SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                  END
                END
              ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
                ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                  ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
              ELSE
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
```

```
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
D02PROG_ENDE: .
/*--------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_RED_1 := 55;
              AVG_TRAVEL_TIME := 18;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
              G_EXTENSION := 23;
```

```
            MIN_RED := 29;
            MAX_EXTENSION := 50;
          END;

/* EXPRESSIONS */
          Veh_Detec_1 := Detection (1) > 0;
          Veh_Detec_2 := Detection (2) > 0;
          Ped_Detec := Detection (3) > 0;
          Min_Green_Stage1 := T_green (1) >= T_green_min (1);
          Min_Green_Stage2 := T_green (2) >= T_green_min (2);
          Min_Green_Stage3 := T_green (3) >= T_green_min (3);
          Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
          Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
          Gap_Out_1 := Headway (1) >= MIN_GAP;
          Gap_Out_2 := Headway (2) >= MIN_GAP;
```

/* MAIN PROGRAM */

```
S00Z002:    IF NOT Detec_Stg_1 THEN
S02Z002:      IF Presence (1001) THEN
S03Z002:        IF Stage_active (1) THEN
S04Z002:          Detec_Stg_1:= 1
                ELSE
S03Z003:          Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z004:          IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z004:            Detec_Stg_1:= 1
                  END
                END
              END
            END;
S00Z007:    IF Detec_Stg_1 THEN
S04Z007:      GOSUB Bus_Stage
            ELSE
S00Z010:      GOSUB General_Stage
            END
PROG_ENDE:    .
/*----------------------------------------------------------------------------*/
```

VAP Code S5: Cut and Recall

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\Cut&Recall\Two Stages + Ped\Cut &
Recall\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1);
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION;
D01S01Z005:   Remaining_Green:= MAX_GREEN_STG1- Current_Green_Stg1; NoCut:=
(Remaining_Green >= G_EXTENSION)
            END;
D01S00Z007: IF Stage_active (1) THEN
D01S01Z007:   IF NOT R THEN
D01S02Z007:     IF T_green (1) < Absolute_Extension THEN
D01S03Z007:       IF NoCut THEN
D01S04Z007:         IF T_green (1) >=Req_Extension THEN
D01S05Z007:           Detec_Stg_1:= 0
                    END
                  ELSE
D01S05Z009:         Interstage( 1,2)
                  END
                ELSE
D01S05Z010:       Detec_Stg_1:=0; Interstage( 1,2)
                END
              ELSE
D01S01Z012:     IF T_green (1) >= MIN_RED THEN
D01S05Z012:       Detec_Stg_1:= 0; R:= 0
                END
              END
            END;
D01S00Z015: IF Stage_active (2) THEN
D01S04Z015:   IF T_green (2)>= T_green_min (2) THEN
D01S05Z015:     Interstage (2,3)
              END
            END;
D01S00Z018: IF Stage_active (3) THEN
D01S04Z018:   IF T_green (3)>= T_green_min (3) THEN
D01S05Z018:     R:= 1; Interstage (3,1)
              END
```

```
            END
D01PROG_ENDE: .
/*------------------------------------------------------------------------------*/

SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                  END
                END
              ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
                ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                  ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
```

```
                  ELSE
D02S01Z014:         IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z014:           Interstage( 2,3)
                    ELSE
D02S01Z015:           IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:             Interstage( 2,1)
                      ELSE
D02S01Z016:             IF Ped_Detec THEN
D02S02Z016:               IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:                 Interstage( 2,3)
                          END
                        ELSE
D02S01Z018:               IF Veh_Detec_1 THEN
D02S02Z018:                 IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:                   Interstage( 2,1)
                            END
                          END
                        END
                      END
                    END
                  END
                END;
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:       IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:         Interstage( 3,1)
                  ELSE
D02S02Z022:         IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:           Interstage( 3,2)
                    ELSE
D02S02Z023:           IF Min_Green_Stage3 THEN
D02S03Z023:             Interstage( 3,1)
                      END
                    END
                  END
                END
D02PROG_ENDE: .
/*--------------------------------------------------------------------------------*/


/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_RED_1 := 55;
              AVG_TRAVEL_TIME := 18;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
```

```
        MIN_GAP := 2;
        G_EXTENSION := 23;
        MIN_RED := 29;
        MAX_EXTENSION := 50;
      END;

/* EXPRESSIONS */
      Veh_Detec_1 := Detection (1) > 0;
      Veh_Detec_2 := Detection (2) > 0;
      Ped_Detec := Detection (3) > 0;
      Min_Green_Stage1 := T_green (1) >= T_green_min (1);
      Min_Green_Stage2 := T_green (2) >= T_green_min (2);
      Min_Green_Stage3 := T_green (3) >= T_green_min (3);
      Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
      Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
      Gap_Out_1 := Headway (1) >= MIN_GAP;
      Gap_Out_2 := Headway (2) >= MIN_GAP;



/* MAIN PROGRAM */

S00Z002:    IF NOT Detec_Stg_1 THEN
S02Z002:      IF Presence (1001) THEN
S03Z002:        IF Stage_active (1) THEN
S04Z002:          Detec_Stg_1:= 1
                ELSE
S03Z003:          Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z004:          IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z004:            Detec_Stg_1:= 1
                  END
                END
              END
            END;
S00Z007:    IF Detec_Stg_1 THEN
S04Z007:      GOSUB Bus_Stage
            ELSE
S00Z010:      GOSUB General_Stage
            END
PROG_ENDE:    .
/*------------------------------------------------------------------------*/
```

VAP Code S6: Always Green Bus

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\AlwaysGreenBus\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1);
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION
            END;
D01S00Z006: IF Stage_active (1) THEN
D01S01Z006:   IF NOT R THEN
D01S02Z006:     IF T_green (1) < Absolute_Extension THEN
D01S03Z006:       IF T_green (1) >=Req_Extension THEN
D01S04Z006:         Detec_Stg_1:= 0
                  END
                ELSE
D01S04Z008:       Detec_Stg_1:=0; Interstage( 1,2)
                END
              ELSE
D01S01Z009:     IF Presence (1001) THEN
D01S04Z009:       R:= 0
                ELSE
D01S01Z010:       IF T_green (1) >= MIN_RED THEN
D01S04Z010:         Detec_Stg_1:= 0; R:= 0
                  END
                END
              END
            END;
D01S00Z013: IF Stage_active (2) THEN
D01S03Z013:   IF T_green (2)>= T_green_min (2) THEN
D01S04Z013:     R:= 1; Interstage (2,1)
              END
            END;
D01S00Z016: IF Stage_active (3) THEN
D01S03Z016:   IF T_green (3)>= T_green_min (3) THEN
D01S04Z016:     R:= 1; Interstage (3,1)
              END
            END
D01PROG_ENDE: .
```

```
/*---------------------------------------------------------------------------*/

SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                  END
                END
              ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
                ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                  ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
              ELSE
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
```

```
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
D02PROG_ENDE: .
/*------------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_RED_1 := 55;
              AVG_TRAVEL_TIME := 32;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
              G_EXTENSION := 42;
```

```
            MIN_RED := 42;
            MAX_EXTENSION := 50;
          END;

/* EXPRESSIONS */
          Veh_Detec_1 := Detection (1) > 0;
          Veh_Detec_2 := Detection (2) > 0;
          Ped_Detec := Detection (3) > 0;
          Min_Green_Stage1 := T_green (1) >= T_green_min (1);
          Min_Green_Stage2 := T_green (2) >= T_green_min (2);
          Min_Green_Stage3 := T_green (3) >= T_green_min (3);
          Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
          Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
          Gap_Out_1 := Headway (1) >= MIN_GAP;
          Gap_Out_2 := Headway (2) >= MIN_GAP;

/* MAIN PROGRAM */

S00Z002:  IF NOT Detec_Stg_1 THEN
S02Z002:    IF Presence (1001) THEN
S03Z002:      IF Stage_active (1) THEN
S04Z002:        Detec_Stg_1:= 1
              ELSE
S03Z003:        Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z004:        IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z004:          Detec_Stg_1:= 1
                END
              END
            END
          END;
S00Z007:  IF Detec_Stg_1 THEN
S04Z007:    GOSUB Bus_Stage
          ELSE
S00Z010:    GOSUB General_Stage
          END
PROG_ENDE:  .
/*----------------------------------------------------------------------------*/
```

VAP Code S7: Unprotected Compensation

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\tt\Extension & Recall &
Compensation\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1);
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION
            END;
D01S00Z006: IF Stage_active (1) THEN
D01S01Z006:   IF NOT R THEN
D01S02Z006:     IF T_green (1) < Absolute_Extension THEN
D01S03Z006:       IF T_green (1) >=Req_Extension THEN
D01S04Z006:         Detec_Stg_1:= 0
                  END
                ELSE
D01S04Z008:       Detec_Stg_1:=0; Interstage( 1,2)
                END
              ELSE
D01S01Z009:     IF Presence (1001) THEN
D01S04Z009:       R:= 0
                ELSE
D01S01Z010:       IF T_green (1) >= MIN_RED THEN
D01S04Z010:         Detec_Stg_1:= 0; R:= 0
                  END
                END
              END
            END;
D01S00Z013: IF Stage_active (2) THEN
D01S01Z013:   IF T_green (2)>= T_green_min (2) THEN
D01S03Z013:     Compensation_Stg2:= 1; Req_Com_2:=(MAX_GREEN_STG2-T_green (2));
D01S04Z013:     Interstage (2,3)
              END
            END;
D01S00Z016: IF Stage_active (3) THEN
D01S03Z016:   IF T_green (3)>= T_green_min (3) THEN
D01S04Z016:     R:= 1; Interstage (3,1)
              END
```

```
            END
D01PROG_ENDE: .
/*-----------------------------------------------------------------------------*/

SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                  END
                END
              ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
                ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                  ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
```

```
              ELSE
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
D02PROG_ENDE: .
/*------------------------------------------------------------------------------*/

SUBROUTINE Compensation_Stage;  /* Compensation_Stage.vv */
D03S00Z001: Com_Max_Green_2:=MAX_GREEN_STG2 + Req_Com_2;
D03S00Z002: Max_Com_Green_Stage2:=(T_green (2) >=Com_Max_Green_2);
D03S00Z003: IF NOT (Veh_Detec_2) THEN
D03S00Z004:   Compensation_Stg2:= 0; Req_Com_2:=0
            END;
D03S00Z006: IF Stage_active( 1 ) THEN
```

```
D03S01Z006:   IF Veh_Detec_1 THEN
D03S03Z006:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D03S04Z006:       Interstage( 1,2)
                ELSE
D03S03Z007:       IF Max_Green_Stage1 AND Ped_Detec THEN
D03S04Z007:         Interstage( 1,3)
                  END
                END
              ELSE
D03S01Z009:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D03S04Z009:       Interstage( 1,2)
                ELSE
D03S01Z010:       IF Max_Green_Stage1 AND Ped_Detec THEN
D03S04Z010:         Interstage( 1,3)
                  ELSE
D03S01Z011:         IF Veh_Detec_2 THEN
D03S03Z011:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D03S04Z011:             Interstage( 1,2)
                      END
                    ELSE
D03S01Z013:           Compensation_Stg2:= 0; Req_Com_2:=0;
D03S01Z014:           IF Ped_Detec THEN
D03S03Z014:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D03S04Z014:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D03S00Z016: IF Stage_active( 2 ) THEN
D03S01Z016:   IF Veh_Detec_2 THEN
D03S02Z016:     IF Compensation_Stg2 THEN
D03S03Z016:       IF Max_Com_Green_Stage2 AND Ped_Detec THEN
D03S04Z016:         Interstage( 2,3); Compensation_Stg2:= 0; Req_Com_2:=0
                  ELSE
D03S03Z017:         IF Max_Com_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z017:           Interstage( 2,1); Compensation_Stg2:= 0; Req_Com_2:=0
                    ELSE
D03S03Z018:           IF Max_Com_Green_Stage2 THEN
D03S04Z018:             Compensation_Stg2:= 0; Req_Com_2:=0
                      END
                    END
                  END
```

```
                ELSE
D03S02Z020:       IF Max_Green_Stage2 AND Ped_Detec THEN
D03S04Z020:         Interstage( 2,3)
                  ELSE
D03S02Z021:         IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z021:           Interstage( 2,1)
                    END
                  END
                END
              ELSE
D03S01Z021:     Compensation_Stg2:= 0; Req_Com_2:=0;
D03S01Z023:     IF Max_Green_Stage2 AND Ped_Detec THEN
D03S04Z023:       Interstage( 2,3)
                ELSE
D03S01Z024:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z024:         Interstage( 2,1)
                  ELSE
D03S01Z025:         IF Ped_Detec THEN
D03S03Z025:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D03S04Z025:             Interstage( 2,3)
                      END
                    ELSE
D03S01Z027:           IF Veh_Detec_1 THEN
D03S03Z027:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D03S04Z027:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
D03S00Z030: IF Stage_active( 3 ) THEN
D03S03Z030:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D03S04Z030:     Interstage( 3,1)
              ELSE
D03S03Z031:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D03S04Z031:       Interstage( 3,2)
                ELSE
D03S03Z032:       IF Min_Green_Stage3 THEN
D03S04Z032:         Interstage( 3,1)
                  END
                END
              END
            END
```

```
D03PROG_ENDE: .
/*--------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_RED_1 := 55;
              AVG_TRAVEL_TIME := 18;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
              G_EXTENSION := 23;
              MIN_RED := 29;
              MAX_EXTENSION := 50;
            END;

/* EXPRESSIONS */
            Veh_Detec_1 := Detection (1) > 0;
            Veh_Detec_2 := Detection (2) > 0;
            Ped_Detec := Detection (3) > 0;
            Min_Green_Stage1 := T_green (1) >= T_green_min (1);
            Min_Green_Stage2 := T_green (2) >= T_green_min (2);
            Min_Green_Stage3 := T_green (3) >= T_green_min (3);
            Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
            Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
            Gap_Out_1 := Headway (1) >= MIN_GAP;
            Gap_Out_2 := Headway (2) >= MIN_GAP;

/* MAIN PROGRAM */

S00Z002:    IF NOT Detec_Stg_1 THEN
S02Z002:      IF Presence (1001) THEN
S03Z002:        IF Stage_active (1) THEN
S04Z002:          Detec_Stg_1:= 1
                ELSE
S03Z003:          Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z004:          IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z004:            Detec_Stg_1:= 1
                  END
                END
              END
            END;
S00Z007:    IF Detec_Stg_1 THEN
S04Z007:      GOSUB Bus_Stage
            ELSE
```

```
S00Z008:      IF Compensation_Stg2 THEN
S04Z008:        GOSUB Compensation_Stage
              ELSE
S00Z010:        GOSUB General_Stage
              END
            END
PROG_ENDE:    .
/*------------------------------------------------------------------------*/
```

VAP Code S8: Protected Compensation by Need

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\tt\Extension & Recall & Protected
Compensation\T_Junction.vv */


VAP_FREQUENCY 1;




/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1);
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION
            END;
D01S00Z006: IF Stage_active (1) THEN
D01S01Z006:   IF NOT R THEN
D01S02Z006:     IF T_green (1) < Absolute_Extension THEN
D01S03Z006:       IF T_green (1) >=Req_Extension THEN
D01S04Z006:         Detec_Stg_1:= 0
                  END
                ELSE
D01S04Z008:       Detec_Stg_1:=0; Interstage( 1,2)
                END
              ELSE
D01S01Z009:     IF Presence (1001) THEN
D01S04Z009:       R:= 0
                ELSE
D01S01Z010:       IF T_green (1) >= MIN_RED THEN
D01S04Z010:         Detec_Stg_1:= 0; R:= 0
                  END
                END
              END
            END;
```

```
D01S00Z013: IF Stage_active (2) THEN
D01S01Z013:   IF T_green (2)>= T_green_min (2) THEN
D01S03Z013:     Compensation_Stg2:= 1; Req_Com_2:=(MAX_GREEN_STG2-T_green (2));
D01S04Z013:     Interstage (2,3)
              END
            END;
D01S00Z016: IF Stage_active (3) THEN
D01S03Z016:   IF T_green (3)>= T_green_min (3) THEN
D01S04Z016:     R:= 1; Interstage (3,1)
              END
            END
D01PROG_ENDE: .
/*----------------------------------------------------------------------------*/
```

```
SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                  END
                END
              ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
                ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                  ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
```

```
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
              ELSE
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
```

```
D02PROG_ENDE: .
/*------------------------------------------------------------------------------*/

SUBROUTINE Compensation_Stage;  /* Compensation_Stage.vv */
D03S00Z001: Com_Max_Green_2:=MAX_GREEN_STG2 + Req_Com_2;
D03S00Z002: Max_Com_Green_Stage2:=(T_green (2) >=Com_Max_Green_2);
D03S00Z003: IF NOT (Veh_Detec_2) THEN
D03S00Z004:   Compensation_Stg2:= 0; Req_Com_2:=0
            END;
D03S00Z006: IF Stage_active( 1 ) THEN
D03S01Z006:   IF Veh_Detec_1 THEN
D03S03Z006:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D03S04Z006:       Interstage( 1,2)
                ELSE
D03S03Z007:       IF Max_Green_Stage1 AND Ped_Detec THEN
D03S04Z007:         Interstage( 1,3)
                  END
                END
              ELSE
D03S01Z009:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D03S04Z009:       Interstage( 1,2)
                ELSE
D03S01Z010:       IF Max_Green_Stage1 AND Ped_Detec THEN
D03S04Z010:         Interstage( 1,3)
                  ELSE
D03S01Z011:         IF Veh_Detec_2 THEN
D03S03Z011:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D03S04Z011:             Interstage( 1,2)
                      END
                    ELSE
D03S01Z013:           Compensation_Stg2:= 0; Req_Com_2:=0;
D03S01Z014:           IF Ped_Detec THEN
D03S03Z014:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D03S04Z014:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D03S00Z016: IF Stage_active( 2 ) THEN
D03S01Z016:   IF Veh_Detec_2 THEN
D03S02Z016:     IF Compensation_Stg2 THEN
D03S03Z016:       IF Max_Com_Green_Stage2 AND Ped_Detec THEN
```

```
D03S04Z016:         Interstage( 2,3); Compensation_Stg2:= 0; Req_Com_2:=0
                  ELSE
D03S03Z017:         IF Max_Com_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z017:           Interstage( 2,1); Compensation_Stg2:= 0; Req_Com_2:=0
                    ELSE
D03S03Z018:           IF Max_Com_Green_Stage2 THEN
D03S04Z018:             Compensation_Stg2:= 0; Req_Com_2:=0
                      END
                    END
                  END
                ELSE
D03S02Z020:       IF Max_Green_Stage2 AND Ped_Detec THEN
D03S04Z020:         Interstage( 2,3)
                  ELSE
D03S02Z021:         IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z021:           Interstage( 2,1)
                    END
                  END
                END
              ELSE
D03S01Z021:     Compensation_Stg2:= 0; Req_Com_2:=0;
D03S01Z023:     IF Max_Green_Stage2 AND Ped_Detec THEN
D03S04Z023:       Interstage( 2,3)
                ELSE
D03S01Z024:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z024:         Interstage( 2,1)
                  ELSE
D03S01Z025:         IF Ped_Detec THEN
D03S03Z025:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D03S04Z025:             Interstage( 2,3)
                      END
                    ELSE
D03S01Z027:           IF Veh_Detec_1 THEN
D03S03Z027:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D03S04Z027:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
D03S00Z030: IF Stage_active( 3 ) THEN
D03S03Z030:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D03S04Z030:     Interstage( 3,1)
```

```
              ELSE
D03S03Z031:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D03S04Z031:       Interstage( 3,2)
                ELSE
D03S03Z032:       IF Min_Green_Stage3 THEN
D03S04Z032:         Interstage( 3,1)
                  END
                END
              END
            END
D03PROG_ENDE: .
/*-----------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_RED_1 := 55;
              AVG_TRAVEL_TIME := 18;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
              G_EXTENSION := 23;
              MIN_RED := 29;
              MAX_EXTENSION := 50;
            END;

/* EXPRESSIONS */
            Veh_Detec_1 := Detection (1) > 0;
            Veh_Detec_2 := Detection (2) > 0;
            Ped_Detec := Detection (3) > 0;
            Min_Green_Stage1 := T_green (1) >= T_green_min (1);
            Min_Green_Stage2 := T_green (2) >= T_green_min (2);
            Min_Green_Stage3 := T_green (3) >= T_green_min (3);
            Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
            Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
            Gap_Out_1 := Headway (1) >= MIN_GAP;
            Gap_Out_2 := Headway (2) >= MIN_GAP;
```

/* MAIN PROGRAM */

```
S00Z002:    IF NOT Compensation_Stg2 THEN
S01Z002:      IF NOT Detec_Stg_1 THEN
S02Z002:        IF Presence (1001) THEN
S03Z002:          IF Stage_active (1) THEN
S04Z002:            Detec_Stg_1:= 1
```

```
                  ELSE
S03Z003:            Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z004:            IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z004:              Detec_Stg_1:= 1
                    END
                  END
                END
              END
            END;
S00Z007:    IF Detec_Stg_1 THEN
S04Z007:      GOSUB Bus_Stage
            ELSE
S00Z008:      IF Compensation_Stg2 THEN
S04Z008:        GOSUB Compensation_Stage
              ELSE
S00Z010:        GOSUB General_Stage
              END
            END
PROG_ENDE:    .
/*------------------------------------------------------------------------------*/
```

VAP Code S9: Compensation by Traditional Inhibit

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\tt\Extension & Recall & Inhibit &
Compensation\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1);
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION
            END;
D01S00Z006: IF Stage_active (1) THEN
D01S01Z006:   IF NOT R THEN
D01S02Z006:     IF T_green (1) < Absolute_Extension THEN
D01S03Z006:       IF T_green (1) >=Req_Extension THEN
D01S04Z006:         Detec_Stg_1:= 0
                  END
                ELSE
```

```
D01S04Z008:        Detec_Stg_1:=0; Interstage( 1,2)
                 END
               ELSE
D01S01Z009:      IF Presence (1001) THEN
D01S04Z009:        R:= 0
                 ELSE
D01S01Z010:        IF T_green (1) >= MIN_RED THEN
D01S04Z010:          Detec_Stg_1:= 0; R:= 0
                   END
                 END
               END
             END;
D01S00Z013: IF Stage_active (2) THEN
D01S01Z013:   IF T_green (2)>= T_green_min (2) THEN
D01S02Z013:     Start (inhibitTimer_2); inhibit_2:=1;
D01S03Z013:     Compensation_Stg2:= 1; Req_Com_2:=(MAX_GREEN_STG2-T_green (2));
D01S04Z013:     Interstage (2,3)
               END
             END;
D01S00Z016: IF Stage_active (3) THEN
D01S03Z016:   IF T_green (3)>= T_green_min (3) THEN
D01S04Z016:     R:= 1; Interstage (3,1)
               END
             END
D01PROG_ENDE: .
/*-----------------------------------------------------------------------------*/

SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                 ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                   END
                 END
               ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
                 ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                   ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
```

```
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
              ELSE
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
```

```
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
D02PROG_ENDE: .
/*-----------------------------------------------------------------------------*/
```

```
SUBROUTINE Compensation_Stage;  /* Compensation_Stage.vv */
D03S00Z001: Com_Max_Green_2:=MAX_GREEN_STG2 + Req_Com_2;
D03S00Z002: Max_Com_Green_Stage2:=(T_green (2) >=Com_Max_Green_2);
D03S00Z003: IF NOT (Veh_Detec_2) THEN
D03S00Z004:   Compensation_Stg2:= 0; Req_Com_2:=0
            END;
D03S00Z006: IF Stage_active( 1 ) THEN
D03S01Z006:   IF Veh_Detec_1 THEN
D03S03Z006:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D03S04Z006:       Interstage( 1,2)
                ELSE
D03S03Z007:       IF Max_Green_Stage1 AND Ped_Detec THEN
D03S04Z007:         Interstage( 1,3)
                  END
                END
              ELSE
D03S01Z009:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D03S04Z009:       Interstage( 1,2)
                ELSE
D03S01Z010:       IF Max_Green_Stage1 AND Ped_Detec THEN
D03S04Z010:         Interstage( 1,3)
                  ELSE
D03S01Z011:         IF Veh_Detec_2 THEN
D03S03Z011:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D03S04Z011:             Interstage( 1,2)
                      END
                    ELSE
D03S01Z013:           Compensation_Stg2:= 0; Req_Com_2:=0;
D03S01Z014:           IF Ped_Detec THEN
```

```
D03S03Z014:            IF Min_Green_Stage1 AND Gap_Out_1 THEN
D03S04Z014:              Interstage( 1,3)
                       END
                     END
                   END
                 END
               END
             END
           END;
D03S00Z016: IF Stage_active( 2 ) THEN
D03S01Z016:   IF Veh_Detec_2 THEN
D03S02Z016:     IF Compensation_Stg2 THEN
D03S03Z016:       IF Max_Com_Green_Stage2 AND Ped_Detec THEN
D03S04Z016:         Interstage( 2,3); Compensation_Stg2:= 0; Req_Com_2:=0
                  ELSE
D03S03Z017:         IF Max_Com_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z017:           Interstage( 2,1); Compensation_Stg2:= 0; Req_Com_2:=0
                    ELSE
D03S03Z018:           IF Max_Com_Green_Stage2 THEN
D03S04Z018:             Compensation_Stg2:= 0; Req_Com_2:=0
                      END
                    END
                  END
                ELSE
D03S02Z020:       IF Max_Green_Stage2 AND Ped_Detec THEN
D03S04Z020:         Interstage( 2,3)
                  ELSE
D03S02Z021:         IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z021:           Interstage( 2,1)
                    END
                  END
                END
              ELSE
D03S01Z021:     Compensation_Stg2:= 0; Req_Com_2:=0;
D03S01Z023:     IF Max_Green_Stage2 AND Ped_Detec THEN
D03S04Z023:       Interstage( 2,3)
                ELSE
D03S01Z024:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z024:         Interstage( 2,1)
                  ELSE
D03S01Z025:         IF Ped_Detec THEN
D03S03Z025:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D03S04Z025:             Interstage( 2,3)
                      END
                    ELSE
```

```
D03S01Z027:           IF Veh_Detec_1 THEN
D03S03Z027:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D03S04Z027:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
D03S00Z030: IF Stage_active( 3 ) THEN
D03S03Z030:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D03S04Z030:     Interstage( 3,1)
              ELSE
D03S03Z031:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D03S04Z031:       Interstage( 3,2)
                ELSE
D03S03Z032:       IF Min_Green_Stage3 THEN
D03S04Z032:         Interstage( 3,1)
                  END
                END
              END
            END
D03PROG_ENDE: .
/*------------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktivOvv <> 1 ) THEN
              prog_aktivOvv := 1;
              MAX_RED_1 := 55;
              AVG_TRAVEL_TIME := 18;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
              G_EXTENSION := 23;
              MIN_RED := 29;
              MAX_EXTENSION := 50;
            END;

/* EXPRESSIONS */
            Veh_Detec_1 := Detection (1) > 0;
            Veh_Detec_2 := Detection (2) > 0;
            Ped_Detec := Detection (3) > 0;
            Min_Green_Stage1 := T_green (1) >= T_green_min (1);
            Min_Green_Stage2 := T_green (2) >= T_green_min (2);
```

```
            Min_Green_Stage3 := T_green (3) >= T_green_min (3);
            Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
            Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
            Gap_Out_1 := Headway (1) >= MIN_GAP;
            Gap_Out_2 := Headway (2) >= MIN_GAP;

/* MAIN PROGRAM */

S00Z002:    IF inhibit_2 THEN
S01Z002:      IF inhibitTimer_2 >= 180 THEN
S04Z002:        Stop (inhibitTimer_2); Reset (inhibitTimer_2); inhibit_2:=0
              END
            END;
S00Z005:    IF NOT inhibit_2 THEN
S01Z005:      IF NOT Detec_Stg_1 THEN
S02Z005:        IF Presence (1001) THEN
S03Z005:          IF Stage_active (1) THEN
S04Z005:            Detec_Stg_1:= 1
                  ELSE
S03Z006:            Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z007:            IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z007:              Detec_Stg_1:= 1
                    END
                  END
                END
              END
            END;
S00Z010:    IF Detec_Stg_1 THEN
S04Z010:      GOSUB Bus_Stage
            ELSE
S00Z011:      IF Compensation_Stg2 THEN
S04Z011:        GOSUB Compensation_Stage
              ELSE
S00Z013:        GOSUB General_Stage
              END
            END
PROG_ENDE:    .
/*--------------------------------------------------------------------------*/
```

VAP Code S10: Compensation by Improved Inhibit

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\tt\Extension & Recall & Inhibit &
Compensation\Suggested_Inhibit\Extension & Recall & Inhibit & Compensation\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1);
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION
            END;
D01S00Z006: IF Stage_active (1) THEN
D01S01Z006:   IF NOT R THEN
D01S02Z006:     IF T_green (1) < Absolute_Extension THEN
D01S03Z006:       IF T_green (1) >=Req_Extension THEN
D01S04Z006:         Detec_Stg_1:= 0
                  END
                ELSE
D01S04Z008:       Detec_Stg_1:=0; Interstage( 1,2)
                END
              ELSE
D01S01Z009:     IF Presence (1001) THEN
D01S04Z009:       R:= 0
                ELSE
D01S01Z010:       IF T_green (1) >= MIN_RED THEN
D01S04Z010:         Detec_Stg_1:= 0; R:= 0
                  END
                END
              END
            END;
D01S00Z013: IF Stage_active (2) THEN
D01S01Z013:   IF T_green (2)>= T_green_min (2) THEN
D01S02Z013:     Start (inhibitTimer_2); inhibit_2:=1;
D01S03Z013:     Compensation_Stg2:= 1; Req_Com_2:=(MAX_GREEN_STG2-T_green (2));
D01S04Z013:     Interstage (2,3)
              END
            END;
D01S00Z016: IF Stage_active (3) THEN
D01S03Z016:   IF T_green (3)>= T_green_min (3) THEN
D01S04Z016:     R:= 1; Interstage (3,1)
```

```
            END
          END
D01PROG_ENDE: .
/*--------------------------------------------------------------------------------*/

SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                  END
                END
              ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
                ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                  ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
```

```
                END
              ELSE
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
D02PROG_ENDE: .
/*------------------------------------------------------------------------------*/


SUBROUTINE Compensation_Stage;  /* Compensation_Stage.vv */
D03S00Z001: Com_Max_Green_2:=MAX_GREEN_STG2 + Req_Com_2;
D03S00Z002: Max_Com_Green_Stage2:=(T_green (2) >=Com_Max_Green_2);
D03S00Z003: IF NOT (Veh_Detec_2) THEN
D03S00Z004:   Compensation_Stg2:= 0; Req_Com_2:=0; Stop (inhibitTimer_2); Reset
(inhibitTimer_2); inhibit_2:=0
            END;
```

```
D03S00Z006: IF Stage_active( 1 ) THEN
D03S01Z006:   IF Veh_Detec_1 THEN
D03S03Z006:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D03S04Z006:       Interstage( 1,2)
                ELSE
D03S03Z007:       IF Max_Green_Stage1 AND Ped_Detec THEN
D03S04Z007:         Interstage( 1,3)
                  END
                END
              ELSE
D03S01Z009:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D03S04Z009:       Interstage( 1,2)
                ELSE
D03S01Z010:       IF Max_Green_Stage1 AND Ped_Detec THEN
D03S04Z010:         Interstage( 1,3)
                  ELSE
D03S01Z011:         IF Veh_Detec_2 THEN
D03S03Z011:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D03S04Z011:             Interstage( 1,2)
                      END
                    ELSE
D03S01Z013:           Compensation_Stg2:= 0; Req_Com_2:=0; Stop (inhibitTimer_2); Reset
(inhibitTimer_2); inhibit_2:=0;
D03S01Z014:           IF Ped_Detec THEN
D03S03Z014:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D03S04Z014:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D03S00Z016: IF Stage_active( 2 ) THEN
D03S01Z016:   IF Veh_Detec_2 THEN
D03S02Z016:     IF Compensation_Stg2 THEN
D03S03Z016:       IF Max_Com_Green_Stage2 AND Ped_Detec THEN
D03S04Z016:         Interstage( 2,3); Compensation_Stg2:= 0; Req_Com_2:=0; Stop
(inhibitTimer_2); Reset (inhibitTimer_2); inhibit_2:=0
                  ELSE
D03S03Z017:         IF Max_Com_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z017:           Interstage( 2,1); Compensation_Stg2:= 0; Req_Com_2:=0; Stop
(inhibitTimer_2); Reset (inhibitTimer_2); inhibit_2:=0
                    ELSE
D03S03Z018:           IF Max_Com_Green_Stage2 THEN
D03S04Z018:             Compensation_Stg2:= 0; Req_Com_2:=0; Stop (inhibitTimer_2); Reset
(inhibitTimer_2); inhibit_2:=0
```

```
                    END
                  END
                END
              ELSE
D03S02Z020:     IF Max_Green_Stage2 AND Ped_Detec THEN
D03S04Z020:       Interstage( 2,3)
                ELSE
D03S02Z021:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z021:         Interstage( 2,1)
                  END
                END
              END
            ELSE
D03S01Z021:   Compensation_Stg2:= 0; Req_Com_2:=0; Stop (inhibitTimer_2); Reset
(inhibitTimer_2); inhibit_2:=0;
D03S01Z023:   IF Max_Green_Stage2 AND Ped_Detec THEN
D03S04Z023:     Interstage( 2,3)
              ELSE
D03S01Z024:     IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D03S04Z024:       Interstage( 2,1)
                ELSE
D03S01Z025:       IF Ped_Detec THEN
D03S03Z025:         IF Min_Green_Stage2 AND Gap_Out_2 THEN
D03S04Z025:           Interstage( 2,3)
                    END
                  ELSE
D03S01Z027:         IF Veh_Detec_1 THEN
D03S03Z027:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D03S04Z027:             Interstage( 2,1)
                      END
                    END
                  END
                END
              END
            END
          END;
D03S00Z030: IF Stage_active( 3 ) THEN
D03S03Z030:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D03S04Z030:     Interstage( 3,1)
            ELSE
D03S03Z031:   IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D03S04Z031:     Interstage( 3,2)
              ELSE
D03S03Z032:     IF Min_Green_Stage3 THEN
D03S04Z032:       Interstage( 3,1)
                END
```

```
            END
          END
        END
D03PROG_ENDE: .
/*------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
        IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
          prog_aktiv0vv := 1;
          MAX_RED_1 := 55;
          AVG_TRAVEL_TIME := 18;
          MAX_GREEN_STG1 := 50;
          MAX_GREEN_STG2 := 20;
          MIN_GAP := 2;
          G_EXTENSION := 23;
          MIN_RED := 29;
          MAX_EXTENSION := 50;
        END;

/* EXPRESSIONS */
        Veh_Detec_1 := Detection (1) > 0;
        Veh_Detec_2 := Detection (2) > 0;
        Ped_Detec := Detection (3) > 0;
        Min_Green_Stage1 := T_green (1) >= T_green_min (1);
        Min_Green_Stage2 := T_green (2) >= T_green_min (2);
        Min_Green_Stage3 := T_green (3) >= T_green_min (3);
        Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
        Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
        Gap_Out_1 := Headway (1) >= MIN_GAP;
        Gap_Out_2 := Headway (2) >= MIN_GAP;
```

/* MAIN PROGRAM */

```
S00Z002:    IF inhibit_2 THEN
S01Z002:      IF inhibitTimer_2 >= 180 THEN
S02Z002:        Stop (inhibitTimer_2); Reset (inhibitTimer_2); inhibit_2:=0;
S04Z002:        Compensation_Stg2:= 0; Req_Com_2:=0
              END
            END;
S00Z005:    IF NOT inhibit_2 THEN
S01Z005:      IF NOT Detec_Stg_1 THEN
S02Z005:        IF Presence (1001) THEN
```

```
S03Z005:         IF Stage_active (1) THEN
S04Z005:           Detec_Stg_1:= 1
                 ELSE
S03Z006:           Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z007:           IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z007:             Detec_Stg_1:= 1
                   END
                 END
               END
             END
           END;
S00Z010:   IF Detec_Stg_1 THEN
S04Z010:     GOSUB Bus_Stage
           ELSE
S00Z011:     IF Compensation_Stg2 THEN
S04Z011:       GOSUB Compensation_Stage
             ELSE
S00Z013:       GOSUB General_Stage
             END
           END
PROG_ENDE:    .
/*----------------------------------------------------------------------------*/
```

VAP Code S11: Differential Priority (= >5mins Late)

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\Debuged\ManyBuses_07.03.15\Effective Red\Two
Stages + Ped\Extension & Recall_LateBus\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1);
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION
            END;
D01S00Z006: IF Stage_active (1) THEN
D01S01Z006:   IF NOT R THEN
D01S02Z006:     IF T_green (1) < Absolute_Extension THEN
D01S03Z006:       IF T_green (1) >=Req_Extension THEN
D01S04Z006:         Detec_Stg_1:= 0
```

```
                END
              ELSE
D01S04Z008:     Detec_Stg_1:=0; Interstage( 1,2)
              END
            ELSE
D01S01Z009:   IF Presence (1001) THEN
D01S04Z009:     R:= 0
              ELSE
D01S01Z010:     IF T_green (1) >= MIN_RED THEN
D01S04Z010:       Detec_Stg_1:= 0; R:= 0
                END
              END
            END
          END;
D01S00Z013: IF Stage_active (2) THEN
D01S03Z013:   IF T_green (2)>= T_green_min (2) THEN
D01S04Z013:     Interstage (2,3)
            END
          END;
D01S00Z016: IF Stage_active (3) THEN
D01S03Z016:   IF T_green (3)>= T_green_min (3) THEN
D01S04Z016:     R:= 1; Interstage (3,1)
            END
          END
D01PROG_ENDE: .
/*--------------------------------------------------------------------------------*/

SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
              ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                END
              END
            ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z005:       Interstage( 1,2)
              ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
```

```
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
              ELSE
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
                      END
                    END
                  END
                END
              END
            END;
```

```
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
D02PROG_ENDE: .
/*---------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_RED_1 := 55;
              AVG_TRAVEL_TIME := 18;
              LATE := 660;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
              G_EXTENSION := 23;
              MIN_RED := 29;
              MAX_EXTENSION := 50;
            END;

/* EXPRESSIONS */
            Veh_Detec_1 := Detection (1) > 0;
            Veh_Detec_2 := Detection (2) > 0;
            Ped_Detec := Detection (3) > 0;
            Min_Green_Stage1 := T_green (1) >= T_green_min (1);
            Min_Green_Stage2 := T_green (2) >= T_green_min (2);
            Min_Green_Stage3 := T_green (3) >= T_green_min (3);
            Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
            Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
            Gap_Out_1 := Headway (1) >= MIN_GAP;
            Gap_Out_2 := Headway (2) >= MIN_GAP;
```

```
/* MAIN PROGRAM */


S00Z002:    IF NOT Detec_Stg_1 THEN
S03Z002:      IF Headway (1001) >= LATE THEN
S04Z002:        Late_Bus := 1
              END
            END;
S00Z004:    IF NOT Detec_Stg_1 THEN
S01Z004:      IF Late_Bus THEN
S02Z004:        IF Presence (1001) THEN
S03Z004:          IF Stage_active (1) THEN
S04Z004:            Detec_Stg_1:= 1; Late_Bus := 0
                  ELSE
S03Z005:            Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z006:            IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z006:              Detec_Stg_1:= 1; Late_Bus := 0
                    END
                  END
                END
              END
            END;
S00Z009:    IF Detec_Stg_1 THEN
S04Z009:      GOSUB Bus_Stage
            ELSE
S00Z012:      GOSUB General_Stage
            END
PROG_ENDE:    .
/*----------------------------------------------------------------------------*/
```

VAP Code S12: Exit Detection (Weak Exit)

```
PROGRAM T_Junction; /* C:\Users\Rabbit\Desktop\Exit_Detector\Two Stages + Ped\Extension &
Recall\T_Junction.vv */


VAP_FREQUENCY 1;



/* ARRAYS */


/* SUBROUTINES */


SUBROUTINE Bus_Stage;  /* Bus_Stage.vv */
D01S00Z003: IF Presence (1001) THEN
D01S01Z003:   Current_Green_Stg1:= T_green (1); ReqFrom:= BusNr;
D01S01Z004:   Req_Extension:= G_EXTENSION + Current_Green_Stg1;
Absolute_Extension:=MAX_GREEN_STG1 + MAX_EXTENSION
```

```
            END;
D01S00Z006: IF Stage_active (1) THEN
D01S01Z006:   IF NOT R THEN
D01S02Z006:     IF T_green (1) < Absolute_Extension THEN
D01S03Z006:       IF T_green (1) >=Req_Extension THEN
D01S04Z006:         Detec_Stg_1:= 0
                  END
                ELSE
D01S04Z008:       Detec_Stg_1:=0; Interstage( 1,2)
                END
              ELSE
D01S01Z009:     IF Presence (1001) THEN
D01S04Z009:       R:= 0
                ELSE
D01S01Z010:       IF T_green (1) >= MIN_RED THEN
D01S04Z010:         Detec_Stg_1:= 0; R:= 0
                  END
                END
              END
            END;
D01S00Z013: IF Stage_active (2) THEN
D01S03Z013:   IF T_green (2)>= T_green_min (2) THEN
D01S04Z013:     Interstage (2,3)
              END
            END;
D01S00Z016: IF Stage_active (3) THEN
D01S03Z016:   IF T_green (3)>= T_green_min (3) THEN
D01S04Z016:     R:= 1; Interstage (3,1)
              END
            END
D01PROG_ENDE: .
/*-----------------------------------------------------------------------------*/

SUBROUTINE General_Stage;  /* General_Stage.vv */
D02S00Z002: IF Stage_active( 1 ) THEN
D02S01Z002:   IF Veh_Detec_1 THEN
D02S02Z002:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
D02S03Z002:       Interstage( 1,2)
                ELSE
D02S02Z003:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z003:         Interstage( 1,3)
                  END
                END
              ELSE
D02S01Z005:     IF Max_Green_Stage1 AND Veh_Detec_2 THEN
```

```
D02S03Z005:       Interstage( 1,2)
                ELSE
D02S01Z006:       IF Max_Green_Stage1 AND Ped_Detec THEN
D02S03Z006:         Interstage( 1,3)
                  ELSE
D02S01Z007:         IF Veh_Detec_2 THEN
D02S02Z007:           IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z007:             Interstage( 1,2)
                      END
                    ELSE
D02S01Z009:           IF Ped_Detec THEN
D02S02Z009:             IF Min_Green_Stage1 AND Gap_Out_1 THEN
D02S03Z009:               Interstage( 1,3)
                        END
                      END
                    END
                  END
                END
              END
            END;
D02S00Z011: IF Stage_active( 2 ) THEN
D02S01Z011:   IF Veh_Detec_2 THEN
D02S02Z011:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z011:       Interstage( 2,3)
                ELSE
D02S02Z012:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z012:         Interstage( 2,1)
                  END
                END
              ELSE
D02S01Z014:     IF Max_Green_Stage2 AND Ped_Detec THEN
D02S03Z014:       Interstage( 2,3)
                ELSE
D02S01Z015:       IF Max_Green_Stage2 AND Veh_Detec_1 THEN
D02S03Z015:         Interstage( 2,1)
                  ELSE
D02S01Z016:         IF Ped_Detec THEN
D02S02Z016:           IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z016:             Interstage( 2,3)
                      END
                    ELSE
D02S01Z018:           IF Veh_Detec_1 THEN
D02S02Z018:             IF Min_Green_Stage2 AND Gap_Out_2 THEN
D02S03Z018:               Interstage( 2,1)
                        END
```

```
                      END
                    END
                  END
                END
              END
            END;
D02S00Z021: IF Stage_active( 3 ) THEN
D02S02Z021:   IF Min_Green_Stage3 AND Veh_Detec_1 THEN
D02S03Z021:     Interstage( 3,1)
              ELSE
D02S02Z022:     IF Min_Green_Stage3 AND Veh_Detec_2 THEN
D02S03Z022:       Interstage( 3,2)
                ELSE
D02S02Z023:       IF Min_Green_Stage3 THEN
D02S03Z023:         Interstage( 3,1)
                  END
                END
              END
            END
D02PROG_ENDE: .
/*--------------------------------------------------------------------------*/

SUBROUTINE Cancel_Bus_Stage;  /* Cancel_Bus_Stage.vv */
D03S00Z003: Detec_Stg_1:= 0; R:= 0
D03PROG_ENDE: .
/*--------------------------------------------------------------------------*/

/* PARAMETERS DEPENDENT ON SCJ-PROGRAM */
            IF( prog_aktiv = 1 ) AND ( prog_aktiv0vv <> 1 ) THEN
              prog_aktiv0vv := 1;
              MAX_RED_1 := 55;
              AVG_TRAVEL_TIME := 18;
              MAX_GREEN_STG1 := 50;
              MAX_GREEN_STG2 := 20;
              MIN_GAP := 2;
              G_EXTENSION := 23;
              MIN_RED := 29;
              MAX_EXTENSION := 50;
            END;

/* EXPRESSIONS */
            Veh_Detec_1 := Detection (1) > 0;
            Veh_Detec_2 := Detection (2) > 0;
            Ped_Detec := Detection (3) > 0;
            Min_Green_Stage1 := T_green (1) >= T_green_min (1);
```

```
            Min_Green_Stage2 := T_green (2) >= T_green_min (2);
            Min_Green_Stage3 := T_green (3) >= T_green_min (3);
            Max_Green_Stage1 := T_green (1) >=MAX_GREEN_STG1;
            Max_Green_Stage2 := T_green (2) >=MAX_GREEN_STG2;
            Gap_Out_1 := Headway (1) >= MIN_GAP;
            Gap_Out_2 := Headway (2) >= MIN_GAP;
```

/* MAIN PROGRAM */

```
S00Z002:    IF Presence (1001) THEN
S04Z002:      BusNr:= BusNr + 1
            END;
S00Z004:    IF Presence (2001) THEN
S04Z004:      ExBusNr:= ExBusNr + 1
            END;
S00Z007:    IF NOT Detec_Stg_1 THEN
S02Z007:      IF Presence (1001) THEN
S03Z007:        IF Stage_active (1) THEN
S04Z007:          Detec_Stg_1:= 1; ReqFrom:= BusNr
                ELSE
S03Z008:          Remaining_Red_1:= MAX_RED_1 - T_red (1);
S03Z009:          IF AVG_TRAVEL_TIME< Remaining_Red_1 THEN
S04Z009:            Detec_Stg_1:= 1; ReqFrom:= BusNr
                  END
                END
              END
            END;
S00Z012:    IF Detec_Stg_1 THEN
S03Z012:      IF Presence (2001) AND (ExBusNr = ReqFrom) THEN
S04Z012:        GOSUB Cancel_Bus_Stage
              END
            END;
S00Z015:    IF Detec_Stg_1 THEN
S04Z015:      GOSUB Bus_Stage
            ELSE
S00Z018:      GOSUB General_Stage
            END
PROG_ENDE:    .
/*------------------------------------------------------------------------------*/
```

Signal Controller Outputs

T Junction with Pedestrian Crossing (Extension and Recall: 150m Detection)

Sample Outputs

Output O1: (*.LSA) File

```
Signal Changes Protocol

File:     c:\users\rabbit\desktop\extension&recall_vs_distance_10bus\150m\t_junction.inp
Comment:
Date:     05 August 2015 06:25:20
VISSIM:   5.40-08 [38878]

SC 1  SGroup   1  Link      6  Lane  1  At   48.5
SC 1  SGroup   1  Link      6  Lane  2  At   53.0
SC 1  SGroup   1  Link      3  Lane  1  At   27.0
SC 1  SGroup   2  Link     10  Lane  1  At   27.6
SC 1  SGroup   3  Link     18  Lane  1  At   10.7
SC 1  SGroup   3  Link     17  Lane  1  At   12.6

     1.0;     0.0;        1;       1; red/amber ;     1.0; VAP      ;       0;
     3.0;     0.0;        1;       1; green     ;     2.0; VAP      ;       0;
    10.0;     0.0;        1;       1; amber     ;     7.0; VAP      ;       0;
    13.0;     0.0;        1;       1; red       ;     3.0; VAP      ;       0;
    16.0;     0.0;        1;       3; green     ;    16.0; VAP      ;       0;
    23.0;     0.0;        1;       3; red       ;     7.0; VAP      ;       0;
    34.0;     0.0;        1;       1; red/amber ;    21.0; VAP      ;       0;
    36.0;     0.0;        1;       1; green     ;     2.0; VAP      ;       0;
    43.0;     0.0;        1;       1; amber     ;     7.0; VAP      ;       0;
    46.0;     0.0;        1;       1; red       ;     3.0; VAP      ;       0;
-------------------------------------------------------------------------------
 25038.0;     0.0;        1;       1; amber     ;    74.0; VAP      ;       0;
 25041.0;     0.0;        1;       1; red       ;     3.0; VAP      ;       0;
 25044.0;     0.0;        1;       2; red/amber ;   104.0; VAP      ;       0;
 25046.0;     0.0;        1;       2; green     ;     2.0; VAP      ;       0;
 25066.0;     0.0;        1;       2; amber     ;    20.0; VAP      ;       0;
 25069.0;     0.0;        1;       2; red       ;     3.0; VAP      ;       0;
 25073.0;     0.0;        1;       3; green     ;   122.0; VAP      ;       0;
 25080.0;     0.0;        1;       3; red       ;     7.0; VAP      ;       0;
 25091.0;     0.0;        1;       1; red/amber ;    50.0; VAP      ;       0;
 25093.0;     0.0;        1;       1; green     ;     2.0; VAP      ;       0;
```

```
 25143.0;     0.0;        1;        1; amber     ;    50.0; VAP      ;       0;
 25146.0;     0.0;        1;        1; red       ;     3.0; VAP      ;       0;
 25149.0;     0.0;        1;        2; red/amber ;    80.0; VAP      ;       0;
 ------------------------------------------------------------------------------

 43111.0;     0.0;        1;        2; amber     ;    20.0; VAP      ;       0;
 43114.0;     0.0;        1;        2; red       ;     3.0; VAP      ;       0;
 43118.0;     0.0;        1;        3; green     ;    98.0; VAP      ;       0;
 43125.0;     0.0;        1;        3; red       ;     7.0; VAP      ;       0;
 43136.0;     0.0;        1;        1; red/amber ;    50.0; VAP      ;       0;
 43138.0;     0.0;        1;        1; green     ;     2.0; VAP      ;       0;
 43188.0;     0.0;        1;        1; amber     ;    50.0; VAP      ;       0;
 43191.0;     0.0;        1;        1; red       ;     3.0; VAP      ;       0;
 43194.0;     0.0;        1;        2; red/amber ;    80.0; VAP      ;       0;
 43196.0;     0.0;        1;        2; green     ;     2.0; VAP      ;       0;
```

Output O2: (*.LZV) File

```
Distribution of Signal Times

File:     c:\users\rabbit\desktop\extension&recall_vs_distance_10bus\150m\t_junction.inp
Comment:
Date:     05 August 2015 06:31:58
VISSIM:   5.40-08 [38878]

Time: 1800.0 - 43200.0


SC 1, Average Green Times:
   Signal group;         t;
              1;      50.9;
              2;      17.4;
              3;       7.0;


SC 1, Green Times:
t|SG;    1;    2;    3;
  0;     0;    0;    0;
  1;     0;    0;    0;
  2;     0;    0;    0;
  3;     0;    0;    0;
  4;     0;    0;    0;
```

```
  5;     0;    0;    0;
  6;     0;    0;    0;
  7;     0;   38;  401;
---------------------------
 49;     1;    0;    0;
 50;   236;    0;    0;
 51;    71;    0;    0;
----------------------------
SC 1, Red Times:
t|SG;    1;    2;    3;
----------------------------
 50;   266;    0;    0;
 51;     0;    0;    0;
 --------------------------


 79;     0;    1;    2;
 80;     0;  237;    3;
 81;     0;   71;    3;




SC 1, Signal group 1, Green Times:  (Mean:  50.9)
 ------------------------------------------------------------------------------------------
-
 49   1  *
 50 236
*******************************************************************************************
*******************************************************************************************
******************************************************
 51  71  ***********************************************************************

SC 1, Signal group 1, Red Times:  (Mean:  47.3)
 ------------------------------------------------------------------------------------------
-
 49  11  ***********
 50 266
*******************************************************************************************
*******************************************************************************************
************************************************************************************

-------------------------------------------------------------------------------------------
--
```

Appendix C

Output O3: (*.LDP) File

```
SC/Detector Record   [2015-08-05 06:25:20]



SC 1;  Program file: vap216.dll;  Import files: T_Junction.VAP,
Burgess_Rd_vs_Glen_Eyre_Rd.pua;  Program No. 1;  Simulation run

       SSS
       iii
       ggg
       ...SS
       DDDtt
      SiiiaaSSS
      issstttt
      mpppeeaaa
      ulll  ttt
      laaaDDeee
      .yyyEE
      s   TTDDD
      eSSS  EEE
      cGGG12TTT
      o   00
      n   00
      d12311123

    1.0=.......
    2.0=.......
    3.0I.......
    4.0I.......
    5.0I.......
    6.0I......|
    7.0I......|
    8.0I......|
    9.0I......|
   10.0/......|
   ------------------------

 1980.0I....|||
 1981.0I.....||
 1982.0I....|||
 1983.0I....|||
 1984.0I....|||
 1985.0I....|||
 1986.0I....|||
 1987.0I.....||
 1988.0I..|.|||
```

```
 1989.0I..|.|||
 1990.0I....+||
 1991.0I....|||
 1992.0I....|||
 1993.0I....|||
 1994.0I....|||
 1995.0I....|||
 1996.0I....|||
 1997.0I....+||
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 2001.0I....|||
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 2006.0I...||||
 2007.0I...|.||
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 2009.0I....|||
 2010.0I....+||
 2011.0I....|||
 2012.0/....|||
 2013.0/....|||
 2014.0/....|||
 2015.0.....|||
 2016.0.....|||
 2017.0.....|||
 2018.0.=...|||
 2019.0.=...|||
 2020.0.I...|||
 2021.0.I...|||
 2022.0.I...|||
 2023.0.I...|||
 2024.0.I...|||
 2025.0.I...|||
 2026.0.I...|||
 2027.0.I...|||
 2028.0.I...|||
 2029.0.I...|||
 2030.0.I...|||
---------------------------
43191.0.....|||
43192.0.....|||
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43193.0.....|||
43194.0.=...|||
43195.0.=...|||
43196.0.I...|||
43197.0.I...|||
43198.0.I...|||
43199.0.I...|||
43200.0.I...|||
```

Output O4: (*.RSZ) File

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Table of Travel Times

File:     c:\users\rabbit\desktop\extension&recall_vs_distance_10bus\150m\t_junction.inp
Comment:
Date:     05 August 2015 06:25:20
VISSIM:   5.40-08 [38878]

No.    1 (BR (SW)              ): from link    14 at  550.0 m to link    15 at   60.6 m, Distance 1100.0 m
No.    2 (BR (NE)              ): from link    16 at  500.0 m to link    13 at  215.3 m, Distance 1099.9 m
No.    3 (GR_L (NW)            ): from link    12 at  500.0 m to link    15 at  107.7 m, Distance 1100.0 m
No.    4 (GR_R (NW)            ): from link    12 at  501.0 m to link    13 at  224.3 m, Distance 1100.0 m
No.    5 (P1                   ): from link    17 at    4.0 m to link    17 at   32.0 m, Distance   28.0 m
No.    6 (P2                   ): from link    18 at    4.0 m to link    18 at   32.0 m, Distance   28.0 m
No.    7 (BR (SW)              ): from link    14 at  551.0 m to link    15 at   61.6 m, Distance 1100.0 m
No.    8 (BR (NE)              ): from link    16 at  501.0 m to link    13 at  216.3 m, Distance 1099.9 m

  Time;  Trav;#Veh;  Trav;#Veh;  Trav;#Veh;  Trav;#Veh;  Trav;#Veh;  Trav;#Veh;  Trav;#Veh;  Trav;#Veh;
  VehC;  Car;;       Car;;       Car;;       Car;;       Pedestrian;;    Pedestrian;;    Uni Link-1;;    Uni Link-1;;
  No.:;     1;    1;      2;    2;      3;    3;      4;    4;      5;    5;      6;    6;      7;    7;      8;    8;
 Name;BR (SW);BR (SW);BR (NE);BR (NE);GR_L (NW);GR_L (NW);GR_R (NW);GR_R (NW);P1;P1;P2;P2;BR (SW);BR (SW);BR (NE);BR (NE);
 43200; 162.0;6040; 157.2;5748; 202.3;1897; 197.4; 767;  66.5;2152;  67.9;2129; 148.9; 111; 145.6; 110;
```

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Accompanying Materials

1. Ahmed, B. et al (2016) *Investigating bus priority parameters for isolated vehicle actuated junctions*, Transportation Planning and Technology, Vol. 39, No. 1, pp. 45-58.

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Investigating bus priority parameters for isolated vehicle actuated junctions

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ABSTRACT

Bus priority at traffic signals has been implemented in many cities around the world. At signalised junctions, priority can be given by altering signal timings in favour of approaching buses. In usual practice, this is achieved by either extending the green period for an approaching bus or recalling the green stage, if the signal is currently red for the bus. These bus priority methods reduce junction delays for buses and thus improve bus speed and reliability. At isolated junctions in the UK, the parameters used to implement these priority methods are only based on the requirements for green extensions. These parameters may not always be effective for recalls. This study was undertaken to explore whether bus priority benefits can be improved by considering new priority parameters effective for both methods.

This research has involved the application of the VISSIM microscopic simulation software to evaluate existing and new strategies for bus priority at isolated signal controlled junctions operating under D-system vehicle actuation (VA). During evaluation, bus travel time savings and impacts on general traffic have been considered. The performance of these methods on various junction types has been evaluated. New advanced bus priority methods based on new priority parameters have been developed and their performance has been compared with the existing methods.

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Bus priority; vehicle actuation; traffic signal; microscopic simulation

1. Introduction

Buses are the predominant form of public transport in most towns and cities in many countries, including the UK (Hounsell and McLeod 1999). With their large carrying capacity, buses make effective use of limited road space, and can therefore make a substantial contribution to reducing traffic congestion (Cheney 1992). However, buses themselves are often affected by congestion, leading to a decrease in speed and an increase in bus travel time variability and service irregularity. Providing priority to buses plays an important role to protect bus services from the effects of traffic congestion and to improve route frequencies, speeds and reliability (IHT 1997), thus improving levels of service for bus passengers and encouraging modal change. 'Keeping buses moving' (DETR 1997) details a number of bus priority measures that can be considered to assist buses.

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Among these methods, bus priority at traffic signals is the most relevant where opportunities for segregated systems are not available and/or where numerous traffic signals exist. At signalised junctions, priority can be given by altering signal timings in favour of approaching buses. In usual practice, this is achieved by either extending the green period for an approaching bus or recalling the green stage, if the signal is currently red for the bus. These forms of bus priority have been implemented in many cities in USA, UK, Japan, France, Denmark, Sweden, Switzerland, Finland, Germany, Australia, Austria, Italy and New Zealand (Gardner et al. 2009). To provide bus priority at traffic signals, buses are usually detected upstream of the signal stopline by physical detectors. In most AVL systems, instead of physical detectors virtual detectors (GPS positioning) are used. Depending on signal status at the time of detection and expected arrival time of the buses at the stopline, buses are provided priority by extension or recall method. To predict the signal status when a bus arrives at the stopline and to provide priority based on it, bus travel time from detection point to stopline needs to be estimated.

Bus priority at vehicle actuated (VA) junctions started in London in the 1970s, but the first major evaluation trial occurred in the SELKENT area of London in 1987–1988 (University of Southampton 1988). The success of the trial led to the expansion of bus priority at 300 more VA controlled junctions in the outer areas of London. Most of the priority detectors were sited at 70 m upstream of the stopline from the consideration of journey time variability. At present, bus priority is installed (TRG 2011) at 509 pedestrian signals and 1389 signalised junctions (844 SCOOT junctions and 545 VA junctions) in London. In those junctions, all detected buses are given priority by extending the present green if necessary or recalling the next green more quickly if detected during red. Benefits achieved from bus priority and impacts on general traffic largely depend on implemented priority methods, priority parameters, junction types and traffic flow conditions. For example, bus priority benefits from an extension could be low depending on the detector distance. Delay to non-priority arms from a recall could be very high. This paper investigates these issues and explores enhanced priority parameters and methods to improve bus travel time savings including considering delays to non-priority arms.

In this study, the usual extension and recall methods considering a 70-m detection distance at VA signal controller have been modelled and evaluated by using VISSIM microscopic simulation tool. During evaluation, bus travel time savings and impacts on general traffic have been considered. The performances of these methods on cross-junction and T-junction types have been evaluated. Detecting buses further upstream (than 70 m) of the stopline based on new parameters has also been considered. To deal with the journey time variability issue due to early detection, exit detection near the stopline to cancel priority action has been modelled. A new advanced bus priority method termed 'always green for bus' has been developed based on new parameters and its performance has been compared with the existing methods.

2. Priority objectives

Buses are given priority at traffic signals targeting one or many objectives. Most common objectives are as follows.

2.1. Bus journey time savings

Bus priority at traffic signals can be targeted to improve the journey time of buses through a junction. Shorter journey times could give a competitive edge to buses in comparison to general traffic and encourage modal change. If this is the only criterion, then providing similar priority to all buses is the best strategy to reduce overall bus delay (TRG 1997; McLeod 1998; Maxwell et al. 2003).

2.2. Bus regularity/punctuality

Bus regularity and punctuality are key factors in passenger perception of bus service performance. Punctuality is the measure showing the percentages of buses on time taking account of the accepted tolerance. This is used in low-frequency timetabled services. Regularity is the measure showing the variation in headways (the interval between consecutive buses travelling on a route) in comparison to the scheduled headway. This is used in high-frequency headway-based services. These measures affect passenger waiting times at bus stops. If this is the only criterion, then providing high priority to late buses and no priority to others is the best strategy to improve regularisation (TRG 1997; McLeod 1998; Maxwell et al. 2003).

2.3. Total economic benefit

Total economic benefit is another potential objective function for bus priority at traffic signals. This is calculated on the basis of the performance of buses and all other traffic at a junction, including the effects of passengers on board and waiting for buses. This criterion takes account of general traffic in addition to the benefits to the buses when calculating total economic benefits. Providing high priority to late buses and extensions only to others is the best strategy to maximise economic benefit (TRG 1997; McLeod 1998; Maxwell et al. 2003).

Improving bus journey time (BJYT) is the main focus of this paper by exploring new priority parameters for currently used and new advanced priority methods.

3. Priority parameters

To provide bus priority at VA junctions by various methods, buses are detected on priority approaches some distance from the stopline. Depending on the signal status at the time of detection, normal signal timings are overridden by the implemented priority methods. For example, if a bus is detected during green, the duration of green is held at least for the duration of the expected bus travel time from the detection point to the stopline, subject to a maximum green time. If a bus is detected during red, the duration of red is reduced based on minimum time constraints of non-priority stages. After bus priority, the signal runs according to its normal timings. The effectiveness of these priority methods is largely controlled by the priority parameters used. The main parameters considered in this study are described below.

3.1. Detector location

Detector distance is one of the most influencing parameters for priority extensions. The guidelines for detector siting are therefore based on the needs of green extensions. Such optimal siting for green extensions may not be optimal for recalls. Earlier detection of buses can increase the benefit of a bus extension provision and in the case of priority recalls minimise the delays to the buses by starting shortening of non-priority stages earlier. Although an increase in detection distance from the stopline increases the theoretical effectiveness of bus priority, the prediction accuracy of the bus arrival time at the stopline is likely to reduce. This could degrade the performance of the bus priority to some degree. Hence, the optimum detector distance is a compromise between the need for detection as soon as possible and the need for accurate journey time prediction (TRG 2007).

The ideal detector distance for a junction depends on the site-specific characteristics that include bus speed, the journey time variability and the value of priority maximum time (PVM) used. Furthermore, the ideal location may be constrained by various other field factors such as the link length, the presence of a bus stop and a pedestrian crossing. In this paper, links without bus stops are considered. This applies to the situations where there is either no bus stop on the link or the bus stop is well upstream of the 'normal' bus detector location. Ideal detector distances for different link types without bus stops and free flow speeds are given in Table 1 (TRG 2007).

The detector distances for different link types given in Table 1 are based on the recommended BJYT values of 10 s for priority extension time (PVE) of 13 s. Here, BJYT is the average bus journey time taken to travel the detector distance at free flow speed and PVE is defined in the subsection below. Table 1 also shows general agreement with the guidelines that advise placing the detector at a location giving a BJYT of 10–15 s to the stopline (DfT 2000). Bus detectors should be normally located downstream of any 'unpredictable' elements, such as pedestrian crossings or bus stops, as the time spent at such elements is highly variable.

3.2. Priority maximum time

The PVM parameter specifies a further maximum running period which commences at the expiry of the normal maximum running period if a priority extension timer is running. PVM is a user-defined parameter which sets a maximum adjustment to the extension green time in a cycle. A typical value of 15 s is used at VA junctions in London (TRG 2007). If this parameter is set low for operational reasons, there is no benefit in siting the bus detector to give a higher journey time, as extensions equal to

Table 1. Ideal detector distance for different link types without bus stops.

Link type description	Speed limit (mph)	Average free flow speed (m/s)	Ideal detector distance (m)
30 mph link with some interference from pedestrian or parking/loading activities	30	7	70
30 mph link with no noticeable interference from pedestrian or parking/loading activities	30	9	90
40 mph link	40	13	130

this higher journey time will not be permitted. Hence, it is recommended to site a detector such that detector to stopline journey time does not exceed the PVM value (TRG 2007).

Higher values of PVM allow greater opportunities for extensions but it should not be set so high that it would cause unacceptable delay to non-priority traffic (Khasnabis and Rudraraju 1997) or other problems such as exit blocking. The higher value increases delay savings from priority extensions but can worsen the impact on non-priority stages at congested junctions. Hence, a PVM value of 20 s is recommended (TRG 2007) unless a junction is congested. At congested junctions, PVM may be set to a lower value provided that it is greater than or equal to PVE. It is to be noted that if PVE is set to 13 s (as in current practice), the higher value of PVM will only be used by buses arriving during the extended green period. However, a higher value of PVM would allow a higher value for PVE (and greater detector distance) which should anyway produce higher bus priority delay savings.

3.3. Priority extension time

PVE is the length of time a VA controller that holds the priority phase at right of way when a bus is detected. This depends on the detector distance and should be equal to the expected bus travel time between the bus detector and the traffic signal stopline. This may be calculated from the average free-flow bus travel time between the bus detector and the traffic signal stopline (BJYT) plus some extra time to cover variations in the journey time. Extra time equal to 30% of BJYT is appropriate for links without bus stops and that of 50% of BJYT for detection at bus stops (TRG 2006).

3.4. Priority minimum time

When a priority recall is activated, the green phase may be terminated at the end of the phase minimum if an opposing phase is recalled by a bus. To give the bus sufficient time to clear the stopline, a priority minimum green period is required which is longer than the normal minimum green. The priority minimum time should therefore take account of BJYT and variations in the queuing vehicles in front of it. If queue lengths vary by time of day, the priority minimum time may also need to be varied. For practical purposes, it is recommended to use a priority minimum time of 10–20 s depending on the junction circumstances. A priority minimum time of 10 s may be used at a junction during off-peak periods when the junction is not congested (TRG 2007). A priority minimum time of up to 20 s may be used during peak periods when the junction can be congested (TRG 2007). But priority minimum time should be junction specific. For example, in peak hours, junctions having on average 15 cars waiting in the queue during red will need 30 s at least to cross the stopline by the last vehicle considering an average discharge rate of 2 s/car. In the worst case, if the bus is detected at the end of the queuing cars, the minimum green time needs to be higher than 30 s in this scenario to cover journey time variability.

4. The models

Two realistic junctions of different types have been modelled using the VISSIM microscopic simulation model. They are adapted from two junctions in Southampton, UK.

Table 2. Signal details.

Junction type	Signal stages	Max green (s)	Min green (s)	Red/amber (s)	Amber (s)	Intergreen (s)
Cross-junction	1	25	7	2	3	7
	2	15				
	3	15				
T-junction	1	40	7	2	3	7
	2	20				

Table 3. Modelled traffic flows (evening peak).

	Junction/link	SW	NE	NW	SE
Flows (vehicles/hour)	Cross-junction	570	450	360	360
	T-junction	810	786	408	

One of the junctions is a cross-junction adapted from a junction in Portswood. The other is a T-junction based on Burgess Road at the Glen Eyre Road junction in Highfield. These junctions were chosen because all approaches of these junctions have bus routes and all roads in the network also have bus routes in both directions. Bus frequency and passenger activity within the area are high. Both of the junctions are very busy during peak hours and have different types of bus services. During red time on priority arms, queue builds up to15–20 cars on average during peak hours. Signal details (Table 2 and Figure 2) have been obtained from field data. Traffic flows (Table 3), bus services and frequencies and bus stops dwell time distributions have been modelled based on field data. Figure 1 shows the locations and basic layout of the modelled cross-junction and T-junction.

In this study, one bus service Uni-link 1 has been modelled. This service runs every 10 minutes through Portswood Road in both directions in the cross-junction. In the T-junction, it runs through Burgess Road in both directions. To model a realistic headway deviation of buses, dummy bus stops with dwell time distribution $N\,(180, 60)$ were modelled at the beginning of the bus routes. In the model, buses were generated at a regular interval of 10 minutes, whereas in the real world, buses cannot maintain this perfectly regular headway for various reasons. Buses can be early, on time or late compared to scheduled headway. This is reflected in the model by using a dummy bus stop at the beginning of the bus route, where the waiting time of each bus varies according to the specified distribution. The modelled dwell time was based on the lateness profile of bus services at their

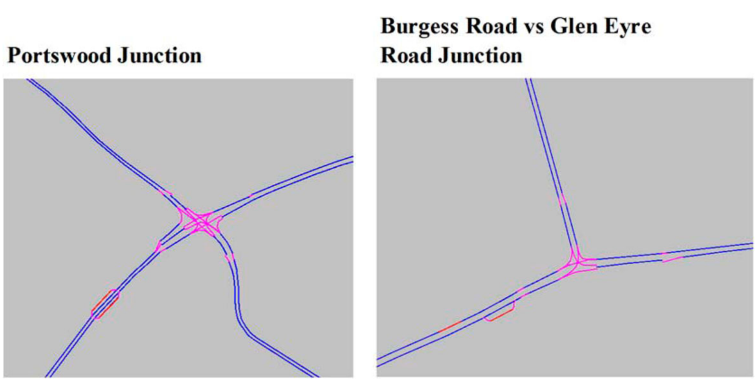

Figure 1. (Colour online) Cross-junction and T-junction.

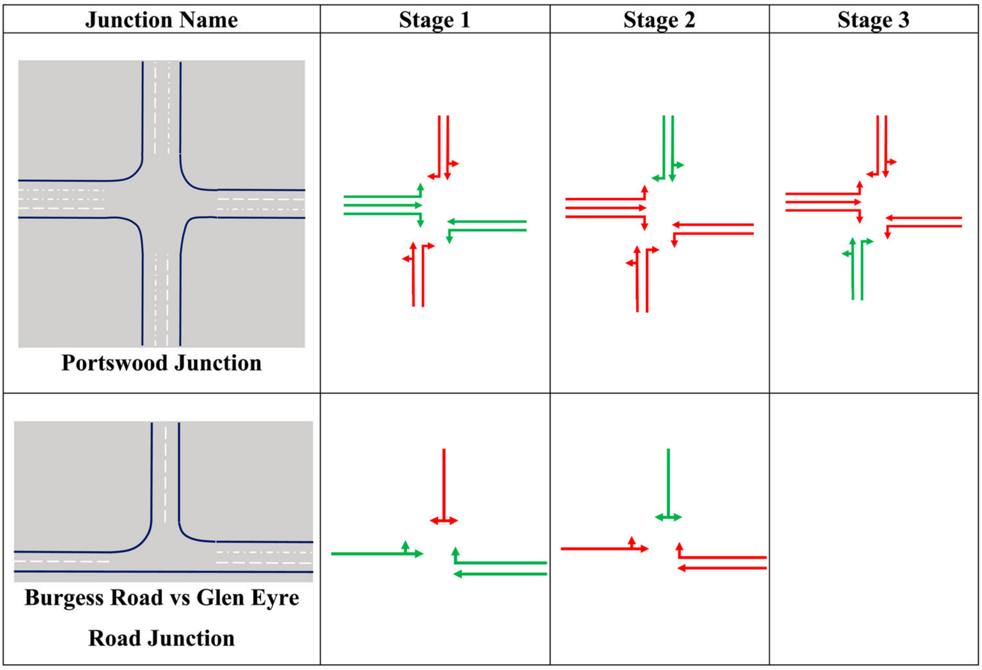

Figure 2. (Colour online) Stage diagram.

origin in practice (Shrestha 2003). As buses are generated at regular intervals, the modelled dummy bus stop delays them according to the distribution of lateness. But delaying buses at the beginning of the route has little impact on the presented results in this paper because all buses were considered for priority irrespective of their lateness. But it will have significant impact on the results of differential bus priority where only late buses are considered for priority, which needs to be explored.

5. Priority methods

In this study, priority methods used in practice (i.e. extension and recall) and a new priority method 'always green for bus' have been implemented for providing bus priority. Facilities sometimes used on street to help non-priority arms such as inhibit and compensations were not implemented at this stage in this research.

5.1. Extension

A green extension involves the extension of the green phase of the bus route upon detection of a bus before the normal green period ends. The green time for the priority approach is extended based on the estimated travel time from detection point to stopline and pre-specified maximum green extension (or max-timer). Figure 3 illustrates the extension method for a three-stage junction.

The amount of extension needed depends on estimated travel time from the detection point to stopline and the remaining green time. If estimated bus travel time is equal to or less than remaining green time at the time of bus detection, priority is not needed. But if

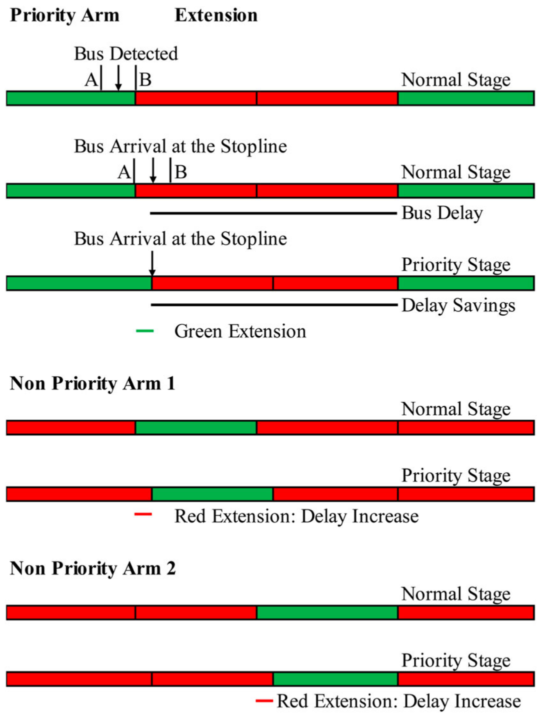

Figure 3. (Colour online) Phase diagram without and with extension.

estimated bus travel time is higher than the remaining green time at the time of detection, an extension equal to the time difference between the estimated travel time and remaining green time is provided. If a bus is detected at the last second of the green time, maximum extension will be needed. Table 4 illustrates implemented PVEs for different detection distances.

Even though PVE values are substantial for 162 and 212 m detection distances, it has little impact on the overall average signal cycle time. However, where the cycle contains a priority extension, the cycle time is increased. Additional PVE time is added to the cycle time. These PVE values do not have any impact on the length of non-priority stages.

5.2. Recall

This strategy provides an early green phase to the bus route upon detection during the red period. It involves the shortening of either all or some selected non-bus phases. Shortening of a pedestrian phase is not allowed and minimum green time constraints

Table 4. Priority extension time (PVE) calculation.

Detector distance (m)	Average bus journey time (BJYT) (s)	30% Extra to cover journey time variations (TRG 2007) (s)	Priority extension time (PVE) (s)
70	9	3	9 + 3 = 12
112	14	5	14 + 5 = 19
162	20	7	20 + 7 = 27
212	27	8	27 + 8 = 35

Figure 4. (Colour online) Phase diagram without and with recall.

for non-priority phases are implemented. Figure 4 illustrates the recall method for the three-stage junction.

A recall causes more disruption to other traffic than a green extension because it would incur more interference to the traffic signal settings (McLeod 1998). But it saves modest overall bus travel time. If a detector is placed at the usual location (70–90 m from stopline), during peak hours it is likely that due to red signal buses may subject to a long traffic queue far away from the detector, so a priority call may not be triggered immediately (Figure 5).

5.3. Always green for bus

In this newly proposed method, buses are detected early and the signal timing is adjusted so that the detected bus will always arrive at the stopline during green period. The distance of detector from the stopline depends on minimum green time constrains, intergreen times, average bus speed and length of queuing traffic during red. To implement this

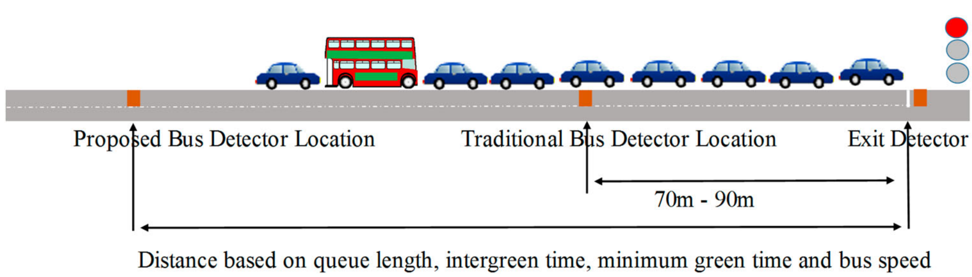

Figure 5. (Colour online) Limitations when bus detector is located close to the junction.

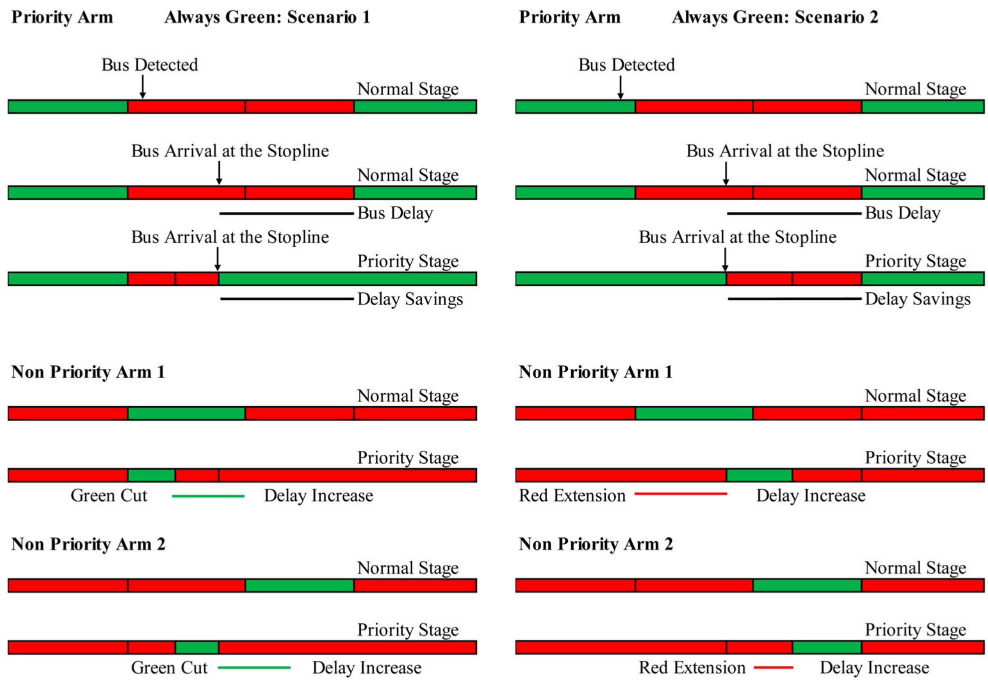

Figure 6. (Colour online) Phase diagram without and with always green for bus.

method, bus travel time from detection point to stopline should be equal to or greater than minimum green time plus intergreen time for non-priority arms. If a bus is detected during green, green period will be held on the basis of estimated travel time from detection point to stopline. If a bus is detected during red, green will be recalled early in a way that bus arrives at the stopline during green. So, theoretically, bus does not need to stop at the traffic signal. This method is a combination of extension and recall by detecting buses early. Figure 6 illustrates ‘always green for bus’ method for the three-stage junction.

For this method, the detector distance is calculated as follows:

$$\text{Detection distance } (m) = (\text{minimum green} + \text{inter green time}) \text{ of non priority stage} * \text{average bus speed} + \text{average queue length during red.}$$

Table 5 shows detector distances to provide always green for buses. The average queue lengths during red used in this table are based on historical data. The PVE parameters to be used for these detector distances are similar to those given in Table 4.

Table 5. Calculation of detector distances (always green for bus).

Minimum green + intergreen (s)	Average bus speed (m/s)	Average queue length during red (m)	Criteria	Detection distance (m)
7 + 7	8	100	Queuing traffic not considered (off peak condition)	(7 + 7)*8 = 112
7 + 7			Half of the queuing traffic considered (interpeak condition)	(7 + 7)*8 + 0.5*100 = 162
7 + 7			Queuing traffic considered (peak condition)	(7 + 7)*8 + 100 = 212

6. Results and interpretation

The models were run for 12 hours for each implemented bus priority method considering different detection distances. The bus priority benefit shown here is the average journey time saving per junction considering all buses in typical peak conditions.

Bus priority benefits vary with the junction type. If the priority arm has a longer green period, then the benefits from extension will be less because most of the buses detected during green will not need an extension. This explains why the T-junction shows lower bus travel time savings from extensions compared to the cross-junction.

Recalls provide higher bus travel time savings (Table 6) compared to extensions as shown for the T-junction because more buses get such priority compared to extensions. However, recalls have a greater negative impact on general traffic. The benefits from recalls at the cross-junction are lower compared to extensions because the priority arm is more congested compared to the T-junction. The longer traffic queue increases the possibility of more buses not being detected at the traditional detection distance (of 70 m). So recalls are less effective in the cross-junction compared to the T-junction. Benefits can be increased by combining extensions and recall together (Table 6).

If the detector is very close to the stopline, buses may arrive during red at the end of queuing cars upstream of the detector. So buses may not be detected and therefore not get priority. This explains why a recall with 70 m detection distance is less beneficial than 112 m detection (Tables 6 and 7).

On the other hand, if a detector is sited too far from the stopline for recall only, buses detected during green may be stopped at red period if signal changes occur before crossing the stopline. A recall is only provided if a bus is detected during red. There are some cases when a bus is detected during green, so recall is not provided but actually the bus needs recall because the detector is so far away that signal will change to red before the bus arrives at the stopline. So when buses are detected very far from the stopline the

Table 6. Travel time savings per vehicle per junction from 70-m detection distance.

Detector distance: 70 m

	T-junction			Cross-junction		
Priority method	Non-priority approach cars savings (s)	All approach car savings (s)	Bus savings (s)	Non-priority approach cars savings (s)	All approach car savings (s)	Bus savings (s)
Extension	−0.3	1.275	1.3	−0.15	0	6.3
Recall	−0.9	−0.025	4.8	−2.4	−0.8	6
Extension and recall	−1.2	−0.4	6.4	−1.6	−0.15	12.9

Table 7. Travel time savings per vehicle per junction by recall only.

Recall

	T-junction			Cross-junction		
Detector distance (m)	Non-priority approach cars savings (s)	All approach car savings (s)	Bus savings (s)	Non-priority approach cars savings (s)	All approach car savings (s)	Bus savings (s)
112	−1.1	1.3	5.8	−1.3	−0.375	6.1
162	−1.2	1.45	4.3	−0.1	0.4	6.4
212	−0.9	0.25	4	−0.85	−0.025	6.3

Table 8. Travel time savings per vehicle per junction by 'always green for bus'.

Always green for bus (extension + recall)

Detector distance (m)	T-junction Non-priority approach cars savings (s)	All approach car savings (s)	Bus savings (s)
112	−2.3	0.275	9.6
162	−2.35	0.6	11.9
212	−3.2	0.5	13.2

Table 9. Green time savings by priority stage per cycle.

Always green for bus

	T-junction: priority approach		
Detector distance (m)	Without exit detection average green (s)	With exit detection average green (s)	Savings (s)
112	40.3	40.1	0.2
162	40.6	40.3	0.3
212	41.1	40.7	0.4

number of buses provided with a recall can be less than the number of buses needing a recall. That explains why a 212-m detection distance performs less well than the 162-m detection (Table 7). For recall detection, detector siting should be ideally affected by queue length. Further study is needed to understand the impact of detection distance on the performance of the recall method. But these limitations can be overcome by using the 'always green for bus' method.

Table 8 shows the bus delays savings for all traffic from 'always green for bus' method at the T-junction. It is evident from this table that bus travel time savings are much higher compared to other methods (Table 6) because in this method, buses are detected early compared to the usual detector siting practice and buses do not need to stop at the traffic signal. However, this strong bus priority method can have higher negative impacts to non-priority arms, as shown in Table 8. In practice, the impact on non-priority arms could be minimised by implementing compensation and/or inhibit facilities and this will be tested in future work. Early detection also increases the BJYT variability. However, this negative impact could be reduced by implementing an exit detector to cancel unnecessary priority to buses which have already crossed the stopline. Initial results of this facility are shown in Table 9.

The performance of the exit detector depends on the accuracy of journey time prediction. If journey time can be predicted accurately, the saving from an exit detector will be limited. Link and junction characteristics influence the prediction accuracy. If it is difficult to predict the journey time accurately due to various factors, a higher safety margin needs to be considered to avoid wasted green time due to the priority call. The higher the safety margin, the more effective an exit detector would be. To understand the performance of exit detectors to reduce the negative impact of bus priority, further research will be carried out.

7. Discussion

The 'Always green for bus' method represents strong bus priority but it could have a higher negative impact on non-priority arms especially when bus frequency is high. As already noted, this negative impact on general traffic could be minimised by using several compensation and/or inhibit strategies. Another possibility is to implement 'differential priority', where only selected buses are awarded priority (e.g. according to whether they are late or not). This would cause fewer priority actions and, consequently, less disbenefits to non-priority traffic.

The bus priority methods described above for isolated VA junctions were developed before the advent of satellite/AVL bus detection systems and considered a single detection point upstream of the junction, for simplicity and cost reasons. However, modern systems such as iBus use 'virtual' detection (Hounsell et al. 2008) and have the capability to monitor a bus's progress on the approach link by using multiple detection points. Initial simulation modelling has indicated how useful this could be particularly where BJYT is highly variable, where a busstop exists on the approach or where an exit detector is valuable. Changing detection points dynamically as queue lengths change could also be of benefit. These are areas where more research is needed, if the full capabilities of modern systems are to be realised.

8. Conclusions

Bus priority at traffic signals has been implemented in a number of cities around the world. The most common methods of giving priority are: extending the present green time if a bus is detected during the green period and recalling the next green time earlier if a bus is detected after the green period. Even though the benefit from an extension is much higher than a recall for an individual bus, the number of buses getting extensions is much smaller than those getting recalls. Hence, the overall priority benefit from recalls is usually higher than that from extensions. The benefit from priority extensions increases with the increase in the detector distance from the stopline but this also increases the journey time variability (and sometimes wasted priority time). Current practice in London – the leading UK city with bus priority – is to detect buses 70–90 m from the stopline giving ~13 s of BJYT. As this detector distance is based on extensions only, it is not optimal for recalls. For recalls, this paper has shown that detection distance based on average junction queue length is much more beneficial. For this purpose, detection distance should be dependent on junction characteristics and time of day (peak, off peak or interpeak hours). This paper has shown that bus priority benefits can be improved by exploring optimum detection distance based on average queue length during red, intergreen time and minimum green time of non-priority arms. In addition, a new 'always green for bus' method theoretically gives much higher bus travel time savings than the other methods, albeit with some additional disbenefit to non-priority traffic. The main recommendation from this paper is that the new strategies proposed should now be tested on street.

Disclosure statement

No potential conflict of interest was reported by the authors.

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