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FACULTY OF ENGINEERING AND THE ENVIRONMENT

Evaluating the Environmental Impacts of Bus Priority Strategies at Traffic Signals

by

Jing Zhang

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Thesis for the degree of Doctor of Philosophy

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Doctor of Philosophy

EVALUATING THE ENVIRONMENTAL IMPACTS OF BUS PRIORITY STRATEGIES AT TRAFFIC SIGNALS

by Jing Zhang

Buses, the main form of public transport in many urban areas, are considered as an efficient and environmentally friendly transport mode because of their high passenger capacity. The concept of bus priority was originally proposed to protect buses from urban traffic congestion so that buses can be perceived as a faster mode than private cars. One such measure which is expanding in extent and sophistication is bus priority at traffic signals – or Bus Signal Priority (BSP) Strategies. The previous research on BSP has mostly focused on its effectiveness on improving bus efficiency and bus regularity/punctuality, as well as the impacts on general traffic. However the potential environmental impacts that could be caused by BSP have not been studied, particularly on emissions -despite this being an increasingly important criterion in transport assessments. For bus priority implementations this could be particularly important, if the small disbenefits to a large number of the non-priority vehicles outweigh the benefits to buses. This lack of knowledge and potential concern has been the main motivation for this research.

The thesis sets out a comprehensive review on the state-of-the-art BSP systems and evaluation approaches. It revealed that microscopic traffic simulation models are the most appropriate approach for this study with the ability to model different BSP strategies in various user-defined scenarios. The Aimsun model was selected after review and comparison. From the review on the measurement and modelling approaches for transport related emissions, instantaneous emission models were found to be able to estimate emission behaviour by relating emission rates to vehicle operation during a series of short time intervals (often one second) and for a small scale. This was required by this study as at junction areas emissions could be dominated by vehicle operational modes where the traditionally 'average speed' models were unable to accurately capture the emission variations. The dynamic and individual-oriented features of microsimulation models and instantaneous emission models enabled their integration at various spatial and temporal levels and at different levels of vehicle aggregation.

After calibration and validation to some critical parameters in Aimsun, a signalised junction under VA control was set up, and two BSP strategies were modelled, - one including green extension and early green recall facilities and the other one including additional compensation and inhibition facilities. These strategies were applied to 18 typical scenarios, involving variables of 'degree of saturation', traffic flows and bus flows.

The results illustrated the importance of strategy optimising in the more challenging conditions of junctions operating under high degrees of saturation and /or high bus flows. The worst-case scenario was in heavy traffic conditions with high bus flows and BSP on the minor road only, when emissions could increase by about 10%. Under a free flow condition implementing BSP on the main road is an environmentally friendly measure with emissions reductions of up to 6%.The thesis also describes a method to value emissions in monetary terms, so that operational and emissions impacts can be compared in common units. Application of this method indicated that the impact of emissions is much smaller than that for delay/journey time impacts, though some under-estimation in emissions valuation is suspected.

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DECLARATION OF AUTHORSHIP

I, Jing ZHANG, declare that the thesis entitled

Evaluating the Environmental Impacts of Bus Priority Strategies at Traffic Signals

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

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

Signed: ………………………………………………………………………..

Date:…………………………………………………………………………

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DEFINITIONS AND ABBREVIATIONS

AGD	Above Ground Detector
AIMSUN	Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks
AQEG	Air Quality Expert Group
ARTEMIS	Assessment and Reliability of Transport Emission Modelling and Inventory Systems
AVL	Automatic Vehicle Location
BS	British Standard
BSP	Bus Signal Priority
CBA	Cost Benefit Analysis
CMEM	Comprehensive Modal Emissions Model
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPERT	COmputer Program to calculate Emissions from Road Transport
CVS	Constant Volume Sampler
DECADE	Development and Validation of a highly accurate emissions simulation tool capable of comparatively assessing vehicles operating under dynamic conditions
DECC	Department of Energy and Climate Change
Defra	Department for Environment Food and Rural Affairs
DfT	Department for Transport
DGV	Digitised Graz Method
DMRB	Design Manual for Roads and Bridges (UK)
DoS	Degree of Saturation
EC	European Commission
ECE	Economic Commission for Europe
EEA	European Environmental Agency
ENTRANCE	Energy savings in TRANsport through innovation in the Cities of Europe
EPA	Environmental Protection Agency (USA)
EUDC	Extra-Urban Driving Cycle
FHWA	Federal HighWay Administration (USA)
HBEFA	Handbook of Emission Factors
HC	Hydrocarbons
HCM	Highway Capacity Manual (USA)
HGV	Heavy Goods Vehicle
LDV	Light Duty Vehicle
MEET	Methodologies for Estimating Air Pollutant Emissions from Transport
MOBILE	Mobile Source Emission Factor Model (USA)
MODEM	Modelling of emissions and fuel consumption in urban areas
MOVA	Microprocessor Optimised Vehicle Actuation
NAEI	National Atmospheric Emissions Inventory (UK)
NAQS	National Air Quality Strategy
NEDA	New European Driving Cycle
NMHC	Non-methane Hydrocarbons
NMVOC	Non-methane Volatile Organic Compound
NO_2	Nitrogen dioxide
O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
PAHs	Polycyclic aromatic hydrocarbons

PARAMICS	PARAllel MICroscopic simulation
PEARS	Program for Economic Assessment of Road Scheme (used in Scotland)
PHEM	Passenger car and Heavy-duty Emission Model
PM	Particle matters
ppb	parts per billion. (The number of units of mass of a contaminant per 1000 million units of total mass)
SCOOT	Split Cycle Offset Optimisation Technique
SMARTEST	Simulation Modelling Applied to Road Transport European Scheme Tests
SO_2	Sulphur dioxide
TfL	Transport for London
THC	Total Hydrocarbons
TRL	Transport Research Laboratory Ltd.
TRG	Transport Research Group (of University of Southampton)
UTC	Urban Traffic Control
VA	Vehicle Actuation
VAP	Vehicle Actuated Programming (used in VISSIM)
VeTESS	Vehicle Transient Emissions Simulation Software
VISSIM	Verkehr In Städten - SIMulationsmodell" (German for 'Traffic in cities - simulation model')
VOC^1	Vehicle Operating Cost
VOC^2	Volatile Organic Compound

Abbreviations used in the case study

BL	Baseline VA signal control
BP1	Bus Priority strategy 1 involving Green Extension and Early Green Recall
BP2	Bus priority strategy 2 involving Green Extension, Early Green Recall, Compensation and Inhibition

CHAPTER 1

INTRODUCTION

1.1 Background of the Research

The *Environment Act 1995* imposed a duty to the UK Secretary of State to prepare and publish the National Air Quality Strategy containing policies with respect to the assessment or management of the quality of air (Part IV). Policies regarding this were required to be kept under review and modification by the Secretary of State from time to time with consultancy with other bodies such as new environment agencies, local government, industry or any others which were considered to be appropriate. In section 82 of the *Environment Act 1995* Local authorities were required to cause periodic review and assessment on the air quality and the likely future quality within their areas and relevant time period against air quality standards and objectives. Under the *Environment Act* the first National Air Quality Strategy (NAQS) was adopted in1997, and it has continuously evolved and been updated on the basis of reviewing and modifying the previous standards and objectives on air pollutants and set out new frameworks towards clearer air quality and a better ecosystem.

The pollutants covered in NAQS (Department for Environment Food and Rural Affairs (Defra) 2007a) which are considered to be health and environment hazards are Particle matters (PM_{10} and $PM_{2.5}$), Nitrogen dioxide (NO_2), Ozone (O_3), Sulphur dioxide (SO_2), Polycyclic aromatic hydrocarbons (PAHs), Benzene, 1,3- butadiene, Carbon Monoxide (CO), and Lead. Limit values of these pollutants with regard to road transport have been set out towards a tighter restriction in both UK and EU regulations and practice. Carbon dioxide (CO_2) is not directly harmful to people's health and has not been regulated before, but due to its widely recognised impacts on climate change, the Energy White Paper (Department of Energy and Climate Change (DECC) 2003) introduced a long term aim of reducing CO_2 emissions by 60 percent by 2050.

Road transport is a key source of many air pollutants. It is especially considered to be one of the main sources of harmful pollutants PM, NOx, CO, and Hydrocarbons (National Atmospheric Emission Inventory (NAEI) 2010). Road transport is also a key source of green house gases. According to the newest 2008 data from Department for Transport (DfT) (2010) road transport is responsible for about 18.9% of the UK's total domestic green house gases. For the transport sector, almost all green house gases are from CO_2, about 99% in 2008 data. The regulated emission pollutants from road transport according to the EU emission standards are PM, NOx, CO, and Total Hydrocarbons (THC), and the limit value of Non-methane Hydrocarbons (NMHC) was newly introduced in EU standard V and VI. CO_2 limit has not been clearly and legally introduced before but a voluntary agreement between EU countries and auto manufactures was in place since 1998 to commit their resolution on targeting the CO_2 reduction. On 23 April 2009 the legislation on CO_2 from new passenger cars was officially published by the European Parliament and the Council of European Union as part of their integrated approach to reduce the CO2 emissions from light-duty vehicles (*REGULATION (EC) No 443/2009)*.

The *Environment Act 1995* suggested that traffic management schemes could be used to reduce air pollution. The NAQS 1997 confirmed that local authorities had to be aware of any air quality impacts resulting from their traffic management. The NAQS 2007 sets out the UK's latest air quality objectives, and the measures selected to achieve the desired improvements in air quality are based on the previous strategies and development ever since. In section 59, it consistently states that:

> *'The UK Government and the devolved administrations strongly believe that air quality issues should be dealt with in a holistic and multi-disciplinary way. In drawing up action plans, local authority environmental health/pollution teams are expected to engage local authority officers across different departments, particularly, land-use and transport planners to ensure the actions are supported by all parts of the authority.'*

This indicates that for any proposed traffic management operations local authorities have to be aware of its air quality impacts and appropriate environmental assessment is required. The evaluation of any traffic management or control strategy should be considered in a multi-criteria manner so that the performance of all related aspects can be fully examined and evaluated. In the light of such policies, significant research on exploring the environmental impacts of different traffic management measures have been conducted since the introduction of NAQS, and several representative studies and papers are reviewed in Chapter 2.

Bus priority is a measure which has been introduced to improve bus efficiency. The concept of bus priority was originally proposed to protect buses from urban traffic congestion so that buses can be perceived as a faster mode than private cars. Therefore the previous studies have mainly focused on evaluation of the efficiency performance. As suggested by NAQS, a more comprehensive evaluation for bus priority considering its environmental impact is necessary.

This research attempts to investigate the environmental impacts when implementing different bus signal priority strategies. Thus a comprehensive evaluation covering efficiency, emissions, and fuel consumption can be achieved.

1.2 Statement of the Problem

Bus priority strategies consist of physical measures, signal priority, and integrated measures. Signal priority is the focus for this study. Bus signal priority has become more popular in urban areas because of the technology development and the restriction on land use..

Signal priority can be applied to buses approaching junctions in mixed traffic, or combined with physical priority measures, e.g. bus lanes. Forms and strengths of bus priority vary according to physical and signal characteristics at different sites. In theory, signal priority involves modifying the normal signal operation process in a variety of ways, generally including green extension and recall to reduce bus delay time at junctions. Compensation or inhibition needs to be considered on congested road networks to avoid excessive additional delays to non-priority traffic. Some other measurements such as stage skipping may also be applied in extreme situations. (Definitions to the terms are reviewed and presented in Chapter 2)

The original purpose of bus priority was mainly for improving bus efficiency or regularity, therefore most of the previous research has either focused on evaluating priority measures or exploring how new technologies could be applied for more sophisticated strategies. However, in this process, potential environmental impacts caused by bus priority, including changes of emissions and fuel consumption for both buses and general vehicles have not been studied. The qualitative and quantitative relationships between efficiency benefits gained from bus priority and the resulting environmental effects have not been fully understood. Furthermore, the environmental impacts can be influenced by the forms of bus priority strategies, the conditions of traffic flow, the bus flows and the composition of vehicle types.

In this study, besides the evaluation on efficiency, the scope of evaluation extends to environmental impacts, i.e. emissions and fuel consumption. Research objectives, method, case study and analysis are presented in the following chapters.

1.3 Research Objectives

Six main research objectives are established for this study, which are listed as follows:

(1) Review the latest developments in systems and strategies for bus priority using traffic signals;
(2) Review the impacts of bus priority with particular emphasis on emissions;
(3) Determine the best approach for emission estimation for bus priority at traffic signals;
(4) Develop a simulation approach to assess bus priority strategies, allowing the assessment of efficiency, emissions and fuel consumption;
(5) Apply the simulation model to a case study with a range of scenarios to quantify the relative impacts of different strategies;
(6) Develop recommendations for modelling methodologies and for strategy selection.

1.4 Methodology

In order to achieve the aim of this study, a comprehensive review on 2 main parts is required. One is a review on modelling and evaluation for bus signal priority and the other one is a review on emission and fuel consumption modelling and evaluation. Chapter 2 reviews the current measures of bus signal priority, the evaluation criteria and modelling approaches. Chapter 3 reviews the emission and fuel consumption modelling covering most state-of-the-art models according to aggregation levels and applicable scales. As instantaneous emission models are more suitable for this study compared to others, a critical review on several representative instantaneous emission models is presented and one model is selected after comparison and trial studies.

Bus priority is modelled using a microscopic simulation tool, and the output from the microsimulation is used for emission calculation using the instantaneous emission model seleted. Chapter 4 presents the methodology of modelling bus signal priority involving the selection of a microsimulation package- Aimsun, the calibration of Aimsun and the modelling method for 3 bus signal priority measures at a Vehicle Actuation (VA) signal controlled junction. The simulation scenarios and evaluation process are proposed in Chapter 5, considering a number of key factors.

A case study is then conducted in Chapter 6 using the methodology described above. 18 simulation scenarios are modelled and 3 signal control plans including 1 baseline and 2 priority measures are implemented for each scenario. The results on efficiency improvement and impacts on emissions and fuel consumption are analysed. A further monetary evaluation is then introduced for both aspects, so that an overall comparison analysis can be processed using a unified criteria.

Discussions on the strength and weakness of this study and recommendations on bus priority strategy implementation under different traffic conditions are presented in Chapter 7. Conclusions and future work are then made in Chapter 8.

The main study process is illustrated in **Figure 1.1**.

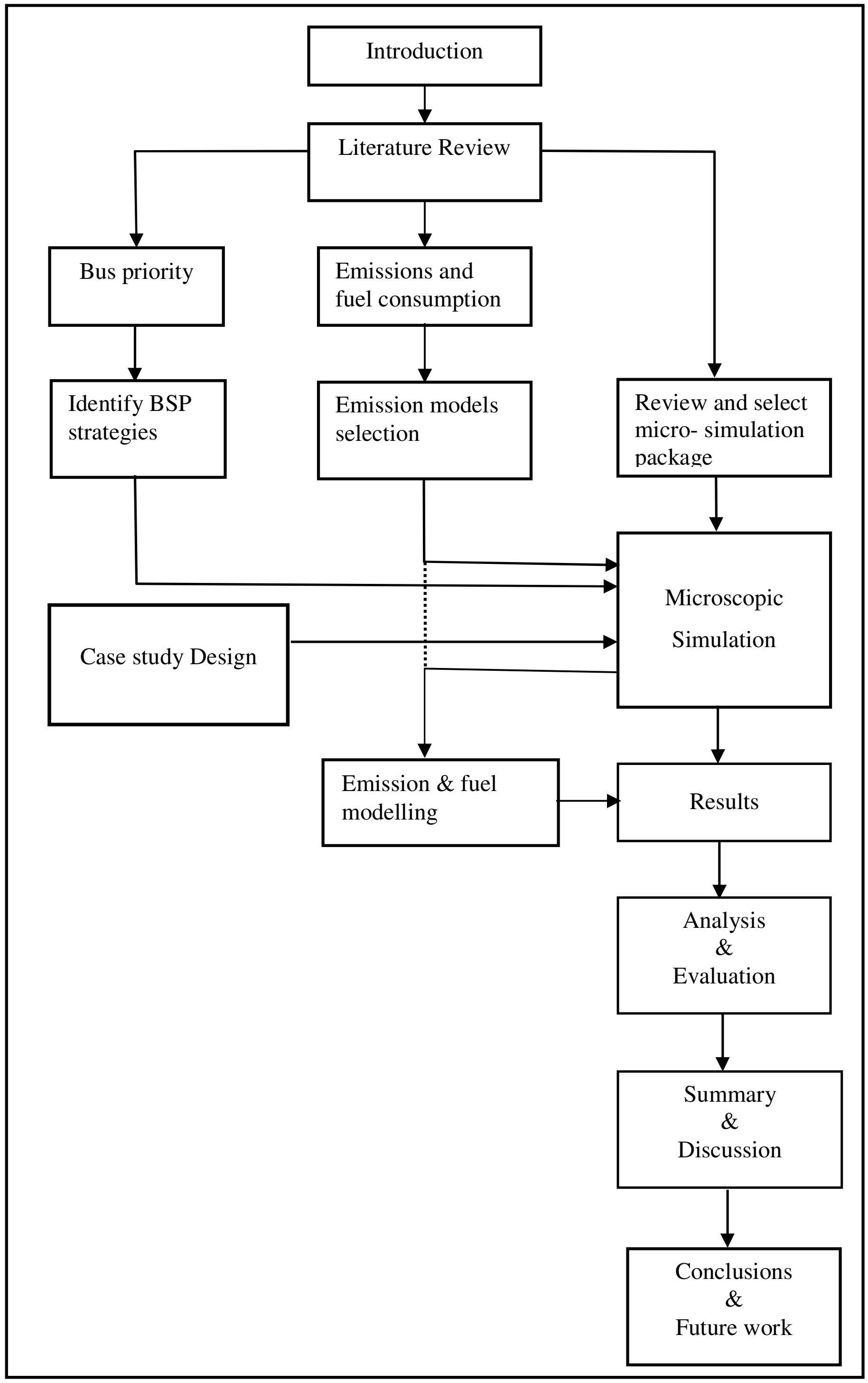


Figure 1.1 Study process

CHAPTER 2

BUS SIGNAL PRIORITY: A REVIEW OF MEASURES, MODELLING APPROACHES AND EVALUATIONS

This chapter presents a literature review on bus signal priority, in terms of measures, modelling approaches and evaluations. The measures cover the state-of-the-art strategies for bus signal priority practised in the UK and worldwide, mainly including the options of forms and architecture of priority, the implementation and performance of priority and facilities involved. This is necessary to assure that modelling and assessment in later chapters of this study focus on the latest systems and strategies as implemented on street. The second part reviews 3 possible bus priority evaluation approaches for this study, which are field measurement, macroscopic modelling and microscopic modelling. This is to advise the possible modelling methods for this study. The third part reviews previous studies on evaluation of bus priority strategies, mostly focusing on efficiency. Due to the limited literature on assessing the impacts of bus priority on the environment, several similar studies on evaluation of environmental impacts of other traffic control/management measures are reviewed to inspire possible methods for environmental evaluation for this study.

2.1Measures of Bus Signal Priority (BSP) Strategies

2.1.1 The role of BSP

Buses, the main form of public transport in many urban areas are considered as an efficient and environmentally friendly transport mode because of their high passenger capacity. Especially in cities with dense traffic volumes and strict entering and parking policies, buses appear as one of the most cost-effective and flexible travel modes. In cities where there is no urban rail or underground transport, bus transport is often the principal mode of public transport. For example, Transport for London (TfL) (2008) states that in the year to March 2008, there were more than 2,176 million passenger journeys made on the bus network in London. This was a five percent increase on the previous year, and bus passenger numbers reached their highest level since 1962. The UK government (DfT 2004) has consistently made it clear that 'the bus has a crucial part to play in present and future transport policy. In the short term, buses provide the best means of increasing public transport services.'

Travelling by bus has been promoted via various measures. The concept of bus priority was originally introduced to protect buses from urban traffic congestion so that buses can be perceived as a faster mode than private cars. In general, bus priority includes physical measures such as bus lanes or bus ways, priority measures at traffic signals, and integrated measures combining them both. Bus signal priority is the focus in this study.

Bus signal priority measures can be implemented at junctions where buses share the same lanes with general traffic, or can be used in conjunction with bus exclusive lanes. Giving bus priority at traffic signals is important in both occasions. For situations where buses mix with general traffic, bus signal priority is the only option, whilst for buses on exclusive lanes implementing signal priority at junctions is also a key measure to maintain the benefit obtained from bus lanes. Bus exclusive lanes are implemented on road sections and often end at a short distance from a junction, usually through the use of 'set-back' for bus lanes (as shown in **Figure 2. 1**). The set-back distance is usually required to maintain the junction capacity to allow movement of general traffic through the junction. In this case, buses may still be delayed by general traffic at the junction, but the bus lane enables buses to avoid long queues which may occur.

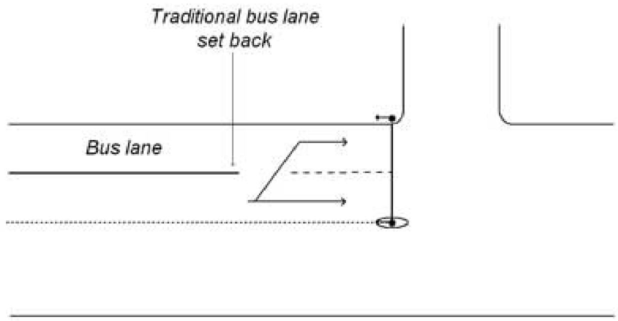


Figure 2. 1 Bus lane set-back (Source: DfT 2004)

In both cases -buses mix with general traffic and buses on exclusive lanes, - giving priority to buses at traffic signals is important to obtain a maximum benefit. Bus signal priority is closely related to and largely relies on the forms and sophistication of signal control systems at junctions, it is necessary to review the existing signal control methods.

2.1.2 Traffic signal control systems

The forms and sophistication of bus signal priority can be shaped or influenced by the traffic signal control systems at junctions. Before determining the bus priority measures to be modelled in this study, it is necessary to understand the configurations of traffic signal control systems at junctions. Signal controlled junctions can be categorised into 2 main groups, isolated junctions and co-ordinated junctions. For any types of signalised junctions, the basic elements and terms used in the UK include signal sequences, stages, phases, cycle time and intergreen period. The first sub-section reviews the general terms and principles for signal timing. The explanations for these terms are reviewed in the following sub-section, which is a direct extraction from Design Manual for Roads and Bridges (DMRB) TA16/81 (DfT 1981). The commonly applied signal control methods for the2 types of signalised junctions, i.e. isolated and co-ordinated are then reviewed.

2.1.2.1 Basic principles of traffic signal timing (from DMRB TA16/81)

Signal sequences

The signal sequence at junction traffic signals in Great Britain is red, red +amber, green, amber and red. The standard duration for an amber signal is a fixed three seconds and for the red + amber signal is a fixed two seconds. The green and the red signal duration can be a fixed time period or a variable, depending on the algorithms of signal control. It should be noted that for many other countries, ‘red+ amber’ display is absent and the end of a red signal is directly followed by the start of green.

Stage

The British Standard (BS) definition to a stage is: “indication by traffic signals during a period of the signalling cycle that gives right of way to one or more particular traffic movements”. A stage is usually determined from the start of an amber period and always ends at the start of the following stage. Stages usually, but not always, contain a green period. They are arranged to follow each other in a predetermined order but stages can be omitted, if not demanded, to reduce needless delay.

Phase

The BS definition to a phase is “a set of conditions that fixes the pattern of movement and waiting for one or more traffic streams during the signalling cycle”. Where two or more streams are always signalled to proceed simultaneously then they may share the same phase. Two or more phases may overlap in time. A phase is usually considered as commencing at the start of the green display and ending at the start of the amber display to the traffic streams on the phase in question. A series of phases is usually arranged in a predetermined order but some phases may be omitted if not demanded and it is safe to do so.

Cycle

A complete series of stages during which all traffic movements are served in turn is known as a cycle. The cycle time is the sum of each of the stage times.

Intergreen Period

The period between the end of the green display on one stage and the start of the green display on the next stage is known as the intergreen period. It comprises an amber display, the red + amber display and may also contain a period when the red signals are shown to all approaches simultaneously. The minimum time for this period is four seconds, when the amber and red + amber periods overlap by one second. With a five second intergreen the amber and red + amber periods occur consecutively. Any period over five seconds will include a period where red signals are shown to all approaches simultaneously.

An example of 3-staged signal control plan for a cross road junction including the terms introduced above is illustrated in **Figure 2. 2**.

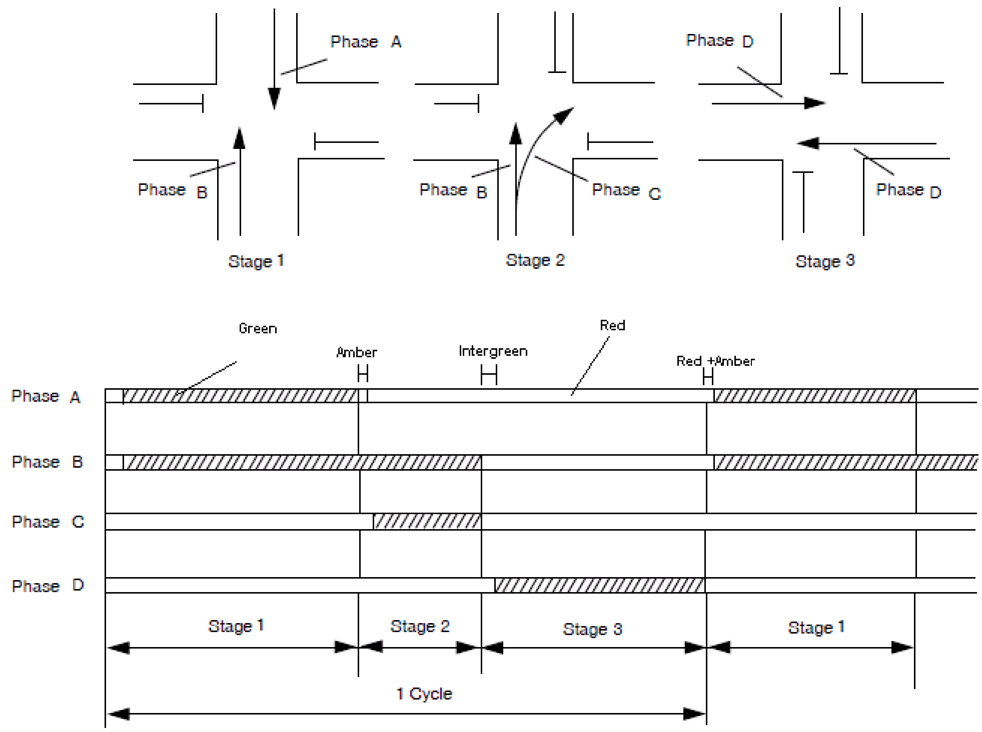


Figure 2. 2 An example of Staging and phasing diagram (Modified based on the figure from Source: DMRB (DfT 1981))

On the basis of the general principles for signal timing as described above, the control strategies for isolated and co-ordinated junctions are reviewed in the succeeding sections.

2.1.2.2 Isolated junctions

Signal control strategies at isolated junctions are independently designed considering traffic flow situations only at the junction concerned. The signal control plan at an isolated junction can be fixed time or vehicle actuated. Fixed time signal control does not require any vehicle detection facilities and is designed based on historical traffic flow data. Vehicle actuated signal control can be implemented in different forms subject to detection facilities and controlling methods.

Fixed timing

With fixed time control, signal timings are calculated off-line, and implemented using the traffic controllers at the site locally. It uses historic traffic data to generate optimum plans that usually vary by time of day and day of week. The optimum cycle time and green duration for each phase is determined by minimising the average delay time according to the traffic conditions. **Figure 2. 3** below (extracted from Salter and Hounsell 1996) demonstrates the relationship between the optimum cycle time and the delay time.

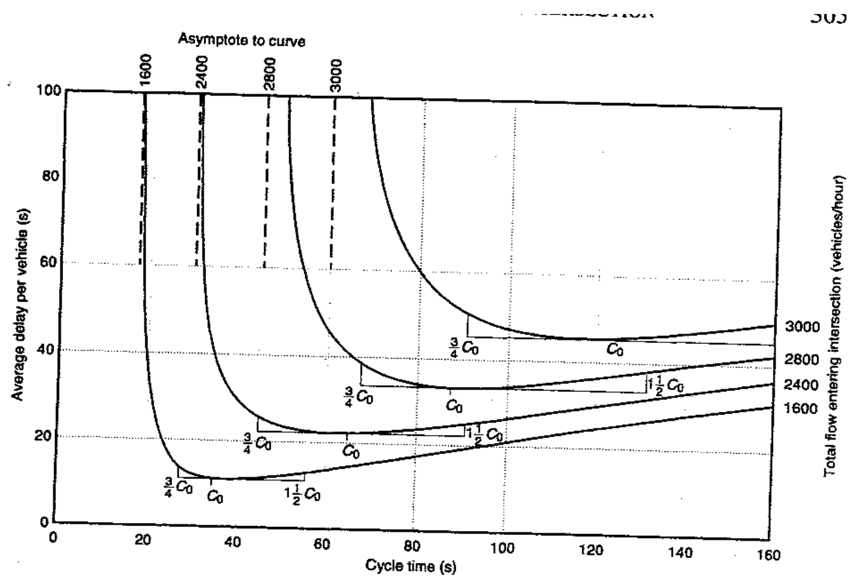


Figure 2. 3 Effect on delay of variation of the cycle length (based on Road Research Technical Paper 56) (Source: Salter and Hounsell 1996)

Once the cycle time and green split for each phase for a certain period of time has been determined, this timing pattern repeats itself regardless of traffic fluctuations. This signal control method is the simplest timing method and does not require any vehicle detection facilities. It has been replaced by more advanced and intelligent signal control strategies and is rarely used nowadays.

VA Control

In UK there are 2 main forms of vehicle actuation (VA) signal control systems at isolated junctions: the system-D and MOVA (Microprocessor Optimised Vehicle Actuation). Generally VA signal control systems use traffic information obtained from detectors to allocate green time based on current traffic demand. The basic principle is to set a minimum green time and extend the green time until it reaches a critical gap or a maximum green. The maximum green can be a preset value or a variable that is calculated real time by optimising delay or queues. VA has considerable merit compared with fixed timing control and has been the standard method for isolated junctions. System-D and MOVA are reviewed respectively as follows.

System D

System D was developed in the 1960s to replace pneumatic detectors. According to Detector instruction MCE 0108C by Highway Agency (2002), there are normally three loop detectors in system D, although fewer can be used. The furthest, at 39 metres from the stop line is normally nominated as “X”. Traditionally this demands the green if the signals are on red and otherwise extends the green. The next two are “Y” and “Z” and traditionally only extend the green. The layout of loop detectors in system D is illustrated in **Figure 2.** 4 below:

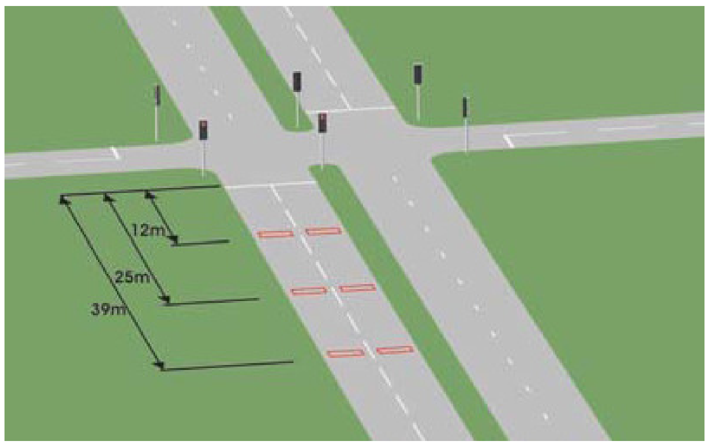


Figure 2. 4 System-D detector layout (Source: DfT 1999)

Once a green signal is displayed, the green duration maybe continuously extended by vehicles detected moving towards the signal. If there is no vehicle detected or the green duration has reached the maximum value, the current phase loses the right-of-way and the signals switch to the next stage.

Above Ground Detectors (AGDs) can be used effectively instead of loop detectors. Traffic advisory leaflet 16/99 (DfT 1999) gives details of the usage of AGDs: Above ground detectors are aimed at the approaching traffic and set at a vertical angle to detect cars in the approach lane(s) when they reach a point 40m from the stop line. Normally the above ground detectors should be mounted on the nearside primary pole, as shown in **Figure 2. 5**.

Figure 2. 5 Above Ground Detectors (Source: DfT 1999)

Based on the vehicle information obtained from vehicle detectors, the main parameters involved in signal control method in System D are described as follows:

> **Minimum green**: The shortest green duration allowed for a phase; 7 seconds is commonly used as the absolute minimum green for safety reason.
>
> **Maximum green:** The maximum amount of green time allowed for a phase. This value can be calculated by adding a certain period of time to the phase split calculated using the optimum cycle time.
>
> Once this value is reached, the signal will switch to the next stage regardless the current demand.
>
> **Gap-out:** When the vehicle headway exceeds the predefined maximum value, which means there is less or no demand from current phase, the signal will switch to the next stage.
>
> **Seconds per actuation:** This is the number of seconds the minimum green is extended for each actuation.

MOVA

MOVA (**M**icroprocessor **O**ptimised **V**ehicle **A**ctuation) signal control strategy was researched and developed by TRL (Transport Research Laboratory) during 1980s to address some problems observed in the VA control, e.g. the inefficient usage of green phase and difficulty in setting up maximum green time effectively. It pointed out in the Traffic Advisory Leaflet 3/97 (DfT 1997) that the TRL/DoT trials had shown that MOVA reduced delays by an average of 13% compared to the earlier VA system.

MOVA has two operational modes; the first deals with uncongested conditions and the second with situations when the junction becomes overloaded/ congested with large queues on one or more approaches. Before congestion occurs, MOVA operates in a delay minimising mode; if any approach becomes overloaded, the system switches to the capacity maximising mode. Ideally, the detectors should be placed about 8 seconds cruise time from the stop line for the upstream-most detectors (known as the IN-detectors) and 3.5 seconds for the detectors nearer the stop line (known as the X-detectors). The detector settings for a MOVA controlled junction are shown in **Figure 2. 6**.

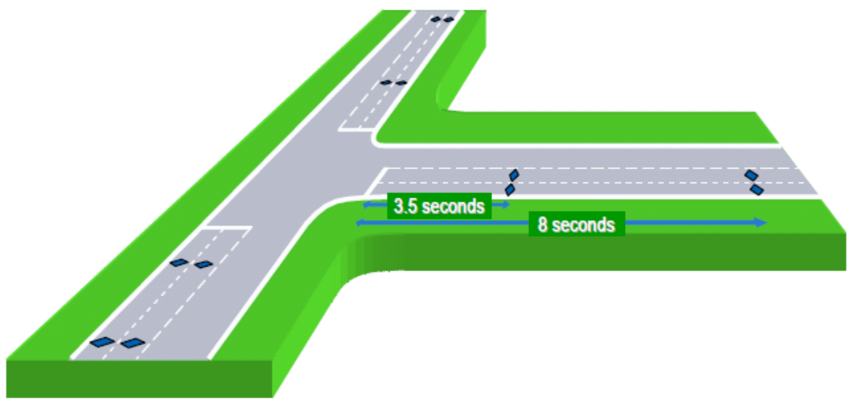


Figure 2. 6 Detector locations in MOVA (Source: MOVA)

The green time operated in MOVA is calculated based on the vehicle information from detectors. MOVA calculates the green as follows (extracted from MOVA manual):

> **Calculated minimum green:** the initial minimum-green period needed to clear all the vehicles that are estimated to be queuing between the stop line and the X-detector (typically between the absolute minimum and about 15 seconds, or enough to clear the maximum number of vehicles that could queue between the stop line and the X-detector)
>
> **Searching for end-of-saturated flow:** if the queue extends upstream of the X-detector, saturated flow continues after the calculated minimum green has timed out. In most circumstances MOVA will continue the green until

saturated flow has ended- which will occur when the gaps between vehicles exceed a pre-determine time. MOVA also incorporates a real time traffic model, which is interrogated every second to see whether the phase should change to minimise the overall traffic delay. A maximum green time may have to be set where queuing and saturated flow is extensive.

2.1.2.3 Co-ordinated junctions

Coordinated control is normally implemented when junctions are closely spaced causing traffic platoons to occur. Coordinated junctions are operated under an Urban Traffic Control (UTC) system so that all signals in an area can be synchronised to allow a green platoon for vehicles. It is designed to achieve a network benefit. Both fixed time and traffic responsive control methods can be implemented at co-ordinated junctions. The principles are described as follows.

Fixed time UTC

The fixed time control plan for co-ordinated junctions is calculated off -line using historic traffic data in a network covering a number of junctions. Optimum signal settings are calculated for the modelled network by minimising overall delay and queues, for different times of a day and different days. Vehicle detection is not needed for this system.

TRANSYT is a commonly used fixed time UTC system in the UK and worldwide. It is an off-line computer program which can quickly assess individual junction performance and also produces optimum fixed-time co-ordinated traffic signal timings in any network of roads for which traffic flows are known. According to Vincent et al (1980), The TRANSYT model has 2 main elements; the traffic model and signal optimiser. The model predicts the value of a ‘Performance Index’ for the network, for any fixed-time plan and set of average flows that are of interest. The performance index is a measure of the overall cost of traffic congestion and is usually a weighted combination of the total amount of delay and the number of stops experienced by traffic. The optimisation process adjusts the signal timings and checks, using the model, whether the adjustments reduce the performance index (PI) or not. By adopting only those adjustments which reduce the PI, signal timings are successively improved. In this case, the objective is to minimise the PI.

Traffic responsive UTC

Traffic responsive UTC uses vehicle detection information to continuously monitor the road network online and predict the best signal plan for the current traffic conditions. SCOOT (**S**plit **C**ycle **O**ffset **O**ptimisation **T**echnique) (2008) is a successful example of a traffic responsive UTC system which is able to adjust traffic signal timings continuously to adapt to traffic fluctuations so that vehicle delay time can be minimised. The adaptation is aimed at minimising wasted green time at intersections and reducing stops and delays by synchronising adjacent sets of signals. The changes in signal timings are made such that they are small enough to avoid major disruptions in traffic flow, but are frequent enough to allow rapid response to changing traffic conditions. The operation mechanism of SCOOT is described below, which is directly extracted from SCOOT manual.

The operation of the SCOOT model is summarised in **Figure 2. 7**.

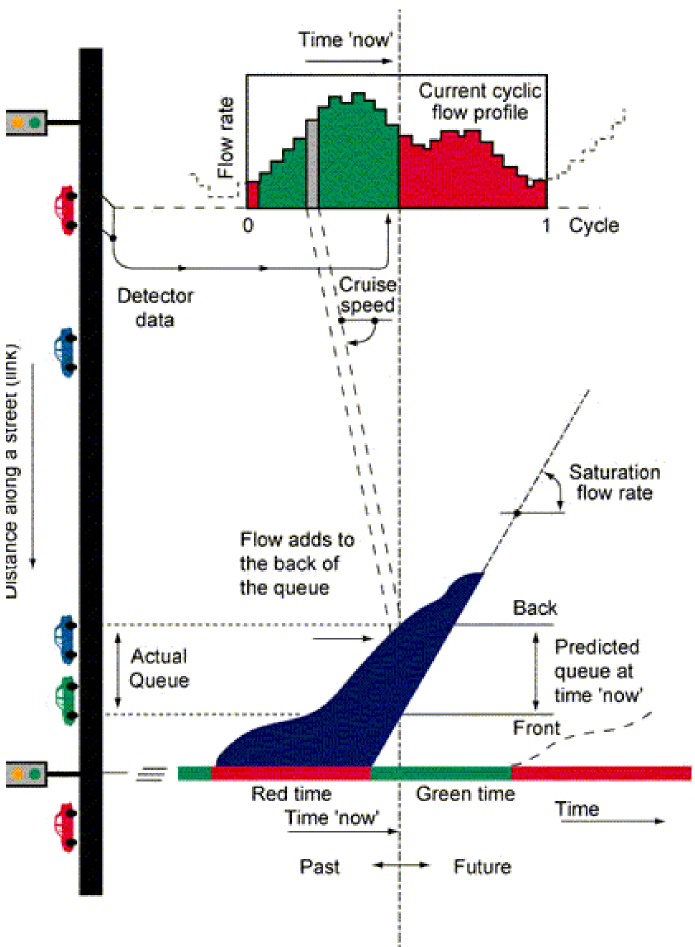


Figure 2. 7 Operation of SCOOT (Source: SCOOT Manual)

'SCOOT obtains information on traffic flows from detectors. As an adaptive system, SCOOT depends on good traffic data so that it can respond to changes in flow. Detectors are normally required on every link. Their location is important and they are usually positioned at the upstream end of the approach link. Inductive loops are normally used, but other methods are also available.

When vehicles pass the detector, SCOOT receives the information and converts the data into its internal units and uses them to construct "Cyclic flow profiles" for each link. The sample profile shown in the diagram is colour coded green and red according to the state of the traffic signals when the vehicles will arrive at the stopline at normal cruise speed. Vehicles are modelled down the link at cruise speed and join the back of the queue (if present). During the green, vehicles discharge from the stopline at the validated saturation flow rate.

The data from the model is then used by SCOOT in three optimisers which are continuously adapting three key traffic control parameters - the amount of green for each approach (Split), the time between adjacent signals (Offset) and the time allowed for all approaches to a signalled intersection (Cycle time). These three optimisers are used to continuously adapt these parameters for all intersections in the SCOOT controlled area, minimising wasted green time at intersections and reducing stops and delays by synchronising adjacent sets of signals. This means that signal timings evolve as the traffic situation changes without any of the harmful disruption caused by changing fixed time plans on more traditional urban traffic control systems.'

To sum up, signal control methods can be varied according to network scales, the detection facilities and the requirement of sophistication. Bus signal priority can be implemented into these traffic signal control systems using various methods. The options of bus priority forms and architectures implemented worldwide are reviewed in the next section.

2.1.3 Forms of BSP strategies

There are 2 main elements involved in providing a signal priority to a bus, the physical infrastructure and signal control strategies. The physical infrastructure includes bus detection facilities, a signal control system and a communication system. This section focuses on the forms of signal control strategies. They vary according to bus priority schemes. Generally bus signal priority can be categorised into 2 groups according to optimisation purposes, which are full priority and differential priority. The same concepts are also referred as absolute (unconditional) priority and conditional priority in some other countries, e.g. U.S. (Furth and Muller 2000). In this study, 'full' and 'differential' terms are applied in the following chapters. Full priority is used to improve bus speed. With full priority, any bus detected at the detector point can be given a priority signal if it arrives during the predefined green extension or recall time intervals subject to the signal control strategy operation.

Differential priority is determined and awarded to improve regularity (for maintaining the desired headway) or punctuality (for maintaining the schedule adherence). This indicates that for headway-based bus services, priority may only be granted to buses which have large headways to the front bus, whilst for schedule-based services, priority may only be granted to buses running late to schedule.

For either of the 2 categories, there are a number of basic forms of bus signal priority, reviewed as follows.

Hounsell (1988) identified 4 basic bus priority forms under UK practice adopted at isolated junctions operating under D-system VA (which remains the most prevalent form of isolated junction control in the UK), which are:

1. Priority extension

This allows the green time to be extended beyond its normal maximum when an approaching bus is detected towards the end of the green period, thus preventing delay caused by the red signal.

2. Priority recall

Green time is recalled when an approaching bus is detected in the red aspect which reduces the remaining red time to a minimum to buses by either limiting competing stage lengths to a minimum or omitting them altogether.

3. Compensation

Compensation can be given in stages where a non-priority stage is curtailed due to a priority call on a competing stage, subject to demand.

4. Inhibit

This facility prevents bus priority from being granted in consecutive cycles, as can occur where bus flows are high, in order to minimise the negative impacts on non-priority traffic, and allow compensation to be effective.

For larger road networks with numerous junctions under, an Urban Traffic Control (UTC) system such as SCOOT system, various forms of bus priority can be modelled (SCOOT 2008). Apart from the 4 forms mentioned above, more sophisticated ‘recovery’ and ‘restrictions’ strategies can be modelled to re-synchronise the timings back to the normal SCOOT optimisation, explained as follows.

● ***Recovery:***

Once the bus passes through the signals, a period of recovery occurs to allow the system to absorb the added queues caused by giving extra green time to the bus phase. Four options for recovery are provided for operation after extensions and recalls as follows.

- DN - do nothing recovery accepts the change which has taken place in the signal timings due to the action of bus optimisation and updates SCOOT with these timings. SCOOT then optimises as normal.
- MS - minimum stage recovery consists of running stages to a minimum to resynchronise with SCOOT timings.
- DS - degree of saturation recovery is similar to MS recovery but instead of running stages to a minimum, stages are run short to a length constrained by the degree of saturation. (Default after extensions.)
- LS - long stage recovery consists of running stages long to resynchronise with SCOOT timings. Stages are still subject to their maximum stage length. (Default following recalls.)

● ***Restriction on priority:***

The amount of priority given to buses can be restricted depending on the saturation of the junction as modelled by SCOOT. Normally the junction is not allowed to become oversaturated, and buses may not be given priority in some circumstances (e.g. when the degree of saturation is high).

In circumstances when greater bus delay savings are desired, ‘stage skipping’ may be applied. This allows one or more traffic 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. Pedestrian stages may also be skipped, although this is often not allowed for safety reasons. For instance, if a bus that requires stage 3 is detected during stage 1, the signals can change straight from stage 1 to stage 3. Stages that may be skipped are specified in the SCOOT data.

Similarly to the forms and terms used in UK, a handbook on transit signal priority (Smith et al. 2005) summarised several transit signal priority (TSP) treatments implemented in US cities, which were called as active priority. The TSP treatments used in the US are shown as follows:

– ***Green extension***
– ***Early green (red truncation)***
– ***Actuated transit phase***
–***Recovery***

Other forms can be considered under extreme conditions, including the following:

– ***Phase insertion***

This is a special priority phase inserted within the normal signal sequence. The phase can only be inserted when a transit vehicle is detected and requests priority for this phase. An example would be the insertion of a leading left-turn-only phase for transit vehicles entering an off-street terminal on the opposite side of the street that would only be provided when requested by the presence of a transit vehicle.

– ***Phase rotation***

This means the sequences of phases are rotated.

It can be seen that for any types of junctions and control methods, i.e. isolated or co-ordinated, fixed timing or vehicle actuated, the green extension and recall (early green) strategies are the most commonly used priority measures. For heavy flow traffic conditions, compensation and inhibition must be considered. Recovery and restriction using the same concept can be realised in SCOOT. Other facilities such as stage skipping, phase insertion or phase rotation can be only considered under extreme conditions when very high priority is required.

2.1.4 Bus detection facilities

Bus detection technology is a vital part in the implementation of bus priority strategies. To provide priority to individual buses, the first information the control centre (or controller) needs to know is that the bus is approaching the signal. In other words, the locations of individual buses need to be identified before giving signal priority to the buses. Therefore the bus detectors need to be able to distinguish buses and identify the locations. The following two sections present a review on the bus detector types and detector locations.

2.1.4.1 Bus detector types

Hounsell et al (2004) summarised 3 forms of detection technology according to the locations of detectors fitted, which are:

- ***Infrastructure equipment only:***
  This involves detecting buses using methods such as the 'long loop' in which buses are identified by their length/area and 'signature processing' systems in which a bus is detected according to its unique signature profile received at the controller. No bus equipment is required in this form.

- ***On –bus and local infrastructure:***
  This involves some form of bus transponder and communication with inductive loop or beacon detectors on the approach to an intersection. Another system is an Infra-red emitter equipped on the front of the bus which can send an optical message to the traffic signal for priority request.

- ***On-bus and central infrastructure:***
  This involves the use of on-board equipment for bus location (e.g. the GPS navigator), and usually, radio-based communications between each bus and a control centre. The communications can vary from traffic channels with 'polling' to systems with GPRS (General Packet Radio Service) technology.

Detection methods can also be classified as Selective Vehicle Detection (SVD) and Automatic Vehicle Location (AVL) techniques. SVD such as loops and roadside facilities are located at fixed points on the road network, often requiring communication between transponders fitted on buses. The SVD system uses roadside beacon detection to provide bus priority, 'When a bus passes a beacon, the transceiver installed on the bus sends a signal to the beacon which then transmits a signal to the traffic signal controller (TfL 2006a). The traffic signal controller then manages the sequence of the lights to assist the transit of the bus through the junction. AVL has an on-board means for locating vehicle's position and reports it to a vehicle management system. It is used by many bus management systems and is increasingly popular. The report by DfT (2004) outlined the technologies available for AVL Bus Priority as being:

- Global Positioning System (GPS);
- General Packet Radio Service (GPRS);
- Fixed reference points;
- Milometer; and
- Door open and close indicator

AVL systems allow the real-time location of individual buses to be monitored. It allows the location of a bus to be compared against a schedule, by which priority can be provided to a bus running late to its schedule, or to be compared against the desired bus headways in high frequency services. When the on-bus AVL system determines that the bus is at the priority detection point, it will transmit a bus detection signal, priority level and possibly a vehicle identifier. The signal control system, e.g. SCOOT, will then provide the appropriate priority to the bus as defined in the SCOOT data.

The development of in-vehicle GPS technology appears as an innovative means for providing consistent vehicle location information, thus becoming more popular in BSP implementation. In 2005 Transport for London purchased one of the worlds largest real-time passenger information and fleet management systems with the objectives of equipping 8000 vehicles with GPS tracking and installing 500 passenger information signs -called iBus (TfL 2008). iBus is a state-of-the-art Automatic Vehicle Location (AVL), radio and an on-bus passenger information display and announcement system - to every bus and garage across London, over 8000 buses and 90 garages. It was introduced after overcoming performance limitations of GPS in urban environment (e.g. urban canyons and multi-pathing). It does this by using a combination of technologies to deliver the accuracy required from the AVL part of the system, including Global Positioning System (GPS) satellite technology and 'map matching' with inputs from a Gyroscope and the bus’s speedometer/odometer.

The development of detection technology provides a more accurate and intelligent locating estimation for individual buses. The forms of detectors may vary in practical applications, but all of them can be characterised by their measuring capabilities, such as vehicle counting, presence measuring, speed measuring, distinguishing different vehicle types etc. In modelling bus priority strategies, these features are important to identify and track buses when giving priority decisions to buses.

2.1.4.2 Bus detector locations

The best location for bus detection is a compromise between the need for providing the advanced notice at the furthest upstream point for the approaching bus and the requirement of accurate journey time prediction between bus detector and stopline (Hounsell et al 2004). The distance from the traffic signal where the request is sent determines the length of green extension. In ideal situations, the prioritised bus should be able to successfully pass through the junction at the last second of predefined extension time, with no passing failure or any waste of extension green. In practice, an extra time period is always added to the needed time to assure provision of bus priority. To find out the appropriate bus detection positions for this study, several studies suggesting detector locations were reviewed, as listed below.

Hounsell (1988) indicated that for selective detectors, the locations can be up to 150m upstream of the stopline, with intermediate detectors as required.

Bretherton et al (1996) evaluated bus priority in SCOOT by using the STEP microsimulation and found that a location of 70m-100m upstream was recommended for London, and detectors must be located downstream of bus stops.

Koonce et al (2002) examined detection range setting method for bus priority based on case study in Portland, U.S. 3 factors were identified to dictate bus arrivals in detection range setting, including the speed at which the vehicle was travelling, the impedance it experienced, and the stops that it made. The initial operating concept was to set the detection point at a distance of 40 feet (12m) downstream of a bus stop. Field tests in Portland city indicated that in several locations these factors together limited the detection range to less than 300 feet (91.4m).

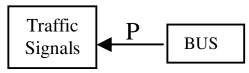
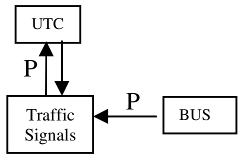
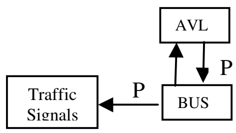
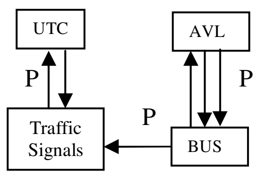
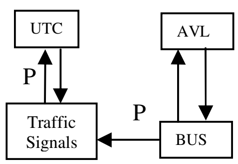
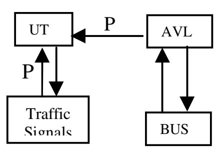
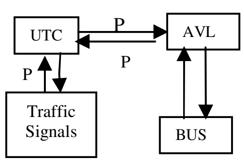
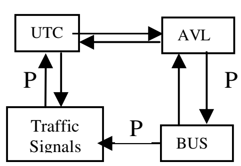
The latest report 'guidelines for implementing bus priority at VA junctions using iBus system' (Transportation Research Group (TRG)2007) sugg*ests the ideal detector distance of 70-130m at links without bus stops with speed limits ranging from 30 to 40mph. At links with bus stops, bus priority is normally triggered once a bus stopped at a bus stop moves 2m away from the bus stop after closing its doors.* This is the latest and most appropriate guideline for this study and the suggested distance is used for later study.

2.1.5 Options of BP architecture and worldwide implementation

2.1.5.1 Architectures of bus signal priority

A review of bus priority applications all over the world involving different techniques was introduced in the PRISCILLA project (2002). Eight categories of bus priority architectures were identified as illustrated in **Table 2. 1** depending on the local traffic control systems which exist, available resources, and other city/ country specific factors.

Table 2. 1 Categories of BP architectures in PRISCILLA (Source: PRISCILLA 2002)

Architecture category	Architecture (P=priority request)	Examples/ cities	Priority options	
			Centralised	Decentralised
1		Examples in many European cities		√
2		Examples in many European cities	√	√
3		Aalborg Helsinki		√
4		London	√	√
5		Zurich	√	
6		Southampton Toulouse Turin Cardiff Gothenburg	√ √ √ √ √	 √ √
7		CGA	√	
8		Genoa	√	√

The specification for each category can be summarised as follow:

Category 1. This architecture involves bus priority at isolated junctions, without the use of AVL or UTC. Buses are typically detected using transponders, tags, or through entering an infra-red detection zone.

Category 2. This architecture is similar to category 1, except that the traffic signals and the priority provided operate under UTC.

Category 3. This involves the use of AVL to determine bus-specific priority levels, which are then transmitted from the buses to each traffic signal controller on the route. With no UTC involved, signal control is isolated/ decentralised.

Category 4. This architecture is similar to category 3, except that the traffic signals are under UTC. There is no communication between AVL and UTC, resulting that bus-specific priority requests are routed from the AVL centre to UTC via the bus and traffic signal controllers.

Category 5. With this architecture, used in Zurich, Switzerland, AVL is used predominantly for fleet management. Buses and trams are given 'absolute' priority using loop detection.

Category 6. This involves one-way communication of bus location and priority requirements from an AVL centre directly to UTC. AVL becomes the primary source of bus location upstream of signalised junctions for priority purposes.

Category 7. Common in many French cities, involving centralised UTC/AVL integration; UTC plays an active role in informing AVL of each proposed signal stage change at each junctions, and requesting the location of any approaching buses or trams which should influence the stage change time(i.e. where priority is needed.)

Category 8. This architecture illustrates the highest level of two-way communication between the system components. In the example in Genoa, Italy, buses are allocated a priority level by the AVL centre and transmit this directly to the traffic signals for implementation subject to UTC command. At a higher level, strategic data is transferred between the AVL and UTC centres.

Out of these 8 categories, there are 2 main architectures applied in UK, category 4 and 6. Category 4 is called 'Decentralised AVL-UTC communications' and category 6 is called 'Centralised AVL-UTC communications'. The working principles for these 2 architectures are illustrated in **Figure 2. 8** and **Figure 2. 9** (Hounsell & McLeod 1999).

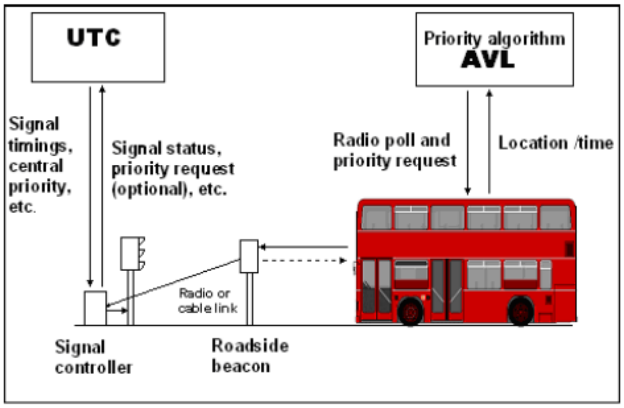


Figure 2. 8 Decentralised AVL-UTC communication BP architecture used in London (Source: Hounsell & McLeod 1999)

From the Hounsell et al.'study (2000), in the system shown in **Figure 2. 8**, a bus updates its position with the help of roadside beacons placed at strategic locations supplemented by an odometer on each bus. The control centre communicates with the bus using Band III radio at every ~30 seconds to get its present location. The control centre then determines the priority level request (PLR) of the bus depending upon its lateness. The calculation of lateness is carried out for each bus at the priority calculation points (PCP) specified on the route. The priority level request (PLR) determined is then sent back to the bus at the next polling. The bus then transmits its priority request to the traffic controller when detected at the approach of each signal controlled junction. The decision to implement the requested priority is taken at the local or central level depending on the type of priority (extension/recall) required.

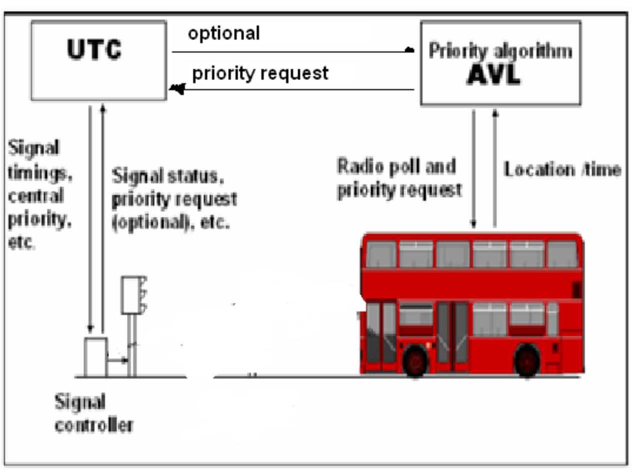


Figure 2. 9 Centralised AVL-UTC communications' bus priority architecture

The system in **Figure 2. 9** involves the use of AVL for bus or tram location and the use of a priority algorithm in the AVL centre to determine the priority requirements for each bus or tram (e.g. according to its headway or adherence to schedule). A priority request is then passed from the AVL system to UTC control defining the priority level requested at that time or location for that bus or tram.

2.1.5.2 Worldwide implementations and performance

3 cases are reviewed in the following section to help establish the bus signal priority strategies to be studied. These 3 cases are respectively in London (UK), Zurich (Switzerland) and Los Angeles (US).

London

The first active bus priority scheme SELKENT (Hounsell 1995) was implemented in South East London and KENT in 1987 for isolated junctions. This scheme covered 56 signalised non-UTC junctions and included 900 London buses with transponders fitted. The success of the SELKENT scheme led to a scale extension and development to both fixed time and traffic responsive Urban Traffic Control systems. Then it was followed by the SVD Bus Priority both at fixed time and traffic responsive urban traffic control systems. The PROMPT (Priority and Informatics in Public Transport) (Hounsell et al 1996) project developed bus priority at traffic signals under traffic responsive SCOOT UTC system and SPRINT (Selective Priority Network Technique) (Hounsell et al 1997) was developed for those under fixed time UTC in London.

Bus–SCOOT trials tested by Bretherton (1996) applied 4 priority strategies in Camden SCOOT region of London, respectively are:

Central Extensions;
Central Extensions +Recall;,
Local Extensions; and
Local Extensions + Recalls.

The results show that local extensions produce the best benefits to buses with the least disruption to other traffic. Recalls give further benefits to buses at the expense of other traffic. Results also suggest that higher bus delay savings can be obtained at junction with lower degree of saturation.

Developments since 2005 have included implementations of the iBus (TfL 2008) system on 8000 buses and at nearly 2000 traffic signals using GPS and GPRS technology, but with similar forms of bus priority strategy.

Zurich

Nash (2003) stated that Zurich had been successful at implementing a comprehensive transit priority program with very impressive results. Zurich's traffic signal priority program was implemented as result of a 1977 citizen's initiative that provided funding and political support for transit priority improvements. It attempts to take the minimum time necessary for transit priority compared to other means, enabling it to provide transit priority without hurting traffic circulation. The transit signal priority consists of transit vehicle and traffic volume detectors on the streets, transmitters on transit vehicles, and computers in the central control centre. There are 3 detectors located along the bus route towards the junction, which respectively are located 300 meters upstream, 100 meters upstream, and one just after the intersection stop line. The computers use the information of vehicle locations from these 3 detectors to adjust traffic signal phases and timing to optimize passage of the transit vehicle through the intersection.

Zurich's approach of providing transit vehicle priority is only to add 5 to 8 seconds (extension only) of green time dynamically to a phase if the green time can be added at the right point in the cycle. This strategy has been proved to be the most efficient method for Zurich, with the custom-designed equipment and under its unique environment. No other form of priority (e.g. Green recall) was implemented.

Los Angeles (Smith et al 2005)

The City of Los Angeles has developed a suite of traffic control software packages for real time traffic management which includes Adaptive Traffic Control System (ATCS)®, Traffic Signal Control Program (TSCP)®, Smart Transit Priority Manager (STPM)®, and Transit Priority System (TPS)®. 654 intersections and 283 buses were equipped with signal priority facilities.

The transit signal priority is centralised with communication between local controllers and control centre, from where the priority signal is sent. Loops, due to the high reliability and ease for installation, are applied for bus detection, with corporation of transponders fitted on buses. Priority is differentially granted to buses whose headway to the previous bus is equal or greater than the defined headway. No priority is granted to early buses or buses less than 6s late.

3 priority strategies were implemented in LA, which were:

Extension;

Recall; and

Phase hold (restriction).

Based on an adaptive signal control system, generally only 10% of cycle time is allowed to give for bus priority, which is 6-15 seconds. The results suggest extension is more effective than early green because it saves the entire red time.

These 3 examples demonstrate that in real world implementation, green extension and recall are the most common forms of priority. Green extension is more effective than recall as it saves the entire red time and causes the least disruption to other traffic. Recalls give further benefits to buses at the expense of other traffic. Other measures such as restriction may also be needed when demand is high. These real life examples can provide some general expectation of the effectiveness of implementing priority strategies for the later study.

2.1.6 Summary

This part mainly reviewed the measures of bus signal priority. A review on UK traffic signal control systems was firstly presented as the signal control environment formed the baseline of implementing any bus priority strategies. The requirement for the forms and the sophistication of bus priority strategies largely depend on the signal control systems the junctions apply. The commonly used forms and bus detection facilities for bus signal priority are then reviewed to assure the modelling and assessment in this study focus on the latest systems implemented on street. The literature suggests that the green extension and recall are the most commonly used priority strategies and compensation and inhibition are needed when traffic flow is high. The worldwide implementation of bus priority including the architecture and examples were reviewed to inspire the forms and expected results for the modelling of bus signal priority in later chapters.

2.2 Evaluation approaches for BSP

There are 2 potential approaches to evaluate bus signal priority strategies. One is real-world measurement, and the other one is computer simulation. Mathematical and analytical approaches may also be possible, but generally only for relatively straightforward studies. Simulation can be divided into 2 categories which are macroscopic simulation and microscopic simulation. These 3 options are now reviewed so that a best approach for this study can be determined.

2.2.1 Field measurement

From the review in 2.1.2, bus priority strategies can be implemented under various traffic signal control systems, such as fixed time and vehicle actuated junctions, isolated and co-ordinated junctions. To measure and evaluate the performance of bus signal priority, the basic method to measure bus/vehicle journey time on street is to collect field data directly on-board (e.g. count bus journey time on-board between stops along a known bus route) or use data from vehicle detectors (e.g. inductive loops) to estimate bus speed or travel time between different detection points. The more state-of-the-art measurement typically involves automatic number plate recognition (ANPR) technique or GPS system to selectively measure journey time of individual vehicles.

For a typical before-and-after study on real sites, field data of journey time needs to be collected for both before and after scenarios over multiple days for statistical tests. In order to evaluate more scenarios involving a number of factors such as different bus flows, traffic flows and bus priority strategies, the sites should be able to provide these variations, or these factors can be found in other similar sites. In addition, other factors that may influence the experiments should be carefully considered, such as pedestrian movements, unexpected incidents etc. Field measurement is a relatively costly approach to evaluate bus priority. Furthermore, direct measurements of emissions from buses and a large sample of general traffic would be complex, costly and impractical for a PhD study. If considering the study purpose of evaluating emissions which requires emission estimation for both buses and cars, this approach appears to be impractical. This approach has therefore been rejected.

2.2.2 Macroscopic traffic modelling

Macroscopic traffic modelling has been commonly used for modelling and evaluating urban traffic situations, normally used in combination with traffic assignment models. They are developed on the basis of traffic flow theory according to the statistical relationships between flow, speed and density. The typical examples of macroscopic traffic models used in the UK are SATURN, TRANSYT, LINSIG, CONTRAM etc, although CONTRAM can be considered as a mesoscopic model because a more detailed level of aggregation can be achieved. The complexity of macroscopic simulation has significantly increased during recent decades, mainly due to the rapid development of computer science and the introduction of concepts/ driving behaviour models from the development of microscopic traffic simulation models. Some of these macroscopic models nowadays are able to model traffic on a street or an intersection level, however the detailed driving behaviour models, as used in microscopic simulation models are not included in macroscopic models so that the individual vehicle travelling trajectories can not be modelled.

Bus signal priority strategies can not be modelled by macroscopic traffic models as they are not based on a second-by-second modelling approach and the signal plans can not be modified according to the requirements of individual buses. The features of macroscopic simulation models exclude the possibility of its application for this study. Therefore a more sophisticated approach is required for this study.

2.2.3 Microscopic simulation Modelling

Microscopic simulation models are able to imitate the behaviour of individual entities over time in the system. Since people realise that the traditional methods have many limitations in assessing the complex transport network and predicting a new technology or system implementation, micro-simulation shows its advantages in modelling different components in the transport system and the interactive effects. Basically, a traffic microscopic simulation model is an integration of several essential driving behaviour models such as car-following, lane-changing, gap-acceptance, overtaking, looking ahead, and so on. Vehicles generated into the simulated network proceed according to the rules defined in driver behaviour models and other predefined traffic and signal rules. For each simulation step, the dynamic information for each vehicle, e.g. speed, acceleration, position, are all recorded by the system and can be extracted by users. Moreover, the period of analysis can be split into several time slices, allowing the users to observe and evaluate the build-up, dissipation and duration of traffic congestion Federal HighWay Administration (FHWA) (2003). More detailed explanation on the comparisons of models is presented in the later section 4.1. The following sections of this chapter focus on the review of the representative microsimulation models.

According to a brief guidance note of using micro simulation for TfL (2003), there is a variety of Micro-Simulation packages available worldwide. The SMARTEST Project (Bernauer et al 1997) found more than 60 developers producing modelling programs around the world. Most of these models are not available to the public as they are produced and used only within a small research community for some specific research purposes.

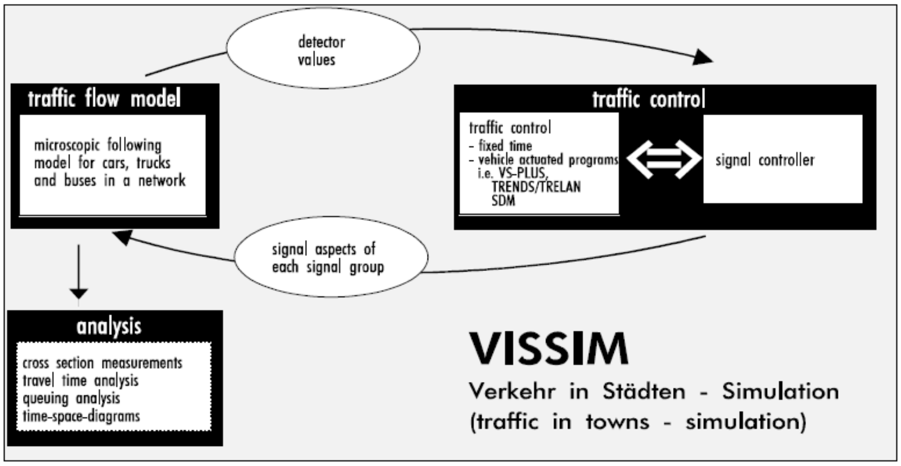
There are 3 commercialised and most widely used microsimulation packages in the UK, which are VISSIM, AIMSUN, and PARAMICS. These software packages all have developed and evolved rapidly with frequent update to continuously meet the emerging user requirements. Selecting one package that satisfies research needs is the first step for this research. This selection criteria and process is described in Chapter 4 in detail. However despite of the general capabilities the selection should be focused on the particular study purpose.

These 3 microsimulation software are reviewed from 2 aspects mainly concerned in this study: capability in modelling bus signal priority strategies and the possibility of integration with emission models, in preparations for the later comparison and selection of the microsimulation model in Chapter 4.

2.2.3.1 VISSIM

VISSIM (PTV 2001), is a time-step and behaviour-based simulation model for urban traffic and public transit operations.

It internally consists of 2 different programs, exchanging detector calls and signal status through an interface. The traffic simulator is a microscopic traffic flow simulation model including car following and lane changing logic. The signal state generator is a signal control software polling detector information from the traffic simulator on a discrete time step basis (can be as small as 1/10 second). It then determines the signal status for the following second and returns this information to the traffic simulator. The working principle of VISSIM is shown in **Figure 2. 10**.



Communication between traffic simulator and signal state generator

Figure 2. 10 VISSIM working principle (Source: PTV 2001)

With the increasing usage of actuated signal control methods in urban areas, VISSIM provides a user defined signal control programme capable of editing most of the signal control commands in current road networks, including transit signal priority, ramp metering, adaptive signal control, and etc. The working flowchart for VISSIM modelling a signal controlled intersection is shown in **Figure 2. 11**.

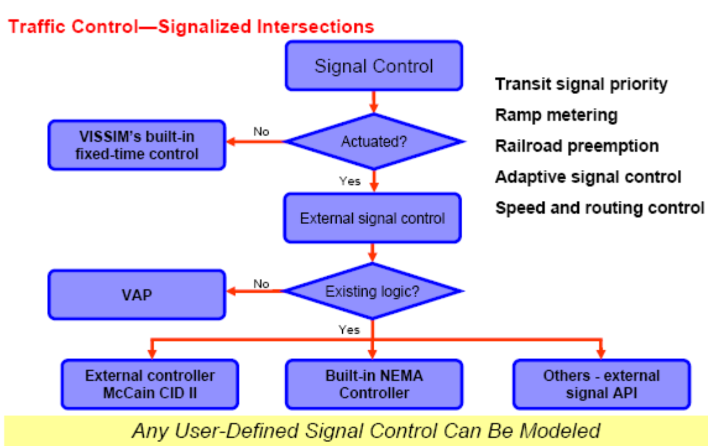


Figure 2. 11 VISSIM signalling working flowchart (Source: PTV training course 2007)

Within this procedure, for non-built-in signal control strategies, VAP and VISVAP provide a platform for users to generate their own signal control logic to simulate more complex signal control algorithms. VAP (Vehicle Actuated Programming) is a text file using a simple built-in programming language to command and create the signal control commands for the

VISSIM network. VISVAP enhances the use of free-defined signal control logic using the VAP language in offering a tool for creating and editing program logics as flow charts. An example is shown in **Figure 2. 12**.

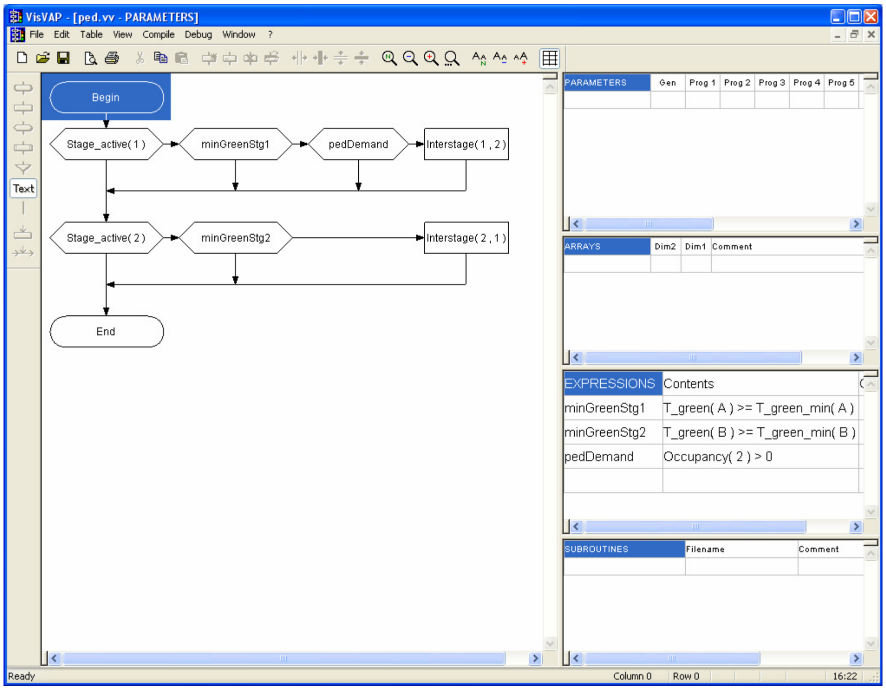


Figure 2. 12 An example of VAP and VISVAP in VISSIM (Source: PTV VisVAP User manual)

A report produced by University of Minnesota (Xiao et al 2005) states that 'The model is capable of producing measures of effectiveness commonly used in the traffic engineering profession like total delay, stopped-time delay, stops, queue lengths, fuel emissions, and fuel consumption. The model has been successfully applied as a useful tool in a variety of transportation projects such as development and evaluation of transit signal priority logic, the evaluation and optimization of traffic operations in a combined network of coordinated and actuated traffic signals, analysis of slow speed weaving and merging areas, and so on.

However, VISSIM does not provide amendable interfaces for most parameters, e.g. reaction time, vehicle generation modelling, and driving behaviour parameters in car-following and lane-changing models. These parameter values are fixed values and are not open to users for any changes.

For emission modelling, a separate environmental model-Evnpro (Environmental Program) - was developed using 'Vehicle Record' files produced by VISSIM since it can output data at each simulation step related to each single vehicle in the network. Evnpro comprises 2 emission models QUARTET and MODEM models (see section 3.3.5). The integration of

VISSIM with emission modelling is shown in **Figure 2. 13**. The information required to run the QUARTET model is based on data present in the VISSIM record file.fzp. For MODEM application, engine capacity and year of construction need to be considered. In the version of the program distributed, these are obtained from Vehicle Licensing Statistics 1998 for the UK.

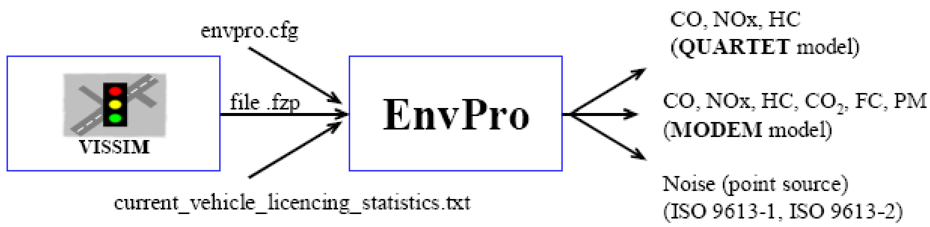


Figure 2. 13 Integration of VISSIM and Emission model (Source: PTV training course 2007)

There seems to be very limited information on the application and evaluation of using these 2 emission models in literature. The possible reason is the concern of the reliability of these 2 emission models. They were the early attempts of instantaneous emission models and had not been updated ever since. The detailed discussion and appraisal of speed-acceleration based instantaneous emission models are presented in Chapter 3.

2.2.3.2 AIMSUN

AIMSUN was developed by TSS (Transportation Simulation Systems) in 1986. The previous version is called AIMSUN/GETRAM which was frequently mentioned in literature. The newer version is named AIMSUN NG and then followed by the present version of Aimsun 6 (Aimsun User Manual 2008). The new version provides the transport modelling environment including macro, meso and micro models in a single software application. **Figure 2. 14** below illustrates the environment of Aimsun including the microscopic simulator and mesoscopic simulator. The microscopic simulator is the focus here. The Micro-simulator follows a microscopic simulation approach. This means that like all other microsimulation tools, the behaviour of each vehicle in the network is continuously modelled throughout the simulation time period while it travels through the traffic network, according to several vehicle behaviour models (e.g., car following, lane changing).

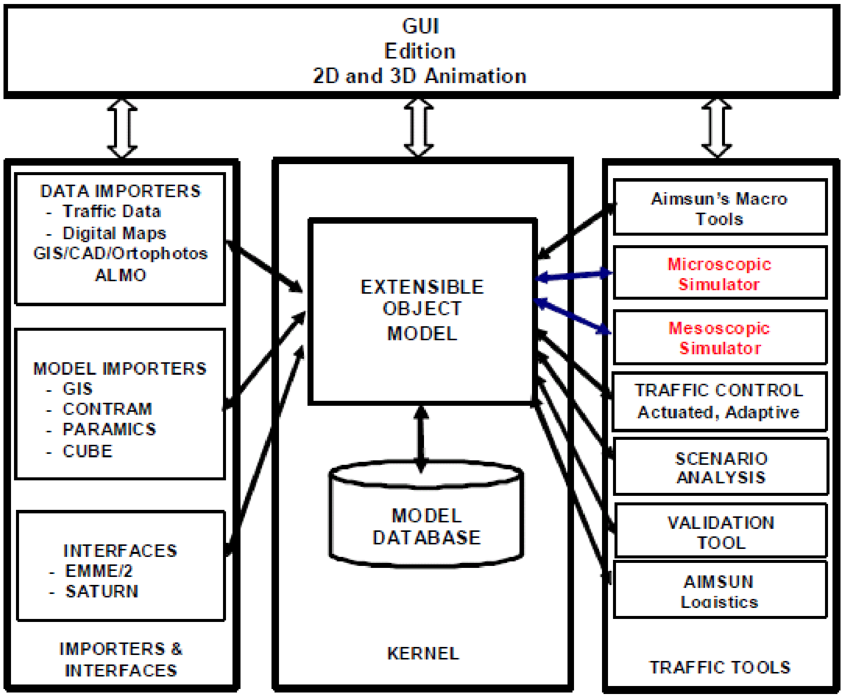


Figure 2. 14 Aimsun environment

AIMSUN provides an extensible environment that any kind of new functionality can be added by users through 3 general mechanisms, the SDK (Software Development Kit), Scripting and AIMSUN API module. The SDK offers access to Kernal and Graphical User Interface allowing the inclusion of new functionalities at both levels; it is the same tool that TSS use for developing new functionalities, new graphical elements, new editors and dialogs, etc. The Scripting is an extension possibility written by Python, with typical tasks for collecting data from the model, modifying data, writing data, and modifying the meta data model. Therefore generally the SDK and Scripting are used for editing static information before the start of a simulation. The last option is AIMSUN API, an optional module where an extra licence is needed, towards dynamic information change during a simulation. The API module provides several hundreds of functions relative to kinds of traffic management systems and facilities. These API functions and the interface enable modelling all types of bus signal priority strategies.

For modelling vehicle actuated signal control plans and bus signal priority using API interface, the logic can be written in C++ or Python programming language through the AIMSUN API interface. For every simulation step, the system checks the detection information and logic, and the signals change accordingly.

Compared with other tools, AIMSUN is more open and user friendly, allowing any reasonable amendments and changes to the simulator. It provides several choices for defining parameters and built-in models. For example, it provides 4 types of vehicle generation models and 4 car-following models which can be used for different flow situations. Reaction time for vehicles on road sections and stop line can be user defined as either fixed values or a distribution.

For vehicle emissions and fuel consumption modelling, AIMSUN (Version 6) (2009) provides 2 environmental models, namely the fuel consumption model and pollution emission model, described as follows:

(1) Fuel consumption model:

The AIMSUN Fuel Consumption Model assumes that each vehicle is either idling, or cruising at a constant speed, or accelerating or decelerating. The state of each vehicle is determined and the model then uses the appropriate formula to calculate the fuel consumed for this state. Details are reviewed in Chapter 3.

(2) Pollution emission model:

2 emission models are included in Aimsun. For previous versions, MODEM was embedded, while the Panis model (see chapter 3.3.5) has been integrated since version 6. MODEM in Aimsun, like in VISSIM, is provided as an empty frame with cells to be filled by users; however the values are not available to the public. These 2 emission models are reviewed in detail in chapter 3, so no further discussion is made here.

2.2.3.3 PARAMICS

PARAMICS (PARAllel MICroscopic simulation) was originally developed by Quadstone Ltd in Edinburgh, U.K., as part of a European ‘DRIVE’ project. S-PARAMICS is reviewed in this study. The PARAMICS suite comes in 6 modules: modeller, processor, analyser, monitor, programmer and estimator. The modeller is the core simulation engine, responsible for network representation, vehicle movement and behaviour, and traffic control. PARAMICS also provides the application programmer interface for users to implement customised simulation functions and connect to an external software (PARAMICS User Guide 2006).

The PARAMICS programmer is the API gateway that links the PARAMICS modeller to the external functions or programmes. By using the API, a user can extract data from, or write data in to the simulation model's internal memory. User defined plug-in functions can also be implemented for certain control actions as ITS functions require. However, there is very little literature available on successful applications of the API, especially in bus priority.

The fuel consumption model used in PARAMICS is PEAR- Program for Economic Assessment of Road Scheme User Guidance (Transport Scotland 2008), which is an economic assessment guide for Scotland. PEARS carries out trip-based assessments of changes in travel time costs and vehicle operating costs. The costs of a trip-based assessment are derived by aggregating the costs of each individually modelled vehicle on the network. DMRB guidance is adopted for emission modelling in PARAMICS. The emission factors provided in the DMRB guidance are the same as those in NAEI (described in Chapter 3), based on average speed and mainly aiming at predict emissions for a relatively large scale.

2.3 Evaluation of BSP on efficiency

Bus priority was originally designed to improve bus efficiency therefore much research has been conducted to evaluate its performance on efficiency focuses on time evaluation. The commonly mentioned indicators in literature include travel time reduction, delay saving, waiting time reduction, and speed increase. Valuation of time can be found in Web TAG 3.5.6 (DfT 2009a) on annual basis so that economic evaluation on efficiency improvement can be carried forward.

2.3.1 Indicators for efficiency evaluation

This section reviews some previous studies on evaluation of bus priority, so that the commonly used indicators can be identified and the appropriate ones for this study can be selected. Dale et al (1999) evaluated the impacts of transit signal priority scheme proposed in Seattle area, US. Both field studies and simulation by VISSIM were conducted. Nine Measures of Effectiveness were proposed in this study including: (1) Total intersection delay, (2) Minor movement delay, (3) Minor movement "cycle failures" (i.e. the number of vehicles which must wait for more than one cycle length), (4) Bus travel time, (5) Bus schedule reliability, (6) Bus intersection delay, (7) Intersection delay per person, (8) Vehicle emissions, and (9) Accident frequency. Hounsell et al (2000) evaluated 2 priority strategies_ the full priority to all buses and headway-based priority that implemented in West London using field trials. This study used delay saving time and passenger excess waiting time as evaluation indicators for full and differential priority. Hounsell et al (2004) investigated the potential for alternative detection points in a case study using a simulation model SIMBOL (Shrestha 2002) and used bus delay time as the optimisation indicator. Hill et al (2001) studied bus priority implementation in Cardiff. The operating strategy is to give priority to late buses only via SCOOT, and used bus journey time and delay time as evaluation indicators.

We can see that journey time (or travel time) or delay time are the most common indicators for evaluating the performance of bus priority on efficiency. These 2 parameters have been widely used in previous literature for evaluating bus priority schemes. The concept of journey time is straightforward. It is defined as the absolute time travelled by a vehicle from point A to point B. The definition of delay time at signal controlled intersections is a complex issue and has not been standardised. In particular it varies from the conventional statistical models and microscopic simulation models.

Traditionally, a commonly used approach to predict delay at traffic signals has been based on work by Webster (1958). He introduced a combination method of queuing theory and digital computer simulation to calculate delay at intersections under fixed time operation. The average delay time per vehicle on a particular intersection is given by the equation:

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

Where

d= average delay per vehicle,

c= cycle time,

λ = proportion of the cycle that is effectively green for the phase under consideration (that is, effective green time/cycle time),

q= flow,

s= saturation flow,

x= degree of saturation, which is the ratio of actual flow to the maximum flow that can be passed through the approach (that is q/ λ s)

In Highway Capacity Manual (Transportation Research Board 2000), delay time for each vehicle can be defined as 'the difference between the expected travel time (the time it would take to traverse the system under ideal conditions) and the actual travel time'. The average delay time for a network is the sum of individual delay times, as shown in formula below.

$$d = \sum (\textit{actual time- expected time})_i / n$$

Where

d=average delay time (seconds/vehicle)

i= the i^{th} vehicle

n= total number of vehicles for the aggregation level concerned

Using microsimulation models, the delay time for each vehicle can be calculated internally by estimating the real travel time and expected travel time. Average delay time for different levels of aggregation, such as for traffic streams, road sections, intersections or the whole system then can be collected. This is because the dynamic features of microsimulation allow the journey time for each individual vehicle to be collected individually and continuously and thus the time difference between the actual and expected journey time can be individually calculated.

2.3.2 Monetary evaluation for efficiency

Monetary evaluation in this study aims to unify the benefit and cost generated by operating different BSP scenarios, covering the valuation of journey time, emissions and Vehicle Operation Costs (VOCs). As the main indicators for efficiency are journey time and delay time, monetary evaluation for efficiency mainly concerns values of time. Values of time as proposed in Cost-Benefit Analysis in transportation economics are reviewed below.

2.3.2.1 Cost-Benefit Analysis

Generally, costs related to goods and services can be relatively easy to be established using market prices. In transportation economics, the method of Cost Benefit Analysis is commonly used for appraisal. As stated in Web TAG 3.5.4 (DfT 2006a), **'**Cost Benefit Analysis aims to take account of all the ways in which a project affects people, irrespective of whether those effects are registered in conventional financial accounts. It can be described in two different ways - as a calculus of willingness-to-pay or as a calculus of social costs and benefit**s**. These lead to two different ways of presenting the cost-benefit accounts, but (if properly carried out) both lead to the same valuation of net social benefit.

The Treasury definition of 'cost benefit analysis' referred from Her Majesty's Treasure (HMT) (2003) in Web TAG 3.5.6 is:

> *'Analysis which quantifies in monetary terms as many of the costs and benefits of a proposal as feasible, including items for which the market does not provide a satisfactory measure of economic value. (HMT 2003).'*

The concept of cost benefit analysis can therefore be very broad. At the present time, monetised cost benefit analysis includes changes in business and consumer travellers' journey time, vehicle operating costs, fares and other change. It also includes the impacts on private sector providers' revenues and costs, changes in the numbers of accidents, the effects of better transport interchange on traveller journey times, but excludes impacts on personal and freight security and other transport interchange quality factors and impacts of noise. It also subsumes the accessibility impacts to the extent that the cost benefit analysis takes account of all significant behavioural responses. It currently excludes the 'journey ambience' impacts, option values, impacts on local air quality and greenhouse gas levels, reliability impacts, impacts on landscape, townscape, heritage of historic resources, biodiversity, water environment and physical fitness as no money values for these have yet been established by the Department. It also excludes any wider economic impacts, including impacts on land use; and the impacts on integration with land-use policies and other Government policies. However it claims that impacts not included in monetised cost benefit analysis must be taken into account in assessing overall value for money.

Among the included factors in Cost-Benefit analysis as listed, 2 indicators directly related to this study are values of time and the VOCs. They are reviewed in the following 2 sections 2.3.2.2 and 2.3.2.3. Other aspects such as fares, providers' revenues and costs, accidents and the effects of better interchange are not considered in this study, partly because of the lack of relevant studies and data, and partly because theses aspects are not included in the scope of this study. The impacts on emissions which have not been currently included in the Cost-Benefit analysis, i.e. the valuation of emissions are studied this study and the existing methods are reviewed in chapter 3.

2.3.2.2 Value of Time

The value of time in transportation economics is the opportunity cost of the time that a passenger spends on one journey. It is one of the important elements used for cost-benefit appraisals. For most routine economic appraisals of transport projects the recommended prices from DfT can be used. The latest values are expressed in average 2002 prices and values.

Values of time are given separately considering working and non-working time, for drivers and passengers, for different transportation modes, for travellers within different income categories and for different purposes of travelling. Details can be found in Web TAG 3.5.6 (DfT 2009a), however despite the complex categorisation for time valuation, a simplified version using average values of time per vehicle for any time is considered to be adequate for the efficiency evaluation for this study. **Table 2. 2** below extracted from Web TAG 3.5.6 shows the market price values of time per vehicle, considering factors of mode split, vehicle occupancy, travel purposes, travel time etc, based on 2002 prices and values.

Table 2. 2 Market price values of time per vehicle in 2002 (£/veh, 2002 prices and values) (Source: DfT 2009a)

Vehicle Type and Journey Purpose	Weekday					Weekend	All Week
	7am – 10am	10am – 4pm	4pm – 7pm	7pm – 7am	Average Weekday		
Car							
Work	30.74	30.00	29.61	29.81	30.18	31.68	30.18
Commuting	5.84	5.79	5.69	5.69	5.74	5.74	5.74
Other	7.58	7.89	8.08	7.86	7.90	8.74	8.21
Average Car	10.97	12.05	9.90	9.77	10.88	9.22	10.46
LGV							
Work (freight)	12.22	12.22	12.22	12.22	12.22	12.83	12.22
Non – Work (Commuting and Other)	6.70	6.70	6.70	6.70	6.70	9.31	7.29
Average LGV	11.55	11.55	11.55	11.55	11.55	12.41	11.63
OGV1							
Working	10.18	10.18	10.18	10.18	10.18	10.18	10.18
OGV2							
Working	10.18	10.18	10.18	10.18	10.18	10.18	10.18
PSV (Occupants)							
Work	19.80	15.11	19.80	24.24	18.57	13.88	17.33
Commuting	18.45	6.83	22.50	23.43	15.68	3.94	12.61
Other	35.97	47.28	32.38	30.58	38.69	50.06	41.68
Total	74.21	69.22	74.68	78.25	72.93	67.87	71.62

The annual rates of growth in values of time are also given in Web TAG, extracted as in **Table 2. 3**. For a given year from 2002 onwards, the average value of time should be calculated using the forecast growth values on the basis of 2002 values.

Table 2. 3 Forecast growth in the working and non-working values of time in WebTAG 3.5.6 (DfT 2009a)

Table 3b: Forecast Growth in the Working and Non-Working Values of Time

Range of Years	Work VOT Growth (% pa)	Non-Work VOT Growth (% pa)
2002 – 2003	2.44	1.95
2003 – 2004	2.55	2.04
2004 – 2005	1.67	1.34
2005 – 2006	2.18	1.74
2006 – 2007	1.97	1.57
2007 – 2008	-0.09	-0.07
2008 – 2009	-5.38	-4.31
2009 – 2010	0.52	0.41
2010 – 2011	2.75	2.20
2011 – 2012	2.52	2.01
2012 – 2013	2.54	2.03
2013 – 2014	2.54	2.03
2014 – 2015	2.05	1.64
2015 – 2016	2.05	1.64
2016 – 2021	1.67	1.34
2021 – 2031	1.67	1.34
2031 – 2051	1.97	1.58
2051 onwards	1.91	1.53

2.3.2.3 Vehicle Operating Costs (VOCs[1])

VOCs[1] are considered to be a directly related cost during a journey. This section introduces the latest vehicle operating cost (VOC) values recommended by the Department of Transport for use in economic appraisals of transport projects. Values of VOC are considered separately for fuel and non-fuel costs.

Prices of fuel costs can be easily found from Web TAG 3.5.6 (DfT 2009a), as shown in **Table 2. 4**.These figures are annual average observed values provided by DECC. Figures for average cars and average Light Good Vehicles (LGVs) represent the weighted averages of the corresponding petrol and diesel figures where the weights used are the proportions of total car / LGV fuel consumption that are forecast to be petrol and diesel in each year. In **Table 2. 4**, ‘Petrol’ is a weighted average between Ultra Low Sulphur Petrol (standard unleaded) and Super Unleaded. Super Unleaded is assumed to constitute 10% of the petrol market by 2030. ‘Diesel’ comprises both Ultra Low Sulphur and Sulphur Free varieties. The resource cost of fuel VOCs is net of indirect taxation. The market price is gross of indirect taxation and is therefore the sum of the resource cost and fuel duty, plus VAT (that is, market price = [resource cost + fuel duty] x [1 + VAT]). In work time the perceived cost of fuel VOCs is the cost perceived by businesses. Values for fuel duty in **Table 2.4** take account of all changes announced in the 2009 Budget Report (HMT April 2009) and confirmed in the 2009 Pre-Budget report (HMT, December 2009).

Table 2. 4 prices of fuel from year 2002(pence/litre) (Source: DfT 2009a)

Year	Resource Cost (pence per litre)				Duty (pence per litre)		VAT (%)	
	Petrol	Diesel	Av. Car	Av. LGV	Petrol	Diesel	Petrol	Diesel
2002(actual)	16.7	18.4	17.0	18.1	45.8	45.8	17.5	17.5
2003(actual)	18.2	19.6	18.5	19.4	44.8	44.8	17.5	17.5
2004(actual)	20.2	21.4	20.5	21.3	44.6	44.6	17.5	17.5
2005(actual)	25.0	28.0	25.9	27.7	43.7	43.7	17.5	17.5
2006(actual)	27.7	30.5	28.6	30.2	42.6	42.6	17.5	17.5
2007(actual)	27.7	29.5	28.3	29.3	42.8	42.8	17.5	17.5
2008(actual)	35.1	42.5	37.7	41.9	43.2	43.2	17.5	17.5
2009	)				45.8	45.8	15.0	15.0
2010	)				48.0	48.0	17.5	17.5
2011	)				49.3	49.3	)	
2012	) See	Table	14		50.6	50.6	)	
2013-17	)				51.9	51.9	) 17.5	17.5
2018-21	)				51.8	51.8	)	
2022-26	)				51.7	51.7	)	
2027-30	)				51.6	51.6	)	

The elements making up non-fuel vehicle operating costs include oil, tyres, maintenance, depreciation and vehicle capital saving (only for vehicles in working time). The non-fuel elements of VOC are combined in a formula of the form:

$$C = a_1 + b_1/v$$

Where:

C = cost in pence per kilometre travelled,

V = average link speed in kilometres per hour,

a_1 is a parameter for distance related costs defined for each vehicle category, and b_1 is a parameter for vehicle capital saving defined for each vehicle category (this parameter is only relevant to working vehicles).

The parameters needed to calculate the non-fuel vehicle operating resource costs are given in **Table 2. 5**. These parameters are in 2002 prices and exclude indirect taxation. More details of the valuation methodology can be found in the Web TAG.

Table 2. 5 Non-fuel resource Vehicle Operating Costs (Source: DfT 2009a)

Vehicle Category	Parameter Values	
	a_1 pence/km	b_1 pence/hr
Car		
Work	4.069	111.391
Non-Work Car (commuting and other)	3.151	-
Average Car	3.308	19.048
LGV		
Work	5.910	38.603
Non-Work (commuting and other)	5.910	-
Average LGV	5.910	33.970
OGV1	5.501	216.165
OGV2	10.702	416.672
PSV	24.959	569.094

The average values for cars and buses are used in this study.

2.4 Evaluation of BSP and environmental impacts

As described before, most previous studies have been focused on efficiency evaluation, and the lack of environmental evaluation can be perceived from the literature. The background described in chapter 1 suggests that for any proposed traffic management operations the local authorities have to be aware of its air quality impacts and appropriate environmental assessment. In this study, the potential impacts resulting from bus signal priority, i.e. changes of emissions and fuel consumption, both on buses and general traffic need to be thoroughly investigated. The previous section reviewed the methodology of evaluating BSP on its efficiency performance. This section focuses on how to evaluate its environmental impacts. The traffic related emissions and air pollution are briefly introduced in 2.4.1 to bring out the pollutants involved in this evaluation, and then a review of an early study on evaluation of emissions and fuel consumption for bus priority is presented in 2.4.2. This early study remains an attempt to include emissions and fuel consumption as part of evaluation for bus priority strategies. However the evaluation methods were relatively coarse. Due to the limitations of such studies, some relevant studies on emissions estimation of other traffic control/management are reviewed in 2.4.3.

2.4.1 Traffic related emissions and air pollution

Vehicles emit a wide range of pollutants during their operation, mainly including carbon monoxide (CO), nitrogen oxide (NO_X), multiple hydrocarbons (HC), and additionally a range of particulate matters (PM) from diesel vehicles. These air pollutants are harmful to human health and environmentally damaging at a local level. For example, particulate matters increase the risk of death from cardiovascular and respiratory diseases and lung cancer. Inhalation of concentrated CO can prove fatal as it reduces the oxygen-carrying capacity of the blood and may result in asphyxiation. The mechanism of how these pollutants, i.e. CO, NOx, HC, and PM contribute to human health hazards is relatively well understood now. The sources and formation of these pollutants from fuel in the internal combustion engines have been clear and well established. Such emissions are regarded as major contributors to airborne pollution, especially in urban or industrialised areas. For petrol vehicles, for more than 20 years by the European norm (or US and Japan), tailpipe emissions of CO, HC, and NOx have been regulated in gram/ kilometre for passenger cars or gram/ kW for heavy duty engines, known as Euro I –VI standards. For diesel engines, particulate matter (PM), measured by gravimetric methods are regulated in addition. Concerns on carbon dioxide (CO_2) have been raised increasingly in recent years due to the recognition of its significant contributions on climate change. It has not yet been regulated as an exhaust emission; however CO2 reduction targets have been proposed. In EU emission trading scheme it was agreed that the EU had to make an eight per cent reduction on 1990 levels by the first Kyoto Protocol commitment period (2008 - 2012). A more detailed review of emission pollutants and air pollution can be found in chapter 3.

2.4.2 ENTRANCE- Evaluation of BSP on emissions

The ENTRANCE (ENergy savings in TRANsport through innovation in the Cities of Europe) Project (TRL et al 1997) aimed to reduce delays to buses at traffic signals and to improve the reliability of services. It assessed the delay savings to buses, complying with the evaluation of benefits for energy consumption and the environment from the reduction in bus delays. Both on-street surveyor data and SCOOT data were used in this study to estimate bus delay savings before and after implementing bus priority at traffic signals. Priority forms of 'Green extension' and 'Early recall' facilities were tested in SCOOT version 3.1, and recovery was implemented subject to user-defined control parameters.

The evaluation of energy and emissions of implementing bus priority used the first version (version 1.1) of HB-EFA (The Handbook Emission Factors for Road Transport) for both buses and passenger cars. HB-EFA was originally developed in Germany and Switzerland (INFRAS 1995) which stands for Workbook on Emission Factors for Road Transport. This is an emission factor model which requires average link speed as model input and estimates emissions on an aggregated level. The emission factors were modelled based on measurements of legislative test cycle data. This was done for vehicles up to Euro-I. Euro II to IV were estimated using reduction factors applied to Emission- I factors. More details of this emission modelling method are represented in Chapter 3. The newest version is HB-EFA 3.1 which was released in 2010.

The average speed data on each link required by the HB-EFA model is calculated by dividing travel distance by journey time. The emission results indicated that bus emissions reduced as a result of the priority measures, and overall benefit for all traffic was seen only for particles (PM) and NOx, at an approximate rate of 13% and 10% reductions. This is because buses were the dominant contributor to these 2 pollutants thus changes in bus operation can have a relatively greater impact on these two pollutants. According to the emission model structure, at relatively low speed sections, the emissions generally increase as vehicle speed reduces. Therefore in some links where car speed was reduced by the bus priority measures, consequently emissions and fuel consumption increased. For pollutants of

HC and CO, as the cars made the larger contribution to the total emission amount, the savings for buses were outweighed by increases for cars. An increase of 13% and 7% increase was estimated for pollutant CO and HC for overall traffic.

ENTRANCE can be regarded as an early investigation on evaluation of the emission impacts when implementing bus priority at traffic signals. It provides a useful start point for this study, however there are several points need to be noted.

1. The ENTRANCE project was conducted in 1996 before the introduction of EU emission legislation therefore the vehicles were much more polluting than vehicles now, especially for PM from buses.
2. The fleet compositions studied in ENTRANCE were significantly different compared to the fleet nowadays.
3. The emission modelling is developing fast and many more advanced emission models are available now. The HB-EFA model used in ENTRANCE was an average speed model which only took average speed into account. It was not able to reflect the emission changes relating to instantaneous speed /acceleration change.

2.4.3 Review on emission estimation for traffic control strategies

Apart from ENTRANCE, there have been very few studies on the evaluation of impacts of emissions after implementing bus priority strategies. However it is suggestive and useful to review some similar studies, i.e. emission estimation for traffic control related strategies, in order to suggest possible emission modelling approaches for this study. A number of studies have been done to investigate the effects of different traffic control measures on emissions. Hallmark et al. (2000) conducted research using the MEASURE model to study the effect on carbon monoxide emissions caused by different signal timing settings at an intersection level. The MEASURE model took mesoscopic data (road segment and census block) about vehicle activity and technology and employed modal emission rates developed in-house. Coelho et al (2005) adopted a modal emission approach developed by Frey et al. (2001) to measure the impact of speed control traffic signals on pollutant emissions. The reason that Coelho et al selected the modal emission model in their research was that firstly other models such like MOBILE or COPERT were too aggregate for the analysis of emissions at intersection level, and secondly as the focus of the study was the relative impacts of the speed signal, there was less concern about the absolute values of emissions although this model was based on measurement only for one vehicle and its accuracy was still questionable. MOBILE and COPERT are reviewed in Chapter 3. Boulter (2001) measured the impacts of traffic calming measures on vehicle exhaust emissions. Both physical measurement and emission modelling approaches were used in this research. Driving cycles were firstly developed based on real driving to imitate driving behaviour at speed calming sites, and then these driving cycles were tested on a chassis dynamometer to obtain the corresponding exhaust emissions. In this study the MODEM model was used for assessment and was modified towards a better accuracy in particular relation to traffic calming measures. MODEM is reviewed in Chapter 3. Midenet et al (2004) attempted to measure CO_2 at a signalised intersection with real-time adaptive control. In this study an elemental model for emission estimation was designed to reflect signal impacts on speed profiles for an isolated intersection. The impacts on fuel consumption and pollutant emissions were estimated using average costs and calibrated using driving cycles. Nesamani et al (2007) applied an emission factor model MOBILE 6 to estimate vehicular emissions by capturing traffic variations, but it also mentioned that the proposed model underestimated the total emissions but with potential to be further improved.

These studies applied different emission models according to their requirements on pollutants concerned, study scales and model availability. From the review we can see that emission modelling is a fast moving area and a large number of emission models based on different levels of aggregations have been developed, while their pros and cons are also noticeable. This suggests that a comprehensive review on emission modelling is necessary for later study so that a most appropriate model can be chosen for this study. The next chapter presents a dedicated review on emission modelling and selection for this study.

2.5 Summary

In this chapter, bus signal priority is reviewed from 3 aspects - measures, modelling approaches and evaluations.

The literature suggests that the green extension and recall are the most commonly used priority strategies and compensation and inhibition are needed when traffic flow is high. Bus detector forms and locations are reviewed and values are suggested. This is to assure the modelling and assessment in this study focus on the latest systems implemented on street.

The architecture options are then briefly described to present the worldwide application of the signal priority within Urban Traffic Control systems. Bus signal priority strategies can be examined and evaluated by field measurement, and can also be modelled using computer based simulation method. The two main types of simulation approaches, i.e. macroscopic simulation and microscopic simulation therefore are reviewed. Microscopic simulation is considered to be the best approach to model Bus priority at traffic signals. Evaluation of bus signal priority is reviewed from 2 aspects, the efficiency performance and the environmental impacts.

For efficiency evaluation, the most commonly used indicators are travel time and delay time, then monetary evaluation can be carried forward using value of time as suggested in Web TAG by DfT. For the evaluation of environmental impacts, previous research is limited. The early study ENTRANCE was reviewed as this was the first and probably the only one including evaluation on emissions and fuel consumption for bus priority strategies. Some relevant studies on assessing environmental impacts of other traffic or signal control methods are then reviewed to inspire emission evaluation methods for this study. Detailed reviews on emission modelling and the selection for the model used for this research is presented in the following chapter.

CHAPTER 3

REVIEW OF EMISSION AND FUEL CONSUMPTION MODELLING

Emission modelling is a fast moving research area, with any emission models produced and under development for transport applications at different levels. This chapter provides a detailed review on emission and fuel consumption modelling, followed by discussions and recommendations for selecting an emission model for this study. The first part of this chapter presents an introduction relating to vehicle emissions and fuel consumption involving the pollutant formation, their hazards, emission regulations, and then a review of factors affecting vehicle emissions. The second part presents emission measuring techniques which to a large extent shapes but also constrains the development of emission models, as well as their accuracy and precision. Especially for instantaneous emission models a great number of challenges still exit (reviewed in 3.3.5) due to the limitation of measuring and data collection techniques. The third part of this chapter is the key section providing a comprehensive review of emission models according to the levels of aggregation. Four categories of models are reviewed, discussed and recommendations are made. Fuel consumption as reviewed in 3.4 is usually modelled together with emission models and is relatively less complex. Comparisons of 9 models selected from the 4 categories are made, in terms of levels of aggregation, accuracy, coverage and limitations. Considering both the requirements of the study and the capability of existing emission models, the best available model is selected. To make the emission results comparable, the valuation method for air pollutants is further reviewed.

3.1 Introduction to vehicle Emissions and fuel consumption

3.1.1 Formation and hazards of vehicle exhaust pollutants

Vehicle pollutants are formed in internal combustion engines resulting from unburned or partially burned fuel. The fuel, both petrol and diesel used in vehicles are produced from oil refinement. The chemical elements contained in petrol or diesel fuel are mostly carbon and hydrogen, weighting approximately 97-98%, with traces of compounds of nitrogen and sulphur. Petrol fuel consists of a mixture of hydrocarbons with between 4 and 12 carbon atoms per molecule. Diesel fuel typically contains hydrocarbon species with between 8 and 21 carbon atoms per molecule. The nature of diesel that contains bigger carbon compounds indicates that in general more particulate matters (PM) can be formed during combustion due to inefficient combustion.

The combustion process in an internal combustion engine for a pure hydrocarbon fuel with adequate oxygen follows the chemical reaction:

$$C_xH_y + O_2 \rightarrow CO_2 + H_20$$

This reaction means under an ideal condition, the only products of hydrocarbon fuel are carbon dioxide and water. However for an impure fuel in a real engine combustion process, a proportion of hydrocarbons that can't be efficiently burned are emitted into the air, in the form of gas hydrocarbon emissions (C2-C6) or liquid or solid (C6 to C15+) particles. The gas hydrocarbons can be estimated separately as different species or counted as total hydrocarbons (THC). The liquid and solid particles are mixed with dust and other compounds in this process, normally counted as Particulate Matters (PM). Carbon monoxide (CO) is a product of incomplete combustion and occurs when carbon in the fuel is partially oxidized rather than fully oxidized to carbon dioxide (CO2). Most of the NOx emission is from the ambient air in the combustion engine rather than the fuel itself, although traces of Nitrogen compounds exits in fuel. Details of formation and hazards of these pollutants are given as follows:

Hydrocarbons (HC)

Hydrocarbons or unburned/incompletely oxidised hydrocarbons cover a series of products. 'It is almost certain that the survival of hydrocarbons in the exhaust emissions mainly are from the wall effects within the combustion chamber (Science Research council 1976).' In most emission models the HC (Hydrocarbons) or THC

(Total Hydrocarbons) or Volatile Organic Compounds (VOC) mentioned normally refer to the sum of all hydrocarbon species that remain in a vapour phase when sampled at 190°. Methane is the most common VOC species but excluded from hydrocarbon emissions in some models as it is not a toxic gas. However methane is counted as one of the greenhouse gases like carbon dioxide. It is important to clarify what species are modelled when using any emission models so that the results from different models can be comparable. Hydrocarbon emission is one of the regulated exhaust emissions from road transport. Hydrocarbons react in the presence of nitrogen oxides and sunlight to form ground-level ozone (O_3), a major component of smog. Ozone irritates the eyes, damages the lungs, and aggravates respiratory problems. It is the most widespread and intractable urban air pollution problem. Most species of exhaust hydrocarbons are toxic, such as benzene (C6H6), with the potential to cause cancer.

Of the large number of species that hydrocarbon covers, particularly Non-Methane Volatile Organic Compounds (NMVOC) is more concerned in air quality evaluation. A report by NAEI (2010) summarised sources and time series of Non-Methane Volatile Organic Compounds (NMVOC) in the atmosphere in England. It suggests that 20% of the NMVOC emissions arise from combustion sources, of which the transport sector dominates.

Carbon monoxide (CO)

Carbon monoxide (CO) is a product of incomplete combustion and occurs when carbon in the fuel is partially oxidized rather than fully oxidized to carbon dioxide (CO2). Carbon monoxide is highly toxic to humans and animals in higher quantities. It reduces the flow of oxygen in the bloodstream and is particularly dangerous to persons with heart disease. The presence of CO may be taken as a strong indicator of incomplete combustion. The Air Quality Strategy (Defra 2007a) shows that total UK CO emissions are dominated by those from road transport, particularly those from petrol engined vehicles and vehicles travelling at low speeds on urban roads.

Compared to the levels of CO emission from petrol engines, diesel engines emit relatively little CO and are not a significant source of ambient CO levels (Heywood 1988). In the report by NAEI (2010) it states that since 1990, CO emissions from road transport sources have reduced quite significantly due to improvements to the development of more efficient engine combustion technology, the increased use of catalytic converters and the growth in diesel engine use.

Nitrogen oxides (NOx)

Nitrogen oxides, like hydrocarbons, are precursors to the formation of ozone. NOx also contribute to the formation of acid rain as they react with ammonia, moisture, and other compounds to form nitric acid vapour and related particles.

NOx is the sum of NO and NO_2. NOx, different to the formation process of HC, CO and CO_2 as direct reaction involving the fuel, is formed due to the partial or complete oxidation of the nitrogen from the air admitted to the cylinder. 'NO formation begins first at the locations in the chamber newest the ignition point where the temperature is the highest. The principle oxide of nitrogen formed in combustion processes is NO and the overall rate of NO formation increases with high temperature and pressure. (Springer and Patterson 1973).' Because temperatures are the highest when an engine operates under high speed and load conditions, NOx emissions rates are the highest at high average vehicle speeds. Most of the NOx in vehicle exhaust is usually present as NO, whereas most of the NO_2 in the atmosphere is formed by the reaction of NO with ozone (O3). NO_2 can also be formed at normal temperatures when NO is catalysed by HC. It is widely accepted that the proportion of NOx in vehicle exhaust which is emitted as primary NO_2 is 5%. However this is based on relatively old measurements, from vehicles without after-treatment systems. It has been suggested that recent increases in NO_2 proportion in NOx are linked to exhaust after-treatment devices, such as oxidation catalysts and continuously regenerating traps (CRTs) (e.g. Carlaw and Beevers 2004). A report by Defra (2007b) indicates that the fraction of NOx emitted as NO_2 is considerably in excess of 5%, with values in the range 20-70% for Euro 3 diesel cars.

According to NAEI (2010), road vehicles contributed 30% of total UK NOx emissions in 2007. Since 1990 there has been a steady decline in emissions due to the introduction of catalytic converters on cars and stricter regulations on truck emissions.

Particulate Matters (PM)

According to Springer and Patterson, (1973) 'Particulate matters (PM) is one vehicle exhaust emission consisting of a mixture of particles that can be solid, liquid or both, are suspended in the air and represent a complex mixture of organic and inorganic substances. Liquid particulates are observed primarily in diesel engines at light load and the solid particulates consist of an agglomeration of carbon and hydrocarbon molecules Elemental carbon (soot) is one of the primary PM components that generates from the transport sector (Air Quality Expert Group (AQEG) 2005). PM emissions from internal combustion engines are formed both in the combustion cylinder and in the exhaust system. As the fuel droplets burn, solid carbonaceous particles are formed. In the exhaust, these particles agglomerate to form chains and adsorb a layer of volatile hydrocarbons and sulphates (Heywood, 1988). PM varies in size, composition and origin. The major PM components are sulphate, nitrates, ammonia, sodium chloride, carbon, mineral dust and water. PM can be classified according to their sizes into 2 types, the coarse fraction is called PM_{10} and smaller or fine particles are called $PM_{2.5}$. PM_{10} describes the diameter of the particles are less than or equal to 10 μm, and $PM_{2.5}$ are those less than or equal to 2.5 μm in diameter. PM seriously affects health, increasing deaths from cardiovascular and respiratory diseases and lung cancer. Measurement of PM is challenging and uncertainty remains as to the details of the formation processes (Heywood, 1988; Burtscher, 2001).

It is widely recognised that diesel engines emit a greater mass of PM than petrol engines, due to the nature of diesel fuel that contains bigger carbon compounds. Emissions from road transport have varied across the time-series as a number of factors have combined. The main source of road transport emissions is exhaust gases from diesel engines. Emissions from diesel vehicles have been growing due to the growth in heavy-duty vehicle traffic and the move towards more diesel cars (AQEG 2005). Since around 1992, however, emissions from diesel vehicles have been decreasing due to the penetration of new vehicles meeting tighter PM_{10} emission regulations (i.e. Euro emission standards).

Carbon dioxide (CO_2)

CO_2 is the product of the complete combustion process in engines, which dominates the overall exhaust emissions. CO_2 has no significant impacts on the local environment; however it is now widely recognised as the main source of global warming and climate change. To tackle global climate change, the Kyoto protocol was adopted in 1997 aiming at reducing the CO_2 emissions, and till 2009 187 countries had signed and ratified the protocol. This protocol is the first time in human history that a CO_2 reduction target was legislated by international law agreed by many countries in the world. It allows for several "flexible mechanisms", such as emissions trading. The EU Emissions Trading Scheme is one of the policies introduced across the European Union (EU) to help meet its greenhouse gas emissions reduction target under the Kyoto Protocol. The EU has to make an 8% reduction on 1990 levels by the first Kyoto Protocol commitment period (2008 - 2012). The UK Kyoto target is 12.5%.

The transport sector shares about 24% of the total man made CO_2 emissions in the UK (DECC 2011), and is the 'under performing sector' in contributing to the CO2 reduction target. **Table3. 1** shows CO_2 emissions from the main sectors.

Table3. 1 Sources of Carbon Dioxide emissions, 1990-2009(Mt)

	1990	1995	2000	2005	2006	2007	2008	2009
Energy Supply	241	210	202	216	220	216	209	185
Road Transport	109	111	116	120	120	121	117	113
Business	110	104	104	94	91	89	87	76
Residential	79	81	87	84	82	78	80	75
Other	50	46	40	36	33	33	31	25
Total	590	551	549	550	546	538	525	474

All figures are for the UK and Crown Dependencies only, and exclude Overseas Territories.

In London, TfL (2006) planned to make a 30% reduction in CO2 emissions by 2025 in transport sector on a 1990 base. The target has to be achieved by various means. For example Car tax in the UK has changed from 2009, with vehicles classified according to the levels of carbon dioxide they emit- the most polluting cars pay the highest tax, while these 'environmental friendly' vehicles (up to 100g CO2/km) pay nothing.

There are 2 facts regarding transport related CO2 are of particular concern, as stated in a report by European Environmental Agency (EEA) (2009a) as follows:

> '*Between 1990 and 2007, CO2 emissions from transport rose by 29 % in the EU-27. This increase was observed for both passenger transport and freight transport. These increases were mainly due to growing transport demand, characterised by large increases in passenger kilometres and tonne kilometres (freight). Transport is the sector in which the negative emission drivers (transport demand and increasing share of road transport) most outgrew the positive emission drivers (fuel efficiency and fuel shift).*'

> '*For passenger road transport, a relative decrease in the use of public transport is also noteworthy. Efficiency improvements in passenger cars have not been sufficient to counteract this trend. For freight road transport,*

> *an increased share of road freight transport as opposed to other transport modes supplemented the increased transport demand for goods. Modal shift is therefore taking place in the wrong direction, especially in the EU-12.'*

Due to the increased recognitions of the impacts of CO2 emissions from road transport, The new *REGULATION (EC) No 443/2009 of 23 April 2009* (Normally referred as the EU emission standards) set the CO2 emission performance standard in for new light duty vehicles. It set the scope and 'specific emission targets' for manufactures which will commence 1 January 2012.
From this point of view, it indicates that either stronger policies on cleaner fuel/vehicle usage need to be addressed or a stronger priority strategy of public transport needs to be promoted.

3.1.2 Regulations of vehicle emissions

Vehicle emissions in different countries are regulated by their own standards. Regulations normally involve 3 aspects through a vehicle's life time, which are type approval test, conformity of production test, and annual in-service check. A manufacturer has to apply a type approval test before a particular model can be marketed. A conformity of production test is required to ensure that the standards achieved during the type approval test are still maintained during large-scale production. The annual in-service check is usually conducted during the MOT test, and only for vehicles older than 3 years. The name 'MOT' is derived form the Ministry Of Transport, a defunct UK government department but it still officially used. A MOT test is a compulsory annual test in the UK of safety and exhaust emissions. In Europe, the pollutant emissions from road vehicles are regulated separately for light- duty vehicles (cars and light vans) and heavy-duty vehicles (trucks and buses). EU emissions regulations are a number of regulatory acts with continuous amending directives. It provides progressively tighter emission limits which are typically referred to as pre-Euro, Euro 1, Euro 2, Euro 3, Euro 4, Euro 5/6. However there is no simple correlation between the new emission standards and the amending directives. For example, the emission limits that came into effect on 1/1/97, often referred to as the Euro II, standards were specified in *directive 94/12/EC* for passenger cars, but in *directive 96/69/EC* for heavy motor cars and light-duty vans. The emission standard currently in force is Euro 4 adopted from 2005for type approval of motor vehicles. New Euro 5 standards have already been agreed by European Council and Parliament which will come into effect from 2010, and the limit values can be found as *REGULATION (EC) No 715/2007.* Vehicle exhaust pollutants involved in

Emission standards are CO, HC, NOx, PM and the limit of combination of HC and NOx in older regulations. **Table3. 2** below gives an example of EU emission standards for petrol cars under standards 3 and 4.

Table3. 2 Example of EU Emission standard 3 and 4

EU Emission standards for gasoline cars (< 2.5 t laden, ≤ 6 seats for pre-Euro III, and up to 9 seats for Euro III and Euro IV standards), g/km

Euro Standard	Directive	Implementation Type approval	Test cycle				
				CO	HC	NO_x	HC+ NO_x
pre-Euro I	70/220/EEC		ECE 15 + EUDC	up to 10.0			up to 2.55
Euro I	91/441/EEC	1/1/1993	ECE 15 + EUDC	2.72			0.97
Euro II	94/12/EC	1/1/1996	ECE 15 + EUDC	2.20			0.70
Euro III	98/69/EC	1/1/2000	ECE 15* + EUDC	2.30	0.20	0.15	-
Euro IV	98/69/EC	1/1/2005	ECE 15* + EUDC	1.00	0.10	0.08	-

ECE 15* is very similar to the original ECE 15 but it start-up phase is modified: The 40 seconds idle period from engine crank to the start of bag sampling is deleted to give simultaneous engine crank and bag sampling start.

3.1.3 Review of fuel and vehicle types

There are 2 basic factors that have impacts on vehicle emissions, one is fuel type and the other is vehicle type /or engine type. These factors need to be categorised in emission measuring and modelling process.

3.1.3.1 Fuel types

As reviewed in previous sections, road transport contributes a significant proportion to air pollution and greenhouse gas emissions. Road transport is also the largest consumer of the petroleum supply in the UK.

A report by the DECC (2009a) states that '*of the total UK petroleum demand, the road transport accounts 55% based on 2008 figure. Transport's dominant share of UK demand is the culmination of rising absolute demand for transport fuels, declining industrial demand, and a significant shift away from the use of fuel oil to generate electricity. This trend growth in transport's share of oil demand is expected to continue in the future.*'

This indicates that apart from the progressively tighter emission limit standards, our considerations for reducing air pollution, greenhouse gas emission and fuel consumption have to be more sustainable. To reduce the reliance on oil the government published its Renewable Energy Strategy (DECC, 2009b), which set out Government plans for meeting the UK target of 15% of energy consumption from renewable sources by 2020. It suggested that the UK would have 10% renewable energy in transport, mainly from Biofuels, hydropower and others, which will have no or significantly less impacts on our environment.

In recent decades, cleaner and greener fuel technologies have been promoted and new vehicle models using new or improved sources of energy have been developed and marketed. Currently most road vehicles are still petrol or diesel engined, but some new engines using renewable energy power have emerged, such as CNG (Compressed Natural Gas) engines, electric and hybrid engines, fuel cell engined, and hydrogen power. Expanding the new energy share has become the direction of new vehicle development. The conventional fuel types (petrol or diesel) remain the most convenient, reliable and efficient energy supply to vehicle engines nowadays, new energy powered engines can dominate once the breakthrough of some fundamental problems can be achieved, such as hydrogen storage, fuel-cell cost and charging problems, and social impact that may be caused by using bio-fuel on a large scale (a brief explanation for each fuel type can be found in the following summary).

A brief summary of the typical fuel types is presented as below:

Petrol and Diesel

Petrol is the most conventional fuel type and is widely used for vehicles, especially light duty vehicles, such as cars and vans. Petrol vehicles produce less local air pollution with their lower NOx and particulate emissions compared to diesel engines.

Diesel vehicles have significantly lower CO_2 emissions and higher engine efficiency compared to petrol but they emit higher levels of NOx and particulates than petrol vehicles. However, for new produced cars, 'New diesel cars are more detrimental to the environment and to health than new petrol-driven cars. Diesel cars have improved considerably over the last ten years, but exhaust emission control technology in petrol cars has developed faster.' (Swedish environmental Protection Agency 2008).

The introduction of emission legislation during early 90s has largely reduced the emissions from both petrol and diesel vehicles as manufactures must keep exploring new technologies to meet the emission standards when producing new vehicle models. New vehicles have been much cleaner than before compared to the fleet 20 year ago. However the increase of traffic and car ownership may have partially counteracted the overall emission reduction made by emission legislation. Therefore it is necessary to explore and make use of less polluting energy sources.

Bio-fuel

Bio-fuel is produced from oil of crops such as oilseed rape, sunflowers and soya beans, and from waste cooking oils. They are usually sold in blends of up to 5% with petrol or diesel and although they are not completely carbon neutral (because of the energy used to grow and process them) they offer significant carbon savings over petrol and diesel and are compatible with most vehicles. Some vehicles engines, known as "flex fuel vehicles" can run on a blend of up to 85% bio-ethanol and 15% petrol, known as E85, as well as just petrol. Therefore a great potential to reduce fuel reliance can be seen. The availability of these vehicles is currently limited but improving. However, disadvantages are considerable, as crops for fuel require considerable water for irrigation-which may prove an important limitation. Changes in agricultural land use to grow fuel crops may result in increase of food price, especially for those vulnerable areas where poverty still exits.

LPG and CNG

LPG (Liquid Petroleum Gas) has proved popular due to Government tax incentives that make fuel relatively cheap. However, the Government has started to reduce the tax differential between LPG and conventional fuels and will continue to do so over coming years. Vehicles using LPG tend to be dual-fuel and can run on either petrol or LPG. On local emissions LPG vehicles tend to have cleaner exhausts than petrol vehicles, and sit between diesel and petrol vehicles CO2 emissions.

CNG (Compressed Natural Gas) offers even lower CO2 emissions than LPG, nearly as low as diesel, and with very low particulate emissions. However, at present there are few CNG cars available on the UK market. CNG vehicles can also run on bio-methane, offering even lower CO2 emissions.

Electric Vehicles (EVs)

A number of Electric Vehicles are available. They are cheap to run and have virtually no emissions at the point of use, although when the batteries are charged emissions are created at power stations if electricity is generated by burning fossil fuel. The drawbacks for electric vehicles have been the battery technology, although improving, remains heavy, short lifed and expensive. In the past, electric vehicles had a limited range – typically 50 miles – and could take several hours to recharge, therefore only suitable as an urban runabout for shorter journeys. The lack of dedicated and rapid plug-in charging points may also be a barrier for people to buy electric cars.

However the technologies for EVs have developed very fast. According to an electric vehicle delivery plan for London (Major of London 2009), 'The battery technology, particular the lithium-ion batteries have developed at a rapid pace. The technology has also developed to extend the ranges of vehicles to in excess of 100-130 kms'. For areas with serious air quality problems such as in urban cities, EVs appear a green option. To encourage and promote the usage of electric cars, London government has announced several policies including a 100% congestion charge exemption and discounted parking in some boroughs. A 25% discount up to £5,000 government subsidy was available from January 2011 to encourage people to buy electric or plug-in hybrid cars.

Hybrid Vehicles

Hybrid vehicles have become common and reliable now. One of the most successful models can be the Toyota Prius. They use a conventional petrol engine in conjunction with an electric motor and a battery. The extra power of the electric motor allows a smaller petrol engine to be used and for it to be loaded more efficiently. This can reduce CO_2 and local pollutant emissions significantly at low speed in urban roads when the electric motor and battery can be in charge, generating zero emissions. However on motorways the emissions can not be reduced as the conventional petrol engines need to be fully operated to generate sufficient power to reach the speed requirement. Some hybrids operate on their electric motor alone for short periods of time at low speeds. At least 3 hybrid models are available in the UK. In addition to 'full' hybrids, 'micro' hybrids are also available. In these models the electric motor does not provide power to propel the vehicle, but allows the petrol engine to stop when the vehicle comes to a halt.

Hydrogen

The only exhaust emission from hydrogen powered vehicles is water. Hydrogen vehicles generate zero emissions on the road however the process to produce hydrogen is usually not emission free. In fact for industrial hydrogen production, it can be obtained through many thermo-chemical methods utilizing natural gas, coal (by a process known as coal gasification), liquefied petroleum gas, biomass (biomass gasification), or as a microbial waste product called bio-hydrogen or Biological hydrogen production. Almost all of the hydrogen produced in the U.S. today is by steam reforming of natural gas and for the near term, this method of production will continue to dominate (National Renewable Energy Laboratory 2008). This means the overall emissions generated and fuel consumed needs to be carefully calculated before any promotion of hydrogen vehicles. In addition, there are some technical challenges which need to be considered, including hydrogen storage and distribution, refuel stations, and limited vehicle range. At present the hydrogen engined vehicles are still in the early stages of development, and it will take some years before they become common on our roads. 5 hydrogen fuel cell buses are being introduced in London as part of Clean Urban Transport for Europe (CUTE) trial (TfL 2007) and for the next step; detailed design for the 10 hydrogen buses is already well underway. Following testing, the buses will enter service in 2010.

It should be noted that the development of new vehicles using clean energy should be kept in line with the development of renewable energy supply. Take electric vehicles as an example, only when the electricity generated by renewable resources such as wind, tidal, or nuclear energy is proportionally increased to cover the demand from electric vehicles (i.e. the shares of conventional energy resources of coal, oil, gas decrease), the advantages of electric vehicles on eliminating the overall air pollution and greenhouse gas emissions can be proved. Otherwise the cost of generating electricity from combustion may counteract the benefits of emission and fuel savings by using new energy.

3.1.3.2 Vehicle types

Vehicle sizes/weight, engine capacities and fuel types are the most basic factors determining vehicle emissions and fuel consumption. In the design and developing process of emission modelling, emissions should be collected from the most representative vehicle models in pre-defined vehicle categories. Emission models normally require data on the proportion of vehicle types, including fuel types, emission standards, and engine sizes. Therefore vehicle and fuel types in this study are reviewed from 3 aspects, fuel types, engine capacities, and proportion of vehicles in terms of emission standards. These 3 aspects are the main static input for emission models (see chapter 3).

Table3. 3 shows data on the proportions of fuel types used by licensed cars from historic statistics (DfT 2009b), while it assumes that all buses use diesel fuel. The data are applied in the case study in later chapters.

Table3. 3 Proportion of fuel types used by licensed cars: 2000-2009 (Source: DfT 2009b)

Thousands/*Percentages*

Year	Petrol		Diesel		Petrol/Gas		Gas[1]		Electric		Hybrid Electric		Other[2]		Total
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	
2000	21,233	*87*	3,153	*13*	19	-	1	-	-	-	-	-	-	-	24,406
2001	21,641	*86*	3,460	*14*	21	-	3	-	-	-	1	-	-	-	25,126
2002	21,839	*85*	3,912	*15*	23	-	6	-	-	-	1	-	-	-	25,782
2003	21,805	*83*	4,400	*17*	24	-	10	-	-	-	1	-	-	-	26,240
2004	21,977	*81*	5,011	*19*	25	-	13	-	-	-	3	-	-	-	27,028
2005	21,876	*79*	5,596	*20*	26	-	14	-	1	-	8	-	-	-	27,520
2006	21,635	*78*	6,135	*22*	27	-	16	-	1	-	17	-	-	-	27,830
2007	21,432	*76*	6,716	*24*	27	-	18	-	1	-	32	-	-	-	28,228
2008	21,064	*74*	7,227	*25*	27	-	23	-	1	-	47	-	-	-	28,390
2009	20,651	*73*	7,694	*27*	26	-	26	-	1	-	61	-	-	-	28,459

1 Includes gas, gas bi-fuel and gas-diesel
2 Includes vehicles propelled by steam

Vehicle types also need to be categorised according to their engine capacity or weight limit in emission measurement and modelling. Therefore cars licensed by engine capacity from 2000 to 2009 are listed in **Table3. 4**.

Table3. 4 Licensed cars by engine capacity from 2000 to 2009(Source DfT 2009b)

Thousands/*Percentages*

Year	1 - 1,000cc		1,001 - 1,550cc		1,551 - 2,000cc		2,001 - 2,500cc		2,501 - 3,000cc		3,001cc +		Total	Avg eng cap
	N	%	N	%	N	%	N	%	N	%	N	%		
2000	1,516	*6*	8,421	*35*	12,076	*49*	1,208	*5*	665	*3*	519	*2*	24,406	1,679
2001	1,473	*6*	8,559	*34*	12,510	*50*	1,326	*5*	701	*3*	556	*2*	25,126	1,689
2002	1,424	*6*	8,633	*33*	12,940	*50*	1,454	*6*	739	*3*	589	*2*	25,782	1,700
2003	1,352	*5*	8,651	*33*	13,224	*50*	1,578	*6*	799	*3*	634	*2*	26,240	1,713
2004	1,320	*5*	8,785	*33*	13,652	*51*	1,703	*6*	881	*3*	687	*3*	27,028	1,724
2005	1,276	*5*	8,793	*32*	13,976	*51*	1,794	*7*	960	*3*	721	*3*	27,520	1,735
2006	1,258	*5*	8,764	*31*	14,128	*51*	1,879	*7*	1,051	*4*	749	*3*	27,830	1,744
2007	1,246	*4*	8,802	*31*	14,317	*51*	1,957	*7*	1,130	*4*	775	*3*	28,228	1,751
2008	1,251	*4*	8,862	*31*	14,368	*51*	1,963	*7*	1,174	*4*	773	*3*	28,390	1,751
2009	1,264	*4*	8,935	*31*	14,309	*50*	1,971	*7*	1,211	*4*	769	*3*	28,459	1,751

For each fuel type and vehicle size, emission models require the information of their general emission levels according to European legislation classes, i.e. Pre-Euro to Euro 4-6. **Figure3. 1** and **Figure3. 2** from TERM 34 (EEA 2009) shows the shares of pre-Euro and Euro 1-4 vehicles for the average of 30 EEA member countries, including the UK. These data are applied in the case study.

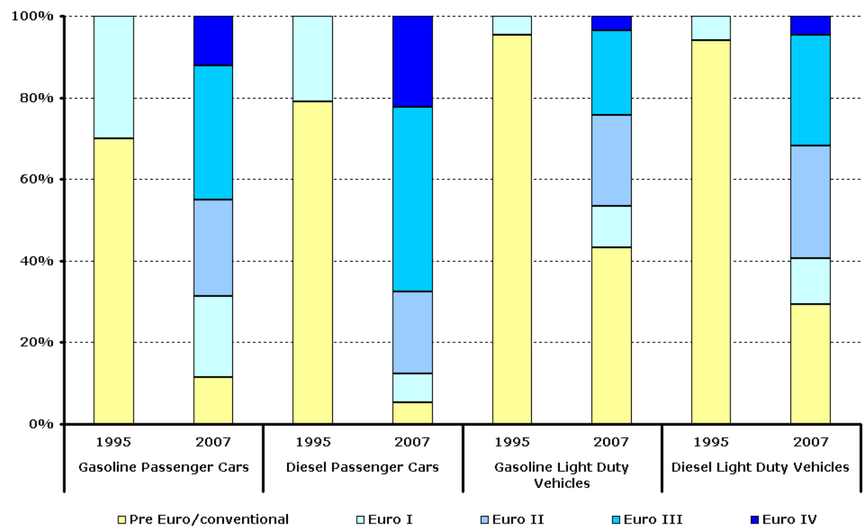


Figure3. 1TERM34 Estimated share of pre Euro/conventional and Euro I-V gasoline and diesel passenger cars and light-duty vehicles

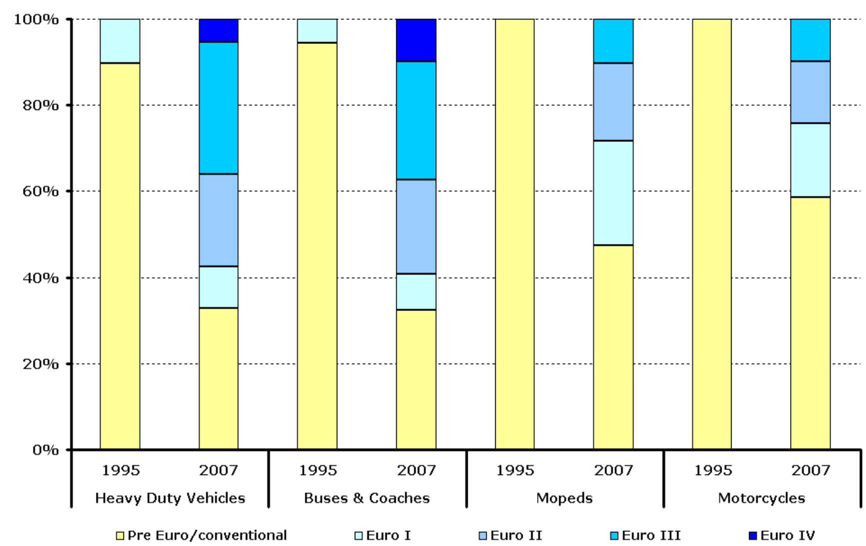


Figure3. 2 TERM34 Estimated share of pre Euro/conventional and Euro I-V heavy-duty vehicles, buses and coaches and conventional and 97/24/EC mopeds and motorcycles

3.1.4 Factors affecting vehicle emissions and fuel consumption

To determine the impact of bus signal priority strategies on vehicle emissions and fuel consumption, it is important to understand the complex relationships between vehicle emissions/fuel consumption and factors affecting it.

Vehicle energy and emission rates are influenced by numerous variables. These variables are classified by Ahn et al (2002) into 6 broad categories: travel-related, weather-related, vehicle-related, roadway-related, traffic-related, and driver-related factors. The travel-related factors account for the distance and number of trips travelled within an analysis period, while the weather-related factors account for temperature, humidity, and wind effects. Vehicle-related factors account for numerous variables including the engine size, the condition of the engine, whether the vehicle is equipped with a catalytic converter, whether the vehicle's air conditioning is functioning, and the soak time of the engine. The roadway-related factors account for the roadway grade and surface roughness, while the traffic-related factors account for vehicle-to-vehicle and vehicle-to-control interaction. Finally, the driver-related factors account for differences in driver behaviour and aggressiveness.

Abbott et al. (1995) divided the factors affecting vehicle emissions and fuel consumption into 2 broad categories:

> (1) Technical factors relating to the design and engineering of the vehicle: its weight, engine types, exhaust after-treatment, aerodynamic properties, etc., and
> (2) Operational factors relating to the way in which the vehicle is used: its speed, rate of acceleration, maintenance, road gradient, etc.

The technical factors describe the static properties of a vehicle, i.e. the vehicle technology development, while the operational factors are relevant to the dynamic information of a vehicle while moving, i.e. driver behaviour.

To achieve the tightening emission legislation especially the long and short-term CO2 reduction goals, investment and research by car manufacturers for greener vehicle models has focused on new technologies such as 'idling stop technology' (or 'stop-start technology'), exhaust after-treatment technology, vehicle weight reduction technology and alternative fuel engines (detailed examples as listed below). These new technologies are expected to reduce emissions at various levels.

Idling stop technology (stop-start technology) is a system that automatically shuts down the internal combustion engine when a car is stationary to reduce the engine idling time, e.g. while parked or at traffic lights, and it restarts when the vehicle returns to motion. Research conducted by Yoshitaka and Masaaki (2002) showed that vehicles fitted with idling stop support system have saved 6% fuel and on urban roads in particular, the saving ratio was 13%.

Bishop et al. (2007) performed chassis dynamometer tests to determine the fuel economy improvement of a stop-start system, noting a 5.3% reduction in fuel consumption in the city FTP75 test cycle. This technology has been applied in more and more new vehicle models by a number of car manufactures. For example, all 2.0-liter front-wheel-drive models in the all new Mazda3 models are equipped with idling-stop system and the restart takes place in only 0.35 seconds (MAZDA). The Toyota group has developed the 'Toyota Optimal Drive', which represents an entire range of new engines, design innovations and transmissions to bring in a step-change in fuel economy and emissions, and the 'stop and start system' is one of the innovations which has been fitted in the 1.33-litre VVT-i petrol Yaris, Auris and Urban Cruiser models. It states that Stop & Start saves fuel and emissions in urban conditions by seamlessly stopping and restarting the engine at lights or in stationary traffic. This helps to boost combined fuel economy by up to 18 per cent (Toyota). Today, almost all car manufacturers offer car models with stop and start system, such as C2 and C3 models by Citroën; Mini model by BMW; Fiat5000 by Honda and etc. It can be foreseen that in order to meet the continuously tightened emission limits and the demand of fuel economy, the idling stop system, as one of the solutions will be used in a wider scope.

However, idling-stop technology is still at the early stage and the proportion of idling-stop fitted vehicles in the current fleet is not clear. Most of the emission prediction models (including the Panis model) have not included this technology.

Exhaust after-treatment technologies such as catalysts have been used in all new vehicles as part of the integrated approach to control tailpipe emissions under the increasingly tightened EU emission legislations. The Association for Emissions Control by Catalyst (AECC) classifies 3 main technologies for exhaust after-treatment, mainly including catalyst converters, Particulates filters and traps and absorbers. The three-way catalysts are the main technologies to control emissions from petrol engines. While the engines are operating at normal driving temperature, the catalysts can simultaneously oxidise CO and HC to CO2 and water while reducing NOx to nitrogen. Particulates filters are generally used with diesel engines to remove diesel particulate matter (PM), but in principle can be used with other types of engine/fuel combinations. Absorbers can collect and store certain pollutants, especially NOx or HC when the engine operating conditions are ideal for conventional catalysts to achieve their full potential. The implementation of after-treatment technology is a significant factor influencing vehicle emissions, however as this technology is normally used in combination with other technologies in order to meet the emission standards and the devices are normally fitted in the vehicles as a whole, most of the current emission models do not distinguish the individual function of after-treatment technology.

Apart from the technical issues, it has been widely recognised that the operational factors, i.e different driving styles are important in exhaust emissions and fuel consumption. A study conducted by Ericsson (2001) in Sweden showed that rapid acceleration (>1.5 m/s2) resulted in a significant increase in the emission of HC, NOx and CO2 and fuel consumption.

According to El-Shawarby et al. (2005) mild acceleration, 40% of the maximum vehicle acceleration envelope, will lead to the highest accumulated fuel consumption and emission rates per acceleration event (compared with normal and aggressive acceleration, 60% and 100% of the maximum envelope). This is because a longer acceleration time is required to reach the desired speed, but aggressive acceleration results in higher fuel consumption and HC and CO emission rates over a fixed distance. Thew (2007) found that aggressive driving based on sudden acceleration and deceleration resulted in fuel wastage of approximately 33% at high speeds in the highway and about 5% around towns. New technologies and devices have been proposed and tested to encourage sustainable driving with smoother acceleration and deceleration behaviour. An in-vehicle acceleration advisor tool studied in Sweden by Larsson and Ericsson (2008) is a driver support tool that increases resistance in the accelerator pedal when the driver tries to accelerate too hard. The foot-LITE project (2007) aims to create a revolutionary driver information system designed to educate and encourage safer and greener driving and longer term behavioural changes.

It is clear that the ways ahead for research, technologies and policies on environment and transportation are towards less emitting vehicles, improved fuel economy and tools for promotion of greener driving behaviour. Apart from the continuous development on alternative fuels for vehicles, e.g. electric cars, Biofuels and hybrid vehicles, the improvement of vehicles using conventional fuels, i.e. petrol and diesel is also crucial as the conventional vehicles still remain as the major and most reliable forms at present as well as in the near future. The wider implementation of new vehicle technologies and promotion of more sustainable driver behaviour can result in a potential overall reduction in emissions and fuel consumption. However for a long-term estimation for future fleet, the extent of reduction caused by new vehicle technologies and improved driving patterns needs to be considered in conjunction with changes in other factors, such as fuel quality, proportion of vehicles with new forms of energy and any other development in new technologies.

In current emission models (including Panis model as used for this study), most of these factors are not taken into consideration or only considered using a simple correction factor. This is mainly because many of these new technologies are still at their early stage of development or implementation, therefore the proportion of vehicles fitted with these new technologies (e.g. idling stop system) is still very small and its direct impact on the emissions and fuel consumption to the entire fleet can be negligible. The inclusion of these factors in the future emission models, under the assumption that the implementation of such technologies become common and significant in the future, may take some years to achieve a usable and valid model. Emission measurement and modelling are costly and time-consuming processes which require a reasonably large sample of different vehicle models to be representative of the current on-road vehicle compositions. A good emission model is not only about the advanced methodologies and technologies it uses, but also needs to cover a relatively large number of vehicle models to produce reliable and practical emission data for advisory and decision-making purposes.

Relating to this study the reasons that implementing BSP strategies may have an impact on vehicle emissions and fuel consumption are those factors relating to vehicle operation behaviour (e.g. speed and acceleration, or sometimes considered as engine power and engine speed). As this study focuses on the impacts of before and after implementing BSP, the vehicle fleet, and the drivers with different driving habits are supposed to be the same, therefore the relative impacts of those external factors, e.g. new technologies, are considered to be insignificant.

In the emission modelling process, the vehicle static information normally used to categorise vehicles, while operational factors such as speed and acceleration, or engine power and engine speed are the main parameters in developing an emission model. For each predefined vehicle category emissions are measured and analysed against these factors. A review of emission measurement and modelling is presented in the following 2 sections.

3.2 Review of emission measurement for model development

3.2.1 Emission measurement techniques

Emission models are developed based on emission measurement. For emissions measurement, considering the strong influence of vehicle technology specifications and vehicle status when emissions are generated, vehicles in different categories are tested separately according to a set of representative driving cycles. Vehicles are categorised in terms of emission standards (European legislation), fuel type, engine size, vehicle weight, mileage and etc. The driving cycles are designed according to the requirement of modelling scales and aggregation levels.

Watkins (1996, p16) described the common methods for vehicle emission estimation. There are 3 ways to collect monitoring data: (1) Engine dynamometer measurement; (2) Chassis dynamometer measurement; and (3) On-road measurement. The first 2 methods both apply test unit 'driving cycles' to derive emission factors using engine dynamometer or chassis dynamometer test facilities. Both of these facilities are highly controllable lab environments, repeatable operation and highly standardised. Therefore these 2 methods are typically used for type approval and conformity of production tests. The on -road measurement involves measurement of emissions from vehicles driven in a real-world situation. Although the on-road measurement is considered to be able to simulate the real driving situation, due to the limitations of testing technology and data reliability, it is traditionally only used as complementary data sources when developing emission models. The on road measuring methods use on-board in-vehicle emission measuring equipment or remote sensing technique.

A Driving Cycle is an emission measurement widely used in the world but applied by different regulations. The driving cycles used for regulatory testing are highly standardised but not necessarily representative of real world operation (Samuels et al, 2002; Farnlund and Engstrom, 2001; Estetes-Booth et al 2001). In particular they only cover a limited area of the vehicle operating map, with high power and high speed-low load conditions being under-represented (Younglove et al, 2005). The most widely used 3 driving cycles are FTP(Federal Test Procedure) test drive cycles in the US, the official Europe ECE (Economic Commission for Europe) for European countries and Japanese 10-16 mode cycles. In this study, the EU driving test cycles are briefly described.

The current measurement methodology employed in Europe for laboratory tests, e.g. Engine dynamometer measurement and Chassis dynamometer measurement is called New European Driving Cycle (NEDC), which is a regulatory drive cycle developed for emission testing of commercial on-road cars and light duty vehicles in the EU. A driving cycle consists of 4 repeated ECE-15 driving cycles and an Extra-Urban Driving Cycle (EUDC), representing the typical driving process. The extra-urban driving cycle (EUDC) segment is added after the fourth ECE cycle to account for more aggressive high-speed driving models. It is a carefully designed driving profile lasting 1200 seconds, attempting to cover the main speed ranges in urban and sub-urban roads. With the collected emission data with respect to the corresponding speed during a driving cycle, the relationship can be studied towards an emission model. **Figure3. 3** represents an example of the NEDC driving cycle with speed/ time series during testing.

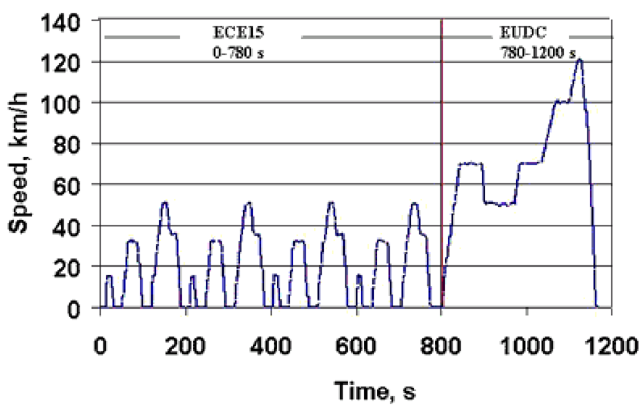


Figure3. 3 ECE 15 and NEDC drive cycle profiles (Source: ISO definition of standard driving cycles 2003)

Driving cycles may vary in forms and durations due to different measuring purposes, but they are the mostly highly controllable and repeatable process compared to other measurements. However even for the highly standardised laboratory testing, Abbott et al (1995) found that:

> *'Vehicle exhaust emission rates are inherently very variable, and repeat tests on a single vehicle can give results that differ by tens of percent; tests on different vehicles of the same type may vary by a factor of ten. This variability will be encountered whatever measurement technique is employed, although laboratory conditions provide the best way to control repeatability'.*

Samaras et al (1997) stated that *'recent evidence suggests that even average emission measurements for pollutants can vary considerably between laboratories*'.

This suggests that emission measurement itself even for the most highly controlled measurement is a complex and highly variable process. It might be caused by the measuring facilities and techniques, but is also due to the complex nature of combustion process in the engines.

On- road emission measurement are usually used to evaluate the impact of air quality under a certain traffic operating condition (e.g. De Vlieger et al 2000 and Lenaers 1996). It provides the opportunity to measure data directly under real world driving conditions. The 2 main methods used for on-road measurements, 'on-board' and 'remote sensing' techniques are described as follows:

> **On-board emission measurement equipment** (an exhaust sampler) is normally attached to the tailpipe of a vehicle which is driven on the road during a test. An example of the early staged samplers can be a mini version of CVS (Constant Volume Sampler) used in laboratory tests, such as the device developed by the Warren Spring Laboratory (Potter et al, 1986; Potter and Savage, 1982). An example of more recent on-board emission measurement systems can be the OBS-2000 series developed by HORIBA, Japan. They are able to measure the instantaneous emissions such as CO, CO_2, THC and NO_x and fuel consumption on board. On-board system is able to measure the continuous emissions along the driving route, therefore it is used to capture the variation of emissions under different driving behaviour.
>
> **Remote sensor** is a device installed at road side so exhaust emissions can be detected when the vehicles drive by. An Infra-red source is positioned at one side of the road and a detector on the opposite side. In operation the IR source continuously generates IR beam towards the detector and the emissions emitted from vehicles passing through the beam are measured and analysed according to absorption spectroscopy principle. The remote sensing technique can measure a large number of vehicles crossing the IR beam, however it is only able to measure emissions from a cross section from where vehicles pass by, and emissions from each vehicle during its whole journey can not be measured. Remote sensing has been used in many studies as it appears to be a non-intrusive, cost effective and less time-consuming technology. However the accuracy and lower limit of detection of

individual remote measurements depend on how the exhaust plume disperses and what part of the plume is intersected by the detection beam (Boulter 2001). The overall accuracies have been reported by the University of Denver as 5% and 15% for CO and HC respectively.

3.2.3 Summary and discussion for emission measurement

In summary, emission measuring methods typically consist of Engine dynamometer measurement, Chassis dynamometer measurement, and On-road measurement. The first 2 methods are conducted in highly standardised and controllable laboratory environments. They both apply the test units of driving cycles. The third on-road measuring method either applies an on-board device or a remote sensor. It is usually used to measure the variety of operational modes in real-world driving, so as to study driving behaviour under different operational conditions.

Emission measurement is the base for developing emission models. The purpose of reviewing emission measurements is to better understand how the emission models are derived and the associated advantages and disadvantages. In fact, emission measuring techniques and sampling methods directly influence the scope, aggregation levels and accuracy of emission models. Emission data collection and sampling procedures vary according to measurement purposes and modelling requirements. For aggregated emission models developed in a laboratory environment, bag sampling is traditionally used. It tests a constant proportion of the diluted exhaust gas collected via a constant volume sampler (CVS) in a bag made from inert material. The gases collected during a driving cycle are analysed later to provide average values for the whole driving cycle time. This method is relatively simple, and it provides average values that can not be directly related to the detailed vehicle operation. Therefore this measuring method is commonly used for aggregated emission models, such as average speed models, which is reviewed in 3.3.3. In order to model emissions by relating emission rates to vehicle operation during a series of short time steps (often one second), such as instantaneous models (see section 3.3.4), continuous sampling is necessary. Continuous sampling and analysis requires that the emission analysers be physically attached to the exhaust and the gas analyser must be able to read the emission data for the required time interval correctly, e.g. every second or less.

The complexity of instantaneous emission models has increased during the last 10-15 years and progress has been made towards better accuracy and precision (Boulter et al 2007). However there are a number of fundamental problems associated with continuous sampling.

The main concern is that a result measured at a particular moment may well be a damped and delayed response to an event some time earlier (Abbott et al, 1995). A detailed discussion on instantaneous emission models is presented in section 3.3.5.3.

3.3 Review of vehicle emission modelling

An emission model is an algorithm used to reproduce or represent emissions from driving cycle measurement. Generally, emissions and fuel consumption models are established from 2 levels of aggregations: Macroscopic levels and Microscopic levels, which are also named as aggregated models and Instantaneous models (or dynamic models). The former ones are usually used to predict emissions on a large scale, i.e. total emissions produced by all the vehicles on a national or regional level. Microscopic models are used at an operational level to predict emissions on small scales or for short time intervals, e.g., the second-by-second emissions of individual vehicles. The general principles, the widely used emission models on both levels, and related comparison and discussions are reviewed in the following sections.

3.3.1 General principles

MEET (Methodologies for Estimating Air Pollutant Emissions from Transport) project (European Commission (EC) 1999)) was an European Commission sponsored project within the 4th Framework Program (1996-1998), providing a general methodology for emission calculations which had been widely accepted by most of the European experts, presented in following equation.

$$E = E_{hot} + E_{start} + E_{evaporative}$$

where:

E	is the total emission
E_{hot}	is the emission produced when the engine is hot
E_{start}	is the emission when the engine is cold
$E_{evaporative}$	is the emission by evaporation
	(Only for VOCs (Volatile Organic Compounds))

The hot emissions and cold start emissions are exhausted from tailpipe. The amount/rate of pollution of the cold start emissions is much higher since the engine uses fuel inefficiently when it starts below its normal operating temperature. Evaporative emissions normally come from volatile compounds in fuels occurring in a number of different ways, e.g. while refilling the tank.

Hot Emissions

Hot emissions are emissions emitted from the tailpipe when the engine is operated under normal operating temperature. Most emission models mainly deal with hot emissions. Cold start and evaporate emissions are modelled separately using a different methodology. Hot emission models are reviewed in later sections (3.3.2-3.3.5) in more detail.

Cold Start Emissions

Cold start and evaporate emissions are usually included in models where the estimation of emissions is based on per trip and average speeds. Emissions exhausted from cold start status to the operating temperature are much higher than normal situation due to the less effective fuel consumption. Under this condition, the cold start emissions should be modelled independently from the emission models. **Figure3. 4** illustrates the cold emission.

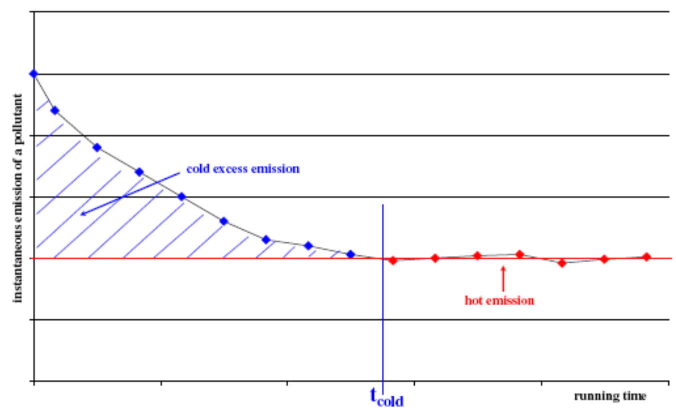


Figure3. 4 Cold start emissions illustration (Source: MEET (EC 1999))

As cold emissions only occur during the early part of a journey, in the MEET method, they are expressed as an amount produced per trip, and not over the total distance travelled. It assumes that the general model is a function of temperature, average speed and travelled distance.

Evaporative Emissions

Evaporative emissions occur in a number of different ways. Fuel vapour is expelled from the tank each time it is refilled, the daily increase in temperature causes fuel vapour to expand and be released from the fuel tank, and vapour is created wherever fuel may be released to the air, especially when the vehicle is hot during or after use. There are therefore a number of different emission factors, $e_{evaporative}$, depending on the type of evaporative emission. Generally, these factors are a function of the ambient temperature and the fuel volatility. Similarly, a number of activity data are also needed, including total distance travelled and numbers of trips according to the temperature of the engine at the end of the trip.

For hot emission modelling, Cloke et al (1998) conducted a survey as part of the DRIVE 2 'KITE' project, and divided the emission models throughout Europe into 3 main groups with increasing level of complexity, which were:

(1) Emission factor models,
(2) Average speed models, and
(3) Modal models (or instantaneous models).

A discrete approach named 'traffic-situation' or' traffic-characteristics' models should also be included in the later review as they can be used at a street level and emissions are calculated with consideration of more detailed traffic situations rather than average speed only.

Therefore these 4 types are reviewed in 3.3.2 to 3.3.5 including modelling methodology, representative models and followed by critical appraisal.

3.3.2 Emission factor models

A summary of the emission factor models in Cloke et al (1998)'s report is that

> *'The emission factor models use a simple calculation method…The emission factors are derived from the mean values of repeated measurements over a particular driving cycle and are often expressed in mass of pollutant per unit distance (e.g. g/vehicle km)'.*

Generally emission factor models are used for emissions from macro scales, such as national or regional emissions from all vehicles for a long time period, e.g. 1 month or 1 year. Emission factor models normally require the total traffic volume and total vehicle-kilometres travelled by all traffic. The general principle of emission factor models according to Esteves-Booth et al (2002) is 'to multiply the vehicle-kilometres travelled by each vehicle type by an emission factor for each pollutant being considered'. 2 main emission factor models are reviewed as follows:

NAEI

The newly updated **NAEI** (National Atmospheric Emissions Inventory) (2010) provides 2 different modelling approaches for road related emissions, one is emission factor modelling and the other is average speed emission modelling. The emission factors are derived via a methodology named emission maps at a 1km resolution and are produced annually. The emission maps are used by AEA and other organisations for a variety of Government policy support work at the national scale. **Figure3. 5** gives an example of pollutant CO for UK in 2007, in unit of tonne/ $1km^2$. The CO calculated in this figure is from different sources such as industry, domestic, transport and others. Emission factors for road transport for a local area can be calculated by the share of CO at road transport sector at that area. This model is highly aggregated and should be used for large areas.

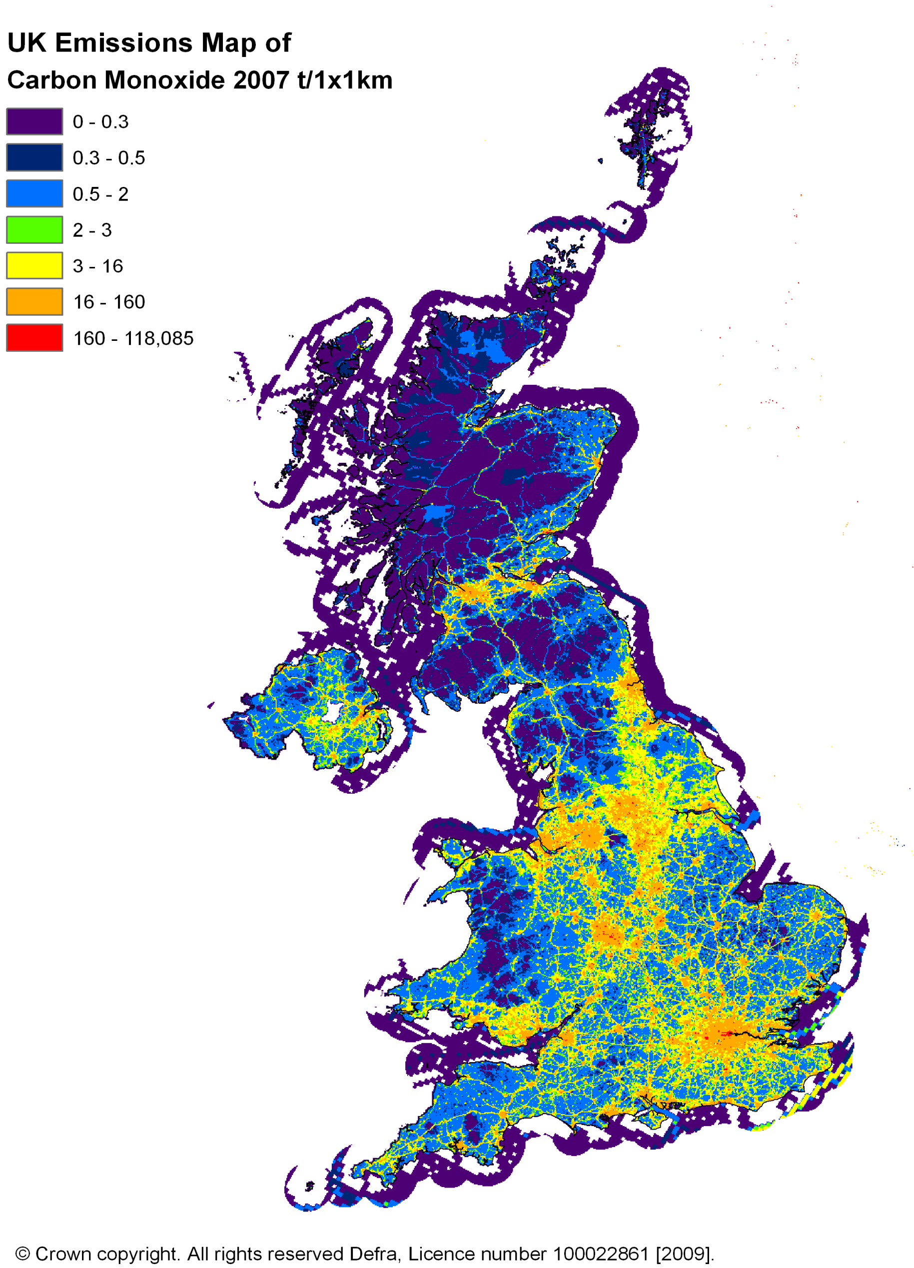


Figure3. 5 UK Emission map of Carbon monoxide in 2007, unit t/1*1 km (Source: NAEI 2010)

COPERT

COPERT is the COmputer Programme to calculate Emissions from Road Transport. The latest version is COPERT 4 updated in 2007. It calculates emissions from road transport based on an average speed methodology. The COPERT 4 methodology has been included as part of the EMEP/CORINAIR Emission Inventory Guidebook as an algorithm for road transport. There are 2 levels of methodologies involved in the new version. One methodology is called the simpler methodology which is for the national level. In this model only one single value for each pollutant of each vehicle type is given for one country. **Table3. 5** is extracted from EEA (2006) showing the emission factors applied in the UK.

Table3. 5 Bulk emission factors (g/kg fuel) for UK (Source: EEA 2006)

Category	UK					
	CO	NOx	NMVOC	CH_4	PM	CO_2
Gasoline PC	51.43	6.79	5.40	0.87	0.03	3.18
Diesel PC	1.91	11.96	0.44	0.06	0.77	3.14
Gasoline LDV	99.40	16.29	6.55	0.38	0.02	3.18
Diesel LDV	6.65	14.84	1.55	0.11	1.33	3.14
Diesel HDV	6.22	31.65	0.65	0.34	0.60	3.14
Buses	6.14	31.08	1.48	0.54	0.79	3.14
Mopeds	258.50	11.09	197.15	5.17	4.68	3.18
Motorcycles	378.98	11.07	35.83	5.52	0.75	3.18

The other methodology is called detailed methodology built around the average-speed approach, where input variables include fuel variables, activity data, driving conditions and other variables. This model is reviewed in 3.3.3.

Since emission factor models are developed for large scales, e.g. one emission factor for a nation wide scale, which is obviously not suitable for this study, so no further review on this type of models is presented.

3.3.3 Average speed models

Average speed models are based on speed-related emission functions generated by the measurement of the emission rates over a variety of trips at different speed levels. This type of models is widely used on a road network scale, including a large number of models. . A report by Barlow and Boulter (2009) aiming to review the use of average vehicle speed to characterise hot exhaust emissions and to provide recommendations for the NAEI. It covered 3 average speed models; MEET, COPERT and ARTEMIS (the sub average-speed model), which are reviewed as follows.

3.3.3.1 Available average speed models

MEET

For hot emissions, the activity related emission factor, e_{hot}, is expressed primarily as a function of the average speed of the vehicle. Modification factors (which may themselves be functions of other variables) allow corrections to be made for the road gradient, the load carried by a vehicle, the degradation of pollution controls with increasing mileage of the vehicle, and the ambient temperature. Thus, for one vehicle type and pollutant, the emission factor can be expressed as the following equation:

$$\boldsymbol{e_{hot} = f\,(v) \times GC \times LC \times MC \times TC}$$

where:

e_{hot} is the corrected hot emission factor

$f\,(v)$ is the average speed dependent emission factor for standard conditions

GC, LC, MC & TC are factors to correct for gradient, load, mileage, temperature respectively.

The hot emission factors derived in average speed emission models are usually calculated via a mathematical (e.g. polynomial) formula with regard to speed $\boldsymbol{v}$, considering the combination of vehicle classification, fuel types and driving parameters. Therefore for each pollutant emission rates are expressed as forms of an ‘emission rate-speed curve’ or a ‘look-up prediction table’. For example, **Figure3. 6**shows how an emission rate-speed curve is fitted to the NOx emission factors measured for several Euro 3 diesel vehicles over a range of driving cycles.

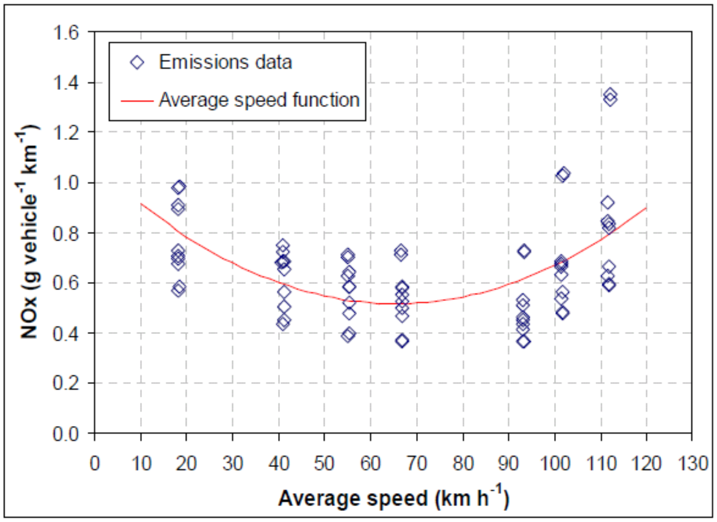


Figure3. 6 Average speed emission function (red line) for NOx emissions from Euro 3 diesel cars< 2.0 litres. The blue points show the underlying emission measurements (Barlow et al 2001)

CORPET

COPERT 4 (2008) COPERT is a free program widely used in European countries. It was a project based on CORINAIR Emission Inventory, and financed by the European Environment Agency (EEA). It collaborated with the **MEET** project (1996-1998) and **COST 319** action on the Estimation of Emissions from Transport (1993-1998), the **PARTICULATES** project (Characterisation of Exhaust Particulate Emissions from Road Vehicles), a European Commission (DG Transport) **PROJECT** within the 5th Framework Program (2000-2003), and updated with the **ARTEMIS** project. It is also a joint **JRC/CONCAWE/ACEA** project on fuel evaporation from gasoline vehicles (2005-2007)**.** The first released version was in 1989 and the COPERT 4 is updated recently.

The methodology for hot emission modelling applied in COPERT for average speed approach is referred as the ‘detailed methodology’ or the ‘Tier 3’ method in later versions. Similarly to MEET, emission factor on each pollutant in CORPET is calculated as a function of average speed, and the generic function used is:

$$EF = (a + c \times V + e \times V^2)/(1 + b \times V + d \times V^2)$$

Where EF is the emission factor for a pollutant in unit of (g/km)

V is the vehicle speed (km/hr)

Parameters *a* to *e* are given in a set of tables according to pollutant and vehicle types (Euro 1- Euro 4).

ARTEMIS average-speed model

The **ARTEMIS Project** "Assessment and reliability of transport emission models and inventory systems" (EC 2007) was a 7 year project funded by the 5th framework programme of the European Commission, aimed at combining the experience from different emission calculation models and ongoing research in order to arrive at a harmonised methodology for emission estimates at the national and international level. It is a following step after 3 model developments in Europe: MEET Project and the COST 31 Action and German and Swiss emission model HBEFA.

ARTEMIS contains 1 main model which is the traffic situation model (reviewed in 3.3.4) and 4 sub-models. The kinematic regression model within ARTEMIS is based on the average speed approach. Similar to the COPERT, it uses the same form for emission factor calculation, but values of coefficients are different.

An example of a comparison of the NOx emission factor-speed curve derived from COPERT and ARTEMIS is shown in **Figure3. 7Error! Reference source not found.**. It shows that all average speed models use a similar curve with higher values of Emission Factors for very low and very high speeds, but the smallest EF value for the speed at around 50km/hour.

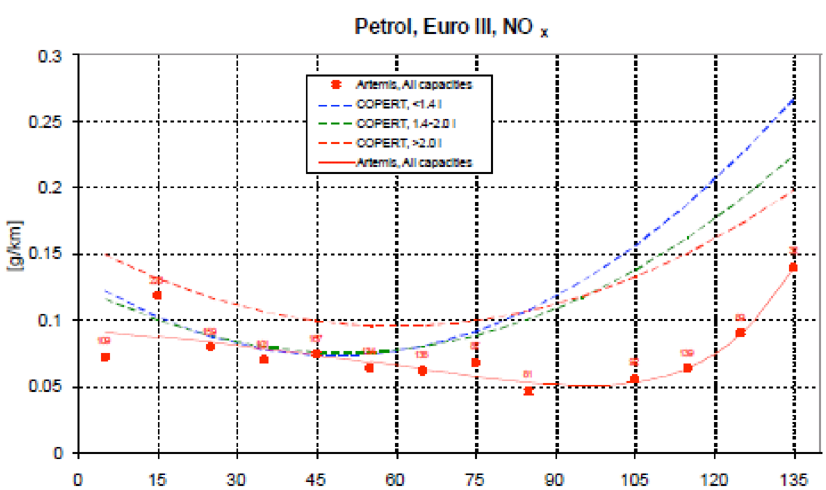


Figure3. 7 Petrol Euro 3 NOx emission functions according to average speed in Artemis model and comparison with COPERT 3 functions

In the UK, Boulter et al (2008) proposed new emission factors for the NAEI on the basis of the ARTEMIS (AS) database and methodology, therefore the current NAEI emission model and data can be treated as the adjusted ARTEMIS in the UK.

3.3.3.2 Discussion of average speed models

There are numerous average speed models being used currently worldwide for emission estimation at a scale such as around a region or a city or a relatively large road network. Other examples of average speed models include the UK DMRB model and the MOBILE Model in the US. They all apply a similar methodology of modelling each emission pollutant based on an average speed; some may require more detailed input for vehicle categories or region types (e.g. motorway, rural or urban driving).

The 'emission rate-speed' curves vary depending on the type of vehicles and the pollutants, but they generally show high emissions at slow average speeds when the vehicle operation is inefficient because of stops, starts and delays, a tendency to high emissions at high speeds because of the high power demand on the engine, and minimum emissions in the middle speed range at which fuel is burned most efficiently.

Average speed models have gained sound recognition and credibility, as for a large spatial and temporal scale they appear accurate enough to the extent which users expect. Barlow and Boulter (2009) summarised that *'a number of factors have contributed the widespread use of the average-speed approach. For example, it is one of the oldest approaches, the models are comparatively easy to use, a number of models are available free of charge, and there is a reasonably close correspondence between the required model inputs and the data generally available to users'*.

However there are a number of limitations associated with average speed models:

(i) Trips having very different vehicle operation characteristics can have the same average speed. E.g. a 10 minute trip with constant speed of 40mph and a 5 minute trip at 80mph with a following 5 minute delay have the same average speed but actually with significantly different emissions. Therefore, average speed models are not able to capture emission variations caused by operational differences.

(ii) Average speed models are considered to be only suitable for a large spatial and temporal scale where the road characteristics are not dominated by vehicle operating behaviour, thus the effects of acceleration, deceleration, and stop-go conditions are statistically smoothed (Barth et al, 1996).

(iii) Average speed models may underestimate emissions when applied to a small network, e.g. a junction where emissions are dominated by vehicle operational behaviour.

(iv) Average speed models could be sensitive to the speed variation only because it applies the continuous polynomial function forms; however it may not be able to correctly reflect the reasons for speed change, such as details of acceleration and deceleration, and the results could be misleading when comparing emissions from slightly different average speeds.

(v) The shape of an average speed function is not fundamental, but depends on, amongst other factors, the types of cycles used in development of the functions. For example, each cycle used in the development of the functions typically represents a given real-world driving condition, but the actual distribution of these driving conditions in the real world will vary by time and location. (Barlow and Boulter 2009)

Nevertheless, average speed models, due to a number of merits, have been widely used and in general are able to provide sensible emission estimation for large scales. However for a small study scale where emissions are dominated by vehicle operational behaviour, as in this research, more sophisticated emission models are required.

3.3.4 Traffic-characteristic based models

Traffic characteristic based emission models or traffic situation models can be used at a street level. In this type of model, emissions are calculated with consideration of more detailed traffic situations rather than average speed only. This approach is a non continuous or discrete model, in contrast to instantaneous, kinematic or average speed models (INRETS 2007). The main idea of Traffic-characteristic based models was to develop a model which is easy to use but also inclusive of different traffic conditions apart from average speed. There are 2 main Traffic characteristic models, the HBEFA model and ARTEMIS Traffic Situation model. The traffic situation model developed in the ARTEMIS is very similar to HBEFA, but more widely applicable to other European countries.

The HandBook of Emission FActors (HBEFA) is based on reference emission factors for different categories of vehicles. The latest version is HBEFA 3.1 produced in 2010 (INFRAS 2010). This model is widely used in Germany, Austria and Switzerland from where the emission data originally came. Data for Sweden and Norway are included in the latest version and data for France are presently being prepared.

These models apply a methodology in which average emission rates are correlated with a number of 'traffic situations' as a combination of road configurations, speed limits and traffic conditions. In ARTEMIS, the traffic situations are determined by 4 parameters: the area (urban/rural areas), the road type (a functional hierarchy), the speed limit and the level of service (in 4 levels, free flow, heavy, saturated, and stop-go) as shown in **Figure3. 8**.

Overview Traffic Situations

			Speed Limit											
Area	Road type	Levels of Service	30	40	50	60	70	80	90	100	110	120	130	>130
Rural	1 Motorway-National	4 levels						x	x	x	x	x	x	x
	2 TrunkRoad/Primary-National	4 levels				x	x	x	x	x	x			
	3 Distributor/Secondary	4 levels			x	x	x	x	x	x				
	4 Local/Collector	4 levels			x	x	x	x						
	5 Access-residential	4 levels	x	x	x									
Urban	1a Motorway-National	4 levels						x	x	x	x	x	x	
	1b Motorway-City	4 levels				x	x	x	x	x	x			
	2a TrunkRoad/Primary-National	4 levels					x	x	x	x	x			
	2b TrunkRoad/Primary-City	4 levels			x	x	x	x	x					
	3 Distributor/Secondary	4 levels			x	x	x	x						
	4 Local/Collector	4 levels			x	x								
	5 Access-residential	4 levels	x	x	x									

Return

Figure3. 8 Overview of traffic situations in ARTEMIS-TS model

There are about 250 traffic situations defined in this model aiming to reflect all the existing road traffic situations in the Europe. For each traffic situation and for each vehicle category, a speed curve recorded in real-world conditions which implicitly represents a particular driving pattern is used to determine the corresponding emission factor. An example of speed curve for one traffic situation (black circle) and one vehicle category (red circle) is shown in **Figure3. 9**.

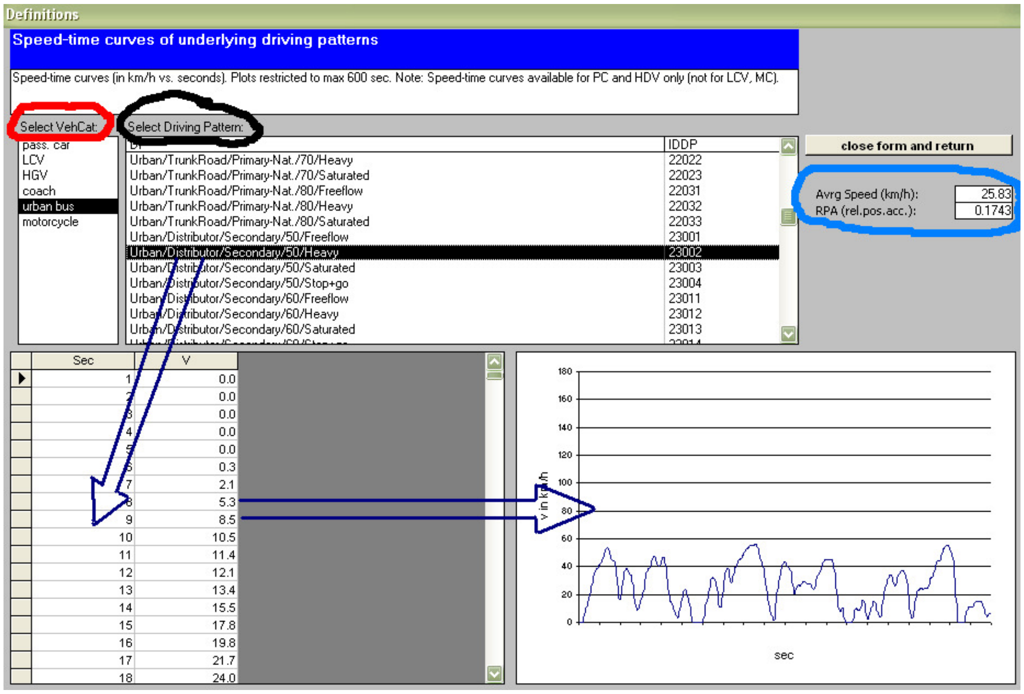


Figure3. 9 An example of speed-time curve for its underlying driving pattern

For each of the speed curve, according to the average speed in the recorded time period and the relative positive acceleration (RPA) value (blue circle), an overall emission factor for each regulated pollutant (i.e. CO, HC, NOx), CO_{2m} and fuel consumption is supplied for calculation. The above example shows that for a specific vehicle type (in this example a Euro3 15-18t standard bus) at a particular road gradient and load situation (both 0 in this example) driving on a secondary road with speed limit 50km/h during heavy traffic situation in urban area, the typical average speed would be 25.83km/h with the RPA 0.1743. According to the model database, emission factors for this scenario are shown in the first row in the table below. Another traffic situation shown in the same table as the second row is a similar road type but with different speed limit and traffic condition.

Urban bus standard >15-18t, Euro 3 (Gradient =0%, Load=0%)

IDDP	Driving Pattern	V(km/h)	RPA	HC(g/km)	CO	NOx	CO2m	FC
23002	Urban/Distributor/ Secondary/50/Heavy	25.85	0.1743	0.48621	2.4211	8.77155	925.86	293.35
23013	Urban/Distributor/ Secondary/60/Saturated	21.95	0.1753	0.55734	2.624	9.71127	981.12	310.89

Therefore in practice, it is up to users to find out the best emission factor sets which match their case. Users need to match the characteristics of their target roads, streets or links to those predefined traffic-situations in the database, which in some cases can be difficult. For example, for some similar traffic situations with close average speed and RPA values, it is difficult to decide which one is the most appropriate situation.

Boulter et al (2007) also stated that *'asking the user to define the traffic situation using a textual description of speed variation or dynamics may lead to inconsistencies in interpretation. Even qualitative descriptions, such as those employed in the HBEFA, may be beyond many users, and are obviously open to interpretation.'*

Traffic characteristics models originally came from the idea to incorporate both speed and dynamic characteristics of road traffic situations. The input data required are much simpler than other emission models but according to INRETS (2007) it is less precise compared to instantaneous or kinematic or average speed models. As a discrete model, it can not estimate vehicle emission variations caused by driving operational changes.

3.3.5 Instantaneous emission models

Instantaneous emission models are considered as the state-of-the-art generation of emission models. This type of model has been developed rapidly for a number of reasons, e.g. the demand to better understand the impacts of driving operation conditions on vehicle emissions, the demand to map emissions on a smaller spatial scale (i.e. a junction) and shorter time period (i.e. several seconds), and the improvement of measuring equipment and techniques.

Boulter et al (2007) explained the rational of instantaneous emission modelling: instantaneous emission models aim to provide a precise description of vehicle emission behaviour by relating emission rates to vehicle operation during a series of short time steps (often 1 second). Several terms have been used to describe such models, including 'modal', 'micro-scale', 'continuous' and 'on-line'(De Haan and Keller 2000). As the term 'instantaneous' has been more widely used in the literature, it is adopted in this study. Instantaneous emission models require detailed and precise information on vehicle operation and instantaneous kinematic data, such as second-by-second speed and acceleration data. Obtaining such data was difficult for many users in the past which has largely restricted the development and their applications. One solution to this problem is using microscopic traffic simulation models to generate the required model inputs. The instantaneous and individual output from microsimulation such as sec-by-sec speed provides a great source for such emission models, thus emissions can be calculated at a much finer level.

Modal models, mentioned in many literatures, are the first generation of instantaneous emission models which allocate emission rate factors to the specific modes of vehicle operation encountered during a trip. Four typical operation modes are defined, i.e. idle, acceleration, deceleration and cruise mode. Emission factors are determined in the form of a matrix, representing combination of vehicle speed ranges (e.g. every 10km/hour) and acceleration rate ranges (e.g. every 0.5-1.0 ms^{-2}). MODEM is an example of this type. As modal models are mainly based on speed-acceleration matrix, they are grouped into 3.3.5.1.

In general, instantaneous emission models are developed and expressed via 2 approaches, one is speed-acceleration based, and the other is engine power based. These 2 types are reviewed and discussed in the following sections.

3.3.5.1 Instantaneous models based on speed and acceleration

Many studies (e.g. Hansen et al. 1995; Joumard et al. 1995; Ahn et al. 2002) have been conducted attempting to set up a speed-acceleration matrix to provide instantaneous emissions and fuel consumption rates. The review of instantaneous emission models by Boulter et al (2007) summarised a number of models, for example, models apply either speed and acceleration matrix (e.g. Pischinger and Haghofer 1984; Sorensen and Schramm 1992) or speed and the product of speed and acceleration matrix (e.g. Jost et al 1992; Hassel et al 1994; Joumard et al 1995). These mentioned models were mostly developed before introducing EU legislation and most of them have not been updated ever since or are unavailable to the public. Two more recent models are selected and reviewed for this study, the MODEM model and the Panis model. The MODEM model is the most widely used and mentioned speed and acceleration based instantaneous model developed during the 90s in the form of modal structure. The Panis model provides instantaneous emission factors derived from functions using a non-linear multiple regression model.

MODEM Model

The **MODEM** model (Joumard et al 1995) considers hot emissions only and was firstly developed as part of European Commission's DRIVE programme, aiming to determine the most important vehicle parameters that influence the emissions and fuel consumption of passenger cars. Emission measurements were conducted in 3 laboratories in France, Germany and the UK covering 150 vehicles in total designed to represent the 1995 European fleet. This model attempted to seek other parameters that influence emissions and fuel consumption rates rather than speed data in the previous average speed models, therefore acceleration rate was introduced as an additional variable. The modelling principle of MODEM is that the engine power determines the rate of emission, and the power required depends on the speed and the rate of acceleration. Therefore the emission data were analysed with respect to vehicle speed (km/h) and the product of speed and acceleration (m^2/s^3). An example of NOx emission factors in MODEM for petrol cars 1.4-2.1 litres of engine displacement is shown in **Figure3. 10**.

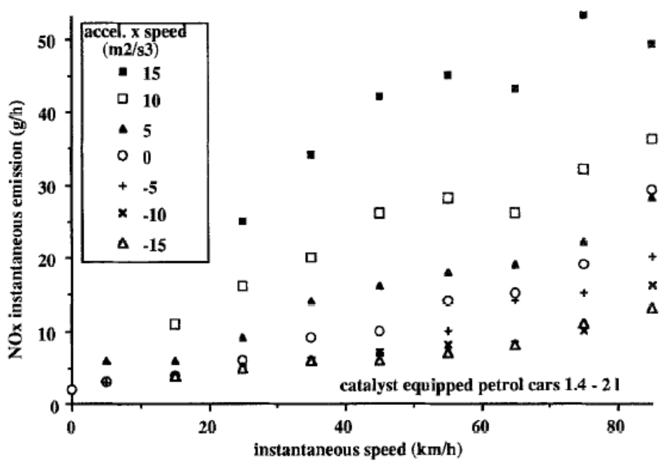


Figure3. 10 NOx instantaneous emissions from catalyst equipped petrol cars with engines 1.4-2.1 as a function of speed and speed* acceleration (Source: Joumard et al 1995)

The authors found that the agreement between measured and calculated rates of emissions via MODEM (original) was poor due to several potential sources of error (details were given in their paper), however it has been cited (Barlow et al 2007) that the poor agreement did not necessarily invalidate the principles of the method of calculation. It also stated that this emission model 'should be able to produce a good estimate of the emissions of carbon monoxide, hydrocarbons and oxides of nitrogen for a typical traffic stream based on the instantaneous operating parameters of the vehicles. More importantly, it will be able to compare the emissions from trips using different driving parameters, and allows the assessment of any technological innovation which could have an influence on vehicle speeds or other traffic parameters.'

An extended version of MODEM was developed by TRL later with 2 main improvements. The first one is that it extended the speed range higher than 90km/hr which was the max limit in the original version, and the second improvement is that it provided a finer resolution of speed and acceleration bands with 26 speed bands and 36 speed *acceleration bands in total (there were 10 speed bands and 7 speed* acceleration bands in the original version, as shown in **Figure3. 10**).

For the extended version, it has stated in a review by Boulter et al (2007) that although there were some noticeable differences from estimates using the MODEM model, the agreement with the actual measured values was very good despite the PM estimation, therefore PM emission factors derived from the model should be viewed with caution.

Panis Model

A modal instantaneous emission model developed by Panis et al (2006) (referred to as the Panis Model hereafter) is based on the emission measurement on 25 instrument vehicles, including 12 petrol cars, 5 diesel cars, 6 buses and 2 trucks. Emission functions for each vehicle are derived with instantaneous speed and acceleration as parameters using non-linear multiple regression techniques. This model covers NOx, HC, PM and CO2 pollutants. CO was not modelled because it stated that CO though a very toxic gas, hardly causes any negative effects at low levels in the open air. The general function for each pollutatn is shown in equation below:

$$E_n(t) = \max[E_0, f_1 + f_2 v_n(t) + f_3 v_n(t)^2 + f_4 a_n(t) + f_5 a_n(t)^2 + f_6 v_n(t) a_n(t)]$$

Where $v_n(t)$ and $a_n(t)$ are the instantaneous speed and acceleration of vehicle n at time t. E_0 is a lower limit of emission (g/s) specified for each vehicle and pollutant type, and f_1 to f_6 are emission constants specific for each vehicle and pollutant type determined by regression analysis.

An example of the emission function derived for CO2 emission factors in Panis model for a Euro 3 diesel car is shown in **Figure3. 11**.

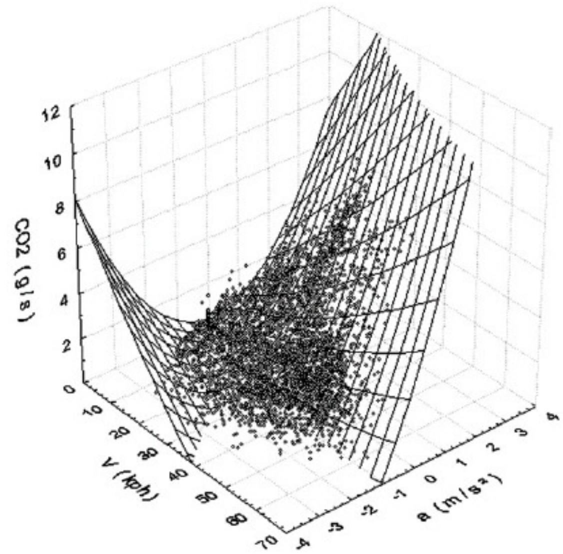


Figure3. 11 An example of CO2 emission factors in Panis model for a Euro 3 diesel car (Source: Panis et al 2006)

It is stated in the paper that the functions were considered sufficiently accurate for use in urban networks, however the results of multi non-linear regression techniques or even more advanced non-parametric statistics were rather disappointing (cross ref. e.g. Cornelis et al 2005). It suggested that engine characteristics models or engine-to-wheel relationships models may prove to be more suitable in the future but at the cost of greater data requirement. As the engine specific data such as engine speed or torque are difficult to obtain for users, some of the current engine based models convert the required engine related data to the kinematic data via physical relationships. Two engine-power instantaneous emission models are therefore reviewed.

3.3.5.2 Instantaneous models based on engine power

Several studies have concluded that emissions should be described in terms of engine speed, load, power, and the changes in these parameters, not just variables relating to vehicle speed(Leung and Williams 2000; Kean et al 2003). From literature, most of the engine power based emission models employ the same methodology using emission maps to calculate emission and fuel consumption rates as functions of engine torque/power and engine speed. Several such models have been developed and recognised worldwide, e.g. PHEM by TU-Graz, CMEM by University of California, Riverside, VeTESS within the EU 5th framework project DECEADE led by MIRA (2002), and EMPA by Atjay et al.(2005) in EMPA Institution. VeTESS considers only one vehicle at a time and one journey at a time, so is not suitable for large fleets and long time emission estimation. This model is not further reviewed in this study. EMPA remains more a concept than a tool for emission prediction, therefore not included in this review. Only the PHEM and CMEM are reviewed and considered in this study due to the issues of comprehensiveness and high recognition.

PHEM

PHEM was initially developed for simulating Heavy Duty Vehicle emission factors, and now covers passenger cars with data collaboration with ARTEMIS and COST 346 projects. As shown in **Figure3. 12**, the model employs the methodology of interpolating the fuel and emissions from steady state emission maps for every second of given driving cycles. A Gear-shift model and transient correction tool are introduced to improve the accuracy. Engine maps are 3 dimensional graphs including normalised engine speed 'n-norm' (ranging from 0%-100%), engine power (rated power 100%) and the emission values are given in $(g/h)/kW_{rated\ power}$.

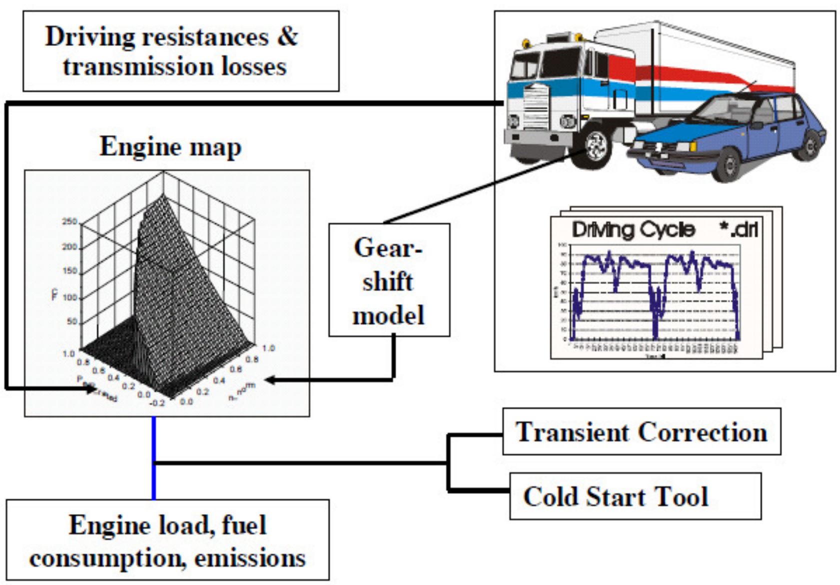


Figure3. 12 Diagram of the model PHEM from TU-Graz (Source: Hausberger et al 2002)

The actual engine power can be calculated according to 6 elements:

$$P = P_{rolling\ resistance} + P_{air\ resistance} + P_{acceleration} + P_{road\ gradient} + P_{transmission\ losses} + P_{auxiliaries}$$

Each of the power elements is a function of dynamic variables such as speed and acceleration and a large number of static variables such as vehicle mass, loading, wheel dimension, road gradient … and other coefficients. The actual engine speed is a function of vehicle speed, the wheel diameter and the transmission ratio of the axle and the gear box, as shown below:

$$n = v \times 60 \times i_{axle} \times i_{gear} \times \frac{1}{D_{wheel} \times \pi}$$

Where:

n is the engine speed

i_{axle} is the transmission ratio of the axle,

i_{gear} is theratio of gear box,

D_{wheel} is the diameter of the wheel.

The power losses between the engine and the wheels are simulated as a function of the actual power, the engine speed and the transmission ratio.

PHEM allows users to define vehicle characteristics in detail although the default values are given for 'average' vehicles which comply with European emission legislation.

CMEM

The Comprehensive Modal Emissions Model (CMEM) is based on engine power, developed by the University of California, Riverside. CMEM uses a physical power-demand modelling approach based on parameterised analytical representation of emissions production (Barth et al 1996). In such a physical model the entire emission process is broken down into different components that correspond to physical phenomena associated with vehicle operation and emissions production.

The general structure of the model is that the second by second tailpipe emission is the product of three components: fuel rate (FR), engine-out emission indices ($g_{emission}/g_{fuel}$), and time dependent catalyst pass fraction (CPF), as shown:

Tailpipe emission= FR • ($g_{emission}/g_{fuel}$) • CPF

where

FR =fuel -use rate in grams/s;

$g_{emission}/g_{fuel}$ =grams of engine-out emissions per grams of fuel consumed; and

CPF= the catalyst pass fraction, defined as the ratio of tailpipe to engine-out emissions. CPF is usually a fraction primarily of temperature, engine-out emissions, and air-fuel ratio.

CMEM is composed of six modules, as indicated by the marked boxes (1)- (6) in **Figure3. 13**: (1) engine power demand; (2) engine speed; (3) fuel/air ratio; (4) fuel-rate; (5) engine-out emissions; and (6) catalyst pass fraction. The model as a whole requires two groups of input (rounded boxes in Figure3. 13): A) input operating variables; and B) model parameters. The output of the model is tailpipe emissions and fuel consumption.

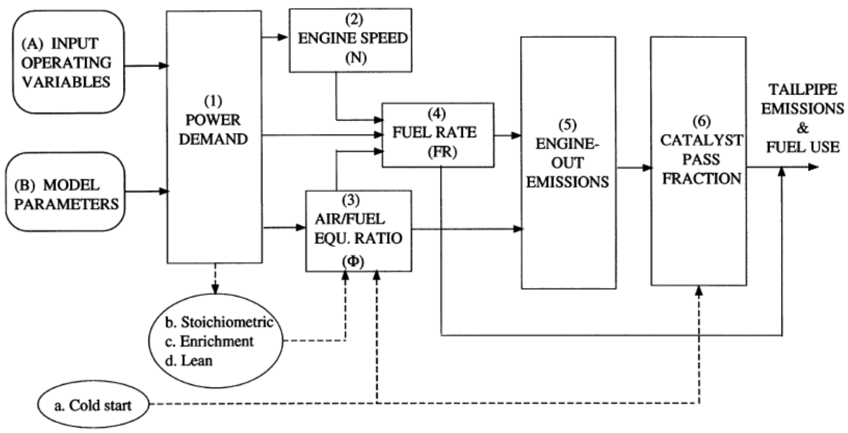


Figure3. 13 CMEM emission model architecture (Source: Barth et al 1996)

The details of theories and functions used in each sub module can be found in the model user manual or the NCHRP Project 25-11 Final report. For user application, the 2 groups of input data are summarised in the **Table3. 6**.

Table3. 6 Operating variables and model parameter input data for CMEM

A) Operating variables	B) Model parameters
θ - road grade (2) P_{acc} - accessory power in hp (3) v - speed trace in mph (2, 4, 5) T_{soak} – soak time (min) SH – specific humidity (grains H_20/lb)	***Specific Vehicle Parameters*** M - vehicle mass in lb. (2) V - engine displacement in liter (12) N_{idle} – idle speed of engine (7) Trlhp - coastdown power in hp (2) S - eng spd./veh spd. in rpm/mph (5) Q_m - max torque in ft.lb (7) N_m - eng spd. in rpm @ Q_m (7) P_{max} - max power in hp N_p - eng spd. in rpm @ P_{max} (7) N_g - number of gears ***Generic Vehicle Parameters*** η - indicated efficiency (12) R(L) - gear ratio (5)

The model parameters in column B can be obtained externally from public sources, e.g. sources of automotive statistics, and are further divided into *specific vehicle parameters* and *generic vehicle parameters*. The *generic vehicle parameters* are ones that may not necessarily be specified on a vehicle-by-vehicle basis, but are rather specified generically for entire vehicle classes. The main input required by A) Operating variables is the speed profile at a fine time resolution.

The CMEM model is usually considered not representative of the UK or European situations, as the vehicle types/fleet and emission standards behind the model are relevant to the United States. Barlow et al (2007) suggested that in order to use CMEM in Europe, a correspondence between the US emission standards and EU emission standards must therefore be established a process which is not straightforward for a number of reasons.

3.3.5.3 Discussion of instantaneous emission models

Instantaneous models are the newest generation of emission models, and the advantages of such models are summarised as follows:

(i) Emissions can be calculated from single vehicles according to their instantaneous speed profiles or engine power profiles.
(ii) Such models are able to capture the emission variation taking into account the driving dynamics; therefore emissions at a small scale can be predicted.
(iii) Such models provide a potential application to identify the ‘hot-spot’ at junction/link levels which will allow air pollution problems to be targeted at more local scales.

However the questioning of instantaneous models always exists due to a number of fundamental problems, mainly due to problems from continuously measuring and sampling process. For example Atjay and Weilenmann (2004) noted that during measurement in the laboratory, an emission signal is dynamically delayed and smoothed, and this makes it difficult to align the emissions signal with the vehicle operating conditions. Boulter et al (2007) stated that it is extremely difficult to measure emissions on a continuous basis with a high degree of precision, and it is not straightforward to allocate those emission values to the correct operating conditions. Until very recently such distortions resulting from signal delays and damping has been taken into account by 2 models, one is EMPA and the other one is PHEM. However these 2 models are still kept within their own research community and are not open to the public.

The literature also shows that the emissions predicted using different instantaneous models can be very different. Due to the complex nature of emission formation, measurement and modelling process, some of these differences can not even be properly explained. For example, a comprehensive evaluation of instantaneous emission models conducted by Barlow et al (2007) compared predicted emissions from 2 instantaneous models MODEM and PHEM (HDV and PC parts) with measured data and found out that relative total errors of 2 models ranged from -62% to +25,476% (p38). The extremely high errors were caused by a few tests which produced very low measured emissions. The relatively large range of relative total errors is partly because the measured emissions were much more variable, with large differences between different tests on the same vehicle driven over the same cycle, and even larger differences with different vehicles over the same cycle, so the measured results would be influenced by the small number of very high values. However even considering the median values only, the relative total error of PHEM and MODEM to the measured results were 169.5% and 163.3% (p38). It also found that both models predicted CO2 and fuel consumption very accurately- in most cases CO2 was within 20% of the measured values. For other pollutants, in some cases one is better than the other and in some other cases vice versa. For example, MODEM model was better than PHEM for CO, HC, NOx from Euro I cars but PHEM was better for Euro III diesel cars. Emissions from heavy vehicles predicted by PHEM appeared to be close the measured results while MODEM did not include heavy duty vehicles in the model database.

Another issue of using instantaneous models, apart from the accuracy and variation concerns is the cost and difficulties of obtaining input data for them. The input data such as instantaneous speed of individual vehicles are not widely available to many users, which consequently has limited the use of such models to the research community. Only recently, the development of microsimulation can be used to partly address this problem.

Nevertheless, instantaneous emission models are still a developing area. There are some associated problems from continuous emission measurement and modelling approaches, however this type of model has its obvious advantages that allow users to identify emission variation from driving dynamics, to estimate emissions continuously, and to observe the emission peaks in terms of specific time and locations.

3.3.6 Considerations when modelling emissions for BSP strategies

The primary consideration when modelling traffic emissions for various BSP strategies is the spatial and temporal scale that emission models are designed and suitable for. Generally it is easier to estimate emissions on a large scale using aggregated emission models as the required input data are relatively easy to obtain. However these models are not capable of modelling the dynamics of emissions at operational levels, where the emissions are dominated by vehicle operating modes rather than average speed. Instantaneous speed models appear to be more suitable for estimating emissions for a small network such as an isolated junction. However these models usually acquire more detailed and extensive input data which has largely limited their application.

Microscopic traffic simulation modelling provides a solution to the data problem as the second-by-second output speed data of single vehicles can be used as input to some instantaneous emission models, especially the 'speed-acceleration' based models. 'Engine power' based models require much more input such as engine speed, max torque, and etc, which are more difficult to obtain in real applications. Therefore microsimulation model can be better linked with 'speed-acceleration' emission models rather than engine power based models. In fact the 'output' and 'input' process of instantaneous speed data can be straightforward, but the credibility of such speed profiles representing the correct driving modes, i.e. acceleration/deceleration rates, is uncertain. As the previous validation/calibration process for micro simulation mostly has been conduced on a macro level by comparing flow volume, link speed, vehicle delays etc, a speed/acceleration profile representing a realistic driving behaviour is crucial for instantaneous emission models; otherwise any potential benefits from using instantaneous models may be lost. Therefore a method to calibrate the distribution of vehicle acceleration/deceleration rates needs to be developed.

3.4 Measurement and modelling of fuel consumption

Fuel consumption refers to the amount of fuel used per vehicle per distance, commonly litres per 100km. Measuring fuel consumption is relatively simple and straightforward. The direct measurement normally utilises equipment called a 'flow metre' or 'volume meter' to estimate fuel in the tank. Numbers of meters needed may vary based on the design of fuel tank and the requirement of precision. The metre normally involves an embedded model to calculate fuel flow from detecting the throttle positions. For example, De Vlieger (1997) measured on-board fuel consumption using the PLU 401-108 apparatus to measure the fuel consumption. It consists of a volumetric sensor and a support system. The sensor is accurate to within 1% in the range of 0.5/60/h-1. The measured volume flow together with the fuel density yields the mass flow.

The modelling of fuel consumption can be based on carbon balance theory. Carbon balance method follows a simple chemical reaction for the combustion of a hydrocarbon fuel (such as petrol, diesel, CNG), shown as follows:

$$\boldsymbol{C_xH_y + (x+y/4)\,O_2 = x\,CO_2 + y/2\,H_20} \quad \textit{(Source: MEET (EC 1999))}$$

where:
CxHy is the fuel (a compound of carbon and hydrogen)
O2 is oxygen from the air
CO2 is carbon dioxide
H2O is water
Therefore the fuel consumption can be derived using the equation outlined below:

$$[FUEL] = (12 + r_1) \times \left\{ \frac{[CO_2]}{44} + \frac{[CO]}{28} + \frac{[HC]}{(12 + r_2)} + \frac{a[PM]}{12} \right\}$$

The fuel consumption modelling in **MEET** adopted this method. The masses of carbon in reactants and products remain the same in accordance with their molecular weight. Because there must be a carbon balance between the total carbon in the fuel and the total carbon in the combustion products, the fuel combustion mass can be estimated from the sum of Carbon products from CO2, CO, VOC, PM, and HC.

A more detailed method was proposed by Akcelic (1982), distinguished fuel consumption according to 4 modes, idling, cruising, accelerating and decelerating. This method was combined in Aimsun as one of its environmental models.

For idling and decelerating vehicles, the rate (in ml/s) can be assumed to be constant.
For an accelerating vehicle, it is given by the formula:

$$F_a = (c_1 + c_2 a v)$$

Where c_1 and c_2 are constants and a and v are the vehicle acceleration and speed respectively.

For a cruising vehicle moving at speed v, the following fuel consumption equation has been determined by Akcelic [AKC82]. It contains three constants: k_1, k_2, and v_m, which need to be determined empirically for each vehicle type.

$$\frac{dF}{dt} = k_1\left(1 + \frac{v^3}{2v_m^3}\right) + k_2 v$$

Where:
v_m is the speed at which the fuel consumed per km is a minimum.

K1 and k2 are determined by equations as below:

$$k_1 = \frac{(F_1 - F_2)v_1 v_2 v_m^3}{180(2v_2 v_m^3 - 2v_1 v_m^3 + v_2 v_1^3 - v_1 v_2^3)}$$

$$k_2 = \frac{2F_2 v_2 v_m^3 - 2F_1 v_1 v_m^3 + F_2 v_2 v_1^3 - F_1 v_1 v_2^3}{360(2v_2 v_m^3 - 2v_1 v_m^3 + v_2 v_1^3 - v_1 v_2^3)}$$

For each time step in the simulation, the state of each vehicle is determined as idling, accelerating, cruising or decelerating. The fuel consumed during the simulation time step, Δt, will then be calculated for each vehicle according to its state using the formulae given in **Table3. 7**.

Table3. 7 Consumed fuel modelling in AIMSUN (Source: AIMSUN)

Vehicle State	Fuel Consumed (ml) during Δt
Idling	$F_i \ \Delta\mathrm{t}$
Accelerating with acceleration a (m/s/s) and speed v (m/s)	$(c_1 + c_2 a v)\,\Delta\mathrm{t}$
Cruising at speed v (m/s)	$(k_1(1+(\frac{v}{2v_m})^3) + k_2 v)\,\Delta\mathrm{t}$
Decelerating	$F_d \ \Delta\mathrm{t}$

Where:

F_i and F_d are the fuel consumption rate in ml/s for idling and decelerating vehicles respectively and constants c_1 and c_2 need to be calibrated.

3.5 Comparison and selection of emission models

3.5.1 Comparison of emission models

From the literature, it is obvious that a large number of emission models have been developed and used for different purposes. It is crucial to find out the best available model for this study. The selection of emission models for comparison and evaluation is based on the following considerations:

(i) The comparison should cover average speed, traffic-situation and instantaneous emission models, because average speed models are the most recognised and widely used tools, traffic situation models are designed for street levels though some drawbacks have restricted their applications, and instantaneous models attempt to model emissions from small spatial and temporal scales which appear to be the state-of-the-art models.

(ii) In order for the model application in the case study, vehicle categories involved in these models should be compared. The main vehicle categories considered in the case are cars and buses, while vehicle types such as trucks, HGVs and LGVs are not included in the case study for simplicity reason.

(iii) For cars and buses, the fleet composition in terms of fuel types and emission legislation should reflect the realist traffic condition for the UK road network, therefore the coverage of vehicle categories should be evaluated.

(iv) The types of vehicle pollutants regulated by Euro emission standards should be covered by all emission models; however there are some discrepancies in pollutant description. For example, total hydrocarbons (THC) and VOCs (or Non-Methane VOCs) are referred interchangeably in different models. This is incorrect as THC would include methane whilst VOC would not. CO_2 have been modelled as direct CO_2 or ultimate CO_2 or both in different models. This may lead to misunderstanding in result interpretation if the exact pollutant elements are not carefully identified.

(v) The requirement of input data is important in selecting emission models. The complexity varies significantly among different emission models, therefore the detailed information demanded by the models should be reviewed and compared.

Nine most commonly mentioned emission models are selected for comparison, ranging from average speed, traffic situation and instantaneous levels. The models are CORPET, MEET, ARTEMIS-Average speed model, ARTEMIS-Traffic Situation model, HB-EFA model, Panis model, MODEM, PHEM and CMEM. These models are compared in terms of vehicle categories coverage (**Table3. 8**), pollutants types modelled (**Table3. 9**) and input data requirement (**Table3. 10**). Precision, accuracy and uncertainty of models are reviewed.

Table3. 8 Vehicle categories covered in emission models (cars and buses only)

			Models								
Vehicle categories	Fuel	Emission legislation	COPERT (AS)	MEET (AS)	ARTEMIS (AS)	ARTEMIS (TS)	HBEFA (TS)	MODEM (Modal)	Panis (MR)	PHEM (EM)	CMEM (PD)
Cars	Petrol	Pre-Euro	×	√	√	√	×	√		√	Not applicable
		Euro I	√	√	√	√	√	√		√	
		Euro II	√	√	√	√	√	√	√ *	√	
		Euro III	√	√	√	√	√	√		√	
		Euro IV	√	√	√	√	√	√		√	
		Euro V	×	×	√	√	×	×		×	
	Diesel	Pre-Euro	√	√	√	√	√	√		√	not applicable
		Euro I	√	√	√	√	√	√		√	
		Euro II	√	√	√	√	√	√	√*	√	
		Euro III	√	√	√	√	√	√		√	
		Euro IV	√	√	×	√	√	√		√	
		Euro V	×	×	×	√	×	×		×	
	LPG	Pre-Euro	×		√	√	×	×		×	not applicable
		Euro I	×		√	√	×	×		×	
		Euro II	×	Average for all	√	√	×	×	√*	×	
		Euro III	×		√	√	×	×		×	
		Euro IV	×		√	√	×	×		×	
		Euro V	×		√	√	×	×		×	
	CNG	Pre-Euro	×	×	√	√	×	×	×	×	not applicable
		Euro I	×	×	√	√	×	×	×	×	
		Euro II	×	×	√	√	×	×	×	×	
		Euro III	×	×	√	√	×	×	×	×	
		Euro IV	×	×	√	√	×	×	×	×	
		Euro V	×	×	√	√	×	×	×	×	
	Hybrid	Euro IV	×	×	√	√	×	×	×	×	×
Buses	Diesel	Pre-Euro	√	√	√	√	√	×		√	not applicable
		Euro I	√	√	√	√	√	×		√	
		Euro II	√	√	√	√	√	×	√*	√	
		Euro III	√	√	√	√	√	×		√	
		Euro IV	√	√	√	√	√	×		√	
		Euro V	√	×	√	√	×	×		√	

AS: Average Speed   MR: Multi Regression   PD: Power Demand

TS: Traffic Situation   EM: Engine Map

* average function for all petrol/diesel/LPG cars and Diesel buses for the 2010 fleet of urban traffic

Table3. 9 Emission pollutants covered by emission models

Emission Pollutants	COPERT (AS)	MEET (AS)	ARTEMIS (AS)	ARTEMIS (TS)	HBEFA (TS)	MODEM (Modal)	Panis (MR)	PHEM (EM)	CMEM (PD)
CO	√	√	√	√	√	√	×	√	√
NOx	√	√	√	√	√	√	√	√	√
HC	√	√	√	√	√	√	√	√	√
PM	√	√	√	√	√	√	√	√	√
CO2 (measured)	×	×	√	√	×	×	×	×	√
CO2 (ultimate)	×	√	√	√	√	√	√	×	√
Fuel Consumption	√	√	√	√	√	√	×	√	√

AS: Average Speed — MR: Multi Regression — PD: Power Demand

TS: Traffic Situation — EM: Engine Map

Table3. 10 Input data required by 9 models

Models	Vehicle emission categories	Average speed	Traffic situation	Instantaneous speed curve	Gear shifting	Torque/ power	Engine speed	Road gradients	Vehicle load
COPERT (AS)	√	√	×	×	×	×	×	×	×
MEET (AS)	√	√	×	×	×	×	×	×	×
ARTEMIS (AS)	√	√	×	×	×	×	×	√	√
ARTEMIS (TS)	√	√	√	×	×	×	×	√	√
HBEFA (TS)	√	√	√	×	×	×	×	√	√
MODEM (Modal)	√	×	×	√	×	×	×	√	×
Panis (MR)	√	×	×	√	×	×	×	×	×
PHEM (EM)	√	×	×	√	*(1)	*	*	√	√
CMEM (PD)	√	×	×	√	*(2)	*	*	√	×

*(1) Gear shitf behaviour is modelled for 3 types of drivers, i.e. fast driver, economic driver and average driver

*(2) Gear ratio is for determing engine speed, can be selected from a set of given gear schedules

* Intermediate data which are determined via instantaneous speed

From the tables above, it can be seen that most emission models are able to calculate emissions for petrol and diesel passenger cars, normally ranging up to Euro IV standard whilst some may cover Euro IV based on prediction. The Panis model uses a unified emission factor for all passenger cars based on a prediction of 2010 UK traffic composition. MODEM is only developed for passenger cars so emission factors for buses are not included. All other models cover diesel buses from pre-Euro to Euro IV. CMEM is based on US vehicle standards so the categories according to Euro standards are not applicable to it.

All regulated emission pollutants are covered by these models except that Panis model does not include CO emissions, as it claimed CO hardly cause any negative effects at low levels ain the open air. Hydrocarbons are usually referred as either total hydrocarbons (THC) or VOCs. There are very few statements in the models to clarify what species of hydrocarbons are modelled, which may become a potential source leading to misunderstanding or misinterpreting the HC results. Fuel consumption is covered in most models except the Panis model. Measured CO2 has not been commonly modelled in current models expect CMEM and ARTEMIS (both AS and TS) models. Details of fuel consumption modelling method are not clearly reported but the carbon balance method is most likely to be adopted in most models.

The required input data for average speed models, as the name suggests are average speed for each vehicle category. It is relatively easy to obtain and simple to use. For traffic situation models, traffic situation is needed in addition which can be matched up by referencing the predefined traffic situations in model database. Instantaneous speed and acceleration rate is compulsory for all the 4 instantaneous speed models. For engine power based instantaneous models the information relating to engine performance, such as engine speed, or gear shifting is needed. However for most models this has been included in some sub-models that can be converted from instantaneous speed.

These tables provide a summary of basic features of these emission models. In order to select the best available model for this study, a trial study was conducted, as presented in the next section.

3.5.2 Selection of an emission model- via a trial study

3.5.2.1 Introduction

From the review to the emission models presented above, 3 models were firstly selected for a testing in a trial study, including an average speed model, a traffic-situation model and an instantaneous model.

Among the 3 average speed models reviewed, ARTEMIS (AS) model uses the similar methodology with COPERT and MEET, but developed and upgraded from MEET and COST 31 Action. COPERT average speed model has been updated recently, also collaborative with ARTEMIS. Therefore the ARTEMIS (AS) model represents the newest and most comprehensive average speed model so far. As average speed models are widely recognised therefore it is necessary to include an average speed model in the trial study as a baseline to suggest an approximate emission level and to compare with other models. As reviewed previously, in the UK, the newly adjusted NAEI model is based on ARTEMIS (AS) model to better represent UK vehicle conditions, therefore NAEI is used for the trial study.

ARTEMIS (TS) model is tested as the state-of-the-art traffic situation model in the trial.

Instantaneous emission models appear to be the most appropriate models for this study. CMEM is available to the public, however this model was developed based on US vehicle fleet and emission standard, which is not compliant to UK or EU situation. Therefore CMEM has to be excluded for this study. For the other 3 instantaneous models, MODEM, Panis model and PHEM model, MODEM was developed based on 1995 vehicle fleet before introducing the EU emission legislation thus the data may not be suitable for the fleet nowadays. In addition MODEM does not include heavy duty vehicles so that bus emissions can not be calculated using MODEM.

PHEM was initially developed for simulating HDV emission factors and now covers passenger cars as well. From model description it appeared to be appropriate to this study as it is an instantaneous model based on engine power which should be more accurate than the speed-acceleration based approach. The passenger car part of PHEM model even adjusted the signal distortion problem existing in most instantaneous models. This model was frequently mentioned in previous reports (e.g. Boulter et al, 2007 and Barlow et al, 2007), however this model had not been made generally available to researchers at the time this comparison had to be made. For the practical reason, it can not be tested and used for this study.

The Panis model compared to other instantaneous emission models is directly available. The advantages of Panis model are that firstly it was developed based on 2010 UK fleet including petrol and diesel cars and buses, and secondly it can be easily integrated with microsimulation models. Therefore the Panis model was used in the trial study.

3.5.2.2 Trial description

The trial study was based on an isolated artificial junction created in Aimsun. To avoid too many potential factors and uncertainty from different sources that may confuse the main test purpose, the junction was kept simple. It is a 2 lane, one way cross roads junction with no turning movements, with lane widths of 3.5m. W-E is considered to be the main road with relatively high traffic flows and N-S road is considered to be minor road with low flows. One bus line is served in one direction along the main road from west to east. The junction is shown in **Figure3. 14** .

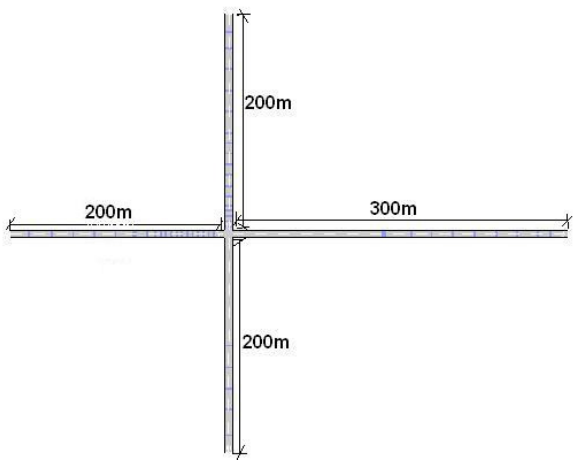


Figure3. 14 Junction layout for trial study for emission model selection

The traffic demand for this study was set to be 1230 cars/hour for the main road and 960 cars/ hour for the side road. This is to represent a free flow situation with degree of saturation of about 0.6, in order to allow implementation of a relatively strong bus priority strategy. Bus frequency was set as 12 buses/ hour (every 5 minutes) to represent a typical headway-based bus service which is commonly operated in big cities such as London. The consideration of vehicle types in this study is simplified for the trial. It assumed that the general traffic was constituted cars only, and all cars were Euro-III petrol, with weight of less than 2.5t, and capacity of 1400cc-2000cc. It assumed all buses were diesel Euro 3 single deck buses, with weight of 15-18t.

3 signal control strategies were simulated, including a baseline signal control with fixed signal timing (noted as ‘BL’), one signal strategy introducing a mild bus priority strategy ‘Green Extension’ (noted as ‘E’) and one introducing strong bus priority strategy ‘Green Extension and Recall’ (noted as ‘E+R’). Using the simulated results from Aimsun, emissions using the 3 emission models were collected, calculated and compared.

3.5.2.3 Results

Four pollutants can be calculated using these emission models, however to avoid confusion, only CO2 emissions estimated under 3 signal control scenarios are illustrated in **Figure3. 15**, **Figure3. 16** and **Figure3. 17.** Other pollutants generally follow the same trend.

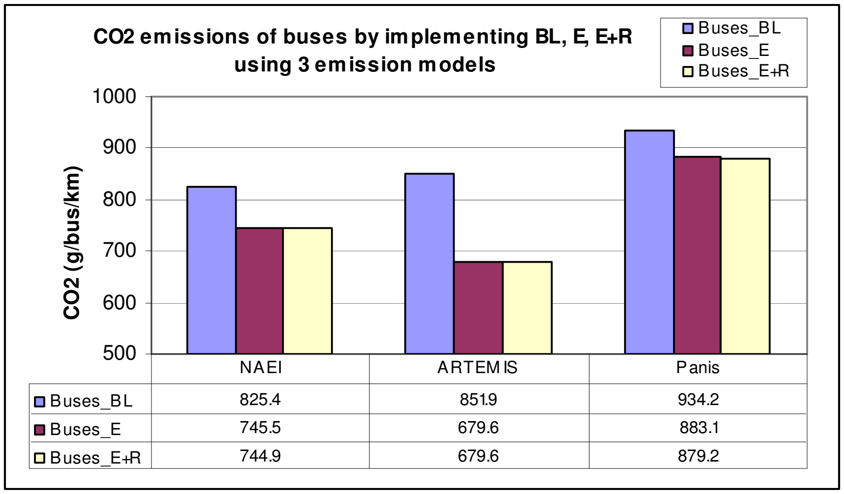


Figure3. 15 CO2 emissions of buses under 3 signal control strategies via 3 emission models

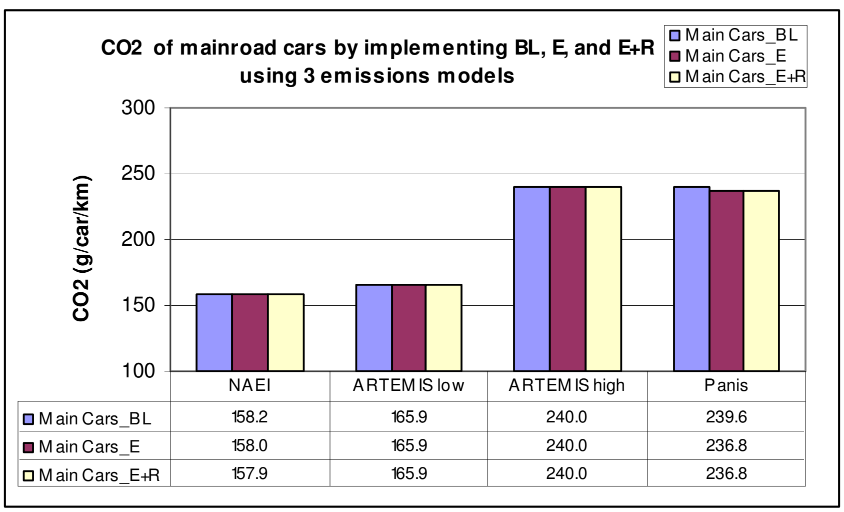


Figure3. 16 CO2 emissions of cars from main road under 3 signal control strategies via 3 emission models

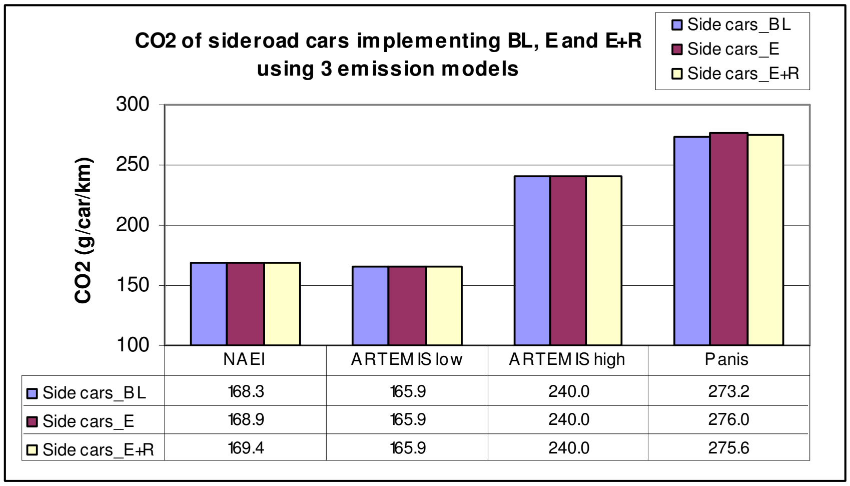


Figure3. 17 CO2 emissions of cars from side road under 3 signal control strategies via 3 emission models

Note that from the figures we can see results using ARTEMIS vary depending on the traffic situations users have chosen. Different choices can lead a big range of emission estimation. For example in this case, 2 traffic situations, named as ARTEMIS low and ARTEMIS high, which both appeared to be suitable for the case produced CO2 emissions with about 45% difference(e.g. for CO2 emissions of cars on both roads, the 2 results are 165.9g/hour and 240.0g/hour).

Results suggested that generally NAEI produced the lowest value and Panis model produced the highest value. This is as expected as it is normally believed that the average speed model underestimated emissions as it neglects the driving dynamics. In this case for a small junction as the accelerating and decelerating behaviour dominates, it could be predicted that the emissions using average speed should be underestimated at a great extent.

These figures also show that ARTEMIS model is not able to capture the changes in emissions when implementing different signal control methods, e.g. bus priority strategies, if the traffic condition has not been significantly affected, e.g. from free flow to heavy condition. NAEI model which uses a continuous polynomial function of average speed can reflect the small changes in speed so as the emissions, however making conclusions for an operational behaviour dominated junction based on the changes caused by the small changes of average speed could be wrong.

3.5.2.4 Conclusions and discussion

From the review and the trial study, firstly we can rule out the option of traffic-situation models, because of the following 2 main reasons:

1. Traffic situation models such as ARTEMIS, attempt to provide a more realistic emission model with consideration of the underlying driving behaviour for different traffic situations, and meanwhile still easy to use and requires less information. However, selecting a proper traffic- situation in the database could be difficult and dangerous. Users need to match up information such as road characteristics, traffic conditions, speed limits, average link speed and etc. to the provided traffic-situations and road classifications. As the results show, the low values and high values of emission factors selected from the database led to a big gap of results. This flexibility can result in misinterpretation and confusion to the results.
2. This type of model is not able to reflect the emission changes caused by the driving dynamics. As the results show using ARTEMIS all 3 signal control strategies produced the same emission result. Therefore in this study the emission dynamics by implementing bus priority strategies at traffic signals can not be correctly modelled.

The average speed model NAEI seems sensitive to the traffic signal control strategies; however it is actually only sensitive to the change of average speed of the link that influenced by the variation of traffic signals. For a network that is dominated by driving operating modes, this type of models could wrongly reflect the emission change. As reviewed in previous sections, average speed models normally apply the polynomial functions to predict emissions against average speed. It is tested in the trial to provide a general benchmark of emission level and should not be used for this study.

Panis model is able to model emissions on a continuous and instantaneous basis. The emissions calculated by this model are the highest compared to the other 2 models. This is as expected because more emissions are supposed to be produced during acceleration mode. The figures above show that this model is able to reflect the emission changes caused by implementing bus priority strategies at traffic signals.

Combining the previous review of emission models and the trial study, Panis model is the best available option, and is therefore used in later study.

3.6 Valuation of air pollutions

Valuation of time in transport economics has been reviewed in Chapter 2. It is based on the concept of willingness to pay in cost-benefit analysis. Valuation of air pollutions is closely related to the environmental economics, so environmental economics is firstly reviewed in 3.6.1. Then the approach of valuing air pollutants is presented in 3.6.2.

3.6.1 Environmental economics

A brief review on the fundamentals of environmental economics is presented here. According to Callan and Thomas (2000), ‘Environmental economics is concerned with identifying and solving the problem of environmental damage, or pollution, associated with the flow of residuals. Although pollution is defined differently in different contexts, it can be defined generally as the presence of matter or energy, whose nature, location, or quantity has undesired effects on the environment.’ Cost-Benefit Analysis (CBA), as reviewed in chapter 2, is probably the most widely known procedure for the analysis of economic efficiency, it is also currently considered for the assessment of environmental effects. In valuing the environmental impact of a project, the concepts of cost and benefit can be defined in different ways. The valuation of environmental effects can be complex due to the limited understanding of to what extent and what kind of environmental effects should be valued. The concepts of cost and benefit within environmental economics can be interpreted in different ways with different concerns.

In early work conducted by The Organisation for Economic Co-operation and Development (OECD) (1974) it clarified that the cost concept employed should depend upon the question to be answered, and the ways of measuring cost could be done via total investment outlays, the total expenditure demanded for pollution control operation and the total annualised costs. Schulz and Schulz (1999) pointed out that for a CBA assessment taking into account environmental effects, the monetary assessment of environmental effects can be carried out on the basis of a cost-of-damage-abatement approach covering noise and exhaust-gas pollution, the separating effects of thorough fears on pedestrians, and the deterioration of living conditions and communications. Due to the complex nature of environmental effects, it is difficult to give sensible money values to pollution, or noise or other effects. Therefore during the previous decades, the environmental factors included in CBA were in non-monetary forms. Even now the method of quantifying the environmental effects is still at large extent subject to assumptions and uncertainty.

Within this context, a method for approximating the impact of changes of air pollution called damage cost was introduced by Defra (2006) to suggest a range of money values for air pollutions, as reviewed in the next section.

3.6.2 Damage cost

Damage cost is the state-of-art method to approximate the monetised values of air pollution. These values of the damage are considered in terms of impacts and damages the pollutant has on human health, materials, and crops.

The damage costs aim to reflect the marginal damage costs of pollution, i.e. the additional marginal effect of one extra tonne of pollution (or the removal of one extra tonne of pollution). The costs are expressed as cost (£) per tonne of pollutant emitted, or the converse, the benefit (£) per tonne of pollutant reduces. The methodology can be used to value the benefits of air quality impacts of certain policies or projects when the only information available is the amount (in tonnes) of pollutant that is reduced or increased.

This approach applied a multi-disciplinary assessment conducted by 11 interdepartmental organisations including Defra (Department for environment, food and rural affairs), Department of Health, Department for Transport, Department of Trade and Industry, and etc. Impacts and damages (£) per tonne for the pollutants PM10, SO2, NOx, and VOCs have been derived for the UK (for UK damages) accounting for variation in the location and type of emission.

It should be noted that the damage cost should be used with critical review and the high uncertainty needs to be addressed. A list of caveats has been given in the report (Defra 2006) for any application as the damage cost method is based on a number of assumptions, and a number of other important effects have not been included in this approach. It addressed that the use of damage cost estimates is only recommended in certain circumstances, e.g.:

> ‘• as part of a filtering mechanism to narrow down a wide range of policy options to a smaller number that are then taken forward for more comprehensive assessment;
>
> • where air quality impacts are expected to be ancillary to the primary objectives. ’

Due to the great deal of uncertainty, the damage costs use a range of values (from low to high) incorporating different assumptions. For example the range of values for PM contains 3 different assumptions in terms of the different concentration-response functions for the chronic mortality effect of particles (i.e. a low central and high estimate of concentration of 1%, 6% and 12% per 10ug.m^{-3}), different lag times for the chronic mortality effect (i.e. zero and 40 year lag) and a range of monetary values are included in the central values recommended for hospital admissions. **Table3. 11** shows the damage cost set out in the damage cost guidance by Defra (2008). It is advised that these values should be used as estimates for the annual pulse approach. These values are per tonne of pollutant (reduced) in 2005 prices, split out by pollutant type and by sector, for PM. It is recommended applying an increase of 2.5% per annum (in line with the Treasury Green Book) to adjust for prices. Details of prices for other pollutants can be found in the report.

Table3. 11 Damage cost values (by pollutants and sectors) Source: Defra 2008 (IGCB(A))

Values in £ per tonne	**Annual pulse damage costs**		
(2008 prices)	*Low*	*High*	*Central*
PM (Transport)[7]	34,753	50,439	44,430
o Central London	158,820	230,508	203,048
o Inner London	163,338	237,065	208,824
o Outer London	106,691	154,849	136,402
o Inner conurbation	84,449	122,568	107,967
o Outer conurbation	52,478	76,163	67,090
o Urban big	62,555	91,791	79,975
o Urban large	50,391	73,137	64,424
o Urban medium	39,618	57,501	50,651
o Urban small	25,022	36,316	31,990
o Rural	10,773	15,636	13,773
PM (ESI)	1,738	2,522	2,222
PM (Domestic)	20,157	29.255	25,770
PM (Agriculture)	6,951	10,088	8,886
PM (Waste)	14,944	21,689	19,105
PM (Industrial)	19,071	26,228	23,103
NO_X	681	993	875
SO_2	1,208	1,698	1,496
NH_3	1,407	2,050	1,884
SPC	22	29	24

DfT report 'Guidance on value for money' (2006) suggests some central values for emission valuation for transport projects (all in 2000 prices), using the Defra recommendation at that time. However it stated that those values were reviewed by Defra, so the values as shown in **Table3. 11** are considered to be more up-to-date.

The value for CO2 is modelled by a different method mainly considering its effect on climate change rather than the damage to human health, material or crops. The carbon price within EU emission trading scheme Phase II was suggested as over 20 Euro/tCO_2 in the first half of 2008 (Committee on Climate Change (CCC), 2008, p. 149). The average price was 22 Euro/tCO_2 in the second half of 2008, and 13 Euro/tCO_2 in the first half of 2009. The carbon price given by DfT report 'Guidance on value for money' was £70 per tonne of carbon (2000 prices), uplifted by £1 p.a. thereafter.

The Stern Review (2006) suggested that the current treatment of carbon significantly undervalued the cost of carbon. The review suggested a cost of $85 per tonne of CO2 roughly equating to £240 per tonne of carbon and that carbon emissions should be appraised using a near-zero discount rate on the grounds of intergenerational equity.

3.7 Summary

This chapter has providede a detailed review on emission measurement and modelling approaches. Four levels of emission models are reviewed including emission factor models, average speed models, traffic situation based models and instantaneous models. Generally emission factor models are used for emissions from macro scales, such as national or regional emissions from all vehicles for a long time period, e.g. 1 month or 1 year. Emission factor models normally require the total traffic volume and total vehicle-kilometres travelled by all traffic. Average speed models are based on speed-related emission functions generated by the measurement of the emission rates over a variety of trips at different speed levels. This type of models is widely used on a road network scale. Barlow and Boulter (2009) summarised that *'a number of factors have contributed the widespread use of the average-speed approach. For example, it is one of the oldest approaches, the models are comparatively easy to use, a number of models are available free of charge, and there is a reasonably close correspondence between the required model inputs and the data generally available to users'*. The main limitation of average speed is they can not capture emission variations caused by the operational differences. Traffic situation models appear to be suitable at a low spatial scale, normally refers to a street scale. Users need to match the characteristics of their target roads, streets or links to those predefined traffic-situations in the database. However, as Boulter et al (2007) stated that asking the user to define the traffic situation using a textual description of speed variation or dynamics may lead to inconsistencies in interpretation. Instantaneous emission models are considered as the state-of-the-art generation of emission models. They can calculate emissions on a second-by-second basis considering both speed and operating status. Instantaneous emission models require detailed and precise information on vehicle operation and instantaneous kinematic data, such as second-by-second speed and acceleration data. Obtaining such data was difficult for many users in the past which has largely restricted the development and their applications. One solution to this problem is using microscopic traffic simulation models to generate the required model inputs. However the questioning of instantaneous models always exists due to a number of fundamental problems. The main problem is the signal delays and damping in emission measuring and sampling process which leads to emission distortions and incorrect assignment of emission factors.

A comprehensive comparison between 9 most widely referred emission models has been made in terms of 3 aspects, respectively listed in **Table3. 8** to **Table3. 10**. The comparison provides the guidance for selecting the most applicable emission models for later case study.

NAEI model, ARTEMIS (TS) model and Panis model were tested in a trial study, and Panis model appeared to be the best available emission model for this study.

CHAPTER 4
MODELLING BUS PRIORITY VIA MICROSCOPIC SIMULATION

The first part of this chapter describes the selection procedure for a microsimulation tool for modelling BSP, and Aimsun is considered to be the most appropriate option for this study. The validity of Aimsun was then tested from 3 aspects and some parameters were calibrated The modelling methodology for the traffic signal control in Aimsun, including the baseline VA signal control and 2 bus priority strategies are described in 4.3 and 4.4.

4.1 Microscopic simulation

4.1.1 Why microsimulation?

Three potential approaches for modelling bus signal priority have been reviewed in chapter 2, which are field measurement, macroscopic simulation and microsimulation. Microscopic simulation appears to be the only option with the capability for bus priority modelling for this study. It is important to first understand what micro-simulation offers in relation to traditional modelling approaches. A guideline proposed by Highway Agency (2007) states that *'micro-simulation modelling is the best suited to the modelling of situations where there are many interactions between individual elements of the network and driver behaviour.'* In such situations, traditional models and empirical approaches have limitations.

Field measurement and macroscopic modelling approaches are not appropriate for this study, due to the following reasons:

(i) A number of traffic scenarios need to be modelled in this study, including different combinations of traffic flows, bus frequencies and priority strategies. Therefore it is impractical and costly to conduct a before-and-after study for each scenario on-street. In addition, for a real experiment at a junction, the main evaluation indicators, i.e. journey time and emissions, may be influenced by other real-world factors, such as characteristics of specific layouts, gradients, pedestrian movement, unexpected incidents, turning movement and etc. It can be difficult to isolate the impacts of implementing bus priority strategies from other factors.

(ii) The traditional field measurement facilities (loops) can only detect vehicle speed discontinuously at detection points which can not be related back to individual vehicles; therefore the change of speed profile of each vehicle can not be identified. These speed data are not fine enough for emission modelling using instantaneous models for this study. Macroscopic modelling approach has to be excluded due to the same reason.

(iii) As discussed in chapter 3, real world emission measurement is not applicable for this study. This means that if using field measurement for BP implementation, the measurement should be able to provide the required input data for emission modelling, i.e. continuous speed data of each individual vehicle, including buses and passenger cars. It might be possible to obtain speed profiles from buses with GPS fitted, however it is extremely difficult or impractical to measure the continuous speed profiles for individual cars with adequate sample size.

Similarly, the common traffic modelling packages (TRANSYT, LINSIG etc), known as macro modelling tools, which can provide an aggregated efficiency output, are not able to provide input for emission modelling.

Compared with the other 2 evaluation approaches, i.e. field measurement and macroscopic traffic simulation, the microscopic traffic simulation is able to model bus signal priority strategies and its capability to output dynamic and individual vehicle trajectories enables the integration with instantaneous emission models. Microscopic traffic models are considered to be the most appropriate approaches for this study, due to the following reasons:

(i) Due to the dynamic and individual features of micro-simulation models, they allow users to create any signal control plans for any intersections, either using fixed timing, or actuated control logic (e.g. NEMA methodology) or any external control plans via API (Application Programming Interface) functions and C++ or python languages. For this study, the API functions provide a platform for realising user defined baseline signal control plan (in this case is VA D-System) and bus priority strategies.

(ii) In microscopic simulation models, a detector is modelled as a device with a set of capabilities for users to select to imitate capabilities of real detectors, basically including functions like vehicle count, presence, speed, occupancy and headway for passing vehicles. Most simulation models also provide an option for detectors to distinguish buses from general traffic if buses are set as equipped vehicles.

(iii) In the micro-simulation modelling process, the dynamic and individual travel profiles for each vehicle can be retrieved so that the integration of instantaneous emission models can be further introduced.

Micro-simulation models have become very popular in recent years, and they have been used for a number of purposes. They can especially provide a good test-bed to explore and illustrate the predicted impacts of traffic management schemes before potential implementation on a street. In chapter 2, three widely used microsimulation packages were reviewed; the following content presents a review of the selection criteria and process.

4.1.2 Selection of a micro simulation model-Aimsun

As reviewed in chapter 2, three most widely used packages, i.e. VISSIM, AIMSUN and PARAMICS have been indentified and relevant details have been reviewed. The selection was conducted at the beginning of this study therefore the comparison of their capabilities and features mainly referred to the versions at the time if not mentioned otherwise.

To select a proper simulator for this study, several comparison reports/ papers on microsimulation were reviewed. SMARTEST (Bernauer et al 1997) conducted by University of Leeds sought to identify the gaps between model capabilities and user requirements. The authors concluded that a good micro-simulation model in the future should be comprehensive so that it has the capabilities of not only dealing with common traffic problems but also modelling various ITS functions as well. They also noted the need to calibrate the models. Almost during the same period, Schmidt (2000) conducted a comparison of four widely-used simulation models CORSIM, AIMSUN, INTERGRATION and CONTRAM I. The outcome of the study was a set of recommendations for the use of simulation models in the future. It pointed out that the micro simulation models, if properly calibrated, could be very useful in understanding the dynamic nature of traffic though they take time handling the input.

Research carried out by University of Minnesota (Xiao et al 2005) produced a methodology in selecting a microscopic simulator via comparative evaluation of AIMSUN and VISSIM. The authors presented a simulation model selection process took into account quantitative and qualitative criteria. The qualitative evaluation process included functional capabilities, input/output features, ease of use and quality of service. Quantitative evaluation considerations included accuracy, completion efforts and the parameters involved. They also presented a grading scheme in order to reduce subjectivity in the evaluation process. It concluded that both simulators were able to model most of the standard traffic modelling requirements. Results from a case study indicated that

> *'there are only some minor differences in the features and accuracy of the models'.*
>
> The author also addressed that *'the selection of a simulator by different users even for the same site may lead to the selection of different simulators. One reason is that evaluation process is subjective affecting*

> *the grades of all criteria, and the other reason is different needs dictate different weights by the users further differentiating the simulators'.*

A comparison study for 3 widely used microsimulation software in the US was conducted by Jones et al (2004). It covered CORSIM, the most widely used micro simulation in the US for nearly 30 years; SimTraffic, using many of the same driving behaviour models as CORSIM but with a better interface; and AIMSUN with an additional dynamic trip assignment and ITS modelling function. The authors concluded that

> *'AIMSUN is the most sophisticated of the 3 models, providing advanced features not found in either CORSIM or SimTraffic. But validation and calibration are also essential for producing reliable results.'*

Diakaki et al. (2003) applied Aimsun to investigate the TUC (Traffic responsive Urban Control) performance. In addition to examining traffic-responsive control and its advantages in saturated traffic conditions, the work also examined priority control for transit vehicles in a coordinated urban traffic control systems, covering green extension and red recall facilities. This work demonstrated the capability of Aimsun in simulating advanced traffic signal control strategies which is needed in this study.

Another comparison study between PARAMICS and AIMSUN was conducted by Tan (2005) based on a Singapore case study. The simulation tools were compared in 6 aspects: user interface, network modelling capabilities, traffic behaviour, statistical output, runtime performance, and other advanced features. In this paper, author showed the preference on PARAMICS over AIMSUN in its visually realistic graphical animation, better integration of different functional modules, and offering a much more comprehensive API for modelling of advanced ITS functions. AIMSUN showed its strength in the ease of network coding, modelling bus transit systems, and basic functions in express way traffic management system. However it also concluded that 'the ITS simulation software market is dynamic. Updated versions and additional plug-ins are constantly being released by developers. For a project with a different expectation or evaluation criteria, a different choice of simulation tool may be possible.'

From the literature, it can be concluded that among the 3 micro-simulation models, AIMSUN, VISSIM, and PARAMICS, each of them has been chosen as recommended tool for different purposes of research. However AIMSUN appears to be a more recommended choice in transit modelling, advanced traffic signal control modelling and the open coding interface for users. It also highly suggested that selection needs to be based on particular research purposes, and different requirements to the simulation tools may lead to a different choice of simulator.

For this study, a micro-simulator must be able to model the following 4 main parts:

- Bus detector modelling
- Bus signal priority strategies modelling;
- Fixed and vehicle activation signal control modelling;
- Integration with emissions and fuel consumption modelling.

Other secondary aspects include:

- User friendly interface;
- Ease to use;
- Available output provided; and
- Programming requirement.

According to these criteria, a brief selection procedure was conducted at the early stage of this research by comparing VISSIM, AIMSUN, and PARAMICS, mainly focusing on the details of their features, driving behaviour models adopted, input required etc. Comparison relating to interests of this study is shown in **Table 4. 1**.

Table 4. 1 Comparison of simulation software VISSIM, AIMSUN, and PARAMICS

MAIN REQUIREMENTS			
	VISSIM	**AIMSUN**	**PARAMICS**
Provide bus distinguish detection?	YES	YES	YES
System can identify, store and track bus ID detected?	Unknown	Yes, though indirectly accomplished by API functions.	Unknown,
Able to model vehicle actuated signal control plans?	YES VAP (Vehicle Actuated Programming) program with about 60 functions. VisVAP signal for creating user defined control flowchart	YES NEMA implemented as default ; can also model external control logic Via API module including large number of functions (about 280).	YES API and large number of functions
Able to simulate Bus priority?	YES Using detectors to identify the bus and VAP and VisVAP to programme priority signal control	YES Using detectors to identify buses and programme any signal control plan in API module	YES Using detectors to identify the bus and programme any signal control plan in API module
Environmental module provided?	YES, But need to buy extra license for the module. Environmental module is based on QUARTET and MODEM project	YES Default module is instantaneous models of MODEM and Panis.	YES emissions data provided by the TRL, Details not clearly stated
Able to integrate new emission models?	Unknown. The Plug-in interface unknown.	New model can be programmed via API.	Unknown
OTHER REQUIREMENTS			
Programming language in use is:	VAP	C++ and Python	VB
Quality of representation to driving behaviour models	Limited info. Car-following and lane-changing models in German.	Very detailed description of driving behaviour models.	Limited information
Needed output available?	YES	YES	YES
User friendly interface?	YES,	YES, Realistic graphical display, Multi-scenarios for one network.	Limited information
Open secondary develop environment?	Limited information	YES, Provides the exact environment as the developer use	Limited information

According to the review on related modelling study and comparisons listed **Table 4. 1**, Aimsun is capable of modelling all of the proposed requirements, especially appears more powerful than others in modelling bus priority and integrating with emission models. For some other specific traffic functions which have not been included in the released versions, it provides an open environment to users for any further development for their own interests and study requirements. Therefore Aimsun was selected for this research.

4.2 Testing the validity of Aimsun simulation model

During the last 3 decades of development and examination, the reliability and capability of microsimulation models have improved significantly and received more recognition. However, as a microscopic simulation model, though the driver behaviour models have been continuously modified towards a more realistic representation, the limitation from its innate characteristics cannot be ignored, which is the nature of complexity of driving (human) behaviour. There are many parameters in microsimulation models provided by means of distributions which may lead to a certain level of uncertainty and inaccuracy in the results. Although the default parameters are provided as global values based on huge validation and calibration processes, for the requirement of accuracy and precision, there is always a necessity of careful calibration for each specific project involving simulation.

4.2.1 Introduction

Validation and calibration is crucial to any microsimulation projects in order to obtain sound and reliable simulation results. The general idea is to assess how close the simulated results are compared to the real world situation and how to modify the results by adjusting the related model parameters. Rakha et al (1996) attempted to propose a clear definition for verification, validation and calibration for microscopic simulation models, as follows:

‘*Model verification*’ is defined to be the process of determining if the logic that describes the underlying mechanics of the model, as specified by the model designer, is faithfully captured by the computer code. Model verification therefore determines if, independent of the validity of the logic or the theory from which the logic is derived, the corresponding computer program produces the desired outputs (in terms of accuracy, magnitude, and direction).

‘Model validation’ is considered to be the process of determining to what extent the model’s underlying fundamental rules and relationships are able to adequately capture the targeted

emergent behaviour. In other words, can car- following, lane-changing and gap acceptance rules utilized by the model produce the corresponding capacities, queue sizes, speed distributions and weaving effects.

'Model calibration' is the adjusting process for validation. It is the process to modify the default input parameter values, that describe the underlying mechanics, in order to reflect the observed local traffic conditions being modelled, and thereby generate a model that more closely reflects real-world conditions. '

There are several validation methods for micro-simulation models, and traditionally it is done by comparing 2 sets of output data, primarily including traffic volumes, speeds, travel times, and queues. One data set is from the real data collection and the other from simulation. Calibration is processed via a 'trial-and-amend' procedure of modifying behaviour parameters, such as headway factors, reaction time, lane changing variables, and etc, to finally obtain a best representative model.

From the previous chapters, it has been explained that in this study most concerns about the output are:
1) If the simulation model is able to generate reliable results on bus delay savings when implementing the proposed bus signal priority strategies, and
2) If the vehicles' individual driving behaviour, i.e. the individual and instantaneous speed-time profiles, are valid to produce accurate emissions.

The methods to calibrate and validate Aimsun for this study were developed and decided in the early stage of this PhD study, considered in conjunction with the later case study. An artificial junction was considered to be the best available option for this study, due to a number of reasons described in Chapter 6. Therefore for this study, the validity of Aimsun was examined from 3 levels. Firstly, vehicles' individual acceleration and deceleration rates produced in Aimsun should be valid in terms of the distributions of the maximum values. This is to ensure the validity of the emission results calculated using emission models which apply acceleration and deceleration as a key factor. Secondly the saturation flow of a given road, as a general and overall indicator of the validity of a microsimulation model, should be valid. Thirdly, the output of implementing bus priority strategies, i.e. the delay savings buses can obtain from different strategies should be valid. Calibration and validation from these 3 aspects are presented in the following section.

4.2.2 Calibration of vehicle parameters on a micro level

Vehicle parameters such as acceleration and deceleration rate are crucial in emission prediction using instantaneous emission models. The traditional approach of calibration may to some extent have neglected the validity of vehicle behaviour at a microscopic level such as vehicles' instantaneous and individual speed and acceleration, which consequently has restricted the applications in instantaneous emission models, due to accuracy and credibility issues. This part reviews some state-of-art method for calibrating such parameters for cars and buses, so that a more realistic and reliable instantaneous speed profiles can be generated in Aimsun.

4.2.2.1 Literature on calibration of car parameters at micro level

Few studies have been done on calibrating and reproducing traffic phenomena at the microscopic level, largely due to difficulties and cost in collecting field data at this level. This is now starting to change with research carried out to calibrate car parameters in car-following models using GPS equipped vehicles.

Car following models are one of these important driving behaviour models used in microscopic simulation models. In Aimsun the Gipps model (1981) is used and several updates have been released to achieve a better reproduction of real traffic phenomena. One of the most important properties of Gipps car-following model, according to the author, is that 'the parameters in the model correspond to obvious characteristics of drivers and vehicles so that most can be assigned values without resorting to elaborate calibration procedures'. The vehicle parameters in Gipps car-following model comprise the desired speed, maximum acceleration, normal deceleration, maximum deceleration and reaction time. The original values used in Gipps model for the trial simulation are stated as 'reasonable values', as shown in **Table 4. 2:**

Table 4. 2 Original values for vehicle parameters (cars only) proposed in Gipps model 1981

Desired speed (v_n)	a normal distribution, *N (20.0, 3.2^2) m/sec*,
Maximum acceleration (a_n)	a normal distribution, *N (1.7, 0.3^2)m/sec^2*,
Maximum deceleration (b_n)	equated to -2.0a_n,
Estimation of leader's max deceleration ($\hat{b}$)	minimum of {-3.0, (b_n -3.0)/2} *m/sec^2*,
Reaction time (τ)	2/3 second.

Brockfeld et al (2003) calibrated and validated 10 car-following models using the same set of GPS data recorded on a test track in Japan. A comparison study was then performed to identify the difference among models. Punzo and Simonelli (2005) investigated the performance of 4 microsimulation models, including Gipps model after calibrating the model parameters using real GPS data. The parameters for Gipps model (used in Aimsun) proposed in this study, based on data from urban roads in Naples Italy are shown in **Table 4. 3.**

Table 4. 3 Values for vehicle (cars only) parameters for Aimsun (Source: Punzo and Simonelli, 2005)

	Mean	Variance
Desired speed (v_n)	16.152 *m/sec*,	*12.280*
Maximum acceleration (a_n)	3.331*m/sec^2*	*4.189*
Maximum deceleration(b_n)	-3.801 *m/sec^2*	*5.949*
Estimation of leader's Max deceleration ($\hat{b}$)	-4.783 *m/sec^2*	10.613
Reaction time (τ)	0.567second	0.024

4.2.2.2 Calibration of bus parameters using iBus data

There has been very limited research on calibration of vehicle parameters for urban buses, although buses are a very important component in the urban traffic system and a big contributor to traffic related emissions. Generally it is perceived that buses have a lower speed, acceleration and deceleration rate compared to cars, but there has not been detailed research on investigating the proper values for bus parameters in Gipps model. Zhang et al (2011) attempted to propose more up-to-date values for bus parameters using iBus data.

(2011) attempted to propose more up-to-date values for bus parameters using iBus data. This paper, which evolved from this PhD research, is included in Appendix X. Three bus-related parameters in Aimsun were calibrated including Maximum acceleration rate, Maximum-normal deceleration rate and Speed acceptance level.

'*Maximum acceleration*' is used in Gipps model as the maximum acceleration a vehicle can achieve under any circumstances.

'M*aximum-Normal deceleration*' is defined as the maximum deceleration that vehicles can use under normal driving conditions, in other words, the comfortable maximum deceleration drivers can use under non-emergency conditions. Generally different drivers have different perceptions of their own limits on max speed, acceleration or deceleration. Among drivers these limits should be normally distributed.

'*Speed acceptance level*' is a parameter used in Aimsun to describe how well drivers are willing to obey the speed limits, or can be interpreted as the 'level of goodness' of drivers or the degree of acceptance of speed limits.

The new values proposed are summarised in **Table 4. 4**.

Table 4. 4 Suggested values for bus parameters in Gipps model and Aimsun software (Zhang et al 2011)

	Mean	Std. Deviation	Min	Max
Speed acceptance	1.03	0.06	0.97	1.09
Max acceleration	1.70	0.21	1.07	2.12
Normal deceleration	2.42	0.35	1.37	3.11

These values are used in the case study in later chapters.

4.2.3 Validation of saturation flow

After the calibration of vehicle parameters on a micro level, it is useful to check whether saturation flow is valid. Saturation flow can be treated as a parameter to reflect the overall performance of the driving behaviour models, mainly the car-following model. Saturation flow is the maximum flow per unit time (usually per hour) across a stop-line, assuming continuous green. It is an integrated indication of several important driving behaviour factors, including vehicle speed, head way distribution and reaction time. Therefore it is assumed that a well functioned saturation flow in microsimulation is representative for a valid driving performance. Saturation flow can be either observed from a saturated road segment or can be predicted by mathematical equations below (Kimber et al 1986). To test the saturation flow for this study, 2 sets of saturation flow, one calculated from the mathematical equation and one collected from simulation are compared.

4.2.3.1 Calculating saturation flow from method by Kimber et al

The method proposed by Kimber et al to calculate lane saturation flow takes into account geometric factors and timing proportions only, including the position of the lane (near or non-nearside), the width of the lane and its gradient, and the radius of any turning movements.

For any unopposed streams, as what the case is, the saturation flow S1 is given by

$$S_1 = (S_0 - 140d_n) / (1 + 1.5f/r) \ pcu/h$$

Where $S_0 = 2080 - (42d_g * G) + 100 * (w - 3.25)$

d_n =1 for nearside lanes and 0 otherwise,

d_g =1 for uphill and 0 otherwise,

G=entry gradient (%),

w= lane width at entry (m),

f=proportion of turning vehicles in the lane,

r= radius of curvature of vehicle path (m).

For the junction in this case study with the lane width for all arms as 3m and no turning movement, the calculated saturation flow for each lane is 1915 pcu /h.

4.2.3.2 Saturation flow from on line simulation observation

The saturation flow data in real world is normally collected via counting the vehicles passing the stop line during effective green time when there is continuous flow. It is obvious that in practice the flow across the stop line can not commence or terminate instantly when encounter the start of red or the end of green. A saturation flow discharge figure (**Figure 4. 1**) is normally used for illustrating the phenomenon, where there is 1.4s ‘start displacement time’ lost at the beginning of green, and 2.9s ‘end displacement time’ can be treated as green time from the end of green till in amber period. Assuming a saturated road segment, vehicles during the period in between can be counted as saturation flow vehicles.

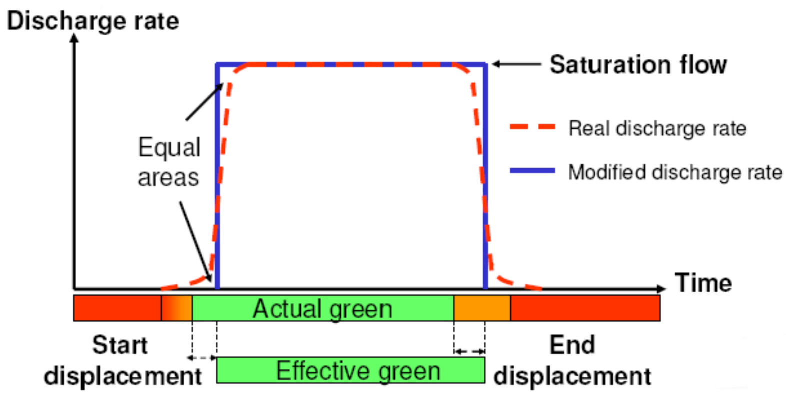


Figure 4. 1 Discharging illustration for saturated vehicles across stop line (source: OSCADY)

To obtain a saturated traffic condition in Aimsun, a very large flow volume was used (e.g. 6000 cars/ hr/lane) to produce continuous traffic flow. A fixed signal timing was used for the vehicle counting, and actual green time for the target flow was 20 seconds. Vehicle counting starts from approximately the 4th second of green time and stops till the end of amber time. The simulation step is set as 0.1 second. For example in one counting interval, the total number of cars crossing the stop line was 20, and the time used is 19.3 seconds, then in this case the saturation calculated is 1865 pcu/h. Repeat the same procedure for 20 times, and the collected saturation flow data are shown in

Table 4. 5.

Table 4. 5 Saturation flow observation in Aimsun

Time commences (mm:ss.0)	Time ends (mm:ss.0)	Time interval (s)	Number of cars	Saturation Flow (pcu/h)
01:40.6	02:00.6	20.0	20	1800
02:29.3	02:48.3	19.0	22	2084.211
03:19.5	03:37.3	17.8	20	2022.472
04:06.9	04:25.0	18.1	20	1988.95
04:55.3	05:13.5	18.2	21	2076.923
05:42.0	06:00.9	18.9	20	1904.762
06:30.2	06:49.8	19.6	20	1836.735
07:45.0	08:05.0	20.0	21	1890
08:35.3	08:55.1	19.8	20	1818.182
09:25.6	09:45.1	19.5	20	1846.154
10:40.3	11:00.6	20.3	21	1862.069
11:29.8	11:48.6	18.8	20	1914.894
12:18.5	12:37.6	19.1	20	1884.817
13:08.0	13:26.5	18.5	20	1945.946
13:59.1	14:19.0	19.9	21	1899.497
15:15.3	15:34.2	18.9	20	1904.762
16:05.6	16:25.9	20.3	21	1862.069
16:56.5	17:15.6	19.1	20	1884.817
17:46.5	18:05.0	18.5	20	1945.946
18:35.8	18:55.4	19.6	20	1836.735
Mean				1910
Std. Dev				79.96
Std. Error mean				17.88

The table shows that from 20 observation data, the average saturation flow in Aimsun is 1910 pcu/h.

4.2.3.3 Comparison and summary

The saturation flow calculated from mathematical formula and from online simulation observation appears to be very close. To test the hypothesis that a sample comes from a population with a known mean but an unknown standard deviation, the one-sample t test is used.

For the following t-test, 1915pcu/hour (μ_0) calculated by the empirical formula is considered to be the hypothetical population mean and 1910pcu/hour (μ_1) from simulation as the observed sample mean.

One-sample t-test:

1). Hypotheses

H0: $\mu_0 = \mu_1$

H1: $\mu_0 \neq \mu_1$

2) Critical area

α=0.05 (two-tailed)

df=19

3) Test statistic

Std. Error mean=17.88

t = (1915-1910)/17.88=0.28

The 2-tailed p-value= 0.78>0.05

4) Make decision

Fail to Reject H0.

Since we have no enough evidence to reject the null hypothesis, we can assume there is no significantly difference between these 2 mean values. This indicates the simulated saturation flow is valid and the basic drive behaviour models in Aimsun are capable to reproduce realistic traffic flows. For convenience reason, 1900pcu/h/lane is used as the saturation flow for signal calculation in later chapters.

4.2.4 Validation of bus delay time

As reviewed in previous chapters, one of the main indicators to assess the performance of bus priority strategies at traffic signals is bus delay saving time. To further confirm the validity of the simulation model, bus delay time before and after bus priority is compared with the delay time calculated from empirical formulae.

The empirical method used here was developed by Vincent et al (1978) to evaluate bus signal priority. This method can be used to predict bus delay savings for a simple two-stage/phase signal controlled junction. The method is briefly described as follows:

The symbols are first defined as:

$\bar{t}$ = average time for a bus to travel from the outer detector to the stop line during the last part of the green stage (secs.)

c = cycle time (secs.)

g_1 = green time for priority stage (secs.)

$g_2 \ldots g_n$ = green time for non-priority stages (secs.)

g_m = minimum green time (secs.)

λ_1 = the proportion of time which is green for the priority stage (i.e. $\lambda_1 = g_1$ /c)

r = period during which a priority call can be initiated (secs.)

b = bus flow per hour on priority stage.

At a junction with 2 stage operation and buses serving on one stage,

For green extension strategy:

The proportion of buses gaining an extension = ($\bar{t}$ -2)/c, allowing for traffic treating the first seconds of amber as being effectively green.

The saving for buses gaining an extension = ($c-g_1$) secs

$\therefore$ The average delay saving = ($\bar{t}$ -2)*($c-g_1$)/c secs/bus

This gives results as shown in **Table 4. 6**.

Table 4. 6 Average delay saving per bus on priority stage due to priority extension

t seconds	λ_1					
	0.2	0.3	0.3	0.5	0.6	0.7
4	2	1	1	1	1	1
8	5	4	4	3	2	2
12	8	7	6	5	4	3
16	11	10	8	7	6	4
20	14	13	11	9	7	5

For recall strategy:

Assuming a Poisson distribution for bus arrivals, the probability (p0 that no buses arrive during a period (r) is :

$$p = e^{-rB/3600}$$

$\therefore$ The probability of one or more buses arriving during $r = 1\text{-}p$

$\therefore$ The proportion of cycles having a priority call, $\beta = 1 - p$

The proportion of buses gaining a priority call = $\frac{3600}{C} * \beta * \frac{1}{B}$

The average saving per benefitted bus = $\frac{g_2}{2}$ secs

$\therefore$ Average delay saving = $\frac{3600}{C} * \beta * \frac{1}{B} * \frac{g_2}{2}$

This gives results as shown in **Table 4. 7**.

Table 4. 7 Average delay saving per bus on priority stage due to priority recall

g_2 (secs)	B (buses/hr)				
	10	20	40	60	80
20	3	2	2	1	1
30	4	4	3	3	2
40	8	6	5	4	4
50	11	9	7	6	5
60	16	13	9	7	6

A trial simulation was conducted to compare the delay saving time from simulation and from the method described above. The trial simulation operates under fixed signal timing with cycle time of 48 seconds. The green time for the bus stage is 23 seconds and for non-bus stage is 15 seconds. Green extension time is 10 seconds, and minimum green required under Recall facility is 7 seconds.

The bus delay saving time calculated by Vincent method and obtained from simulation is summarised in **Table 4. 8**.

Table 4. 8 Bus delay saving time from simulation and from Vincent method

	Bus delay saving (seconds/bus)	
	Vincent method	Simulation
Green extension	[4, 8]	3.86
Recall	≈ 2	1.42

It can be seen that these 2 sets of results are comparable, but the simulated results are slightly smaller than the results calculated from Vincent method. This can be explained by the difference of delay definition by the 2 approaches. In microsimulation, the definition of vehicle delay time takes into account of the time lost when vehicles are accelerating, decelerating or disrupted by red signals, so the delay time ought to be greater than the value predicted by the statistical method. The simulation results on bus delay saving appear to be reasonable and valid, which suggests a valid model from an aggregated level.

4.3 Modelling the baseline signal control plan

Signal control design in this study comprises 2 main parts, the baseline signal control plan for the junction and the bus signal priority strategies. The modelling of baseline signal control plan in Aimsun is presented in this section.

4.3.1 Consideration of study scale

As reviewed in Chapter 2, signal control plans at traffic signals depend on the types of junctions, i.e. isolated or coordinated. For each type there are a number of options to implement, e.g. MOVA for isolated junctions and SCOOT for coordinated junctions. The full bus signal priority strategies are widely applied at isolated junctions. Differential priority strategies are more eligible to be implemented at a large network. The overall benefits of differential priority may be only perceived in a larger road network as the achievement of a better headway or punctuality requires priority at several junctions. However a larger network which inevitably involves more variations (e.g. more complex signal control algorithm, more turning movement, traffic fluctuations, bus stops, and etc) will lead to a complexity that may confuse the objective of this research. This can make it difficult to isolate the effects of bus signal priority strategies from the effects of all the other accompanying factors from traffic variations. Therefore an isolated junction is studied and VA system-D signal control plan and full priority strategies are modelled.

A key potential concern with emissions from bus priority is that, whilst buses should produced less emissions, (smaller) disbenefits to other traffic might outweigh these benefits when aggregated. It is therefore necessary to assess this point, including under ‘unfavourable’ conditions. These include isolated junctions, where the control strategy is less sophisticated/adaptable and the potential for higher than desired disbenefits to non-priority traffic are greater.

4.3.2 Modelling Vehicle Actuation (VA) signal control plan

In theory, there are 2 types of VA signal control plan, the semi-actuated and full-actuated. In semi-actuated signal control, the major traffic movements are the ones active unless there is a conflicting call from a minor movement. Detectors are only required on minor roads. In fully- actuated signal control, all phases are actuated so detectors are required for all movements. Semi- actuated control is normally used where there is a distinguish traffic flow difference which can be found between major and minor movements. In this study, as the traffic flows from both directions are manipulated and varied in order to obtain a set of scenarios, the fully-actuated signal control is used in the case study. This signal control form is actually the most common situation in the UK traffic signalling.

The forms of detectors for traffic were reviewed in Chapter 2, in this study the detectors for general traffic are in form of above-ground detectors, which is able to overlook 39m of the road length from the stop line. At each second, the detectors check if there are any cars in their covered areas and deliver this information to the system to determine the signal status for the next time step.

There are a number of parameters used in VA signal control plan. For the VA system-D, the main parameters include the following:

● *Minimum green:* The minimum green time initially assigned to a phase, which is 7s in practice for safety consideration.

● *Maximum green or Max-Out:* This is the maximum limit of extension for a particular phase. When the green phase extends to this limit, the current phase terminates despite any demand for further green extension. This is the main variable needs to be determined for VA signal timings.

This value can be determined via 2 methods according to traffic signal timing manual (FHWA 2008). One method used by some agencies is to establish the maximum green setting based on an 85th to 95th percentile probability of queue clearance. A second method for establishing the maximum green setting is based on the equivalent optimal pre-timed timing plan. It requires the development of a pre-timed signal timing plan based on delay minimization. The minimum-delay green interval durations are multiplied by a factor ranging from 1.25 to 1.50 to obtain an estimate of the maximum green setting.

● *Seconds per actuation:* This is the number of seconds each time the green period is extended when a vehicle is detected. In the D-system, the value is set as 1s.

● *Passage time:* This is the time allowed for a vehicle to travel at a selected speed from the detector to the stop line. This value is normally set as the same as ‘seconds per actuation', in order to make sure the vehicles detected at a time can be completely cleared before the next detection.

● G*ap-out:* This is the maximum time gap allowed between 2 consecutive detections of vehicles. If there is no vehicle detected when the gap-out limit is reached, and the meantime there is green demand from conflicting movements, the green time for current phase terminates.

The principle of VA signal control is illustrated in **Figure 4. 2**. At the beginning of each phase, a minimum green duration is automatically assigned to the phase (7 seconds in this study). At each simulation step, if the above ground detectors detect any vehicles in their covering areas, then 1 second is added to the current phase duration from the detection time. The decision-making process is operated at the end of each simulation step. If meanwhile there is traffic demand on the conflicting directions but the current phase length is still within the maximum green time, the green signal of this phase stays till next call of 'right of way' from either direction. If there is constant traffic demand on the current phase, but the green duration already reaches the maximum green time allowed, the green signal has to end and switch to another stage, referred as Max-Out. If at any point of time at the current stage there is no vehicle in the detection area, it triggers the Gap-out action, and then the signal changes to the next stage.

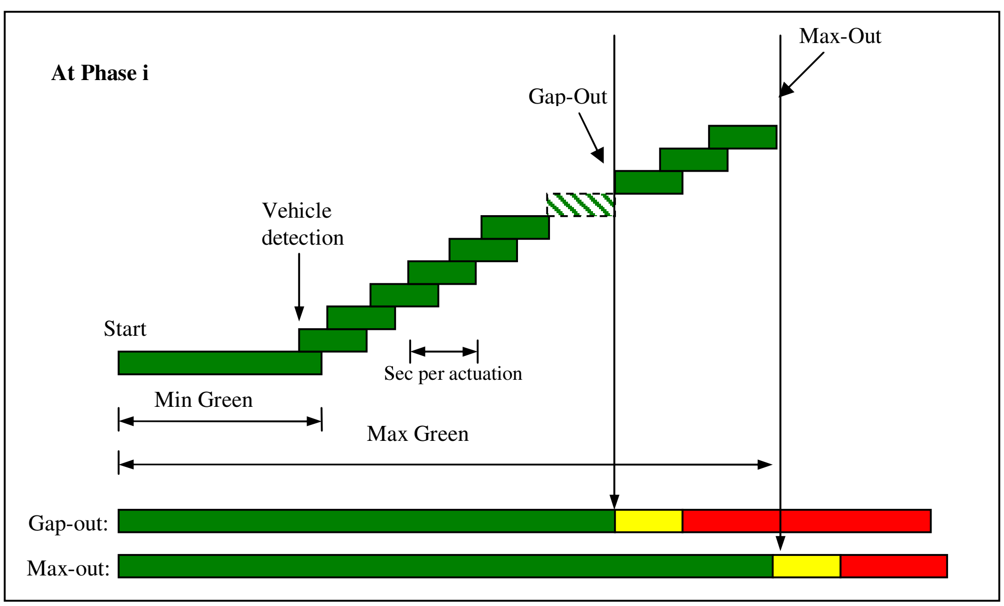


Figure 4. 2 Illustration of VA signal control plan

The VA signal control logic has been programmed into Aimsun in this progress using Python language in Aimsun via the API interface. In microsimulation, the system needs to make a decision every time at each simulation step about the signal status for the next time step and the green duration of the current phase. The logic of determining the signal status and phase duration, taking phase 1 as example is shown in the **Figure 4. 3** flow chart. The determination process applies to the next phase in the same manner. The python codes of VA and BP can be found in Appendix I.

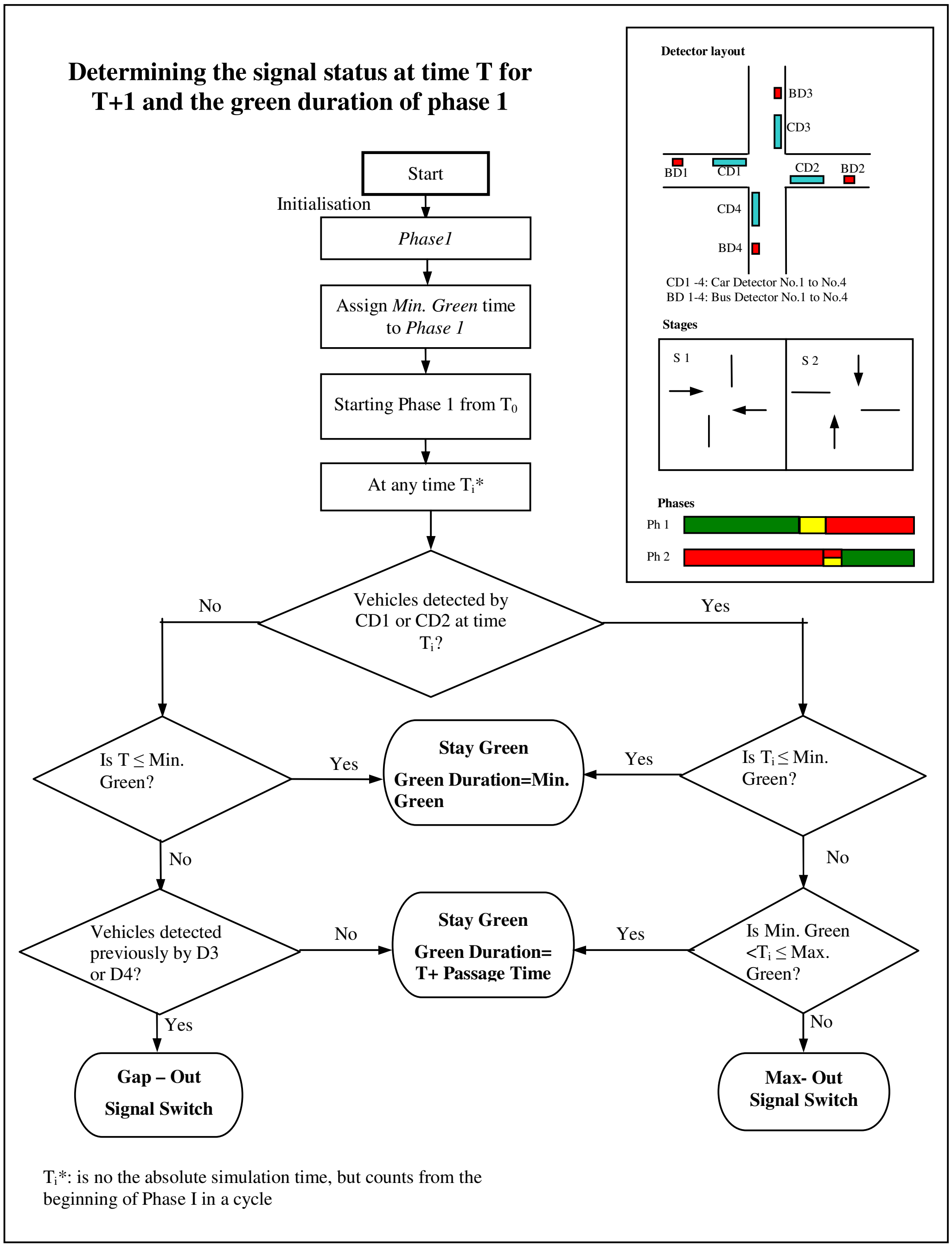


Figure 4. 3 VA signal control logic flowchart

4.4 Modelling bus priority strategies

As reviewed in Chapter 2, 4 basic forms of bus priority, i.e. green extension, recall, compensation and inhibition are modelled. 2 bus priority strategies combing these 4 forms are described below.

- BP1: Green extension + Recall
- BP2: Green extension+ Recall+ Compensation+ Inhibition

4.4.1 BP1: Green extension+ Recall

This strategy contains 2 forms, green extension and recall. Green extension only deals with buses arriving at the bus detector during the green time. Buses arriving at other signal status (i.e. red, amber or red and amber) are not considered. The general idea is to give a fixed green extension time to the prioritised bus to ensure it can pass through the junction without signal delay. When a bus is detected during the current green time, a fixed time period is immediately added to the current green time, even if the new green duration including the added extension time exceeds the pre-defined maximum green time. The green extension time lasts till the last second or the next bus detection within the current extension. After the completion of green extension, the VA signal control of the junction is reactivated. During the green extension time period, VA control is overwritten by the bus priority logic and no longer functions. **Figure 4. 4** shows an example of how green extension works in the VA control environment.

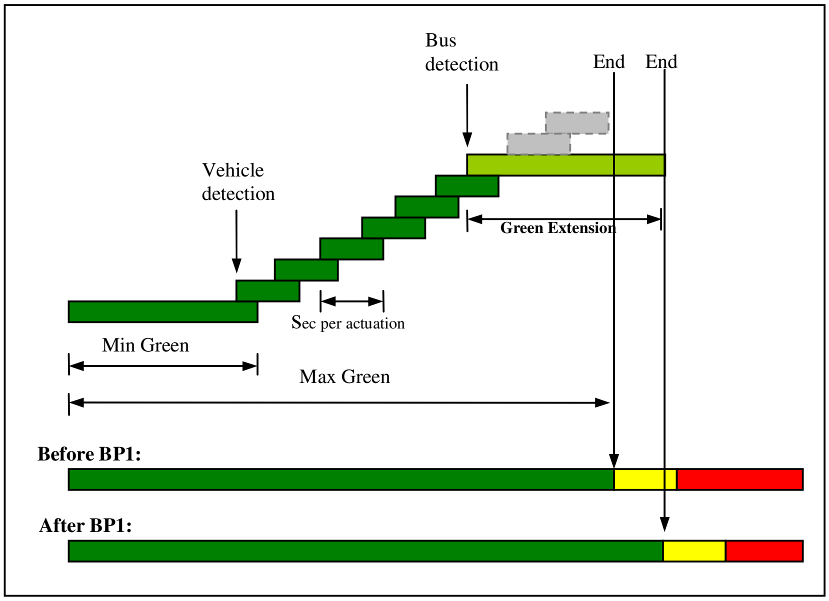


Figure 4. 4 Implementing Green extension in VA signal control

A Recall is activated for buses arriving during a red phase which then require an early green to reduce waiting time at red signals. This strategy truncates the current green time for the opposite traffic regardless of the demand. If a bus is detected during red, the green signal for the opposite traffic immediately stops and changes to amber/red, and then red, therefore the bus only needs to wait for a minimum time for green. **Figure 4. 5** illustrates how extensions and recalls work in VA.

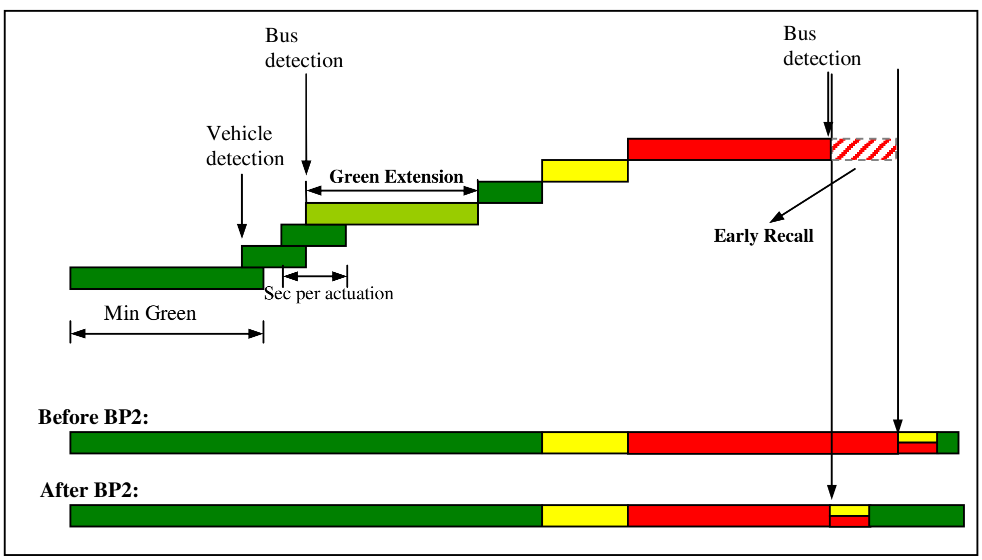


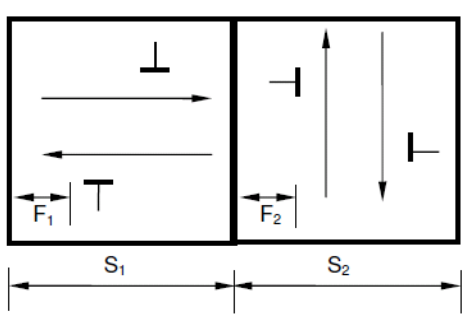
Figure 4. 5 Implementing BP1_ Green extension + Recall strategy in VA signal control

Recalls can reduce bus delay significantly but at the cost of extra delay to opposite traffic. BP2 is a combined control strategy, which is comparatively stronger than BP1. However there are 3 rules when implementing BP2, as shown in below

1). Recall can be only activated after the minimum green period (7s).
2). Recall is implemented together with green extension.
3). BP2 should be only implemented for light traffic flow conditions where no severe side effect, i.e. delay or queues to general traffic will be caused.

4.4.2 BP2: Green extension + Recall + compensation + inhibition

If the side effect to non-priority traffic when implementing the recall strategy is of concern, then compensation and inhibition is necessary, especially for higher traffic flow situations. Compensation and inhibition always operate together to ensure that the time lost to non-priority traffic can be repaid without disruption caused by another recall during compensation time. Compensation is an extension time added to the maximum green duration to the non-priority traffic for the following cycle if recall has been given to a bus in the previous cycle, and meanwhile inhibition should be in action to prevent any further recall during this cycle. However adding the compensation does not necessarily increase the length of green time to the new maximum green every time, but only used if needed. The compensation time length for a 2 stage junction can be calculated according to the method given in the TfL's user guide (2001) for 'Bus Priority- Selective vehicle detection in London (U/2706/TO/382)', as shown below:



Where
S = overall stage length,
F = stage fixed period (i.e. Intergreen + Minimum)

Compensation resulting from a priority call to stage 1 is calculated according to the Formula below (Symbols explained above).

$$C2 = \frac{(S2 - F2)}{2S2} \times (S2 + F2)$$

As the stage length remains under different DoS scenarios, the compensation time also varies accordingly for each DoS scenario.

Inhibition can be treated as a timer to ensure the completion of compensation and prevent any other recalls. Compensation and inhibition lasts for one cycle only. The implementation of compensation and inhibition is briefly illustrated in **Figure 4. 6**.

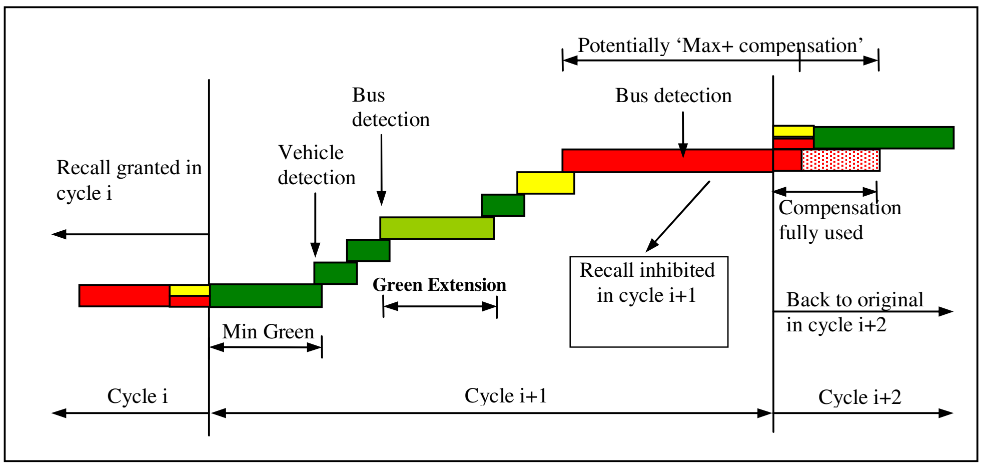


Figure 4. 6 Implementing BP2_ Green extension + Recall + Compensation + Inhibition strategy in VA signal control

4.4.3 Realising bus priority strategies in VA controlled junction in Aimsun

Aimsun applies a phase-based approach in which the cycle of the intersection is divided into phases, where each phase has a particular set of signal groups with right of way at the same time. The duration of a phase is the duration of the green time of the signal groups assigned to the phase. A signal group consists of the set of movements that are controlled by the same indications of traffic lights. **Figure 4. 7** shows an example of the signal groups and phases applied in this case study.

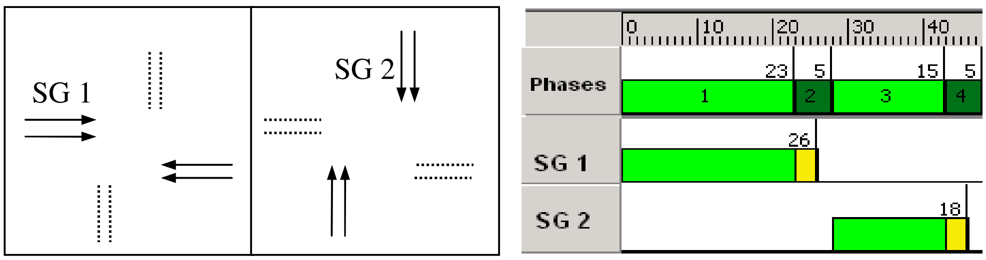


Figure 4. 7 Signal groups and signal phases defined in Aimsun

It shows that the main signal phases are phase 1 and 3, while phase 2 and 4 are the clear-up phases. Aimsun uses the continental signal settings where no 'red/amber' is defined in the signal, therefore red/amber period which applied in UK is best to be modelled as half red and half green time.

The details of 2 bus priority strategies have been described and illustrated in previous sections. The logic of implementing bus priority strategies, BP1 and BP2 in VA is shown in flow charts in **Figure 4. 8** and **Figure 4. 9**. The python coding in Aimsun is programmed according to the logic, and the details can be found in Appendix 1.

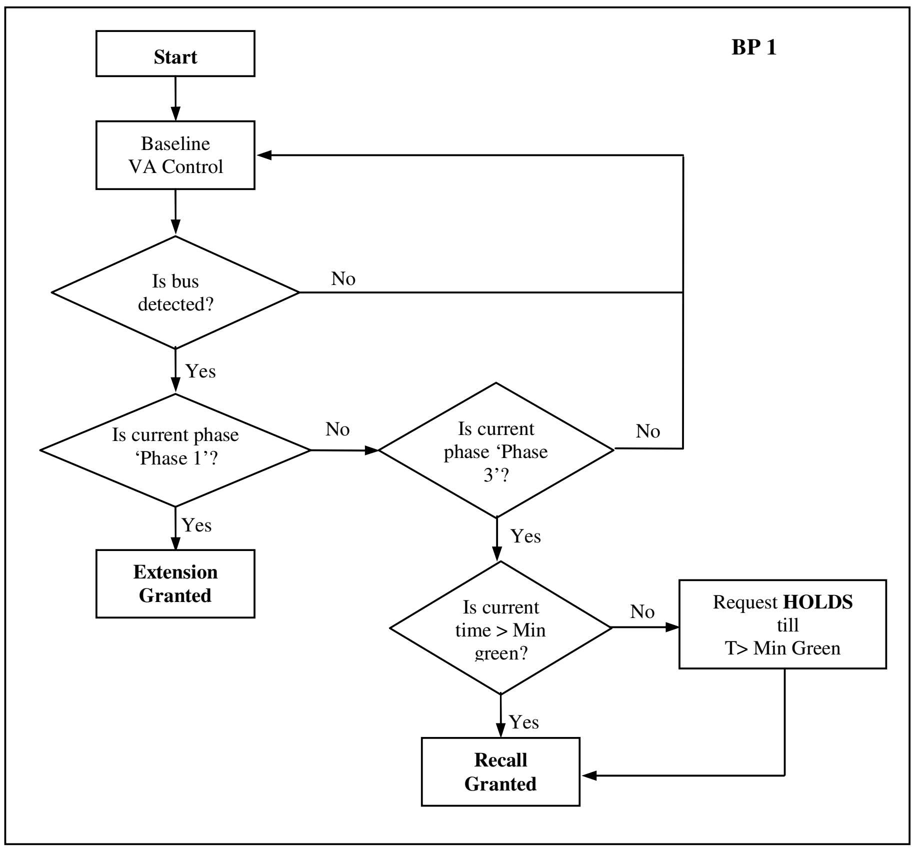


Figure 4. 8 Implementing BP1 in VA control

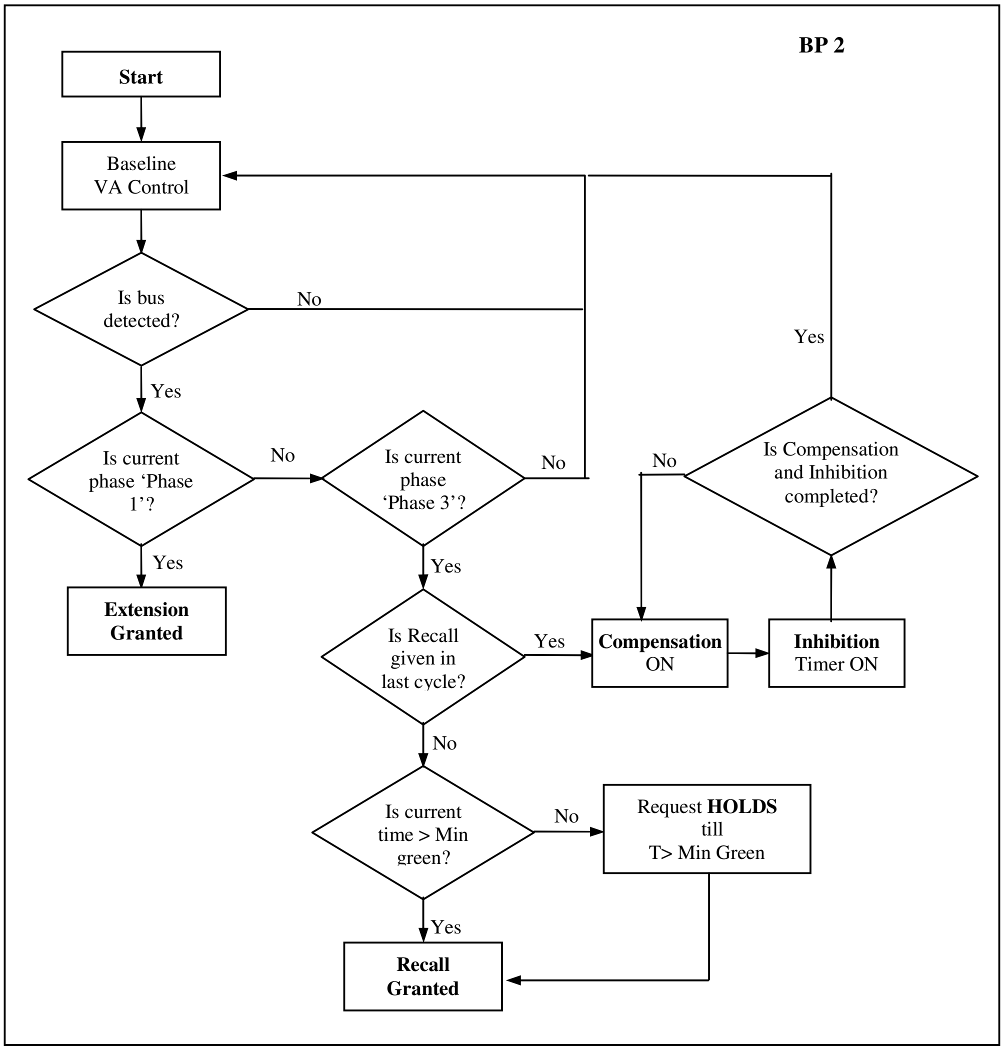


Figure 4. 9 Implementing BP2 in VA control

Following the logic of implementing 2 priority strategies in VA controlled junction in Aimsun, it was necessary to test how well the logic works in the Aimsun programming interface. There are 2 ways to test the correctness of the codes in Aimsun, one is by on-line visual observation and the other one is by off-line signal analysis. On-line observation was done at the beginning stage of coding by observing the vehicle movements, detector usage and signal status to judge if the codes work properly. It is useful for the early stage to find out obvious logic errors. Aimsun also provides a log window so that the signal status and priority actions can be instantaneously and accurately output on the log during simulation. Off-line analysis helps to obtain an overall picture of the signal variation after the entire simulation period via programming. It can be in form of a text file containing 9 columns, which are the simulation time (in seconds), vehicle detector status from 4 arms, bus detector status from 2 arms, signal status of signal group 1 and signal status of signal group 3.

Figure 4. 10, **Figure 4. 11** and **Figure 4. 12** were converted from the text files for 10 hours of simulation the green duration time of Phase 1 and 3 in each signal cycle. The 3 figures represent the signal situations for VA baseline, BP1 strategy in VA and BP2 strategy in VA. The DoS value is 0.8 in the example and the pre set maximum green duration for phase 1 and 3 are 41s and 32s.

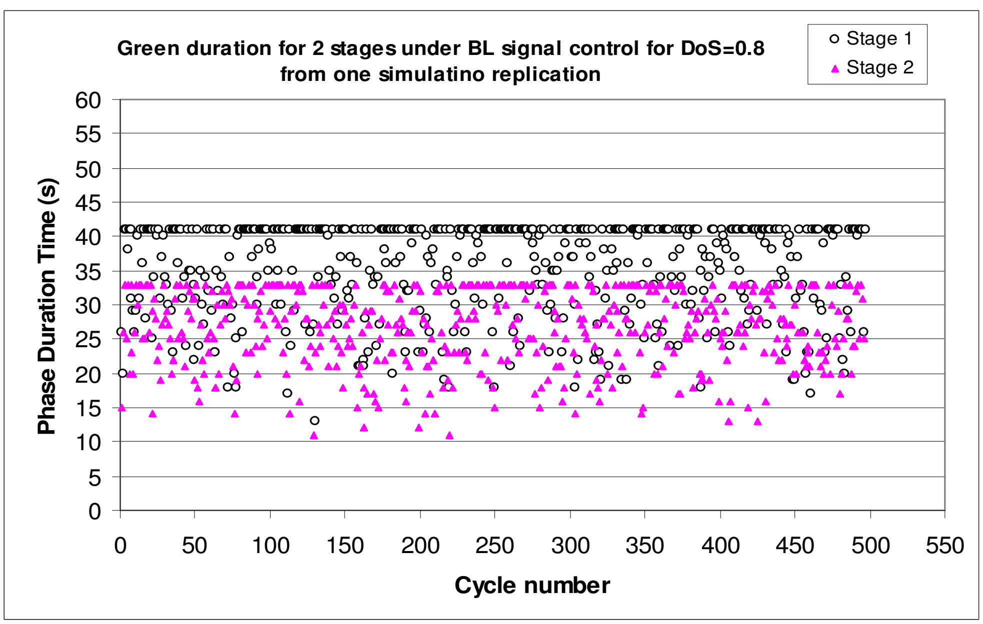


Figure 4. 10 Green duration for 2 stages under BL signal control for DoS 0.8

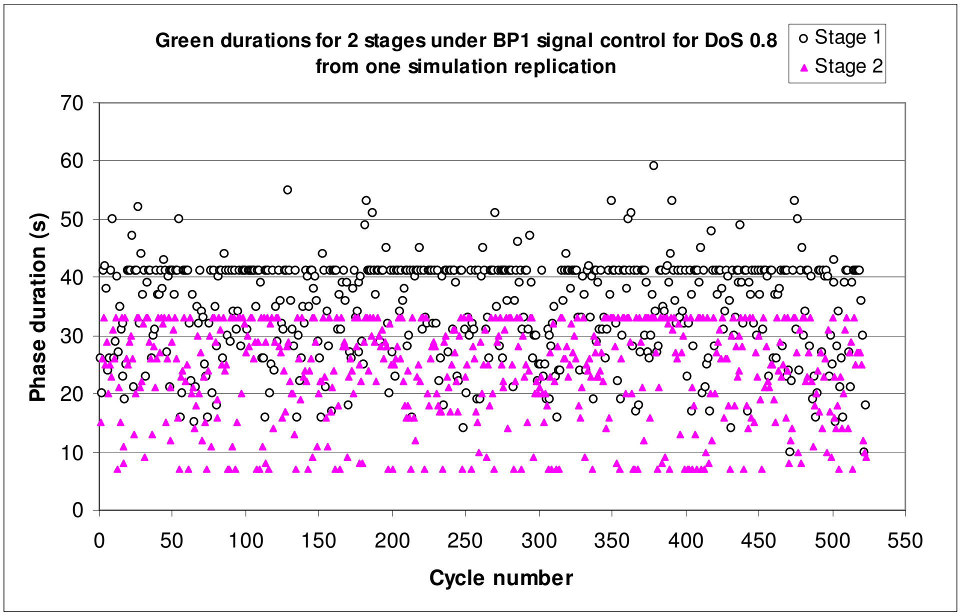


Figure 4. 11 Green durations of 2 stages under signal control with BP1 strategy for DoS0.8

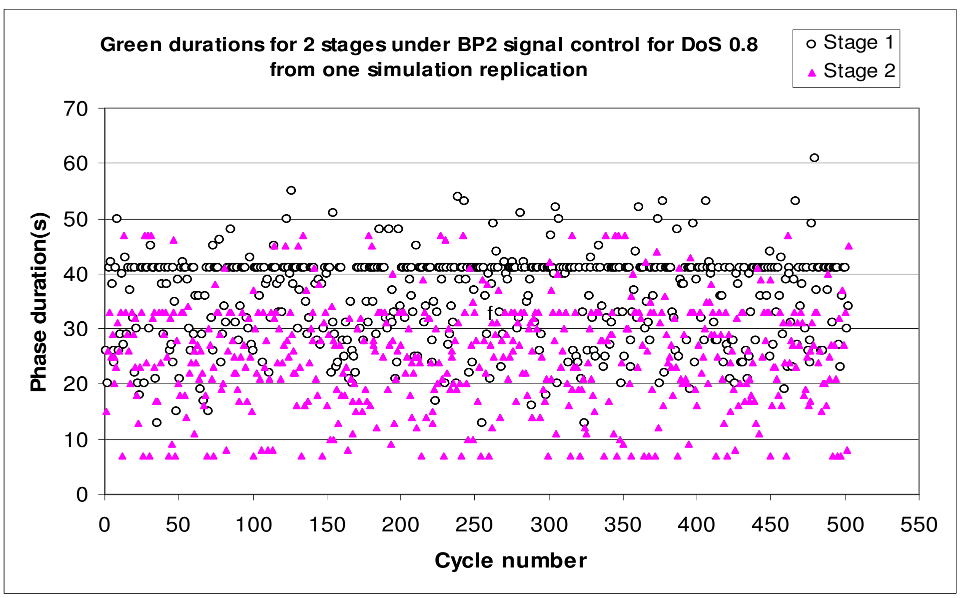


Figure 4. 12 Green durations of 2 stages under signal control with BP2 strategy for DoS0.8

Comparing the green duration time of the 2 stages in the first 2 figures, we can see 18.5% of buses have been granted green extensions (37 times of extension in 10hours for a total number of 200 buses). There have also been an increasing number of green durations with 7 seconds the minimum green time for stage 2. This indicates the recall strategies have been frequently operated.

Comparing the green duration time under BP1 and BP2 strategies, as shown in the latter 2 figures, we can see that at some point the green duration for stage 2 has been extended over the maximum green time defined in VA signal control logic, and the meanwhile the number of 7s the minimum green duration for stage 2 has decreased. This indicates that compensation and inhibition facilities have functioned as required.

These 3 figures visually have demonstrated that the VA signal control logic, the BP1 and BP2 priority strategies have functioned as expected. These illustrations provide a mean in aid of examining and checking if the programmed logic work as expected.

After careful programming for VA, BP1 and BP2, the signal control plans have been set up and simulated for the proposed simulation scenarios. The simulation scenarios and the evaluation process are then introduced in the next chapter.

CHAPTER 5

SIMULATION SCENARIOS AND EVALUATION PROCESS

This chapter proposed 18 scenarios for simulation considering a number of key factors, including Degree of Saturation flows (DoS), the ratios of conflicting traffic flows and bus frequencies. The evaluation process is then summarised for the later case study.

5.1 Identifying key factors for simulation

There are several factors identified which could influence the impacts of bus signal priorities. These would be Degree of Saturation (DoS), bus flows, the flow ratios of critical traffic streams (on major and minor flows) and the bus priority strategy. These key factors are described in the following sub-sections and values/ranges are suggested.

5.1.1 Degree of saturation (DoS)

The degree of saturation (DoS) is the ratio of flow to capacity (also referred as Ratio of flow for Capacity: RFC) used to examine whether the road is near its capacity or not, as shown in equation below:

DoS=Flow/Capacity

The capacity of a road section under signal control is defined as the maximum number of vehicles that can cross the stop line in effective green time in an hour: (saturation flow* effective green time)/ cycle time, in equation of:

$$Capacity=\frac{gS}{C}$$

Where:

g is the effective green time

S is the saturation flow of the arm

C is the cycle time

This indicates that the number of vehicles crossing the stopline in a given period of time depends not only on the traffic flow and the saturation flow, but also the proportion of time during which the signal is effectively green (λ) (Salter and Hounsell 1996).

The combination of these 2 equations can be described in an equation below as:

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

where:

q is the traffic flow

C is the cycle time

g is effective green time

S is Saturation flow

This indicates that to design a certain value of Degree of Saturation (DoS) for an arm to a junction, 4 parameters need to be determined the first, which are the actual traffic flow, the saturation flow and the signal timing plan.

According to the traffic signal timing manual (FHWA, 2008), '*movements with DoS values less than 0.85 are considered under-saturated and typically have sufficient capacity and stable operations. For movements with DoS of 0.85 to 1.00, traffic flow becomes less stable due to natural cycle-to-cycle variations in traffic flow. The closer a movement is to capacity, the more likely that a natural fluctuation in traffic flow (higher demand, large truck, timid driver, etc.) may cause the demand during the cycle to exceed the green time for that cycle. The result would be a queue that is carried over to the next cycle, even though the overall demand over the analysis period is below capacity. In cases where the projected DoS exceed 1.00 (demand exceeding capacity) over the entire analysis period, queues of vehicles not served by the signal each cycle are likely to accumulate and either affect adjacent intersections or cause shifts in demand patterns…If possible, the DoS values should be less than 0.9'*

Implementing bus signal priority strategies under different DoS values can lead to considerably different junction performance on both efficiency and emissions. Under a relatively free flow traffic condition, the additional queuing vehicles generated by changing original signal timing can be discharged very quickly and buses can obtain significant delay savings. Meanwhile the smooth and high speed vehicle flows produce the most moderate emissions and fuel consumption. At a heavy or congested junction operating near its capacity, any slight signal disturbance from implementing bus signal priority could cause long queues. The side effect becomes worse if stronger bus priority strategy is implemented, e.g. bus priority without compensation or inhibition. Emission output under heavier traffic conditions increases as more low-speed driving and stop-and-go behaviour is performed under heavy or congested traffic conditions than free flow conditions. This can be illustrated by an empirical 'speed-flow' and an 'emission-speed' relationship chart, as shown in **Figure 5. 1** and **Figure 5. 2**.

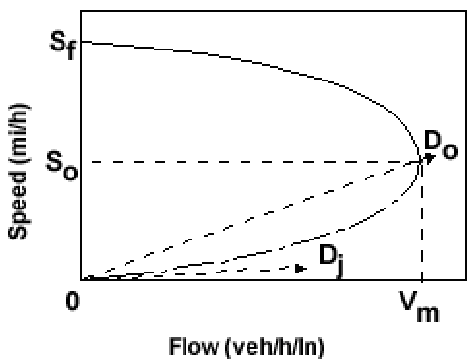


Figure 5. 1 Speed-flow relationship (Source: HCM)

Where

S_f: free flow speed;

S_o: the speed when the flow reaches the maximum flow V_m;

V_m: maximum flow;

D_o: critical density when the flow reaches to the maximum flow V_m;

D_j: jam density

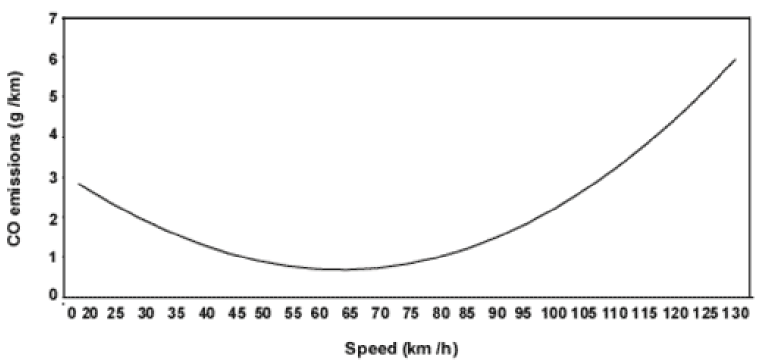


Figure 5. 2 Speed- CO relationship (Source: Department for Transport, UK)

Figure 5. 1 shows that the average link speed decreases from ‘free-flow high speed’ to the ‘capacity speed’ when the flow increases to the maximum point- capacity. **Figure 5. 2** shows that the average vehicle CO emissions reach the lowest point at the most efficient speed of about 60km/h, when vehicle engines operate under the most efficient fuel combustion. These two relationships indicate that traffic flow conditions influence the average link speed, which consequently influence the emissions.

To fully understand and evaluate the performance of bus signal priority under different traffic flow conditions, 3 values of DoS were selected and simulated in this study, representing free flow, heavy flow and near congested flow conditions, as shown in **Table 5. 1**.

Table 5. 1 DoS Values modelled in this study

	Free flow	Near-capacity flow	Near Congestion flow
Naming	DoS 0.6	DoS 0.8	DoS 0.9
DoS Values	0.6	0.8	0.9

According to the equations above, traffic flows for each DoS value can be derived accordingly together with traffic signal timings plans. Details on determination of car flows, baseline traffic signals for each DoS are presented in Chapter 6.

5.1.2 Bus flows

As reviewed in chapter 2, bus services can be categorised into 2 groups according to frequency, the headway- based bus services and schedule based bus services. According to DfT (2010b), the commonly accepted threshold to distinguish these 2 types of headway is 10 mins. If a bus operates with a higher frequency than 10 mins, it is treated as a headway-based bus service, and if a bus frequency is less than 10 mins, the service is considered as schedule based service. As bus signal priority has much less impact on the schedule based bus operation, only headway-based bus services are modelled in this study. The common bus service frequency for headway based buses in London is normally at least every 5 minutes, which is about 12 buses per hour.

As at central areas in cities there are usually several bus services running at the same route at some road sections, the bus frequency can be higher than 12 buses hour. In this study two bus flows, both representing the bus flow from combined bus routes, are modelled in this study, one is 20 buses/ hour and one is a high frequency of 60 buses/ hour. This is to ensure the modelling covers both the typical bus operation on street and the extreme situation. A deviation of 1minute for headway is introduced. Bus flows are summarised in **Table 5. 2**.

Table 5. 2 Bus frequencies –Normal and high

	Normal frequency	High frequency
Bus flow Naming	B1	B2
Combined bus flows	20 buses/hour	60buses/hour

5.1.3 Ratios of car flows

For a junction operated under VA system –D signal control, the decision to extend green time at each simulation step is made according to vehicle arrival but not the real time delay optimisation, so the delay time of minor road can be greater then main road. The difference becomes more obvious when the flows are more unevenly distributed. When implementing bus priority strategies at a signal controlled junction, the balance or the evenness of traffic flows from conflicting stages is important. In other words, implementing bus priority to buses running on main road or minor road can result in a significant difference on delay time/ or journey time savings. Therefore the ratio of priority general traffic and non priority general traffic is considered to be a factor needs to be included in the design of the case study. In this study 3 Ratios of flow (R) values are modelled for each DoS value, as shown in **Table 5. 3**, to represent buses from major road, evenly distributed road and minor road.

Table 5. 3 Values of Ratio of car flows (R)

	Main road	Even road	Minor road
R values	1/3	1/1	3/1
Naming	R1/3	R1/1	R3/1

The traffic flows can be calculated according R values and other parameters, which is described in the case study in Chapter.

5.2 Proposal of simulation scenarios

Considering all the factors indentified in section 5.1, 18 simulation scenarios in total for this study have been proposed. For each scenario, 3 signal control methods, i.e. BL, BP1 and BP2 were modelled. The hierarchy of the scenarios is shown in **Figure 5. 3**.

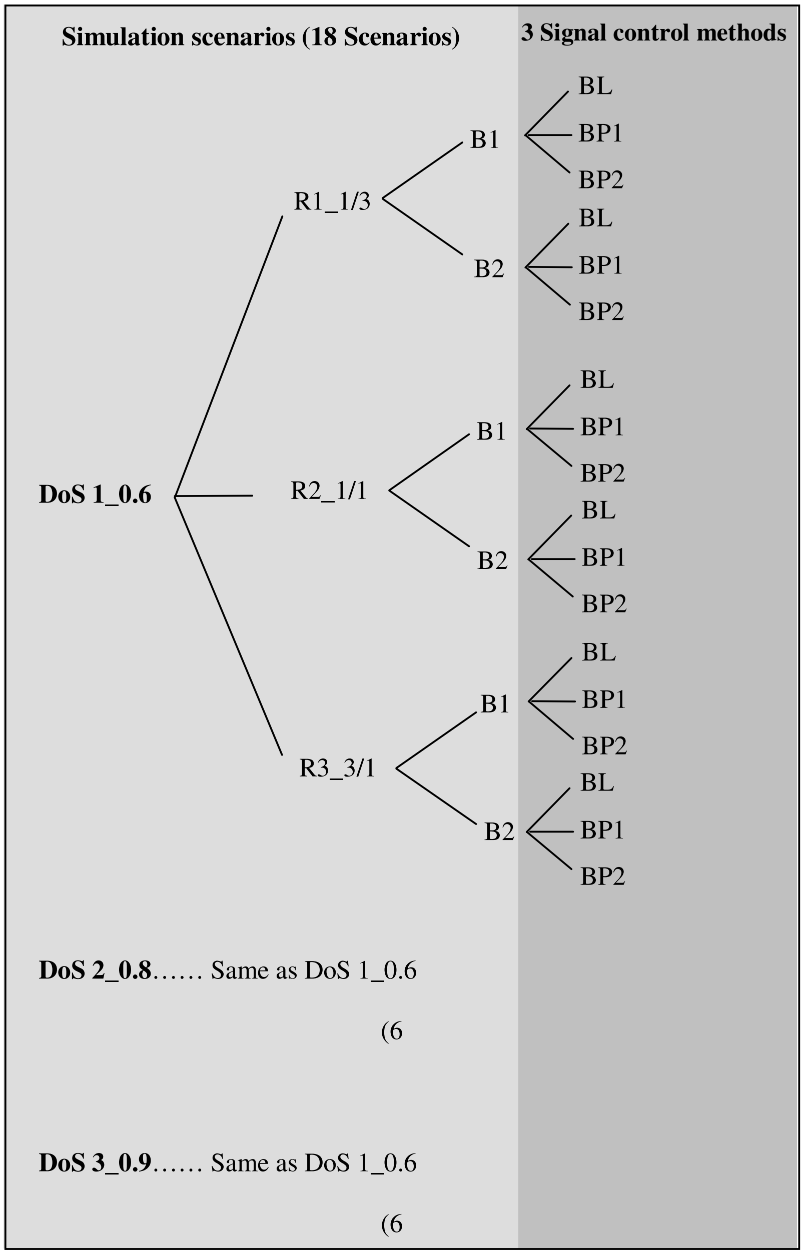


Figure 5. 3 Simulation scenarios

5.3 Evaluation process

To establish the evaluation process for this study, it is necessary to understand the working of Aimsun and panis models in more detail, as follows:

5.3.1 Working mechanism of Aimsun model

Aimsun, as briefly reviewed in 2.2.3.2, is a microsimulation tool based on a set of core driving behaviour models, such as car-following, lane changing and gap acceptance models to represent vehicle movements. As car-following and lane-changing models are most relevant for vehicle movements at road sections towards a signalised junction, as modelled in this study, the principles of these 2 models are described as follows:

Car-following model in Aimsun

The car-following model used in Aimsun is based on the model developed by Gipps (1981). Gipps car-following model is a safety distance model or collision avoidance model. In this type of model vehicles follow the general rule that they accelerate to achieve their desired speed and decelerate when they have to avoid a collision with the leading vehicle while trying to maintain their desired speed. The Gipps model has been embedded in the Aimsun simulation package. The original Gipps model was developed in 1981 and a few modifications concerning the estimation of the leader's deceleration have been made in later versions of Aimsun, to avoid the model crashing as a result of vehicle collisions. This results in the model removing some of the smaller headways which occur in practice. . The basic idea of Gipps model is to set limits on the performance of drivers/vehicles and use these limits to calculate a safe speed with respect to the preceding vehicle.Whilst this process may not reflect traffic operation precisely, it is considered to be a reasonable approximation in the context of this research where different bus priority strategies are being compared.

In Aimsun, Gipps model consists of 2 main components, acceleration and deceleration and a modified estimation of the leader's deceleration. The model is described as follows.

The maximum speed to which of a vehicle (n) can accelerate during a time period (t, t+T) is given by:

$$V_a(n,t+T) = V(n,t) + 2.5a(n)T\left(1 - \frac{V(n,t)}{V^*(n)}\right)\sqrt{0.025 + \frac{V(n,t)}{V^*(n)}}$$

Where

V(n,T) is the desired speed of the vehicle n at time t;

V*(n) is the desired speed of the vehicle (n) for current section;

a(n) is the maximum acceleration for vehicle n;

T is the reaction time.

The max speed on the other hand the same vehicle (n) can reach during the same time interval (t, t+T), according to its own characteristics and the limitations imposed by the presence of the leader vehicle (n-1) is:

$$V_b(n,t+T) = d(n)T + \sqrt{d(n)^2T^2 - d(n)\left[2\{x(n-1,t) - s(n-1) - x(n,t)\} - V(n,t)T - \frac{V(n-1,t)^2}{d'(n-1)}\right]}$$

Where

d(n)(<0) is the maximum deceleration desired by vehicle n;

x(n,t) is the position of vehicle n at time t;

x(n-1, t) is the position of preceding vehicle (n-1) at time t;

s(n-1) is the effective length of vehicle (n-1);

d'(n-1) is an estimation of vehicle (n-1) desired deceleration.

In any case, the definitive speed for vehicle (n) during time interval (t, t+T) is the minimum of those previously defined speeds:

$$V(n, t+T)=\min \{V_a(n, t+T), V_b(n, t+T)\}$$

In the newest Aimsun version to date, a new parameter has been introduced which defines the minimum headway between the leader and follower as a new restriction on the deceleration component. This is because in previous versions prior to v4.1.3 the estimation of the leader's deceleration was taken as the proper desired deceleration of the leader vehicle. In the case where the ratio between the follower's and leader's deceleration capabilities is relatively high, the above deceleration component of the car-following model presents instabilities which may cause some vehicles to drive too close to the leader. The new model considers the leader's deceleration as a function of a new parameter 'α' defined per vehicle type named Sensitivity Factor. The algorithm is elaborated in the Aimsun user manual (2009) hence not reviewed here.Again, this is not considered significant for this research where the focus is on relative rather than absolute values.

Lane-changing model in Aimsun

The lane-changing model used in Aimsun can be considered as a development of the Gipps lane-changing model (Gipps 1986a and 1986b). Lane change is modelled as a decision process, analysing the necessity of the lane change (such as for turning manoeuvres determined by the route), the desirability of the lane change (to reach the desired speed when the leader vehicle is slower, for example), and the feasibility conditions for the lane change that are local, depending on the location of the vehicle in the road network.

The lane-changing model is a decision model so that at each simulation step, a question is asked in order to update a vehicle’s behaviour, i.e. is it necessary to change lanes? The answer depends on 2 situations, -the turning requirement and the speed requirement, i.e. if the vehicle needs to change its current lane to another to make a turn, or if the vehicle speed is lower than its desired speed so that it requires a lane-change to overtake the vehicle in front. Three zones inside a section are defined in the lane-changing model representing 3 levels of lane-changing motivation/desirability.

Gap acceptance, overtaking, look-ahead and on/off-Ramp models are also important models for describing vehicle movement. As these models are not closely related in this study, the mechanisms are not presented here. Details can be found in the users manual.

Around these basic driving behaviour models, other models such as traffic modelling (e.g. vehicle generation modelling), traffic control modelling (e.g. signal control modelling, give way modelling and ramp metering), public transport modelling (e.g. trains, trams and buses) and environmental modelling (e.g. fuel consumption and emissions) are included to present a comprehensive road network. Once a vehicle is generated into the network, it has a set of static attributes relative to the vehicle itself, such as vehicle length/width, desired speed, max acceleration and deceleration rate and etc. Each vehicle has an origin and a destination which can be determined either by specifying turning movements at junctions or by O-D matrices. During its journey, it has to abbey the rules set in the driving behaviour models (e.g. car-following and lane-changing behaviour), the signal control plans at signalised junctions and give-way rules for priority junctions and all other rules/strategies specified in the model or by users. For each simulation step, the model checks and updates the network and makes necessary changes according to the rules and the current conditions.

The general logic of simulation process in Aimsun is illustrated in Figure 5.4. At each simulation step, the system updates firstly according to its scheduling list (i.e. 'Update Control' box) such as traffic signal control which does not depend on other activities. After this, a set of loops start to update the entities of the simulated road network, including road sections, junctions, vehicles and etc. Vehicles on the network are updated according to the driving behaviour models, e.g. car-following and lane-changing. The vehicles newly generated into the network and the vehicles leaving the network are processed and updated according to vehicle generation models or the O-D matrices in conjunction with traffic assignment models. Depending on the user requirements, the simulation performance can be output at the end of simulation.

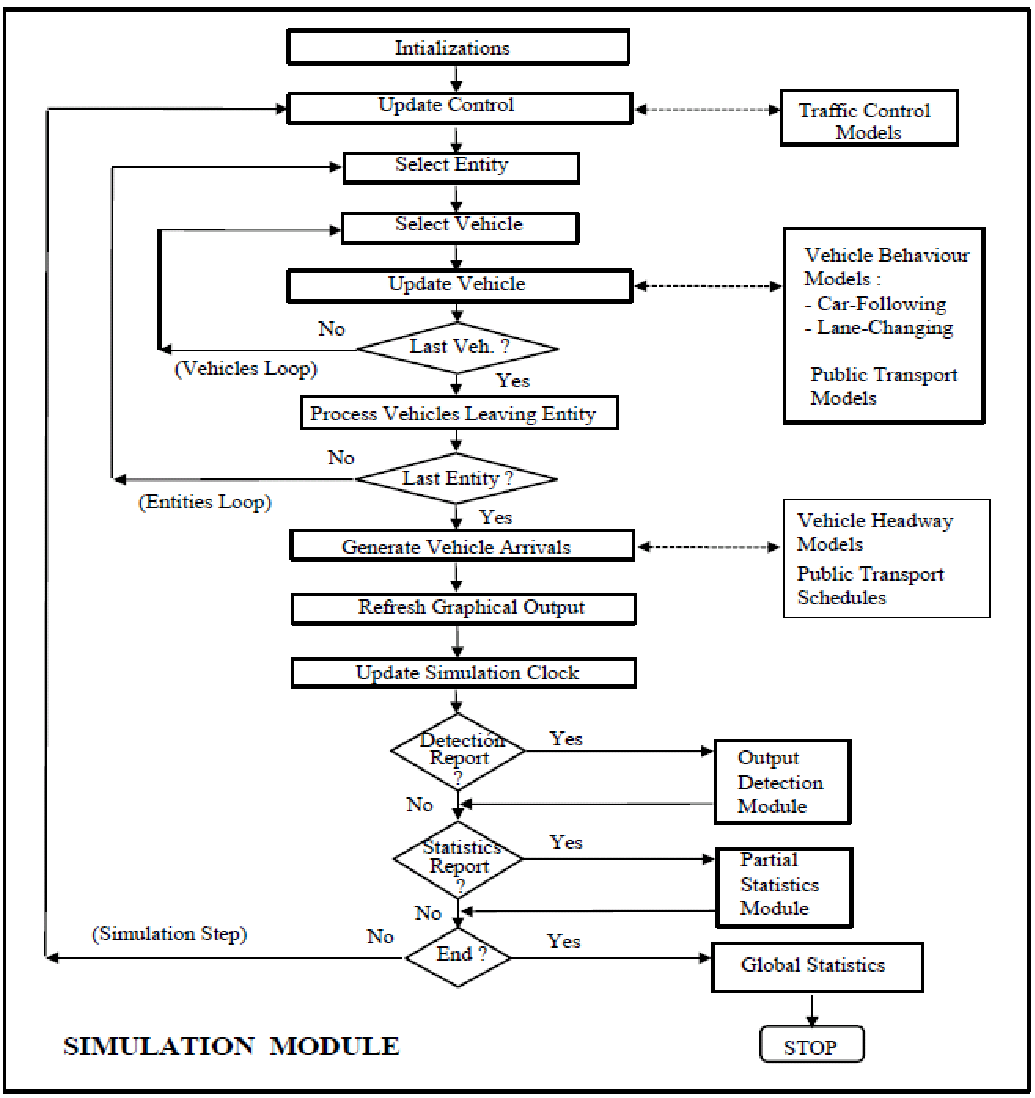


Figure 5.4 The simulation process in AIMSUN (Source AIMSUN User manual)

5.3.2 Integration of Aimsun and Panis model

As reviewed in 3.3.5.1, the Panis model is a speed-acceleration based instantaneous emission model. The Panis model is incorporated in Aimsun to calculate emissions using instantaneous vehicle movement data from Aimsun. For each vehicle at each simulation step the instantaneous speed and acceleration is recorded in Aimsun and input to Panis model to produce emission output. The integration of Aimsun and Panis models is illustrated in Figure 5.5

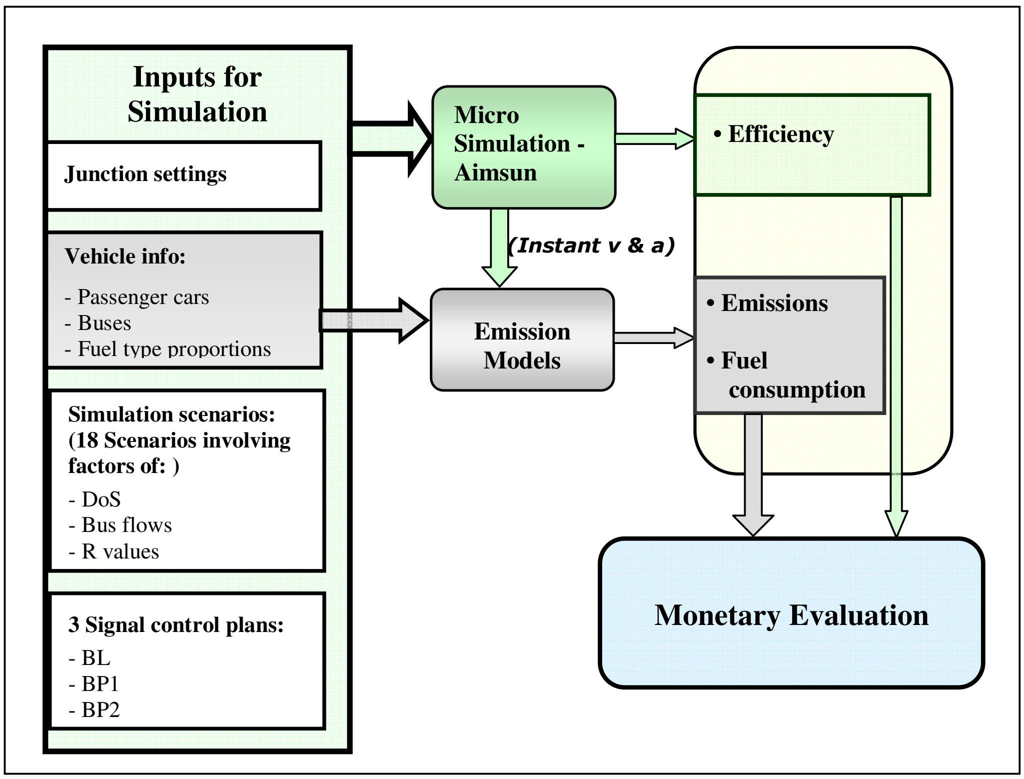


Figure 5.5 Simulation and evaluation process

The input data required by Aimsun includes 4 categories, which are the physical settings of the junction, the vehicle information, the simulation scenarios and the signal control plans. Efficiency output including journey time and delay time can be obtained directly from Aimsun. Instantaneous speed and acceleration output from Aimsun, together with the static vehicle information are required as input for emission and fuel consumption models. Results of emissions and fuel consumption can be obtained from emission models. The Panis emission model has been recently embedded in Aimsun therefore emissions from this emission model can be directly exported. The monetary evaluation for efficiency, emissions and fuel consumption is conducted at the end.

Figures 5.6 and 5.7 below are 2 snapshots during a simulation run, respectively showing the profiles of speed & acceleration and CO2 emissions of a car travelling at a signalised junction. This car was travelling at a constant high speed before it encountered the red light at the junction and had to wait for about 20s, then it accelerated when the traffic light turned green and managed to achieve its desired speed. The speed variation (i.e. the small deceleration and acceleration behaviour) at the final part of its journey was caused by an overtaking action by another car when it was forced to slightly slow down.

Figure 5.6 shows the vehicle movement profiles, i.e. speed and acceleration. For emission estimation, Aimsun recorded the second-by-second vehicle movement data for all individuals and then fed them into the embedded Panis model to calculate second-by-second emissions. Figure 5.7 shows the CO2 emissions for this particular car during its journey. The emission data can be aggregated at different levels required by users, i.e. emissions for different vehicle types- cars and buses, emissions at different road sections, or emissions by all vehicles. To store and output the second-by-second trajectories of each vehicle for one simulation run (i.e. 10 hours) would require enormous storage capacity and has negligible contribution to the study;, in the following case study and analysis, only the averaged data at a certain aggregation level are produced. These 2 figures serve for demonstration purposes only.

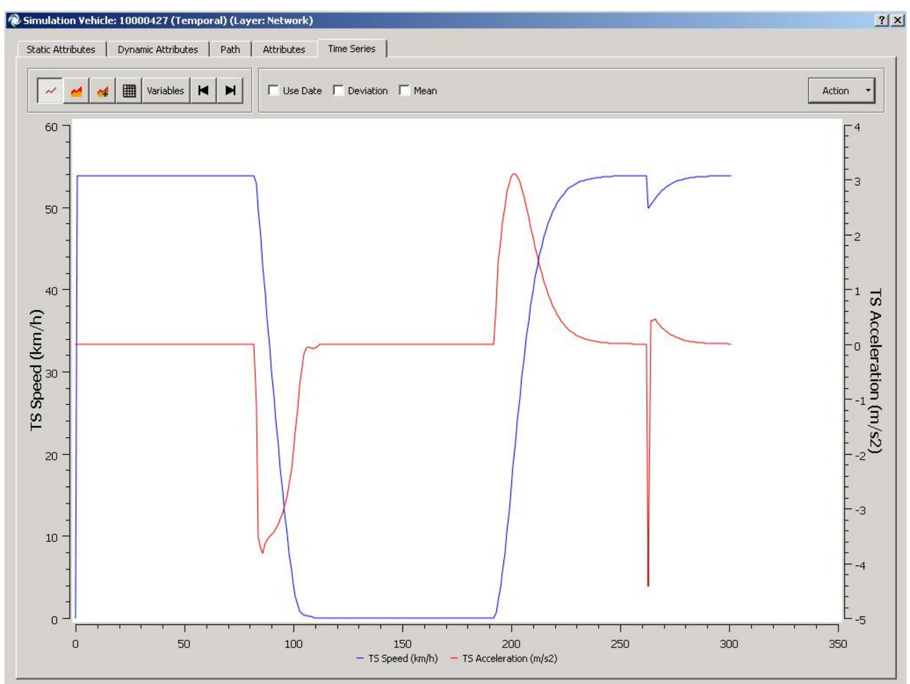


Figure 5.6 Speed (blue) and acceleration (red) rate of a car approaching and leaving a signalised junction

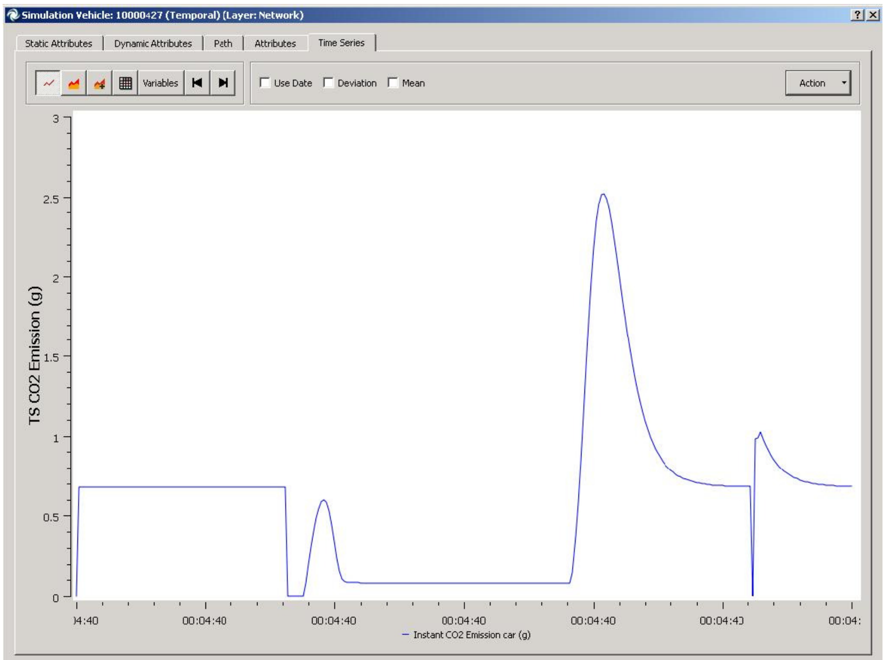


Figure 5.7 CO2 emissions of a car approaching and leaving a signalised junction

Note that the simulation step was set as 0.25 second, therefore each unit on the X axis is ¼ second.

These 2 figures confirm that the instantaneous vehicle emissions predicted by a speed-acceleration based instantaneous emission model are sensitive to both speed and acceleration rate. The emissions rates of other pollutants vary but generally follow a similar trend, apart from the speed, emissions increase dramatically at acceleration period. This is convincing as the literature (as presented in chapter 3) has pointed out that acceleration is a key factor and a large percentage of emissions is generated during the stop-go period. The figures show that for the first part when the car was travelling at a stable speed of 53km/hr with zero acceleration rate, the CO2 emission rate is constant at about 0.7g/second; when the car decelerated at the red light to an idling stage the emissions started decreasing to a smaller emission rate of about 0.1g/second. Note that for a short period of waiting, typically at signalised junctions, a driver would let the engine idle while for a relatively longer waiting period, some drivers may choose to switch off the engine when the emissions would be zero. The deceleration stage lasts about 4 seconds and the idling stage of this particular car lasts about 20 seconds. The maximum acceleration rate occurred when the car was accelerating to reach its desired speed. For this car, the maximum acceleration rate is about 3m/s2 and at the same time the peak CO2 rate is about 2.5g/second, more than 3 times

larger than the emission rate at normal stable driving. When the speed became stable at a constant speed, the emission rate also decreased from the peak to the normal rate.
It is recognised that fuel consumption and emissions also depend on gear changing characteristics of the engine/driver concerned, not just on the acceleration rate. This issue is discussed further in the 'limitations' section later in the thesis. It is concluded there that, whilst this is a limitation, models incorporating engine performance at this level of detail have not yet been developed sufficiently for use in this research.

The described above figures have confirmed that the working of the integration of Aimsun and Panis emission model is appropriate for this study and the emission rates at cruising, idling, accelerating stage are also reasonable compared to emission standard III (This car was defined as a EU-III car). It should also be noted that this research involves comparing different BP strategies using a single modelling approach, so that it is relative rather than absolute quantities which are particularly important.

5.4 Summary

This chapter has presented an overall evaluation framework for the later case study. Firstly the key factors which need to be involved in this study were identified. Three DoS values, 0.6, 0.8 and 0.9 have been proposed to represent free flow, near-capacity flow and congested traffic conditions. Two bus flows, 20buses/ hour and 60 buses/ hour, have been proposed to represent normal bus frequency and high bus frequency as the higher bus frequency has greater impact when implementing bus signal priority strategies. Three R values, 1/3, 1/1 and 3/1 have been proposed as it is considered to be significant when implementing signal priority to buses on roads with different traffic conditions, i.e. buses on major road, minor road, and even flowed road. Considering these factors, 18 simulation scenarios in total have been proposed. For each one, three bus priority strategies need to be modelled, including the Baseline VA signal control without any priority (noted as BL), BP1 which includes green extension and recall strategies and BP2 which includes additional compensation and inhibition facilities. The performance of efficiency, emissions and VOCs needs to be evaluated. Monetary evaluation for these 3 aspects needs to be conducted to obtain comparable results and to provide recommendations.

Details of this case study, including modelling and the results are presented in the next chapter.

CHAPTER 6 CASE STUDY

This chapter presents a case study based on the methodology of modelling bus priority as described in Chapter 4 and the simulation scenarios proposed in Chapter 5.The first part describes the procedure for determining the input values for simulation, including the junction layout, the vehicle information, and the parameter. The impacts of implementing bus signal priority strategies are then analysed and compared from 3 aspects: Efficiency (delay), emissions and the overall monetary values.

6.1 Inputs for the Case Study

As described in 5.3, the input data required for simulation includes 4 categories, which are the junction settings, the vehicle information, the simulation scenarios and signal control plans. This section describes how to determine the values involved in these 4 aspects.

6.1.1 Junction settings

The geometric scale of the case study should be determined according to the principle that it has to be large enough to cover all vehicles' speed variation caused by signal changes and meanwhile it also should be small enough to only cover the area with speed variation caused by signals. In addition, the case should also exclude other interference that may increase the complexity of the case and confuse the study objective. In line with the settings of DoS values and R values described in Chapter 5, the traffic flows and the corresponding signal control timings for each DoS and R value need to be determined. The modelling logic and parameters for the Baseline VA signal plan and the 2 bus priority strategies have been described in Chapter 4.

As reviewed in Chapter 2, there are 2 main categories of bus signal priority, full priority and differential priority. The full bus signal priority strategies are widely applied at isolated junctions. The overall benefits of differential priority may be only perceived in a larger road network with a relatively large number of (co-ordinated) junctions as the achievement of a better headway or punctuality may require differential priority at several junctions. However a larger network which inevitably involves more variations (e.g. more complex signal control algorithm, more turning movements, traffic fluctuations, bus stops, and etc) will lead to a complexity that may confuse the objective of this research. This may make it difficult to isolate the effects of bus signal priority strategies from the effects of all the other accompanying factors from traffic variations. Therefore an isolated junction is studied here and full priority strategies are applied and evaluated.

The junction is designed as a crossroad junction with 4 arms, all with 4 lanes and 2 ways, as shown in **Figure 6. 1**. Detectors for general traffic and buses are placed on all arms. General traffic is detected within 40 metres of the stopline on each arm- consistent with the standard VA control process using above-ground microwave detectors. A single bus detector is placed 120 metres upstream of each stopline, again consistent with current UK guidelines reviewed in Chapter 2.

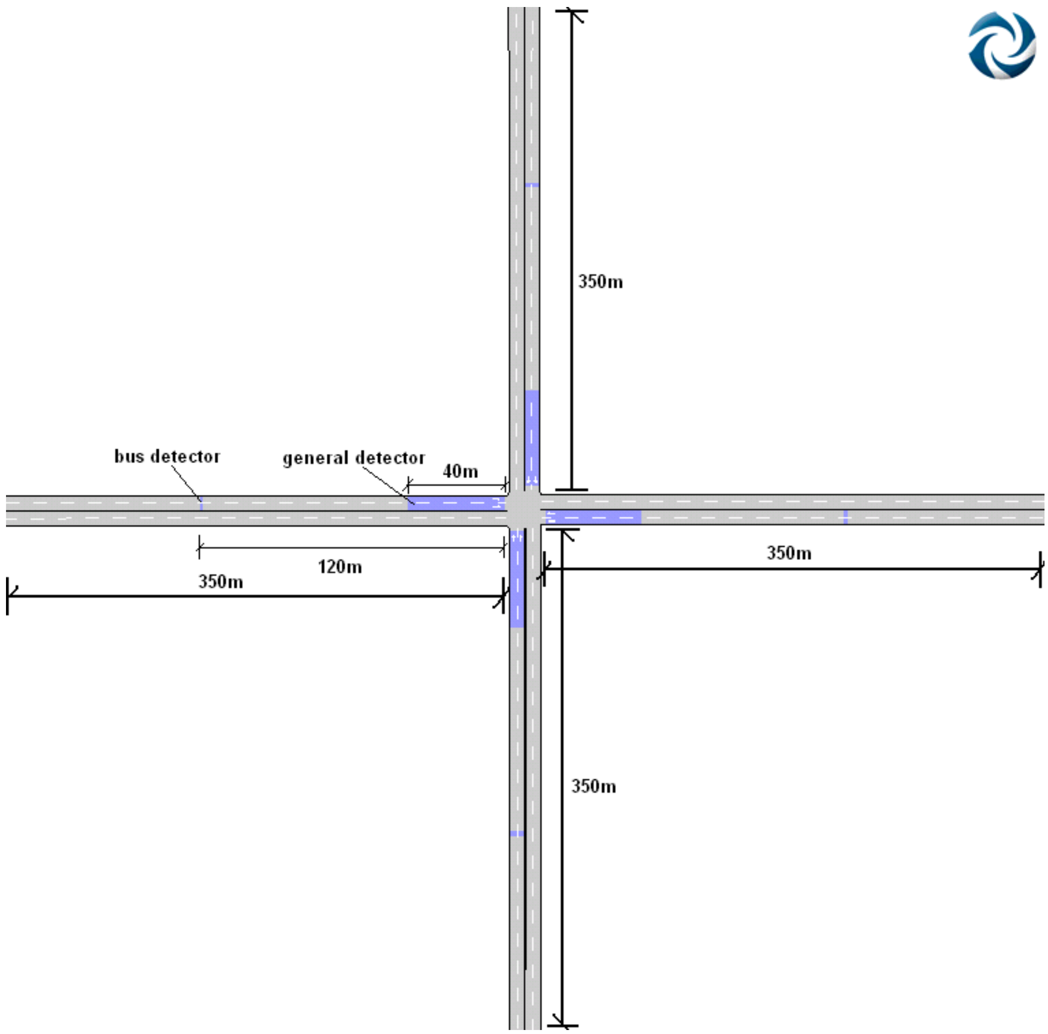


Figure 6. 1 Geometry layout of the case

The length of each arm has to cover all vehicles' speed profiles from a stable status when entering the network including the effects of any queuing to another stable status when leaving the network. For entering vehicles, this means that the speed of some vehicles which encounter non-green signals at the junction should be completely recovered before the exit arm is terminated. A stable status means a vehicle has reached its constant desired speed.

The constant desired speed is defined by a number of other parameters in Aimsun. Before introducing the method of determining the length of the arms, it is necessary to review some definitions of parameters used in Aimsun.

Maximum desired speed:

This is the maximum speed, in km/h, that one type of vehicle can travel at any point in the network. Drivers tend to travel at their desired speed in each section but the environment (i.e. speed limit, preceding vehicle, adjacent vehicles, traffic signals, signs, blockages, etc) conditions their behaviour.

Section speed limit:

Maximum allowed speed (in km/h) for the vehicles travelling through a section. Depending on the characteristics of the drivers, they may or may not follow speed limit recommendations; drivers may adjust their response to the speed limits according to their own knowledge and decision on 'speed acceptance' (see this definition below).

Speed acceptance:

This parameter ($\theta \geq 0$) can be interpreted as the degree of acceptance of speed limits. $\theta \geq 1$ means that the vehicle will take as maximum speed for a section a value greater than the speed limit, while $\theta \leq 1$ means that the vehicle will use a lower speed limit. The next section explains how maximum desired speed for a vehicle is calculated for different parts of the network.

Desired speed for each vehicle on each section

In the car-following model in Aimsun, the desired speed, the section speed limit and the speed acceptance, among others, define the desired speed for each vehicle on each section. The desired speed of a vehicle driving on a particular section or turning is calculated by the following functions.

$$v_{\max}(i,s) = MIN[S_{\lim it}(i,s), v_{\max}(i)]$$

Where

$$S_{\lim it}(i,s) = S_{\lim it}(s) \bullet \theta(i)$$

Where

$v_{max}(i)$ is the maximum desired speed of the vehicle i;

$\theta(i)$ is the speed acceptance of vehicle i;

S_{limit} (s) is the speed limit of the section or turning s

A speed limit of 30mph (about 48km/h) has been predominantly used in urban areas in UK, therefore the road type 'signalised streets' with a speed limit of 50km/h in Aimsun has been adopted for this case study.

Note: The term 'Desired speed' is used referring to 'desired speed under a specific speed limit' in this chapter hereafter.

The method to determine the arm length for the case study is illustrated in **Figure 6. 2**. To determine the start and end points of a road, e.g. the West-East road, 20 detectors were placed on both the upstream and downstream sections, with spaced at 20m intervals near the stopline and more densely spaced (10m or 5m) further away.

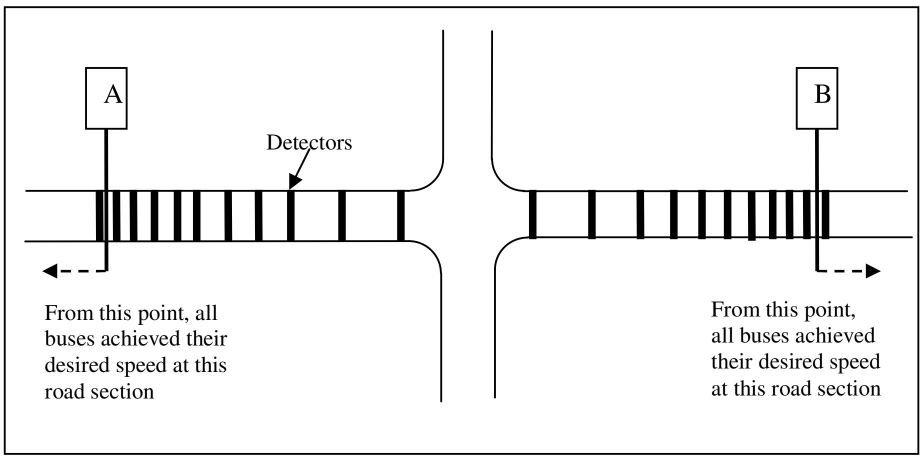


Figure 6. 2 Method to determine the length of the junction arms

The trial simulation for the testing was conducted under a heavy traffic situation (i.e. DoS=0.9) when queues is most likely to happen, therefore requiring the longer arm length to be simulated than in lighter traffic conditions. Bus speed has been used for testing at detector points as buses have lower acceleration and deceleration rates compared to passenger cars, therefore they require a longer distance to achieve/ recover to their desired speed. The distance needed by buses was therefore used as the arm length required in this case study. For a 10 hour simulation trial using VA signal control under a DoS value of 0.9, instant speed of each bus passing by each detector was recorded and compared with its desired speed. If from a point where all buses were able to travel at their desired speed, then we can say that this point can be used as the start/end point for the arm length.

The results showed the start point should be about 200m away from the stopline and the end point should be 300m away from the stopline. This indicates that the speed of buses when entering the junction was influenced 200m away by the queuing or slow moving vehicles downstream when encountering red signals. The 300 metre arm length downstream required was mainly decided by the acceleration rate of buses when they attempt to achieve their desired speed at the downstream section. As traffic is modelled on both directions, the larger value of 300 metres should be used. For practical reasons, an extra length of 50 metres is added as marginal length to cover any flow fluctuation. This allows all the scenarios to be modelled except for over-saturation, where the strategy of bus priority studied here is anyway less likely to be employed.

6.1.2 Vehicle information

Only cars and buses have been introduced in this study. Other vehicle types such as trucks or vans were not considered. Fleet composition according to the EU emission standard (i.e. EU I to EU VI) is an important factor in emission estimation as the parameter values in emission models are given for different EU standards. However as the Panis emission model is derived on the basis of the 2010 UK fleet composition there is no need to specify the fleet composition for the case study.

The proportion of fuel types is needed for estimating fuel consumption. According to the review in Chapter 3, the proportion of petrol and diesel usage for cars was set as 73% and 27% respectively. All buses are assumed to be diesel engined. The percentage usage of other fuel type is very low and therefore not considered here.

6.1.3 Determining traffic flows for Simulation scenarios

As introduced in chapter 5, 18 simulation scenarios involving 3 DoS values, 3 R values and 2 bus flows have been proposed for the case study. For each DoS value, the specified traffic flows for each arm of the junction needed to be determined. As already explained in Chapter 5, the DoS is the ratio of flow to capacity, as shown in the following equation:

DoS=Flow/Capacity

The capacity of a road section under signal control can be calculated by the following equation:

$$Capacity=\frac{gS}{C}$$

Where:

g is the effective green time

S is the saturation flow of the arm

C is the cycle time

Combining the 2 equations above, the DoS can be described as follows:

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

where:

q: traffic flow

C: cycle time

g: effective green time

S: Saturation flow

So the traffic flow q can be described as follows:

$$q=\frac{DoS \bullet g \bullet S}{C}$$

From the equation we can see that for a given DoS value, the flow can be derived from the cycle time and green time, given that saturation flow is a constant. At an isolated junction the fixed timing signal control method towards optimum average delays can be found in Salter and Hounsell (1996), and the equations used are listed as below.–

$$y_i=\frac{q_i}{S_i}$$

$$Y=\sum_{i=1}^{n} y_i$$

$$L=\sum_{i=1}^{n}(I_i-1)$$

$$C=\frac{1.5L+5}{1-Y}$$

Where:

q_i is traffic flow;

S_i is saturation flow;

y_i is ratio of flow

Y is the sum of y_i;

I_i is the intergreen time;

L is total lost time;

C is cycle time;

g_i is effective green time;

To avoid unnecessary complexity, only straight ahead flows have been modelled, so that a simple 2 stage signal control plan can be applied.

For a 2 stage signal control plan, only 2 critical traffic flow 'y' values are needed, marked as y1 and y2. Assuming DoS_1 represents DoS for stage 1 and DoS_2 for stage 2, the Y value can be derived as follows:

$$\because\ DoS = \frac{Flow}{Capacity} = \frac{q}{g/C \bullet S} = \frac{y}{g/C}$$

$$\therefore\ \frac{g}{C} = \frac{y}{DoS}$$

$$\therefore\ \frac{g_1}{C} = \frac{y_1}{DoS_1}, and\ \frac{g_2}{C} = \frac{y_2}{DoS_2}$$

and $g_1 + g_2 + L = cycletime = C \Rightarrow \frac{g_1}{C} + \frac{g_2}{C} + \frac{L}{C} = 1$

$$\therefore\ \frac{y_1}{DoS_1} + \frac{y_2}{DoS_2} + \frac{L}{C} = 1$$

$$\therefore\ C = \frac{L}{1 - (\frac{y_1}{DoS_1} + \frac{y_2}{DoS_2})}$$

Assume DoS_1=DoS_2, then

$$C = \frac{L}{1 - (\frac{y_1 + y_2}{DoS})}$$

$$C = \frac{L}{1 - (\frac{Y}{DoS})}$$ ……………………………………………..Equation 6-1

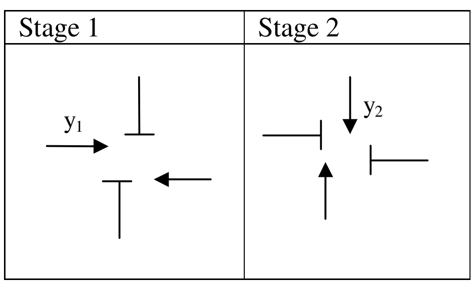
Equation 6-1 provides the method to suggest a set of 'Y' values under a given DoS. A 'Y' value is the sum of the y_i, i.e. ratio of flows, therefore the traffic flows '*q*' can be derived from y values. The 'Y' value should be constrained by 2 conditions:

(1) C<=120s
(2) Y<DoS

An example of determining traffic flows for DoS =0.6 is given below.

For a crossroad junction operated under 2 stage fixed signal timing plan (as shown in **Figure 6. 3**), using Equation 6-1, assuming the total lost time 'L' is 8s for a 2 stage timing plan and in order to keep the cycle time less than 120s, then the maximum 'Y' value can be used is 0.56. Any other Y values less than 0.56 can be used but the meanwhile the minimum green time needs to be no less than 7 seconds. The stages and phases for the example are illustrated as follows.

Stages:



Phases:

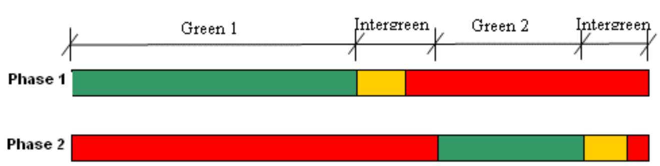


Figure 6. 3 staging and phasing of fixed timing signal control plan for this study

To design the flow sets for Y =0.56, the possible combinations of 'y1' and 'y2' values are infinite. This example only shows 3 combinations of 'y1+y2' which are (0.14 +0.42), (0.28+ 0.28) and (0.42+0.14), representing y1/y2=1/3, 1/1 and 3/1. Using the method described above, the critical flows for W-E and N-S directions can be easily calculated and are summarised in **Table 6. 1**.

Table 6. 1 Proposal of some critical traffic flow combinations when DoS=0.6

No.	DoS	Y value (2 Assumed)	Cycle time	R ratio	Critical y values		Critical Flows	
					y1	y2	W-E	N-S
1	0.6	0.56	120	R1(1/3)	0.14	0.42	532	1596
2	0.6	0.56	120	R2(1/1)	0.28	0.28	1064	1064
3	0.6	0.56	120	R3(3/1)	0.42	0.14	1596	532

Assuming saturation flow=1900cars/lane/hour (The method to calculate saturation flow is reviewed in 4.2.3)

It should be noted that the purpose of doing this is to suggest and select a set of traffic flows covering the typical cases in the real world. These traffic flows are needed as inputs in the simulation scenarios.

Using the same method, the flows under DoS=0.8 and DoS=0.9 have been calculated, assuming the 'Y' values under DoS 0.8 and DoS 0.9 are 0.7 and 0.8. The traffic flows for the 18 simulation scenarios are summarised in **Table 6. 2**. Note that for W-E and E-W car flows, the values exclude the equivalent pcu of buses.

Table 6. 2 Traffic flows for 18 simulation scenarios for case study (Unit: pcu/hr)

Categories / Traffic flows		DoS=0.6			DoS=0.8			DoS=0.9		
		Y=0.5			Y=0.7			Y=0.8		
		q1/q2=1/3	q1/q2=1/1	q1/q2=3/1	q1/q2=1/3	q1/q2=1/1	q1/q2=3/1	q1/q2=1/3	q1/q2=1/1	q1/q2=3/1
Bus flow=20 (=40pcu/h)	**Traffic streams**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**	**Scenario 9**
	Cars_ W-E (B)	435	910	1385	625	1290	1955	720	1480	2240
	Cars_ E-W (B)	435	910	1385	625	1290	1955	720	1480	2240
	Cars_ N-S	1425	950	475	1995	1330	665	2280	1520	760
	Cars_ S-N	1425	950	475	1995	1330	665	2280	1520	760
Bus flow=60 (=120pcu/h)		**Scenario 10**	**Scenario 11**	**Scenario 12**	**Scenario 13**	**Scenario 14**	**Scenario 15**	**Scenario 16**	**Scenario 17**	**Scenario 18**
	Cars_ W-E (B)	355	830	1305	545	1210	1875	640	1400	2160
	Cars_ E-W (B)	355	830	1305	545	1210	1875	640	1400	2160
	Cars_ N-S	1425	950	475	1995	1330	665	2280	1520	760
	Cars_ S-N	1425	950	475	1995	1330	665	2280	1520	760

Note: Traffic streams with (B) means bus flow is with this traffic stream.

6.1.4 Determining parameter values in signal control plans

The methodology for modelling signal control plans including the baseline VA signal plan and 2 bus priority strategies has been described in Chapter 4. The values for parameters involved in the signal control plans for the case study are determined in this section.

6.1.4.1 Parameter values for Baseline VA Control

Section 4.3.2 described the VA signal control being modelled in this study and the involved parameters. The main parameter values to be determined are minimum and maximum green time.

The minimum green time

This value has been normally set as 7 seconds, as typically used in practice.

The maximum green time

Using the second method reviewed in Chapter 4, i.e. multiplying the minimum-delay green interval durations by a factor ranging from 1.25 to 1.50, the maximum green time for scenarios are determined and summarised in **Table 6. 3**.

Table 6. 3 Parameter values for Signal control plans for 18 scenarios (Unit: second)

	Signal timings	**DoS=0.6**			**DoS=0.8**			**DoS=0.9**		
		Y=0.5			**Y=0.7**			**Y=0.8**		
		q1/q2=1/3	**q1/q2=1/1**	**q1/q2=3/1**	**q1/q2=1/3**	**q1/q2=1/1**	**q1/q2=3/1**	**q1/q2=1/3**	**q1/q2=1/1**	**q1/q2=3/1**
		Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**	**Scenario 9**
Bus flow=20	Max green Stage 1 (s)	19	29	39	23	37	51	25	41	57
	Max green stage 2 (s)	39	29	19	51	37	23	57	41	25
	Compensation time (s)	18	12	6	21	17	9	28	19	10
Bus flow=60	Max green Stage 1 (s)	The same as values above (for 9 scenarios)								
	Max green stage 2 (s)									
	Compensation time (s)									

6.1.4.2 Parameter values for bus priority strategies

Green extension

This is a fixed value. Bus detectors are placed 120m upstream of the stopline for each entry, which indicates an approximate 10 seconds for buses to clear the junction from this point at the speed of about 45km/hour. In practice an extra time period is always added to account for bus speed variability, therefore the green extension time is set as 13 seconds in the case study.

Early recall

Early recall can only be activated after the minimum green time of 7 seconds.

Compensation time

The method to calculate the compensation time has been reviewed in chapter 4. It is related to the overall stage length and the stage fixed period including intergreen time and minimum green time. Therefore the values for parameter vary in different signal control plans. The values are also summarised in **Table 6. 3.**

6.2 Summary of simulation scenarios

In summary, 18 simulation scenarios have been set up for each of the three types of bus signal priority strategies including 3 DoS values, 3 flow evenness ratios, and 2 bus flows. For simplicity reasons, a naming method is used in later analysis:

$$\text{DoS}\underbrace{(\ldots)}_{\text{(From 0.6, 0.8 and 0.9)}}\text{\_R}\overbrace{(\ldots)}^{\text{(From 1/3, 1/1 and 3/1)}}\text{\_B}\underbrace{(\ldots)}_{\text{(From20 and 60)}}$$

where

DoS value is chosen from 0.6, 0.8 and 0.9;

R value is chosen from 1/3, 1/1 and 3/1;

B value is chosen from 20 and 60.

An example:

DoS0.6_R1/1_B20 represents the simulation scenario when DoS is 0.6, flow evenness ratio is 1/1 and the bus flow is 20 buses/hour.

For each scenario, 3 signal control plans, i.e. BL, BP1 and BP2 are implemented.

For each scenario, 10 random seeds have been simulated and each one lasts for 10 hours. A 10 hour period is used as it is considered to be long enough to include enough buses (200 buses per day when the bus flow is 20/hr and 600 buses per day when bus flow is 60/ hr).

The simulation results in terms of delay, emissions and monetary values for all the scenarios are analysed in the following sections.

6.3 Results analysis: Delay

As explained in chapter 2, the most commonly used indicators to evaluate the effects of implementing bus priority strategies on efficiency are delay and travel time. Travel time is less sensitive than delay for efficiency evaluation but more appropriate in the overall monetary evaluation. Delay is more commonly used for BSP appraisal, therefore the results of delay are analysed in this section and travel time is used for the later monetary evaluation.

Delay for 3 vehicle streams is discussed separately in the following section, which are buses, cars sharing the same signal stage with buses (noted as Cars_Priority stage), and cars on the non-priority stage (noted as Cars_Non priority stage). The 3 streams are demonstrated in **Figure 6. 4**. Note that buses are always on W-E and E-W directions but may be on the 'major road' or the 'minor road' in different scenarios, according to the relative traffic flows on the W-E (E-W) and N-S (S-N) arms for that scenario.

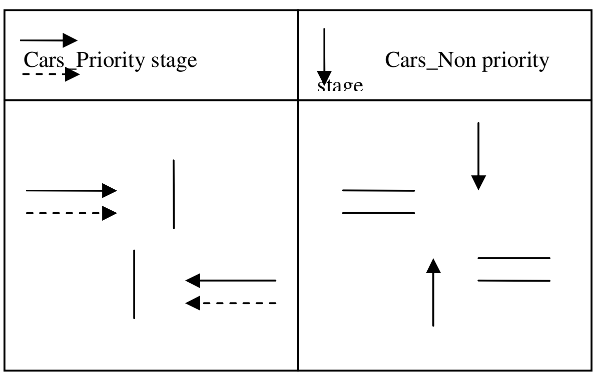


Figure 6. 4 Demonstration of 3 vehicle streams for delay analysis

6.3.1 Overview of delay

Table 6. 4 presents a summary of delay for all scenarios when implementing BL, BP1 and BP2. The results are grouped according to the 3 vehicle streams (i.e. cars_ priority stage, cars_ non priority stage and Buses), 3 DoS values (i.e. 0.6, 0.8 and 0.9), 3 R values (i.e. R1/3, R1/1 and R3/1) and 2 bus flows (i.e. B20 and B60). The percent change of delay after implementing BP1 and BP2 are also given in the same table. Generally implementing the bus priority strategies has reduced bus delay as expected. Cars sharing the same signal stages as buses have also benefited to a smaller extent for most scenarios but a disbenefit can be observed for some scenarios mainly due to the non-optimum compensation facility in

BP2. This is discussed in later sections. The delay to cars on the non-bus stage has been increased by a variable amount according to the scenarios.

The following analysis of delays is all based on the data from this table. An overview is firstly presented in this section, and the delay is further discussed in more detail for each DoS value.

Table 6. 4 Summary of vehicle delay time for all scenarios (unit: second/vehicle)

DoS & Bus flow	R ratio (q1/q2)	Cars_ Priority stage					Cars_ Non priority stage					Buses				
		BL	BP1	BP2	Percent difference (BP1-BL)/BL	Percent difference (BP2-BL)/BL	BL	BP1	BP2	Percent difference (BP1-BL)/BL	Percent difference (BP2-BL)/BL	BL	BP1	BP2	Percent difference (BP1-BL)/BL	Percent difference (BP2-BL)/BL
DoS=0.6																
B20	R1/3	19.26	17.79	18.53	-7.66%	-3.80%	10.06	12.15	11.73	20.80%	16.61%	22.81	7.94	9.49	-65.20%	-58.41%
	R1/1	14.54	13.45	13.88	-7.49%	-4.52%	14.48	16.60	15.96	14.66%	10.19%	17.83	8.26	9.23	-53.66%	-48.24%
	R3/1	9.95	9.43	9.57	-5.18%	-3.80%	19.73	20.79	20.63	5.36%	4.56%	12.37	6.07	6.21	-50.93%	-49.83%
B60	R1/3	19.23	13.68	17.92	-28.89%	-6.84%	10.28	18.59	14.11	80.88%	37.32%	23.21	6.94	12.44	-70.11%	-46.42%
	R1/1	14.45	11.72	13.14	-18.90%	-9.09%	14.85	21.70	18.87	46.17%	27.12%	17.07	7.55	9.81	-55.79%	-42.53%
	R3/1	9.98	8.79	9.12	-11.93%	-8.62%	19.80	23.70	22.93	19.74%	15.81%	11.58	6.00	6.46	-48.16%	-44.17%
DoS=0.8																
B20	R1/3	28.77	25.04	29.95	-12.97%	4.11%	14.43	20.61	17.63	42.85%	22.14%	32.08	10.83	18.67	-66.23%	-41.81%
	R1/1	21.49	19.37	21.51	-9.84%	0.13%	21.35	28.26	25.50	32.39%	19.46%	23.88	12.07	14.49	-49.48%	-39.34%
	R3/1	14.24	13.41	13.79	-5.86%	-3.19%	28.87	32.89	31.99	13.92%	10.83%	14.99	10.12	10.54	-32.47%	-29.70%
B60	R1/3	29.08	16.28	30.31	-44.02%	4.26%	14.74	257.50	22.46	1646.64%	52.37%	32.07	9.23	25.81	-71.22%	-19.54%
	R1/1	21.81	13.53	21.80	-37.96%	-0.04%	21.58	284.46	29.97	1218.03%	38.87%	23.53	11.05	19.94	-53.02%	-15.26%
	R3/1	14.59	11.64	13.55	-20.26%	-7.17%	28.77	66.84	36.82	132.31%	27.98%	15.08	10.72	12.38	-28.91%	-17.93%
DoS=0.9																
B0	R1/3	33.64	28.04	37.88	-16.65%	12.60%	18.56	49.43	23.81	166.37%	28.31%	36.90	12.50	24.81	-66.12%	-32.78%
	R1/1	26.30	22.72	27.60	-13.60%	4.94%	26.07	47.60	32.57	82.62%	24.94%	28.51	14.81	19.66	-48.06%	-31.06%
	R3/1	18.38	16.86	18.02	-8.28%	-1.97%	33.34	42.65	38.51	27.91%	15.51%	19.51	13.07	14.15	-33.02%	-27.50%
B60	R1/3	33.76	15.80	38.77	-53.21%	14.85%	18.91	274.16	29.87	1350.14%	58.02%	36.53	9.38	34.53	-74.33%	-5.48%
	R1/1	26.76	13.25	28.62	-50.50%	6.95%	26.18	350.52	39.55	1238.94%	51.09%	28.39	12.00	28.25	-57.71%	-0.50%
	R3/1	19.01	13.72	17.96	-27.82%	-5.54%	33.37	460.71	45.83	1280.81%	37.36%	19.48	12.34	16.45	-36.62%	-15.54%

6.3.1.1 Effects of bus priority strategies (BP1 and BP2)

The impacts of implementing BP1 are stronger than BP2. In general, the delay of buses with BP1 has reduced to a greater extent while the general traffic sharing priority stage has also benefited, to a smaller extent. These delay savings are at a cost of delay increases of cars on the non-priority stage. **Figure 6. 5** shows a typical example of delay when implementing 3 signal control plans, (i.e. Baseline, BP1 and BP2) for scenario DoS0.6_R1/1_B20. Delay of three vehicle streams, i.e. Buses, Cars_Priority stage and Cars_Non-priority stage are illustrated in this figure.

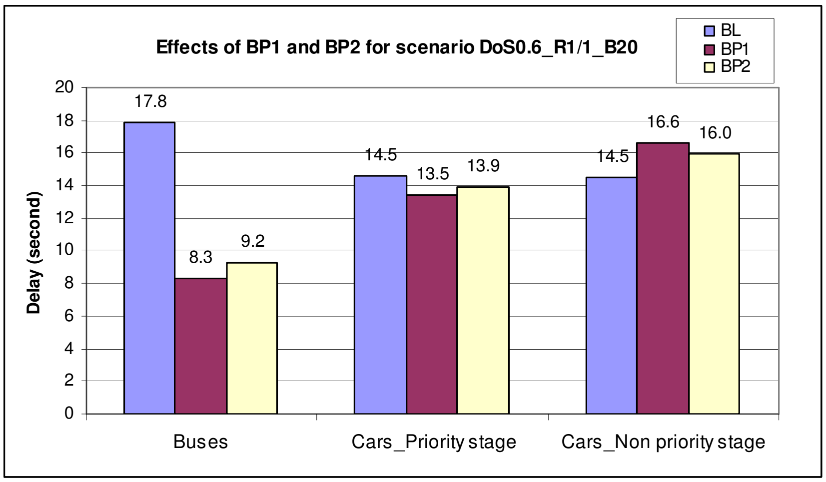


Figure 6. 5 Delay of 3 vehicle streams (Buses, Cars on thePriority stage and Cars on the Non-priority stage) when implementing BL, BP1 and BP2 for scenario DoS0.6_R1/1_B20

We can see that after implementing BP1 strategy, a 53 % reduction of bus delay has been achieved, (from 17.8s to 8.3s). Cars on priority stage have also gained about 7% delay saving (from 14.5s to 13.5s). This is because the overall proportion of green time allocated to the priority stage has increased due to bus priority. For cars on non-bus stage there is a 15% increase in delay, (from 14.5s to 16.6s). The BP2 strategy has resulted in less effect on all vehicle streams because the compensation and inhibition facilities has reduced the strength of bus priority by introducing compensation facilities to the non-priority traffic.

This is a typical example of the effect on delay when implementing 2 bus priority strategies. Scenarios with other DoS values, R values and bus flows generally have a similar trend but to various extents. The level of delay changes is also influenced by other factors such as DoS values, R values and bus flows, which are presented separately in later sections. For some particular scenarios the impacts can be extreme, due to the individual or combined effects by these factors. The following discussion therefore focuses on the effects of these factors.

6.3.1.2 Effect of DoS values

As an example, **Figure 6. 6** shows the delay to Cars on the priority stage when implementing BL, BP1 and BP2 in 3 scenarios under 3 DoS values 0.6, 0.8 and 0.9 with the fixed R and B values (R=1/3 and B=20). The figure shows under the same signal control the delay of cars on the priority stage has increased with the increasing DoS values. The delay under BL has increased by 49% from DoS 0.6 to 0.8 (19.3s to 28.8s) and by a further 17% from DoS 0.8 to DoS 0.9 (28.8s to 33.6s). The same trend can be found for the other 2 signal control strategies -BP1 and BP2.

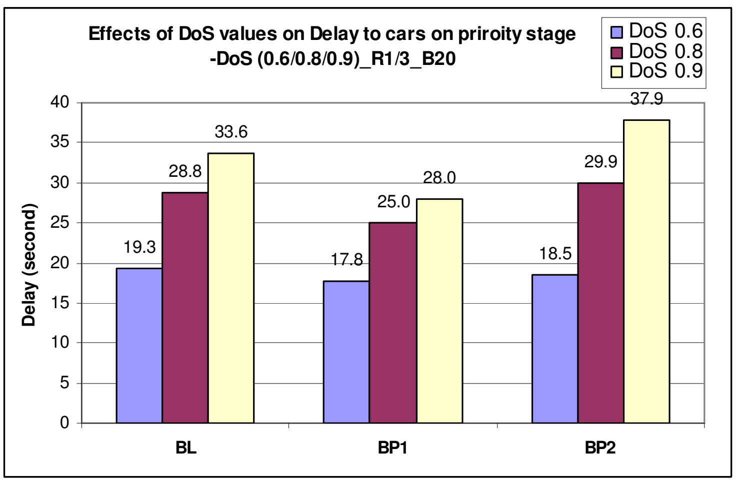


Figure 6. 6 Effects of DoS values on delay to cars on the priority stage for scenarios DoS (0.6/0.8/0.9)_R1/3_B20

The same trend can be found for other vehicle streams and in other scenarios, with the data presented in **Table 6. 4**. This shows that in addition to the percent change caused by implementing bus priority strategies, the absolute values of delay increase with increasing DoS values. For evaluating the overall performance of efficiency, this difference on the absolute values could result in the difference in the later overall monetary valuation.

Figure 6. 6 is an example showing a scenario with relatively good performance. If combine the effects of other factors such as R values and Bus flows, the effects of DoS values can be significantly enlarged. For example using B60 instead of B20, the performance of some particular scenarios under the 3 DoS values has seriously deteriorated. **Figure 6. 7** shows the combined effects when implementing strong bus priority (BP1) under heavy traffic

conditions (DoS 0.8 and 0.9) to a high bus flow (B60) where we can see the delay to cars on the non priority stage has substantially increased (from 18.6s in DoS0.6 to 257.5s in DoS0.8). This is because for a heavier traffic condition, the capability of the junction to tolerate flow and signal fluctuation decreases. The excessive queues on the non-priority stage generated by implementing strong and frequent bus priority strategies can not be discharged immediately or within short time intervals thus more queues have been accumulated. As a result, substantial delay has occurred for non -priority traffic.

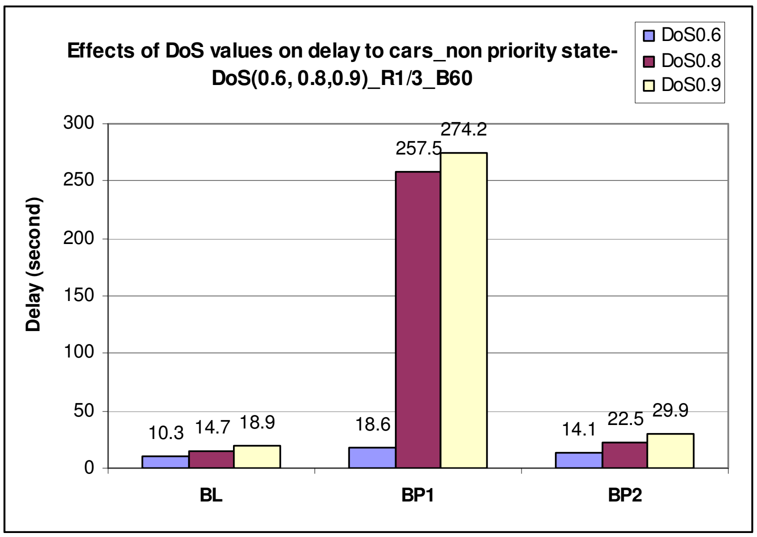


Figure 6. 7 Effects of DoS values on delay to cars on the non priority stage with high bus flow– DoS (0.6/0.8/0.9)_R1/3_B60

6.3.1.3 Effects of R values (q1/q2)

The 'R' value describes the flow evenness of a junction. R1/3 can be regarded as buses on the minor road and R3/1 can be regarded as buses on the main road. R1/1 represents evenly distributed flows on all arms in a junction. For a particular DoS value, an obvious delay difference between R values can be seen. **Figure 6. 8** shows an example of delay to 3 vehicle streams for 3 R values under the BL signal control, (i.e. buses, cars on the priority stage and cars on the non-priority stage).

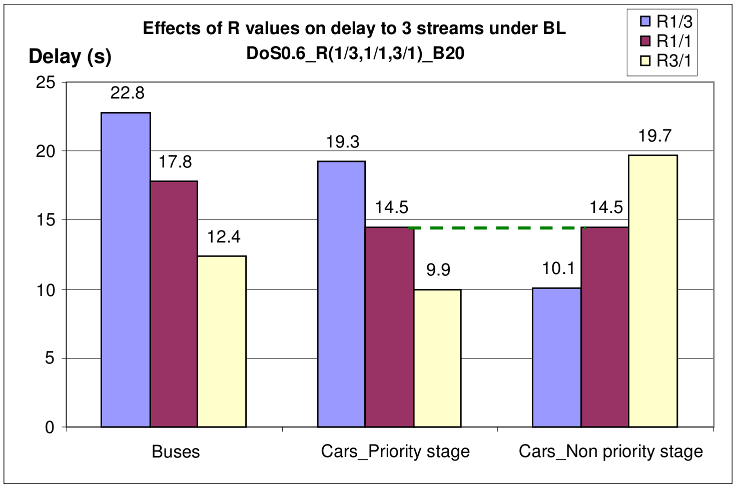


Figure 6. 8 Effects of R values on delay to 3 streams under BL signal control

Generally when R value is 1/1, i.e. the flows are balanced on all arms, the delays of the 2 car streams, i.e. cars_Priority stage and Cars_Non priority stage are very similar (both 14.5s in this figure). When the flows from the 2 directions are unevenly proportioned, i.e. comparing delay of the 2 car streams for R3/1 or R1/3, the delay for the 2 streams becomes uneven. This can be explained by the empirical delay estimation formula developed by Webster (1958) which was reviewed in 2.3.1. The delay difference in terms of R values is mainly caused by the different proportions of effective green in a cycle for different R values, given a fixed intergreen time. For R1/1 when the proportions of effective green time for both stages are the same then so as the delay to both car streams. For R1/3 or R3/1, the proportion the effective green time for the lighter traffic in a cycle is smaller than the proportion for heavier traffic; the delay to the lighter traffic is therefore greater.

The R value also has a considerable impact on the effectiveness of bus priority. The most extreme impacts of R values always appear with combined effects of high bus flows and strong bus priority strategies. For example as shown in **Figure 6. 9** for the high DoS value 0.9, the delay increase to the non-priority cars after implementing BP1 on minor or non-main road (i.e. R1/3 and R1/1) was extremely high, as 257.5s and 284.5s respectively. However when buses are on the main road (R3/1), the delay increase to these cars was much smaller.

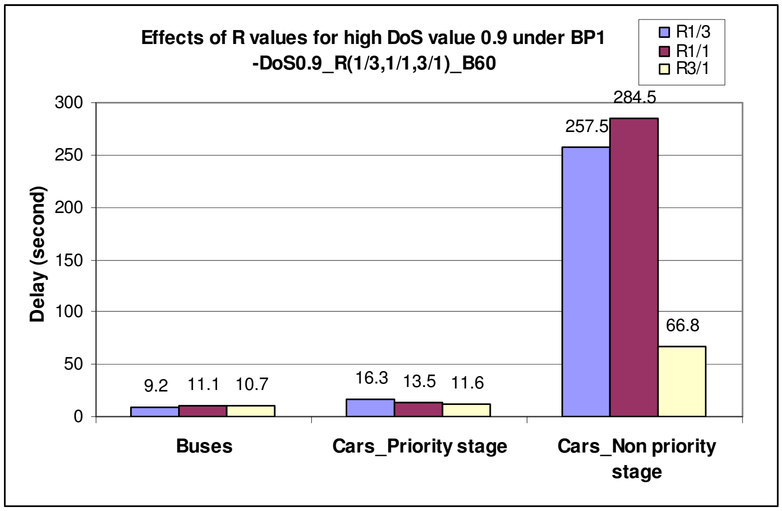


Figure 6. 9 Effects of R values for high DoS value 0.9 under BP1 for scenarios DoS0.9_R(1/3,1/1,3/1)_B60

6.3.1.4 Effects of B values (bus flows)

There are two B values (bus flows) considered in this study. B20 (20buses/hour) represents a typical bus frequency in urban cities and B60 (60buses per hour) represents a high bus frequency in areas with dense bus routes. A low bus frequency has not been studied here as impacts on emissions should be low. The cases study showed that when bus flow was high, giving priority to all buses could result in severe excessive delay to general traffic on the non-bus stage. It was especially obvious with heavy traffic conditions and buses on the minor road. **Figure 6. 10** shows an example of the effects of bus flows on delay to cars on the non-priority stage for scenario DoS0.8_R1/3 with both B20 and B60.

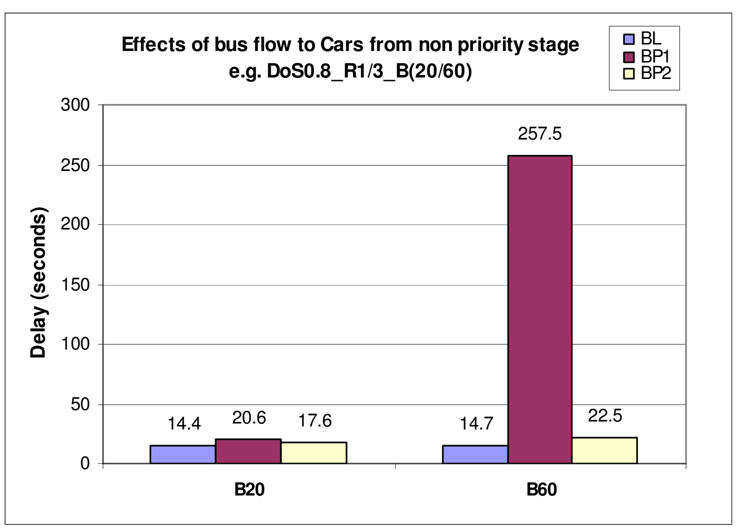


Figure 6. 10 Effects of bus flows to Delay of Cars_ Non priority stage for Scenario DoS0.8_R1/3_B(20/60)

When bus flow was 60 per hour, implementing BP1 had resulted in a 1650% delay increase to the cars on non-priority stage (from 14.72s to 257.5s). This was mainly due to the largely increased frequency of giving green extension and recall to buses which has reduced the green time for cars on the non priority stage. Implementing BP2 has reduced this severe impact but still resulted a 52.12% delay increase (from 14.7s to 22.5s). Compared with the scenario with B20 with other factors, the side effects for B20 were much lower. The percentage increase of delay to cars from the non-priority stage after implementing BP1 and BP2 for B20 were respectively 43.42% and 22.09% (from 14.4s to 20.6s for BP1 and 17.6s for BP2).

The following 3 sections analyse delay under each DoS value. For each DoS, the best and the worst-case scenarios in terms of the side impacts to the non-priority traffic are identified and analysed.

6.3.2 Delay for DoS 0.6

DoS 0.6 represents a relatively free flow situation. It means the junction has potential to tolerate and absorb queues caused by implementing bus priority strategies at traffic signals. Comparing with the other 2 DoS values, scenarios under DoS 0.6 were the least affected in general. As the results shown in **Table 6. 4**, in all 6 scenarios under DoS 0.6, buses have benefited from both priority strategies to a large extent, with delay savings ranging from 48.16% to 70.11% for BP1 and 42.53% to 58.41% for BP2. The car streams sharing the same signal stage with buses have also gained moderate delay savings ranging from5.18% to 28.89% after implementing BP1 and 3.80% to 9.09% savings after BP2. The cars on the non priority stage have been affected with a delay increase ranging from 5.36% to 80.88% after BP1 and 4.56% to 37.32% after PB2. In general, the effects on delay changes after implementing BP1 were greater than BP2.

The Best-case scenario in DoS0.6

Figure 6. 11 shows the best case scenario in DoS 0.6 -DoS0.6_R3/1_B20 in terms of the minimum delay increase to the non priority traffic, with delay increase by 5.36% and 4.56% after BP1 and BP2 respectively. In this case, buses have gained about 50% delay savings after implementing BP1 and BP2. This means for this scenario, buses can achieve large benefit on delay savings while the side effects to the non priority traffic are the minimal. For this scenario the difference of the impacts by strategies BP1 and BP2 is not obvious.

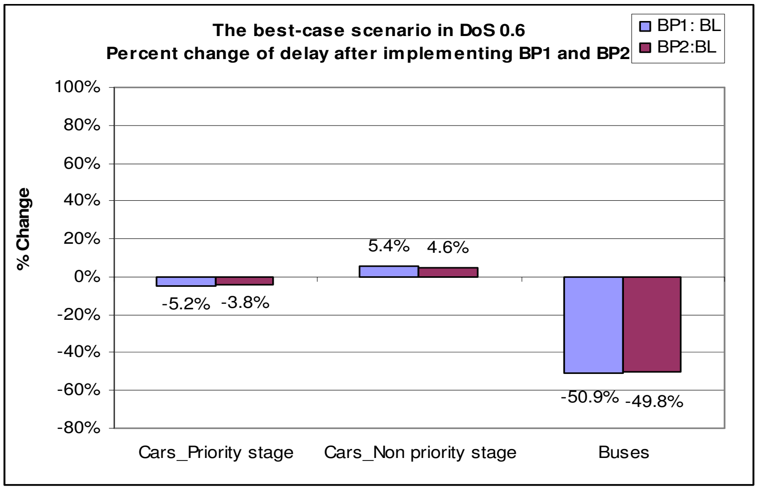


Figure 6. 11 The best-case scenario in DoS 0.6 in terms of the minimum delay increase to the non priority traffic

The Worst-case scenario in DoS 0.6

The worst case scenario in DoS 0.6 in terms of the maximum delay increase to cars on the non priority stage is DoS0.6_R1/3_B60 (as shown in **Figure 6. 12**) with a maximum of 80.88% (from 10.28s to 18.59s) delay increase to the non-priority traffic.

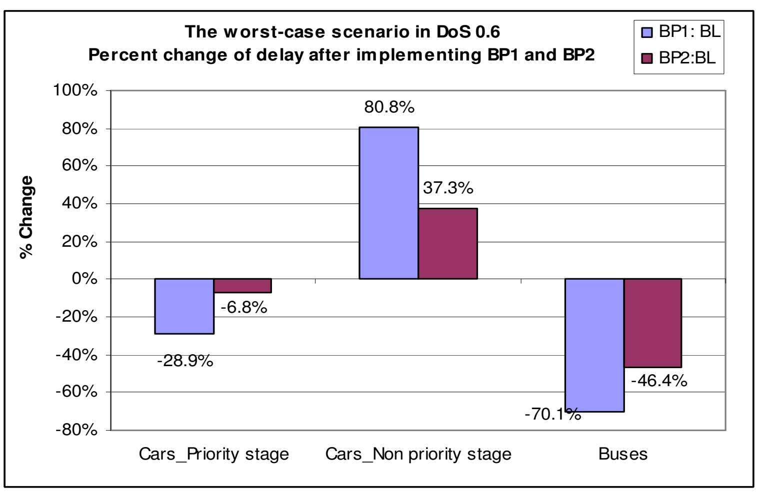


Figure 6. 12 The worst-case scenario in DoS 0.6 in terms of the maximum delay increase to the non priority traffic

For this scenario buses have been able to gain a 70% delay reduction on (from 23.2s to 6.9s) after implementing BP1 and cars on the priority stage have obtained a 27.63% delay savings (from 19.2s to 13.7s). The extent of delay savings for both buses and priority car traffic is greater than in the best-case scenario, however the delay to the cars on the non-priority stage for this scenario has increased by 80.88% after implementing BP1, from 10.3s to 18.6s. Again, implementing BP2 has reduced the strength of bus priority as expected and eased the side effect, at a cost of reducing the benefit to buses. From the so-called 'best' and 'worst' scenarios in the delay analysis, it is obvious that an optimising criterion or an 'acceptance level' needs to be set up to help decide the 'best' scenario in real implementation- whether a scenario with moderate benefit to bus delay savings with the minimum impact to the general traffic or a scenario with the maximum benefit to buses but with a moderate side impact to the non-priority traffic.

In summary, the results indicated that for DoS 0.6, buses were able to obtain noticeable delay savings in all scenarios after implementing BP1 and BP2. For the general traffic on the non priority stage, the worst case scenario in terms of the maximum delay occurred for high bus flows on the minor road, i.e. R 1/3 and B60. However compared with the higher DoS values in the later analysis, the highest side impacts for DoS 0.6 were still relatively low (about 7s/car increase after BP1 and 3s/car increase after BP2).

6.3.3 Delay for DoS 0.8

For a heavier traffic condition with DoS value 0.8, implementing BSP has a greater impact to the general traffic compare with a freer traffic condition. **Table 6. 4** shows for all scenarios in DoS 0.8 buses were still able to gain a range of 32.47% to 71.22% delay savings after implementing BP1, and a range of 15.26% to 39.34% delay savings after implementing BP2. It is obvious that the extent of bus delay savings in DoS 0.8 after implementing BP2 has been reduced compared to DoS 0.6, yet still considerable. The delay of car traffic on the non-priority stage has substantially increased by a range of 13.92% to 1646.64% after BP1 and a range of 10.83% to 52.37% after BP2. The most extreme delay increase to the non-priority traffic after BP1unde DoS 0.8 occurred in 3 scenarios with high bus flows (B60). The increase was especially extreme with buses on the minor road. Cars on the priority stage were able to achieve a range of 5.86% to 44.02% delay savings after implementing BP1 and the extent has been largely reduced after BP2 with some scenarios a maximum 4.11% delay increase can be observed.

DoS 0.8 represents a traffic situation that under the baseline signal plan all queuing vehicles can be cleared within a cycle. However implementing BP1 has reduced the capacity of arms N-S and S-N due to the reduction of total green time assigned to their stage therefore congestion can occur. **Figure 6. 13** demonstrates the delay of cars on the non-priority stage with B60 when implementing BL, BP1 and BP2 for all 3 R vales.

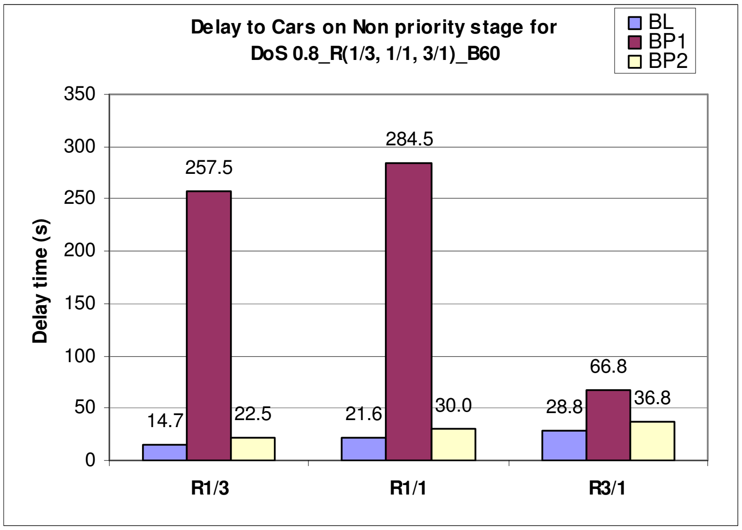


Figure 6. 13 Delay to cars on the non priority stage for scenarios DoS0.8_B60 for 3 R values (i.e. 1/3, 1/1 and 3/1)

For R 1/3 and 1/1, the delay to cars on the non priority stage after implementing BP1 has increased by more than 1000%. It should be noted that the delay (257.5s and 284.5s) have been underestimated and the actual delay should be higher than these values and delay for R1/3 should be higher than that for R1/1. This is because during simulation, queuing vehicles on the non-priority stage were constantly formed due to frequent bus priority provision; entering vehicles had to wait outside of the network to enter. As the flow was much greater than the capacity of the arm, at the end of the simulation, a large number of vehicles could not enter the arm. Aimsun did not take these vehicles into account in the delay calculation until they entered the network. Therefore the actual flow on the non-priority stage after implementing BP1 was less than the designed flow and the delay has been underestimated. In practice, implementing BP1 without considering compensation or inhibition for high DoS values is impractical and is not recommended. For the following delay analysis for DoS 0.8 and DoS 0.9, only BP2 strategy is the focus.

After implementing BP2, buses were still able to obtain considerable delay savings while the delay changes to cars on the priority stage became unclear where we can observe delay increase for some scenarios. This is probably due to the over added compensation time to the non-priority traffic due to very frequent demand for bus priority when bus flow is high. Compensation time is a fixed time period added in the next cycle to the opposite flows after a recall is granted, therefore it might be not sophisticated enough to reflect the real time signal demand of the opposite traffic. This could have disturbed the signal timings based on optimal delay.

The best-case scenario in DoS 0.8

The best-case scenario in DoS 0.8 in terms of the minimum impact on the non-priority traffic was when implementing BP2 to lower bus flow on the main road only-scenario DoS0.8_R3/1_B20. The percentage change of delay after BP2 for 3 traffic streams for this scenario is illustrated in **Figure 6. 14.**

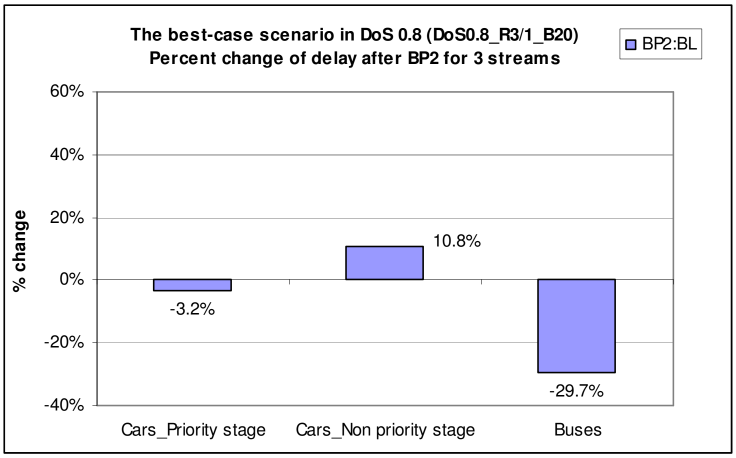


Figure 6. 14 The best-case scenario in DoS 0.8 in terms of the minimum delay increase to the non priority traffic

The figure shows that after implementing BP2 buses have achieved a 29.7% delay saving while cars on the priority stage have also benefited by 3.2% delay reduction. Delay of cars on the non-priority stage has increased by 10.8 which is about 3 seconds per car in this case.

The worst-case scenario in DoS 0.8

The worst case scenario, excluding the extreme impacts of implementing BP1, is DoS0.8_R1/3_B60 as shown in **Figure 6. 15**. It shows that after implementing BP2 only 19.54% bus delay saving has been achieved (from 32.1s to 25.8s) but a 52.37% delay increase has been added to the non-priority traffic (from 14.74s to 22.5s). A 4.26% delay increase to the cars on the priority stage was also observed (from 29.1s to 30.3s), probably due to the compensation settings as explained previously. This scenario shows that the efficiency of the junction has been affected because of the implementation of bus priority strategies.

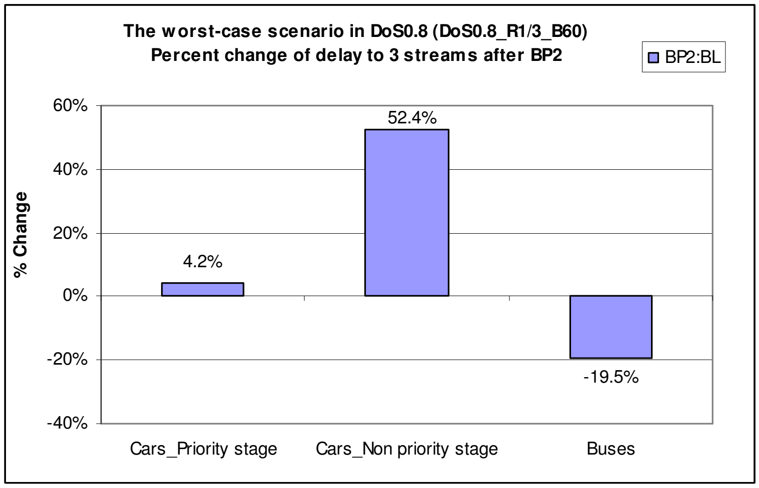


Figure 6. 15 The worst-case scenario in DoS 0.8 in terms of the maximum delay increase to the non-priority traffic

In fact, for all 3 scenarios with B60, the increase of delay to cars on the non-priority stage was relatively high than for B20. As shown in **Figure 6. 16**, a clear trend can be seen that the percentage delay increase to the non-priority traffic when bus flow was 60 has more than doubled to the delay increase when bus flow was 20. The least delay increase for B60 was 28.37% and for B20 is 10.9%.

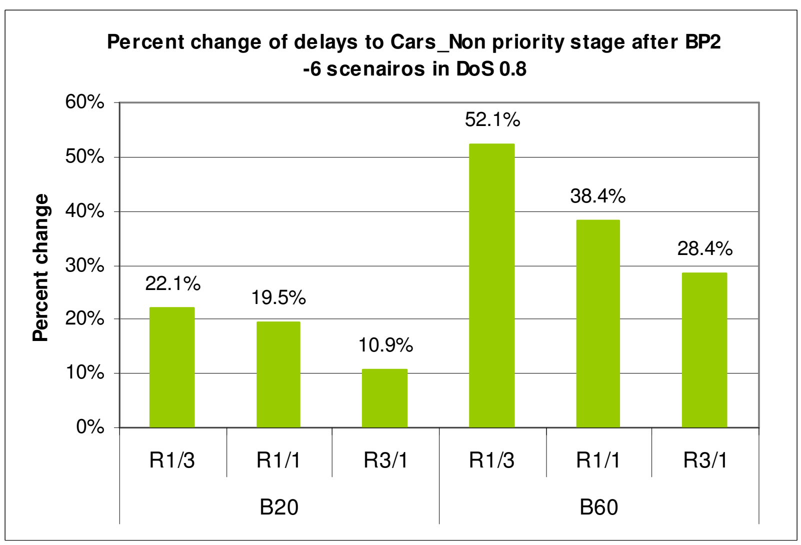


Figure 6. 16 Percent change of delays to Cars_ Non priority stage after implementing BP2 for 6 scenarios for DoS0.8

This suggests that when traffic condition becomes heavier, more scenarios have deteriorated from implementing bus priority strategies. When the DoS value increases to 0.9, the extents of the side impacts have further increased, as discussed in the following section.

6.3.4 Delay for DoS 0.9

A DoS value 0.9 suggests a near-capacity traffic condition where any small flow fluctuations could cause severe delays and queues. As explained before, BP1 is impractical and not recommended for high DoS values, so only BP2 is discussed here. **Figure 6. 17** shows that for DoS 0.9 the delay savings gained by buses after implementing BP2 have been greatly reduced, and **Figure 6. 18** shows that the side effect to the non priority car traffic has further increased.

For all 3 scenarios with bus flow 20/ hour in DoS 0.9, the maximum bus delay saving after implementing BP2 was 30%, while for bus flow 60/ hour, the delay savings obtained by buses have been greatly reduced to a range of only 0.5% to 15.5%, as shown in **Figure 6. 17**.

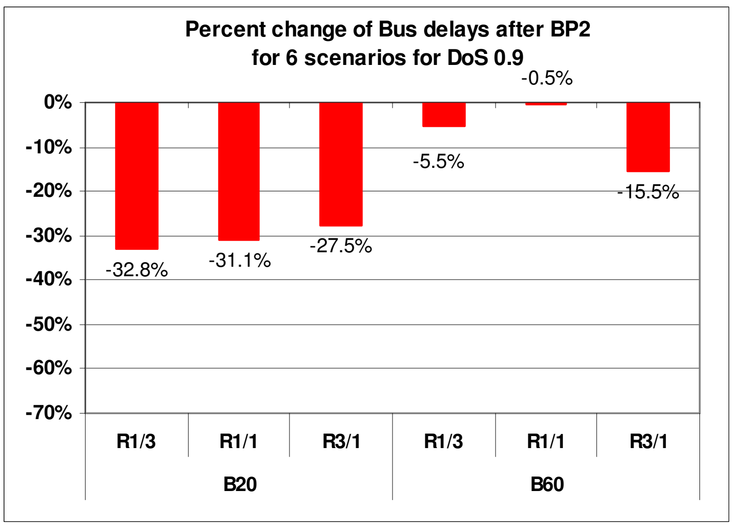


Figure 6. 17 Percent change of bus delays after BP2 for 6 scenarios in DoS 0.9

The delay to cars on the non- priority stage as shown in **Figure 6. 18** has further increased compared to DoS 0.8, especially when bus flow was 60 per hour, the delay increase ranged from 15.5% to 28.3% for B20 and 37.4% to 58.0% for B60.

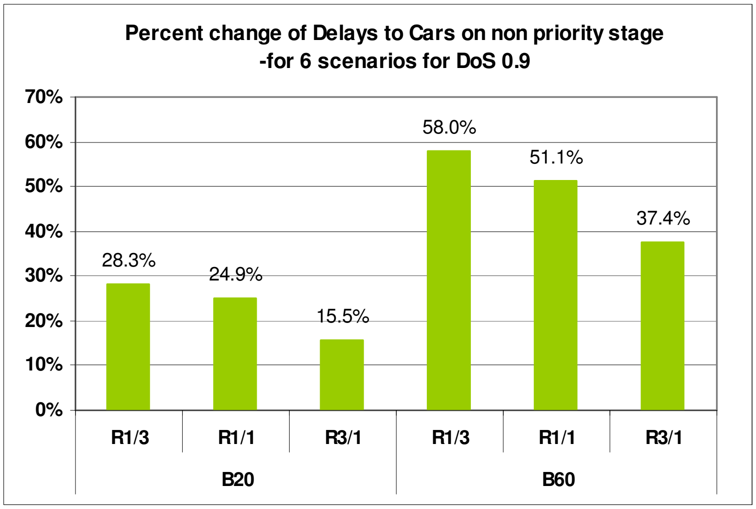


Figure 6. 18 Percent change of delay to Cars on the Non priority stage after BP2 for DoS 0.9

The 2 figures above indicate that when the DoS value is high, implementing bus priority strategies even including compensation and inhibition facilities can be less beneficial and could even cause a net disbenefit. The small delay savings achieved by buses is at the cost of the increased delay to other traffic at a much greater level.

The **best-case** and the **worst-case scenarios** in DoS 0.9 in terms of the minimum and the maximum delay increase to the non-priority traffic were DoS 0.9_R3/1_B20 and DoS0.9_R1/3_B60, which was in accordance with the scenarios in DoS 0.6 and 0.8. The delay increase to the non priority traffic was 15.51% and 58.09% respectively for the best and the worst case scenarios. For these 2 scenarios, the percentage of bus delay savings were 27.5% and 5.48%. For the worst-case scenario, a 14.85% delay increase to the priority car traffic can be observed. These data are not illustrated in figures as the trend is similar to **Figure 6. 14** and **Figure 6. 15**, only worse (i.e. smaller benefit to buses and greater disbenefit to general traffic).

Generally, for heavy traffic conditions, the junction was unable to accommodate the disturbance to the pre-optimised signal control plans, therefore the overall efficiency of the junction has been reduced. The results suggest that implementing BSP at near-capacity junctions may not be an overall beneficial option. For a junction with high DoS value, strong bus priority strategies, e.g. BP1 is not recommended and compensation and inhibition should be considered. However the current method of calculation for the compensation time might be too coarse to reflect the real time traffic demand thus the overall efficiency of general traffic could be reduced.

6.3.5 Average person delay

The previous analysis mainly has focused on the evaluation of average vehicle delays in terms traffic streams, including buses, cars on the priority stage and cars on the non-priority stage. Vehicle delay can be used to evaluate the effectiveness of implementing BSP, i.e. the extent of delay reduction to buses and the side effects to the non priority traffic. The average person delay is also an important indicator. The average person delay is estimated combining delays of vehicles and their average vehicle occupancy. The average occupancy according to Web TAG 3.5.6 (DfT 2009a) for cars is 1.63 and 12.20 for buses (passengers only). Using these 2 values with combination of the delay results per vehicle as shown in **Table 6. 4**, the delay per person can be calculated using equation below:

$$Average \quad person \quad delay = \frac{1.63 \times (delay / car) \sum(cars) + 12.20 \times (delay / bus) \sum(buses)}{Total \quad passengers}$$

The results for scenarios under the 3 DoS values are summarised in **Table 6. 5**, **Table 6. 6** and **Table 6. 7** respectively.

Table 6. 5 Summary of delay per person for DoS 0.6

Delay per person (s)	Signal control plans			Percent Difference (%)	
Scenarios (DoS 0.6)	**BL**	**BP1**	**BP2**	**BP1: BL**	**BP2: BL**
DoS0.6_R1/3_B20	21.1	9.4	10.7	-55.3%	-49.4%
DoS0.6_R1/3_B60	21.4	8.9	13.2	-58.6%	-38.4%
DoS0.6_R1/1_B20	17.1	9.7	10.4	-43.4%	-39.1%
DoS0.6_R1/1_B60	16.6	9.5	11.1	-42.8%	-32.9%
DoS0.6_R3/1_B20	12.9	8.0	8.1	-38.1%	-37.3%
DoS0.6_R3/1_B60	12.3	8.2	8.5	-33.5%	-30.9%

This table indicates that from the viewpoint of average person delay combining passengers on both cars and buses, implementing both BP1 and BP2 has substantially reduced the average person delays in all the 6 scenarios under DoS 0.6. The degree of reduction ranges from 30.9% to 58.6%. Therefore it can be concluded that under a free flow traffic condition, BSP is an effective method to reduce the average delay per person.

Table 6. 6 Summary of delay per person for DoS 0.8

Delay per person (s)	**Signal control plans**			**Percent Difference (%)**	
Scenarios (DoS 0.8)	**BL**	**BP1**	**BP2**	**BP1: BL**	**BP2: BL**
DoS0.8_R1/3_B20	29.9	13.4	19.7	-55.3%	-33.9%
DoS0.8_R1/3_B60	29.9	36.1	25.9	20.8%	-13.4%
DoS0.8_R1/1_B20	23.4	14.5	16.4	-37.8%	-29.8%
DoS0.8_R1/1_B60	23.1	40.1	21.2	73.5%	-8.4%
DoS0.8_R3/1_B20	16.4	12.9	13.1	-21.4%	-19.7%
DoS0.8_R3/1_B60	16.5	16.7	15.1	1.6%	-8.5%

Table 6. 6 shows that under a heavier traffic condition, the degree of benefit of average person delay by implementing BSP has generally been reduced. Implementing BP2 is beneficial to all 6 scenarios, with a range of 8.4% to 33.9% delay reduction per person. The person delay has increased in 3 scenarios after implementing BP1mainly because the extreme delay increase to the non-priority traffic has overweighed the delay savings by buses. As explained before, the disbenefit of cars on the non priority stage for these 3 scenarios especially DoS0.8_R1/3_B60 and DoS0.8_R1/1_B60 has been underestimated, and the real values of person delay should be higher than the displayed values.

The results indicate that for DoS 0.8, implementing BP2 is beneficial to all scenarios in terms of average person delay. Implementing BP1 is beneficial to scenarios with low bus flows (B20) only, and a disbenefit ranging from 1.6% to (more than) 73.5% of person delay would occur to scenarios with high bus flows (B60).

Table 6. 7 Summary of delay per person for DoS 0.9

Delay per person (s)	**Signal control plans**			**Percent Difference (%)**	
Scenarios (DoS 0.9)	**BL**	**BP1**	**BP2**	**BP1: BL**	**BP2: BL**
DoS0.9_R1/3_B20	34.6	18.0	26.1	-47.9%	-24.7%
DoS0.9_R1/3_B60	34.4	38.0	34.5	10.4%	0.3%
DoS0.9_R1/1_B20	28.0	19.1	21.9	-31.8%	-22.0%
DoS0.9_R1/1_B60	28.0	47.8	29.5	70.9%	5.3%
DoS0.9_R3/1_B20	20.9	16.6	17.1	-20.5%	-17.9%
DoS0.9_R3/1_B60	20.9	59.8	19.7	186.1%	-5.7%

Table 6. 7 shows that for 2 scenarios under a higher DoS value, the average delay per person has increased even after implementing BP2, with high bus flows on non-main road. This table indicates that from the viewpoint of average person delay for the whole junction, BP2 is not recommended for high bus flows on minor or non-main road.

6.3.6 Summary of delay

In general, the impacts of implementing BP1 on vehicle delays were stronger than BP2. Buses have gained delay savings to various degrees after implementing both BP1 and BP2. Cars sharing the same signal stages with buses have also gained different levels of delay savings for most scenarios, except for some scenarios under higher DoS values where disbenefits were observed after implementing BP2, with high bus flows on the minor road. This is probably because of the over added compensation time to the non-priority traffic after a recall was granted. Cars on the non-priority signal stage have been affected due to the reduced green time allocated to the non priority stage. For some scenarios implementing BP1 has caused extreme delay increase suggesting severe congestion, therefore is not recommended in real world implementation.

The effects of 3 key factors have been discussed in detail in this section, which were DoS values, R values and Bus flows. Several general points are summarised as follows.

- In general, the higher the DoS is the lower the BSP benefits to buses can be achieved, and the higher disbenefits to the general traffic;
- When implementing BSP to buses on the major road, the side effect to the non priority traffic is relatively small; when buses are on the minor road, implementing priority especially BP1 can result in significant delay increase for some scenarios.
- When buses are on one signal stage (i.e. without conflicting priority demand) the higher the bus flow is the greater the benefit of BSP to buses can be caused. However implementing priority to a high bus flow can result in larger delay increase to the non priority traffic, especially when combined with high DoS values or buses on the minor road.
- The best-case scenarios under 3 DoS in terms of a minimum side effect to the non priority traffic are implementing priority to low bus flows on a major road; the worst-case scenarios, on the contrary are implementing priority to high bus flows on a minor road.

In terms of average person delay for a junction combining vehicle delays and vehicle occupancy, the impacts of implementing BSP under different situations are summarised as follows:

- Implementing both BP1 and BP2 to all scenarios under a free traffic condition (i.e. DoS 0.6) is an overall beneficial measure, with considerable person delay reduction.
- For a heavier traffic condition (i.e. DoS 0.8) an overall disbenefit can be resulted if implementing strong strategy BP1 to the scenarios with high bus flows.

Implementing both strategies to all other scenarios is beneficial, to various extents. For this traffic condition, BP2 is more appropriate and an overall benefit can be obtained for all scenarios to a smaller but still significant extent.

- When the traffic condition gets heavier, i.e. DoS 0.9, similarly to DoS 0.8, implementing BP1 has resulted in delay increase for scenarios with high bus flows. In addition, in this case a slight disbenefit after implementing BP2 was also observed forscenarios with high bus flows on the non-main road (i.e. R1/3 and R1/1). This is probably partly caused by the design of compensation time which is not sophisticated to reflect the real time traffic demand therefore the efficiency of the junction was decreased by implementing BSP. This indicates implementing BSP under a near-capacity traffic condition is not recommended. Near capacity traffic condition is less competent to tolerate the flow fluctuation, therefore the basedlin signal control method, the forms and sophistication of BSP should be better designed and carefully optimised.

6.4 Results analysis: Emissions

The impacts of implementing bus priority strategies on emissions are more complex than delay. The ranges of the percent change for the four pollutants, i.e. CO_2, NOx, VOC and PM vary due to the different mechanism of the formation and emitting process of these pollutants. Meanwhile apart from the key factors such as DoS values, R values and bus flows which affect the impacts of BSP, the proportion of vehicle types is also important. In the following sections an overview of the impacts of BSP on bus and car emissions including effects of the key factors is firstly presented, and then the emissions for each DoS value are discussed. The percent and absolute emission change are both analysed.

Table 6. 8 to **Table 6. 11** summarise the results of average emissions per car, average emissions per bus, and the average overall emissions per hour. These 4 tables contain data for 4 pollutants in all the 18 scenarios when implementing 3 signal control plans, i.e. BL, BP1 and BP2. The percent change of emissions by implementing BP1 and BP2 is also included in the tables. The values for cars and buses are in the unit of g/car and g/bus, and for the combined emissions from all vehicles are in unit of g/hour/junction.

The reason of using 'g/vehicle' for cars and buses is this unit is more comparable among different scenarios because traffic flows for different scenarios vary. It can more clearly demonstrate the **average** emission changes resulted from BSP. If necessary the hourly emissions from cars and buses can be easily calculated by multiply the average emissions (per car or per bus) by the traffic flows summarised in **Table 6. 2**.

For emission evaluation, apart from the percent change, the absolute amounts are also an important indicator. Using g/hour for the overall emissions can provide a better overlook of what the overall emissions (including all cars and buses) are for a scenario and how these emissions have changed due to the implementation of BSP. The absolute values are even more important for CO2 evaluation as to achieve the national or city-wide target (e.g. in London) of reducing CO2 emissions this allows an approximate estimation of hourly/daily or even annually CO2 change .

Table 6. 8 Summary of CO_2 emissions for cars, buses and all vehicles for all scenarios under 3 DoS values (unit: g/car or g/bus for cars and buses, g/hour for all vehicles)

DoS & Bus flow	R	CO_2- Cars (g/car)					CO_2- Buses (g/bus)					CO_2-All vehicles (g/hour/all vehicles)				
		BL	BP1	BP2	Percent difference		BL	BP1	BP2	Percent difference		BL	BP1	BP2	Percent difference	
					BP1/BL	BP2/BL				BP1/BL	BP2/BL				BP1/BL	BP2/BL
DoS=0.6																
B20	R1/3	153.11	156.73	155.55	2.37%	1.59%	1318.6	1206.7	1171.0	-8.49%	-11.20%	595953.24	607186.35	602058.69	1.88%	1.02%
	R1/1	159.23	160.70	160.33	0.93%	0.69%	1309.7	1184.3	1178.6	-9.57%	-10.01%	618517.66	621501.52	619985.50	0.48%	0.24%
	R3/1	154.59	153.23	153.31	-0.88%	-0.83%	1264.2	1134.0	1131.9	-10.30%	-10.47%	600349.11	592699.53	592932.80	-1.27%	-1.24%
B60	R1/3	153.03	163.98	158.06	7.16%	3.29%	1304.6	1142.4	1184.4	-12.43%	-9.21%	623054.64	652320.11	633772.50	4.70%	1.72%
	R1/1	160.54	161.30	160.20	0.47%	-0.22%	1256.6	1152.4	1174.9	-8.29%	-6.50%	646924.04	643379.48	640393.37	-0.55%	-1.01%
	R3/1	155.51	153.48	153.31	-1.30%	-1.41%	1210.4	1121.6	1112.9	-7.33%	-8.05%	626226.37	613675.28	612561.39	-2.00%	-2.18%
DoS=0.8																
B20	R1/3	157.02	164.04	160.60	4.47%	2.28%	1336.24	1221.50	1258.86	-8.59%	-5.79%	849508.23	883988.34	866733.40	4.06%	2.03%
	R1/1	162.00	164.97	163.87	1.83%	1.15%	1301.18	1226.11	1243.57	-5.77%	-4.43%	874924.72	888963.38	883556.02	1.60%	0.99%
	R3/1	156.81	156.83	156.78	0.01%	-0.02%	1246.52	1201.86	1202.50	-3.58%	-3.53%	846619.14	845815.81	845576.77	-0.09%	-0.12%
B60	R1/3	157.97	271.68	165.72	71.99%	4.91%	1333.73	1197.23	1270.88	-10.23%	-4.71%	882500.56	1451989.31	918120.22	64.53%	4.04%
	R1/1	163.35	268.42	166.90	64.33%	2.17%	1301.53	1228.30	1265.51	-5.63%	-2.77%	907892.65	1437269.64	923759.40	58.31%	1.75%
	R3/1	157.93	162.96	157.83	3.19%	-0.06%	1245.71	1216.38	1216.12	-2.35%	-2.38%	877002.54	900796.59	874732.53	2.71%	-0.26%
DoS=0.9																
B20	R1/3	185.29	218.76	191.34	18.07%	3.27%	1353.28	1246.04	1296.53	-7.92%	-4.19%	997965.56	1171247.50	1028534.88	17.36%	3.06%
	R1/1	190.54	201.30	194.03	5.65%	1.83%	1346.22	1271.90	1296.33	-5.52%	-3.71%	1025355.12	1080252.19	1042661.60	5.35%	1.69%
	R3/1	184.80	185.31	185.25	0.28%	0.24%	1301.85	1250.16	1260.15	-3.97%	-3.20%	994397.56	996037.48	995924.45	0.16%	0.15%
B60	R1/3	186.32	274.06	198.77	47.09%	6.68%	1352.63	1204.37	1324.34	-10.96%	-2.09%	1027669.10	1464497.39	1089223.27	42.51%	5.99%
	R1/1	192.20	274.37	199.97	42.75%	4.04%	1335.76	1239.04	1334.67	-7.24%	-0.08%	1056529.78	1468152.87	1095907.86	38.96%	3.73%
	R3/1	186.74	270.03	187.47	44.60%	0.39%	1300.74	1225.21	1259.42	-5.81%	-3.18%	1026690.72	1445255.02	1027927.44	40.77%	0.12%

Table 6. 9 Summary of NOx emissions for cars, buses and all vehicles for all scenarios under 3 DoS values (unit: g/car or g/bus for cars and buses, g/hour for all vehicles)

DoS & Bus flow	R ratio (q1/q2)	NOx- Cars (g/car)					NOx- Buses (g/bus)					NOx-All vehicles (g/hour/all vehicles)				
		BL	BP1	BP2	Percent difference		BL	BP1	BP2	Percent difference		BL	BP1	BP2	Percent difference	
					BP1/BL	BP2/BL				BP1/BL	BP2/BL				BP1/BL	BP2/BL
DoS=0.6																
B20	R1/3	0.22122	0.22681	0.22519	2.52%	1.79%	11.336	10.230	10.221	-9.76%	-9.84%	1049.67	1048.31	1042.13	-0.13%	-0.72%
	R1/1	0.23114	0.23365	0.23272	1.09%	0.68%	11.082	10.188	10.203	-8.07%	-7.93%	1081.48	1072.95	1069.78	-0.79%	-1.08%
	R3/1	0.22345	0.22162	0.22174	-0.82%	-0.77%	10.650	9.875	9.875	-7.28%	-7.28%	1044.25	1021.92	1022.35	-2.14%	-2.10%
B60	R1/3	0.22093	0.23681	0.22882	7.19%	3.57%	11.221	9.914	10.287	-11.65%	-8.33%	1459.79	1437.86	1431.82	-1.50%	-1.92%
	R1/1	0.23243	0.23421	0.23275	0.77%	0.14%	10.770	9.975	10.138	-7.38%	-5.87%	1473.64	1432.28	1436.85	-2.81%	-2.50%
	R3/1	0.22422	0.22228	0.22242	-0.86%	-0.80%	10.343	9.739	9.730	-5.84%	-5.93%	1418.80	1375.66	1375.62	-3.04%	-3.04%
DoS=0.8																
B20	R1/3	0.22558	0.23644	0.23124	4.82%	2.51%	11.728	10.422	10.881	-11.14%	-7.22%	1416.58	1447.39	1429.33	2.17%	0.90%
	R1/1	0.23453	0.23937	0.23781	2.06%	1.40%	11.197	10.427	10.591	-6.88%	-5.41%	1452.89	1462.85	1457.96	0.69%	0.35%
	R3/1	0.22486	0.22527	0.22529	0.18%	0.19%	10.590	10.211	10.233	-3.58%	-3.37%	1390.04	1384.64	1385.19	-0.39%	-0.35%
B60	R1/3	0.36388	0.53287	0.37066	46.44%	1.86%	11.683	10.239	11.185	-12.36%	-4.26%	1848.50	2706.96	1882.95	46.44%	1.86%
	R1/1	0.23565	0.41755	0.24216	77.19%	2.76%	11.176	10.407	10.898	-6.88%	-2.48%	1867.65	2745.55	1884.07	47.01%	0.88%
	R3/1	0.22598	0.23547	0.22669	4.20%	0.31%	10.601	10.316	10.382	-2.68%	-2.07%	1784.02	1815.16	1774.49	1.75%	-0.53%
DoS=0.9																
B20	R1/3	0.26591	0.32142	0.27608	20.88%	3.82%	11.972	10.578	11.260	-11.65%	-5.95%	1632.82	1895.81	1671.85	16.11%	2.39%
	R1/1	0.27593	0.29445	0.28240	6.71%	2.34%	11.576	10.728	11.014	-7.32%	-4.85%	1677.39	1757.49	1700.04	4.78%	1.35%
	R3/1	0.26576	0.26712	0.26700	0.51%	0.47%	11.003	10.530	10.612	-4.30%	-3.56%	1612.67	1610.28	1611.33	-0.15%	-0.08%
B60	R1/3	0.40815	0.53970	0.42643	32.23%	4.48%	11.936	10.270	11.739	-13.96%	-1.65%	2073.40	2741.69	2166.26	32.23%	4.48%
	R1/1	0.27782	0.42998	0.29128	54.77%	4.84%	11.512	10.484	11.502	-8.94%	-0.09%	2102.05	2813.30	2169.79	33.84%	3.22%
	R3/1	0.26673	0.42009	0.26883	57.50%	0.79%	10.972	10.384	10.689	-5.35%	-2.58%	2013.28	2757.11	2007.00	36.95%	-0.31%

Table 6. 10 Summary of VOC emissions for cars, buses and all vehicles for all scenarios under 3 DoS values (unit: g/car or g/bus for cars and buses, g/hour for all vehicles)

DoS & Bus flow	R ratio (q1/q2)	VOC- Cars (g/car)					VOC Buses (g/bus)					VOC-- All vehicles (g/hour/all vehicles)				
		BL	BP1	BP2	Percent difference BP1/BL	Percent difference BP2/BL	BL	BP1	BP2	Percent difference BP1/BL	Percent difference BP2/BL	BL	BP1	BP2	Percent difference BP1/BL	Percent difference BP2/BL
DoS=0.6																
B20	R1/3	0.19632	0.20126	0.20023	2.52%	1.99%	1.00460	0.94085	0.94456	-6.35%	-5.98%	750.40	767.52	763.75	2.28%	1.78%
	R1/1	0.20514	0.20753	0.20757	1.17%	1.18%	0.99075	0.94253	0.94544	-4.87%	-4.57%	782.93	790.87	791.06	1.01%	1.04%
	R3/1	0.19842	0.19753	0.19775	-0.45%	-0.34%	0.96844	0.93037	0.93052	-3.93%	-3.92%	757.49	753.40	754.23	-0.54%	-0.43%
B60	R1/3	0.19570	0.21278	0.20487	8.73%	4.68%	0.99449	0.92386	0.94451	-7.10%	-5.03%	756.36	812.92	786.00	7.48%	3.92%
	R1/1	0.20551	0.21150	0.20951	2.92%	1.95%	0.97088	0.92870	0.93723	-4.34%	-3.47%	789.87	808.66	802.09	2.38%	1.55%
	R3/1	0.19832	0.19857	0.19875	0.13%	0.22%	0.94801	0.91883	0.91837	-3.08%	-3.13%	762.89	762.03	762.63	-0.11%	-0.03%
DoS=0.8																
B20	R1/3	0.21540	0.22714	0.22421	5.45%	4.09%	1.02740	0.94927	0.97739	-7.61%	-4.87%	1149.23	1209.22	1194.42	5.22%	3.93%
	R1/1	0.22673	0.23474	0.23355	3.53%	3.01%	0.99409	0.95015	0.95950	-4.42%	-3.48%	1207.94	1249.03	1243.01	3.40%	2.90%
	R3/1	0.21550	0.21704	0.21711	0.71%	0.75%	0.96245	0.94166	0.94308	-2.16%	-2.01%	1148.48	1156.12	1156.50	0.67%	0.70%
B60	R1/3	0.22767	0.51980	0.24737	128.31%	8.65%	1.02290	0.93774	0.99574	-8.33%	-2.65%	1156.56	2640.56	1256.63	128.31%	8.65%
	R1/1	0.22780	0.60736	0.24186	166.61%	6.17%	0.99334	0.94751	0.97791	-4.61%	-1.55%	1216.84	3142.22	1287.34	158.23%	5.79%
	R3/1	0.21646	0.24219	0.22062	11.89%	1.92%	0.96369	0.94711	0.95175	-1.72%	-1.24%	1157.43	1287.17	1177.87	11.21%	1.77%
DoS=0.9																
B20	R1/3	0.26296	0.33968	0.28110	29.18%	6.90%	1.04175	0.95683	0.99908	-8.15%	-4.10%	1398.72	1799.07	1492.97	28.62%	6.74%
	R1/1	0.27823	0.31129	0.29245	11.88%	5.11%	1.01709	0.96697	0.98373	-4.93%	-3.28%	1478.27	1650.49	1552.10	11.65%	4.99%
	R3/1	0.26232	0.26700	0.26611	1.78%	1.44%	0.98534	0.95947	0.96347	-2.63%	-2.22%	1394.29	1418.29	1413.70	1.72%	1.39%
B60	R1/3	0.27512	0.54220	0.31015	97.08%	12.73%	1.03955	0.93928	1.02930	-9.65%	-0.99%	1397.59	2754.37	1575.57	97.08%	12.73%
	R1/1	0.27979	0.65717	0.30937	134.88%	10.57%	1.01340	0.95238	1.01257	-6.02%	-0.08%	1482.12	3395.57	1632.33	129.10%	10.14%
	R3/1	0.26571	0.65573	0.27504	146.79%	3.51%	0.98249	0.95051	0.96780	-3.26%	-1.50%	1408.74	3388.14	1455.25	140.51%	3.30%

Table 6. 11 Summary of PM emissions for cars, buses and all vehicles for all scenarios under 3 DoS values (unit: g/car or g/bus for cars and buses, g/hour for all vehicles)

DoS & Bus flow	R ratio (q1/q2)	PM- Cars (g/car)					PM- Buses (g/bus)					PM—All vehicles (g/hour/all vehicles)				
		BL	BP1	BP2	Percent difference		BL	BP1	BP2	Percent difference		BL	BP1	BP2	Percent difference	
					BP1/BL	BP2/BL				BP1/BL	BP2/BL				BP1/BL	BP2/BL
DoS=0.6																
B20	R1/3	0.02642	0.02778	0.02727	5.15%	3.18%	0.24385	0.19636	0.17766	-19.48%	-27.14%	103.18	107.28	104.98	3.98%	1.75%
	R1/1	0.02843	0.02881	0.02841	1.33%	-0.07%	0.24242	0.18620	0.18369	-23.19%	-24.23%	110.62	110.91	109.37	0.26%	-1.13%
	R3/1	0.02661	0.02611	0.02614	-1.89%	-1.79%	0.22479	0.16499	0.16383	-26.60%	-27.12%	103.50	100.43	100.51	-2.97%	-2.89%
B60	R1/3	0.02635	0.03071	0.02829	16.54%	7.35%	0.24173	0.17044	0.18850	-29.49%	-22.02%	108.32	119.56	112.03	10.38%	3.42%
	R1/1	0.02912	0.02917	0.02852	0.16%	-2.08%	0.22212	0.17598	0.18595	-20.77%	-16.28%	117.00	114.40	112.67	-2.22%	-3.70%
	R3/1	0.02744	0.02617	0.02640	-4.62%	-3.81%	0.20339	0.16322	0.15869	-19.75%	-21.98%	109.89	102.97	103.49	-6.30%	-5.83%
DoS=0.8																
B20	R1/3	0.02791	0.03076	0.02907	10.22%	4.17%	0.25276	0.20573	0.22069	-18.61%	-12.69%	151.28	165.29	156.74	9.26%	3.61%
	R1/1	0.02930	0.03014	0.02972	2.86%	1.41%	0.24260	0.21117	0.21854	-12.96%	-9.92%	158.41	162.16	160.09	2.37%	1.06%
	R3/1	0.02786	0.02771	0.02769	-0.55%	-0.61%	0.22056	0.20128	0.20134	-8.74%	-8.71%	150.42	149.23	149.15	-0.79%	-0.84%
B60	R1/3	0.02836	0.06959	0.03098	145.38%	9.25%	0.25322	0.19614	0.22551	-22.54%	-10.94%	159.26	365.29	170.93	129.36%	7.33%
	R1/1	0.02993	0.05833	0.03075	94.89%	2.73%	0.24333	0.21232	0.22719	-12.74%	-6.63%	166.63	309.04	169.82	85.46%	1.91%
	R3/1	0.02848	0.02889	0.02811	1.44%	-1.31%	0.21982	0.20702	0.20630	-5.82%	-6.15%	157.87	159.19	155.17	0.83%	-1.71%
DoS=0.9																
B20	R1/3	0.03420	0.04695	0.03606	37.27%	5.44%	0.25964	0.21745	0.23755	-16.25%	-8.51%	184.42	250.38	193.72	35.77%	5.04%
	R1/1	0.03519	0.03844	0.03595	9.21%	2.13%	0.26107	0.23107	0.24075	-11.49%	-7.79%	189.64	206.02	193.17	8.64%	1.86%
	R3/1	0.03422	0.03404	0.03412	-0.50%	-0.29%	0.24452	0.22251	0.22674	-9.00%	-7.27%	184.19	182.85	183.31	-0.73%	-0.48%
B60	R1/3	0.03482	0.06895	0.03880	98.00%	11.43%	0.26078	0.19960	0.24813	-23.46%	-4.85%	192.55	362.25	212.01	88.13%	10.10%
	R1/1	0.03600	0.05670	0.03782	57.49%	5.05%	0.25714	0.21690	0.25639	-15.65%	-0.29%	198.32	301.05	207.50	51.80%	4.63%
	R3/1	0.03489	0.04895	0.03445	40.27%	-1.26%	0.24557	0.21236	0.22689	-13.52%	-7.61%	191.99	261.39	188.64	36.14%	-1.75%

6.4.1 Overview of emissions

Similarly to the factors (i.e. DoS values, R values and bus flows) affecting the performance of BSP on vehicle delays, the impacts on emissions are also largely influenced by these factors. For emissions, the degrees of impacts for different pollutants are not the same. An overview of the impacts on emissions is presented as follows.

6.4.1.1 Effects of BSP on bus emissions

Figure 6. 19 shows the percent change of emissions for 4 pollutants (CO_2, NOx, VOC and PM in different colours) from buses after implementing BP1 (in unit of g %/bus) for all the scenarios. **Figure 6. 20** shows the percent change of bus emissions after implementing BP2. The data in these 2 figures can be also found in the 4 summary tables (**Table 6. 8** to **Table 6. 11**).

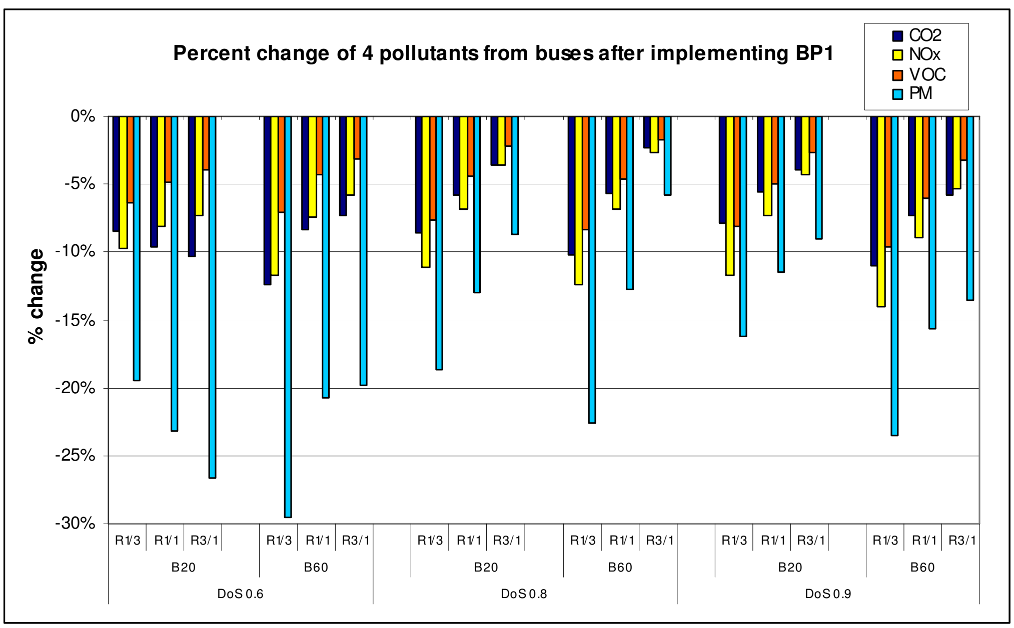


Figure 6. 19 Percent change of 4 pollutants (CO_2, NOx, VOC and PM) from buses after implementing BP1

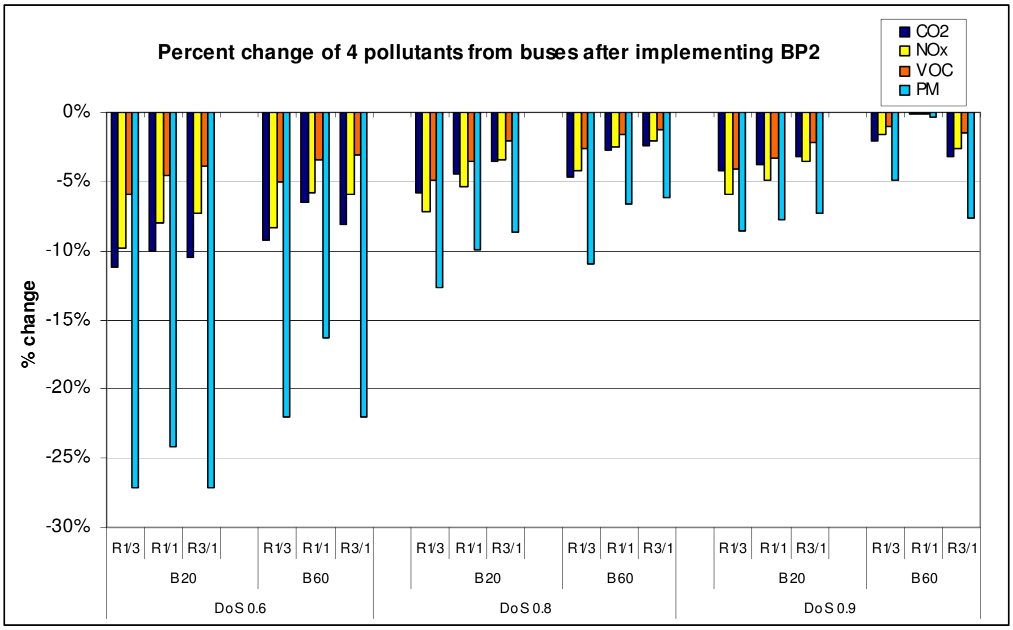


Figure 6. 20 Percent change of 4 pollutants (CO_2, NOx, VOC and PM) from buses after implementing BP2

It is clear that implementing both BP1 and BP2 have effectively reduced the emissions from buses for all scenarios to various extents, dependent on other factors. These factors are discussed later. It indicates that apart from the considerable delay savings bus were able to achieve after implementing BSP, bus emissions have also been greatly reduced. Generally implementing BP1 has reduced bus emissions to a large extent with less variation among scenarios, while the extent of bus emission reduction made by BP2 was relatively smaller especially for scenarios with increasing DoS values. This is because for BP1, buses were targeted to be given priority regardless of the impacts to the non priority traffic so in all scenarios buses could travel almost equally freely after BP1. For BP2 the degree of emission reduction was reduced with increasing DoS values, this is due to the action of compensation and inhibition when more buses were rejected to be given signal priority thus a greater proportion of buses could not pass through the junction freely.

It can be also seen from these 2 figures that the extents of emission changes among the 4 pollutants vary, as summarised as follows.

PM-buses

The percent reduction of PM emissions from buses is the greatest with a maximum percent of nearly 30. This is a significant benefit because of 2 reasons. Firstly as reviewed in Chapter 3 PM is a highly toxic pollutant which seriously affects human health and increases the respiratory diseases and lung cancer, therefore PM has been valued by a very high damage cost (e.g. £203,048/tonne in central London area) (see Section 3.6). Secondly diesel engines (most HGV and buses use diesel engines) emit a greater mass of PM than petrol engines therefore small proportion of bus flows can be a significant contributor to the overall PM emission reduction. Data in **Table 6. 11** indicates that in average the PM emissions per bus is nearly 10 times of the PM emissions per car (e.g. for scenario DoS0.6_R1/3_B20_BL, PM per bus is 0.24385g, and per car is 0.02642g). Therefore implementing BSP to buses is an effective measure to reduce PM emissions from buses and consequently may have an overall benefit to the environment and human health.

CO2-buses

CO2, as reviewed in Chapter 3, has no significant impacts on the local environment but is the main source of climate change. The CO2 from buses have been reduced by a range of 2.35% to 12.43% after implementing BP1 and by a range of 0.08% to 11.20% after implementing BP2. It indicates that for some scenarios a good percent of CO2 reduction can be achieved and BSP could be used as a measure to reduce CO2 emissions.

NOx- buses

NOx emissions from buses have been reduced by a range of 2.68% to 13.96% after implementing BP1, and by a smaller range of 0.09% to 9.84% after BP2.

VOC- buses

In general diesel engine vehicles produce less VOC emission than petrol engines. The percent reduction of bus VOCs is the mildest among the 4 pollutants, ranging from 1.72% to 9.65% after implementing BP1, and ranging from 0.99% to5.98% after BP2.

6.4.1.2 Effects of BSP on Car emissions

The impacts of implementing BSP on the overall car emissions are a combined result from the generally reduced car emissions from the priority stage and the increased car emissions from the non-priority stage. The different extents/ amount of the increase and decrease may lead to an unknown combined result. This is also the main motivation for this study.

Figure 6. 21 and **Figure 6. 22** illustrate the percent change of emissions of all 4 pollutants from cars on the priority and non-priority stages after implementing BP1. **Figure 6. 23** and **Figure 6. 24** illustrate the percent change of emissions of all 4 pollutants from cars on the priority and non-priority stages after implementing BP2.

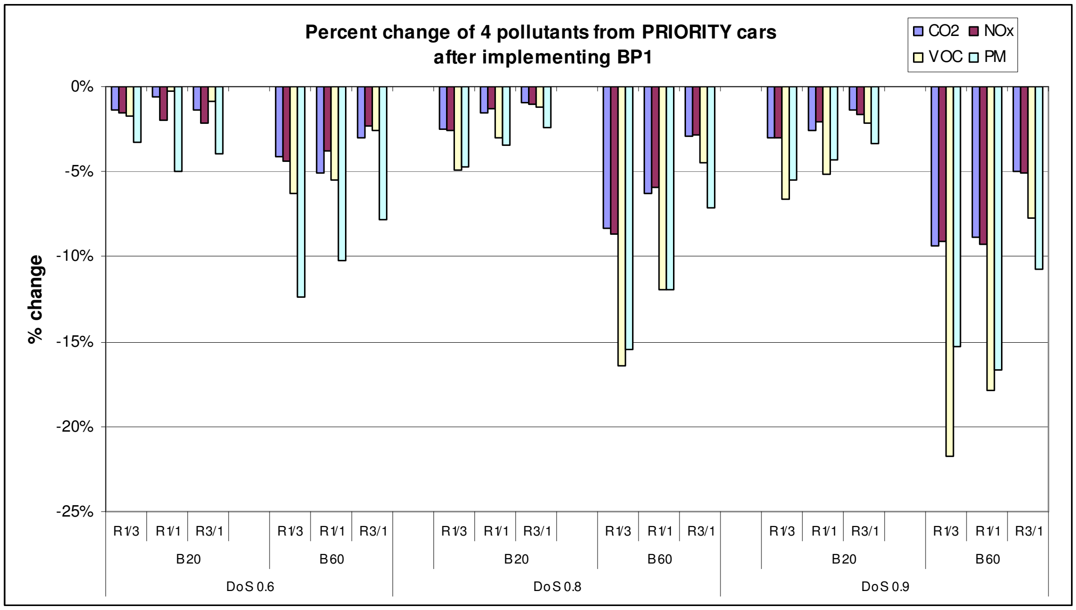


Figure 6. 21 Percent change of 4 pollutants from cars on the priority stage after implementing BP1

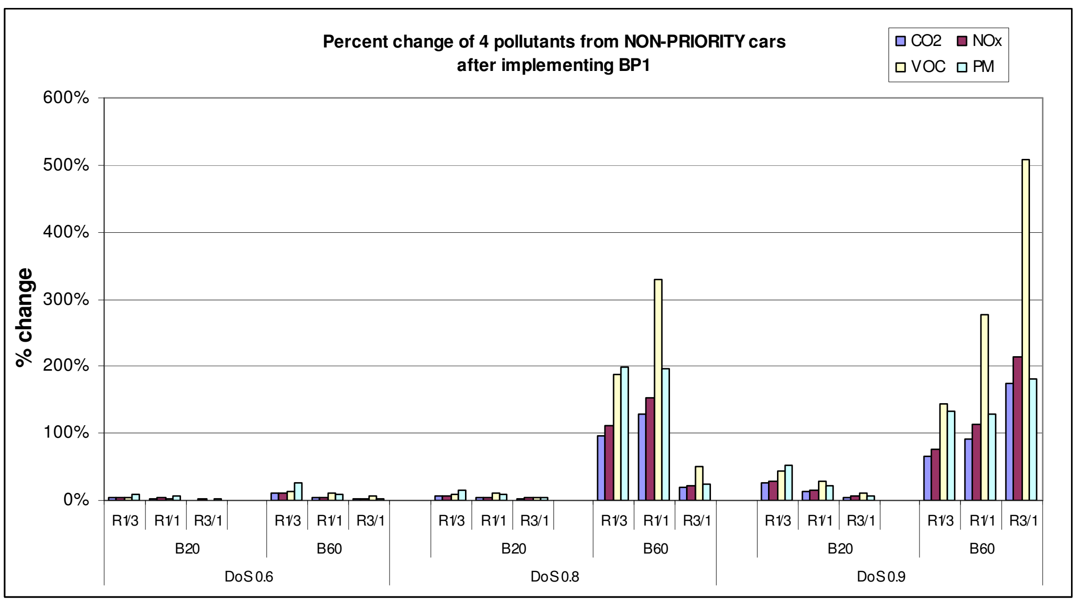


Figure 6. 22 Percent change of 4 pollutants from cars on the Non- priority stage after implementing BP1

Figure 6. 21 shows that after implementing BP1, emissions from cars on the priority stage in all scenarios have been reduced, by a maximum 15.47%. The extents of the reduction were generally greater for scenarios with high bus. The extent of reduction also increase with increasing DoS values. This is because vehicles have already produced more emissions in a heavier traffic flow condition due to more frequent deceleration and acceleration

operation. The implementation of BSP, especially for a higher bus flow has also given more green time to the cars sharing the priority signals which has led to a much smoother travel experience for them with much less deceleration-acceleration operation, consequently led to a higher extent of emission reduction for these cars.

Figure 6. 22 shows that the emissions from cars on the non-priority stage have all increased after implementing BP1. The extent was relatively small for DoS 0.6, but for scenarios under higher DoS values (0.8 and 0.9) especially with R1/3 and R1/1 the increase was extreme. (Again note that the values for these extreme scenarios maybe underestimated.) This trend is in agreement with the delay increase after implementing BP1 to high bus flows under high DoS values.

The extreme impacts on emissions have been largely eased after implementing BP2 while the degree of emission reduction obtained by priority cars was reduced. **Figure 6. 23** and **Figure 6. 24** illustrate the percent change of 4 pollutants from cars on the priority stage and the non- priority stage after implementing BP2.

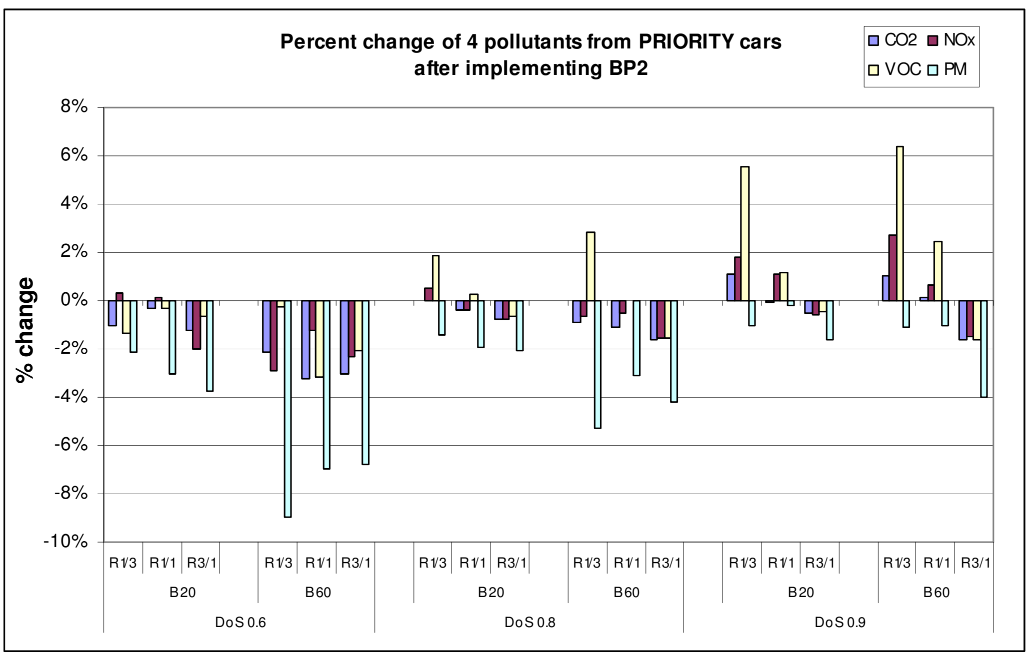


Figure 6. 23 Percent change of 4 pollutants from cars on the priority stage after implementing BP2

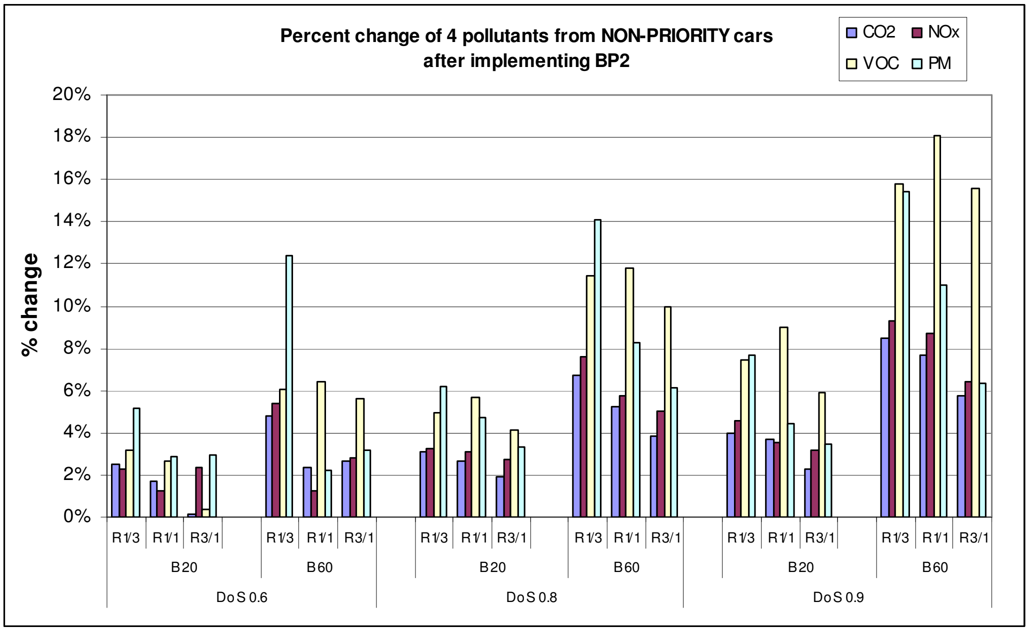


Figure 6. 24 Percent change of 4 pollutants from cars on the Non- priority stage after implementing BP2

After implementing BP2 car emissions from the priority stage have been reduced for most scenarios, to various but smaller extents. For some pollutants and some scenarios the emissions even have slightly increased, e.g. VOC and NOx under higher DoS 0.8 and 0.9 with R1/3 and R1/1. CO2 has increased in 2 scenarios under DoS 0.9 with R value was 1/3. PM emissions were still reduced in all scenarios.

The extreme increase of car emissions from the non-priority stage resulted by implementing BP1 has been effectively lessened by implementing BP2, however the increase was still significant. As expected the extent of emission increase generally has increased with increasing DoS values and increasing bus flows.

In this figure, CO2 emissions from cars on the non-priority stage have increased by a range of 0.15% to 8.46%; NOx by 1.25% to 9.30%; VOC by 0.40% to 18.07%, and PM by a range of 2.94% to 15.40%. For most scenarios the extent (percent change) of emission increase from cars on the non-priority stage was generally greater than the emission reduction from cars on the priority stage, the combined emission change from all cars can be a disbenefit. Considering emissions from all cars in the junction area, the overall change of car emissions after implementing BP1 and BP2 are illustrated in **Figure 6. 25** and **Figure 6. 26**.

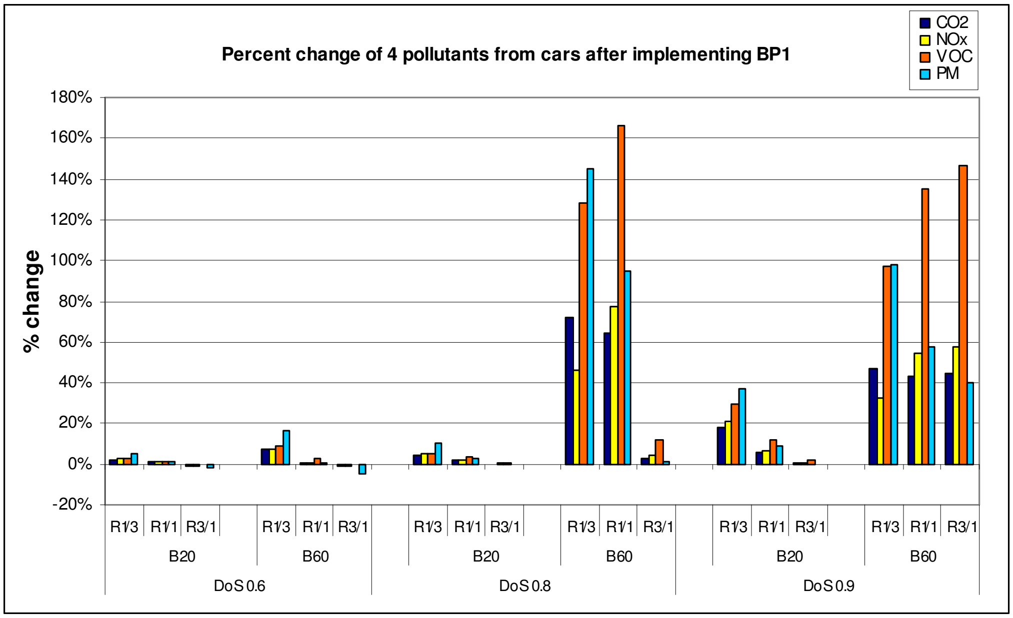


Figure 6. 25 Percent change of 4 pollutants (CO_2, NOx, VOC and PM) from all cars after implementing BP1

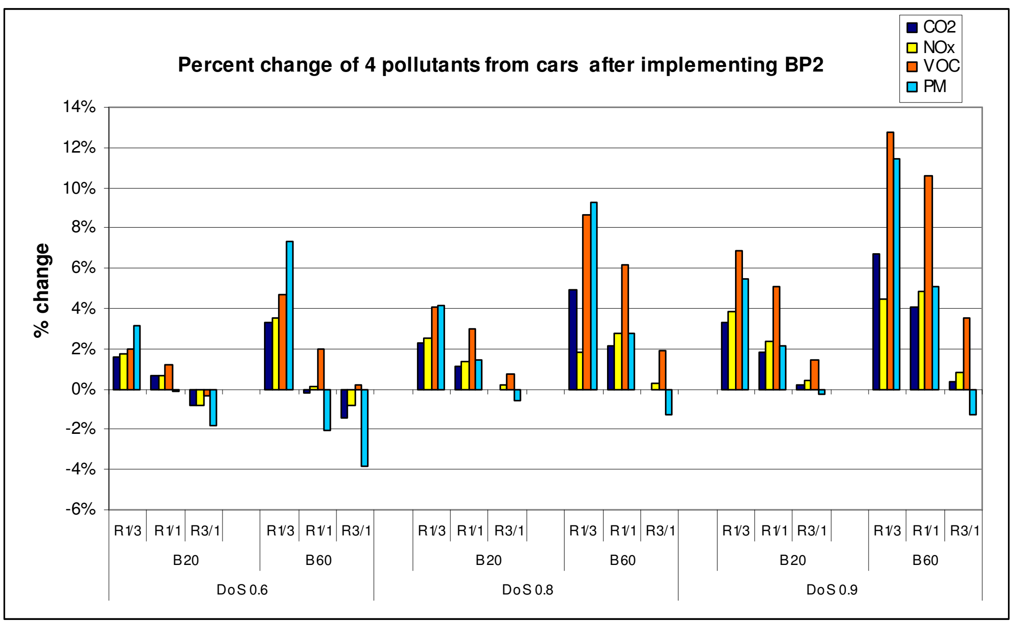


Figure 6. 26 Percent change of 4 pollutants (CO_2, NOx, VOC and PM) from all cars after implementing BP2

Figure 6. 25 shows car emissions have been reduced only for 2 scenarios after implementing BP1- that DoS0.6_R3/1_B20 and DoS0.6_R3/1_B60, with buses on the major road and under free flow traffic. The reduction is generally less than 2% for all pollutants. For most scenarios, implementing BP1 has resulted in emission increase from cars, and the increase is significant for some scenarios when giving priority to high flow

buses under heavy traffic conditions. This is in accordance with scenarios with the substantial delay increase after implementing BP1, where increased delay suggested increased 'stop-and-go' driving operation which consequently led to severe emissions increase. The maximum percent increase of the 4 pollutants is 71.99% for CO2, 77.19% for NOx, 145.39% for PM and 166.61% for VOC after BP1. Note that the actual emissions maybe even higher than these values as some cars were lost out of the simulation network due to congestion so were not taken into account.

The impacts of implementing BP2 are much smaller. **Figure 6.26** shows the percent change of car emissions after implementing BP2 increases with increasing DoS values and increasing bus flows. The extent of increase is the largest when buses were on the minor road the least when buses were on the major road. After implementing BP2, the percent change for all pollutants and under all scenarios has been kept belwo13%. The same 2 scenarios were still beneficial from implementing BP2, by a maximum 4% decrease for PM emissions and less than 2% decrease for other pollutants. The ranges of percent change for the 4 pollutants of cars are listed as follows.

CO2- cars

The percent change of CO2 emissions after implementing BP1 ranges from -1.14% to 71.99%.[*] BP2 has greatly reduced the range to -0.83% to 6.68%.

NOx- cars

The percent change of NOx emissions after implementing BP1 ranges from -0.82% to 77.19%, while the percent change after implementing BP2 ranges from -0.80% to 4.84%.

PM- cars

The percent change of PM emissions after implementing BP1 ranges from -4.62% to 145.38%, while the percent change after implementing BP2 ranges from -3.81% to 11.43%.

VOC- cars

The percent change of VOC emissions after implementing BP1 ranges from –0.45% to 166.61%, and the percent change after implementing BP2 ranges from -0.34% to 12.73%.

The following section discuses the effects of other factors, i.e. DoS values, R values and Bus flows separately.

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[*] This value has been underestimated and could be higher.

6.4.1.3 Effects of DoS values

In most cases the average emissions produced per vehicle have increased in line with the increase of DoS values. All 4 pollutants have the same trend. **Figure 6. 27** shows the average CO2 emissions per car under 3 DoS values for scenario Sce_DoS(All)_R3/1_B20, covering all 3 signal plans, i.e. Baseline, BP1 and BP2. **Figure 6. 28** shows bus emissions for the same scenario. **Figure 6. 27** illustrates that for each signal control strategy, i.e. baseline, BP1 and BP2, emissions per car have increased from DoS 0.6 to DoS 0.8 by around 2 %, but have increased by a further 18% when DoS increased to 0.9. This indicates that when traffic conditions become heavier or congested, the increasing rate of emissions is much sharper.

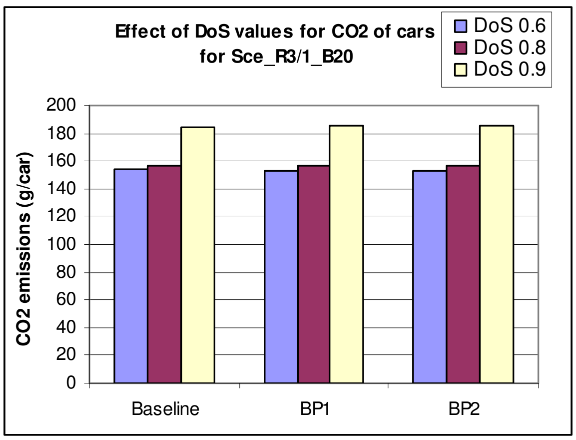

Figure 6. 27 Effect of DoS values on CO2 of cars for Scenarios DoS(0.6/0.8/0.9)_R3/1_B20

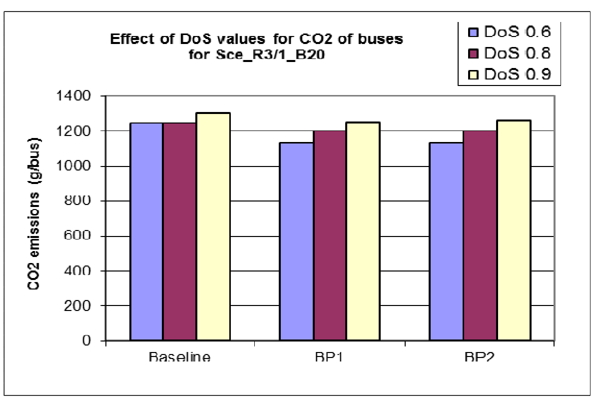

Figure 6. 28 Effect of DoS values on CO2 of buses for Scenarios DoS(0.6/0.8/0.9)_R3/1_B20

CO2 emissions from buses as shown in **Figure 6. 28** have a similar trend, however the increasing rate is much smaller than cars, especially from DoS 0.8 to DoS 0.9, at only about 4%. This is because of the provision of signal priority to some buses has smoothed bus driving so that on average they can drive with less stop and go operations.

Implementing bus priority strategies under different traffic conditions can result in different changes of emissions. **Figure 6. 29** shows an example of the percent change of CO2 emissions from cars after implementing BP1 and BP2 for 3 DoS values for the same R value (R3/1) and same bus flow (B20).

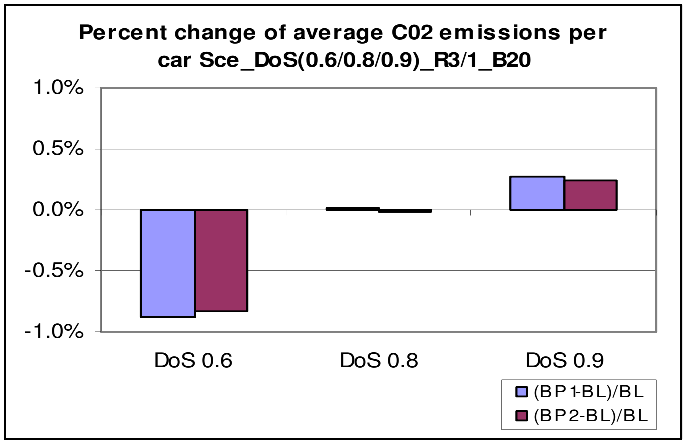

Figure 6. 29 Effects of DoS values on car CO2 emissions for DoS(0.6/0.8/0.9)_R3/1_B20 (percent change)

This figure shows that under 3 DoS values all with low bus flows on the major road, emissions per car is reduced by 0.8% by implementing BP1under DoS 0.6 but increased by about 0.2% under DoS 0.9. This indicates that for the same bus flow on main road, implementing BP is an environmentally friendly strategy under free flow conditions but causes emission increase under heavy flow traffic conditions.

6.4.1.4 Effects of R values

The R values, i.e. q1/q2 values have different effects to buses than to cars.

For buses, as shown in **Table 6.12**, in general the average emissions of buses (g/bus) on the minor road (R1/3) are the highest; and on the major road (R3/1) are the lowest. This is probably because when buses were on minor road (i.e. R1/3), the average proportion of green time per cycle was the minimum among the 3 R values, and therefore there were more possibilities for them to encounter non green signals. This led to more 'decelerate/stop and accelerate' operations for buses thus more emissions were produced.

Table 6.12 Average emissions from buses (g/bus) for 3 R values under DoS 0.6_B20_BL

Buses	CO2 (g/bus)	NOx (g/bus)	VOC (g/bus)	PM (g/bus)
DoS 0.6_R1/3_B20_BL	1318.6489	11.3363	1.0046	0.2439
DoS 0.6_R1/1_B20_BL	1309.6861	11.0818	0.9907	0.2424
DoS 0.6_R3/1_B20_BL	1264.2557	10.6504	0.9684	0.2248

For cars as shown in **Table 6. 13** the highest average emissions occurred when R was 1/1 and the emissions from other R values, i.e. R1/3 and R3/1 were relatively less.

Table 6.12Table 6. 13 Average emissions from cars (g/car) for 3 R values under DoS 0.6_B20_BL

Cars	CO2 (g/car)	NOx (g/car)	VOC (g/car)	PM (g/car)
DoS 0.6_R1/3_B20_BL	153.1130	0.2212	0.1963	0.0264
DoS 0.6_R1/1_B20_BL	159.2269	0.2311	0.2051	0.0284
DoS 0.6_R3/1_B20_BL	154.5871	0.2235	0.1984	0.0266

For cars, the emissions per car in the table are the combined result averaged for all cars from all 4 arms. As the traffic flows in scenarios with R1/3 and R3/1 are only a reverse to each other, the average car emissions for these 2 R values are supposed to be the same. This has been confirmed from the data. The car emissions in scenarios with R1/1 are generally greater than the other 2 R values. One possible explanation is demonstrated in **Table 6. 14**.

Table 6. 14 Average car emissions (g/car) for 2 stages (i.e. 'W-E+ W-E' stage and 'N-S +S-N' stage) for scenarios with DoS 0.6_B20_BL

	Stages	Car flows (Cars/hr/stage)	CO2 (g/car/stage)	Average CO2 (g/car/junction)
R1/3	(Minor road) W-E& E-W	870	166.2	153.1
	(Major road) N-S & S-N	2850	149.1	
R1/1	(even flows) W-E& E-W	1820	159.7	159.2
	(even flows)N-S & S-N	1900	158.8	
R3/1	(Major road)W-E& E-W	2770	150.0	154.6
	(Minor road) N-S & S-N	930	168.1	

This table shows that generally cars on the minor road produced the most emissions and cars on the major road produce the least average emissions. However combining all the cars at the junction for the 3 R values, the average car emissions for R1/1 has overweighed the other two.

6.4.1.5 Effects of B value (bus flows)

High bus flows could result in significant emission increase when combining with higher DoS values and strong BP strategies. When bus priority strategies were implemented to scenarios within a 'clean' zone, meaning free flow traffic conditions and buses on the main road, the bus flows had the minimum effects on car emissions and overall emissions. However when implementing a strong bus priority strategy, i.e. BP1, to buses on non-main road, or under heavy traffic conditions, the effects of bus flows to car emissions start to emerge.

For example **Figure 6. 30** shows the effects of bus flows (i.e. B20 and B60) on CO2 emissions from cars when implementing BP1 to buses on the minor road under DoS 0.6 and DoS 0.8.

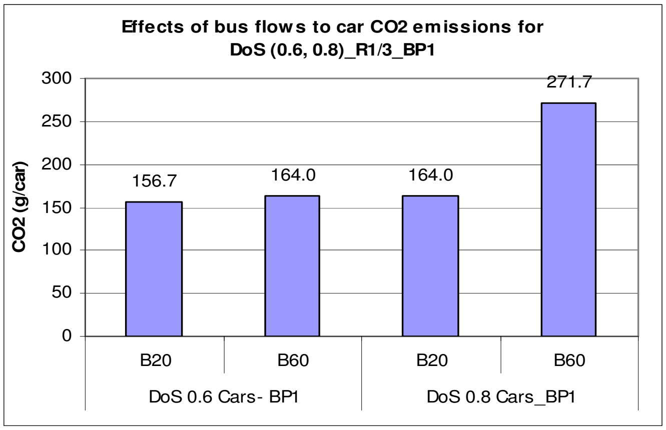

Figure 6. 30 Effects of bus flows to CO2 emissions from cars for scenarios DoS (0.6, 0.8_R1/3_BP1

The figure demonstrates that the effect of bus flows is influenced by DoS values. For a smaller DoS (i.e. 0.6), implementing BP1 to the higher bus flow B60 has relatively moderate impacts on the car emissions, while for a larger DoS value (i.e. 0.8), the impacts of implementing BP to the higher bus flows are much more obvious.

Another issue of bus flow is the percentage of total bus emissions contributed to the overall emissions. As described previously, after implementing BSP bus emissions have been reduced, car emissions on priority stage generally have been reduced but to a smaller extent, car emissions on the non-priority stage have increased. This led to an uncertain tendency for the overall emissions considering both buses and cars. The overall impacts of bus priority on emissions of all vehicles depend on 2 main factors. One is the individual impact on either buses or cars. The other factor is the approximate proportions of the emissions from cars and buses. Generally in practice bus flow is much lower than car flows but each bus produces more emissions than each car.

Table 6.15 shows the percentage of 4 pollutants contributed by buses for all 6 scenarios in DoS 0.6 when implementing BL, BP1 and BP2 signal control plans. It should be noted that this is for DoS 0.6 only and for the other 2 higher DoS values with more car traffic, the percentages of buses and bus emissions are less.

Table 6.15 Percentage of total emissions contributed by buses for 6 scenarios for DoS 0.6, under BL, BP1 and BP2 signal control plans

DoS 0.6	CO2			NOx			VOC			PM		
Percentage of bus emissions	BL	BP1	BP2	BL	BP1	BP2	BL	BP1	BP2	BL	BP1	BP2
DoS0.6_R1/3_B20	4.4%	4.0%	3.9%	21.6%	19.5%	19.6%	2.7%	2.5%	2.5%	4.7%	3.7%	3.4%
DoS0.6_R1/1_B20	4.2%	3.8%	3.8%	20.5%	19.0%	19.1%	2.5%	2.4%	2.4%	4.4%	3.4%	3.4%
DoS0.6_R3/1_B20	4.2%	3.8%	3.8%	20.4%	19.3%	19.3%	2.6%	2.5%	2.5%	4.3%	3.3%	3.3%
DoS0.6_R1/3_B60	12.6%	10.5%	11.2%	46.1%	41.4%	43.1%	7.9%	6.8%	7.2%	13.4%	8.6%	10.1%
DoS0.6_R1/1_B60	11.7%	10.7%	11.0%	43.8%	41.8%	42.3%	7.4%	6.9%	7.0%	11.4%	9.2%	9.9%
DoS0.6_R3/1_B60	11.6%	11.0%	10.9%	43.7%	42.5%	42.4%	7.5%	7.2%	7.2%	11.1%	9.5%	9.2%

From the table we can see that neither traffic signal control plans nor R values have a distinctive impact on the proportion of emissions from buses. Only a slight decrease after implementing BP strategies can be observed mainly due to the slight emission increase from cars. For example the proportion of CO2 emissions of buses for 3 scenarios for bus flow of 20/hr for all 3 signal control plans, are all around 4%. The proportions increased to about 12% when bus flow is 60/hr.

The proportion of NOx from buses is the largest, because diesel engines produce more NOx than petrol engines and buses have much bigger engines than regular passenger cars. For this DoS value the proportion of NOx emissions from buses is about 20% for B20 and more than 40% for B60. This proportion is significant for the overall comparison. The proportion of VOC is the lowest, at about 2%-4% for B20 and about 7% for B60. The proportions of CO2 and PM are similar, both at about 4% for B20 and 11% for B60.

The following sections discuss how the overall emissions, including both buses and cars have changed after implementing BP1 and BP2 for each DoS value. The analysis mainly focuses on two aspects:

1) The percent change of emissions from all vehicles for each DoS values, and
2) The absolute emission change from all vehicles for each DoS values.

Note that the overall traffic flows under DoS 0.6, 0.8 and 0.9 are 3800pcu/hour, 5320pcu/hour and 6080pcu/hour respectively and the emissions for each DoS value is in unit of g/hour/all vehicles .

6.4.2 Emissions for DoS 0.6

Figure 6. 31and **Figure 6. 32** illustrate the percent change of 4 pollutants from all vehicles (including both buses and cars) after implementing 2 bus priority strategies BP1 and BP2 for the 6 scenarios in DoS 0.6.

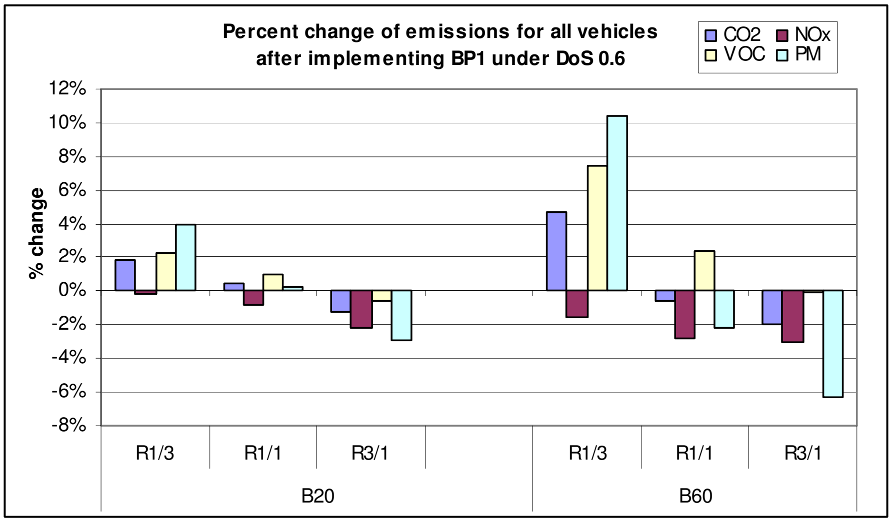

Figure 6. 31 Percent change of emissions for all vehicles after implementing BP1 under DoS 0.6

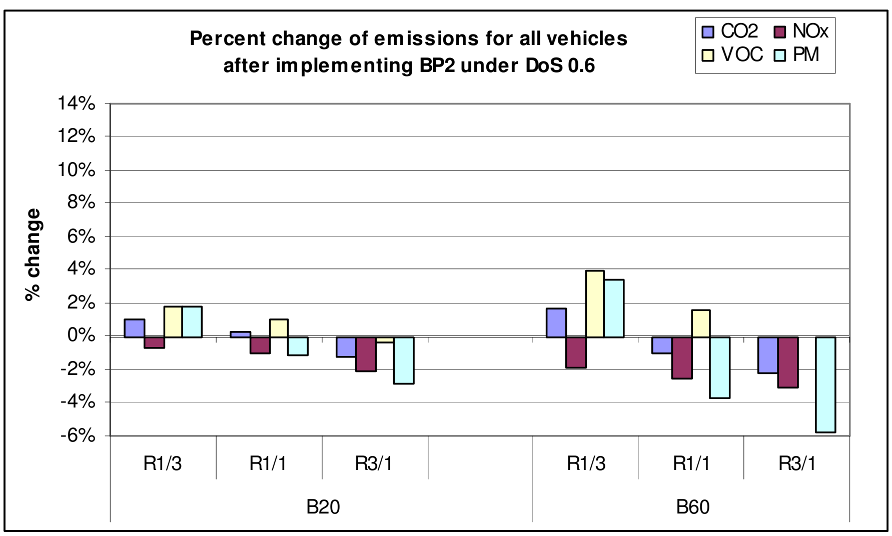

Figure 6. 32 Percent change of emissions for all vehicles after implementing BP2 under DoS 0.6

Table 6. 16 shows the absolute emission changes of the 4 pollutants after implementing BP1 and BP2 for the 6 scenarios in DoS 0.6.

Table 6. 16 Emission change (g/hour/all vehicles) of 4 pollutants after implementing BP1 and BP2 for 6 scenarios in DoS 0.6

Bus flow	R value	CO2 (g/hour/all vehicles)		NOx (g/hour/all vehicles)		VOC (g/hour/all vehicles)		PM (g/hour/all vehicles)	
		BP1-BL	BP2-BL	BP1-BL	BP2-BL	BP1-BL	BP2-BL	BP1-BL	BP2-BL
B20	R1/3	11233.11	6105.45	-1.36	-7.54	17.12	13.35	4.1	1.8
	R1/1	2983.86	1467.84	-8.53	-11.7	7.94	8.13	0.29	-1.25
	R3/1	-7649.58	-7416.31	-22.33	-21.9	-4.09	-3.26	-3.07	-2.99
B60	R1/3	29265.47	10717.86	-21.93	-27.97	56.56	29.64	11.24	3.71
	R1/1	-3544.56	-6530.67	-41.36	-36.79	18.79	12.22	-2.6	-4.33
	R3/1	-12551.1	-13664.98	-43.14	-43.18	-0.86	-0.26	-6.92	-6.4

CO2 change in DoS 0.6

The results show that CO2 emissions have been reduced in 3 scenarios under DoS 0.6, which were DoS0.6_R3/1_B20, DoS0.6_R1/1_B20 and DoS0.6_R3/1_B60. The reduction ranges from 0.55% to 2.18%, equal to 3.5kg to 13.7kg per hour. For the same scenario, BP2 has reduced more CO2 than BP1. Note that this is only for one junction with arm length of 350m for an hour. For a larger scale and a longer term calculation, the reduction can be larger. This suggests that for some particular scenarios, such as under free flow conditions with buses on the major road implementing BSP can be an effective measure to help achieve CO2 reduction target.

CO2 emissions in other 3 scenarios have increased by a range of 0.24% to 1.88%, equal to1.5kg to 11.2kg per hour. Similarly, this can be a significant increase for a larger network and for a longer term. Implementing BP2 is a better choice for these scenarios with almost 50% of the CO2 emission increase can be lessened.

NOx change in DoS 0.6

NOx has been reduced for all scenarios, mainly contributed by bus emission reduction. The percentage reduction ranges from 0.13% to 3.04%, equal to 1.4g to 43.1g per hour.

VOC and PM changes in DoS 0.6

The changes of VOC and PM are similar to CO2, as they all have been reduced in 3 scenarios (DoS0.6_R3/1_B20, DoS0.6_R1/1_B20 and DoS0.6_R3/1_B60) and increased in other scenarios. The reduction range for VOC is from 0.03% to 0.54%, equal to 0.26g to 4.09g per hour. The increase range of VOC is from 1.01% to 2.38%, equal to 7.9g to 56.6g. The reduction range for PM is from 0.03% to 0.54%, equal to 0.26g to 4.09g per hour. The increase range of PM is from 0.26% to 10.38%, equal to 0.3g to 11.2g.

However it is difficult to conclude whether the reduction is critical to the environment or not from the percentage or the emissions changes per hour. The NAQS (2005) set up the standard concentration for a number of pollutants, including NOx and PM. The standard for NOx is 150ppb for one hour mean and 21ppb for annual mean. The standard for PM concentration is 50µg/m^3 for 24hour mean. Parts per billion (ppb) is the number of units of mass of a contaminant per 1000 million units of total mass. However it is difficult to link the emission amount in unit of g/hour to the concentration in unit of ppb or µg/m^3. The conversion may require the dispersion modelling for air pollutions.

6.4.3 Emissions for DoS 0.8

For DoS 0.8, the overall traffic has increased from 3800pcu /h/junction (in DoS 0.6) to 5300 pcu/h/junction. As the bus flow remains the same, the proportion of car traffic is much higher. This suggests that emissions from buses have less weight for bigger DoS values. This section discusses under DoS 0.8 the impacts of emissions after implementing BSP.

Figure 6. 33 and **Figure 6. 34** illustrate the percent change of 4 pollutants from all vehicles (including both buses and cars) after implementing 2 bus priority strategies BP1 and BP2 for the 6 scenarios in DoS 0.8.

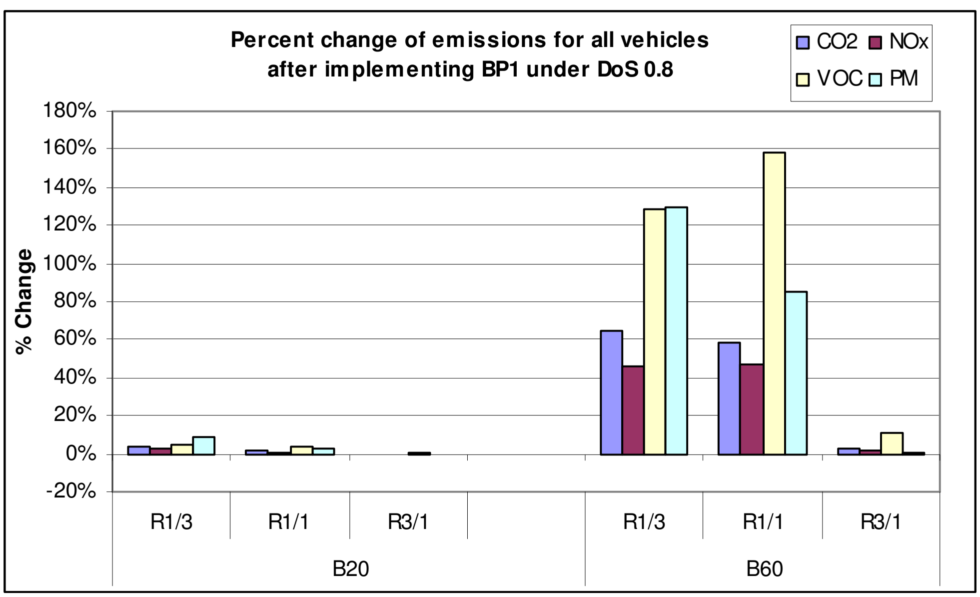

Figure 6. 33 Percent change of emissions for all vehicles after implementing BP1 under DoS 0.8

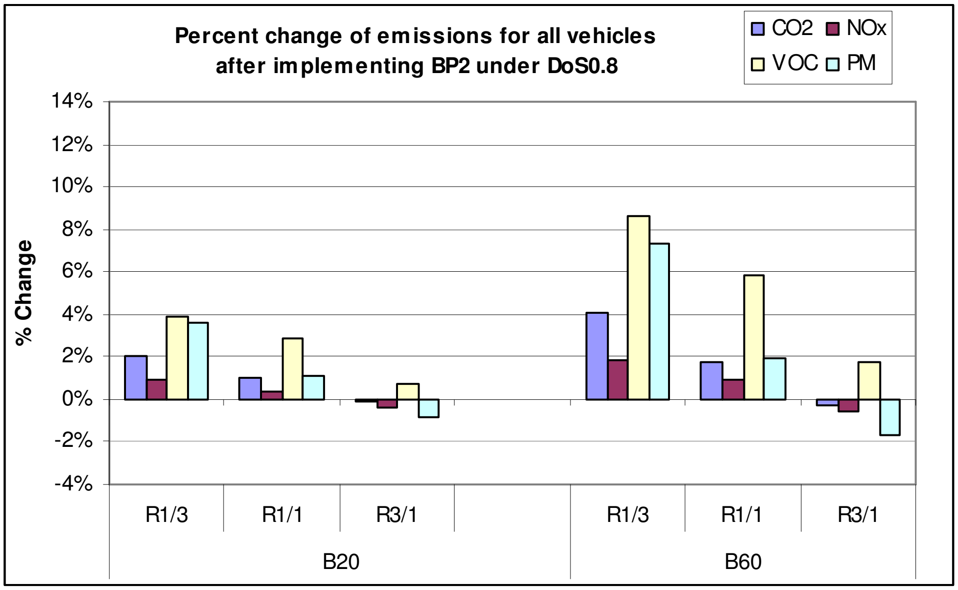

Figure 6. 34 Percent change of emissions for all vehicles after implementing BP1 under DoS 0.8

The 2 figures show that under a heavier traffic condition with DoS 0.8 generally emissions for almost all scenarios have increased except for the 2 best-case scenarios when implementing BP2 to buses on the major road, where a less than 1% emission reduction can still be achieved. Implementing BP1 under DoS 0.8 has caused significant emission increase for scenarios with high bus flows on minor road, which was not an environmentally friendly measure. This is consistent with the previous delay analysis in section 6.3.1.3. These 2 scenarios are also the worst scenarios for delay. Buses were on the minor road and the bus flow was high, so implementing BP1 resulted in frequent priority requirement and the traffic on the non bus stage was seriously affected. A severe delay increase suggested more 'decelerating –accelerating' and 'stop-go' operation occurred, therefore significantly higher emissions were produced.

For the 3 scenarios with low bus flows, BP1 has not resulted in such extreme emission increase but the impacts by BP2 were comparably smaller, only about half of the emission increase resulted by BP1.

As discussed in previous section, BP1 was not recommended for higher DoS values due to substantial delay increase to the non priority traffic, and so as for emission consideration. Therefore the following discussion more focuses on BP2. The data and figure involving BP1 are presented mainly to demonstrate the extent of the side effect.

Table 6. 17 shows the emission change after implementing BP1 and BP2 for 6 scenarios in DoS0.8, in unit of g/hour including all vehicles.

Table 6. 17 Emission change (g/hour/all vehicles) of 4 pollutants after implementing BP1 and BP2 for 6 scenarios in DoS 0.8

Bus flow	R	CO2 (g/hour/all vehicles)		NOx (g/hour/all vehicles)		VOC (g/hour/all vehicles)		PM (g/hour/all vehicles)	
		BP1-BL	BP2-BL	BP1-BL	BP2-BL	BP1-BL	BP2-BL	BP1-BL	BP2-BL
B20	R1/3	34480.11	17225.17	30.81	12.75	59.99	45.19	14.01	5.46
	R1/1	14038.66	8631.3	9.96	5.07	41.09	35.07	3.75	1.68
	R3/1	-803.33	-1042.37	-5.4	-4.85	7.64	8.02	-1.19	-1.27
B60	R1/3	569488.75	35619.66	858.46	34.45	1484	100.07	206.03	11.67
	R1/1	529376.99	15866.75	877.9	16.42	1925.38	70.5	142.41	3.19
	R3/1	23794.05	-2270.01	31.14	-9.53	129.74	20.44	1.32	-2.7

CO2 change in DoS 0.8

Under DoS0.8, scenarios DoS0.8_R3/1_B60 and DoS0.8_R3/1_B20 are still beneficial after implementing BP2, with 0.26% and 0.12% reduction which were equal to 2.3kg and 1.0kg per hour. Compared with CO2 reduction in DoS 0.6, the benefit was relatively small. However this is still beneficial to the environment and effective to help achieve CO2 target.

For other 4 scenarios, CO2 emissions have increased after implementing BP2, with the worst scenario of maximum 35.6kg increase in an hour. This increased amount has more than tripled the maximum CO2 increase in DoS 0.6. Although we can say that more vehicles have contributed more emissions in DoS 0.8 (i.e.3800pcu in DoS0.6 and 5320 pcu in DoS0.8) and the emissions per car only has increased by 4g/car in DoS 0.8 than in DoS 0.6 (as shown in **Table 6. 8**), however to evaluate the impacts on emissions of implementing any traffic schemes, the absolute change on emission amount is an important indicator.

NOx, VOC and PM change in DoS 0.8

NOx and PM have both been reduced in the same scenarios DoS0.8_R3/1_B20 and DoS0.8_R3/1_B60, while VOC was increased probably because the VOC increase has overweighed the VOC reduction as buses contributed a relatively smaller percentage for VOC. For these 2 scenarios NOx has been reduced by 0.35% and 0.53%, equal to 4.85g and 9.53g per hour. PM has been reduced by 0.84% and 1.71%, equal to 1.27g and 2.7g per hour.

Again the extents of NOx and PM reduction (absolute values) were smaller than in DoS 0.6 given that traffic flows in DoS were higher than in DoS 0.6. For scenarios (i.e. DoS0.8_R1/3_B20, DoS0.8_R1/1_B20, DoS0.8_R1/3_B60 and DoS0.8_R1/1_B60) with emission increase after implementing BP2, the extents were all larger than in DoS 0.6. NOx has increased by 0.35% to 1.86%, equal to 5.07g to 34.45g. PM has increased by 1.06% to 7.33%, equal to 1.68g to 11.67g.

Among all 6 scenarios, VOC has increased by a range of 0.70% to 8.65% after implementing BP2, equal to 8.02g to 100.07g per hour.

6.4.4 Emissions for DoS 0.9

The general trend of the emissions under this DoS value is very similar to DoS0.8, but to a larger extent. Meanwhile more scenarios have deteriorated in terms of emissions after implementing BSP, even BP2. **Figure 6. 35** and **Figure 6. 36** illustrate the percent change of 4 pollutants from all vehicles after implementing BP1 and BP2 for the 6 scenarios in DoS 0.9. Again **Figure 6. 35** indicates that implementing strong bus priority strategies, i.e. BP1 to a heavy traffic junction without considering any compensation or inhibition facilities is impractical and not recommended in real world. This can be justified from point of view of both delay and emissions. Therefore the impacts of implementing BP2 are more important and therefore analysed in more detail, as shown in **Figure 6. 36**.

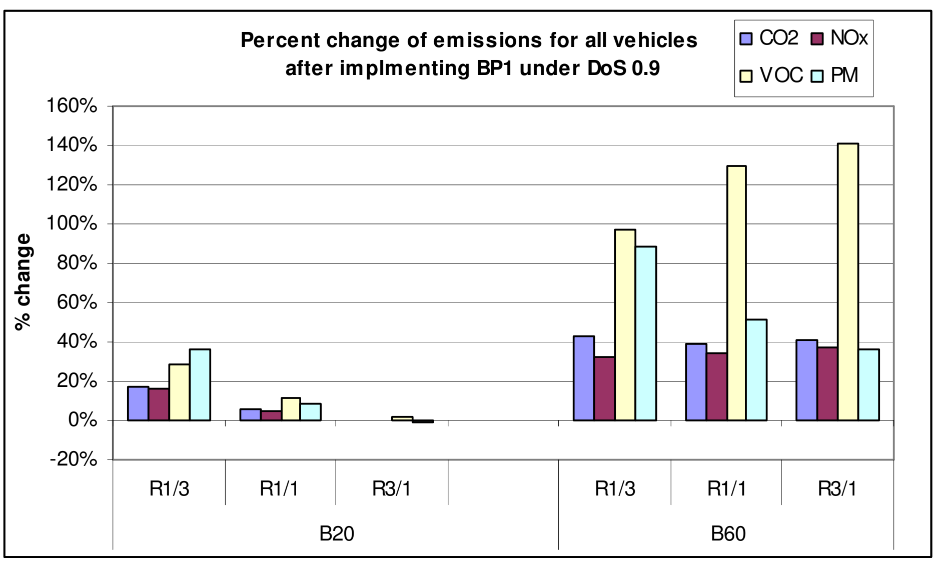

Figure 6. 35 Percent change of emissions for all vehicles after implementing BP1 under DoS 0.9

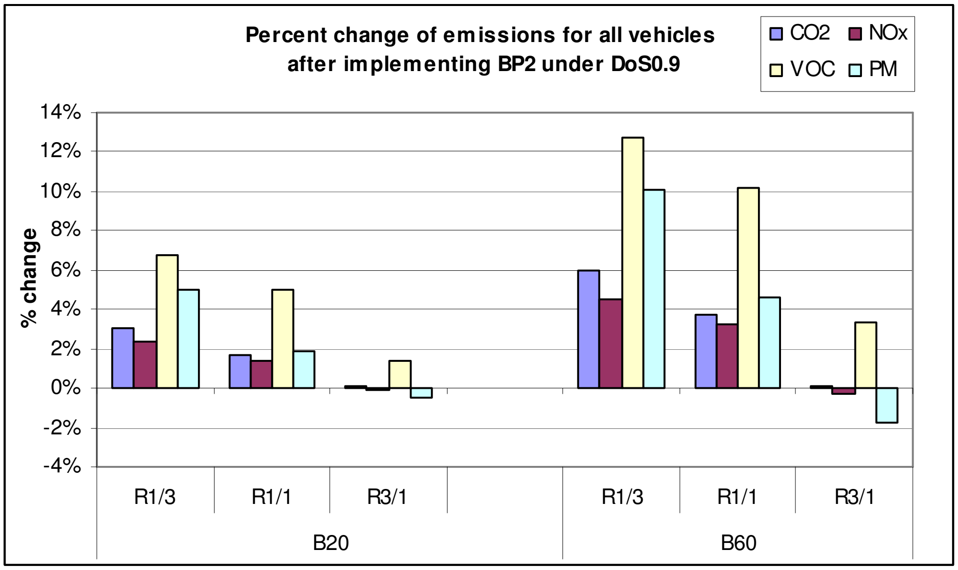

Figure 6. 36 Percent change of emissions for all vehicles after implementing BP2 under DoS 0.9

For DoS 0.9, the figures shows that almost all pollutants in all scenarios after implementing BP2 have increased, to various extents, except NOx and PM which have hold a slight reduction for the best 2 scenarios when buses were on the major road. This is due to the strong contribution of NOx and PM reduction made by buses.

Table 6. 18 show the emission change in 6 scenarios in DoS 0.9.

Table 6. 18 Emission change (g/hour/all vehicles) of 4 pollutants after implementing BP1 and BP2 for 6 scenarios in DoS 0.8

Bus flow	R	CO2 (g/hour/all vehicles)		NOx (g/hour/all vehicles)		VOC (g/hour/all vehicles)		PM (g/hour/all vehicles)	
		BP1-BL	BP2-BL	BP1-BL	BP2-BL	BP1-BL	BP2-BL	BP1-BL	BP2-BL
B20	R1/3	173281.94	30569.32	262.99	39.03	400.35	94.25	65.96	9.3
	R1/1	54897.07	17306.48	80.1	22.65	172.22	73.83	16.38	3.53
	R3/1	1639.92	1526.89	-2.39	-1.34	24	19.41	-1.34	-0.88
B60	R1/3	436828.29	61554.17	668.29	92.86	1356.78	177.98	169.7	19.46
	R1/1	411623.09	39378.08	711.25	67.74	1913.45	150.21	102.73	9.18
	R3/1	418564.3	1236.72	743.83	-6.28	1979.4	46.51	69.4	-3.35

According to **Figure 6. 36** and **Table 6. 18**, all 6 scenarios in DoS 0.9 can result in emissions increase after implementing BP2. Therefore implementing BSP under a heavy flow traffic is not an environmentally friendly measure. The best 2 scenarios in DoS 0.9, in terms of the minimum emissions increase are when buses were on the major road-DoS0.9_R3/1_B20 and DoS 0.6_R3/1_B60.

CO2 changes in DoS 0.9

CO_2 emissions in all scenarios have increased by 0.12% to 5.99%, equal to 1.2kg to 61kg CO_2 increase per hour.

NOx and PM in DoS 0.9

NO_x emissions have been reduced in the best 2 scenarios by 0.08% and 0.31%, equal to 1.34g and 6.28g NO_x reduction per hour. PM emissions have been reduced in the best 2 scenarios by 0.48% and 1.75%, equal to 10.88g and 3.35g reduction per hour.

VOC change in DoS 0.9

VOC emissions have increased in all scenarios in DoS 0.9, by a range of 1.39% to 12.73%, equal to 19.41g to 177.98g per hour.

6.4.5 Summary of emissions

The impacts of implementing bus priority strategies on emissions vary in terms of a number of factors. The impacts of BP1 are generally stronger than BP2 but can be extreme for some scenarios combining the effects of other factors. BP1 can reduce emissions from buses and also cars sharing the same signal stage with buses in all scenarios, but at the cost of even larger emission increase from cars on the non-priority stage, for some scenarios this can be very extreme. BP2 are more recommended under higher DoS values as it can largely lessen the emission increase from the non-priority traffic. Generally the performance of bus priority under free flow traffic conditions, in this study represented by DoS 0.6, is the best among the 3 modelled DoS values.

Under free flow traffic conditions (i.e. DoS 0.6), implementing BSP to 3 scenarios were environmentally beneficial, which were DoS0.6_R3/1_B20, DoS0.6_R1/1_B20 and DoS0.6_R3/1_B60. All emissions in these 3 scenarios have been reduced to various extents. The extent of reduction was the greatest for scenario DoS 0.6_R3/1_B60 where CO_2 emissions have been reduced by 13.6kg per hour. Implementing BSP in other scenarios, i.e. to buses on the minor road has resulted in environmental disbenefits, i.e. 10.7kg per hour more CO_2 was produced for the worst case-scenario DoS0.6_R1/3_B60.

For a heavier traffic condition, i.e. DoS 0.8, implementing BP1 starts to show some extreme impacts on emissions, especially for high frequency buses on the minor road. The impacts continue to deteriorate for a heavier DoS value 0.9, with the emergence of more scenarios with extreme emission increases. Implementing BP2 which comprises compensation and inhibition facilities is able to mitigate the effects as the strength of bus priority has been reduced.

For DoS 0.8, implementing BP2 to 2 scenarios (i.e. DoS0.8_R3/1_B20 and DoS0.8_R3/1_B60) can be considered as environmentally beneficial mainly due to the reduced CO2, NOx and PM. The emission reduction for DoS0.8_R3/1_60 was the greatest where CO2 emissions have been reduced by 2.3kg per hour. Implementing BSP in other 4 scenarios has resulted in environmental disbenefits, i.e. 35.6kg per hour more CO2 was produced for the worst case-scenario DoS0.8_R1/3_B60.

For DoS 0.9, except a small reduction made by NOx and PM in 2 scenarios with buses on the main road, emissions in all scenarios have increased. The case study showed a range of CO2 growth by percentage of 0.12%- 5.99%, which were equal to 1.2kg to 61.5kg more CO2 per hour for an isolated junction with 6080pcu/hour. Therefore implementing BSP under a near-capacity traffic condition is not an environmentally friendly measure.

6.5 Economic evaluation

The approaches used for economic evaluation have been reviewed in chapter 2 and 3 separately for travel time, emissions and VOCs. Using the suggested values for those indicators, a monetary value for each journey can be calculated. This section provides the evaluation of the impacts of implementing bus priority strategies on economic aspects. The monetary evaluation mainly considers the value of time, value of VOC (including fuel and non-fuel costs) and value of emissions. The absolute values are provided in Appendix III and the percent changes are discussed in this section.

6.5.1 Economic evaluation for DoS 0.6

For DoS 0.6, the impact of implementing either BP1 or BP2 on monetary values is relatively small. **Figure 6. 37** shows the percent change after implementing BP1 and BP2 on monetary values for 6 scenarios in DoS 0.6.

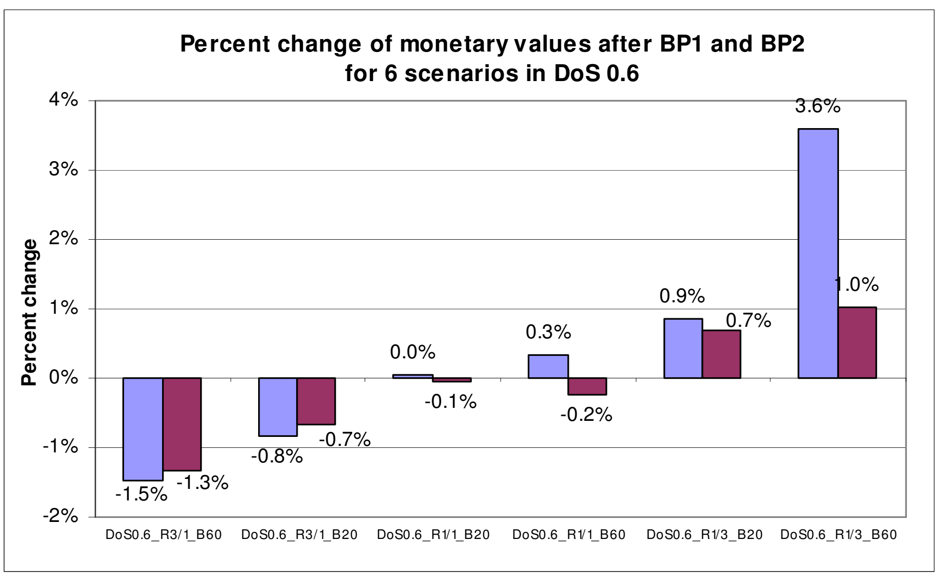

Figure 6. 37 Percent change of monetary values after implementing BP1 and BP2 for 6 scenarios in DoS 0.6

The order of the 6 scenarios in the figure from the left to the right is DoS0.6_R3/1_B60, DoS0.6_R3/1_B20, DoS0.6_R1/1_B20, DoS0.6_R1/1_B60, DoS0.6_R1/3_B20 and DoS0.6_R1/3_B60, showing an increasing trend of the percent change of the overall monetary values. From left to right, the impacts gradually increase and convert from a 'reduction' towards an 'increase'. It indicates implementing bus priority to the 2 scenarios when buses on the major road was an overall beneficial measure under DoS 0.6, and implementing BP to the 2 scenarios when buses were on the minor road has increased the overall costs. The impacts to the 2 scenarios in the middle, i.e. DoS 0.6_R1/1_B20 and DoS 0.6_R1/1_B60 were not obvious as the percentage change is about the 0%.

Table 6. 19 and **Table 6. 20** show the best and worst scenarios in terms of monetary values. For each scenario, the absolute monetary values and the percent changes for 4 aspects for the whole junction are provided, including the value of travel time, the prices of fuel and non fuel consumptions and value of emissions.

Table 6. 19 Monetary values for scenario DoS0.6_R3/1_B60 (Best scenario for DoS 0.6)

DoS0.6_R3/1_B60	Values (£/hour)			Value changes (£/hour)		Percent change	
	BL	BP1	BP2	BP1-BL	BP2-BL	(BP1-BL)/BL	(BP2-BL)/BL
Value of travel time	770.08	758.84	760.18	-11.24	-9.90	-1.46%	-1.29%
Price of fuel cost	232.65	228.19	228.40	-4.47	-4.25	-1.92%	-1.83%
Price of non fuel cost	125.62	124.74	124.79	-0.87	-0.83	-0.70%	-0.66%
Value of emissions	13.96	13.64	13.62	-0.32	-0.34	-2.29%	-2.42%
Sum	1142.31	1125.40	1126.99	-16.90	-15.31	-1.48%	-1.34%

Table 6. 20 Monetary values for scenario DoS0.6_R1/3_B60 (Worst scenario for DoS 0.6)

DoS0.6_R1/3_B60	Values (£)			Savings (£)		Percent change	
	BL	BP1	BP2	BP1-BL	BP2-BL	(BP1-BL)/BL	(BP2-BL)/BL
Value of travel time	792.07	811.04	795.54	18.96	3.47	2.39%	0.44%
Price of fuel cost	231.27	255.47	241.12	24.20	9.85	10.46%	4.26%
Price of non fuel cost	127.34	125.56	125.86	-1.78	-1.49	-1.39%	-1.17%
Value of emissions	13.93	14.52	14.13	0.59	0.19	4.23%	1.38%
Sum	1164.62	1206.60	1176.65	41.98	12.02	3.60%	1.03%

From the tables we can see that value of time and value of fuel are the biggest 2 contributors to the overall cost, counting as almost 90% of the overall cost. The value for emissions is relatively low, which only counts about 1% of the overall cost.

The scenario DoS0.6_R3/1_B60 as shown in **Table 6. 19** represents an 'all-win' scenario where the costs from all 4 aspects have been reduced after implementing BP1 and BP2, by 1.48% and 1.34% respectively. Therefore it can be concluded that for a free flow traffic condition, implementing both bus signal priority strategies to buses on the main road is beneficial in terms of all aspects including travel time, fuel and non fuel consumption and emissions and thus a positive overall monetary cost saving can be achieved. This benefit is greater when bus flow is high.

The worst scenario DoS 0.6_R1/3_B60 as shown by **Table 6. 20** represents high frequency buses on the minor road. For this scenario extending green time to the minor road has resulted in significant delay increasing to the main road traffic which dominated the overall evaluation. The overall increase of monetary value after implementing BP1 and BP2 is respectively 3.6% and 1.03%. These results suggest that under free traffic conditions, giving signal priority to buses on the minor road could cause monetary increase in terms of travel time, fuel cost and emission values. In this case, BP2 is able to mitigate the increasing rate to a more mild level. From the same table, opposite to other indicators, the non fuel cost has been reduced. This is explained by **Table 6. 21**.

Table 6. 21 Non-fuel cost for scenario DoS0.6_R1/3_B60

DoS0.6_R1/3_B60	Non-fuel costs(£/stream/hour)		
Traffic Streams	BL	BP1	BP2
Cars W--E	9.4	9.3	9.4
Cars E--W	9.4	9.3	9.4
Cars N--S	37.1	37.7	37.4
Cars S--N	37.2	37.7	37.4
Buses W--E	17.1	15.8	16.2
Buses E--W	17.1	15.8	16.1
Non-fuel cost for all vehicles	**127.3**	**125.6**	**125.9**

The non-fuel cost was calculated using average link speed which might not be sensitive enough to reflect the effect from instant signal variation, which consequently resulted in a combined increase.

The value of emissions contributed a small percentage to the overall monetary values, but we should use this result with caution. This is because these values were calculated using 'damage cost' approach (reviewed in chapter 3) which is still an early attempt to monetise the effect of pollutions. This approach is based on a number of assumptions and excludes a number of important effects that exist but difficult to be monetised. A list of caveats has been given in a guidance for using damage cost due to its great uncertainty. Therefore the value of emissions might have been underestimated in this study. However for an approximate assessment, this approach still remains the most state-of-the-art and probably the only way to value emissions.

There are a few conclusions can be drawn for DoS 0.6.

- For a relatively free flow traffic condition, representing by DoS 0.6 in this study and can be less, implementing bus priority strategies to buses on the main road can bring a benefit to all aspects including travel time, VOCs and emissions. The difference on the performance of BP1 and BP2 is minimum, i.e.0.8% and 0.7% reduction respectively for scenario DoS0.6_R3/1_B20 after BP1 and BP2. A heavier bus flow can even further boost the overall benefit, for this case study a 1.5% and 1.3% overall reduction after BP1 and BP2can be achieved for B60. For an hour long evaluation for an isolated junction, the overall benefit obtained is about £16.9 and £15.3 respectively for implementing BP1 and BP2.

- If the buses are on a road with evenly distributed flows, the overall monetary change is very small. Although it is still possible to obtain a benefit after implementing BP2, this benefit might be uncertain and subject to change with different parameter settings.
- If the buses are operated on the minor road, the disbenefit of implementing bus priority starts to emerge. When the bus flow is low the change is not obvious but increase with the increasing bus flow. For this case study, implementing BP1 and BP2 have caused 3.6% and 1.0% monetary increase to the modelled junction.

6.5.2 Economic evaluation for DoS 0.8

Similarly to DoS 0.6, the value of travel time and fuel are the biggest 2 contributors to the overall cost, and the value for emissions only accounts for about 1%. The effect of implementing BP1 under DoS 0.8 has dramatically increased, especially for scenarios with high frequency buses on the minor road. **Figure 6. 38** shows the percent change of the monetary values for all 6 scenarios in DoS 0.8 after implementing BP1, with the highest increasing by 223% for the worst scenario which still was very likely to be underestimated. Even for the best scenario, implementing BP1 has resulted in a small monetary increase (0.1%). For the worst scenarios when implementing BP1 to high frequency buses on the non-main road has raised the overall monetary value by 223% and 139%.This figure confirmed that from the overall economic aspect, BP1 is not recommended under high DoS values.

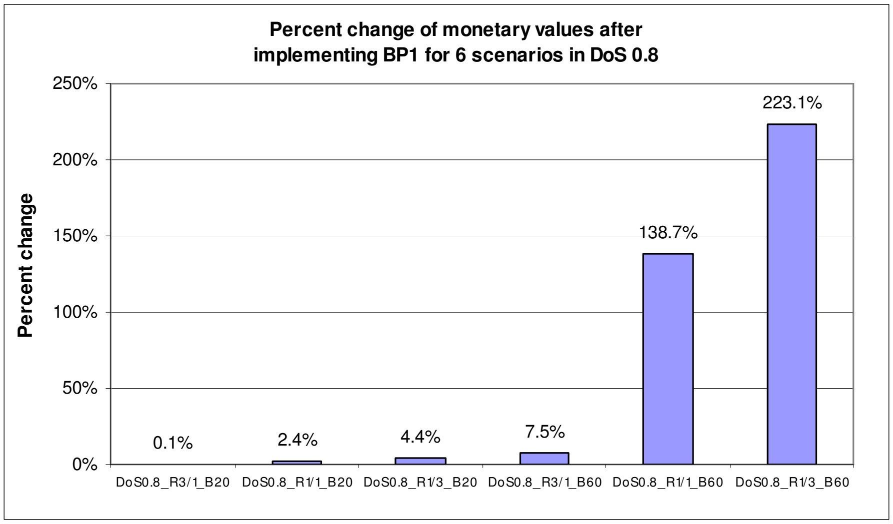

Figure 6. 38 Percent change of monetary values after implementing BP1 for 6 scenarios in DoS 0.8

Introducing 'compensation' and 'inhibition' for bus priority strategy (BP2) has significantly reduced the substantial increase of the economic values by BP1. However even after BP2 the monetary values for all scenarios in DoS0.8 have increased, by a range of 0.2% to 7% as shown in **Figure 6. 39**. This represents £3.12 to £108.16 increase per hour for an isolated junction.

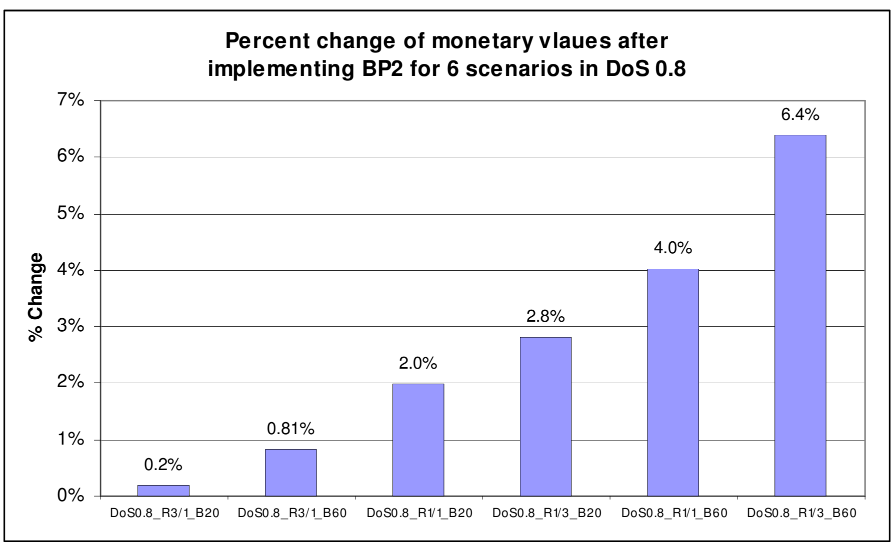

Figure 6. 39 Percent change of monetary values after implementing BP2 for 6 scenarios in DoS 0.8

For DoS 0.8, there are a few conclusions can be drawn:

- Generally implementing bus priority for high DoS value traffic condition is not cost-effective. BP1 strategy which excludes compensation and inhibition is not recommended for high bus flow situations as the cost can be largely increased.
- Implementing BP2 still results in an overall increase to the monetary values, but to a much less extent compared to BP1.
- Similarly to DoS 0.6, when buses are on the main road, implementing priority has the smallest effect compared to other scenarios. On the contrary, implementing bus priority to buses on the minor road can increase the overall cost.
- It should be noted that value of travel time is one of the main contributors to the overall cost. As discussed in delay analysis, the compensation time in BP2 is not a demand responsive setting but a fixed time period, the delays to the traffic on priority stage can be increased by over adding green time to the non priority stage, therefore there is still potential to improve travel time by using a more sophisticated compensation facility.

6.5.3 Economic evaluation for DoS 0.9

DoS 0.9 represents a near capacity junction which was modelled as the heaviest traffic condition in this study. Under this traffic condition, the overall costs of all 6 scenarios have increased to a greater extent compared to DoS 0.8 after implementing bus priority. BP1 due to the extreme increase on all aspects is not discussed here, and only the percent change of the monetary values after implementing BP2 is illustrated in **Figure 6. 40**.

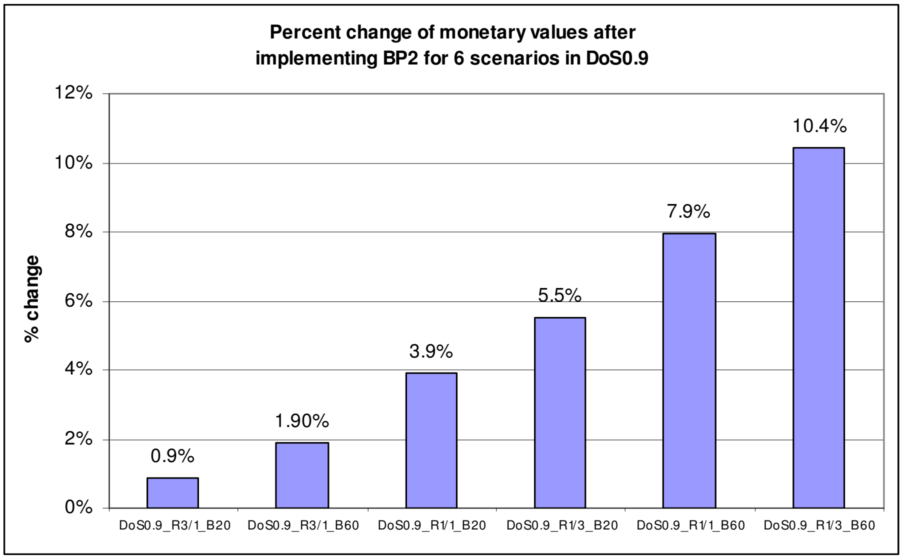

Figure 6. 40 Percent change of monetary values after implementing BP1 and BP2 for 6 scenarios in DoS 0.9

For all scenarios we can see a clear intensified effect compared to DoS 0.8. For the best scenario when low frequency buses were on the main road, the overall monetary values have increased by 0.9%, equal to £15.92 per hour. The maximum increase occurred to scenario DoS0.9_R1/3_B60, by 10.4% which was equal to £210 per hour per junction.

For DoS 0.9, a number of conclusions can be drawn as follows:

- DoS value 0.9 represents a near capacity traffic condition, implementing bus priority has resulted in cost increase for all 6 scenarios, both after BP1 and BP2. As expected, the effect was relatively smaller for the scenarios with low frequency buses on the main road and the effect was greatly enlarged when frequent bus flows were on the minor road.
- BP1 strategy without considering compensation and inhibition should not be considered n due to sharp increase of the overall monetary values. BP2 is more appropriate for traffic conditions with high bus flows and high DoS values.
- For all scenarios in DoS 0.9, even implementing BP2 has resulted in increased travel time, VOCs and emissions, which consequently has led to increased overall monetary values.

6.5.4 Summary of economic evaluation

This section summarises the monetised impact after implementing BP1 and BP2, as shown in **Figure 6. 41** and **Figure 6. 42**. The figures show the percent change of overall monetary values under 3 DoS values, after BP1 and BP2 respectively.

The values used for calculation in these 2 figures include value of travel time, value of VOC and value of emissions. The first 2 factors together contribute about 99% of the overall cost while the emissions if using damage cost theory, only accounts for about 1%.

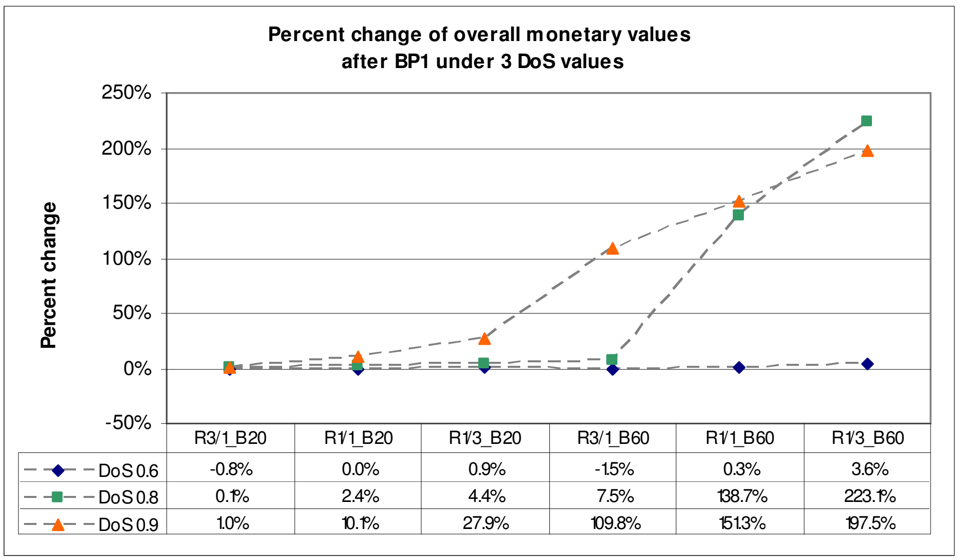

Figure 6. 41 Percent change of overall monetary values after implementing BP1 under 3 DoS values

Figure 6. 41 indicates that under DoS 0.6, an overall cost reduction has been obtained for 2 scenarios (DoS0.6_R3/1_B20 and DoS0.6_R3/1_B60) after implementing BP1. For DoS 0.8 and 0.9, implementing BP1 has caused increased monetary cost in all scenarios, and the increase has gone sharply with increasing bus flows on the minor road. For low or typical bus frequency on the main road, BP1 had the least impacts under all DoS values. Due to the substantial increase on the monetary values for a number of scenarios, especially with high DoS values and high bus flows on the minor road, BP1 is not recommended for these scenarios.

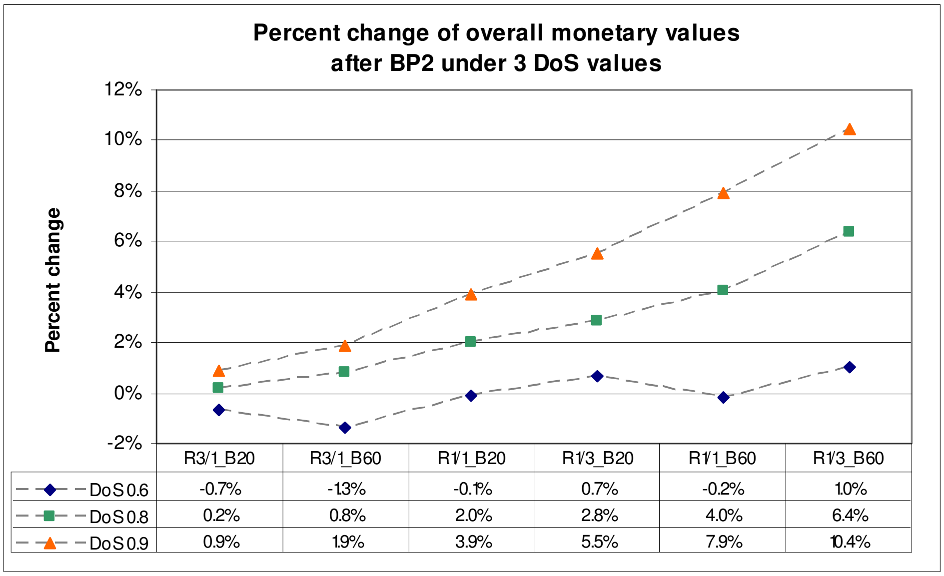

Figure 6. 42 Percent change of overall monetary values after implementing BP2 under 3 DoS values

BP2 was generally able to mitigate the severe side effects caused by BP1, because of the inclusion of compensation and inhibition facilities. **Figure 6. 42** shows a clear pattern of the percent change of the monetary values under 3 DoS values after implementing BP2. DoS 0.8 and 0.9 have a consistent trend but to different extents. The percent change horizontally increases according the scenarios from left to right and also vertically enlarged from low DoS to higher DoS. The scenarios from the left to the right show the order from the least affected to the most affected scenarios. For lower bus frequency on the main road, the overall impact is the minimum in terms of both scenarios and DoS values. For higher bus frequency on the minor road, the overall impact is the greatest among scenarios, and the extent is broadened by higher DoS values.

6.6 Case study in a wider context

The case study in this thesis is based on one junction only. In reality, evaluation of polluting emissions and CO2 on larger scales, e.g. city -wide or even national level is more of interest for decision makers. For example, as reviewed in Chapter 3, TfL (2006) planned to make a 30% reduction in CO2 emissions in London by 2025 in the transport sector on a 1990 base. Various means are needed to achieve this target. Bus priority, which was originally proposed to improve bus efficiency and to encourage public transport, was thought to have a potential effect on traffic emissions and CO2- this is also the motivation of this study. Via this study, an insight of how BP implementation influences traffic emissions at a microscopic level (i.e. one junction) has been recognised, including the effects of traffic conditions, whether the impacts are positive or negative, and the scale of these impacts. The methodology used in this study can be expanded to estimate the overall impacts of BP on emissions and CO2 for a citywide application. According to the results from the case study, it is possible to introduce emissions as one of the evaluation indicators, so that BP can be better designed and implemented with minimal impacts on emissions and CO2, or possibly even designed to reduce traffic emissions and CO2.

Efficiency, e.g. delay saving, has been the main indicator to evaluate the effectiveness of BP implementation, while emissions or CO2 are considered as a secondary indicator. In the future as the environmental issues become more important, the approaches used in this study can be further used to establish and estimate the impacts of implementing BP or other traffic control strategies on the environment.

To approximately understand what the CO2 emissions on a city wide level would be when implementing bus priority at signalised junctions in a city and how the emission change is relevant to the overall CO2 reduction target, a simple example is presented using the results from the case study. This example is only for demonstration purposes. A few general assumptions have been made:

1. ‘There are over 6,000 traffic signal locations in London and some 3000 are computerised as part of the Urban Traffic Control (UTC) network.’ (TfL, 2009) Assume that 30% of the 3000 computerised junctions are fitted with BP facilities.

2. Only the full BP strategy (BP2 as defined in the case study), including green extension, early recall, compensation and inhibition is implemented at all the BP active junctions.

3. Considering the real implementation of BP is constrained by many more factors and parameters, such as strict delay control for non-priority traffic, priority cancelation due to conflicting priority requirement sent from more than 2 buses approaching, coordinated junctions, the strength of BP is expected to be weaker than in the case study. For a very coarse estimation, it is assumed that the effects on CO_2 change after BP is only 20% of the results from case study.

4. Assume the 3 DoS values in the case study can be used to represent traffic conditions at a different time period of a day, i.e. DoS 0.6 as non-peak time, DoS 0.9 as peak hours, and DoS 0.8 as traffic situations between these 2.

5. Assume buses running from 5am to 12 midnight,(i.e. for 19 hours),with 9 hours of DoS 0.6, 6 hours of DoS 0.8 and 4 hours of DoS 0.9.

The case study has shown that the overall change of CO_2 per hour for one junction after implementing BP2 is:

1) For the best case scenarios:
   DoS 0.6: 13kg/hour reduction;
   DoS 0.8: 2kg/hour reduction;
   DoS 0.9: 1kg/hour increase.

2) For the worst case scenarios:
   DoS 0.6: 10kg/hour increase;
   DoS 0.8: 35kg/hour increase;
   DoS 0.9: 39kg/hour increase.

To convert CO_2 changes in kg per year, then the annual change of CO_2 emissions after implementing BP is:
For the best case scenario:
CO_2 change= 3000*30%*20%*((-13)*9+(-2)*6+1*4) = 22t/day= 8000t/year REDUCTION

For the worst case scenario:
CO_2 change= 3000*30%*20%*(10*9+35*6+39*4) = 80t/day=30000t/year INCREASE

Given that

1) London emits about 42 million tonnes of carbon dioxide each year. The road transport sector accounts for about 20% of this which is about 10 million tonnes (TfL 2006);

2) As stated before, the London CO2 target for 2025 is 30% reduction compared to 1990, and the 2010 target was a first half 15% reduction. Assuming this first 15% reduction has been achieved and another 15% needs to be reduced for the following 15 years, so about 0.1 million tonnes of CO2 reduction is to be achieved each year.

Therefore, this preliminary estimation shows that implementing BP could contribute to the overall emission change at a noticeable level, ranging from 8% (8000t/0.1mt) CO2 reduction to the overall London target to 30% (30000t/0.1mt) CO2 increase for the worst case scenario.

It should be noted that these data should not be used for any decision making process as it is oversimplified. The purpose of it is only to demonstrate to approximately what degree the results obtained from the case study relate to the city wide environment and the CO2 reduction target. However it still indicates that a well applied BP system can be environmentally friendly and could be a measure to contribute to the CO2 reduction target. If the BP is implemented without considering the environment, the negative effects could also be significant.

CHAPTER 7

SUMMARY AND DISCUSSIONS

7.1 Summary of the research

This research was initiated from the growing awareness of the impacts of human activities on the environment, such as air pollution and climate change. The *Environment Act 1995* and the National Air Quality Strategy (first published in 1997 and the latest 2007) were published to set out policies with respect to the assessment or management of the quality of air. Road transport is one of the major sources of man-made polluting emissions. These policies indicate that for any proposed traffic management operations local authorities have to be aware of their air quality impacts and appropriate environmental assessment is required.

The aim of this PhD study was to investigate the environmental impacts when implementing different bus priority strategies at traffic signals, to complement the operational criteria which are normally measured, particularly the delay impacts on buses and non-priority traffic.

Bus priority was originally proposed to mainly improve bus efficiency or regularity, therefore most of the previous research has either focused on evaluating priority measures or exploring how new technologies could be applied for more sophisticated strategies. The potential impacts on emissions caused by bus priority have not been studied. The qualitative and quantitative relationships between efficiency benefits gained from bus priority and the resulting environmental effects have not been fully understood. Furthermore, the extent of the impacts can be influenced by the forms of bus priority strategies, the conditions of traffic flows, bus operations in mixed traffic and bus frequencies. These questions have been addressed in this thesis.

The study has focused on an isolated junction where two bus priority strategies were modelled and compared with the baseline signal control plan – the UK's D-system Vehicle Actuation method which is in common use at isolated junctions. One bus priority strategy was named BP1 which involved green extension and early recall facilities. The other strategy was named BP2 which involved 2 additional forms -compensation and inhibition aimed at minimising any disbenefits to general traffic. A number of key factors (the Degree of Saturation (DoS) values, flow ratios of general traffic and bus flows) were identified which could influence the performance. These strategies and key factors were combined and modelled in 18 scenarios using a microsimulation tool-Aimsun, which was selected after a comprehensive review and selection procedure. To assess the impacts on emissions and fuel consumption, an instantaneous emission model was found to be the most appropriate approach for this study, after an extensive review of options. This is due to the complex dynamics of the interrelations between all the variables involved in traffic/bus operations at a signal controlled junction which required that only a computer based model was able to be applied. Using the output from the microsimulation model as the input to the instantaneous emission model, the results on emissions and fuel consumption were obtained and analysed.

A case study was then conducted involving the 18 simulation scenarios, to assess the impacts of bus priority strategies at an isolated junction. The analysis of the impacts included delay, emissions and Vehicle Operation Costs (VOCs). Monetary values were then evaluated using the recommended values of time and VOCs (both fuel and non-fuel cost) and values suggested for emissions based on recent research,

Before drawing conclusions from the results, it is necessary to discuss some issues related to the scope and the methodology of this study.

7.2 Discussions

The aim of this study was to investigate the environmental impacts of implementing bus priority strategies, and it has been achieved with a range of conclusions and recommendations presented in the next chapter. The scope and the methodology adopted in this study, as described in previous chapters, were determined based on an integrated consideration with a range of factors. The following sub-sections discuss some points which were not optimal and can be improved in future work.

7.2.1. The sophistication of Bus priority strategies

Four basic bus priority forms were included -green extension, early recall, compensation and inhibition, grouped into 2 strategies named BP1 (the first 2 forms) and BP2 (all 4 forms). These forms/strategies have been widely used in practice and still are the state-of-the-art systems in the UK for isolated junctions operating under D system VA.

In general, implementing these strategies has reduced bus delay as expected and general traffic on the priority stage has also been benefited to various extents in different scenarios. However for some particular scenarios in the case study, we can see an unexpected delay increase to the general traffic on priority stage after implementing BP2, especially with a high DoS value (e.g. 0.9) and/or a high bus flow on minor road. One potential reason for this is the use of a fixed-time period of compensation was not sophisticated enough in response to the real traffic demand at small intervals; and for an already fragile road network with heavy traffic, any disturbance to the pre-optimised signal control plan could result in severe excessive delay, and therefore disbenefits to all general traffic occurred, even for the general traffic on priority stage.

Another issue of modelling bus priority strategies at traffic signals is the need to consider 'differential' bus priority. In this study, priority was given to all buses regardless of their adherence to the pre-set headways or timetables. This method is used for minimising bus travel time and delay. However for real world implementation, this could make an early bus even earlier, and in this case a differential priority strategy should be more effective. However to model differential bus priority, a larger network is needed to include a longer length of a bus route or several bus stops and junctions so that the headway or punctuality can be checked. For this case, more complicated baseline signal control plans would be needed. The potential problem with the increased complexity of a network is that it will unavoidably introduce more variables, parameters and uncertainties which could make it difficult to isolate the impacts by implementing bus priority, and therefore could confuse the objective of this study. Due to these reasons, for this PhD study, an isolated junction with VA D-system was modelled, however, these 2 issues can be further studied in future work.

7.2.2. Emission modelling

Emission modelling is a complex topic. Instantaneous models are the newest generation of emission models with a set of advantages compared to others. The main advantage is they are able to capture the emission variation taking into account the driving dynamics, therefore emissions at a small scale can be predicted. This key characteristic is also one of the main requirements for this study- to estimate the emission changes of vehicles under different signal control methods when the dynamic and operational driving behaviour significantly influence the emissions. The literature showed that the emissions predicted from different emission models could be significantly different, partly due to the complex nature of a highly variable and uncertain process of emission formation and also due to some fundamental problems existing in instantaneous emission measurements.

There are 2 main approaches for modelling instantaneous emissions, one is based on the instantaneous speed and acceleration which was applied in this study, and the other type is based on engine power. From the literature some research concluded that the engine-power based emission models could better describe emissions in terms of engine speed and engine rather than just variables of speed and acceleration. But, there are also some other studies which have compared several instantaneous models using these 2 different approaches and concluded that for some cases one model was better than the other one and for other cases vice versa (Barlow et al 2007). In general discrepancies of opinions about instantaneous emission models in this field exist and may continue to exist in the near future.

In fact the variation and uncertainty does not only exist in instantaneous emission models. Even for the much widely used older generation of emission models, such as average speed models, the emission factors for the same pollutant for the same vehicle type in different models can be very different. These models normally apply the form of polynomial functions to suggest continuous emission factors according to average vehicle speed. Due to the different sources of original data for emission measurement and the regression methods, the parameter values for these functions in different models vary.

The literature review suggests that on one hand we should be aware of the uncertainty and potential errors of any emission models; but on the other hand, emission modelling is needed for estimating the potential emission impacts of traffic management schemes. Especially for studies required to model the dynamics of emissions at operational levels, where the emissions are dominated by vehicle operating modes rather than average speed, instantaneous emission models appear to be a more suitable and capable option, sometimes the only option.

However emission modelling is a fast moving area and the underperformed elements are evident but not exaggerated. According to the review carried out in this study, instantaneous emission models can be treated as the most appropriate available option for this study. For this PhD study, a speed-acceleration based model was applied. Although an engine based model was also a good option and would be interesting to apply as a comparison, no models of this type were available to be applied. This is because out of the 2 most developed engine-based emission models- CMEM and PHEM,- CMEM was developed in the US which was not applicable to the UK fleet situation and PHEM had not been generally available/released at the time modelling was required in this research.

7.3.3. Emissions evaluation and valuation

To evaluate the environmental impacts caused by implementing any traffic management schemes, emissions have usually been evaluated in terms of the changes of the absolute emitted amounts, mostly separate from other indicators, e.g. efficiency. This is understandable because emissions affect human health, the environment and the eco- system which are difficult to value in monetary terms. Therefore in the Cost-Benefit Analysis method where a range of factors such as time and VOCs can be evaluated using a monetised price, the environmental impacts have typically not been included.

More recently, a state-of-the-art concept called the 'damage cost' has been proposed to approximate the monetised values of air pollution (Defra 2006). This approach applied a multi-disciplinary assessment conducted by 11 interdepartmental organisations, attempting to include as many aspects as possible to reflect the possible damage that emissions could do to human beings and the environment. It aims to reflect the marginal damage costs when an extra tonne of pollution is emitted to the air (or the removal of one extra tonne of pollution). However it also stated in the damage cost approach that *'it is essential to remember that a number of effects are excluded from quantification, including impacts on ecosystems and cultural heritage because quantification is not possible or highly uncertain. Inclusion of these effects would further increase the values.'* It also stressed clearly that these relate only to the environmental effects, they do not include any mitigation costs (i.e. the costs of measures to reduce pollution).

The message was clear that the damage cost method is still an early attempt to monetise emissions and air pollutions, so this approach should only be used with caution. The case study showed that the values of emissions only accounted some 1% to the overall monetary values including values of time and Vehicle Operation Costs. This proportion is undoubtedly underestimated to some extent, but the extent is unknown. The problem of interpreting the proportions/values is the extent to which we should trust the values and whether we can make decisions based on them, in terms of both academic and policy appraisal. In addition, as explained above, this method only models the costs of the damage but not the cost to mitigate the pollution or to repair the damage, therefore the meaning of these monetary values needs to be stressed for policy makers.

For this study, conclusions/recommendations of the impacts on emissions may be better made on the absolute values and the percent changes of emissions rather than the monetary values of emissions. Otherwise if the results are interpreted outside of the context of the limitations of 'damage costs methodology', wrong impressions of the environmental impacts and even wrong decisions on a project or policy could be made. Nevertheless, the damage cost is the only means to approximate the values of emissions, and has to continue to be used until a more reliable methodology is developed or the current one is updated. With these considerations, the monetary values calculated by the damage cost method in this study should be considered as a secondary indicator for emission assessment.

7.2.4. Factors not included in this research

The case study was intentionally kept simple so that the main objective of this study would not be clouded by a number of potentially correlated factors. A range of factors have not been included in the case study, and some of these might be further studied in the future work. Two such examples are:

- **Turning traffic**

  Turning traffic is a common component in real junctions. The inclusion of turning traffic in this study would cause increased overall vehicle emissions (e.g. g/km) compared with junctions with straight-through traffic only. This is because vehicles usually need to decelerate while turning and accelerate back to the driving speed afterwards, which consequently causes more emissions. Furthermore, right turning vehicles may have to idle within the junction, waiting for a suitable gap in the opposing traffic stream. The reasons that this factor is excluded in the case study are:

  1) This factor, compared to the 3 key factors identified for the case (i.e. DoS, bus flow and car flows) is less important. Considering the aim of this study is to evaluate the impacts of implementing bus priority, the potential effect of adding this factor, as expected, will mainly increase overall emissions for both before and after studies for each scenario. Therefore this factor can be treated as a static factor and its effect would be likely to be very small for a before and after study..

  2) This factor introduces more sub-factors, such as the proportions of turning traffic, number of arms with turning traffic, turning directions, alternative signal

control plans. There are already 18 scenarios in the case study (in chapter 6) and for each one 3 signal control plans (i.e. Baseline signal plan without Bus priority, Signal plan with Bus priority 1 and Signal plan with Bus priority 2) simulated. These sub-factors multiply and the combinations would make the case over-complicated.

- **Bus stops were not modelled**

  Bus stops are a main element in urban bus services. In many cases where bus stops are close to the stopline, the effectiveness of implementing bus priority at traffic signals can be affected by the uncertainty of time consumed for alighting and boarding passengers at these stops. For some cases, buses may miss the extended green time for them and priority provision is then wasted. Many researchers have observed that bus stops can reduce the benefits (i.e. bus delay savings) of buses obtained by implementing priority strategies at traffic signals. Zheng et al (2007) modelled the effects of near-side bus stops on bus priority at an isolated junction using VISSIM. The results showed that near-side bus stop may increase transit delays under certain conditions at TSP-enabled intersections. The negative effect happened when the transit vehicle received a green extension but missed the treatment because of the excessive dwell at the near-side bus stop.

  A bus stop is also an obvious factor affecting bus emissions due to ‘stop and go’ behaviour at the stops where they emit more emissions than on the road sections. A study conducted by Rakha and Ding (2003) indicated that vehicle fuel consumption and emission rates increased considerably as a vehicle stop was introduced, especially at high cruising speeds.

  Therefore the potential effects of inclusion of bus stops, if considering the excessive dwell time at stops as may happen in real world, will be reduced bus delay savings for after BP scenarios and increased bus emissions for both before and after BP scenarios.

  This is an area for potential further research.

- **Pedestrian crossings were not modelled**

  Pedestrian crossings are commonly installed at or near traffic signals. The effects of pedestrians comprise 2 aspects, one is the impact on the modelling of bus signal priority and the other is the different traffic signal control logic. Again inclusion of pedestrian crossings would generate a number of new variables which require modelling a number of more scenarios, e.g. the locations of crossings, the pedestrian flow, the forms of crossing facilities etc. These variables could make it difficult to isolate the impacts of emissions by BSP and confuse the study objective and therefore here not been modelled.

The other issue relates to emissions and pedestrians at junctions could be that pedestrians are the most directly affected people because they are directly exposed at the most polluted areas- junctions and they usually need to wait at the crossings for the green signals. A Junction area is most polluted area because of the most frequent ‘stop and go’ or ‘decelerate and accelerate’ driving behaviour. Therefore the emission impacts are mostly closely related to pedestrians. However this seems less related to bus priority strategies, and has therefore not been presented in this study.

- **HGVs and other vehicle types were not modelled**

  HGVs, vans and light duty vehicles have not been included in this study, again to keep the case study simple and reduce the number of unnecessary variables. Other vehicle types could be added in future work. For example a real or a set of hypothetical proportions of HGVs can be tested in a variety of scenarios.

- **Modal shift was not modelled**

  The short-term effect of implementing bus priority strategies is expected to be reduced delay to buses and (with some strategies) improved regularity or punctuality. The longer-term effect could be a modal shift from cars to buses due to the improved level of service provided by buses; therefore a percent of modal shift might be achieved. However how and how much of the shift can be achieved need to be modelled using traffic modelling method which is another issue requiring a longer time to be studied. A more immediate further step from this study could be to conduct a sensitivity study assuming a set of percentages of modal shift.

7.2.5 Limitations of this study

The process of selecting the appropriate research approaches for this study, as presented in chapter 2 and chapter 3, has shown that micro-simulation and instantaneous emission modelling were the most suitable methods among the available options; however their limitations also need to be recognised. In general, the limitations of using these 2 main approaches are rooted in the deficiency of their own modelling methodologies as well as the compatibility in the integration process.

The main limitations of microsimulation, as widely recognised, are whether the embedded driving behaviour models (e.g. car-following, lane changing models) are able to sufficiently represent the complicated traffic situations and the even more complicated human driving behaviour. This is understandable because the performance of human behaviour, including driving behaviour is a combined result of many factors, and some of these factors, for example the driving psychology, are difficult to be well quantified and modelled even using the most advanced mathematical methods. These limitations on this aspect undoubtedly exist in this study as well.

For this particular study, as a computer based approach, microsimultion is able to realise the main tasks, i.e. model various bus priority strategies and VA signal control at junctions. It is also able to easily output results of efficiency (i.e. delay and travel time) at different levels of aggregation. However there are several traffic elements relating to this study that microsimulation are not able to model at a high level of accuracy. For example, Aimsun can not model the boarding and alighting behaviour of individual bus passengers, including their O-D, the interaction between those boarding and alighting passengers and the time consumed at bus stops. As a simplified solution, a normal distribution of bus dwell time at bus stops is introduced with parameters to be calibrated and determined by users. Another element where microsimulation is less well developed at present is in pedestrian modelling, either at road sections without facilities or at crossing facilities. The current pedestrian models seem to be oversimplified, e.g. the current pedestrian model in VISSIM is a modified version based on the car-following modelling method.

Another limitation of using microsimulation, - in fact the limitation of integrating microsimulation and instantaneous emission models is that only the speed-acceleration based emission models can be directly integrated with microsimulation while the engine-power based models require some extra input parameters which microsimulation does not include at present. None of the microsimulation models consider the working mechanism of vehicle engines or their transmission systems. As reviewed in Chapter 3, the opinions towards these 2 types of instantaneous emission models, i.e. speed-acceleration based and engine-power based models are that in terms of the modelling methodology, the latter appears to be more representative and convincing as it directly deals with emission forming and emitting processes during combustion. Therefore, the engine power based emission models appear to be closer to real-world situations. However, as previously stated in Chapter 3, research also has found that the accuracy and precision of the engine power based models is not (yet) noticeably better than the speed-acceleration models, mainly due to the uncertainty of the combustion and emitting process itself, the unsolved problems in emission measurements and errors in modelling processes (e.g. signal delay and damping in emission measuring and sampling process). Therefore at this stage, each approach has its advantages and disadvantages, with neither being demonstrably superior.

For future research, if integrating a microsimulation model and an engine-power based emission model becomes necessary in order to achieve better emission prediction and evaluation, there are 2 main improvements need to be fulfilled:

(1) Sufficient theory and data to have shown that 'the fundamental problems' of emission measuring and modelling for engine power based emission models have been overcome and the accuracy and credibility has significantly improved;
(2) Parameters of vehicles engines and gears relating to emission estimation have been introduced in microsimulation so that, in addition to the kinematic properties of vehicles, the engine related properties can also be available for vehicle emission prediction.

(2) Implications for traffic management strategies

Whilst this research has looked at an isolated junction only, results can have implications for larger scale networks with more complicated traffic and control conditions. Here we can take an example of a bus gating strategy in an urban corridor. This strategy allows buses to progress along a major road whilst general traffic is held back at some traffic signals on the crossways. To obtain a full evaluation, the same approaches as described here can be used to build a gating network with several junctions using microsimulation, e.g. Aimsun, and the emissions can be predicted by instantaneous models, e.g. Panis model. Using the results and patterns from the case study in this research a simple estimation of emission changes in a bus gating system is now discussed.

The results from the case study have shown that for an isolated junction, bus emissions have been reduced at various degrees after implementing BP, e.g. bus CO2 has been reduced by up to 10%. For general traffic the emission change relies on the combined effect of reduced emissions from cars on bus phases and increased emissions from cars on non-bus phases. The combined effect is mainly influenced by the ratio of conflicting traffic volumes, strength of bus priority, bus flows and the traffic conditions.

To evaluate vehicle emissions for a network with a bus gating strategy, bus emissions would be undoubtedly reduced, and car emissions would depend on the offset of traffic on the major road and traffic from all other conflicting minor roads. If the general traffic level on the major road is significantly higher than that from minor road, then it is likely that overall emissions can be reduced by introducing a bus gating strategy, as more vehicles benefit from buses having a smoother journey.

If the traffic from all the minor roads is greater than that on the main road , then the overall emissions might increase. However for a bus gating strategy, the duration of ‘holding’ for general traffic is usually longer than for an ordinary signalised junction. During the waiting time, some drivers may choose to switch off their engines (manually or automatically) and therefore do not generate emissions. As more and more new vehicles are fitted with idling stop technology, which automatically switch off engines after a certain time of idling, emissions from cars on non-bus phases would be less significant. If a certain proportion of vehicles do not produce emissions, either by manually switching off engines or with automatic devices, then even when the conflicting traffic volume is greater, the overall emissions could still be reduced. To determine the proportion, a study to understand the driver behaviour during waiting time at a bus gating controlled road would be necessary.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

The conclusions of this PhD study are presented in addressing the objectives listed in Chapter1. These objectives are re-stated here.

1) Review the latest developments in systems and strategies for bus priority using traffic signals;
2) Review the impacts of bus priority with particular emphasis on emissions;
3) Determine the best approach for emission estimation for bus priority at traffic signals;
4) Develop a simulation approach to assess bus priority strategies, allowing the assessment of efficiency, emissions and fuel consumption;
5) Apply the simulation model to a case study with a range of scenarios to quantify the relative impacts of different strategies;
6) Develop recommendations for modelling methodologies and for strategy selection.

8.1.1 Conclusions for literature review

The literature review in this thesis comprised 2 main parts, the literature on the systems and strategies for bus priority at traffic signals and the methods to evaluate the impacts on emissions. Four main points of conclusions can be drawn from the literature:

(i) The latest and most commonly used forms of bus priority at isolated traffic signals in the UK are green extension and early recall; compensation and inhibition can be given if necessary to reduce the negative effects to traffic on non-priority stages.

(ii) There has been very limited research on evaluating the environmental impacts of implementing bus priority strategies, except an early study -ENTRANCE in 1997,- but the data and method is out of date.

(iii) Emission models can be categorised into 4 groups according to the levels of aggregation and applicable scales, which are emission factor model, average speed models, traffic-situation models and instantaneous models. The first 3 categories are more suitable for a large scale and for longer time evaluation, e.g. emission evaluation for a city wide area and for a month or a year long period. If the evaluation is more concerned with a smaller scale and shorter time period, instantaneous models are better. This type of model can predict second-by-second emissions for individual vehicles.

(iv) When interpreting the results calculated using instantaneous emission models, one should always keep in mind that there are still some problems existing in instantaneous models, as discussed in the chapter 7.

8.1.2 Conclusions on the methodology

Determining the appropriate methodology for this study was a key task, and a number of conclusions for this part can be drawn as follows:

(i) Microscopic traffic simulation models have developed rapidly in recent years. The essential advantage is the real -time presentation for all individual vehicles on a modelled road network, including vehicles' instant speed, acceleration/acceleration rate, location etc on a second-by-second basis (or even finer resolution depending on user settings). This feature allows the real-time interactions between vehicles and signals which from literature is the best option to model bus priority strategies. The 'micro' feature also enables the integration of traffic and emission models at various spatial and temporal levels, especially the instantaneous models that require dynamic and individual vehicle kinematic inputs. Using this approach, the emission evaluation for an operational level can be undertaken. Microsimulation is the best suited method for this study.

(ii) Aimsun has been selected for this study and is able to model different strategies of bus signal priority using an external coding interface (API). Three signal control plans have been successfully modelled, including a baseline VA control plan, a bus priority strategy including green extension and recall, and another priority strategy including additional compensation and inhibition. The performance of Aimsun for this study is promising and its ability to integrate with emission models is state-of-the-art.

(iii) The selection of a microsimulation model should be based on particular purposes. The literature showed all the 3 most widely used models, i.e. PARAMICS, VISSIM, and Aimsun, had been recommended for different purposes with different requirements. Aimsun was selected for this study mainly based on the consideration of the ability to model bus priority and integrate with emission modelling. It also needs to be noted that the selection was conducted at the early stage for this research and as a rapidly developing area other models may have been improved in these aspects as well.

(iv) Some default values of bus related parameters in Aimsun have been calibrated using real data from London iBus system. The suggested new values can more realistically represent bus driving behaviour.

(v) For this study, the instantaneous emission models are the most appropriate option. Normally the requirement for extensive input data is one of the main problems for the application of this kind of emission models. However this has been solved by integration with microsimulation models.

8.1.3 Conclusions from the case study

The case study has examined the impacts of implementing 2 bus priority strategies (i.e. BP1 and BP2)[1] in 18 scenarios involving 3 key factors[2]. The evaluation included delay, emissions and then the overall monetised values. A number of conclusions can be drawn as follows:

8.1.3.1 Overview

(i) Both delay and emissions are influenced by DoS values, major/ minor road buses mixing with (R values) and bus flows (B values), to various extents with different factor combinations.

---

[1] BP1: including green extension and early green recall facilities
BP2: including additional compensation and inhibition facilities

[2] 1. Degree of saturation (DoS),
2. Flow ratios of general traffic flows (R values) and
3.Bus flows (B value)

(ii) The case study showed that in all scenarios, BP1 had a greater range of impacts than BP2 on both delays and emissions. For scenarios with higher DoS values and (high frequency) buses on the minor road, BP1 is not recommended due to severe increase in terms of both delay and emissions.

(iii) Generally after implementing BSP buses have achieved delay and emission reduction by a relatively large extent; cars sharing the same signal stage with buses have been beneficial as well but to a smaller extent. Cars on the non-priority signal stage have been affected to various extents. For some scenarios under heavy flow conditions giving BP1 to high frequency buses on the minor road caused substantial increase on both delays and emissions to the cars on the non-priority stage (major road), which consequently resulted in the overall increase to the whole junction.

8.1.3.2 Conclusions on delay

i) In general the higher the DoS value is the lower the BSP benefits to buses can be achieved, and the higher disbenefits are added to the general traffic;

ii) For any traffic conditions, implementing BSP to low frequency buses on the main road causes the least side effects to the cars on the non-priority traffic, while implementing BSP, especially BP1 to buses on the minor road can result in significant delay increase to the cars on the non-priority stage.

iii) When buses are on the same signal stage (meaning no conflicting priority demand), higher benefits to buses can be achieved when implementing BP1 to higher bus flows, but lower benefits to buses are obtained if implementing BP2 to higher bus flows. For both BP strategies, the higher bus flow causes the larger disbenefit to the non priority traffic.

iv) The best-case scenarios in the 18 simulated scenarios under 3 DoSs in terms of a minimum side effect to the non priority traffic are under a free flow condition implementing priority to low bus flows on a major road; the worst-case scenarios, on the contrary are under a heavy traffic condition implementing priority to high bus flows on a minor road.

v) In terms of average person delay for a junction combining vehicle delays and vehicle occupancy, implementing both BP1 and BP2 under a free flow condition is an overall beneficial measure. For this traffic condition, the benefit from BP1 is even greater than BP2. For a heavier traffic condition (i.e. DoS 0.8), implementing BP2 can still assure an overall benefit for all scenarios at a relatively smaller level compared to DoS0.6, however BP1 results in an overall disbenefit for scenarios with high bus flows on the minor road. For a near-capacity traffic condition (i.e. DoS 0.9), all the benefit is further reduced. In this case for scenarios with high bus flows on the non-main road even implementing BP2 can result in a slight overall disbenefit.

8.1.3.3 Conclusions on emissions

i) Similarly to delay, the same trend of the impacts of key factors can be found in emission changes. In general the higher the DoS value is the lower the BSP benefits to buses can be achieved, and the higher disbenefits are added to the general traffic.

ii) For any traffic conditions, implementing BSP to low frequency buses on the main road causes the least side effects to the cars on the non-priority traffic, while implementing BSP, especially BP1 to high frequency buses on the minor road can result in significant emission increase to the non-priority cars.

iii) Emissions of all 4 pollutants from buses have been reduced after implementing BSP, to various extents. The percent reduction of PM emissions from buses is the greatest which is a significant benefit to air pollution. PM is a highly toxic pollutant which seriously affects human health and increases the respiratory diseases and lung cancer, therefore PM has been valued by a very high damage cost (e.g. £203,048/tonne in central London area).

iv) CO2 is widely recognised as the main source of climate change. The effect of BSP on CO2 reduction should be emphasised. The benefit on CO2 reduction is the greatest when implementing BSP to buses on the major road and under relatively free flow traffic conditions. The greatest CO2 reduction according to the case study was 13.7kg per hour per junction. For a larger scale and longer term, the benefit would also be larger.

v) Generally under a free flow traffic condition, implementing BSP to buses on the major road is environmentally beneficial in terms of all pollutants.

vi) For a traffic condition with DoS 0.8, a smaller level of environmental benefit can still be achieved when only implementing BP2 to buses on the major road.

vii) For a near-capacity traffic condition (DoS 0.9), implementing BSP results in increased CO2 and VOC emissions for all scenarios. A small reduction for PM and NOx can still be obtained when implementing BP2 to buses on the major road only. This is mainly because emissions of these 2 pollutants from buses are a significant contributor which have been greatly reduced, which consequently has led to a slight overall reduction.

8.1.3.4 Conclusions on Economic values

i) Economic evaluation in this study included 3 factors: travel time, fuel and non-fuel cost, and emissions. The values for the first 2 can be found in Web TAG which has been established for a long time and been widely recognised. The values of emissions using the ‘damage cost approach’ are still at the early stage.

ii) The case study shows that the cost of travel time generally accounts for about 70% of the overall cost, the cost of fuel accounts for about 20%, the non-fuel cost accounts for 10%,. and the value of emissions only accounts for about 1%, but there is evidence that this is an underestimation as it only accounts for a proportion of the costs from emissions.

iii) Under a free flow traffic condition, implementing both BSP to buses (both typical and high flows) on the non-minor road can lead to an overall cost reduction, but the cost would be increased for buses from the minor road.

iv) Under heavy flow traffic conditions, the overall cost increases by implementing BSP, and the degree increases with the increasing DoS values and bus flows. The degree of increase is also greater when buses are on the minor road.

8.2 Recommendations for Future work

A number area of future work are recommended to enable this research to be enhanced. These include:

(i) Modelling the impacts for differential bus priority strategies for a larger network. Headway or timetable based priority strategies can be modelled and compared. To do this, the baseline signal timing method for the network should consider co-ordinated signal control systems where operational, particularly SCOOT for the UK.

(ii) Further research on a more sophisticated compensation facility considering the real-time compensation demand.

(iii) Emission modelling using engine-based models when they become available, if they are shown to be robust and more accurate than the 'speed -acceleration' instantaneous model used here.

(iv) Some of other factors as discussed in 7.2 can be modelled in the future, i.e. bus stops, other vehicle types, modal shift and future fleet.

(v) Undertaking a real world emission measurement, perhaps just based on one vehicle, so that the results from emission models and measurements can be compared and the relative errors studied.

(vi) Continued research to provide more comprehensive and robust monetary values for emissions.

APPENDIX I:
VA& BSP CODE IN PYTHON

```
from AAPI import *

#VA and BP logic with updated values for max green duration and compensation time_ 19 Oct 2010 #

#The following code is only for Simulation scenario DoS=0.6_1/1_B1&2 #
#Signal setting including: DoS=0.6, Y=0.5, y1/y2=1/1=0.25/0.25,#
#For fixed timing parameters: cycle time 48s, and g1=19s, g2=19s #
#For VA parameters: Max green time for this simulation is 29s for W-E, and 29s for N-S. Compensation time is
12s #

# =====Parameters realting to VA ==========#
cycleCounter= 0

cycle=0
currentPhase=1
startTime=0
currentTime=0
phaseElapse=0

MaxOutLengthForPhase1=29
MaxOutLengthForPhase3=29
minDuration=7
newDurationTemp=0


iMaxOut=0
iMinOut=0
iCurrentDemand=0
iOppositeDemand=0
simulationStep=0.25
#================================#


#=====parameters relating to BP=====#
# BP Strategy Flags for BP Activation#
BPExtensionFlag=0
BPRecallFlag=0
BPCompensationFlag=0      #0 when ER On, 1 when ERCI on #
BPExtensionTime=14        # Actually 13s given, the last 1s is used for comparing with VA to let VA take
charge#
BPCompensationTime=12     # 12s for DoS=0.6 and max g1=29s max g2=29s #

# Timers for extension and recall #
BPExtensionOn=0
BPExtensionElapse=-1
recallTimerForMin=0


# Timers for compensation#
recallCheck=0
compensationCheck=0
cycleCounterWhenRecalled=-10
#========================#



#===== output storage files in C: disk =====#
output1=open ('C:/busDetectionTime.txt', "w");
output2=open ('C:/phaseDurationTime.txt', "w");
#================================#
```

```
#=========defining functions============#
def NextPhase(currentPhase):
	if currentPhase==1:
		return 3
	elif currentPhase==3:
		return 1

def CurrentDemand(currentPhase, statusWest, statusEast, statusNorth, statusSouth):
	if currentPhase==1:
		if statusWest==1 or statusEast==1:
			return 1
		else:
			return 0
	elif currentPhase==3:
		if statusNorth==1 or statusSouth==1:
			return 1
		else:
			return 0
	else:
		return -1


def OppositeDemand(currentPhase, statusWest, statusEast, statusNorth, statusSouth):
	if currentPhase==1:
		if statusNorth==1 or statusSouth==1:
			return 1
		else:
			return 0
	elif currentPhase==3:
		if statusWest==1 or statusEast==1:
			return 1
		else:
			return 0
	else:
		return -1


def MaxOut(currentPhase,phaseElapse,MaxOutLengthForPhase1,MaxOutLengthForPhase3):
	if currentPhase==1:
		if phaseElapse>MaxOutLengthForPhase1:
			return 1
		else:
			return 0
	elif currentPhase==3:
		if phaseElapse>MaxOutLengthForPhase3:
			return 1
		else:
			return 0
	else:
		return -1


def MinOut(currentPhase,phaseElapse,minDuration):
	if currentPhase==1:
		if phaseElapse>minDuration:
			return 1
		else:
			return 0
	elif currentPhase==3:
		if phaseElapse>minDuration:
			return 1
		else:
			return 0
	else:
		return -1
```

```
def BP(time, timeSta, timeTrans, acycle):
	# BP Logic Begins ============================================================
	global currentPhase
	currentPhase=ECIGetCurrentPhase(276)
	global startTime
	startTime=ECIGetStartingTimePhase(276)
	global currentTime
	currentTime=AKIGetCurrentSimulationTime()
	global phaseElapse
	phaseElapse = currentTime - startTime
	global newDurationTemp
	newDurationTemp = phaseElapse + BPExtensionTime
	global iMinOut
	iMinOut= MinOut (currentPhase,phaseElapse,minDuration)

	global BPExtensionOn
	global recallTimerForMin
	global recallCheck
	global compensationCheck
	global cycleCounterWhenRecalled

	global currentDuration
	global BPExtensionElapse
	global iMinOut



#----------------------Extension--------------------------------
	if currentPhase==1 and BPExtensionFlag==1:
		statusWestBus=AKIDetGetCounterCyclebyId(341, 2)# 2: bus
		statusEastBus=AKIDetGetCounterCyclebyId(526, 2)# 2: bus
		if statusWestBus>0 or statusEastBus>0:
#			AKIPrintString("700,"+"Bus is detected on Phase," +str(currentPhase)+ ", at time," 
+str(currentTime))
#			output1.write("Bus is detected on phase ," +str(currentPhase)+ ", at time," 
+str(currentTime)+ "\n")
#			pCurrentDuration=doublep()
#			pCurrentDurationMax=doublep()
#			pCurrentDurationMin=doublep()

#
	ECIGetDurationsPhase(276,currentPhase,timeSta,pCurrentDuration,pCurrentDurationMax,pCurrentDu
rationMin)
#			global currentDuration
#			currentDuration=pCurrentDuration.value()

#			del pCurrentDuration
#			del pCurrentDurationMax
#			del pCurrentDurationMin

#			if newDurationTemp>=currentDuration: # current duration <= phase elapase + 13
			ECIChangeTimingPhase(276,currentPhase,newDurationTemp,timeSta)
			BPExtensionOn=1
			BPExtensionElapse=0
				#AKIPrintString("BPExtension ON  00 is " +str(BPExtensionOn))
				#AKIPrintString("BPExtensionElapse 00 is " +str(BPExtensionElapse))
#			else:
#				BPExtensionOn=0
#		else:
#			BPExtensionOn=0
```

```
#--------------------Recall----------------------------
		if currentPhase==3 and BPRecallFlag==1 and BPCompensationFlag==0:
			statusWestBus=AKIDetGetCounterCyclebyId(341, 2)			# 2: bus
			statusEastBus=AKIDetGetCounterCyclebyId(526, 2)	# 2: bus
			if (statusWestBus>0 or statusEastBus>0) and iMinOut==1:
#				AKIPrintString("800,"+"Bus is detected on Phase," +str(currentPhase)+ ", at time,"
+str(currentTime))
#				output1.write("800,"+"Bus is detected on Phase ," +str(currentPhase)+ ", at time,"
+str(currentTime)+ "\r\n" )
				ECIChangeDirectPhaseWithInterphaseTransition(276,1,timeSta,time,cycle) # stop
here and change to phase 4 and then 1 immediately
			elif (statusWestBus>0 or statusEastBus>0) and iMinOut==0:
				recallTimerForMin = 1
			if recallTimerForMin == 1 and iMinOut==1:
				ECIChangeDirectPhaseWithInterphaseTransition(276,1,timeSta,time,cycle)
				recallTimerForMin = 0



#--------------------------Recall with Compensation----------------------------
		if currentPhase==3 and BPRecallFlag==1 and BPCompensationFlag==1:

			statusWestBus=AKIDetGetCounterCyclebyId(341, 2)			# 2: bus
			statusEastBus=AKIDetGetCounterCyclebyId(526, 2)


			# Recall
			if recallCheck ==0:
				if (statusWestBus>0 or statusEastBus>0) and iMinOut==1:

		ECIChangeDirectPhaseWithInterphaseTransition(276,1,timeSta,time,cycle) # stop here and change to
phase 4 and then 1 immediately
					cycleCounterWhenRecalled = cycleCounter
					recallCheck =1

				elif (statusWestBus>0 or statusEastBus>0) and iMinOut==0:
					recallTimerForMin = 1

				if recallTimerForMin == 1 and iMinOut==1:

		ECIChangeDirectPhaseWithInterphaseTransition(276,1,timeSta,time,cycle)
					cycleCounterWhenRecalled = cycleCounter
					recallCheck =1

					global recallTimerForMin
					recallTimerForMin = 0
				#AKIPrintString("indicator cyclecounterWhenRecalled 1 is " +
str(cycleCounterWhenRecalled))

			else: # Compensation
				if (cycleCounter == cycleCounterWhenRecalled+1 and compensationCheck ==0):
					global MaxOutLengthForPhase3
					MaxOutLengthForPhase3 = MaxOutLengthForPhase3
+BPCompensationTime   # the original length + 6s  #
					compensationCheck = 1

				if (cycleCounter == cycleCounterWhenRecalled+2):
					MaxOutLengthForPhase3 = MaxOutLengthForPhase3 -
BPCompensationTime
					recallCheck = 0
					compensationCheck = 0

				#AKIPrintString("indicator cyclecounterWhenRecalled 2 is " +
str(cycleCounterWhenRecalled))
```

```
def VA(time, timeSta, timeTrans, acycle):


        # VA Logic Begins ====================================================
        global cycle
        cycle= AKIGetSimulationStepTime()
        global currentPhase
        currentPhase=ECIGetCurrentPhase(276)
        global startTime
        startTime=ECIGetStartingTimePhase(276)
        global currentTime
        currentTime=AKIGetCurrentSimulationTime()
        global phaseElapse
        phaseElapse = currentTime - startTime
        global newDurationTemp
        newDurationTemp = phaseElapse + 1.5

        global MaxOutLengthForPhase1
        global MaxOutLengthForPhase3
        global minDuration

        # Status of presence of each car detector
        statusWest=AKIDetGetPresenceCyclebyId(310, 0)
        statusEast=AKIDetGetPresenceCyclebyId(517, 0)
        statusNorth=AKIDetGetPresenceCyclebyId(519, 0)
        statusSouth=AKIDetGetPresenceCyclebyId(518, 0)

        global iMaxOut
        iMaxOut = MaxOut(currentPhase,phaseElapse,MaxOutLengthForPhase1,MaxOutLengthForPhase3)

        global iMinOut
        iMinOut=MinOut(currentPhase,phaseElapse,minDuration)

        global iCurrentDemand
        iCurrentDemand=CurrentDemand(currentPhase, statusWest, statusEast, statusNorth, statusSouth)

        global iOppositeDemand
        iOppositeDemand=OppositeDemand(currentPhase, statusWest, statusEast, statusNorth, statusSouth)

        global iNextPhase
        iNextPhase= NextPhase(currentPhase)

        # ---------------------------------------VA main body--------------------------------------------------------------#
        if currentPhase==1 or currentPhase==3:
                if (iCurrentDemand==0 and iOppositeDemand==0 and iMaxOut==0 and iMinOut==0)\
                        or (iCurrentDemand==0 and iOppositeDemand==0 and iMaxOut==0 and 
iMinOut==1)\
                        or (iCurrentDemand==0 and iOppositeDemand==0 and iMaxOut==1 and 
iMinOut==1)\
                        or (iCurrentDemand==0 and iOppositeDemand==1 and iMaxOut==0 and 
iMinOut==0)\
                        or (iCurrentDemand==1 and iOppositeDemand==0 and iMaxOut==0 and 
iMinOut==0)\
                        or (iCurrentDemand==1 and iOppositeDemand==0 and iMaxOut==0 and 
iMinOut==1)\
                        or (iCurrentDemand==1 and iOppositeDemand==0 and iMaxOut==1 and 
iMinOut==1)\
                        or (iCurrentDemand==1 and iOppositeDemand==1 and iMaxOut==0 and 
iMinOut==0)\
                        or (iCurrentDemand==1 and iOppositeDemand==1 and iMaxOut==0 and 
iMinOut==1):
                        ECIChangeTimingPhase(276,currentPhase,newDurationTemp,timeSta)
        # output=0: means no error occurred#

                        #AKIPrintString( "phaseElapse is" +str(phaseElapse) )
                        #AKIPrintString( "current phase duration is" +str(newDurationTemp) )
```

```
				elif (iCurrentDemand==0 and iOppositeDemand==1 and iMaxOut==0 and iMinOut==1)\
					or (iCurrentDemand==0 and iOppositeDemand==1 and iMaxOut==1 and
iMinOut==1)\
					or (iCurrentDemand==1 and iOppositeDemand==1 and iMaxOut==1 and
iMinOut==1):

	ECIChangeDirectPhaseWithInterphaseTransition(276,iNextPhase,timeSta,time,cycle) # 0 means no
error
#-----------------------------------------------------------------------------------------------------------------------#


	# VA Logic Ends

=====================================================================


def AAPILoad():
	AKIPrintString( "AAPILoad" )
	return 0

def AAPIInit():
	AKIPrintString( "AAPIInit" )
	return 0

def AAPIManage(time, timeSta, timeTrans, acycle):


	if ECIGetCurrentPhase(276) == 1 and AKIGetCurrentSimulationTime() -
ECIGetStartingTimePhase(276) ==1:
		global cycleCounter
		cycleCounter = cycleCounter + 1
	#AKIPrintString( "cycleCounter = " + str(cycleCounter))

	simulationStep=AKIGetSimulationStepTime()
	BP(time, timeSta, timeTrans, acycle)

	#AKIPrintString( "max green length of phase 3 = " + str(MaxOutLengthForPhase3))
	if BPExtensionElapse>=0:
		BPExtensionElapse=BPExtensionElapse + simulationStep
		#AKIPrintString( "BPExtensionElapse = " + str(BPExtensionElapse))
		#AKIPrintString( "BPExtensionTime = " + str(BPExtensionTime))
		if BPExtensionElapse>=(BPExtensionTime-1):
			global BPExtensionOn
			BPExtensionOn=0
			global BPExtensionElapse
			BPExtensionElapse=-1

	if (currentPhase == 1 and BPExtensionOn==0 and BPExtensionElapse==-1) or currentPhase ==3:
		VA(time, timeSta, timeTrans, acycle)




	#-------changing back facility begins--------------
	if currentPhase!=1:
		ECIChangeTimingPhase(276,1,minDuration,timeSta)
	if currentPhase!=3:
		ECIChangeTimingPhase(276,3,minDuration,timeSta)
	#-------changing back facility ends-------


	if currentPhase==1 or currentPhase==3:
		global phaseElapse
		phaseElapse = currentTime - startTime
		phaseElapseInteger= phaseElapse/0.25
		if phaseElapseInteger%4==0:
```

```
#                                       AKIPrintString( "900,"+ "duration of phase, " + str(currentPhase) + " is, " 
+str(currentDuration) +"at instant time of, " +str(currentTime))
                                       output2.write("Elapse time of phase, " + str(currentPhase) + " is, " +str(phaseElapse) 
+"s, at time of ,  " +str(currentTime)+ ",  "+ "\r\n");

        return 0

def AAPIPostManage(time, timeSta, timeTrans, acycle):
        return 0

def AAPIFinish():
        AKIPrintString( "AAPIFinish" )
        return 0

def AAPIUnLoad():
        AKIPrintString( "AAPIUnLoad" )
        return 0
```

Calibration of bus parameters in microsimulation modelling -an exploratory approach using sec-by-sec bus speed data

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Abstract

In microsimulation traffic models, calibration normally refers to the process to adjust the values of some model parameters in order to obtain a valid simulation output. The most concerned indicators for confirming the validity of simulation output include average traffic flow, link speed, journey time and etc. In practice, these indicators for validation are all on a macroscopic level but the validity of vehicle behaviour at a microscopic level such as vehicles' instantaneous speed and acceleration has not been taken into account. This consequently has restricted its further application such as in instantaneous emission models.

This paper attempts to calibrate 3 vehicle parameters for buses in Gipps car-following model (1981). Gipps model is embedded in a microscopic simulation package -Aimsun, which is used for this study. This paper firstly investigated the kinematic characteristics of bus driving in urban roads from second-by-second bus speed data from London iBus project. Characteristics of bus driving behaviour under different traffic conditions and from different drivers have been analysed. From this point this paper calibrated bus parameters of maximum acceleration rate, normal-maximum deceleration rate and speed limit acceptance level (Definitions for these parameters can be found in section 1). Distributions of these parameters have been analysed and values of these parameters for Gipps model in Aimsun have been suggested. A comparison study of bus emission prediction using an instantaneous emission model was conducted by applying different values of bus parameters. Conclusions and discussions are presented.

1. Introduction

Microscopic simulation models have become increasingly popular during recent decades and have been widely used to assess the likely effects of implementing new traffic management schemes or new traffic related technologies. The core components of microsimulation tools are a number of driving behaviour models functioning together aiming to reproduce vehicle movement on a road network. These models mainly include car-following model, lane-changing model, gap acceptance model and etc. The state-of-practice method to test the validity of a microsimulation model is to compare the simulated outputs against real data on a macroscopic level such as average traffic flow and link speed. Calibration normally refers to the process of altering values of some model parameters such as headway, reaction time and vehicle parameters to identify the best representative parameter values. Calibration and validation are always operated interactively in order to obtain a valid simulation system for a specific study area. This validation and calibration approach should be sufficient for the overall efficiency evaluation but at some extent has to neglect the validity of vehicle behaviour at the microscopic level, i.e. the validity of vehicles' instantaneous and individual kinematic output. Actually, from previous simulation using software Aimsun, we have observed some unrealistic driving behaviour such as very sharp braking or accelerating manoeuvre at stop-go conditions, especially buses. Consequently, although microsimulation model is able to output instantaneous and individual data on vehicles' speed and acceleration, which provides a comprehensive and potential input for other applications such as instantaneous emission models, however due to accuracy and credibility issues, the further application has been greatly restricted.

Only a very few studies have been done on calibrating and reproducing traffic phenomena at the microscopic level, largely due to difficulties and cost in collecting field data at this level. Since very recently researches have been carried out to calibrate car parameters in car-following models using GPS equipped vehicles. Brockfeld et al (2003) calibrated and validated 10 car-following models using a set of GPS data recorded on a test track in Japan. A comparison study is then performed to identify the difference among models. Punzo and Simonelli (2005) investigated the behaviours of 4 microscopic traffic models using GPS data obtained from 4 vehicles in Italy. The performance of 4 models were compared and analysed and suggestions of parameter values were proposed.

There has been very limited research on calibration of vehicle parameters in such models for urban buses, although buses are a very important component in urban traffic system and a big contributor to traffic related emissions. Generally it is perceived that buses have smaller speed, acceleration and deceleration rate compared to cars, but there has not been detailed research on investigating the driving behaviour of buses in urban networks. This study attempted to explore bus driving characteristics in urban areas based on a large number of sec-by-sec bus speed data from London iBus system. Using these data modified values of 3 parameters, i.e. maximum acceleration rate, normal-maximum deceleration rate and speed limit acceptance level in urban area have been proposed for Gipps car following model in Aimsun software.

Among these 3 parameters, 'Maximum acceleration' is used in Gipps model as the maximum acceleration a vehicle can achieve under any circumstances. 'Normal-maximum deceleration' is defined as the maximum deceleration that vehicles can use under normal driving conditions, in other words, the comfortable maximum deceleration drivers can use under non-emergency conditions. 'Speed acceptance level' is a parameter used in Aimsun to describe how well drivers are willing to obey the speed limits, or can be interpreted as the degree of acceptance of speed limits of drivers. Generally different drivers have different perceptions of their own limits on max speed, acceleration or deceleration. Among drivers these limits should be normally distributed.

Using 2 sets of parameter values, i.e. the default and the modified values for these 3 parameters, a comparison case study is conducted to predict bus emissions via an instantaneous emission model.

2. Gipps car-following model and Aimsun

According to authors' knowledge although many car-following models have been developed during recent decades and some of them have been included in microsimulation packages, there has not been such a concept of a perfect or a better model. Road traffic is a complex system involving many factors from various aspects, such as human factors involved in driving behaviour, technology factors included in road and in-vehicle facilities and traffic control /management strategies etc. All the models/simulation packages can at some aspects replicate the real traffic situations but may have their drawbacks on other certain aspects. To judge whether a model is better or not should be in line with the subject to be modelled and the study purposes. Aimsun is selected for this study after a comprehensive literature review (Zhang and Hounsell, 2010). Some selective papers that led to the seletion are listed as follows: According to Brackstone and McDonald (1999) part of the attractiveness of CA (Collision avoidance) models including Gipps model is that it can be calibrated using common sense assumptions about driver behaviour, needing only minimum parameters to allow it to fully function. Panwai and Dia (2005) compared and evaluated 3 main car-following models including Gipps model in Aimsun, psychophysical model in PARAMICS and psychophysical model in VISSIM, and concluded that Gipps model in Aimsun shows the lowest values in both Error Metric (EM) and Root Mean Square (RMS) Error compared to others for several macroscopic output. A comparison study for 3 widely used microsimulation software in the US was conducted by Jones et al (2004). It covers CORSIM, SimTraffic and AIMSUN. The authors concluded that 'AIMSUN is the most sophisticated of the 3 models, providing advanced features not found in either CORSIM or SimTraffic.'

Gipps car-following model is a safety distance model or collision avoidance model. In this kind of models vehicles follow the general rule that they accelerate to achieve their desired speed and decelerate when they have to avoid the collision to the leader vehicle while trying to maintain the desired speed. The Gipps model has been embedded in Aimsun simulation package. The original Gipps model was developed in 1981 and a few modifications about estimation of the leader's deceleration have been made in later versions of Aimsun. The basic idea of Gipps model is to set limits on the performance of driver/vehicle and use these limits to calculate a safe speed with respect to the preceding vehicle.

In Aimsun, the Gipps model consists of 2 main components, acceleration and deceleration and modified estimation of leader's deceleration. The model is described as follows.

The maximum speed to which of a vehicle (n) can accelerate during a time period (t, t+T) is given by:

$$V_a(n,t+T) = V(n,t) + 2.5a(n)T\left(1-\frac{V(n,t)}{V^*(n)}\right)\sqrt{0.025+\frac{V(n,t)}{V^*(n)}}$$

Where

V(n,T) is the desired speed of the vehicle n at time t;
V*(n) is the desired speed of the vehicle (n) for current section;
a(n) is the maximum acceleration for vehicle n;
T is the reaction time.

The max speed on the other hand the same vehicle (n) can reach during the same time interval (t, t+T), according to its own characteristics and the limitations imposed by the presence of the leader vehicle (n-1) is:

$$V_b(n,t+T) = d(n)T + \sqrt{d(n)^2T^2 - d(n)\left[2\{x(n-1,t) - s(n-1) - x(n,t)\} - V(n,t)T - \frac{V(n-1,t)^2}{d'(n-1)}\right]}$$

Where

d(n)(<0) is the maximum deceleration desired by vehicle n;

x(n,t) is position of vehicle n at time t;

x(n-1, t) is position of preceding vehicle (n-1) at time t;

s(n-1) is the effective length of vehicle (n-1);

d'(n-1) is an estimation of vehicle (n-1) desired deceleration.

In any case, the definitive speed for vehicle *(n)* during time interval *(t, t+T)* is the minimum of those previously defined speeds:

$$V(n, t+T)=min \{V_a(n, t+T), V_b(n, t+T)\}$$

In the newest Aimsun version to date, it introduced a new parameter which defined the minimum headway between leader and follower as a new restriction of the deceleration component. This is because in previous versions prior to v4.1.3 the estimation of leader's deceleration was taken as the proper desired deceleration of the leader vehicle. In case that the ratio between the follower's and leader's deceleration capabilities is relatively high, the above deceleration component of the car-following model presents instabilities which may cause some vehicles to drive too close to the leader. The new model considers the leader's deceleration as a function of a new parameter *α* defined per vehicle type named Sensitivity Factor. The algorithm can be referred to the Aimsun user manual (2009) hence not reviewed here.

The default parameter values for buses in Aimsun (version 6) are extracted as shown in Table 1. These parameters are all assumed to follow a truncated normal distribution. The parameters in the bold box have been analysed and calibrated in this study.

Table 1: Default bus parameter values in Aimsun (version 6)

Name	Mean	Deviation	Min	Max	Units
Length	12	2	9	15	meters
Width	2.3	0.5	1.9	3	meters
Max Desired Speed	90	10	80	120	Km/h
Max Acceleration	1	0.3	0.8	1.8	m/s2
Normal Deceleration	2	2	1.5	4.8	m/s2
Max Deceleration	5	2	4.5	8	m/s2
Speed Acceptance	1	0.1	0.9	1.1	
Min Distance Veh	1.5	0.5	1	2.5	meters
Give way Time	50	20	30	80	secs
Guidance Acceptance	75	10	65	90	%
Sensitivity Factor	1	0	1	1	
Minimum Headway	0	0	0	0	secs

In the development of these models the developers usually validate and calibrate the models using some data sets they have access to and publish the results obtained as default values. This initial calibration and validation process is generally able to produce valid simulation output on a whole, but can be subject to the source of data or country sensitive. As the availability of the large number of iBus data from London, a more detailed and specific calibration for bus parameters for London or for UK cities became possible. The following sections describe the data preparation, analysis of bus driving characteristics, and followed by the recommendations of parameter values for urban buses.

3. Data description and preparation

The bus instant speed data used in this study were part of the iBus (TfL, 2008) data collected during 2008 in London. iBus is a state-of-the-art Automatic Vehicle Location (AVL), radio and an on-bus passenger information display and announcement system - to every bus and garage across London, that's over 8000 buses and 90 garages. It used a combination of technologies to deliver the accuracy required from the AVL part of the system, including Global Positioning System (GPS) satellite technology and 'map matching' with inputs from a Gyroscope and the buses speedometer/odometer. In each bus a bus log was fitted to record every bus activity including the sec-by-sec bus speed and their location information.

In this study, 40 bus journeys driven by different drivers running in urban London were selected and used. These journeys were categorised into 2 groups, in order to include 20 journeys in peak time and 20 journeys in off-peak time, so that the real traffic conditions can be fully represented. It should be noted that in London there is no distinguished peak or off peak time period during most of the day time, so the data for off peak time in this study refer to very early morning or late night services. In each group for all 20 journeys (drivers) the speed and acceleration data show a generally similar shape, therefore from each group one example was taken for analysing driving characteristics. The bus running time for one way service ranges from about 45 minutes during off-peak time to about 1 hour during day time. The sec-by-sec speed data are directly available and acceleration or deceleration rate can be derived from speed differential.

Figure 1 shows a fraction of a bus' instantaneous acceleration rate and the corresponding instant speed profile during a short time period.

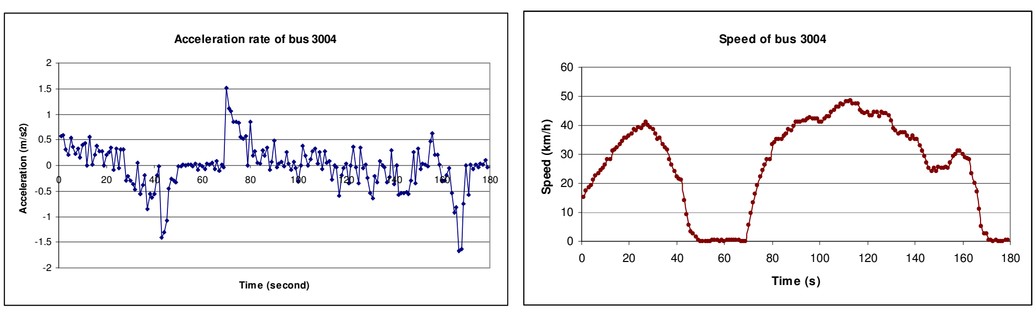

Figure 1: Sec-by-sec bus acceleration rate and speed profiles from iBus data

4. Characteristics of bus driving behaviour

4 bus drivers driving at peak and off-peak time were randomly selected for analysing bus driving characteristics. Speed limit adherence, acceleration and deceleration are the 3 main concerns in this study. As shown in Figure 2, the speed and acceleration pairs (deceleration as negative values) during morning peak and off peak time are plotted and analysed,.

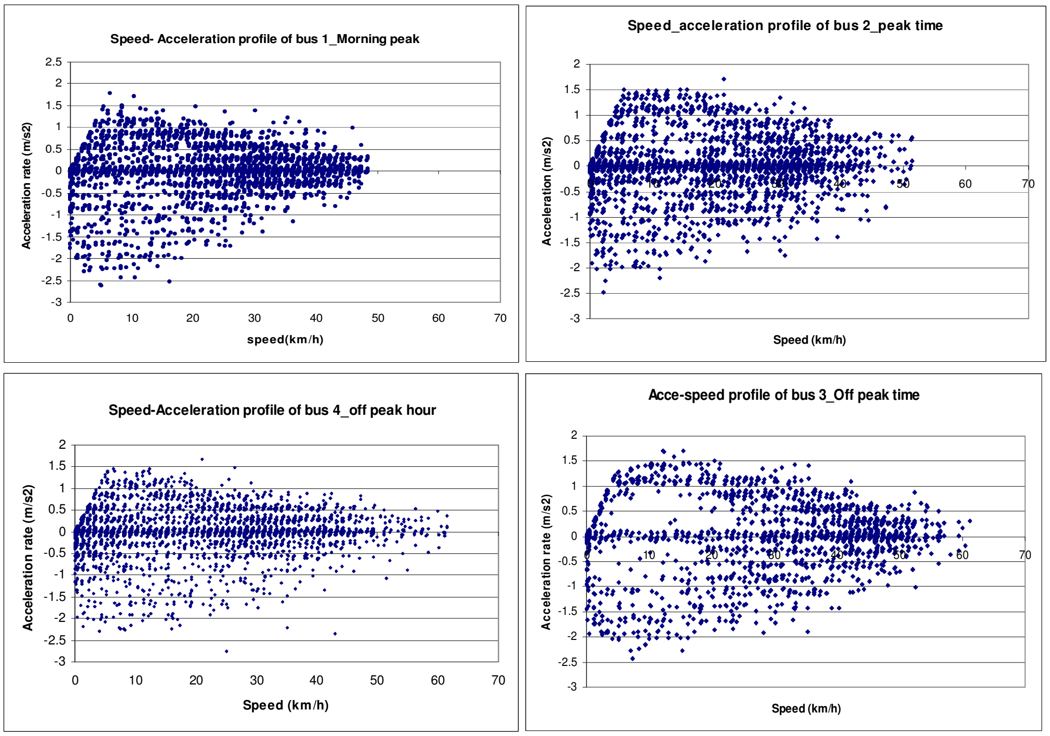

Figure 2: Speed-acceleration profiles of 4 bus drivers during peak and off-peak hours (clockwise from top left: driver 1 at peak time, driver 2 at peak time, driver 3 at off peak time and driver 4 at off peak time)

These figures above illustrate the relationship between speed (as x axis) and acceleration rate (as y axis) at each second. Generally we can see an obvious pattern between acceleration rate and speed with a decreasing boundary line of the maximum acceleration performed by drivers when speed increases. A similar trend can be observed for deceleration rate as well.

For the relationship between acceleration rate (the upper part in each figure) and speed, the general shape shows that from stopping status till before the drivers reach a certain point of low speed (around10km/h), there is an almost linearly increasing relationship between the maximum acceleration and speed. This phenomenon is probably due to the gear changing behaviour at very low speed, especially for 'stop- go' driving conditions at bus stops. When the driving speed goes up, the maximum acceleration decreases which indicates drivers tend to drive more smoothly within a smaller range of acceleration rate. Once they reach their desired speed (e.g. 50km/h), the drivers tend to drive steadily to maintain their current speed with a minimum fluctuation of acceleration.

The relationship between deceleration rate (the lower part in each figure) and speed shows a similar shape as observed in acceleration-speed relationship. However for deceleration-speed profile, there is not a clear linear relationship between the maximum deceleration rate and speed at the very low speed sections. This is probably due to the different mechanisms when drivers accelerate and decelerate. The figures also show that the maximum deceleration rates (absolute values) are greater than the maximum acceleration rates.

The figure shows that the drivers' driving behaviour differs during peak and off-peak times. From Figure 2 we can see that during peak hours, most drivers obey the road speed limit (50km/h) at all times, while at off-peak hours drivers tend to exceed the speed limit at some point.

The difference of driving behaviour among different drivers can be seen in Figure 2. In the bottom right graph showing the acceleration- speed profile of driver 3 at off-peak time, we can observe an area of data missing when speed ranges from 0 to about 30km/h, this indicates that this driver tend to use a larger acceleration rate to achieve his/her desired speed when driving at a lower speed. Compared with bus driver 4 at off-peak driving, assuming that the traffic conditions for these 2 journeys were similar, we may conclude that driver 3 is more aggressive than driver 4.

5. Calibration of bus speed acceptance, acceleration and deceleration

Data from 40 one-way bus journeys from different drivers were originally selected for calibration in this study. The maximum speed, acceleration rate and deceleration rate observed from each bus driver for the 1 hour driving experience is assumed to be the maximum values this driver would like to take in his/her normal driving behaviour. These parameters should be normally distributed within min and max limits. Four values for each parameter, i.e. mean, deviation, min and max values need to be identified.

'Speed acceptance' parameter describes the speed on a road section that one driver perceives as his/her acceptable speed limit, considering the actual speed limit on this road section. From data we can see that most drivers adhere to the road speed limit during day services but they may tend to exceed the limit at some point during early morning or late night driving. This can also be observed from Figure 2. As in Aimsun this parameter is a global variable without distinguish of traffic conditions, this part calculates the speed acceptance based on data including both peak time and off peak time driving.

The 'Maximum acceleration' or 'Normal-maximum deceleration rate' in Gipps model suggests that for each driver, there is a fixed max acceleration/and normal deceleration rate he/she would take under usual driving conditions. It assumes these values that different drivers adopt are normally distributed.

From the 40 data sets collected from 40 drivers, the first step is to test the normality for each parameter. The non-parametric one sample K-S test and an additional Q-Q plot for all the 3 data sets are conducted. After this process 5 data sets which appeared to be unrealistically larger than the rest data have been removed. This could be caused by the inaccuracy of speed recording techniques in the data collecting procedure.

For the 35 remaining data, testing results from the one-sample K-S test are shown in Table 2. The 2 tailed p-values 0.813, 0.998 and 0.832 for these 3 parameters (as shown in Table 2) suggest that the distribution of speed acceptance, maximum acceleration and normal-maximum deceleration is not different from the hypothesised, i.e. normal distribution. The normality is tested by an additional Q-Q plot. All 3 parameters in Q-Q graphs show an obvious straight-line and an example of Q-Q plot for deceleration rate is shown in Figure 3.

Table 2: One-Sample Kolmogorov-Smirnov Test for all 3 bus parameters

		Acceleration	Deceleration	Max Speed
N		35	35	35
Normal Parameters[a,b]	Mean	1.6997869	-2.4168451	51.72457
	Std. Deviation	.20820641	.34945049	7.051821
Most Extreme Differences	Absolute	.108	.066	.105
	Positive	.108	.066	.105
	Negative	-.068	-.060	-.087
Kolmogorov-Smirnov Z		.636	.391	.623
Asymp. Sig. (2-tailed)		**.813**	**.998**	**.832**

a. Test distribution is Normal.

b. Calculated from data.

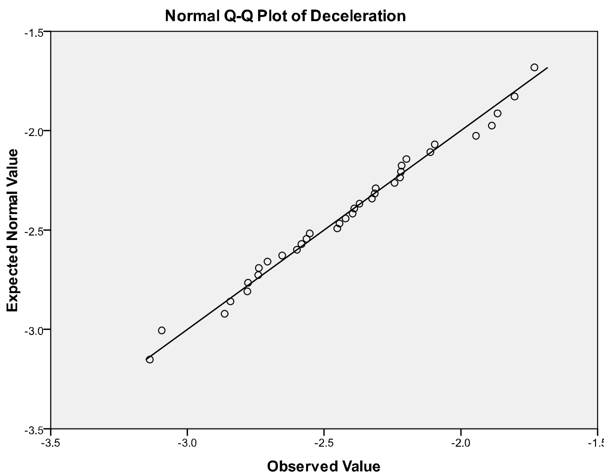

Figure 3: Q-Q plot for speed from 10 drivers

Therefore from the results of statistical tests, it is confident to assume a normal distribution for each of the parameters, with 2-tailed truncation. Within 95% significance level, the mean, deviation, min and max values for each parameter are summarised in Table 3.

Table 3 Suggested values for bus parameters in Gipps model and Aimsun software

	Mean	Std. Deviation	Min	Max
Speed acceptance	1.03	0.06	0.97	1.09
Max acceleration	1.70	0.21	1.07	2.12
Normal deceleration	2.42	0.35	1.37	3.11

Figure 4 and 5 below show the distribution of ‘max acceleration’ and ‘normal deceleration’ for buses, each including the default values in Aimsun and values as proposed in Table 3. We can see that the new parameters are more centralised to its mean than the Aimsun values, especially for deceleration rate. This can largely avoid aggressive braking behaviour observed in the past. The mean value of max acceleration is much greater than Aimsun value, which may imply a more aggressive driving at some point.

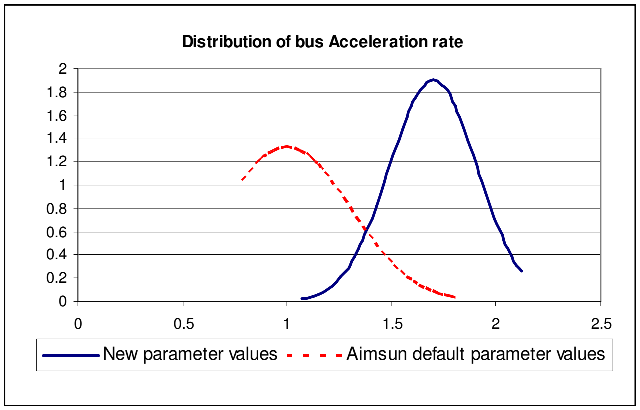

Figure 4: Comparison of 2 distributions of bus acceleration rate

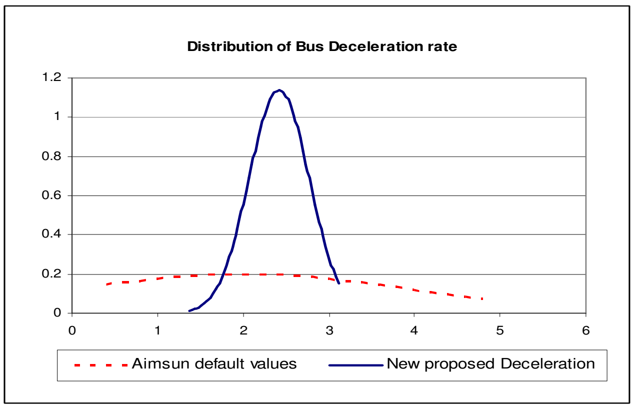

Figure 5: Comparison of 2 distributions of bus deceleration rate

6. Testing bus emissions using 2 sets of bus parameter values

An application to estimate bus emissions using 2 different sets of parameter values, one from default settings in Aimsun and one from values suggested in this paper are conducted using Aimsun. An instantaneous emission model developed by Panis et al (2005) has been used because this type of emission models is sensitive to the instant speed and acceleration change for individual vehicles. Panis emission model has been recently embedded in Aimsun.

A simple cross road junction with 4 arms and each with length of 350m was modelled in Aimsun. The junction is under Vehicle Actuation (VA) signal control plan. 2 traffic conditions were modelled in this paper, with degree of saturation (DoS) values of 0.6 and 0.8. Bus services were from 2 opposite directions and each with a frequency of 20 buses/hour. 10 replications were simulated for each traffic condition, with simulation duration of 10 hours for each. Using the 2 sets values of bus parameters, emissions of CO_2, NO_x, VOC and PM for buses obtained from Panis model have been obtained and compared. Table 4 shows the mean results, Percent difference using new and old bus parameter values and std. Deviation results for all 4 emissions under 2 traffic conditions. Parameter group 1 and 2 represent old default values in Aimsun and the newly proposed values in this paper. T-test was conducted for all emissions, and the results of t and p values are shown in Table 5.

Table 4: Group Statistics for emissions using 2 sets of parameter values and under 2 traffic conditions

	Parameter Groups	N	Mean	Percent difference (New to Old)	Std. Deviation
CO2_DoS=0.8	1 (Old)	10	654.8248	3.74%	9.07363
	2 (New)	10	679.2995		10.45043
NOx_ DoS=0.8	1 (Old)	10	5.58846	0.16%	.06876455
	2 (New)	10	5.59733		.07632045
VOC_ DoS=0.8	1 (Old)	10	.4873935	0.35%	.00691030
	2 (New)	10	.4891204		.00713982
PM_ DoS=0.8	1 (Old)	10	.1273328	3.11%	.00297216
	2 (New)	10	.1312966		.00346639
CO2_DoS=0.6	1 (Old)	10	638.0329	1.70%	13.04425
	2 (New)	10	648.8941		16.13032
NOx_ DoS=0.6	1 (Old)	10	5.43659	-1.32%	.10056560
	2 (New)	10	5.36462		.10837193
VOC_ DoS=0.6	1 (Old)	10	.4884597	-2.62%	.00814476
	2 (New)	10	.4756815		.00834438
PM_ DoS=0.6	1 (Old)	10	.1150529	2.33%	.00412387
	2 (New)	10	.1177362		.00504469

Table 5: Significance test for bus emissions using 2 sets of parameter values

DoS	DoS=0.8				DoS=0.6			
Emissions	CO2	NOx	VOC	PM	CO2	NOx	VOC	PM
t value	-5.592	-0.273	-0.550	-2.745	-1.656	1.539	3.465	-1.302
p-value	0.000	0.788	0.589	0.013	0.115	0.141	0.003	0.209

From Table 4 we can see that under heavy traffic condition (when DoS is 0.8), emissions from buses using new parameters all have slightly increased on average, especially CO2 and PM with 3.74% and 3.11% increase respectively. The difference on these 2 pollutants according to Table 5 is significant $t(18)=-5.592$ for CO2 and -2.745 for PM, $p<0.05$. The difference on NOx and VOC is not significant ($p>0.05$) in this case. Under relatively free flow traffic condition (when DoS=0.6), the percent change of all 4 emissions is not as significant as in heavy flow condition, and we can see that only the difference for VOC is significant different $t(18)=3.465$, $p<0.05$.

This is because max acceleration suggested in this paper is greater than the default value and in emission modelling this parameter is a significant contributor to emission amount. Under heavy traffic conditions when drivers have to drive with more ‘stop-and-go’ operations, significantly more emissions are produced. Under free flow traffic conditions when buses are able to drive at a constant high speed with mild acceleration or deceleration, the maximum values of acceleration or deceleration are less likely to be reached. Therefore the emissions are less sensitive under free flow driving.

7. Conclusions

Microscopic traffic simulation models contain a range of functions describing the behaviour and operation of drivers and vehicles. Most functions have associated default values (e.g. for co-efficients) which modellers are often tempted to use because of the unavailability of alternative data – but these default values are often based on quite restricted datasets. This can lead to modelling inaccuracies which can be significant on occasions.

This conclusion has been illustrated in this paper, taking advantage of automated data from buses in London to calibrate relevant bus acceleration, deceleration and speed statistics. In particular, it was found that actual bus acceleration rates differed significantly from the model default values – causing a significant difference in emissions also.

Data of the quality and resolution used in this study is becoming increasingly available from a range of 'floating vehicles, such as those equipped for real-time location monitoring and route guidance. It is recommended that such data is exploited as far as is practicable for specific calibration purposes when microscopic simulation is being used and results published. This should lead to higher quality microscopic simulation modelling, with associated benefits for users worldwide.

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APPENDIX III: MONETARY VALUES

Scenarios in DoS 0.6

DoS0.6_R1/3_B20	Monetary Values (£/hour/junction)			Percent Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Values of travel time	702.0	703.7	703.5	0.24%	0.21%
Price of fuel cost	218.7	226.4	224.7	3.52%	2.75%
Price of non fuel cost	108.7	108.1	108.1	-0.57%	-0.52%
Values of emissions	13.0	13.2	13.1	1.79%	0.90%
Sum	1042.4	1051.4	1049.5	0.86%	0.68%

DoS0.6_R1/3_B60	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	792.1	811.0	795.5	2.39%	0.44%
Price of fuel cost	231.3	255.5	241.1	10.46%	4.26%
Price of non fuel cost	127.3	125.6	125.9	-1.39%	-1.17%
Value of emissions	13.9	14.5	14.1	4.23%	1.38%
Sum	1164.6	1206.6	1176.6	3.60%	1.03%

DoS0.6_R1/1_B20	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	722.7	720.9	720.7	-0.25%	-0.27%
Price of fuel cost	232.8	235.5	234.5	1.15%	0.76%
Price of non fuel cost	108.8	108.4	108.4	-0.41%	-0.38%
Value of emissions	13.5	13.5	13.5	0.36%	0.07%
Sum	1077.7	1078.2	1077.1	0.04%	-0.06%

DoS0.6_R1/1_B60	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	804.0	806.3	802.8	0.28%	-0.14%
Price of fuel cost	245.9	248.9	245.3	1.24%	-0.23%
Price of non fuel cost	126.8	125.6	125.8	-0.90%	-0.78%
Value of emissions	14.4	14.3	14.3	-0.86%	-1.28%
Sum	1191.1	1195.2	1188.2	0.34%	-0.24%

DoS0.6_R3/1_B20	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	696.2	690.1	690.9	-0.87%	-0.76%
Price of fuel cost	210.0	208.1	208.9	-0.90%	-0.52%
Price of non fuel cost	108.2	107.8	107.8	-0.35%	-0.33%
Value of emissions	13.0	12.9	12.9	-1.41%	-1.37%
Sum	1027.4	1018.9	1020.5	-0.83%	-0.68%

DoS0.6_R3/1_B60	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	770.1	758.8	760.2	-1.46%	-1.29%
Price of fuel cost	232.7	228.2	228.4	-1.92%	-1.83%
Price of non fuel cost	125.6	124.7	124.8	-0.70%	-0.66%
Value of emissions	14.0	13.6	13.6	-2.29%	-2.42%
Sum	1142.3	1125.4	1127.0	-1.48%	-1.34%

Scenarios in DoS 0.8

DoS0.8_R1/3_B20	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1059.7	1100.9	1090.4	3.89%	2.89%
Price of fuel cost	322.8	349.5	335.8	8.27%	4.04%
Price of non fuel cost	150.2	149.9	149.9	-0.20%	-0.20%
Value of emissions	18.4	19.2	18.8	4.12%	2.00%
Sum	1551.2	1619.5	1594.9	4.41%	2.82%

DoS0.8_R1/3_B60	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1162.0	4406.9	1240.7	279.23%	6.77%
Price of fuel cost	337.4	824.2	366.3	144.30%	8.58%
Price of non fuel cost	169.7	193.0	169.5	13.72%	-0.11%
Value of emissions	19.5	32.3	20.3	65.35%	3.95%
Sum	1688.7	5456.4	1796.8	223.12%	6.40%

DoS0.8_R1/1_B20	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1106.4	1134.6	1131.3	2.55%	2.25%
Price of fuel cost	341.0	352.2	348.1	3.28%	2.07%
Price of non fuel cost	150.6	150.4	150.4	-0.09%	-0.09%
Value of emissions	19.0	19.3	19.1	1.56%	0.94%
Sum	1616.9	1656.5	1649.0	2.44%	1.98%

DoS0.8_R1/1_B60	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1198.0	3140.3	1254.3	162.13%	4.70%
Price of fuel cost	354.0	786.2	367.5	122.09%	3.82%
Price of non fuel cost	169.2	198.3	169.3	17.20%	0.04%
Value of emissions	20.1	31.8	20.4	58.32%	1.67%
Sum	1741.3	4156.7	1811.5	138.71%	4.03%

DoS0.8_R3/1_B20	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1047.3	1049.4	1050.6	0.20%	0.31%
Price of fuel cost	320.8	320.7	320.9	-0.05%	0.01%
Price of non fuel cost	149.4	149.2	149.2	-0.13%	-0.11%
Value of emissions	18.3	18.3	18.3	-0.15%	-0.17%
Sum	1535.8	1537.5	1538.9	0.11%	0.20%

DoS0.8_R3/1_B60	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1128.4	1232.9	1141.7	9.27%	1.18%
Price of fuel cost	332.4	350.9	332.8	5.56%	0.11%
Price of non fuel cost	167.2	167.8	167.0	0.34%	-0.12%
Value of emissions	19.4	19.8	19.3	2.54%	-0.35%
Sum	1647.3	1771.5	1660.7	7.54%	0.81%

Scenarios in DoS 0.9

DoS0.9_R1/3_B20	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1283.7	1649.0	1361.4	28.46%	6.05%
Price of fuel cost	391.5	538.9	415.9	37.64%	6.23%
Price of non fuel cost	171.7	175.5	171.9	2.22%	0.15%
Value of emissions	21.6	25.5	22.3	18.05%	3.09%
Sum	1868.5	2389.0	1971.5	27.85%	5.51%

DoS0.9_R1/3_B60	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1391.2	4896.3	1550.3	251.94%	11.43%
Price of fuel cost	405.0	830.9	453.5	105.13%	11.96%
Price of non fuel cost	191.6	221.0	192.8	15.33%	0.61%
Value of emissions	22.7	32.6	24.1	43.44%	6.02%
Sum	2010.6	5980.7	2220.6	197.46%	10.45%

DoS0.9_R1/1_B20	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1345.5	1493.9	1406.8	11.03%	4.56%
Price of fuel cost	409.5	455.5	424.1	11.22%	3.55%
Price of non fuel cost	172.3	173.5	172.5	0.70%	0.16%
Value of emissions	22.2	23.4	22.6	5.45%	1.67%
Sum	1949.5	2146.3	2026.0	10.10%	3.93%

DoS0.9_R1/1_B60	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1443.3	4156.9	1576.3	188.01%	9.22%
Price of fuel cost	420.7	799.1	450.7	89.93%	7.12%
Price of non fuel cost	191.4	234.8	192.8	22.67%	0.72%
Value of emissions	23.3	32.4	24.2	39.01%	3.72%
Sum	2078.8	5223.2	2243.9	151.27%	7.95%

DoS0.9_R3/1_B20	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1269.1	1285.3	1283.0	1.28%	1.09%
Price of fuel cost	387.6	389.6	389.7	0.51%	0.55%
Price of non fuel cost	170.8	170.7	170.7	-0.07%	-0.06%
Value of emissions	21.5	21.6	21.6	0.10%	0.11%
Sum	1849.1	1867.2	1865.0	0.98%	0.86%

DoS0.9_R3/1_B60	Monetary Values (£/hour/junction)			Difference	
	BL	BP1	BP2	BP1: BL	BP2: BL
Value of travel time	1359.9	3163.4	1394.5	132.62%	2.54%
Price of fuel cost	398.7	727.6	401.7	82.48%	0.75%
Price of non fuel cost	189.2	211.4	189.1	11.75%	-0.04%
Value of emissions	22.6	31.7	22.6	40.21%	0.00%
Sum	1970.4	4134.1	2007.9	109.81%	1.90%

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