DEVELOPMENT OF A MICRO-SIMULATION MODEL FOR MOTORWAY ROADWORKS WITH THE USE OF NARROW LANES AND LANE CLOSURE SCHEMES

Zaid Fadhil NASSRULLAH

School of Computing, Science and Engineering

University of Salford

Manchester, UK

Submitted in Partial Fulfilment of the Requirements of the Degree of Doctor of Philosophy, July 2016

Table of Contents

List of Tables

List of Figures

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor ***Dr Saad Yousif*** for his earnest support, invaluable advice and constructive guidance throughout this study. I learnt from him not only much of what I know about the research but also the importance of being committed, caring and supportive.

I gratefully acknowledge the financial support of the Ministry of Higher Education and Scientific Research, Iraq. Thanks to the staff of the Iraqi cultural attaché in London for their support.

I would like to extend my thanks to the staff at the School of Computing, Science and Engineering (CSE) and especially to my co-supervisor Mr Ralph Henson for his support during this research. Thanks to my friends and my colleagues for their help in collecting the data.

Finally, I would like to thank my family for their love, support, encouragement and patience. Thank you for being such a great family. I am so proud of all of you and I am so happy to be part of your lives.

DECLARATION

Some parts of the work presented in this thesis have been presented in the following events:

Nassrullah, Z. and Yousif, S. (2013). Modelling traffic behaviour at motorway roadworks using micro-simulation. Deans Annual Research Showcase, Poster and Abstract, University of Salford, UK.

Nassrullah, Z. and Yousif, S. (2013). Lane-changing models: A literature review. 4th CSE Doctoral School Postgraduate Research Conference, University of Salford, UK.

Nassrullah, Z. and Yousif, S. (2014). Modelling driver-vehicle's characteristics for motorway roadwork. Deans Annual Research Showcase, Poster and Abstract, University of Salford, UK.

Nassrullah, Z. and Yousif, S. (2015). Traffic behaviour at UK motorway roadworks sections with narrow lanes. Deans Annual Research Showcase, Poster and Abstract, University of Salford, UK.

Nassrullah, Z. and Yousif, S. (2015). Modelling traffic behaviour at motorway roadworks sections with narrow lanes using micro-simulation. SPARC Conference. University of Salford, UK.

Nassrullah, Z. and Yousif, S. (2015). Modelling motorway roadworks using S-Paramics. Paramics Microsimulation Workshop, Manchester, UK.

Nassrullah, Z., Yousif, S. and Norgate, S. (2016). Observations of traffic behaviour from UK motorway roadworks sections with narrow lanes. UTSG 48th Annual Conference. The university of the West England, and University of Bristol, UK.

Nassrullah, Z. and Yousif, S. (2016). Modelling driving behaviours at motorway roadworks using micro-simulation. CSE 2016 Annual PGR Symposium, University of Salford, UK.

* Nassrullah, Z. and Yousif, S. (2016). Micro-simulation model for motorway roadwork sections. SPARC Conference. University of Salford, UK.

* This paper won the best presentation prize in the conference.

DEDICATION

To my late father, whom I miss him every day, and my mother, you both will always be in my heart.

ABBREVIATIONS

ADT:	Average Daily Traffic
AIMSUN:	Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks
CARSIM:	CAR following SIMulation model
CORSIM:	CORridor SIMulation model
CSD:	The clear spacing distance
D2LC:	Distance required to initiate the desire of Lane Changing
DAGC:	Driver AGgressiveness Class
DCSL	Drivers' Compliance with Speed Limit
DLC:	Discretionary Lane Changing
DRACULA:	Dynamic Route Assignment Combining User Learning and microsimulAtion
EM:	Error Metric
FDAL:	Following the HGV on Adjacent Lane
FDSL:	Following the HGV on Same Lane
FORTRAN:	FORmula TRANslating System
Fveh:	The following vehicle (when its leader is a HGV)
GEH:	Geoffrey E. Havers statistical test
GHR	Gazis-Herman-Rothery
HGVs:	Heavy Goods Vehicles
IVD:	Individual Vehicles' raw Data
K-S:	Kolmogorov-Smirnov
MIDAS:	Motorway Incident Detection and Automatic Signalling
MITSIM:	Microscopic Traffic SIMulator
MLC:	Mandatory Lane Changing
mph:	Miles per hour
MUD:	Move Up Delay
MUTCD:	Manual on Uniform Traffic Control Devices
N-CD:	Non-Complying Drivers
PARAMICS:	PARAllel MICroscopic Simulation
pcu:	Passenger Car Units

RMSE:	Root Mean Square Error
RMSEP:	Root Mean Square Error Percentage
TBSVeh:	Time Between Successive VEHicles
THRD:	THReshold Distance
THRT:	THReshold Time
TTMSs:	Temporary Traffic Management Schemes
VISSIM:	VlSual SIMulation

SYMBOLS

μ:	The mean of a distribution
μx:	The mean of the observed data
μy:	The mean of the simulated data
σ:	The standard deviation of a distribution
σx:	The standard deviation of the observed data
σy:	The standard deviation of the simulated results
ϕ:	The proportion of restrained vehicles
Δt:	Scanning time (sec)
Δv:	The relative speed between vehicle n and (n-1)
Δx:	The relative distance between vehicle n and (n-1)
a:	The mean of the lognormal distribution
ACC:	The acceleration or deceleration rate of vehicle n (m/sec^2)
ACC_1:	Maximum acceleration of the vehicle (m/sec^2)
ACC_2:	The acceleration required to reach the desired speed (m/sec^2)
ACC_3:	The acceleration for the slow moving vehicle (m/sec^2)
ACC_4:	The acceleration for moving from stationary (m/sec^2)
ACC_5:	The acceleration for non-collision criteria (m/sec^2)
BUF:	Buffer space (m)
$Capacity$:	Maximum throughput (capacity) of motorway roadwork sections (veh/hr)
$Closure$:	The implementation of offside lane closure or inside lane closure as a TTMS (1 if true and 0 if false)
D_{cr}:	Critical difference in the cumulative distributions between two samples
D_{max}:	Maximum difference in the cumulative distributions between two samples
$Delay$:	The average vehicles delay (sec/veh)
DVc:	The desired speed of following vehicle (km/hr)
$Flow$:	The traffic flow of motorway section (veh/hr)
G_{lag}:	Lag gap (m)
G_{lead}:	Lead gap (m)
G_{min}:	Minimum safe constant gap (m)
$G_{min,lag}$:	Lag critical lag (m)

$G_{min,lead}$:	Lead critical gap (m)
HGVs%:	The percentages of Heavy Goods Vehicles (decimal, i.e. 0.15 for 15%)
Inside:	The implementation of inside lane closure as a TTMS (1 if true and 0 if false)
K:	Traffic density (veh/km)
Lrw:	The length of roadwork zone (m)
Lanes:	Number of lanes of motorway (i.e. 2, 3 or 4)
Llead:	Length of leading vehicle (m)
MaxDECC:	Maximum deceleration rate for the subject vehicle (i.e. merger) (m/sec^2)
MaxDECF:	Maximum deceleration rate for the following vehicle (m/sec^2)
MaxDECL:	Maximum deceleration rate for the leading vehicle (m/sec^2)
n:	Sample size
Narrow:	The implementation of narrow lanes as a TTMS (1 if true and 0 if false)
Offside:	The implementation of offside lane closure as a TTMS (1 if true & 0 if false
POSC:	The position of vehicle C (m)
POSF:	The new position of follower (m)
POSf:	The old position of follower (m)
POSL:	The position of leading vehicle (m)
POSN:	The updated position of vehicle n (m), at the end of the current Δt
POSn:	The current position of vehicle n (m)
Q:	Traffic flow (veh/hr)
Q_f:	Free flow (veh/hr)
RND:	The random number generated by the simulation model
Rt:	The reaction time (sec)
s:	The standard deviation of the lognormal distribution
Shift:	The additional time such as 0.25, 0.5 and 1 in seconds
t:	Time (sec)
TBSVeh:	The time between successive vehicles (sec)
TH:	The time headway for each generated vehicle in a simulation model
U:	Theil's inequality coefficient
Um:	Theil's mean difference
Us:	Theil's standard deviation difference
V:	Traffic speed (km/hr)

VC:	The velocity of the subject vehicle (m/sec)
VF:	The velocity of the following vehicle (m/sec)
VL:	The velocity of the leading vehicle (m/sec)
VN:	The updated velocity of vehicle n (m/sec), at the end of the current Δt
Vn:	The current velocity of vehicle n (m/sec)
x_i:	The observed data at time interval i
y_i:	The simulated results at time interval i

ABSTRACT

This study presents a newly developed micro-simulation model for motorway roadwork sections to evaluate the efficiency of different temporary traffic management schemes (TTMSs) such as the use of narrow lanes, offside and inside lane closures. The effect on traffic performance (i.e. capacity and delay) of various parameters (e.g. flow rates, percentage of heavy goods vehicles, roadwork zone lengths and speed limits) has been tested. The reason for building this model from scratch is the inability of an industry standard software package (i.e. S-Paramics), which has been made available for this research, in appropriately presenting traffic behaviour at motorway roadwork sections. The newly developed micro-simulation model was built using the FORTRAN programming language. It was developed based on car-following, lane changing, gap acceptance, lane closure and narrow lanes rules.

Data from four sources (taken from different sets of data from UK motorways sites) were collected and analysed. The data was used in developing, calibrating and validating the model. Observations from motorway roadwork sites with narrow lanes scheme show certain prominent drivers' behaviours, namely avoiding passing HGVs on adjacent lanes and lane repositioning before passing an HGV.

The simulation results revealed that, under low traffic demand, the use of narrow lanes scheme seems to perform better in terms of capacity and delay than both offside and inside lane closure schemes, whereas under high traffic demand associated with high HGVs percentage (i.e. ≥ 25%), the use of offside lane closure scheme seems to perform better in terms of capacity and delay than narrow lanes scheme and inside lane closure scheme. The simulation results showed that the presence of HGVs has a large impact on reducing site capacity. The model also suggests that a stricter speed limit compliance should be imposed on motorway roadwork sections with the use of narrow lanes TTMS in order to maintain higher section capacity and reduced delays. Regression analysis was carried out based on the simulation results in order to provide equations for use in estimating section capacity and delay.

CHAPTER ONE
INTRODUCTION

1.1 Background

Roadwork sections have become the rule rather than the exception on motorways due to the continuous requirement for road maintenance, resurfacing and extension. With Highways England's 2014 five years £15 billion strategic business plan to modernise and maintain England's 6900 km motorways and major A roads network, motorways will be a key area of infrastructure reconstruction. During this time, there will be several closures for road maintenance (www.infrastructure-intelligence.com, 2014). According to Chitturi and Benekohal (2007), nearly 20% of the U.S. National Highway Systems has been reported to be under reconstruction during the peak summer roadwork season.

Roadworks have impacts for safety (i.e. for road users/workers) and capacity (i.e. congestion, queuing and delays). Based on Elghamrawy (2011), there were 745 reported fatalities and 40,700 severe injuries per year at roadwork sections in the USA. The Federal Highway Administration of America (FHWA, 2004) reported that 10% of overall road traffic congestion was due to roadwork sections costing the equivalent of $7.8 billion. According to London First (2012), the total cost of congestion due to roadworks in London alone was around £750 million.

Traffic congestion on roadwork sections is mainly due to high traffic demands approaching the carriageway capacity (or possibly due to the occurrence of incidents/accidents). A variety of temporary traffic management schemes (TTMSs) have been developed and are being used to maintain the maximum carriageway capacity during roadwork periods (see for example the US Manual on Uniform Traffic Control Devices - MUTCD, 2009 and the UK Traffic Signs Manual, Chapter 8, 2009). The most common schemes used at the UK motorway roadwork sections are lane closure and narrow lanes schemes. Freeman et al. (2004) and Bourne et al. (2008) reported that the use of narrow lanes scheme has become very common in the UK in recent years. Although the physical narrowing of lanes (as suggested in some studies such as Warner and Aberg, 2008 and Ahie et al., 2015) makes it harder to exceed the speed limits on the road, the main purpose of using these narrow lanes is to significantly improve the overall capacity under the assumption that three narrow lanes, for example, have a significantly higher capacity than two normal width lanes. However, very limited research has been found in the literature to back up the assumption of using narrow lanes to preserve carriageway capacity during roadworks periods (see for example, Marlow et al., 1992). Therefore, an evaluation of traffic performance is needed at such roadwork sections to evaluate the efficiency of those TTMSs and also to determine the parameters that contribute to the cause of congestion.

Traffic micro-simulation models are an effective technique which can be used in the evaluation of the roadwork sections since the use of on-site trials needs extensive time and funding resources and also it is causing disturbance to traffic stream. According to Hidas (2005) the micro-simulation models have the ability to represent traffic behaviour and help more in implementing different scenarios without causing disruption to traffic operations in the field and without using expensive sources.

1.2 Aim and objectives

The principal purpose of this study is to develop a new traffic micro-simulation model to evaluate the efficiency of different temporary traffic management schemes (TTMSs) at roadwork sections to identify the most suitable scheme that will maximise capacity and minimise delay at such sections. Also, the developed model will be used as a tool to investigate different factors that could affect traffic performance of roadwork sections. The objectives of this study are as follow:

- Conducting a literature review on the concept of modelling motorway roadwork sections in order to produce a realistic traffic microscopic simulation model.
- Collecting field traffic data from several motorway roadwork sections with different TTMSs as well as from normal motorway sections with 2, 3 and 4 lanes; by using camcorders and other sources such as Individual Vehicles' raw Data (IVD).
- Analysing the collected data using statistical tests/methods to gain a better understanding into traffic behaviours.
- Modelling motorway roadwork sections by building a micro-simulation model using an available industry standard software package (S-Paramics) to check its suitability and any limitations in representing roadwork sections based on field data.
- Developing a new traffic micro-simulation model (using a Visual Compact Fortran programming language) that is capable of representing motorway roadwork sections taking into consideration any of limitations of previous models using the existing rules and algorithms and applying the necessary modifications as required.

- Calibrating the developed micro-simulation model with field data and validating it by using other sets of field data.
- Utilising the developed model to study the effect of various traffic parameters such as HGVs percentages, flow rates, roadwork zone lengths and speed limits on site capacity and delay.
- Developing and recommending regression models to estimate section capacity and delay based on the simulation results.

1.3 Thesis outline

The structure of this research has been proposed in such way in order to accomplish the abovementioned objectives. Figure 1.1 illustrates the research structure which consists of seven main sections. These sections are as follow:

- **Section one** (chapter 2) presents the review of literature of motorway roadworks from previous studies in order to identify the important factors of the modelling concept and the limitations of previous models.
- **Section two** (chapters 3 and 4) presents the data collection and analysis in order to build a good understanding in traffic behaviours. The collected data was also used in developing, calibrating and validating the newly developed micro-simulation model. The data was taken from two motorway sections; normal sections (i.e. remote from merging, diverging or roadworks) and roadwork sections.
- **Section three** (chapter 5) describes the development of the S-Paramics simulation model. In addition, the calibration and validation processes and the limitations of the S-Paramics software are also described in the chapter.
- **Section four** (chapter 6) presents the development of the new micro-simulation model; it can be seen from Figure 1.1 that there are five rules (sub-models) have been developed for the new micro-simulation model: car-following, lane-changing, gap acceptance, lane closure and narrow lanes rules. The car-following sub-model describes the interaction between the subject vehicle and its predecessor in the same lane. This sub-model governs the longitudinal movement of vehicles in a stream of traffic. The lane changing sub-model governs the lateral movements of vehicles from one lane to another. The gap acceptance sub-model manages the gap selection behaviour. Lane closure and narrow lanes sub-models describe the behaviour of vehicles at roadwork sections that are operated by a TTMS.

- **Section five** (chapter 7) presents the verification, calibration and validation processes of the newly developed micro-simulation model using real data from the visited sites and from different sources. The results show reasonable behaviour compared with the field data and other simulation models such as VISSIM and S-Paramics.
- **Section six** (chapter 8) presents the applications of the developed model in testing various types of TTMSs and various traffic parameters. It also presents the regression equations that are developed based on the simulation results to estimate section capacity and delay.
- **Section seven** (chapter 9) presents the conclusions and recommendations for future work.

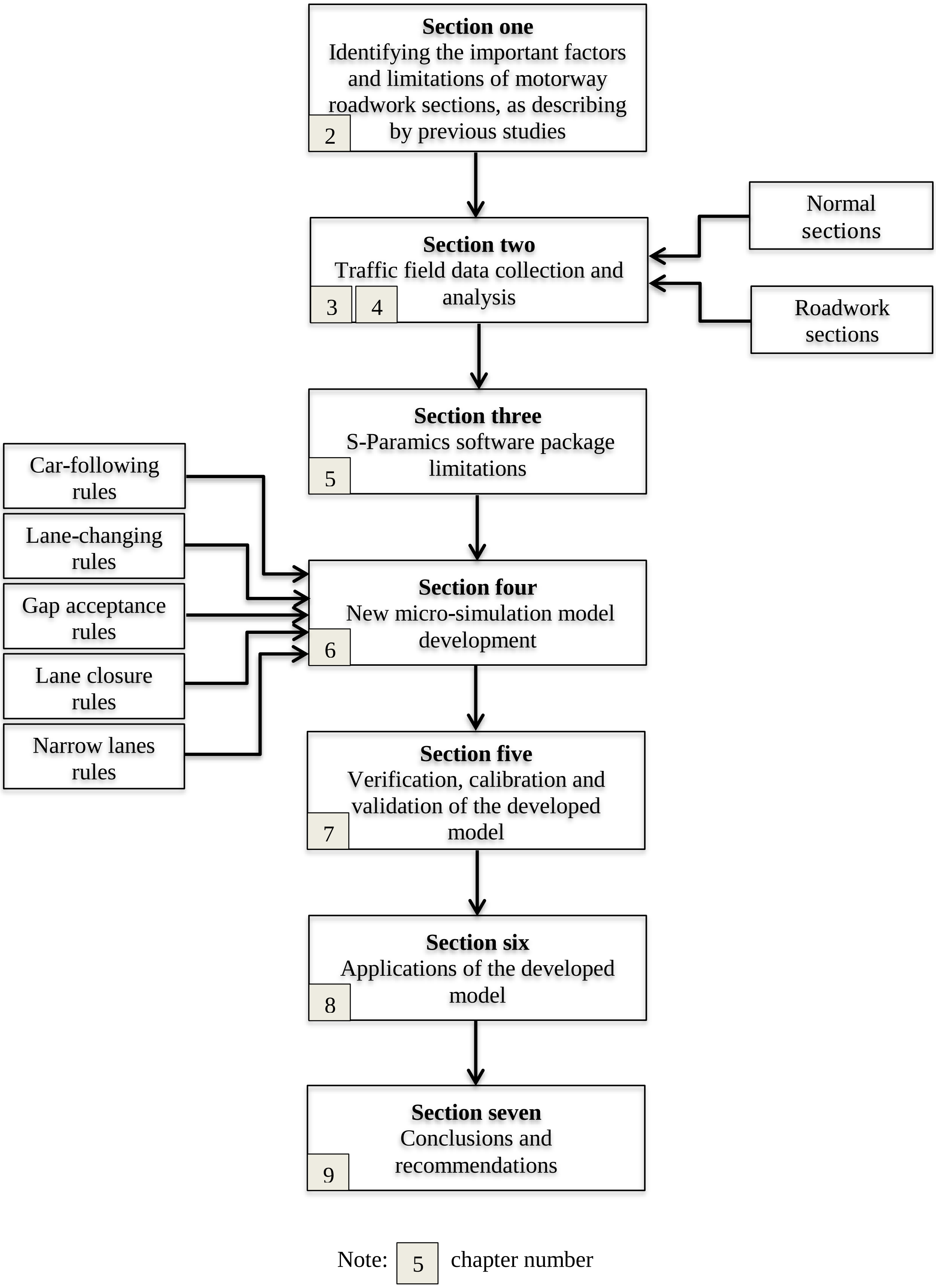


Figure 1.1: Flow chart of the current research

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter describes the types of temporary traffic management schemes (TTMSs) that are applied at motorway roadwork sections and addresses the impacts of roadworks on traffic performance. It also summarises studies/models that have been developed to represent roadwork sections and addresses the main limitations in the existing models. Furthermore, this chapter briefly defines the main types of simulation models and then concentrates on the rules that are applied in microscopic simulation models.

2.2 TTMSs at motorway roadworks

The main objective of implementing traffic management at roadwork sections is to maintain the safety of motorists and workers with the least possible amount of traffic delay. This objective can be achieved via guiding drivers safely and efficiently through the sections of roadworks. Therefore, several sophisticated temporary traffic management schemes (TTMSs) have been developed and are being used, such as lane closure systems, contra-flow systems, tidal flow systems, and lane restriction to heavy good vehicles (HGVs). In addition, the drop in carriageway capacity due to roadwork sites with high traffic demand has led to many techniques being implemented, such as the use of hard shoulders as a temporary running lane and the use of narrow lanes to produce more lanes of traffic within the available space. Some of the TTMSs that can be applied at motorway roadworks are discussed in the following sub-sections. These layouts have been obtained from various design manuals such as the USA Manual on Uniform Traffic Control Devices (MUTCD, 2009) and the UK Traffic Signs Manual (Chapter 8, 2009).

2.2.1 Lane closure scheme

A lane closure scheme is one of the most common layouts applied at motorway roadwork sections, particularly when the work is minor and required for a short period. This system requires closing one or two lanes for roadworks. According to Bourne et al. (2008), there are inconsistent findings about how the side of the lane closure (i.e. whether the offside or inside lane should be closed) affects the carriageway capacity.

2.2.2 Narrow lanes scheme

In recent years the uses of narrow lanes as a TTMS at motorway roadwork sections have become very common in the UK (Freeman et al., 2004 and Bourne et al., 2008). The main purpose of using narrow lanes is to significantly improve the overall capacity under the assumption that three narrow lanes, for example, have a significantly higher capacity than two normal width lanes. However, very limited research has been found in the literature to back up the assumption of using narrow lanes to preserve carriageway capacity during roadworks periods (see for example, Marlow et al., 1992). On the other hand, there is a potential to increase accident risk because of reducing lane widths, particularly in the presence of heavy goods vehicles (HGVs) and when drivers do not comply with the applied speed limit at roadwork sections (Pratt, 1996 and Mahoney et al., 2006). Furthermore, Hall and Rutman (2003) reported that the narrowing lanes enhance the opportunity for sideswipe accidents (i.e. where the side of one or more vehicles has been impacted). They attributed that to the physical constraint caused by narrower lanes and concrete barriers (which are placed on roadway edges) at roadwork sections which creates conditions that are conducive to sideswipe collisions. They also reported that many sideswipe collisions involve wider vehicles, especially HGVs. In the same context, Harb (2009) used data from the Florida Traffic Crash Records Database between 2002 to 2004 (inclusive) and found that HGVs are 44.6% more likely to be involved in single vehicle accidents on motorway roadwork sections compared to HGVs in non-roadwork sections (which may be related to the use of narrower lanes).

It is worth mentioning here that the use of narrow lanes has also been used on normal roadway section (i.e. without roadworks) to reduce traffic congestion. Based on observations from a trunk road in Paris, Cohen (2004) found that the gain in capacity resulting from increasing the number of lanes by narrowing them was about 7% in one direction and 16% for the other direction. The original cross section of the observed carriageway was two by four lanes, 3.5 metres for each lane with a hard shoulder. The cross section was then changed to two by five lanes with 3 metres for the offside lane and four 3.2 metres each lane without the hard shoulder.

2.2.3 Contra-flow scheme

A contraflow system can be implemented on a busy dual-carriageway when nearly the whole width of one side of the carriageway is closed for works. There are two types of contraflow system; one being the full contraflow scheme, when all vehicles on the side where works are taking place (primary traffic) are required to move to the other side (i.e. unobstructed side by work) of the motorway carriageway (secondary traffic). The other type is a partial contraflow scheme when some of the vehicles are moved (one lane diverted) to the secondary carriageway, whereas others vehicles use the primary carriageway. Contraflow systems often use the hard shoulder as a running lane. A buffer zone/lane should be applied to separate the opposing traffic at the secondary carriageway. This may lead to a reduction in lane width to allocate the buffer zone. Summersgill (1985) reported that it is recommended to use a full lane width as a buffer zone to separate the primary and secondary traffic but sometimes only 1.3 m is used as a buffer zone.

2.3 Roadwork site layout

Figure 2.1 illustrates a typical site layout of motorway roadworks operated by a lane closure scheme. According to the Manual on Uniform Traffic Control Devices (MUTCD, 2009), most TTMSs are divided into four zones:

- the advance warning zone (tells upstream traffic about the roadworks ahead),
- the transition zone (moves traffic from the closed lane to the adjacent open lane),
- the activity zone (where works occur), and
- the termination zone (where the TTMS ends).

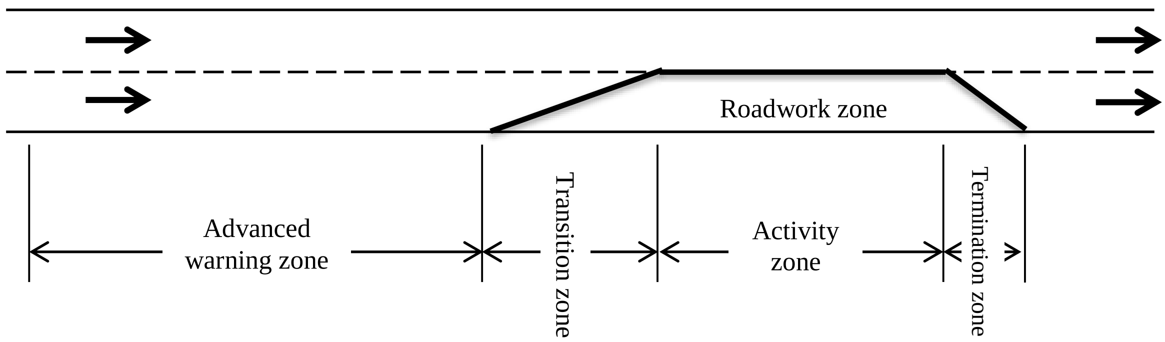


Figure 2.1: Illustration of motorway roadwork site layout operated by lane closure

2.4 Traffic signage at roadworks

Many types of signage have been developed and employed to manage the unusual manoeuvres at motorway roadwork sections, and to provide drivers with clear information about the upcoming obstructions in the motorway. In order to maintain safe and efficient traffic operations at a roadwork section, the traffic signage should be erected in advance of the roadwork sections to give drivers an adequate amount of time to decelerate and make their required manoeuvre. Yousif (1993) reported that the size and type of signs, number of lines on signage and number of words per line, type of information and the familiarity of drivers with the signs affect the required time to process the information.

According to the MUTCD (2009), the traffic signs that are applied within the advance warning zone may vary from a single sign or high-intensity rotating, flashing, oscillating, or strobe lights on a vehicle to a series of signs in advance of the roadwork section. In addition, the placement distance of the warning signs varies and depends on the type of roadway and traffic situations. This distance should be longer on motorways and other high-speed roads compared to lower-speed roads in urban areas.

Bai et al. (2010) determined motorists' responses to warning signs in a rural two-lane highway roadwork section in the USA. The motorists' responses were measured by vehicle speed change before and after the signs. These signs were a portable changeable message sign (PCMS) and a temporary traffic sign (TTS). The results showed that a PCMS either switched on or off was most efficient to reduce the speed of trucks, whereas the TTS was found to be most effective with passenger cars and semi-trailers. The authors concluded that the vehicle speeds were changed due to a combination of the influences of the traffic signs and drivers' awareness of the roadwork. However, the authors did not explain precisely what the reasons were behind the difference in speed reduction between cars and semitrailers under TTS and trucks under PCMS conditions.

2.5 Traffic operation fundamentals

Speed, flow and density are the most significant factors of the traffic stream that are used in evaluating the operations and performance of traffic. Speed and density could be used to represent the quality measure of the traffic stream which can estimate the level of service (LOS) for any type of road (for example urban area roads, trunk roads and motorways). Flow represents the quantity measure of the traffic stream (Salter and Hounsell, 1996). These three elements are defined as follows:

- **Speed** can be defined as the rate of movement of a vehicle which is expressed by distance per unit time (mph or km/hr).
- **Density** is the number of vehicles occupying a given length of road at a specific instant (veh/km).

➢ **Flow** is defined as the number of vehicles passing a given section during a specified period of time (veh/hr).

Considering the speed, density and flow units, it is obvious that the relationship between the three parameters is as shown in Equation 2.1 (Mannering and Washburn, 2012 and Alterawi, 2014).

$$Q = V\ K \qquad \text{Equation 2.1}$$

Where:
Q: traffic flow (veh/hr).
V: traffic speed (km/hr).
K: traffic density (veh/km).

Several studies have been carried out to investigate the relationships between these factors under various conditions of traffic flow. The study by Greenshields (1935) was one of the earliest reported studies in this field. This was then followed by several studies such as Lighthill and Whitham (1955), who proposed an outstanding paper on traffic flow theory based on fluid dynamics; Hall (1987), who analysed the relationships of these parameters using Catastrophe theory; and Heydecker and Addison (2011), who developed a relationship between speed and density to analyse the flow of traffic that operates under variable speed limits. Figure 2.2 shows a general layout of the relationships between the three characteristics (speed, density and flow) of the traffic, assuming a linear speed-density relationship.

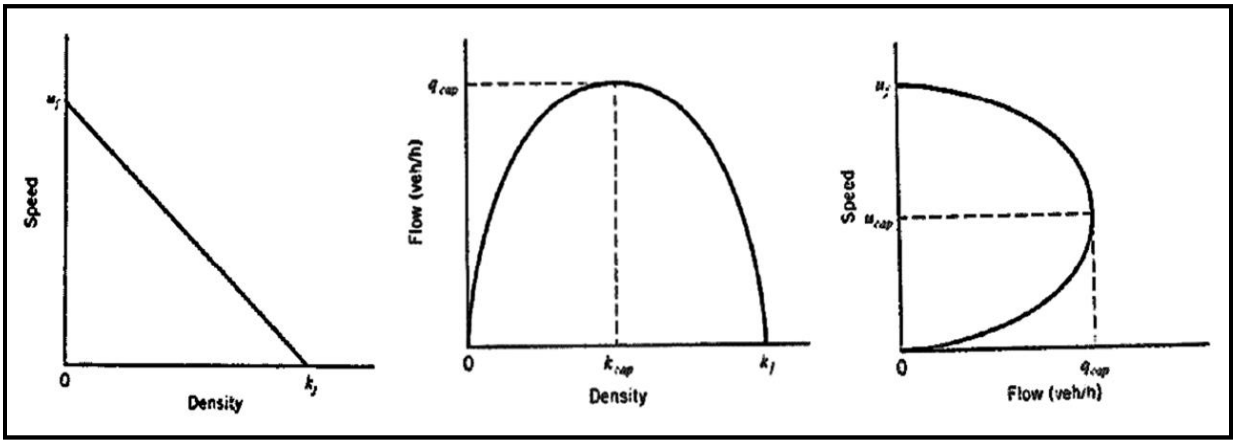


Figure 2.2: Fundamental diagrams of speed-density, flow-density and speed-flow (Mannering and Washburn, 2012)

2.6 Impacts of roadworks on traffic performance

Roadwork sections have many impacts on traffic performance. Congestion and queuing which might lead to an increase in traffic delays and vehicles' emissions, an increase in accident rates and fuel consumption, and a reduction in roadway capacity are examples of these impacts. The following sub-sections give a detailed description of the most likely effects of roadworks.

2.6.1 Reduction in capacity

Capacity can be defined as the maximum number of vehicles that can be reasonably expected to cross a given section of a lane or roadway during a given time period under prevailing roadway, traffic, and control conditions (Highway Capacity Manual, 2000). Morris et al. (2010) reported that the motorway capacity should not be considered as a fixed value, but is variable and depends on several factors. According to Slinn et al. (2005), these factors are as follows:

- The characteristics of the motorway layout which depend on the geometric design of the motorway itself.
- Motorway surface conditions, clarity of road marking, signing and maintenance.
- Traffic composition (i.e. proportions of each vehicle type).
- The numbers and speed of vehicles.
- The ambient conditions which include visibility, weather and time of day.
- Road users' levels of training and competence.

The capacity of a motorway with roadwork sections could be defined as the maximum throughput that can be achieved; the throughput is the number of vehicles passing the roadwork section during a given time period. The maximum throughput (capacity) might be considered as the most important measure that can estimate the roadwork section operational performance. This will help in evaluating the effectiveness of the different TTMSs that could be implemented at roadworks.

Hunt et al. (1991) reported that the flow breakdown without incidents at roadwork sections was found to be in a traffic flow range of 1600 – 2300 pcu/hr/lane (where a pcu is a passenger car unit equivalent to 1 pcu for light vehicles and 2 for heavy vehicles). Note that the maximum traffic flow (i.e. capacity) often occurs just before the flow breakdown. Yousif, (2002) reported that the values of maximum throughputs that were observed by Matthews (1984), formed the basis for the expected maximum throughputs on motorway roadwork sections. Table 2.1 shows these values of throughputs with different TTMSs for a typical traffic composition of 15-20% HGVs.

Table 2.1: Maximum observed throughputs with different traffic management schemes (Yousif, 2002)

Type of TTMS	Maximum Throughput pcu/hr	Maximum Throughput pcu/hr/lane
Lane closure – 1 lane open	1900	1900
Lane closure – 2 lanes open	3770	1890
Two-way traffic (one lane each way)	1770	1770
Segregated contra-flow (primary stream)	3420	1710
Full contra-flow (primary stream)	3500	1750
Contra-flow sites (secondary stream)	3540	1770

The reduction in the motorway capacity at roadwork sections could be attributed to the number of lanes which were withdrawn from the carriageway. In addition, many researchers have agreed that the management of the merge area is the main factor which affects the carriageway capacity (see for example Hunt et al., 1991, Kazzaz, 1998; Yousif, 2002; and Papageorgiou et al., 2008).

2.6.2 Increased delay

Traffic delay at roadwork sections can be divided into two categories: delay because of reduced speed at the roadwork section (due to either posted temporary speed limit or high traffic density occurrences), and delay caused by queuing of vehicles trying to enter the section of roadwork (Bourne et al., 2008). The traffic delay might also be considered as an important measure of performance. This also helps in evaluating the efficiency of the different TTMSs applied at roadwork sections.

2.6.3 Reduction in speed

In the United Kingdom, the speed limit of 70 mph (112 km/hr) on the motorway network became mandatory in 1978. This speed limit corresponds to an 85th percentile of free speed as determined by the Department of Transport (Kazzaz, 1998). In 2011 and based on Butcher (2013), the UK Government intended to consult on increasing motorway speed limit to 80 mph (130 km/hr). However, in some parts of the M1 motorway, the Highways Agency (HA), or what is now referred to as Highways England, had decreased the speed limit to 60 mph between 7am and 7pm for sections between Junctions 28 and 35a. The HA claims that the speed reduction will help to reduce air pollution and congestion and manage traffic speeds more effectively (The Chartered Institution of Highways and Transportation, 2014). At motorway roadwork sections, a temporary mandatory speed limit of 50 mph (80 km/hr) has been implemented to guide drivers safely through such sections (Department for

Transport, 2009). This temporary mandatory speed limit was applied in 1988 instead of the temporary advisory speed limit of the same speed amount (Kazzaz, 1998).

In addition, the presence of TTMSs at roadwork sections can also cause a reduction in drivers' speed. This is because drivers need to be more alert to drive through the TTMS safely which might require them to reduce their speed (Alterawi, 2014).

2.6.4 Reduction in safety level

There is strong evidence to suggest that along the motorway length the roadwork sections are considered unsafe in contrast with the remaining sections of motorway (Chen and Tarko, 2014). According to previous studies (see for example Tarko and Venugopal, 2001; Khattak et al., 2002; and Mahoney et al., 2006) the accident rates during roadwork periods are higher than those periods without roadworks. Likewise, the European Union Road Federation (ERF, 2007) confirms that roadwork sections present a considerably higher risk to road users. Recently, the National Work Zone Safety Information Clearinghouse reported that 609 fatalities were recorded due to work zone accidents in 2012, where the total number of traffic accident fatalities in the same year was 33,561. Therefore, the Federal Highway Administration (FHWA), and the American Association of State Highway and Transportation Officials (AASHTO) are looking to enhance the design practices of roadwork sections in order to control and minimise the fatalities and injuries at roadwork sections. Likewise, the Transport Research Laboratory (TRL) in the UK is seeking to control and minimise the fatalities and injuries and also to maximise the capacity at motorway roadwork sections. The TRL commissioned periodic studies for the safety of major motorways roadworks. These studies were carried out in 1982 (Summersgill, 1985), 1987 (Marlow and Coombe, 1989), 1992 (Hayes et al., 1994) and 2001-2003 (Freeman et al., 2004).

For the safety of road-workers, Sinclair (2010) reported that the working environment of road-workers is unsafe. In 2005, the UK Highways Agency (HA) reported that the number of road-workers killed on motorways and major 'A' roads had increased after two years of decline. However, this number of fatalities kept growing during 2006/07 (Gillard et al., 2008).

2.6.5 Effects of vehicle speed on safety level

According to Bekhor et al. (2013), there is a high correlation between high speeds of vehicles and high accident severity. Therefore, the control of vehicle speed along the motorways network and particularly at roadwork sections is fundamental for safety. At roadwork sections, the vehicle speeds need to be reduced to be compatible with safety requirements at such sections. At the same time, the variation in speeds amongst motorists should be kept low, along the sections of motorway before roadwork sections (sections where the speed limit is 70 mph) and throughout the roadwork section, since the higher differential may produce more accidents (Yousif, 1993 and Geistefeldt, 2011).

The compliance of drivers with the posted temporary speed limit is one of the most significant factors that could enhance safety level and traffic operation at roadwork sections. Summersgill (1985) reported that 93% of drivers exceed the advisory speed limit of 50 mph (80 km/hr). This is consistent with findings by Lines (1985), Kathmann and Cannon (2000) and Yousif (2002) who reported that these poor levels of compliance could be attributed to the absence of speed monitoring systems on site. Wood et al. (2010) suggested that the use of speed cameras or using stationary police cars at motorway roadwork sections will improve compliance with the speed limit. However, additional measures are required to control vehicle speed at roadwork sections.

The obtrusive perceptual countermeasures is one technique of many that have been explored to control this issue, this technique is designed to increase drivers' feeling of speed and sense of danger to force them to decelerate. Allpress and Leland (2010) evaluated two obtrusive perceptual countermeasures arrangements. The results suggest that the obtrusive perceptual countermeasures significantly reduced vehicle speeds at roadwork sections, but the vehicle speeds were still higher than the posted temporary speed limit.

Bella (2005) noticed that the speed of vehicles along the motorway roadwork sections exceeded the temporary speed limit, and the drivers reduced their speed just with the presence of the physical constraint of the roadway at roadworks. Likewise, Paolo and Sara (2012) selected eleven roadwork sites on two-lane rural roads in Italy to investigate the speed of vehicles approaching roadwork sections in order to understand the drivers' speed behaviour. These roadwork sites can be classified into two groups. The first group contains roadwork sites with a physical reduction in lane width, whereas the second group contains those sites without width reduction. The results showed that 98% of vehicles at the beginning of the roadwork sections were observed travelling with speeds higher than the temporary speed limit, and at eight sites this percentage reached 100%. The result also suggests that this percentage reduces with the presence of physical lane width reductions. The authors concluded that the presence of physical lane width reductions will help in decreasing vehicles speeds.

2.7 Review of existing roadworks models

Several models have been developed to represent traffic behaviour and to estimate traffic capacity at roadwork sections. These are mainly mathematical or simulation models, as discussed in the following sub-sections.

2.7.1 Mathematical models

Several researchers have attempted to study the effects of roadwork sections on motorist delays, queues and costs using mathematical models. Cassidy and Han (1993), Schonfeld and Chien (1999) and Chien et al. (2002) developed mathematical models to estimate vehicle delay, queue length and to optimise the roadwork zone length on a single-carriageway highway with two lanes operating under one-way traffic control.

For dual-carriageway motorways, McCoy and Mennenga (1998) developed a model to calculate the optimum roadwork zone length by minimising maintenance, user delay, accident and vehicle operating costs based on average daily traffic (ADT) on a rural four-lane highway (two lanes per direction) with one lane closed at a time for roadworks. Likewise, Chien and Schonfeld (2001) developed a mathematical model to optimise the length of roadwork zones to minimise the user delay, agency and accident cost in four-lane highways (two lanes per direction) with one lane closure, based on ADT. As a conclusion, they reported that shorter roadwork zones tend to alleviate the user delays and increase the agency cost. The main limitations of both models are their formulation which is restricted to only one configuration of highways (i.e. four lanes) with only one lane closure layout applied as a TTMS at roadwork sections, in addition to assuming that there is a constant ADT on highways. This is not a representation of real traffic conditions due to the variations and fluctuations in traffic flow throughout the day.

Jiang and Adeli (2003) developed a model which considers two variables, roadwork zone length and the starting time of the roadwork, to optimise the short-term roadwork total cost (e.g. sum of user delay, construction and accident costs) and traffic delay using average hourly traffic data. In addition, the number of lane closures and the effects of night time construction and seasonal variation were considered in this model. The optimum roadwork zone length was obtained using Bolzmann-simulated annealing neural network.

Racha et al. (2008) developed a mathematical model to estimate the capacity of roadwork sections by analysing the relationships between speed, flow, and density. The model suggests a value of 1550 passenger cars per hour as the base capacity of two-lane roadwork highway sections with one lane closure. The proposed model estimates the capacity of roadwork sections as a function of the heavy vehicle adjustment factor. However, the scope of this model is limited to only one configuration of highway roadwork sections (i.e. a four-lane highway, with two lanes per direction, operated by a one-lane closure scheme). Also, no mention was made of the effect on roadwork section capacity of the lane closure side (i.e. whether the inside or the offside lanes were closed).

Elghamrawy (2011) developed a mathematical model to identify the optimal setup of roadwork sections to minimise the total cost which includes agency, user delay and accident cost. This study takes into account the effects of the temporary speed limit applied at roadwork sections, length of roadwork zone, barrier type, temporary traffic control (TTC) type and starting time. Then, the optimisation model is implemented using genetic algorithms (GAs) in a C++ objected oriented environment.

Weng and Meng (2015) developed a mathematical model to estimate the capacity of roadwork sections based on a speed-flow relationship. The developed model takes into consideration the effects of the roadwork zone length, speed limit applied at the roadwork, heavy vehicle percentage and geometric alignment (deflection angle of the roadway alignment). Weng and Yan (2016) proposed a probability distribution-based capacity model to predict roadwork section capacity. They assumed that the capacity of the roadwork section follows a lognormal distribution.

However, the complexity and inflexibility of using mathematical models for roadwork sections, has led to the adoption of another technique to evaluate capacity and to represent traffic behaviour at such sections. Yousif (1993) and Jiang and Adeli (2004) reported that the representation of traffic behaviour at roadwork sections cannot be mathematically modelled because it is complicated and correlated to a large number of interacting variables.

2.7.2 Simulation models

Several simulation models have been developed to represent traffic behaviour at motorway roadwork sections. Memmott and Dudek (1984) developed a computer model (QUEWZ, Queue and User Cost Evaluation of Work Zones) to estimate the delay costs, speed-change cycling costs of slowing down to go through a work zone, and vehicle operating costs, based on hourly traffic data. Two traffic management schemes including lane closure and crossover can be examined using this model to estimate capacity and average speed through the roadwork section.

Yousif (1993) developed a micro-simulation model to evaluate the effect of road geometry and traffic characteristics on delay and capacity at dual-carriageway roadwork sections. The movement of each vehicle in the model is controlled by a set of car-following rules, whereas the vehicle lane-changing process is based on comparing the available gaps in the adjacent lane with assumed perceptual thresholds. The model was programmed using FORTRAN 77 language and was designed to cover different motorway configurations.

Jiang and Adeli (2004) developed a computer model to determine the freeway roadwork capacity, roadwork zone length estimation and to estimate the users' queues and delays for different traffic management schemes. The model is implemented in an interactive software system, called IntelliZone (Intelligent decision support system for work zone traffic management).

Kim et al. (2013) developed a simple simulation model to estimate roadwork section delays and queue lengths and to provide a decision-making framework that assesses three alternative lane closure systems applied at freeway roadwork sections. The model has been programmed using Visual Basic language within a commercial spreadsheet program (EXCEL).

However, none of these simulation models take into account the effect of using narrow lanes as a TTMS on traffic performance.

Many other traffic micro-simulation models (packages) have been developed to deal with general traffic modelling such as CORSIM (which was developed by the United States Federal Highway Authority, FHWA), VISSIM (which was developed by Planung Transport Verkehr (PTV), a German company) and S-Paramics (which was developed by SIAS Limited, a Scottish company). These models have the ability to represent the behaviour and interaction between individual vehicles on local arterial and regional freeway networks, and also have the ability to simulate different roadway configurations and features (European Commission, 2000). However, Alterawi (2014) reported that roadwork sections can be coded as incidents as there is no direct option for modelling such sections in CORSIM and VISSIM. In addition, Al-Obaedi (2012) stated that one of the main limitations of VISSIM and S-Paramics could be related to the failure to represent some important interactions between vehicles such as courtesy behaviour (e.g. cooperative slowing down) of drivers travelling on the mainline motorway while allowing those vehicles entering from the ramp. In addition, the S-Paramics software also suffers from certain limitations. It is not capable of accurately representing certain important zones of the TTMSs at motorway roadwork sections. The limitations of the S-Paramics software are presented in detail in Chapter 5.

2.8 Simulation techniques

Traffic simulation models are an effective technique which can be used in evaluating transportation facilities. Such models have the ability to represent traffic behaviour without causing disruption to traffic operations in the field. Furthermore, the low-cost, low-risk environment enables the users of such models to assess and evaluate several traffic management alternatives and their effects on traffic operation in a short time by providing a visual environment for determining the best choice for any traffic scenario. Therefore, in the last three decades a wide number of sophisticated traffic simulation models have been developed (Moriarty et al., 2008).

Traffic simulation models can be classified into three types based on the level of detail at which these simulation models describe traffic behaviour. These are macroscopic, mesoscopic and microscopic models (ITE, 2010).

- Macroscopic models describe the traffic as a continuum. They are suitable for large-scale simulations such as simulation of a traffic network at a portion of a city (Aycin, 2001). These models describe traffic characteristics based on average parameters such as flow, speed and density by assuming that traffic flow behaves as a fluid. However, these models cannot represent the interactions between individual vehicles (Al-Obaedi, 2012).
- Mesoscopic models are more refined than macroscopic models and they describe the traffic in much more detail by considering the individual vehicles in groups or cells. However, they still ignore the interaction of vehicles in each individual group (Al-Obaedi, 2012).
- Microscopic models describe the traffic at a detailed level where individual vehicles and the interaction between each other are represented by specific rules such as those used for longitudinal movements (i.e. car-following) and lateral movements (i.e. lane-changing). However, they are more difficult to develop and to calibrate than macroscopic models (Aycin, 2001; Burghout, 2004; and Al-Obaedi, 2012). Regardless

of the difficulty in developing and calibrating microscopic models, these models are more efficient in simulating complicated traffic situations (Burghout, 2004), such as the case of roadwork sections. Also, microscopic simulation models could represent the road geometry even if the traffic management used on site is complex (Alterawi, 2014). Therefore, the microscopic simulation approach has been adopted in this study.

Microscopic simulation models consist of a combination of three important sub-models. These are car-following, lane-changing and gap acceptance models, which will be discussed in detail in the following sub-sections.

2.8.1 Car-following models

Micro-simulation models are commonly built up by using numbers of sub-models; one of the most important sub-models is car-following (Olstam and Tapania, 2004). The car-following model describes the interaction between a vehicle and its leader (the vehicle immediately in front) in the same lane by calculating the acceleration/deceleration rates used in updating the longitudinal position of the vehicle in correspondence to its leader. For any vehicle in traffic, when its acceleration/deceleration rates are known, the speed and position of this vehicle can be easily determined through the manipulation of the standard equations of motion.

In previous studies, several car-following models have been proposed to represent the longitudinal movement of vehicles. The following sub-sections discuss the main groups.

2.8.1.1 Gazis Herman Rothery (GHR) model

The Gazis Herman Rothery (GHR) model represents the earlier well-known car-following model and it was developed in the late fifties at General Motors' Research Laboratories (Brackstone and McDonald, 1999). The GHR model is based on a stimulus-response type of function and its mathematical formulation states that the acceleration of the following vehicle (n) is related to the differences in speeds and spacing between the following vehicle (n) and its leading vehicle (n-1), as shown in Equation 2.2 (Brackstone and McDonald, 1999). Figure 2.3 shows the car-following notations.

$$a_n(t) = \alpha {v_n}^{\beta}(t)\ \frac{\Delta v(t - Rt)}{\Delta x^{\gamma}(t - Rt)} \qquad \text{Equation 2.2}$$

Where:
$a_n(t)$: the acceleration of vehicle n (m/sec^2) applied at time (t),

$v_n(t)$: the speed of vehicle *n* (m/sec) at time (*t*),
$\Delta x(t\text{-}Rt)$: the relative distance (m) between vehicle *n* and *n-1* assessed at earlier time (*t-Rt*),
$\Delta v(t\text{-}Rt)$: the relative speed (m/sec) between vehicle *n* and *n-1* assessed at earlier time (*t-Rt*),
Rt: the driver reaction time (sec), and
α, β, γ: the model parameters.

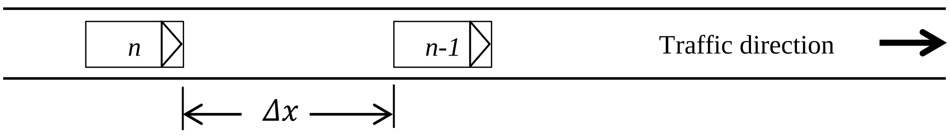


Figure 2.3: Car-following notations

Brackstone and McDonald (1999) provided detailed information about the GHR model parameters values (i.e. α, β and γ), and they also listed the researchers who tried to improve this model during the past five decades. However, the authors reported that due to the large number of contradictory findings of the values used to represent the model parameters, the GHR model is being used less frequently. Gipps (1981) reported that there is no obvious relationship between the parameters of the model and drivers' or vehicles' characteristics. In addition, Olstam and Tapania (2004) reported that the driver of the following vehicle reacts to its leader actions even when the spacing between them is too large. However, some traffic simulation models, such as MITSIM (Yang and Koutsopouls, 1996), used this type of car-following model (Al-Jameel, 2012 and Al-Obaedi, 2012).

2.8.1.2 Safety distance or collision avoidance (CA) models

The main idea of this group of car-following models is to avoid the colliding of vehicles by providing a safe separation distance between the following vehicle and its leader. According to Brackstone and McDonald (1999), Kometani and Sasaki in 1959 produced the first model of this group.

In 1981 Gipps presented a car-following model which depends on the idea of safe distance keeping. The model by Gipps (1981) is based on the assumption that the driver of the following vehicle can select a safe speed to ensure that he/she can bring his/her vehicle to a safe stop if the vehicle in front comes to a sudden stop. The Gipps model has been used in many micro-simulation models such as the DRACULA (Liu, 2005) and AIMSUN (Barceló and Casas, 2005) models.

The CAR-following SIMulation model (CARSIM) (Benekohal, 1986) is another example of a CA model. According to the CARSIM model, the drivers are assumed to maintain a sufficient distance from their leaders to react safely if any changes occur ahead. The CARSIM model can represent traffic in both normal and stop and go conditions (Benekohal and Treiterer, 1988), since the acceleration rate of the following vehicle is selected from five different situations (acceleration/deceleration). The CARSIM model has been used in many micro-simulation models (see for example Yousif, 1993; Purnawan, 2005; Al-Obaedi, 2012; Al-Jameel, 2012; and Alterawi, 2014).

2.8.1.3 Psychophysical or action point (AP) models

According to these models, the driver will perform an action (acceleration or deceleration) when a certain threshold is reached. This threshold can be expressed as a function of the difference between pairs of vehicles in speeds or spacing. According to Ahmed (1999), Leutzbach (in 1968) proposed the psycho-physical model which addresses two limitations of the GHR models. These two limitations are, first, the driver of the following vehicle reacts to its leader actions even when the spacing between them is too large, and second, the driver reacts to small changes in front relative speeds.

The AP models produced perceptual thresholds which represent the minimum value of the stimulus to which the driver will respond (Toledo, 2007). For example, at low space headways the relative speed threshold is small and gradually increases with the space headway. At certain high space headways, this threshold becomes infinity which means that the follower no longer follows its leader. PARAllel MICroscopic Simulation (PARAMICS) (Duncan, 1995) is a good example of this group of models. However, these models suffer from difficulties in calculating and calibrating the perceptual thresholds (Brackstone and McDonald, 1999; and Panwai and Dia, 2005).

2.8.1.4 Other car-following models

There are several other approaches which have been used by researchers to model car-following. The fuzzy logic-based model is one of these approaches. This model is based on the theory that some of the system sets are not crisp but fuzzy (Khodayari et al., 2011). The model divides variables into a number of overlapping sets combining each one with a specific term which describes how sufficiently a variable fits the description of a term (Brackstone and McDonald, 1999). The linear (Helly) model is another approach to the car-following modelling. This model is based on the GHR models and was improved by Helly in 1959 by introducing a desired following distance factor (Panwai and Dia, 2005).

2.8.2 Lane-changing models

Modelling lane-changing is one of the most important parts of any microscopic traffic simulation model (Hidas, 2002; and Toledo et al., 2005). The term lane-changing can be easily defined as the transition of a vehicle from one lane to another.

The process of lane-changing is complex, and several researchers have attempted to represent this process using, for example, empirical and analytical as well as simulation models. The majority of these models classified lane changes as either a discretionary lane-changing (DLC) or a mandatory one (MLC) (see for example Yousif, 1993; Ahmed, 1999; Toledo et al., 2005; Liu, 2005; Choudhury, 2007; Al-Jameel, 2012; and Al-Obaedi, 2012). The DLC is implemented primarily when the driver endeavours to enhance his/her driving conditions, such as speed, by overtaking a slower leading vehicle in front (Gipps, 1986; Yousif, 1993; Sultan and McDonald, 2001; Liu, 2005; Barceló and Casas, 2005; Al-Jameel, 2012; and Al-Obaedi, 2012) or in order to return to their original lane after the overtaking process (Ferrari, 1989; Yousif, 1993; Al-Jameel, 2012; and Al-Obaedi, 2012). For the MLC, this includes those cases in which drivers need to change lanes to reach their destination (e.g. due to the presence of roadworks, merging from slip roads or diverging) or because of traffic regulations. Due to the importance of modelling lane-changing and the varied behaviours of drivers involved in a lane change, it was found necessary to study this parameter in more depth (using observation from sites, as will be discussed later in the next Chapter, and using the literature, as will be discussed in the following sub-sections). This will then inform the assumptions made in the development of the new micro-simulation model.

2.8.2.1 Review of previous lane-changing models

One of the earlier lane-changing models was introduced by Sparmann (1978). The model distinguishes between changes to the inside and to the offside lane. According to the Sparmann model, drivers change to the inside lane because the inside lane does not have obstructions, whereas changing towards the offside lane is motivated by, the current lane having an obstruction (e.g. slow vehicles) and the offside lane having better conditions (Choudhury, 2007).

Gipps (1986) developed a rule-based model that describes the possibility, necessity and desirability of a lane change. The model describes the behaviour of drivers in an urban driving situation; where traffic signals, obstructions and the presence of HGVs affect the driver's lane selection decision. Based on the distance to the intended turn, the driver's behaviour falls into one of three patterns. When the turn is far away, the driver concentrates on maintaining a desired speed and there is no impact on the driver lane-changing decisions. When the turn is close, the driver focuses on being in the correct lane and the speed is unimportant. At middle distance to turn, the driver tends to stay in a pair of lanes that are most appropriate for his/her turn and ignore increasing his/her speed if this involves changing lanes in the wrong direction.

Yousif (1993) developed a micro-simulation model to represent the traffic behaviour on dual-carriageway roads for both normal and roadworks conditions. In normal conditions, the driver changes to a faster lane if he/she is obstructed by a slower leading vehicle which has a speed less than his/her by a magnitude of (R) (suggested by Ferrari (1989) as R =1040/DVc; where, DVc: is the desired speed of follower) otherwise, the driver will stay in his/her current lane. The driver changes to a slower lane if he/she obstructs his/her following vehicle or to return to his/her original lane after the overtaking process. At roadworks, the driver on the closed lane will change lane to an adjacent open lane depending on the distance to the closure point.

Ahmed (1999) modelled the lane-changing process using three steps: a decision to consider a lane change, a choice of a target lane, and the acceptance of gaps in the target lane. The decision/desire of changing lane depends on the satisfaction of the driver with his/her driving condition. One of the important factors that affect the driver's satisfaction is the difference between the current speed of the driver and his/her desired speed. If the driver is not satisfied with the driving conditions in the current lane, then the driver will evaluate the neighbouring lane (i.e. inside and offside lanes) conditions to choose the preferred lane. It should be noted that in the USA both overtaking (using offside lanes) and undertaking (using inside lanes) are allowed, unlike in the UK where undertaking is prohibited on motorways (see section 268 of the Highway Code). The developed lane-changing model by Ahmed (1999) has been tested and validated by using the microscopic traffic simulator laboratory (MITSIMLab).

Al-Obaedi (2012) developed a micro-simulation model for motorway merge sections to study the effectiveness of applying ramp metering systems. In this study, the DLC is applied when drivers are not necessarily required to change their lanes but it is applied when they try to increase their speeds or to return their original lane after an overtaking manoeuvre. The model distinguishes between the desire to change lane and the execution of the lane-changing. The assumptions made for the desirability of lane-changing are mainly similar to those which were proposed by Yousif (1993), whereas the assumptions made for the lane-changing execution are based on whether the lane change is beneficial (i.e. not to be trapped behind a slower leading vehicle in the target lane) and on the availability of sufficient lead and lag gaps in the target lane. At merge sections, when drivers try to merge onto the main line motorway from the ramp (auxiliary lane), the MLC is applied.

Lv et al. (2013) produced a microscopic lane-changing process (LCP) model for modelling lane-changing for multilane traffic. The authors reported that the majority of previous micro-simulation models assumed an instantaneous action for lane-changing manoeuvres, where the turning angle (i.e. the lane changer turns the direction of his/her vehicle towards the target lane with an angle of θ, as shown in Figure 2.4) of the subject vehicle (θ) = 90° and the lane-changing manoeuvre time = 0. In addition, the vehicles that are travelling in the current lane are not affected by the lane-changing manoeuvre. Therefore, they proposed a lane-changing process model which took into consideration the effects of a lane-changing process for both current and target lanes and its lateral movement. However, such an argument is not valid since many previous micro-simulation models (see for example Zia, 1992; Yousif, 1993; Al-Jameel, 2012; and Al-Obaedi, 2012) took into consideration the manoeuvring time and the effect of the lane changing manoeuvre on vehicles that are travelling in current and target lanes. Also, the developed model by Lv et al. (2013) has some limitations such as the model considers only the discretionary lane-changing where the driver changes his/her lane to enhance the driving conditions, while the situation of mandatory lane-changing (merging, diverging, and roadworks) was not taken into consideration. Another weakness of the model is that equal distribution (i.e. lane utilisation) of vehicles among the two lanes of the roadway was used which is not realistic. In addition, some parameters and variables that were used in the model have been given an arbitrary value such as lane-changing angle and driver's reaction time.

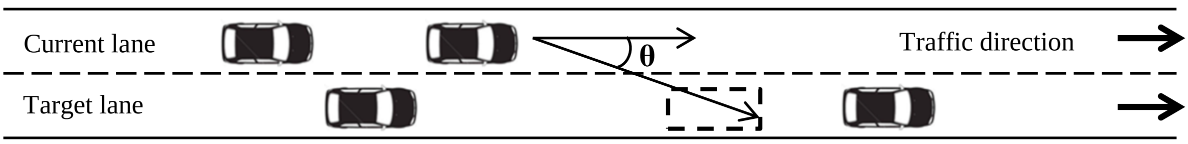


Figure 2.4: Illustration of the turning angle (θ) of the subject vehicle

2.8.2.2 Lane-changing at roadworks

At roadwork sections, the drivers must change their lane because of the presence of a lane closure ahead. Therefore, the lane-changing at those sites can be classified as mandatory lane-changing (MLC). Hidas (2002 and 2005) and Choudhury (2007) proposed three types of lane-changing manoeuvres namely free (normal), forced and cooperative. These types were adopted here in this study and are discussed in the following sub-sections.

i. Free MLC

Under free flow conditions, when there are several opportunities provided for the subject vehicle (i.e. merger) to change lanes without any interactions in terms of speed reduction between the subject vehicle, and the new leading or following vehicles in the target lane, this type of lane-changing manoeuvre (i.e. free MLC) is predominant. In addition, the subject vehicle does not need to change lane urgently since its position is far away from the end of the lane (i.e. lane closure). Hidas (2002) suggested a value of 8 seconds to represents the urgency of the driver to change lane (the urgency of the lane-changing manoeuvre can be represented by the time or distance required to reach to the end of the lane).

ii. Forced MLC

Under congested traffic conditions (i.e. when there are insufficient gap sizes available for the subject vehicle to change lanes) associated with the subject vehicle getting closer to the end of the lane, the subject vehicle would possibly be forcing the lag vehicle (i.e. new follower) in the target lane to slow down in order to widen this gap (i.e. lag gap). Figure 2.5 shows an illustration of lead and lag gaps. Rao (2006) assumed that the subject vehicle will use the forced lane-changing manoeuvre when the remaining time to the end of the lane is lower than 10 seconds.

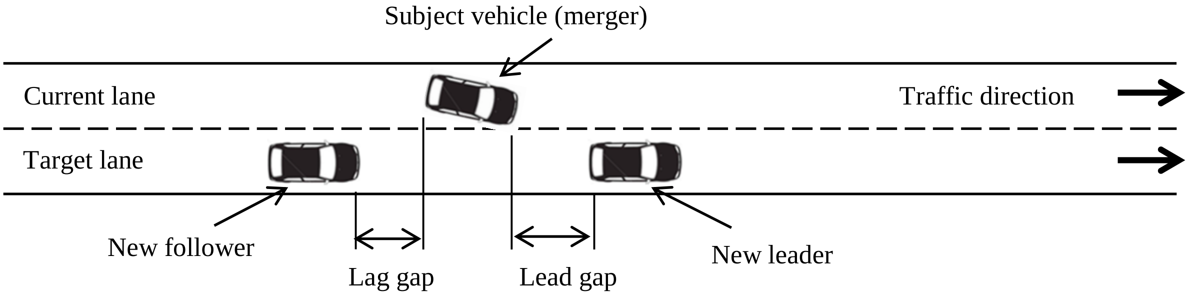


Figure 2.5: Illustration of lag and lead gaps

iii. Cooperative MLC

Without the courtesy of drivers in the adjacent open lane during congested traffic conditions, the vehicles that are travelling in a lane to be closed ahead might be stuck in the closing lane and be unable to change to the adjacent open lane. Hidas (2005) reported that the cooperative lane-changing manoeuvre consists of three mechanisms: firstly, the subject vehicle shows a desire to change lane; secondly, the new following vehicle in the target lane identifies the situation of the subject vehicle and starts to slow down to give way; then, the subject vehicle changes lane when the gap size becomes sufficiently long to perform the manoeuvre safely.

2.8.2.3 Review of previous MLC models

Based on a real traffic data taken from merging and weaving sections under congested traffic conditions, Hidas (2005) developed a new lane-changing model. Although, the results of the developed model show a reasonable performance in representing the real traffic conditions, particularly the speed-flow relationship, the model suffers from some limitations; there is no clear differentiation between the forced and cooperative lane-changing manoeuvres in the formulation of the model. Another shortcoming of the model is represented by ignoring the cooperative yielding behaviour of drivers on motorways (shifting to the adjacent lane). Likewise, Choudhury (2007) developed a freeway merging model which considered the cooperative slowing down behaviour. However, the cooperative yielding behaviour (shifting) is common practice amongst drivers in the UK when trying to help other drivers to merge in front of them. Also, this behaviour (i.e. shifting) has been recommended by the Driving Standards Agency (DSA) (2000). Based on empirical observations from motorway roadwork sections, Hunt and Yousif (1990) reported that under congested conditions, on average one in three drivers travelling on the open lane yield right of way to vehicles which are travelling on the closing lane.

Wang (2006) modelled the cooperative slowing down and yielding behaviours of a following driver in the inside lane of a motorway based on an arbitrary manner. The driver in the inside lane would make a decision whether to move to the adjacent lane/s (i.e. offside lane/s) or to decrease his/her speed in order to provide a sufficient gap for the subject vehicle in the slip road to merge safely. Based on observations for sections of the M8 Motorway, Wang found that the percentage of cooperative slowing down behaviour was found to be 7%, whereas the cooperative yielding percentage was 20%. Likewise, Al-Jameel (2012) developed a micro-simulation model which considered the cooperative slowing down and yielding behaviours of drivers at weaving sections. He supposed that the non-weaving vehicles (i.e. mainline motorway vehicles) will show a courtesy behaviour when the deceleration rate does not exceed the normal deceleration (i.e. -3 m/sec^2). Similarly, Al-Obaedi (2012) developed his model for motorway merge sections. He suggested that for those drivers on the main line motorway showing courteous behaviours to those merging from the ramp, those drivers will reduce their speeds to allow merging vehicles from the ramp and if the speed reduction is higher than the value of R (suggested by Ferrari (1989) as R =1040/DVc; where, DVc: is the desired speed of the following driver), then the driver on the main line motorway will show a cooperative yielding by moving to the adjacent offside lane if there is a sufficient gap in that lane.

Weng and Meng (2011) investigated drivers' merging behaviour at roadwork sections (i.e. transition zone). They reported that the traffic speeds and densities in the merging area affect the drivers' desired merging location. Under congested conditions, the merging location moved downstream.

Few studies have been found in the literature which deal with the modelling of the MLC at motorway roadwork sections (see for example Yousif, 1993 and Weng and Meng, 2011). The majority of the existing MLC studies are concentrated on different roadway sections, such as urban arterials, intersections lane-changing and motorway merging and weaving sections (see for example Zia, 1992; Hidas, 2005; Wang, 2006; Choudhury, 2007; Al-Jameel, 2012; Al-Obaedi, 2012; and Taha and Ibrahim, 2012). The behaviour of drivers at motorway merging and roadwork sections are nearly similar since the drivers at these sections need to change lane to reach their destination.

2.8.3 Gap acceptance model

The gap acceptance model represents the distance or time between successive vehicles travelling in the adjacent (target) lane. This gap splits into lead gap and lag gap: lead gap is the clear spacing between the front of the subject vehicle (merger) and the rear of the new leader, whereas lag gap is the gap between the rear of the merger and the front of the new follower (as shown in Figure 2.5).

Marczak et al. (2013) reviewed several lane-changing models and reported that most of the existing models are based on the gap acceptance theory. According to this theory the driver of the subject vehicle in the current lane (i.e. merger) will compare the available gap in the adjacent lane (target lane) with the so-called critical (minimum) gap; an adjacent gap will be considered acceptable if the adjacent gap is larger than the critical (minimum) gap, if not the adjacent gap will be rejected and another one will be sought (Barceló, 2010 and Zhang et al., 2010). The critical gap has also been divided into lead critical gap which represents the gap between the subject vehicle and the new leading vehicle, and the lag critical gap which is laid between the subject vehicle and the new following vehicle. As a conclusion, the subject vehicle can merge if both lead gap (G_{lead}) and lag gap (G_{lag}) are higher than the lead critical (minimum) gap ($G_{min,lead}$) and the lag critical (minimum) gap ($G_{min,lag}$), respectively (see Equation 2.3).

$$G_{lead} \geq G_{min,lead} \quad and \quad G_{lag} \geq G_{min,lag} \qquad \text{Equation 2.3}$$

There are several factors affecting the values of the critical (minimum) gaps, such as speed of merger, speeds of new follower and new leader, the distance remaining to the end of the lane and reaction time (Ahmed, 1999; Hidas, 2002 and 2005; Lee, 2006; Rao, 2006; Choudhury, 2007; and Al-Obaedi, 2012). Table 2.2 summarises the factors affecting the critical gaps values based on previous studies.

Table 2.2: Summary of factors affecting the critical gap values from previous studies

Name and References	Distance to end of lane	Speed of merger	Speed of new follower	Speed of new leader	Average speed in the target lane	Acceleration/deceleration of merger	Acceleration/deceleration of new follower	Acceleration/deceleration of new leader	Aggressiveness behaviour of new follower	Characteristics of merger	Traffic characteristics in the target lane (density and flow)	Buffer space	Reaction time	Length of offered gap
Yousif (1993)	x	x			x						x			
Ahmed (1999)	x	x	x	x										
Hidas (2002)		x	x	x		x	x	x						
Zheng (2003)		x	x	x										
Hidas (2005)		x	x	x		x	x		x	x				
Liu (2005)		x	x	x		x	x	x				x	x	
Lee (2006)	x	x		x	x		x							
Rao (2006)	x	x		x	x		x							
Wang (2006)		x	x	x		x	x	x					x	
Al-Jameel (2012)		x	x	x		x	x	x					x	
Al-Obaedi (2012)		x	x	x		x	x	x				x	x	
Marczak et al. (2013)	x	x	x	x										x

It can be seen from Table 2.2 that the most influential factor among the proposed models is the speed of the merger, new follower and new leader. This reflects the importance of this factor on the values of the accepted gaps. Such findings are consistent with those of Hidas (2005) and Yousif (1993) who reported that the relative difference in speeds between the merger and those involved in the target lane appears to be the most important factor influencing the accepted lead and lag gaps.

Hidas (2005) proposed two equations for lead critical (minimum) gap and lag critical (minimum) gap, as shown in Equations 2.4 and 2.5 respectively. The development of these equations is based on field observations which confirm that the size of the available gap for the subject vehicle is a function of the relative speed between the merger and new follower/new leader in the target lane.

$$G_{min,lead} = G_{min} + \begin{cases} C(VC - VL) & if\ VC > VL \\ 0 & otherwise \end{cases} \qquad \text{Equation 2.4}$$

$$G_{min,lag} = G_{min} + \begin{cases} C(VF - VC) & if\ VF > VC \\ 0 & otherwise \end{cases} \qquad \text{Equation 2.5}$$

Where:
C: constant gap parameter (Hidas (2005) suggested the constant value = 0.9),
VC: the velocity of the subject vehicle (i.e. merger) (m/sec),
VL: the velocity of the new leader (m/sec),
VF: the velocity of the new follower (m/sec), and
G_{min}: minimum safe constant gap which is independent of the speed difference between vehicles, Hidas (2005) suggested the average value = 2.0 m.

Al-Obaedi (2012) proposed two equations for the lead and lag critical (minimum) gaps based on the safety gap acceptance equation that was proposed by Liu et al. (1995) and Liu (2005) (Liu developed and used this equation in her model, DRACULA), as shown in Equations 2.6 and 2.7. In addition, this safety gap acceptance equation was also adopted by Wang (2006) and Al-Jameel (2012) in their models.

$$G_{min,lead} = Rt(VC) + Max\left[0, \left(\frac{VC^2}{2MaxDECC} - \frac{VL^2}{2MaxDECL}\right)\right] + BUF \quad \text{Equation 2.6}$$

$$G_{min,lag} = Rt(VF) + Max\left[0, \left(\frac{VF^2}{2MaxDECF} - \frac{VC^2}{2MaxDECC}\right)\right] + BUF \quad \text{Equation 2.7}$$

Where:
Rt: the reaction time (sec),
VC: the velocity of the subject vehicle (i.e. merger) (m/sec),
VL: the velocity of the new leader (m/sec),
VF: the velocity of the new follower (m/sec),
MaxDECC: the maximum deceleration rate for the merger (m/sec^2),
MaxDECL: the maximum deceleration rate for the new leader (m/sec^2),
MaxDECF: the maximum deceleration rate for the new follower (m/sec^2), and
BUF: the safety buffer space (m).

Al-Obaedi (2012) suggested that the size of the accepted gaps for the MLC is lower than those used for the DLC. This assumption is consistent with the findings by Yousif (1993), Hidas (2005), Liu (2005), Wang (2006) and Al-Jameel (2012) who reported that the size of the accepted gaps for the MLC is lower than those used for the DLC. In addition, Al-Obaedi (2012) used, in his micro-simulation model, a value of 1.0 m as a default value for the $G_{min,lead}$ when the new leader is faster than the merger and also a default value of 1.0 m is used as a critical (minimum) lag gap ($G_{min,lag}$ = 1.0 m) when the new follower is slower than the merger. This is also consistent with the findings by Hidas (2002 and 2005) who reported that the drivers were observed accepting very short gaps (not more than 1.0-2.0 m), when the relative speed between the merger and the new leading/following vehicle in the target lane is close to zero. Furthermore, based on real traffic data, Hunt and Yousif (1990) reported that when the merger is slower than the new leader, a value of 0.2 seconds was observed for the accepted lead gaps. This value (i.e. 0.2 seconds) has also been observed for accepted lag gap when the merger is faster than the new follower.

2.9 Other related simulation characteristics

2.9.1 Lane utilisation

According to the Highway Capacity Manual (HCM, 2010) lane utilisation (or lane distribution as referred to in the HCM) can be defined as the parameter that is used to describe the distribution of traffic among available lanes in a single direction. The lane utilisation parameter has been used in many simulation models in order to properly distribute simulated vehicles among the simulated lanes, (see for example S-Paramics model which uses the total section flow as an input data then it distributes the input total flow amongst the available lanes by using specific lane utilisation equations).

Several research studies have dealt with the lane utilisation and some proposed regression models for the relationships between the lane utilisation and total traffic flow (see for example Yousif and Hunt, 1995; Zheng, 2003; Al-Jameel, 2012; Al-Obaedi, 2012 and Yousif et al., 2013a). Based on real traffic data taken from the Motorway Incident Detection and Automated Signalling (MIDAS) for the M602 (2-lane motorway in the UK), Yousif et al. (2013a) reported that under free flow conditions, drivers are usually using lane 1 (inside lane), but with the increase of traffic flow, drivers tend to change lanes to lane 2 (offside lane). Also, Yousif et al. (2013a) reported that with the increase in traffic flow, the utilisation of offside lane would rapidly increase until about 2000 veh/hr (when both lanes carry similar amounts of traffic flow). After that, when traffic flow reaches section capacity, the offside lane will carry about 60% of the flow. This was found to be consistent with findings of Yousif and Hunt (1995) and Al-Jameel (2012).

For three-lane motorway, Yousif et al. (2013a) reported that (based on data taken from MIDAS for the M62) under free flow conditions (when traffic flow rates are up to around 500 veh/hr), the majority of vehicles are utilising lane 1 (inside lane). As traffic flow increases, the other lanes (i.e. lanes 2 and 3) will start to have their share of use. After that, when traffic flow reaches capacity, the lane use for both lanes 2 and 3 are approximately similar while vehicles which utilised lane 1 is lower than those utilising lanes 2 and 3. This is different from the finding of Duret et al. (2012), who collected real traffic data from three-lane highway section in Lyon, France. They reported that when traffic flow was lower than 1800 veh/hr no distinct trend of lane utilisation could be observed. As traffic flow increases, lane utilisation increases linearly for lane 3 (offside lane) while decreases linearly for both lanes 1 and 2. The reasons for these differences in lane utilisation between the M62 and the highway in Lyon could be due to the relatively high speed limit implemented in France, and to the high rate of HGVs (25% of total traffic flow is for HGVs) using the highway in Lyon. It should be noted that the applied speed limit for highways in France is 130 km/hr (equivalent to 81 mph). Furthermore, the differences between countries' culture affect the behaviour of drivers which could affect the pattern of lane changes (Nordaen and Rundmo, 2009 and Ferrari, 1989). According to the Highway Capacity Manual (HCM, 2010) the lane utilisation is depending on traffic regulation, traffic composition, speed and volume (traffic flow), the number of and the location of access points, the origin-destination patterns of drivers, and local driver habits. Figure 2.6 illustrates the lanes notations used in this study, for a motorway section with 3 lanes.

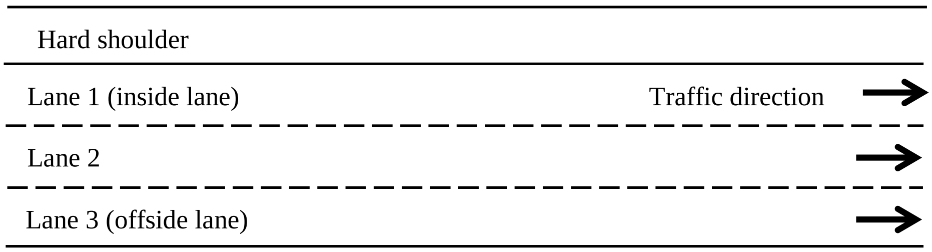


Figure 2.6: Lane's notations

Some research studies have investigated the lane utilisation in respect to traffic density rather than traffic flow such as Knoop et al. (2010) who studied the lane utilisation based on data from Dutch motorways. The authors reported that at moderate to high density lower percentage of lane use was observed for lane 1. Similarly, Lee and Park (2010) studied the lane utilisation against the density and reported that the lane utilisation is affected by the amount of HGVs. However, the main limitation of using traffic density in studying lane utilisation is that the density is not directly measured by loop detectors which are commonly embedded on motorways to collect traffic data (Al-Obaedi, 2012).

2.9.2 Lane changing frequency

Lane changing frequency parameter can be defined as the total number of lane changes observed between all available lanes along a specified section length during a given time period (Zia, 1992). The lane changing frequency parameter has been used by many previous studies (see for example Zia, 1992; Yousif, 1993; McDonald et al., 1994; Al-Jameel, 2012; and Al-Obaedi, 2012) to calibrate/validate many traffic micro-simulation models. According to previous literature, it was found that the frequency of lane changing for normal motorway sections (i.e. far away from merge, diverge or roadwork sections) is correlated to the traffic flow. Brackstone et al. (1998) reported that the frequency of lane changing initially increases with traffic flow; then decreases at high traffic flow since both the number of acceptable gaps and the desire to change lane decreases as flow breakdown approaches.

2.9.3 Accepted gaps at merge sections

Gap acceptance could be considered as an important parameter that affects the lane changing process at merge sections. As mentioned in Section 2.8.3, this gap splits into lead and lag gaps. It was found that there is a need for studying the minimum values of lead and lag gaps required for the lane changing process at the approaches to roadworks sections. Several previous studies (e.g. Hunt and Yousif, 1990; Hidas, 2002 and 2005; Al-Jameel, 2012 and Al-Obaedi, 2012) have estimated the minimum accepted lead and lag gaps based on the relative speed between vehicles involved in the lane changing manoeuvre. According to Yousif (1993) the accepted lead gap can be defined as the time or distance between the lane changing (subject) vehicle and the new leading vehicle in the target lane at the start of the lane changing manoeuvre, whereas the accepted lag gap can be defined as the time or distance between the lane changing (subject) vehicle and the new following vehicle in the target lane at the start of the lane changing manoeuvre (see Figure 2.5).

2.9.4 Courtesy behaviours

According to Wang (2006), Al-Jameel (2012) and Al-Obaedi (2012) the courtesy behaviour consists of two categories. These are: (i) "cooperative slowing down behaviour" when the lag vehicle on the adjacent (open) lane slowed down to increase the lag gap available for the subject vehicle to change lane and (ii) "cooperative yielding behaviour" when the lag vehicle in the adjacent (open) lane moved (shifted) to other adjacent lanes to give way to the subject vehicle (in the closed lane) to merge.

2.9.5 Headway

Time headway can be defined as the time intervals between the passages of successive vehicles passing a reference line on the road (Salter and Hounsell, 1996 and Ha et al., 2012). Figure 2.7 shows an illustration of the time headway. Oner (2011) cited May (1990) who reported that the time headway is one of the important traffic flow characteristics that affects the safety, level of service, driver behaviour and capacity of the transportation system.

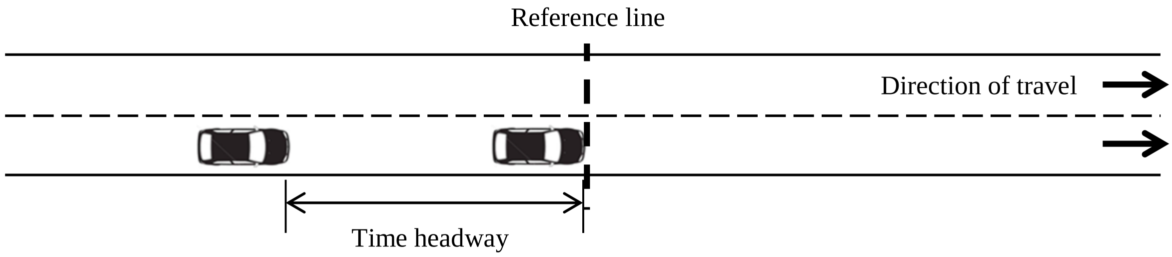


Figure 2.7: Illustration of time headway

To represent the arrival of vehicles to a specific section, different mathematical models have been used by previous research studies. Yousif (1993) used real traffic data to test several headway distribution models. Shifted negative exponential has been found to be a good representation of headway distribution at free flow conditions while under high traffic flow the generalised queuing model was suggested. Al-Obaedi (2012) followed the same technique that has been adopted by Yousif (1993) (i.e. by testing different distribution models using real traffic data), the models that have been tested are the shifted negative exponential, double negative exponential and generalised queuing model. The author reported that not one of the tested models could represent the traffic arrivals for all ranges of tested flow rates. However, he agreed with the findings of Yousif (1993) about using the shifted negative exponential distribution for free to moderate flow rates and generalised queuing distributions could only deal with the heavy flow rates. Likewise, Al-Jameel (2012) tested field data with lognormal distribution and negative exponential with different shifts. He reported that the shifted negative headway distribution showed a good representation of field data than the lognormal distribution.

2.10 Summary

The important findings from this chapter can be summarised as follow:

- Several TTMSs have been developed and are being used. The lane closure scheme is one of these schemes which is used widely. However, there are contradictory findings on whether the offside or inside lane should be closed for roadworks to maintain the traffic capacity (see for example Hunt and Yousif, 1994; Kazzaz, 1998; and Bourne et al., 2008). Therefore, this study will try to find out which lane is better to be closed for roadworks to provide more capacity and less delay.
- The narrow lanes system is another type of TTMSs which is used widely to meet the high traffic demand created during roadworks. However, very little research has been found in the literature to back the assumption of using narrow lanes to preserve the carriageway capacity during roadwork periods. Therefore, an evaluation of the traffic behaviour at motorway roadworks with narrow lanes has been carried out based on field traffic data taken from motorway roadwork sections (see Chapter 4) in order to understand and model this behaviour in the newly developed model.
- Existing mathematical models for roadworks have various limitations, such as the inflexibility of examining the effects of different TTMSs and parameters on traffic performance. Therefore, the micro-simulation approach has been adopted in this study due to the capability of such an approach to represent complicated traffic situations.
- The car-following model is one of the most important components of any micro-simulation model. The CAR-following SIMulation model (CARSIM) which was initially developed by Benekohal (1986) has been adopted in this study with some modifications. Many previous researchers used CARSIM, see for example, Yousif (1993), Purnawan (2005), Al-Obaedi (2012) and Al-Jameel (2012) who tested

several car-following models under different sets of data including different traffic conditions. The tested models are GHR (Gazis et al., 1961), CARSIM (Beneckohal, 1986), WEAVSIM (Zarean, 1987), and Paramics (Panwai and Dia, 2005). The results showed that CARSIM is the most realistic amongst others in representing different traffic conditions.

- The lane-changing manoeuvre forms an essential part of the current study and has been classified into two categories, namely DLC and MLC. In addition, the MLC was categorised into: free, forced and cooperative.
- Several gap acceptance models have been introduced in the literature. However, the model proposed by Al-Obaedi (2012), which was based on the safety gap acceptance model by Liu (2005), has been adopted in this study. This is because it takes into consideration the safety buffer space and the impact of speeds of the involved vehicles on gap acceptance. Also, many researchers have adopted the safety gap acceptance model (see for example Wang, 2006 and Al-Jameel, 2012).

CHAPTER THREE
METHODOLOGY

3.1 Introduction

The aim of this chapter is to present the work that was carried out for collecting and analysing field traffic data. Field data from sites as well as from relevant highway agencies was collected to gain a better understanding into the traffic behaviour at motorway normal and roadwork sections. The data was also used in developing, calibrating and validating the micro-simulation model. The data collected from roadwork sections was mainly used in investigating the gap acceptance, drivers' courtesy behaviour, compliance of drivers with applied speed limit and the behaviour of drivers at narrow lanes roadwork sections, whereas the data taken from normal roadway sections (i.e. far away from merge, diverge or roadwork sections) was mainly used in estimating vehicles' length, drivers' desired speed, time headways between vehicles, lane utilisation, lane changing frequency and manoeuvring time.

3.2 Data collection techniques

In order to collect traffic data, different methods and devices have been proposed in the literature. Loop detectors, radar speed meters, pneumatic road tubes, ultrasonic and passive acoustic, instrumented vehicles and camcorders are examples of these devices (Leduc, 2008 and Al-Obaedi, 2012). However, the literature has shown that the main system used to collect traffic data for the academic research purposes is camcorders; this could be due to the reasonably low cost involved. Furthermore, the camcorders system has many advantageous as reported by Yousif (1993) such as:

- The required data can be collected by one person only,
- The person who collects the data is able to record any comments of events outside the field of the camcorder through the recording system, and
- The camcorder is easy to install on sites.

However, the accuracy of the extracted data provided by this technique (i.e. camcorders) is influenced by the observer/researcher decision.

Loop detectors technique provides traffic data with high accuracy since this technique is not affected by human errors. Also, data taken from loop detectors can be collected and analysed with less efforts. However, loop detectors technique is not capable of providing certain traffic characteristics such as drivers' courtesy behaviour, the number of lane changes and the manoeuvring time for lane changing (however, these characteristics were studied by using camcorders).

For the purpose of this study, two techniques (camcorders and loop detectors) have been used to collect the required data. Two video cameras (Sony HDD Handycam DCR-SR57) were used in collecting the data.

3.3 Site selection

Locating motorway roadwork sites to conduct field surveys is not an easy task. This is mainly because of the temporary nature and short duration of the motorway roadworks. Some of the experienced difficulties are:

- Lack of or inaccurate information from relevant agencies on presence of current motorway roadworks,
- Unavailable vantage points to record data from (i.e. an overhead bridge close to the roadwork section),
- Remote location of some of motorway roadwork sites (such as the case of the M6 site survey beyond Preston and the case of the M1 close to Leeds), and
- Difficulties associated with adverse weather conditions.

However, four categories of field data have been used in this study for both normal and roadwork sections. These four categories are described in the following sections.

3.3.1 Category I: Motorway roadwork sites

Table 3.1 gives a brief description of the roadwork sites selected for the current study. The chosen sites cover different types of temporary traffic management schemes (i.e. lane closure system, narrow lanes system and lane closure with using hard shoulder as a running lane). These sites have been surveyed during 2014 and 2015. Figure 3.1 shows the locations of these sites.

Table 3.1: Summary of motorway roadwork sites (Category I)

Site No.	Site location	Number of lanes	Traffic direction	Date	Total filming duration	Traffic management scheme
1	M1 (J36 – J37)	3	Southbound	Saturday 15/03/2014	1.5 hours (PM)	Offside lane closure with using the hard shoulder as a running lane
2	M67 (J2 – J3)	2	Westbound	Saturday 21/06/2014	3.5 hours (AM & PM)	Offside lane closure
3	M6 (J31 – J32)	4	Northbound	Sunday 31/08/2014	3.5 hours (AM & PM)	Narrow lanes
4	M61 (J2 – J3)	2	Eastbound	Saturday 08/11/2014	2.5 hours (AM)	Drop lane section
5	M61 (J2 – J3)	3	Eastbound	Saturday 08/11/2014	2.5 hours (AM)	Drop lane section
6	M62 (J18 – J19)	3	Eastbound	Sunday 15/03/2015	2.0 hours (AM & PM)	Narrow lanes
7	M62 (J18 – J19)	3	Westbound	Sunday 15/03/2015	2.0 hours (AM & PM)	Narrow lanes

3.3.2 Category II: Normal motorway sections

Different normal motorway sites were surveyed as summarised in Table 3.2 and the location map shown in Figure 3.1, during 2013 and 2014. These sections were chosen to be far away from any merging, diverging and roadwork sections. The selected sites cover two-lane, three-lane and four-lane motorway sections.

Table 3.2: Summary of normal motorway sites (Category II)

Site No.	Site location	Number of lanes	Traffic direction	Date	Total filming duration	Traffic management scheme
8	M60 (J24 – J25)	3	Both directions	Saturday 16/08/2014	6.5 hours (AM & PM)	Normal roadway section
9	M6 (J31 – J32)	4	Southbound	Sunday 31/08/2014	3.5 hours (AM & PM)	Normal roadway section
10	M602 (J2– J3)	2	Eastbound	Tuesday 18/11/2014	3.0 hours (AM)	Normal roadway section
11	M602, M62 & M6	---	From Manchester to Birmingham	Wednesday 17/04/2013	1.5 hours (AM)	Normal roadway section
12	M602, M62, M6 & M58	---	From Manchester to Southport	Wednesday 30/07/2014	1.0 hours (AM)	Normal roadway section

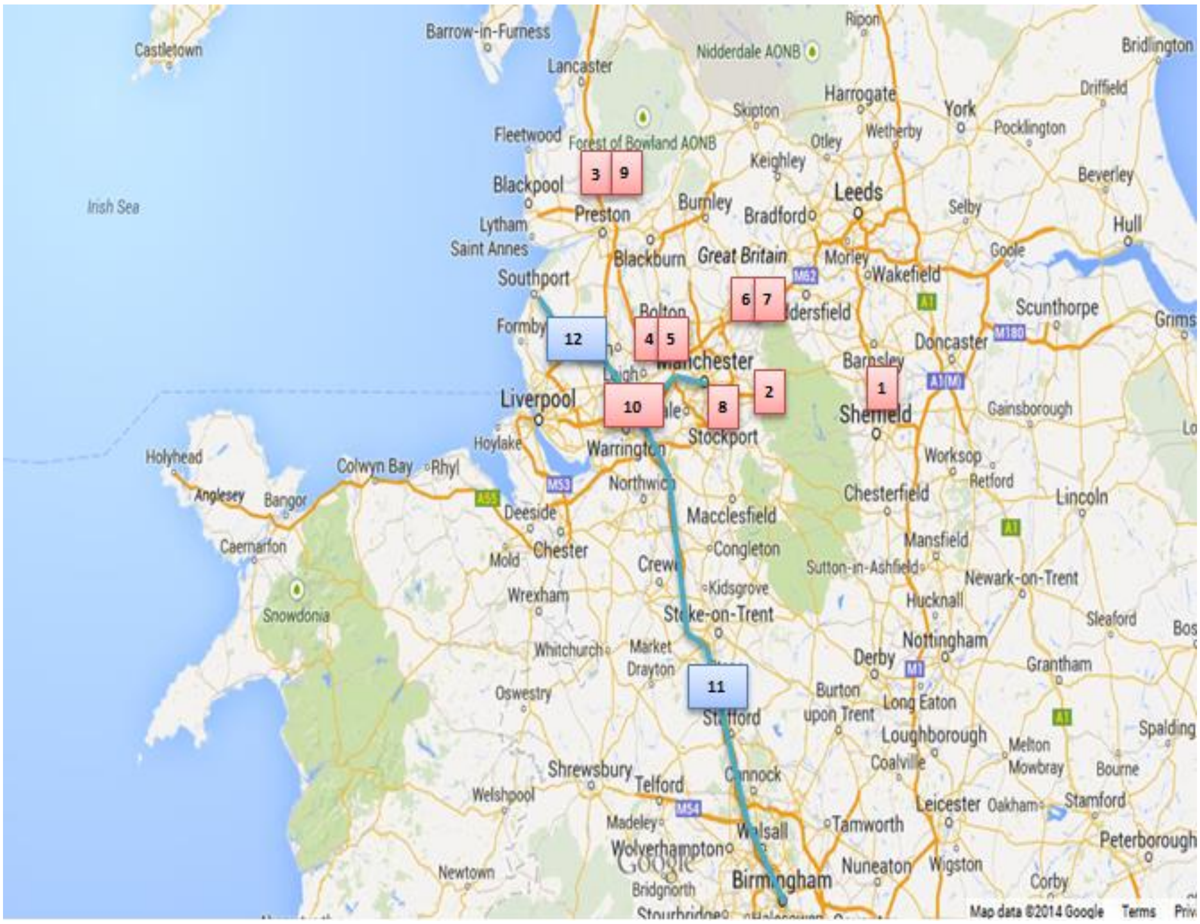


Figure 3.1: Sites locations map (Categories I and II) (Source of map: Google Maps, 2014)

3.3.3 Category III: Loop detectors data (Individual Vehicle Data-IVD)

Field data has been made available which was extracted from the Individual Vehicle Data (IVD) which is obtained from the Highways Agency. This data includes the time headway between vehicles, the length and speed of each individual vehicle. The data was taken from normal motorway sections and collected over several continuous complete days. Table 3.3 shows the descriptions of these sites.

Table 3.3: Summary of IVD sites (Category III)

Site No.	Site location	Number of lanes	Date	Duration
13	M25 (J15 – J16)	4	From 04/05/2002 to 18/05/2002	15 days
14	M42 (J5 – J6)	3	From 22/08/2002 to 20/09/2002	30 days

3.3.4 Category IV: Historical motorway sites

Three video footages taken from two motorway roadwork sites and one normal motorway site from previous studies have been made available and used to extract field traffic data. The reasons for using such historic data are because these have been made available in the current study and the fact that (for the sites with roadwork) it is often difficult to find motorway roadwork sites due to the reasons that were previously mentioned in Section 3.3. The descriptions of this historic data are presented in Table 3.4.

Table 3.4: Summary of historic roadwork sites (Category IV)

Site No.	Site location	Number of lanes	Traffic direction	Date	Total filming duration	Traffic management scheme
15	M61 (J8 – J9)	3	Northbound	Friday 16/08/1996	3.0 hours (PM)	Offside lane closure
16	M6 (J14 – J15)	3	Southbound	Friday 25/10/1996	4.0 hours (AM)	Offside lane closure
17	M60 (J16 – J17)	4	Eastbound	Wednesday 31/07/1996	1.5 hours (PM)	Normal roadway section

3.3.5 Summary of the selected sites

For the purpose of this study, several traffic parameters were studied using the field data that were collected from the surveyed sites. Table 3.5 summaries the details of sites locations, type of data collection techniques and the parameters obtained from the collected data. The following sections in this chapter present the analysis of these parameters and a detailed description of the methods used in extracting the data.

3.4 Headway

As discussed in Section 2.9.5, the time headway is one of the important traffic flow characteristics that affect the safety, level of service, driver behaviour and capacity of the transportation system. Observed time headway data (from sites) will be used and compared with the simulated time headway (from the developed micro-simulation model) for calibration purposes.

3.4.1 Headway distribution models

As mentioned in Section 2.9.5, different mathematical models have been used by previous research studies in order to represent the arrival of vehicles to a specific section. In general, these models could be classified into either single or composite models. The following sub-sections presents the formulation and detailed description of the tested headway distribution models.

Table 3.5: Summary of studied parameters along with selected sites

Site no.	Site location	Purpose	Data collection technique
1	M1 (J36-J37)	- Compliance of drivers with applied speed limit	Video recordings
2	M67 (J2-J3)	- Gap acceptance - Drivers' courtesy behaviour - Compliance of drivers with applied speed limit - Traffic flow, speed and lane utilisation for validation purpose (see Chapter 7)	Video recordings
3	M6 (J31-J32)	- Drivers' behaviour at narrow lanes (see Chapter 4) - Traffic flow and headway distribution for calibration purpose (see Chapter 7)	Video recordings
4	M61 (J2-J3)	- Gap acceptance - Drivers' courtesy behaviour	Video recordings
5	M61 (J2-J3)	- Gap acceptance	Video recordings
6	M62 (J18-J19)	- Drivers' behaviour at narrow lanes (see Chapter 4) - Traffic flow, speed and lane utilisation for validation purpose (see Chapter 7)	Video recordings
7	M62 (J18-J19)	- Drivers' behaviour at narrow lanes (see Chapter 4)	Video recordings
8	M60 (J24-J25)	- Headway distribution - Lane changing frequency - Comparison between drivers' behaviour at roadwork sections with narrow lanes and normal roadway section (see Chapter 4)	Video recordings
9	M6 (J31-J32)	- Lane changing frequency	Video recordings
10	M602 (J2-J3)	- Lane changing frequency - Traffic flow and lane utilisation for validation purpose (see Chapter 7)	Video recordings
11	M602, M62 & M6	- Lane changing manoeuvring time	Video recordings
12	M602, M62, M6 & M58	- Lane changing manoeuvring time	Video recordings
13	M25 (J15-J16)	- Vehicles' types and lengths (see Chapter 6) - Drivers' desired speeds (see Chapter 6) - Traffic flow, speed and lane utilisation for validation purpose (see Chapter 7)	Loop detectors (IVD)
14	M42 (J5-J6)	- Headway distribution - Lane utilisation - Drivers' desired speeds (see Chapter 6) - Traffic flow, speed and lane utilisation for validation purpose (see Chapter 7)	Loop detectors (IVD)
15	M61 (J8-J9)	- Developing, calibrating and validating the S-Paramics software (see Chapter 5)	Video recordings
16	M6 (J14-J15)	- Developing, calibrating and validating the S-Paramics software (see Chapter 5)	Video recordings
17	M60 (J16-J17)	- Comparison between drivers' behaviour at roadwork sections with narrow lanes and normal roadway section (see Chapter 4)	Video recordings

3.4.1.1 Single headway models

i. Negative exponential distribution

Salter and Hounsell (1996) reported that this model is suitable to represent the vehicle arrival rates at free traffic flow conditions. The probability density function is as shown in Equation 3.1:

$$f(t) = exp^{-Qt} \qquad \text{Equation 3.1}$$

Where:
Q: the traffic flow (veh/hr), and
t: the time headway in seconds.

ii. Shifted negative exponential distribution

By shifting the negative exponential distribution by a minimum headway (shift), this model is able to describe vehicle arrival rate for free to moderate flow (Yousif, 1993 and Al-Obaedi, 2012). The form of the shifted negative exponential can be described by Equation 3.2 (Benekohal, 1986 and Alterawi, 2014):

$$TH = shift - \left[\frac{1}{Q} - shift\right] \ln(RND) \qquad \text{Equation 3.2}$$

Where:
TH: the time headway for each generated vehicle in a simulation model,
Shift: the additional time such as 0.25, 0.5 and 1 in seconds, and
RND: the random number generated by the simulation model.

iii. Lognormal distribution

Al-Obaedi (2012) cited Tolle (1976) who reported that the lognormal distribution is suitable to fit headway distribution data under high flow rates. The probability density function is as shown in Equations 3.3 to 3.5 (Zia, 1992; Walck, 1996; and Alterawi, 2014):

$$f(t) = \frac{1}{\sigma t (2\pi)^{0.5}} \, exp^{\frac{-(\ln(t)-\mu)}{2\sigma^2}} \qquad \text{Equation 3.3}$$

$$\mu = ln(a) - \sigma^2/2 \qquad \text{Equation 3.4}$$

$$\sigma^2 = ln\,(\frac{s^2}{a^2} + 1) \qquad \text{Equation 3.5}$$

Where:
a and s: the mean and the standard deviation of the lognormal distribution, respectively, and
μ and σ: the mean and the standard deviation of the normal distribution, respectively.

Branston (1976) and Al-Obaedi (2012) recommended that the values of a and s are to be independent of the traffic flow rate with the following values:

a = 1.6 sec s = 0.4 sec for slower lane

a = l.3 sec s = 0.4 sec for faster lane

3.4.1.2 Composite headway models

i. Generalised queuing model

General queuing model is based on the assumption that vehicles are travelling in random queues. The general queuing model consists of two separate criteria to describe the headway. One is used for free vehicles (i.e. no leading vehicle) while the other one is used for the restrained vehicles (i.e. following a leader). To calculate the restrained vehicles headway, many researchers used the lognormal distribution such as Zia (1992), Yousif (1993), Zheng (2003) and Al-Obaedi (2012), whereas the headway for free vehicles is estimated as the sum of restrained headway and the headway derived from the negative exponential distribution (Branston, 1976; Zia, 1992 and Al-Obaedi, 2012). Equations 3.6 and 3.7 show the proportion of restrained vehicles (ϕ) and free flow vehicles (Q_f), respectively (as suggested by Branston, 1976 and Al-Obaedi, 2012).

$$\phi = a\,.\,Q - \left(0.5\,.\,Q^{0.5}.\,(a\,.\,Q - 1)\right) \qquad \text{Equation 3.6}$$

$$Q_f = Q - 0.5\,.\,Q^{1.5} \qquad \text{Equation 3.7}$$

3.4.2 Testing headway distribution models using real data

For the purpose of this study, three sets of real traffic data collected from two sites with different traffic flow conditions (i.e. ranging from free, moderate to heavy) have been used to test the headway distribution models mentioned earlier in order to select the most appropriate one. The selected headway distribution model will be used to generate vehicles at the start of the developed micro-simulation model.

Table 3.6 shows a brief description of the selected data sets for this test. The selected sites are normal motorway sections (i.e. far away from merge or diverge sections) and consisted of three lanes. The tested headway distribution models are the shifted negative exponential, the lognormal and the generalised queuing model.

Table 3.6: Headway field data details

Data sets No.	1	2	3
Site No.	8	14	14
Site location	M60 (J24 – J25)	M42 (J5 – J6)	M42 (J5 – J6)
Date	Saturday 16/08/2014	Thursday 22/08/2002	Monday 16/09/2002
Time	09:30 – 10:00 AM	09:30 – 10:30 AM	08:15 – 09:15 AM
Data period	30 min	60 min	60 min

Using the shifted negative exponential distribution and based on the data set 3, Figure 3.2 shows good agreement between the observed and the predicted cumulative headway distribution for lanes 1, 2 and 3 with flow rates of about 1390, 1890 and 2090 veh/hr, respectively. This was found to be consistent with the findings of Al-Jameel (2012) who used the shifted negative exponential distribution to generate vehicles in his micro-simulation model on motorways. The best shift values (which gave better results) of 0.75, 0.75 and 0.70 were used for lanes 1, 2, and 3 respectively.

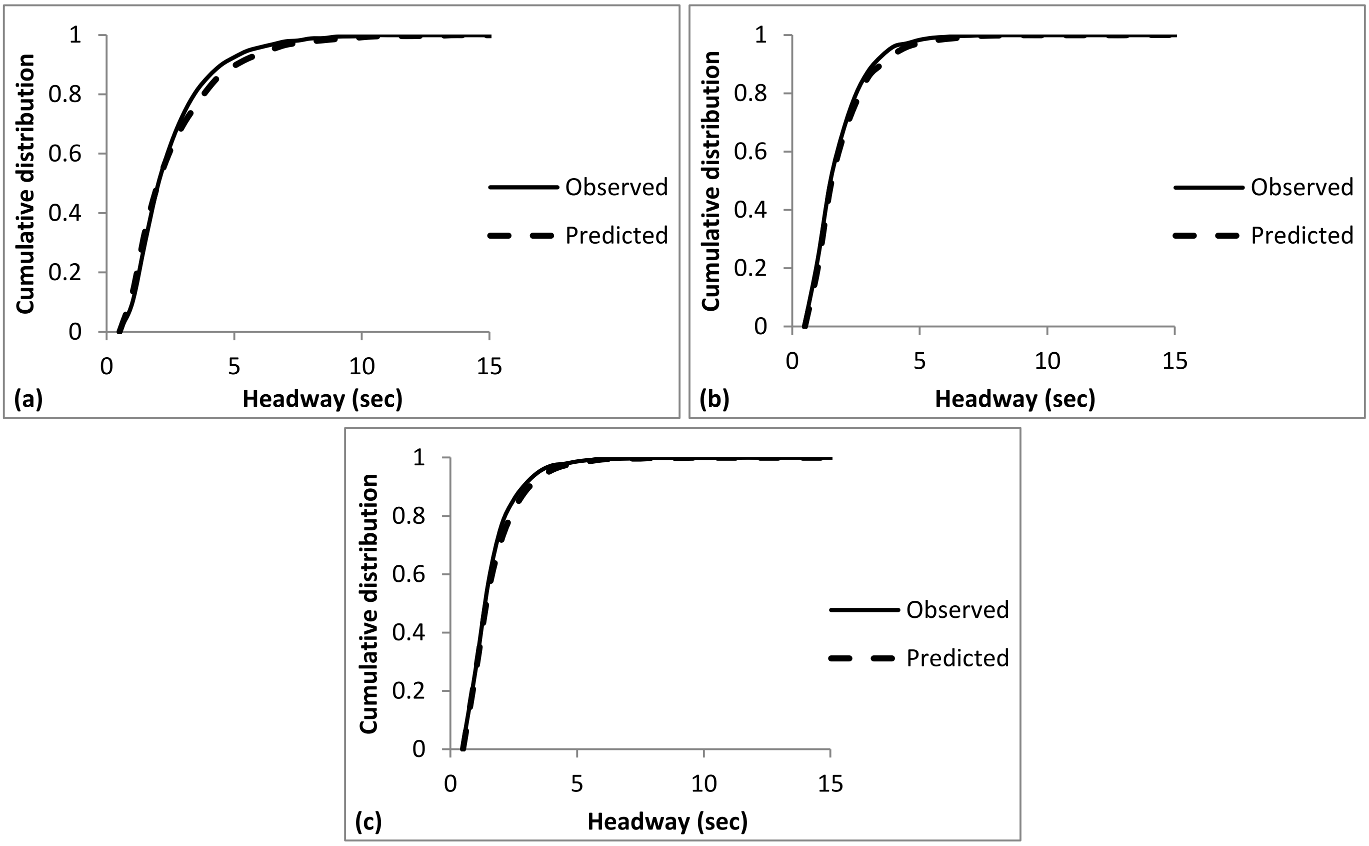


Figure 3.2: Observed and predicted cumulative headway distributions for Site No. 14 - data set 3 (M42) in (a) lane 1, (b) lane 2 and (c) lane 3 using the shifted negative exponential model

The results also show that the generalised queuing distribution could replicate the observed headways under heavy flow on lane 3 better than those under moderate flow on lane 1 (as shown in Figure 3.3), which are based on the data set 3. This shows an agreement with previous researchers' findings such as Zia (1992), Yousif (1993) and Al-Obaedi (2012) who reported that the generalised queuing model could only deal with heavy flow rates. The best mean headway parameters (*a*) that could be achieved for this distribution are 1.6, 1.4 and 1.2 seconds for lanes 1, 2 and 3 respectively, and the best standard deviation parameters (*s*) achieved is 0.4 seconds for all lanes. This was found to be consistent with the findings of Branston (1976) who suggested that values of 1.6 and 0.4 seconds for (*a*) and (*s*) respectively are recommended for slow speed lane and values of 1.3 and 0.4 seconds for (*a*) and (*s*) are recommended for high-speed lane.

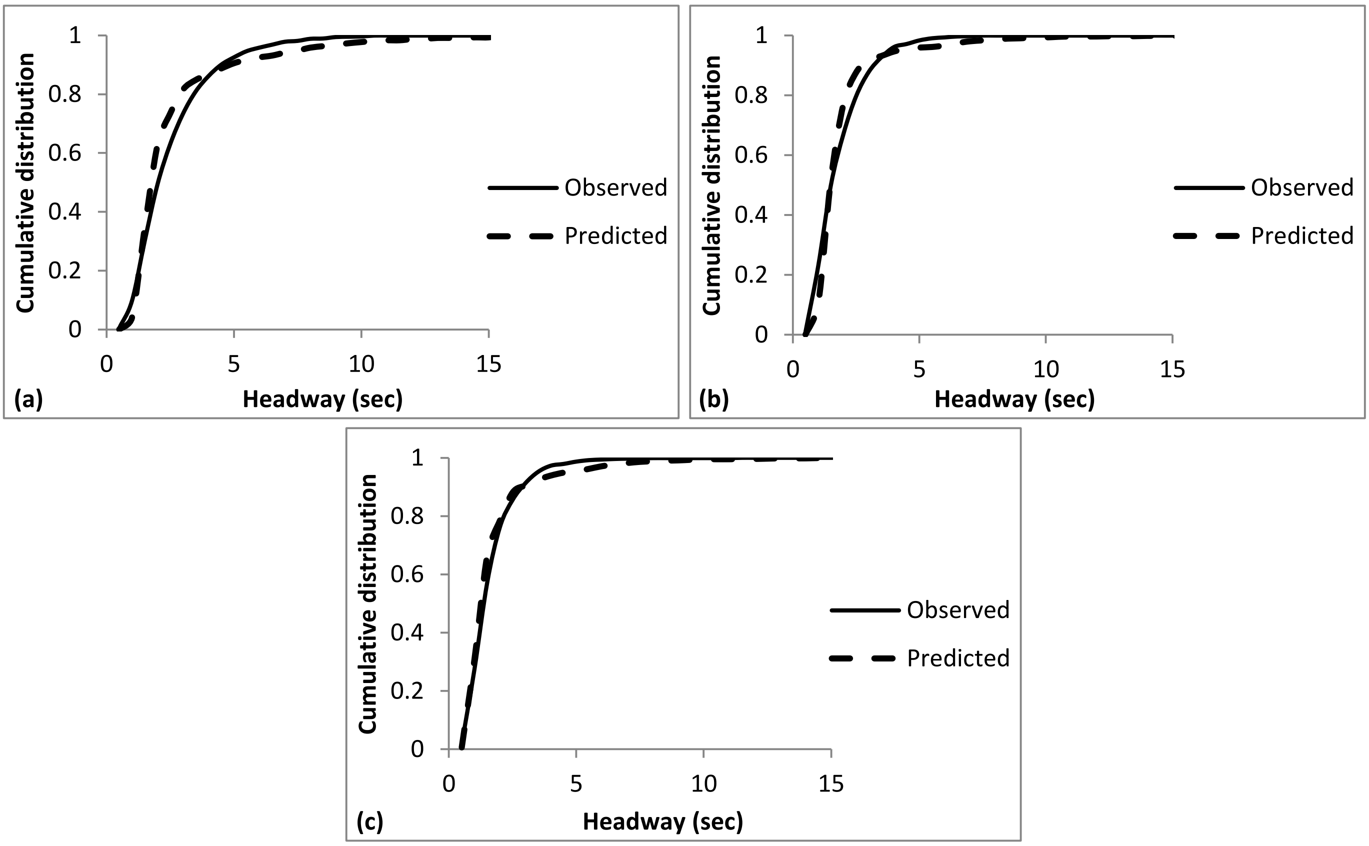


Figure 3.3: Observed and predicted cumulative headway distributions for Site No. 14 - data set 3 (M42) in (a) lane 1, (b) lane 2 and (c) lane 3 using generalised queuing model

Figure 3.4 show the observed cumulative headway distribution and the predicted cumulative headway distribution using the lognormal model for lanes 1, 2 and 3 with flow rates of 1390, 1890 and 2090 veh/hr respectively, based on data set 3. It can be seen from the figure that the lognormal model did not replicate the observed headways very well, especially for lane 1.

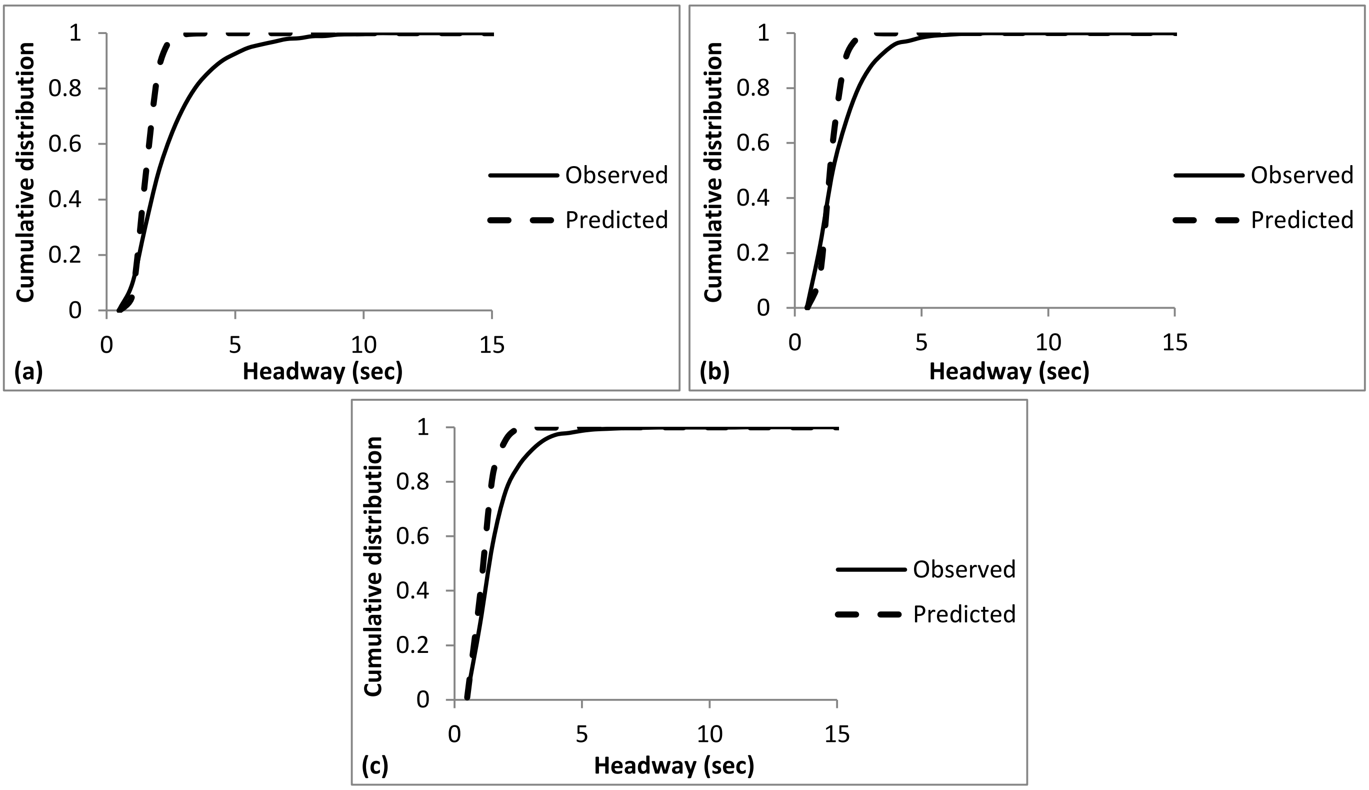


Figure 3.4: Observed and predicted cumulative headway distributions for Site No. 14 - data set 3 (M42) in (a) lane 1, (b) lane 2 and (c) lane 3 using the lognormal model

The Kolmogorov-Smirnov (K-S) non-parametric test for goodness of fit was used to determine the best fit to the data. The test compares the maximum difference D_{max} between two cumulative distributions (i.e. observed and predicted headway) with the critical value D_{cr} which could be obtained from Equation 3.8 or from K-S tables (Hayter, 2002).

$$D_{cr} = 1.36 \sqrt{\frac{n_1 + n_2}{n_1 n_2}} \quad \text{(for 95\% confidence level)} \qquad \text{Equation 3.8}$$

Where:
n_1 & n_2: are the sample sizes.

The results of the goodness of fit using the (K-S) test for all data sets are shown in Table 3.7 which could reflect the above results and findings. It can be seen from the table that not one of the tested models is capable of representing the arrival distribution of traffic for all ranges of tested flow rates. However, the table shows that the shifted negative exponential distribution performs better than both the generalised queuing distribution and lognormal distribution in terms of replicating the observed cumulative headway distribution for all data sets. Therefore, it was decided to use the shifted negative exponential distribution for generating traffic in the developed micro-simulation model.

Table 3.7: Statistical results for testing the headway distribution models using K-S test

Data set No.	1			2			3		
Lane no.	1	2	3	1	2	3	1	2	3
Flow rate (veh/hr)	518	457	158	980	1571	1392	1391	1890	2090
Shifted negative exponential (D_{max})	0.058	0.085	0.171*	0.058	0.043	0.136*	0.046	0.030	0.048*
Generalised queuing (D_{max})	0.172*	0.114*	0.110	0.205*	0.128*	0.151*	0.133*	0.126*	0.092*
Lognormal (D_{max})	0.519*	0.510*	0.677*	0.569*	0.312*	0.269*	0.367*	0.234*	0.251*
K-S critical value (D_{cr})	0.085	0.090	0.153	0.061	0.049	0.052	0.052	0.044	0.042

*: $D_{max} > D_{cr}$

3.5 Lane utilisation

As discussed in Section 2.9.1, lane utilisation can be defined as the parameter that is used to describe the distribution of traffic among available lanes in a single direction (HCM, 2010). In this study, the lane utilisation parameter has been used to properly distribute simulated vehicles among the simulated lanes of the newly developed micro-simulation model.

3.5.1 Testing lane utilisation models using real data

For the purpose of this study, several lane utilisation models proposed by previous studies were tested using real data in order to select the most appropriate models. The selected lane utilisation models will be used to distribute simulated vehicles among the simulated lanes of the developed micro-simulation model.

Three complete days (24 hours in each day) of data from the IVD taken from the M42 (3-lane motorway) were used for this test. Table 3.8 shows the previous lane utilisation models for 3 lanes motorway sections and the test results (i.e. coefficient of determinations, R^2). As mentioned earlier, traffic regulations and local drivers' habits have direct impacts on how vehicles are distributed among the motorway lanes. Therefore, the lane utilisation models listed in Table 3.8 were limited to the previous studies that were developed based on data collected from the UK motorways only.

It is worth mentioning here that, the newly developed micro-simulation model takes into consideration the traffic regulations of the UK motorway (i.e. speed limit of 70 mph, drivers are not allowed to overtake on the inside (undertake) and HGVs are banned from using the offside lane for motorways with 3 or more lanes).

Table 3.8: Testing some previous models of lane utilisation

Names and References	Lane	Lane Utilisation Model (%)	R^2
Yousif and Hunt (1995)	1	$P1 = 608.84Q^{-0.39}$	0.89
	2	$P2 = 100 - P1 - P3$	0.36
	3	$P3 = 0.034 + 0.0179Q - 1.85E\text{-}6Q^2$	0.94
Zheng (2003)	1	$P1 = 0.67106 - 2.4168E\text{-}4Q - 2.9302E\text{-}8Q^2$	0.93
	2	$P2 = 0.4795 - 1.052E\text{-}5Q - 3.018E\text{-}9Q^2$	0.17
	3	$P3 = -0.15061 + 2.522E\text{-}4Q + 2.6284E\text{-}8Q^2$	0.94
Al-Jameel (2012)	1	For $Q \geq 150$; $P1 = 446.94Q^{-0.319}$	0.91
	2	$P2 = 100 – P1 – P3$	0.45
	3	For $Q \geq 150$; $P3 = -4x10^{-8} (Q)^2 + 0.0096Q-2.2136$	0.96
Yousif et al. (2013a)	1	$P1 = 1.732E\text{-}15Q^4 – 2.75E\text{-}11Q^3 + 1.67E\text{-}07Q^2 – 0.000485Q + 0.8412$	***0.94***
	2	$P2 = 2.14E\text{-}19Q^5 – 4.91E\text{-}15Q^4 + 4.68E\text{-}11Q^3 – 2.2E\text{-}07Q^2 + 0.000449Q + 0.1588$	***0.70***
	3	$P3 = 100 – P1 – P2$	***0.96***

Note: P = percentage in lane; Q = traffic flow (veh/hr)

It can be seen from Table 3.8 that all the models presented suggest high coefficient of determination (R^2) values for both lanes 1 and 3. However, the R^2 value for lane 2 seem very low, apart from the suggested models by Yousif et al. (2013a) and therefore these were used in representing lane utilisation.

Also, it is worth mentioning that, Yousif et al. (2013a) have developed other regression models/equations to represent lane utilisation for HGVs. The models/equations suggested by Yousif et al. (2013a) were based on a very large amount of traffic data taken from MIDAS for different motorway sections (i.e. 2, 3, and 4 lanes). Therefore, it was decided to use these equations in distributing the different types of vehicles (i.e. passenger cars and HGVs) among the lanes in the developed micro-simulation model. Table 3.9 shows the summary of these models/equations suggested by Yousif et al. (2013a) for different motorway sections (i.e. 2, 3, and 4 lanes) for both, all vehicles and HGV's.

3.5.2 Lane utilisation at motorway roadwork sections

Lane utilisation is affected by the lane-changing process which is concentrated at sections approaching roadwork. Jin (2010) reported that the presence of merging, diverging, and weaving sections will affect lane utilisation. Therefore, at the approach to roadwork sections (with the use of lane closure scheme) the lane utilisation is significantly different from that at normal roadway sections. In this study, the main reason for collecting lane utilisation data from motorway with roadwork sections is to be used in validating the developed micro-simulation model (as will be discussed later in Section 7.5).

According to the Design Manual for Roads and Bridges – DMRB (2005), the loop detectors should be installed in all new motorways, widened motorways and in all existing motorways during major maintenance. In addition, these loop detectors shall be sited in all running lanes of both carriageways at space intervals of 500 m (plus or minus 20%); exit and entry slip road lanes at junctions, entry slip road lanes to motorway service areas; and within motorway to motorway link roads (DMRB, 2005). However, such information was not available since it proved to be difficult to find loop detectors near roadwork sections (i.e. not all of the existing motorways are equipped with such detectors). Therefore, camcorders have been used to collect the necessary traffic data that is related to the lane utilisation at roadwork sections.

Table 3.9: Yousif et al. (2013a) models of lane utilisation (in terms of total flow rates and HGV flow)

<table>
<tr><th>Name and Reference</th><th>Number of motorway lanes</th><th>Lane</th><th>Lane Utilisation Model (%)</th></tr>
<tr><td rowspan="9">Yousif et al. (2013a) for all vehicles</td><td rowspan="2">2</td><td>1</td><td>$P1 = -1.2E\text{-}11Q^3 + 1.13E\text{-}07Q^2 - 0.000397Q + 0.9294$</td></tr>
<tr><td>2</td><td>$P2 = 100 – P1$</td></tr>
<tr><td rowspan="3">3</td><td>1</td><td>$P1 = 1.732E\text{-}15Q^4 – 2.75E\text{-}11Q^3 + 1.67E\text{-}07Q^2 – 0.000485Q + 0.8412$</td></tr>
<tr><td>2</td><td>$P2 = 2.14E\text{-}19Q^5 – 4.91E\text{-}15Q^4 + 4.68E\text{-}11Q^3 – 2.2E\text{-}07Q^2 + 0.000449Q + 0.1588$</td></tr>
<tr><td>3</td><td>$P3 = 100 – P1 – P2$</td></tr>
<tr><td rowspan="4">4</td><td>1</td><td>$P1 = -2.62E\text{-}12Q^3 + 4.67E\text{-}08Q^2 – 0.000243Q + 0.54$</td></tr>
<tr><td>2</td><td>$P2 = 6.27E\text{-}09Q^2 – 7.64E\text{-}05Q + 0.46$</td></tr>
<tr><td>3</td><td>$P3 = -8.79E\text{-}16Q^4 + 1.775E\text{-}11Q^3 – 1.29E\text{-}07Q^2 + 0.000377Q$</td></tr>
<tr><td>4</td><td>$P4 = 100 – P1 – P2 – P3$</td></tr>
<tr><td rowspan="5">Yousif et al. (2013a) for HGVs</td><td rowspan="2">3</td><td>1</td><td>$P_H1 = 0.976 - 0.0002044Q_H - 0.0000285Q$</td></tr>
<tr><td>2</td><td>$P_H2 = 100 – P_H1$</td></tr>
<tr><td rowspan="3">4</td><td>1</td><td>$P_H1 = 0.862 - 0.0002007Q_H -0.00003943Q$</td></tr>
<tr><td>2</td><td>$P_H2 = 0.154 + 0.00011Q_H + 0.00002143Q$</td></tr>
<tr><td>3</td><td>$P_H3 = 100 – P_H1 – P_H2$</td></tr>
</table>

Note: P = percentage in lane; Q = traffic flow (veh/hr); P_H = percentage of HGVs in lane; Q_H = total HGV traffic flow (veh/hr)

3.6 Lane changing observations

3.6.1 Lane changing frequency

As discussed in Section 2.9.2, the lane changing frequency parameter can be defined as the total number of lane changes observed between all available lanes along a specified section length during a given time period (Zia, 1992). For the purpose of this study, the frequency of lane changing parameter has been investigated based on real traffic data in order to be used in calibrating the developed micro-simulation model.

In this study, field data have been collected from three normal motorway sections to investigate the frequency of lane changing. These are the M6 J31-J32 section with four lanes, the M60 J24-J25 section with three lanes and the M602 J2-J3 section with two lanes. Camcorders were used for collecting the data from each site. Table 3.10 shows the description of field data which was used for studying the frequency of lane changing.

Table 3.10: Lane changing frequency field data details

Site No.	9	8	10
Site location	M6 (J31 – J32)	M60 (J24 – J25)	M602 (J2 – J3)
Number of lanes	4 lanes	3 lanes	2 lanes
Date	Sunday 31/08/2014	Saturday 16/08/2014	Tuesday 18/11/2014
Time	11:40 – 14:10	09:25 – 11:55	09:00 – 11:30
Data period	150 minutes	150 minutes	150 minutes
Section length	150 m	200 m	200 m

The lane changes frequency and total flow rates of the observed motorways have been extracted by playing back the recorded video footages. Using a marker pen, a thin line across the computer screen was sketched at the start of an arbitrary white road marking (at the centre of the computer screen) to help in counting vehicles (e.g. measuring time headways between successive vehicles). Similarly, in order to measure the frequency of lane changing, two thin lines across the computer screen were drawn to cover the distance of section length shown in Table 3.10. For Site No. 9 (M6), for example, the first line was located at the start of an arbitrary white road marking (near from the bottom of the computer screen), whereas the second line was after 16 consecutive white road markings (9 m each, as prescribed in the Traffic Signs Manual (Road Marking - Chapter 5, 2003) away from the first line, to cover the distance close to 150 m. An event recorder (computer programing codes, used as a stopwatch) was used to facilitate the extraction of events which were registered on a spreadsheet whenever a button was pressed on the keyboard. The data were then grouped into 5 minutes intervals (as suggested by previous researchers such as Yousif, 1993 and Al-Obaedi, 2012).

3.6.1.1 Four lanes section

For motorway sections with 4 lanes, Figure 3.5 shows the results of lane changing frequency for the M6 (J31 – J32). In this field survey, a flow ranging from around 4800 veh/hr and up to 6000 veh/hr was covered which seems limited since the low flow rates are excluded from this data. However, previous studies by Chang and Kao (1991), Al-Obaedi (2012) and Al-Jameel (2012) (which cover low to moderate flow rates for 4-lane sections) suggested that the frequency of lane changing initially increases as flow increases. Al-Jameel (2012) reported that the frequency of lane changing (for 4-lane motorway) reaches its maximum value of 1800 (lane changes/hr/km) at flow rate of 4200 veh/hr, after that, the lane changing frequency start decreasing as traffic flow keep increasing. The data was based on using camcorders from the M60 (normal motorway section, far away from merge or diverge sections).

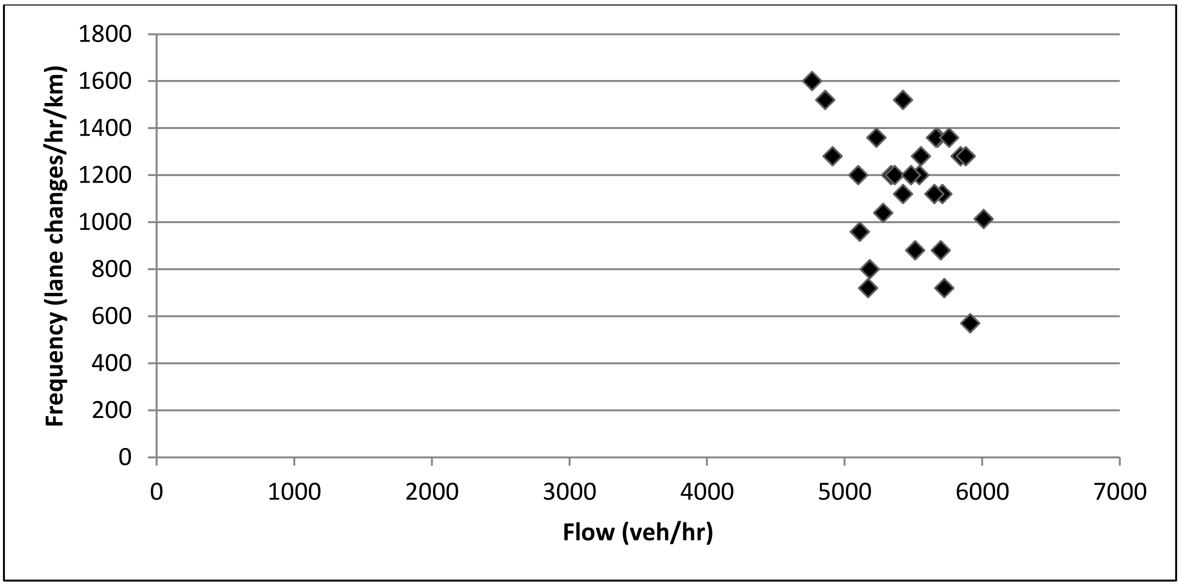


Figure 3.5: Frequency of lane changing for the M6 (4-lane motorway) (Site No. 9)

The results presented in Figure 3.5 for the current data (from the M6, Site No. 9) seem to be consistent with the findings of previous researchers such as Al-Jameel (2012) and Brackstone et al. (1998) who reported that the frequency of lane changing decreases at high traffic flow.

3.6.1.2 Three lanes section

For the M60 (J24 – J25) motorway section with 3 lanes, the available data only covered flow rates less than 3500 veh/hr. The field data suggests that, as traffic flow increases, the frequency of lane changes increases, as shown in Figure 3.6. This is consistent with the findings by Yousif (1993) who reported that the frequency of lane changing initially increases with traffic flow. However, the field data from the M60 (Site No. 8) when compared to the data observed by Yousif (1993) showed higher lane changes frequency than Yousif's data at flow rate of 3000 veh/hr. Yousif (1993) reported that at flow rate of 3000 veh/hr, the frequency of lane changing reaches its maximum value of around 1200 lane changes/hr/km. Then, the lane changing frequency starts to decrease as flow rates exceed this level.

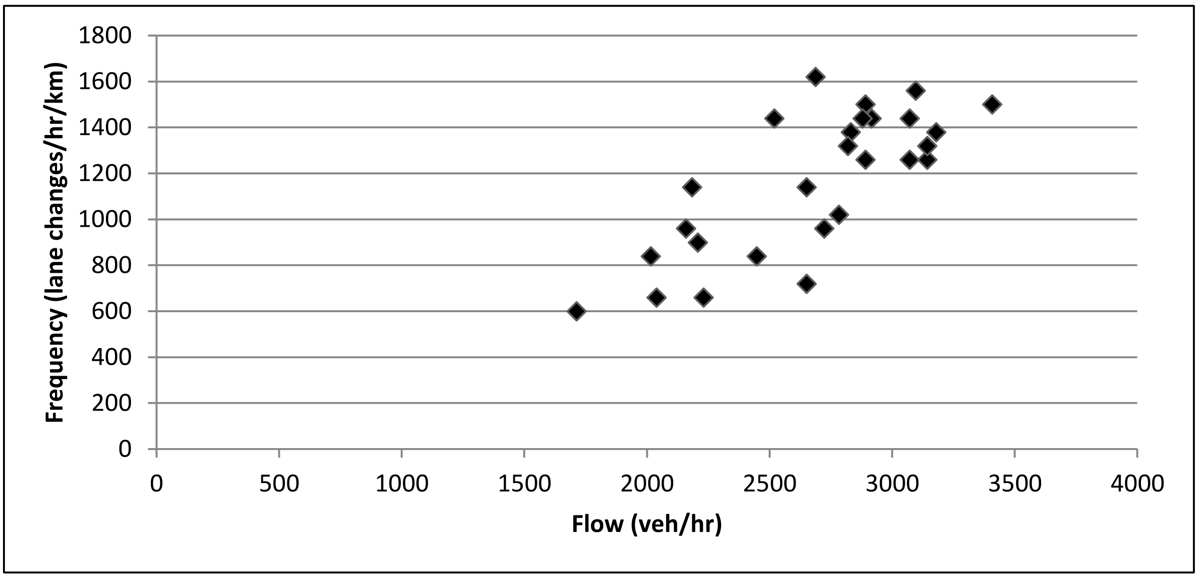


Figure 3.6: Frequency of lane changing for the M60 (3-lane motorway) (Site No. 8)

Furthermore, the field data from the M60 has also been compared with data observed by McDonald et al. (1994). However, the data by McDonald et al. (1994) very scattered, and at flow rate of 3000 veh/hr, the number of lane changes was ranging from 800 to 1600 lane changes/hr/km. In general, all data (i.e. by Yousif, 1993; by McDonald et al., 1994 and the current data from the M60 - Site No. 8) agreed that the frequency of lane changing reached a maximum at flow rate of about 3000 veh/hr. Both previous studies (i.e. Yousif, 1993 and McDonald et al., 1994) used camcorders to collect the data from normal motorway sections. Yousif (1993) collected his data from the M4, whereas McDonald et al. (1994) collected their data from the M27.

3.6.1.3 Two lanes section

Figure 3.7 shows the frequency of lane changing taken from the M602 (J2 – J3), motorway sections, (Site No. 10) with 2 lanes. For this field survey, the flow was limited to a range from around 1200 to 2700 veh/hr (i.e. low and high flow rates are excluded). The field data from the M602 is not showing a clear trend for the lane changing frequency. This could be attributed to the long queues experienced at some intervals during the survey due to the presence of a signalised junction which is located around 1400 m far away (in the downstream direction) from the site.

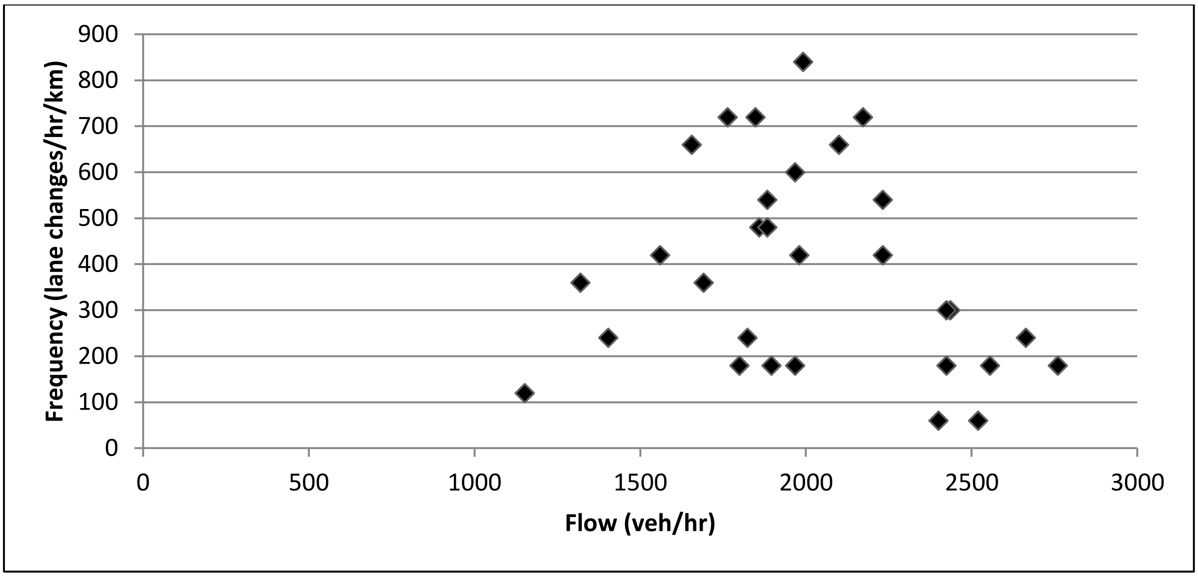


Figure 3.7: Frequency of lane changing for the M602 (2-lane motorway) (Site No. 10)

3.6.1.4 Summary

Based on these results (presented in Figures 3.7 to 3.9), it can be concluded that, the current field data from the M6 (J31 – J32), M60 (J24 – J25) and M602 (J2 – J3) are not reliable to be used in calibrating the developed micro-simulation model since they are proved to be limited. Therefore, other published data taken from previous studies will be used for this purpose (as will be discussed later in Section 7.4.2).

3.6.2 Lane changing manoeuvring time

Lane changing manoeuvring time could be defined as the time required for a vehicle to change its current lane to the adjacent lane. In this study, the manoeuvring time is measured from the instant that a vehicle starts to deviate from its current lane until the rear tyres of the vehicle cross the longitudinal marking line (as suggested by Al-Obaedi, 2012). Two video recordings were collected while travelling as a passenger to investigate this factor (see Table 3.11 for further details).

Table 3.11: Lane changing manoeuvring time field data details

Site No.	11	12
Site location	M602, M62 & M6	M602, M62, M6 & M58
Trips route	From Manchester to Birmingham	From Manchester to Southport
Date	Wednesday 17/04/2013	Wednesday 30/07/2014
Time	10:00 – 11:30	09:00 – 09:45
Data period	90 minutes	45 minutes

The analysis of data revealed that the average manoeuvring time and standard deviations for site number 11 are 3.12 and 0.66 seconds, respectively and 3.19 and 0.11 seconds, respectively for site number 12. These values are found within the reported values by previous studies (as shown in Table 3.12).

Table 3.12: Summary of previous studies for manoeuvring time

Name and reference	**Average (sec)**	**Standard deviation (sec)**
Zia (1992)	3.0	0.86
Yousif (1993)	4.2	1.05
Al-Obaedi (2012)	2.6	0.57

The above-stated results are for passenger cars only. An attempt to estimate the manoeuvring time for HGVs was achieved based on data from site number 11. The average and standard deviation of manoeuvring time for HGVs are 5.12 and 2.1 seconds, respectively. Al-Obaedi (2012) also measured the average manoeuvring time and standard deviation for HGVs and reported lower values of 4.15 seconds and 0.7 seconds. For the purpose of this study, the manoeuvring time for each vehicle (passenger car or HGV) has been generated from a normal distribution, with the statistical values obtained from site number 11, as suggested by previous studies (e.g. Yousif, 1993; Al-Jameel, 2012; and Al-Obaedi, 2012).

3.7 Traffic behaviour at roadworks

3.7.1 Accepted gaps

As mentioned in Section 2.9.3, it was found that due to the importance of the gap acceptance on merging process, there is a need for studying the minimum values of lead and lag gaps required for the lane changing process at the approaches to roadworks sections.

For the purpose of this study, three video recordings from three motorway sections (see Table 3.13) were used to investigate the gap acceptance. The selected sections were the M67

J2-J3 (roadwork section), the M61 J2-J3 (drop lane section, 2 lanes) and the M61 J2-J3 (drop lane section, 3 lanes). Drop lane sections were selected because of the similarity in drivers merging behaviour with that of roadwork sections and the unavailability of sufficient roadwork sections with a good vantage point to collect the data from. However, there are some differences between both sections which include the fact that speed limits might be different (for example, speed limits on motorway roadwork sections are likely to be reduced from 70 mph to 50 mph, whereas this reduction may not apply for drop lane sections).

Table 3.13: Gap acceptance field data details

Site No.	2	4	5
Site location	M67 (J2 – J3)	M61 (J2 – J3)	M61 (J2 – J3)
Number of lanes	2	2	3
Date	Saturday 21/06/2014	Saturday 08/11/2014	Saturday 08/11/2014
Time	11:20 – 14:55	8:45 – 11:15	8:45 – 11:15
Duration	3.5 hours	2.5 hours	2.5 hours
Type of section	Roadwork section with offside lane closure	Drop lane section with offside lane drops	Drop lane section with offside lane drops
Speed limit	50 mph	70 mph	70 mph

Vehicles' speeds and sizes of lead and lag gaps have been extracted by playing back the recorded video footages. Vehicles' speeds were calculated by drawing two screen lines (datum lines) to cover a distance of about 100 m (i.e. 11 consecutive white road markings 9 m each). The time required for a vehicle to cross this distance is then measured using an event recorder. Simple calculations of distance over time were then used to convert the readings into speeds. It is worth mentioning here that the accuracy of speed measurement depends on the measured time which may be affected by human errors (i.e. time taken to manually press a button when vehicle passes the datum line). However, an attempt to check the accuracy of speed measurement was carried out by comparing some speed readings extracted from video recordings with those obtained from a radar speed meter for the same vehicles. In general, the paired results show good agreement between speed readings from video recordings and those from the radar speed meter.

Similarly, to calculate the sizes of lead and lag gaps, many screen lines were drawn on the PC monitor to make grids along the section under study. As the lane changing (subject) vehicle starts to deviate from its current lane, the lag gap is the time required for the following vehicle in the target (adjacent) lane to reach to the position of the subject vehicle at the instant of deviation, whereas the lead gap is the time required for the subject vehicle to reach to the leading vehicle position at the instant of deviation (see Figure 2.5).

Figure 3.8 shows the relationship between relative speeds on the size of accepted lead and lag gaps for the M67, whereas Figure 3.9 shows the results of gap acceptance for the M61 (for both, 2 and 3 lane sections). Values of lead and lag gaps of less than or equal to 5 seconds were only considered in the analysis of the field data where other values (i.e. larger than 5 sec) were omitted from the analysis because they were considered so large. The dashed lines in the figures represent the minimum lead or lag gaps and suggest that the higher the speed differences, the higher the required lead/lag gaps.

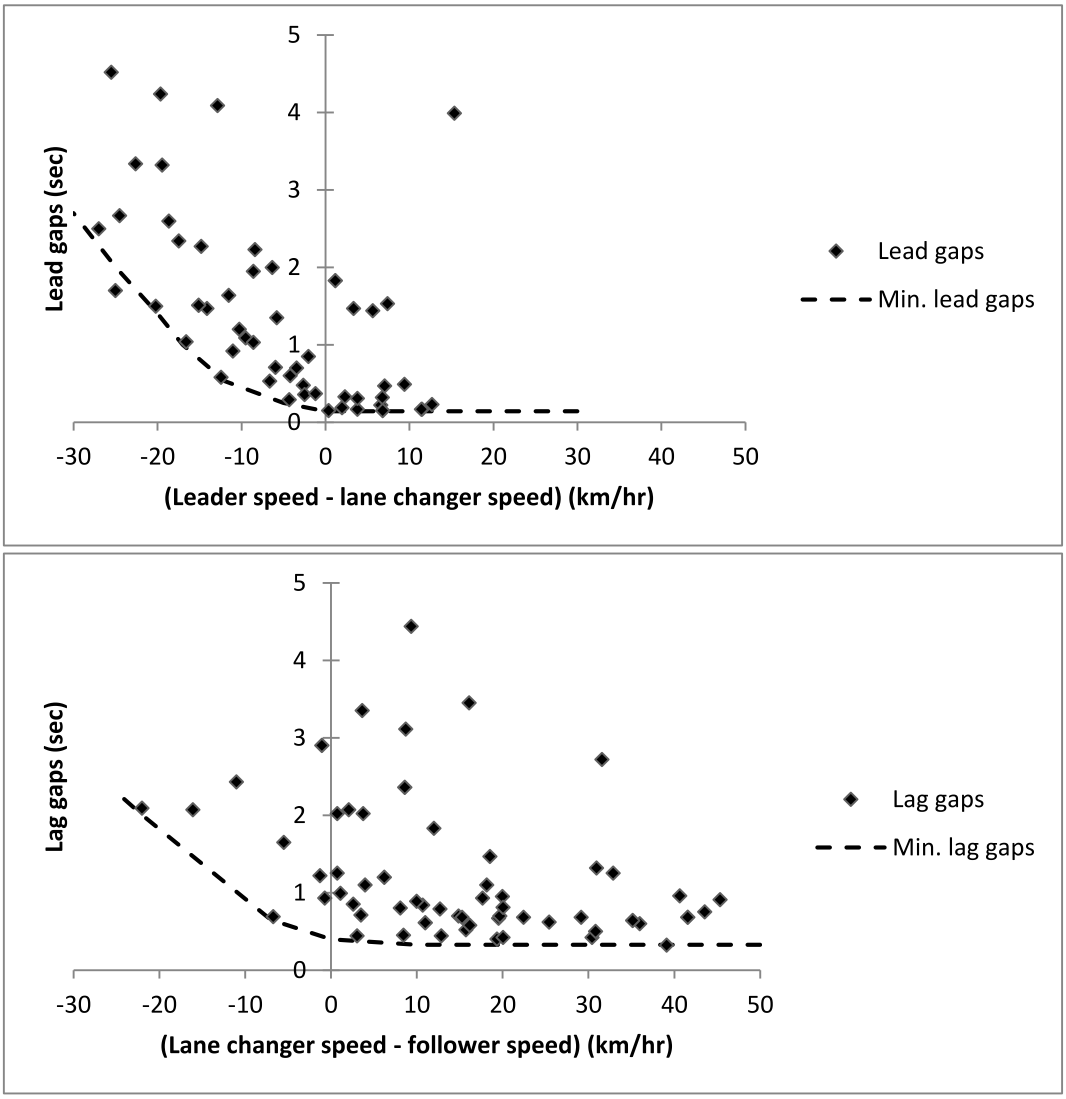


Figure 3.8: Relationship between relative speeds on the size of accepted lead and lag gaps based on data from the M67 (Site No. 2)

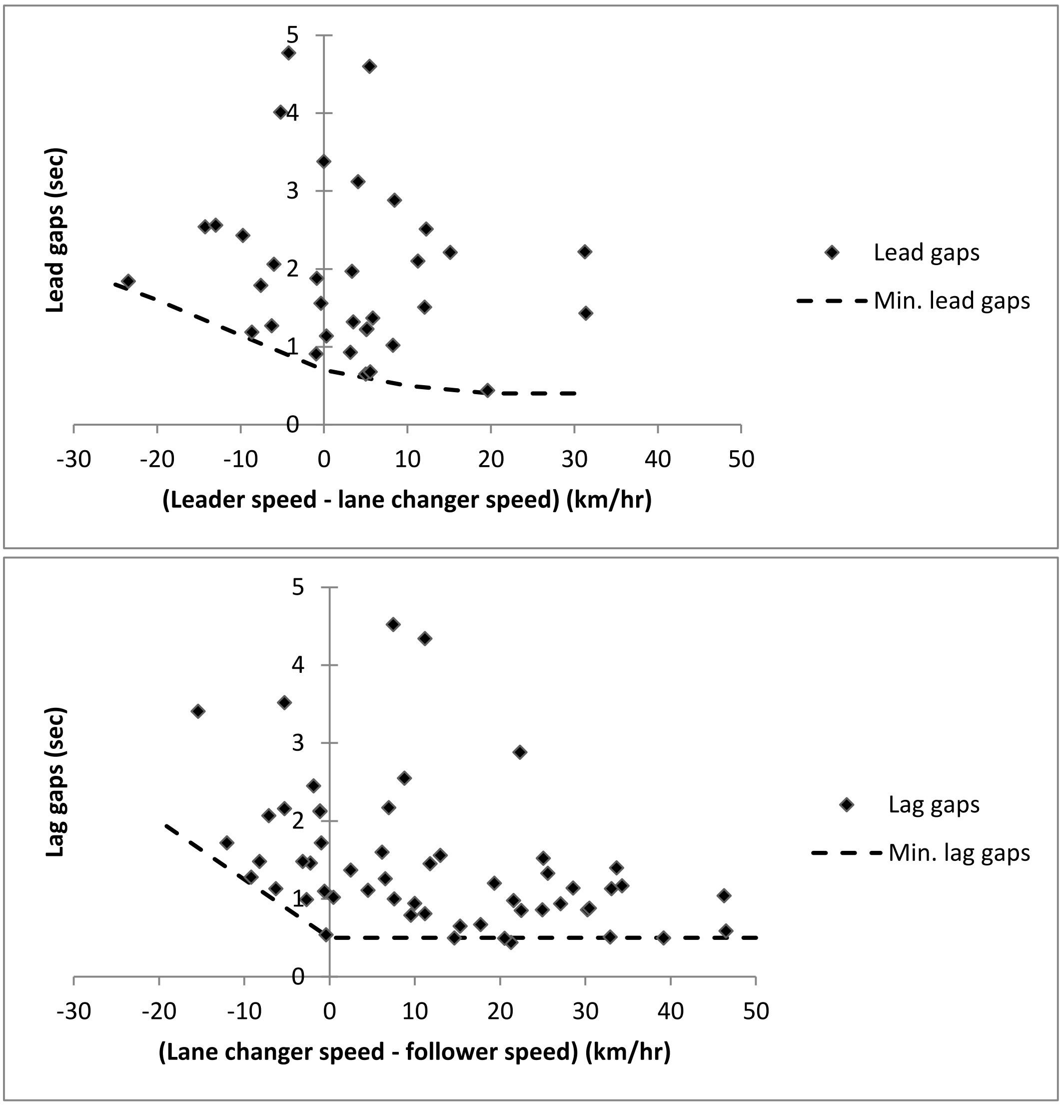


Figure 3.9: Relationship between relative speeds on the size of accepted lead and lag gaps based on data from the M61 (Site No. 4 and 5)

The minimum observed lead and lag gaps for the M67 were about 0.2 and 0.4 seconds, respectively, whereas the minimum lead and lag gaps for the M61 (both sections with 2 and 3 lanes) were about 0.4 and 0.6 seconds, respectively. The difference in the results between the M67 and the M61 could be attributed to the differences in traffic flow conditions between those sites. The flow rates for the M67 site was around 1000 veh/hr, whereas the flow rates for the M61 site were around 300 veh/hr for the 2-lane section (i.e. site no. 4) and 500 veh/hr for the 3-lane section (i.e. site no. 5). However, for the purpose of this study, the results presented in Figure 3.8 from the M67 (Site No. 2) have been used in the development of the new micro-simulation model (see Section 6.6), since the results presented in Figure 3.9 are limited to low flow conditions only.

3.7.2 Courtesy behaviour

In this study, and as discussed in Section 2.9.4, the courtesy behaviour consists of two categories. Firstly, the lag vehicle on the open lane will try to slow down to increase the lag gap available for the subject vehicle to change lane (cooperative slowing down). Secondly, cooperative yielding which occurred at the approach of the roadwork sections, when vehicles in the open lane moved (shifted) to other adjacent open lanes to give way to vehicles in the closed lane to merge.

In this study, only the cooperative slowing down was measured since the cooperative yielding is difficult to obtain accurately from the video playbacks because it is required installing camcorder(s) on overpass bridges upstream the roadwork section in order to calculate the number of lane changings cases. In addition, these cases of lane changing need to be evaluated further to determine which cases have been performed to give way for closed lane vehicles rather than enhancing driving condition.

Field data from the M67 (i.e. site number 2) and the M61 with 2 lanes section (i.e. site number 4) have been used in studying the cooperative slowing down behaviour. It is worth mentioning here that there are some limitations when obtaining such data. These limitations relate to obtaining data for only certain cases where vehicles' rear brake lights were shown and in other cases where front flashing headlights were used (which is common practice for UK drivers to give way to other drivers). For the M61 site, the camcorder was installed facing upstream the drop lane section (i.e. facing the traffic), whereas for the M67 site, the camcorder was installed upstream of the roadwork section facing traffic from behind.

Based on the M67 data, the results suggest that 12% of drivers (of the total number of lane-changing cases) are offering cooperation by slowing down. However, there might be other cases of lag vehicles' rear brake lights were applied but were not considered due to obstruction from the camcorder view caused by the presence of larger vehicles within the traffic. This would result in some underestimation of this cooperative behaviour. However, due to the fact that in some cases the subject vehicle forces the lag vehicle to slow down and to widen the gap (i.e. lag gap), this will result in some overestimation of this cooperative behaviour.

For the M61 data, the results suggest that only 4% of drivers (of the total number of lane changes) were offering cooperation with slowing down. However, there might be other cooperative slowing down cases which are not included in the analysis, since these cases may have happened without flashing the headlights. This low percentage of drivers offering courtesy could be attributed to the local traffic conditions since the M61 site is experienced low traffic condition (around 300 veh/hr) which means that there are several opportunities provided for the subject vehicle to change lanes without any interactions between the subject vehicle and the lead or lag vehicles in the target lane.

3.7.3 Compliance of drivers with speed limit at roadwork sections

As mentioned in Section 2.6.5, the compliance of drivers with the posted temporary speed limit (i.e. 50 mph) applied at motorway roadwork sections is one of the most significant factors that could enhance safety levels and traffic operation through such sections. Two video recordings from the M67 and the M1 (see Table 3.14) have been used to investigate the compliance of drivers with the applied speed limit at roadwork sections.

Table 3.14: Drivers' compliance with speed limit field data details

Site No.	1	2
Site location	M1 (J36 – J37)	M67 (J2 – J3)
Number of lanes	3	2
Date	Saturday 15/03/2014	Saturday 21/06/2014
Time	15:05 – 16:35	11:20 – 14:55
Duration	1.5 hours	3.5 hours
Type of section	Roadwork section with offside lane closure with using hard shoulder as a running lane	Roadwork section with offside lane closure
Speed limit	50 mph	50 mph

The same procedure was followed as in the previous sections to measure vehicles' speeds. Figure 3.10 shows the cumulative distribution of drivers' speeds based on data from the M67 (Site No. 2).

It can be seen from Figure 3.10 that 83% of drivers are not complying with the applied speed limit (i.e. 50 mph). This finding is consistent with Summersgill (1985) who reported that 93% of drivers did not comply and exceeded the speed limit, see Section 2.6.5. Figure 3.10 also shows that the percentage of vehicles that are travelling with speeds less than the speed limit plus 10 mph (i.e. 60 mph) is about 57%. The results obtained from the M67 field survey which presented in Figure 3.10 were used as a basis of realistic assumptions for generating drivers' desired speed at roadwork sections (as will be discussed later in Section 6.7.1).

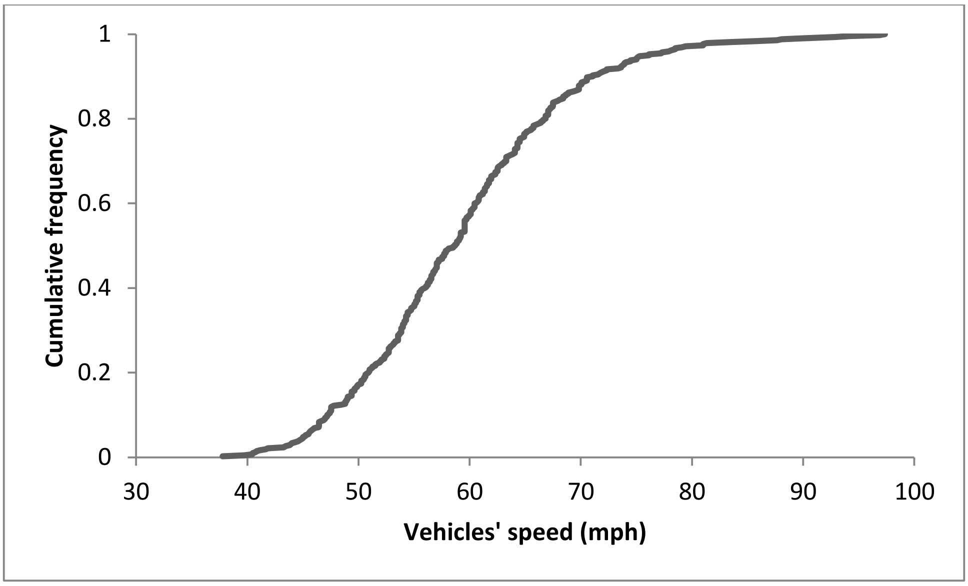


Figure 3.10: Cumulative distribution for drivers' speeds based on data from the M67 (Site No. 2)

It can be seen from Figure 3.10 that 83% of drivers are not complying with the applied speed limit (i.e. 50 mph). This finding is consistent with Summersgill (1985) who reported that 93% of drivers did not comply and exceeded the speed limit, see Section 2.6.5. Figure 3.10 also shows that the percentage of vehicles that are travelling with speeds less than the speed limit plus 10 mph (i.e. 60 mph) is about 57%. The results obtained from the M67 field survey which presented in Figure 3.10 were used as a basis of realistic assumptions for generating drivers' desired speed at roadwork sections (as will be discussed later in Section 6.7.1).

The analysis of the M1 data reveals that only 29% of drivers were observed complying with the applied speed limit. The result of drivers' compliance with speed limit from the M1 was compared with results from the previous study by Yousif (2002) based on data from motorway roadwork sections (M61). Table 3.15 shows the findings which are based on results obtained from cumulative speed distributions.

The table suggests that the drivers who are travelling on the M1 section complied with a speed limit of 50 mph more than those travelling on the M61. This could be attributed to the differences in the weather conditions and speed monitoring systems between both sites. The M1 experienced adverse weather condition, unlike the other site (i.e. the M61). In addition, Yousif (2002) reported that the absence of any speed enforcement devices on the M61 site reflects the poor level of compliance with the speed limit, whereas many speed cameras have been noticed along the M1 site. The table also suggests that the level of compliance with the speed limit for faster lane drivers is lower than that for slower lane, for both current (i.e. M1) and previous (i.e. M61) study. These differences in the levels of compliance between lanes could be attributed to the fact that HGVs and other "slower" moving vehicles are mainly travelling on the slower lane.

Table 3.15: Compliance of drivers with speed limits applied at motorway roadwork sections

Data	Current field data (M1)*			Published data (Yousif, 2002) (M61)**	
Lane no.	Hard shoulder	1	2	1	2
% of drivers travelling with speed below speed limit (i.e. 50 mph)	52%	28%	8%	23%	11%
% of drivers travelling with speed below speed limit + 10 mph (i.e. 60 mph)	99%	97%	80%	84%	63%

*: The M1 site is a 3-lane motorway with offside lane closure (3 lanes open, including the hard shoulder as a running lane).

**: The M61 site was also 3-lane motorway section with offside lane closure (2 lanes open).

3.8 Summary

This chapter presented the analysis of data which is collected from different motorway sites with normal and roadwork sections. The main findings of the chapter can be summarised as follows:

- Video recordings and IVD data taken from normal motorway sections with 3 lanes have been used to fit some headway distribution models (as discussed in Section 3.4). It was found that the shifted negative exponential distribution acceptably replicates the field data for different flow rates. Therefore, the shifted negative exponential distribution has been used in this study.
- IVD data (3 complete days) taken from 3 lanes normal motorway section has been used in testing different lane utilisation models which were proposed by previous studies. The results suggest that the models suggested by Yousif et al. (2013a) represent the most appropriate models among the other tested models in replicating the field data. Therefore, the models by Yousif et al. (2013a) have been used in this study (see Section 3.5).
- Lane changing frequency and manoeuvring time have been estimated based on video recordings taken from normal motorway sections with 2, 3 and 4 lanes (see Section 3.6).

The collected data used in estimating the lane changing frequency proved to be limited, therefore other published data taken from previous studies are used for the purpose of this study (see Section 3.6.1). The average manoeuvring time was found to be around 3 seconds for passenger cars and around 5 seconds for HGVs (see Section 3.6.1).

- Some video recordings taken from motorway roadwork sites in the UK have been used to study traffic behaviour at roadwork sections. This includes estimating gap acceptance values (the results showed that the minimum observed lead and lag gaps for the M67 site were about 0.2 and 0.4 seconds, respectively, see Section 3.7.1); studying drivers' courtesy behaviour (the results showed that 12% of drivers are offering cooperation by slowing down, see Section 3.7.2); and testing the compliance of drivers with the temporary speed limit applied at roadwork sections (the results showed that 83% of drivers are not complying with the applied speed limit, see Section 3.7.3).
- Traffic behaviour at motorway roadwork sections with the use of narrow lanes scheme is also studied based on some video recordings taken from motorway roadwork sections. The field observations revealed that there is some turbulence in the behaviour (as will be discussed in the following chapter).
- Limitations of this chapter include difficulties of acquiring the needed data from motorway roadwork sections (as discussed in Section 3.3) which could affect the accuracy of results. For example, the minimum accepted gaps and the courtesy behaviour factors (see Sections 3.7.1 and 3.7.2) have been studied based on limited data since the heavy flow conditions are excluded from the available data (i.e. M67 and M61). Therefore, field data from motorway roadworks with heavy flow rates are needed to fully evaluate the effects of these factors. Also, the accuracy of the results could be influenced by the shortage of observed section length from the video footage and the methodology used in analysing the data.

CHAPTER FOUR
INVESTIGATION OF DRIVING BEHAVIOURS AT MOTORWAY ROADWORKS WITH NARROW LANES

4.1 Introduction

As mentioned in Sections 1.1 and 2.2.2, the implementation of narrow lanes as a temporary traffic management scheme (TTMS) on UK motorway roadwork sections has been frequently used. The rationale is to free up carriageway space, especially for sites with high traffic demands needing repairs. What remains to be determined is the impact of this work on driving behaviours. This is important due to the need to manage traffic operational turbulence which could affect the capacity and safety levels in roadwork sections. Using camcorders from overhead bridges, observations were made which uncovered two discernible patterns of driving behaviour where narrow lanes are implemented at roadworks, especially when heavy goods vehicles (HGVs) are present: (i) “avoiding” passing/overtaking HGVs travelling in the adjacent lanes and (ii) lane “repositioning” while passing/overtaking. The aim of this chapter is to report on the “avoiding” and lane “repositioning” behaviours to inform the assumptions made in the development of the new micro-simulation model and also to help make recommendations to those using narrow lanes as a TTMS and make them aware of these behaviours (especially on motorway sections carrying high percentages of HGVs).

4.2 Site layout of roadworks with narrow lanes

Figure 4.1 illustrates a typical site layout of motorway roadworks operated by narrowing lanes scheme. As mentioned in Section 2.3, most TTMSs are divided into four zones, namely, the advance warning zone, the transition zone, the activity zone, and the termination zone (MUTCD, 2009).

According to the Traffic Signs Manual (Chapter 8, 2009), the lane width may be reduced from the standard motorway lane width of 3.65 metres to 3.25 metres (desirable minimum) when heavy vehicles are expected, and to an absolute minimum of 3.0 metres where there is a shortage of space. However, the maximum width of lorries on UK roads is 2.55 metres (excluding driving mirrors) and 2.60 metres are permitted for refrigerated vehicles to allow for the extra thickness of the insulation (Regulations 1986 – SI 1986/1078, Butcher, 2009). Also, the widths of buses are found to be 2.55 metres which are obtained from manufacturers' specifications, such as Volvo Buses and the Caetano Levante coaches operated by National Express, whereas typical widths of the larger types of passenger cars are found to be around 2.25 metres which are taken from manufacturers' specifications such as Mercedes-Benz and BMW.

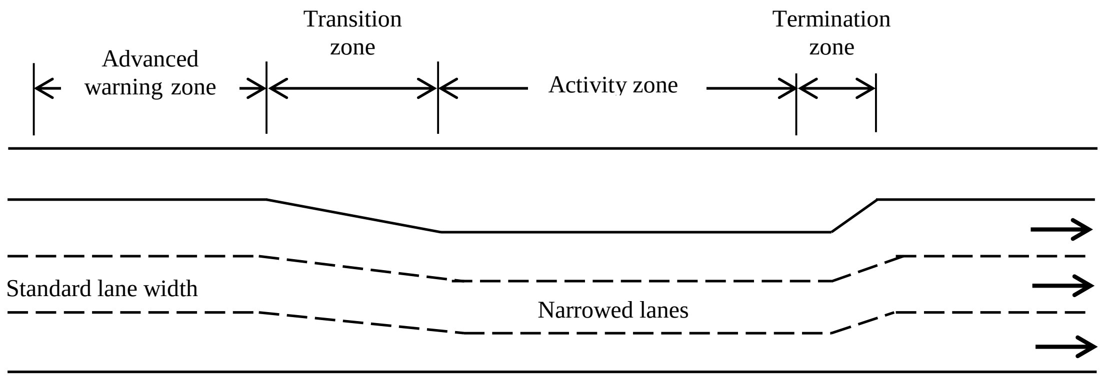


Figure 4.1: Illustration of motorway roadwork site layout operated by narrowing lanes

The Traffic Signs Manual (Chapter 8, 2009) reported that drivers' concentration level is raised when they drive on narrow lanes and this should be taken into consideration when determining the length of the TTMS. Therefore, a 4 km have been suggested as a maximum length of the narrow lanes for roadwork sites, except where otherwise agreed with the Highway Authority.

4.3 Data collection

For the purpose of evaluating and studying the traffic behaviour of UK motorway roadwork with narrow lanes sections, field data (using camcorders) taken from two typical motorway roadwork sites with narrowing lanes has been used. The first site was the M6 motorway northbound between Junctions 31 and 32 (around three and a half hours of video footage were recorded from 11:40 to 15:20 on Sunday, the 31st of August 2014). The second site was the M62 in both directions between Junctions 18 and 19 (two hours of video footage from 11:30 a.m. to 13:30 for each direction was recorded on Sunday, the 15th of March, 2015). For both sites, a speed limit of 50 mph (80 km/hr) was imposed. Table 4.1 illustrates the details of site locations and gives a general description of each site conditions.

Table 4.1: Summary of the selected sites details

Data set No.	1	2	3	4	5
Site No.	3	6	7	8	17
Site location	M6 (J31 – J32)	M62 (J18 – J19)	M62 (J18 – J19)	M60 (J24 – J25)	M60 (J16 – J17)
Traffic direction	Northbound	Eastbound	Westbound	Northbound	Eastbound
Number of lanes	4 lanes	3 lanes	3 lanes	3 lanes	4 lanes
Date	Sunday 31/08/2014	Sunday 15/03/2015	Sunday 15/03/2015	Saturday 16/08/2014	Wednesday 31/07/1996
Time	11:40 – 15:17	11:30 – 13:30	11:30 – 13:30	09:30 – 10:30	15:10 – 15:40
Duration	3.5 hours	2 hours	2 hours	1 hour	½ hour
Type of section	Roadwork section with narrow lanes	Roadwork section with narrow lanes	Roadwork section with narrow lanes	Normal roadway section	Normal roadway section
Speed limit	50 mph	50 mph	50 mph	70 mph	70 mph

The M6 motorway site consists of 4 lanes with narrow lanes applied as a TTMS. The hard shoulder and part of lane 1 were closed for roadworks. The widths of lanes were reduced from 3.65⁝3.65⁝3.65⁝3.65 metres (i.e. the normal standard motorway lane widths) to about 3.25⁝3.00⁝3.00⁝3.00 metres for lanes 1, 2, 3 and 4, respectively. The length of the observed section covered by the camcorder is about 200 m showing traffic movements from before the start of the transition section and also through the activity zone (as shown in Figure 4.2). The camcorders were placed on a footbridge which was located about 1 mile before Junction 32.

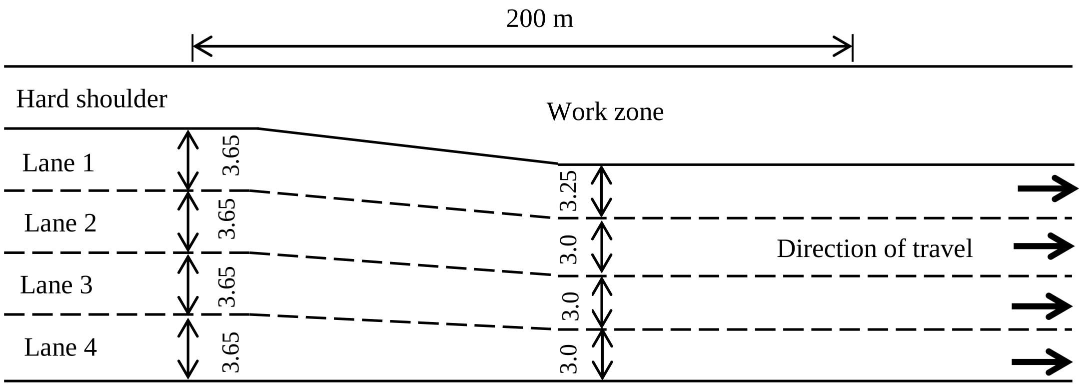


Figure 4.2: Schematic layout of the M6 roadwork site

The M62 motorway site consists of 3 lanes with narrowing lanes applied as a TTMS which extends for about 5 miles starting from Junction 18 and up to Junction 20. The camcorder was placed on an overbridge which was located about 1 mile after Junction 18. The length of the observed section covered by the camcorder is also about 200 m. The hard shoulder and part of lane 1 were also closed for roadworks (as shown in Figure 4.3). Metal barriers were used for this site, whereas plastic cones were used for the M6 site. The widths of lanes were reduced to about 3.25⁝3.00⁝3.00 metres for lanes 1, 2 and 3, respectively.

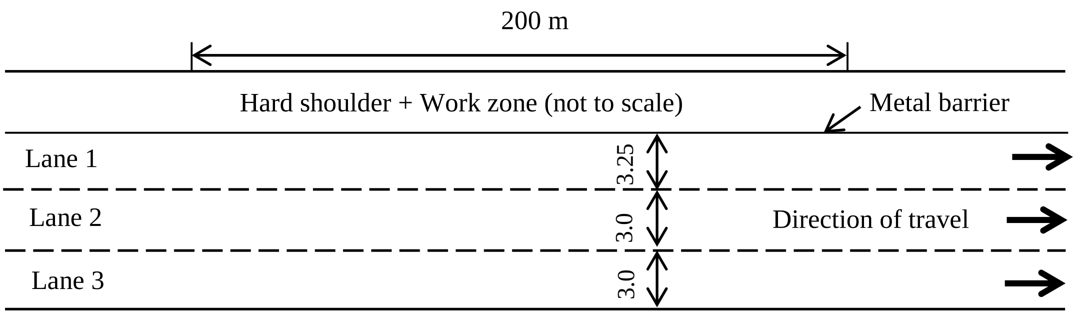


Figure 4.3: Schematic layout of the M62 roadwork site

In addition, two other video recordings from normal roadway sections (i.e. with standard lane width) were taken from the M60 (J24 – J25) and the M60 (J16 – J17, historic data) were used for comparison purposes with data from the narrowing lanes.

4.4 Data analysis

4.4.1 Avoiding behaviour when passing/overtaking HGVs

Field data from narrowing lanes sites showed a relatively high number of observations of passenger car drivers following a HGV travelling on adjacent lanes, avoid passing the HGV even when their lane is clear from vehicles. The number of "avoiders" was calculated by counting the number of drivers who could have the opportunity to pass (or overtake) the HGV but preferred to decelerate or adjust their speed to keep following the HGV rather than passing it (see vehicles "C1" and "C2" in Figure 4.4). It should be noted that the unfamiliarity of drivers with the roadworks layout (i.e. narrow lanes) could be one of the causes of traffic turbulence. However, there was no knowledge of the degree of drivers' familiarity with the road sections chosen for this study.

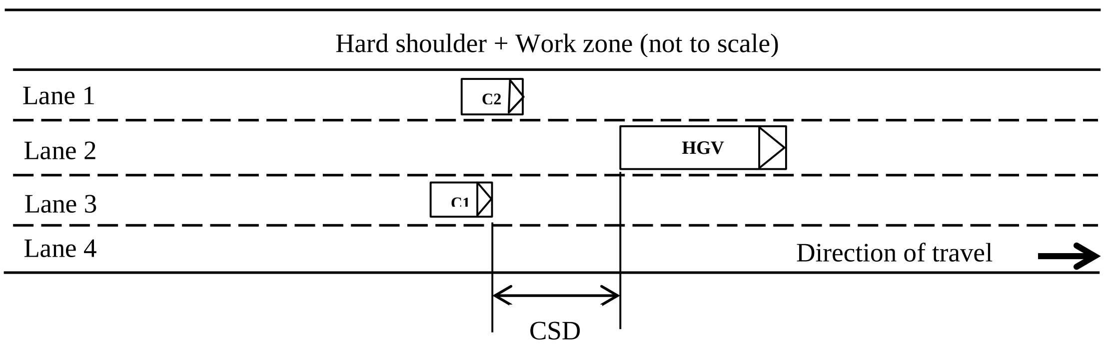


Figure 4.4: Vehicles' positions on motorway sections with narrow lanes ("avoiding" case)

4.4.1.1 Analysing method

The methodology that has been used for this analysis was; firstly, locating a HGV and its following vehicle (Fveh) (i.e. C1 or C2 vehicles) on the adjacent lanes. A distance of 45 metres, which is equivalent to 5 consecutive white road markings (i.e. 9 m each, based on the Traffic Signs Manual, Chapter 5, 2003), has been adopted as a critical value of clear spacing distance (CSD) between the rear of the HGV and the front of its following vehicle on adjacent lanes. This selected CSD distance (i.e. 45 metres) is roughly equal to a time headway of 2 seconds for a 50 mph speed limit. A higher value may affect the accuracy of results due to the shortage of observed section length from the video footage. The criterion for this methodology is shown in the flowchart as illustrated in Figure 4.5.

The path of the Fveh was then traced to see if the Fveh passed the leading HGV within the observed section (i.e. 200 m), and if so, this case was considered as an overtaking case (see vehicle "C3" in Figure 4.6). If not, an evaluation for the speed of the Fveh was then carried out to see if the Fveh was slowing down to avoid passing the HGV while travelling through the observed section. The latter were considered as part of the avoiding sample of cases (as shown in Figure 4.4, vehicles "C1" and "C2"). The slowing down of vehicle Fveh can be judged from tracing the relative distance between the HGV and that Fveh from the start of the observed section (i.e. 200 m) and when approaching from behind the HGV to see if the Fveh is getting closer and starting to decelerate. Also, in some cases, there were cars following the HGV on the same lane (with approximately the same speed of that HGV) while a Fveh overtaking/passing all of these cars and then decelerate when getting closer to the HGV travelling on the adjacent lane (see vehicle "C9" in Figure 4.7).

For cases where the speed of HGV is equal or higher than the speed of Fveh, such cases were ignored from the analysis. However, the accuracy of the results could be influenced by the methodology used in analysing the data and also the evaluation process of the Fveh speed since this evaluation is mainly dependent on the observer judgment.

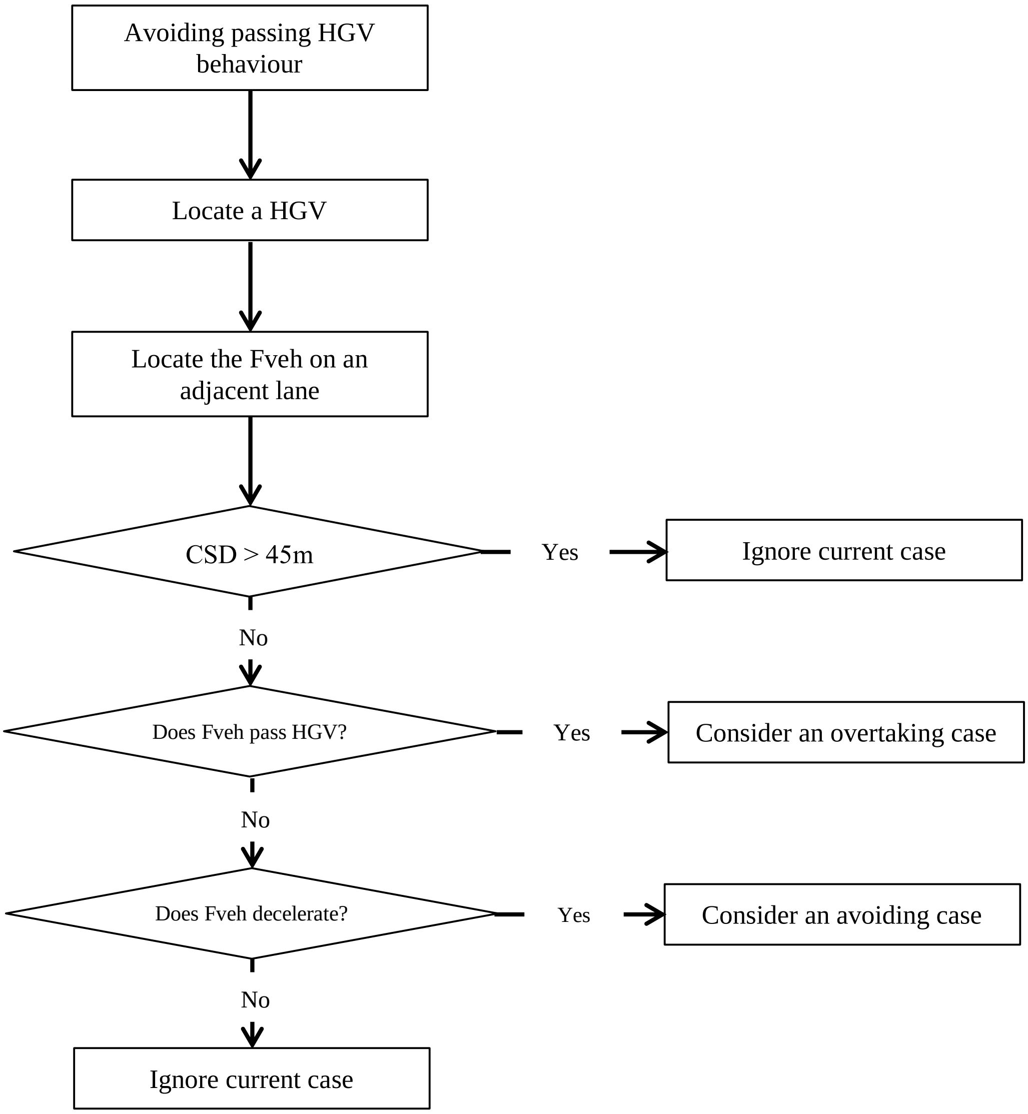


Figure 4.5: Method of estimating avoiding passing HGV

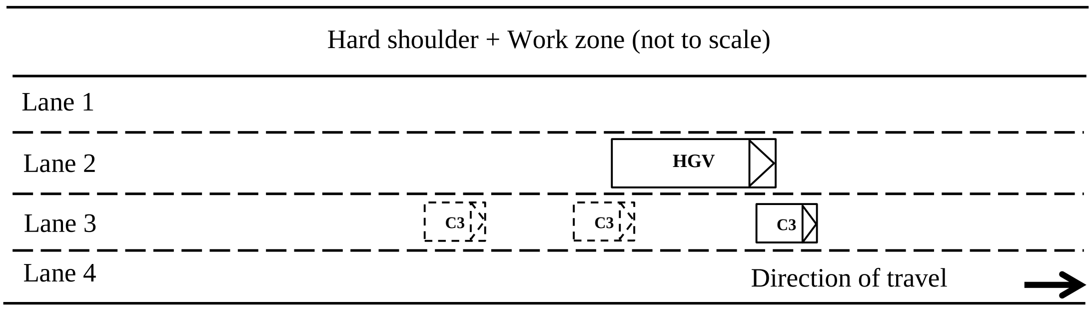


Figure 4.6: Vehicles' positions on narrow lanes motorway section ("overtaking" case)

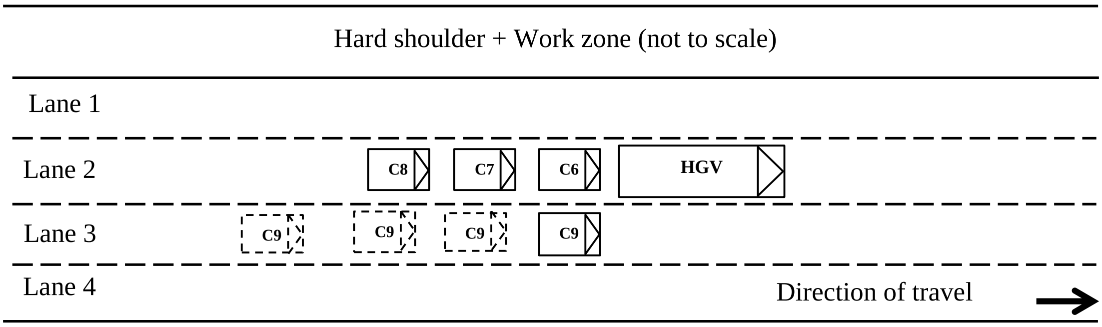


Figure 4.7: Vehicles' positions (slowing down illustration)

4.4.1.2 Results and discussion

Data consisting of 165 cases over a period of 220 minutes from the M6 site (i.e. data set 1) was analysed. The results revealed that about 47% of passenger car drivers who were following a HGV on the adjacent lanes were observed to be "avoiding" passing the HGV. Table 4.2 summarises the numbers of HGVs, numbers of avoiders and passers, as well as the avoiders' percentage for each lane of the M6. The percentage of avoiding behaviour was measured by comparing the calculated number of "avoiders" (i.e. "C1" and "C2") to the total number of passenger car drivers which consisted of normal cases of passing HGVs (i.e. "C3") plus those avoiding ones. The avoiding behaviour percentage was calculated for each lane as well as for all lanes.

Table 4.2: Summary of "avoiding" observations for each lane of the M6 (data set 1)

Lane 1 cases			
	Left lane	Lane 1	Right lane (L2)
No. of HGVs		30	
No. of avoiders	--		9
No. of passers	--		21
Total	--		30
Avoiders %	--		30%
Lane 2 cases			
	Left lane (L1)	Lane 2	Right lane (L3)
No. of HGVs		15	
No. of avoiders	1		4
No. of passers	9		10
Total	10		14
Avoiders %	10%		29%
Lane 3 cases			
	Left lane (L2)	Lane 3	Right lane (L4)
No. of HGVs		120	
No. of avoiders	53		32
No. of passers	29		43
Total	82		75
Avoiders %	65%		43%
Overall percentage of avoiders = 47%			

This behaviour of avoiding passing HGVs could be attributed to the insufficient lateral separation between the HGVs and other vehicles due to the narrow lanes which made drivers feel uncomfortable/unsafe to overtake in such situations. Therefore, they seem to prefer to stay in their lanes travelling behind the HGV vehicles which are positioned in their adjacent lanes rather than passing them (sometimes until crossing the whole roadwork section and where the lanes regain their normal width). The percentage of "avoiders" of those drivers could be considered high. This might affect the capacity of the roadwork section which confirms the suggestion by Marlow et al. (1992) that the operational capacity of single narrow lanes with widths less than 3 m is lower than the lane capacity at conventional roadworks.

Tables 4.3 and 4.4 summarise the numbers of HGVs, numbers of avoiders and passers, as well as the avoiders' percentage for each lane as well as for all lanes for both, data sets 2 and 3, respectively. The results for data set 2 presented in Table 4.3 show good agreement with the results in Table 4.4 (i.e. for data set 3). It can be seen from Tables 4.3 and 4.4 that the overall avoiders percentage has decreased when compared with Table 4.2. This could be attributed to the difference in the road layout between the M6 and the M62 sites. The observed section for the M62 site was located at least after 1 mile from the start of the activity zone (i.e. starting of implementing the narrow lanes) for data set 2 and after about 3.5 miles for data set 3. For the observed section of the M6 site, this covered the movements of vehicles from before the start of the transition zone and also through the activity zone, as shown in Figure 4.2. Therefore, it is believed that the drivers who were travelling on the M62 (for both directions) were more familiar (and therefore more alert) with the presence of narrow lanes than those who were driving on the M6. This may explain the reasons for observing the M62 drivers to be perform more overtaking/passing of the HGVs than those for the M6.

It can be seen from Tables 4.3, 4.4 and 4.5 that there is a noticeable difference (around 80%) in the values of lane 1 avoiders' percentage between the M6 site (i.e. data set 1) and the M62 site (i.e. data sets 2 and 3). A value of 10% has been measured as avoiders' percentage in lane 1 for data set 1, whereas 75% and 100% were measured for data sets 2 and 3 respectively. It should be noted that both sites had similar lane widths of 3.25 m for lane 1, but for the M62 site (as shown in Figure 4.3), a metal barrier was used, whereas plastic cones were used for the M6 site. It may be assumed that the presence of the metal barrier constrains the movements of drivers and make them avoid passing the HGV on the adjacent lane. However, the sample sizes available are relatively small and further data may be required to validate this assumption.

Table 4.3: Summary of "avoiding" observations for each lane of the M62 (data set 2)

Lane 1 cases			
	Left lane	Lane 1	Right lane (L2)
No. of HGVs		58	
No. of avoiders	--		12
No. of passers	--		46
Total	--		58
Avoiders%	--		21%
Lane 2 cases			
	Left lane (L1)	Lane 2	Right lane (L3)
No. of HGVs		33	
No. of avoiders	6		13
No. of passers	2		16
Total	8		29
Avoiders%	75%		45%
Overall percentage of avoiders = 33%			

Table 4.4: Summary of "avoiding" observations for each lane of the M62 (data set 3)

Lane 1 cases			
	Left lane	Lane 1	Right lane (L2)
No. of HGVs		58	
No. of avoiders	--		17
No. of passers	--		41
Total	--		58
Avoiders%	--		29%
Lane 2 cases			
	Left lane (L1)	Lane 2	Right lane (L3)
No. of HGVs		20	
No. of avoiders	1*		7
No. of passers	0*		12
Total	1*		19
Avoiders%	100%*		37%
Overall percentage of avoiders = 32%			

*****Sample size is too small (which might have affected the results).

Similar methodology of data analysis on narrowing lanes has been adopted on sites with normal lane width (i.e. the M60, between J24 and J25, and the M60 between J16 and J17). Table 4.5 summarises the values of avoiding percentage for all sites. It can be seen from this table that the passenger cars avoiding the passing of HGVs has not been observed on normal lane width sections.

Table 4.5: Summary of "avoiding" behaviour for all sites

Site location	Data set No.	Number of observed cases	Duration (minutes)	Overall avoiding (%)
M6 (J31 – J32)	1	165	220	47
M62 (J18 – J19)	2	91	120	33
M62 (J18 – J19)	3	78	120	32
M60 (J24 – J25)	4	28	60	0
M60 (J16 – J17)	5	94	30	0

4.4.2 Lane repositioning before passing HGVs behaviour

Another observation from the narrow lane sections is the lane repositioning of some drivers when approaching from behind a HGV in the adjacent lane. Some drivers were observed overtaking the HGV by driving as far away from the HGV to widen the lateral distance between their vehicles and the HGV and too close to the road marking of their current lane away from the HGV (see vehicle "C5" in Figure 4.8).

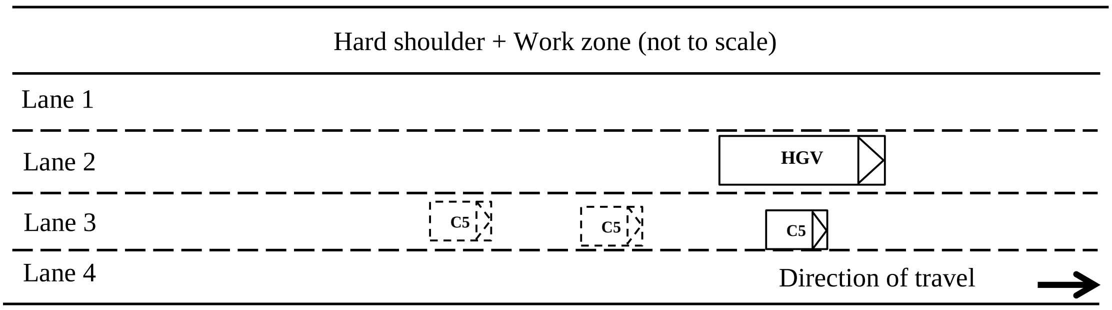


Figure 4.8: Vehicles' positions on motorway section with narrow lanes ("repositioning" behaviour)

Table 4.6 summarises the numbers of HGVs, numbers of lane repositioning and those driving in the centre of the lane (i.e. mid-lane drivers), as well as the percentage of lane repositioning drivers for each lane and for all lanes of the M6. The same lane repositioning behaviour has been noticed for drivers who were following wide vans and caravans. These cases were also analysed and reported on in Table 4.7.

It can be seen from Tables 4.6 and 4.7 that there is some consistency in the results. Also, it can be seen from the Tables that the offside lane (i.e. lane 4) and lane 3 have very high percentages of lane "repositioning". This could be attributed to the relatively high speed of drivers who were driving on lanes 3 and 4 compared to those who were driving on lane 1 and 2. It can also be seen from both Tables that the lane "repositioning" percentage for the inside lane (i.e. lane 1) is equal to zero. This is because the inside lane has a width equal to 3.25 m, whereas the width of other lanes is equal to 3.0 m (as shown in Figure 4.2).

Table 4.6: Summary of lane "repositioning" before passing HGVs observations for the M6 (data set 1)

Lane 1 cases			
	Left lane	Lane 1	Right lane (L2)
No. of HGVs		35	
No. of lane repositioning drivers	--		20
No. of mid-lane drivers	--		15
Total	--		35
Lane repositioning%	--		57%
Lane 2 cases			
	Left lane (L1)	Lane 2	Right lane (L3)
No. of HGVs		10	
No. of lane repositioning drivers	0		7
No. of mid-lane drivers	3		0
Total	3		7
Lane repositioning%	0%		100%
Lane 3 cases			
	Left lane (L2)	Lane 3	Right lane (L4)
No. of HGVs		62	
No. of lane repositioning drivers	2		55
No. of mid-lane drivers	6		3
Total	8		58
Lane repositioning%	25%		95%
Overall percentage of lane repositioning drivers = 76%			

Table 4.7: Summary of lane "repositioning" before passing vans for the M6 (data set 1)

Lane 1 cases			
	Left lane	Lane 1	Right lane (L2)
No. of vans		64	
No. of lane repositioning drivers	--		40
No. of mid-lane drivers	--		24
Total	--		64
Lane repositioning%	--		63%
Lane 2 cases			
	Left lane (L1)	Lane 2	Right lane (L3)
No. of vans		23	
No. of normal drivers			
No. of lane repositioning drivers	0		17
No. of mid-lane drivers	10		1
Total	10		18
Lane repositioning%	0%		94%
Lane 3 cases			
	Left lane (L2)	Lane 3	Right lane (L4)
No. of vans		10	
No. of lane repositioning drivers	1		7
No. of mid-lane drivers	5		0
Total	6		7
Lane repositioning%	17%		100%
Overall percentage of lane repositioning drivers = 62%			

Table 4.8 and 4.9 summarise the numbers of HGVs, numbers of lane "repositioning" of drivers, as well as their percentages for each lane and for all lanes for data sets 2 and 3, respectively, whereas Tables 4.10 and 4.11 show the summary of the lane "repositioning" behaviour of drivers who were following vans for data sets 2 and 3, respectively.

Table 4.8: Summary of lane "repositioning" before passing HGVs for data set 2

Lane 1 cases			
	Left lane	Lane 1	Right lane (L2)
No. of HGVs		45	
No. of lane repositioning drivers	--		42
No. of mid-lane drivers	--		3
Total	--		45
Lane repositioning%	--		93%
Lane 2 cases			
	Left lane (L1)	Lane 2	Right lane (L3)
No. of HGVs		16	
No. of lane repositioning drivers	0		15
No. of mid-lane drivers	2		0
Total	2		15
Lane repositioning%	0%		100%
Overall percentage of lane repositioning drivers = 92%			

Table 4.9: Summary of lane "repositioning" before passing HGVs for data set 3

Lane 1 cases			
	Left lane	Lane 1	Right lane (L2)
No. of HGVs		40	
No. of lane repositioning drivers	--		31
No. of mid-lane drivers	--		9
Total	--		40
Lane repositioning%	--		78%
Lane 2 cases			
	Left lane (L1)	Lane 2	Right lane (L3)
No. of HGVs		12	
No. of lane repositioning drivers	0		11
No. of mid-lane drivers	0		1
Total	0		12
Lane repositioning%	--		92%
Overall percentage of lane repositioning drivers = 81%			

It can be seen from Tables 4.8 to 4.11 that the results seem to be consistent. In addition, the results in these Tables are in agreement with those reported in Tables 4.6 and 4.7. For comparison purposes, field data taken from normal lane width (i.e. 3.65 m) sections was used to investigate the lane "repositioning" behaviour of drivers affected by the presence of HGVs and vans. The analysis of normal lane data shows very little percentage of lane "repositioning" behaviour. Figure 4.9 shows the comparison between all data sets for the lane "repositioning" behaviour. Results of the lane "repositioning" behaviour for the presence of HGVs and vans were then combined for all the selected sites for comparison purposes as there were no significant differences between the results (as shown in Table 4.12).

Table 4.10: Summary of lane "repositioning" before passing vans for data set 2

Lane 1 cases			
	Left lane	Lane 1	Right lane (L2)
No. of vans		42	
No. of lane repositioning drivers	--		30
No. of mid-lane drivers	--		12
Total	--		42
Lane repositioning%	--		71%
Lane 2 cases			
	Left lane (L1)	Lane 2	Right lane (L3)
No. of vans		10	
No. of lane repositioning drivers	0		7
No. of mid-lane drivers	3		1
Total	3		8
Lane repositioning%	0%		88%
Overall percentage of lane repositioning drivers = 70%			

Table 4.11: Summary of lane "repositioning" before passing vans for data set 3

Lane 1 cases			
	Left lane	Lane 1	Right lane (L2)
No. of vans		20	
No. of lane repositioning drivers	--		16
No. of mid-lane drivers	--		4
Total	--		20
Lane repositioning%	--		80%
Lane 2 cases			
	Left lane (L1)	Lane 2	Right lane (L3)
No. of vans		4	
No. of lane repositioning drivers	0		3
No. of mid-lane drivers	0		1
Total	0		4
Lane repositioning%	--		75%
Overall percentage of lane repositioning drivers = 79%			

Table 4.12: Summary of lane "repositioning" percentage for all sites

Site location	Data set No.	Number of observed cases	Duration	Lane Repositioning %
M6 (J31 – J32)	1	204	220 minutes	69%
M62 (J18 – J19)	2	113	120 minutes	82%
M62 (J18 – J19)	3	76	120 minutes	80%
M60 (J24 – J25)	4	44	60 minutes	13%
M60 (J16 – J17)	5	94	30 minutes	12%

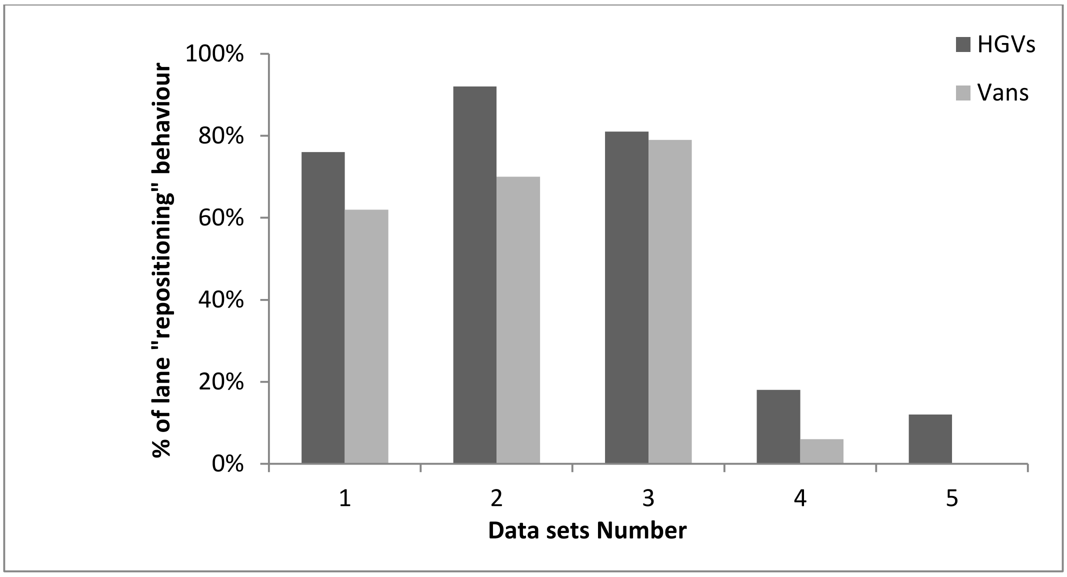


Figure 4.9: Percentage of lane “repositioning” behaviour for the presence of HGVs and vans for each data set

It should be noted here that there may be other factors affecting drivers’ repositioning of themselves on the road. Several studies looked at the effect of driving on a curvature and how narrow lane widths affect the positioning of the vehicle (see for example, Charlton et al. 2014 and Coutton-Jean et al., 2009) and lane keeping affected by the emotional behaviour of drivers due to nervousness and concentration deficits (see for example, Jeon et al., 2014). Other studies, such as Cao et al. (2015), suggest that experienced drivers tend to have better lateral control performance (i.e. lane keeping) when compared with others. This could be due to their ability to process nearby lane markings peripherally in order to stay in position compared to novice drivers (Alberti et al., 2014). Most of these studies were conducted on controlled experimental basis (such as using simulation, questionnaire surveys, controlled sites …etc.). However, based on the data collection method used in the current study, it was not possible to distinguish between, for example, the type of drivers (experience vs. novice), assessing their emotions or in controlling the environment that they were driving through since these factors are beyond the scope of this study.

4.4.3 Other observed behaviours

Other behaviours have also been observed; such as some drivers were observed to prefer staying in the same lane driving behind a HGV and following it with a gap even if they have the opportunity to overtake (see vehicle “C4”, Figure 4.10). Another observation from the narrow lane sections is the hesitation of some drivers when approaching from behind a HGV in the adjacent lane. They were observed to wait a while behind the HGV to assess the situation before speeding up and passing that HGV. However, both cases were not included in the analysis due to the shortage of observed section length from the video footage which could not provide a full view of these behaviours.

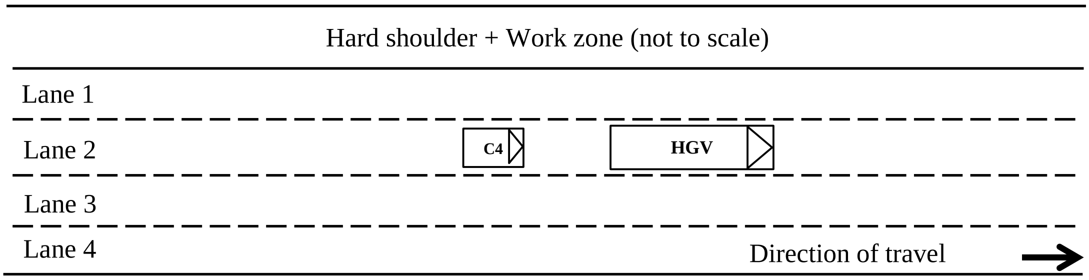


Figure 4.10: Vehicles' positions (keep following a HGV on the same lane)

4.5 Summary

The most important findings of this chapter can be summarised as follows:

- There is a lack of research in studying motorway roadworks operated by using narrowing lanes.
- Field observations (using video recordings) taken from motorway roadwork sections with narrow lanes revealed that there is some turbulence in the behaviour which could affect the capacity and safety levels at such sections.
- The field observations from the UK suggest that there are two predominant behaviours on narrowing lanes scheme applied at roadwork sections. These are, namely, "avoiding" and lane "repositioning" behaviours of passing heavy vehicles including public service vehicles, caravans etc. in the adjacent lane.
- The percentage of "avoiders" could be increased further when metal barriers were in place instead of plastic cones.
- Many drivers who were following a HGV on same or the adjacent lanes were observed to be driving below their desired speed; this phenomenon could lead to deterioration of the section capacity.
- The percentage of lane "repositioning" behaviour increases as speeds of drivers increase. It is believed that this behaviour is unsafe and could lead to an increase in the rate of traffic accidents.

CHAPTER FIVE
LIMITATIONS OF THE S–PARAMICS SOFTWARE

5.1 Introduction

In this chapter, an industry standard traffic software, S-Paramics, has been applied to motorway roadworks to test its validity. This software provides a visual display of vehicles' movements on any selected sections of the modelled road. However, there seem to be some limitations on the accuracy of the representation of such movements, especially within the taper section (i.e. transition zone). This chapter describes these limitations and presents the calibration and validation processes of the developed model using the S-Paramics software.

5.2 S-Paramics software

The *S-Paramics version 2007.1* microscopic traffic simulation software package was made available for use in this study. It is a commonly used micro-simulation software which has the capability of modelling many aspects of transportation networks (i.e. local arterial and regional freeway). Paramics is an acronym for Parallel Microscopic Simulation and was developed by SIAS Limited.

The S-Paramics software provides the user with the option of having several different vehicle types within the traffic mix (e.g. there are 16 built-in types within the software, but the user has the choice to increase/decrease the number of types of vehicles as well as modifying the physical dimensions and the dynamic characteristics of each of these types). Vehicle characteristics (e.g. dimensions and acceleration/deceleration rates) and driver characteristics (e.g. aggressiveness and awareness) can be modified relatively easily as part of the calibration and validation of the model in order to replicate empirical observations. In addition, the users of the S-Paramics software have the option of presenting its output as a real-time visual display. This may be of benefit to the users and model developers in verifying, calibrating and validating the model, as well as helping to demonstrate different options and scenarios to clients and members of the public who may not necessarily be experts in traffic engineering. Therefore, visualisation of vehicles' movements within a network is one of the advantages that S-Paramics provides.

5.3 S-Paramics model development

5.3.1 Data used for the development of the S-Paramics model

It is often difficult to find sites at roadworks and with good vantage points to record data close to the taper section (for example, by filming from an overhead bridge close to the taper section). Therefore, for this research, historic data from two motorway roadworks sites (which were made available for this study) were used for the testing of the S-Paramics software.

Table 5.1 illustrates the details of the sites locations. The data were used in building and developing an S-Paramics model to demonstrate the capability of the software. The first site was on the M61 motorway northbound between Junctions 8 and 9. This site had a slight left hand bend just before approaching the roadwork section. Around three hours of video footage (from 15:20 to 18:30) on Friday, 16 August 1996 was recorded. The second site was the M6 at the southbound direction between Junctions 14 and 15. Four hours of video footage (from 8:00 a.m. to 12:00) was recorded on Friday, 25 October 1996. For both sites, a speed limit of 50 mph (80 km/hr) was imposed and an offside lane (i.e. lane 3) closure was applied, for further details on these two sites see Section 3.3.4. It should be noted here that although the data used for this study seem to go back a long time, it is believed that there have been no significant differences in the layout of roadworks closure to influence drivers' merging behaviour close to the taper section, hence, the justification of using the historic data for the purpose of testing the S-Paramics software in this study.

Table 5.1: Roadworks sites details

Site No.	Site locations	Traffic direction	Number of lanes	Date	Duration (hours)	Speed limit	Type of section
15	M61 (J8 - J9)	Northbound	3 lanes	16/08/1996	3	50 mph	Roadwork with offside lane closure
16	M6 (J14 - J15)	Southbound	3 lanes	25/10/1996	4	50 mph	Roadwork with offside lane closure

The average speed and traffic flow for each lane of the observed motorways have been extracted by playing back the two footages. Using a marker pen, a thin line across the computer screen was sketched in line with the point of start of the taper section (i.e. transition zone) at both roadwork sites to help in counting vehicles (e.g. measuring time headways between successive vehicles). Similarly, in order to calculate vehicles' speeds, two screen lines were drawn to cover a distance close to 100 m. The first line was located at the start of taper, whereas the second line was after 11 consecutive white road markings (9 m each) away from the first line. Simple distance/time calculations were then used to convert the readings into speeds using video playbacks with the help of computer programming codes written for this purpose to act as a stopwatch. The output was formatted and stored on a spreadsheet for further analysis. The data were then grouped into five minutes intervals (as suggested by previous researchers such as Yousif, 1993 and Al-Obaedi, 2012), and to ensure that the data were tailored to the needs of S-Paramics.

5.3.2 Building the S-Paramics model

Following data collection, the building of the S-Paramics model was achieved by setting out the geometry of the M61 site which is similar to the M6 one since both sites had the same traffic management scheme (i.e. offside lane closure) and with the same applied speed limit of 50 mph. To correctly model a section, an image from Google maps for the motorway site was used as a base to create an overlay within AutoCAD. This overlay was then inserted into S-Paramics to the correct scale. Nodes and links were then created. Links carry the geometric design and characteristics of traffic (e.g. number of lanes, directional movements, speeds … etc.), and nodes were created at points where the section changed (i.e. where one lane was withdrawn from the carriageway).

Two types of vehicles were modelled, cars and Heavy Goods Vehicles (HGVs), with their corresponding vehicular composition. The model was run for three hours for both sites (with the first half an hour used as warming-up and the last half an hour used as cooling-down periods). The option of having loop detectors within S-Paramics was used to gather output data for flow rate and average speed for each lane.

5.3.3 Modelling roadwork site layout

As mentioned in Section 2.3, most TTMSs are divided into four zones, namely, the advance warning zone, the transition zone, the activity zone, and the termination zone (MUTCD, 2009). Road closure (activity zone) is one of the options which seems to be directly available within S-Paramics. To model the effect of the presence of the taper section (transition zone) and the advanced warning zone, the option of the "signposting" within S-Paramics was used since there appears to be no other option in S-Paramics for modelling the taper section (Nassrullah and Yousif, 2015). This option (i.e. "signposting") is used as a way of communicating to the approaching upstream vehicles in the simulation that there is lane closure ahead. It helps drivers to reassess their lane choice and get in the correct lane before approaching the closure. According to SIAS Limited (2007), the signposting distance has a significant effect on drivers' behaviour. The modelled drivers were made aware of the presence of the roadworks before they reached the start of the traffic management signage. This was done by increasing the signposting distance. However, according to Walker and Calvert (2015), this increase may not necessarily result in a change in drivers' behaviour which implies that the use of signposting is not effective. Therefore, it is found necessary to have a closer look at the effect of the presence of a taper section and the manner by which lane changes are performed. This is shown in some detail within the next sections.

The default value of 750 m as the signposting distance was used. This value has been changed and tested using data from the M61 and the M6.

5.4 S-Paramics model calibration and validation

Calibration and validation processes are the key for a successful evaluation of any micro-simulation model (Li et al., 2010). If ignored, the data compiled from the software cannot be considered as a true representation of real life situation. Once the section is created on S-Paramics, the collected data are then used as inputs into the software to start the calibration process in order to check that the created section replicates real life situations. Following this, the real data and modelled data can be compared to validate the results. In this study, the verification process of S-Paramics has been checked out through the visualisation of its output for all possible movements of vehicles (Bertini et al., 2002).

5.4.1 Statistical tests

To test the goodness of fit between the observed and modelled traffic flow, three statistical tests were used. These are Root Mean Square Error (RMSE), Root Mean Square Error Percentage (RMSEP) and the GEH statistical test (where GEH stands for Geoffrey E. Havers, who developed the test). The former two tests, shown in Equations 5.1 and 5.2, are used to check the system error in traffic simulation models. Lower values from these two tests represent better representation of the simulated data to the observed real data. According to Hourdakis et al. (2003), satisfactory model results will be achieved if RMSEP is less than 15%. These two tests were adopted by other researchers such as Al-Jameel (2012), Al-Obaedi (2012) and Yousif et al. (2013b), whereas the latter test (i.e. GEH as shown in Equation 5.3), is used and recommended by the Design Manual for Roads and Bridges - DMRB (Department for Transport

1996). This test which is similar to the well-known Chi-squared statistic is used to measure the validity of data from the created model compared to that of the observed data. The GEH statistic value should be ≤ 5 for the link flow to be acceptably reflecting the observed flow data (Department for Transport, 1996). In addition, the RMSE and the RMSEP were applied to test the goodness of fit between the observed and modelled average speed.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad \text{Equation 5.1}$$

$$RMSEP = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - y_i}{x_i}\right)^2} \qquad \text{Equation 5.2}$$

$$GEH = \sqrt{\frac{2(Y - X)^2}{Y + X}} \qquad \text{Equation 5.3}$$

Where,
X: observed flow,
Y: simulated flow,
n: number of time intervals,
x_i: observed data at time interval i, and
y_i: simulated results at time interval i.

It is worth mentioning here that the unit of the RMSE test is similar to the unit of the parameter which was used in the test. For example, when testing the goodness-of-fit between the actual and simulated flow data, the unit of the RMSE will be in veh/hr. The unit for RMSEP test is in percentage, whereas the unit for GEH test is a scalar quantity.

5.4.2 Model calibration

Traffic micro-simulation models consist of several calibration parameters which should be evaluated before the model can be used (Hollander and Liu, 2008). The default values of the S-Paramics have been used to start with for the calibration of parameters. For the signposting distance, the default value of 750 m was used initially and then modified to obtain as close results as possible compared with observed data. All other values for the calibration parameters have been kept the same, including aggression and awareness level, mean headway and minimum gap. The calibration results have been analysed for every 5-minute intervals for each lane to match the real data sets.

Table 5.2 shows the results of the sensitivity analysis conducted on a selection of signposting values ranging from the default value of 750 m and up to 2000 m. For the M61 data (i.e. with free to medium traffic flow conditions), a value of signposting of 1600 m seems to yield better results based on several simulation runs. However, for the M6 data (i.e. with medium to congested traffic flow conditions), this value is close to 2000 m.

Table 5.2: Calibration process for both data sets (M61 and M6)

Data type	Signposting distance (m)	M61 model		M6 model	
		RMSE	GEH	RMSE	GEH
Flow	750 – Default	8.9	2.0	9.8	1.9
	900	8.3	1.7	9.7	1.7
	1000	6.8	1.5	10.6	2.1
	1200	7.3	1.7	10.8	1.9
	1400	7.2	1.4	10.0	1.7
	1600	***6.0***	***1.1***	11.3	2.1
	1800	6.5	1.5	10.3	1.9
	2000	7.1	1.5	***9.3***	***1.6***

An attempt to test the sensitivity of the S-Paramics calibration parameters has been conducted. Different calibration parameters were modified using arbitrary values (within acceptable and logical limits) in order to obtain the best results. These parameters included changing the mean headway, modifying the gap acceptance and varying the drivers' aggression and awareness. None of these parameters had made any considerable effect on the results including, for example, speed.

Traffic flow is used as input and average speeds were used as calibration measures. Figure 5.1 shows the modelled flow versus observed flow data for every time slice for both the M61 and M6 data. Figure 5.2 shows the modelled speed versus observed speed data. The results of the M61 data suggest a close match between observed and modelled speeds, whereas the data set of the M6 is not that close to a good match.

5.4.3 Model validation

In order to validate the developed model, the calibrated model (based on the M61 data) was then used as a basis for the model validation. The collected data from the M6 were used as input for the validation process. Liu and Wang (2007) reported that data from different time periods on the same site or different sites can be used as an independent source for the validation process. A period of two hours was used to execute the validation process. Figure 5.3 shows modelled versus observed speeds for each time slice.

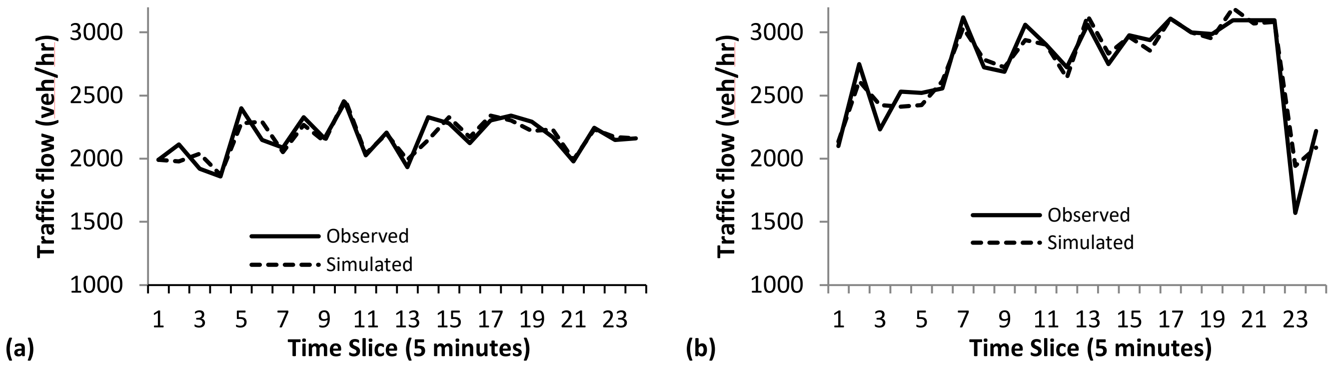


Figure 5.1: Simulated versus observed flow based on data from (a) M61 and (b) M6

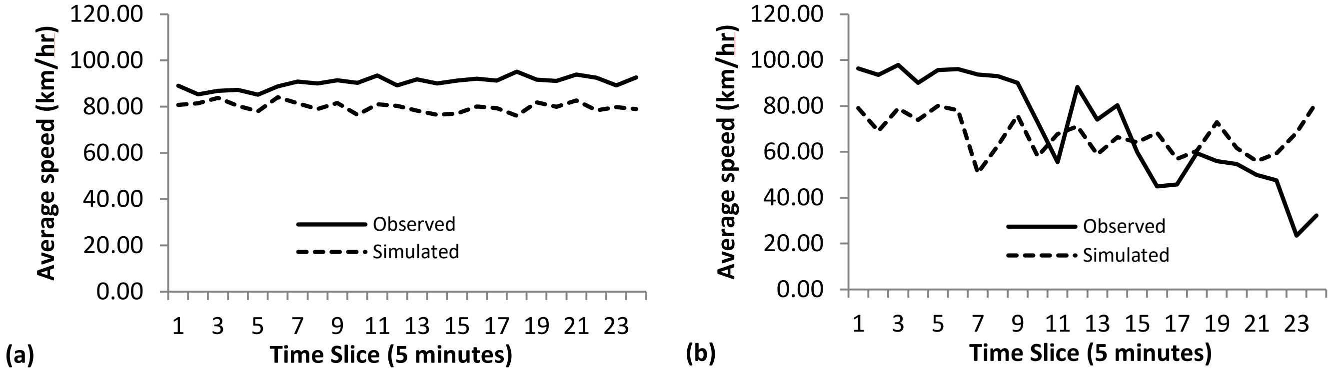


Figure 5.2: Simulated versus observed speed based on data from (a) M61 and (b) M6

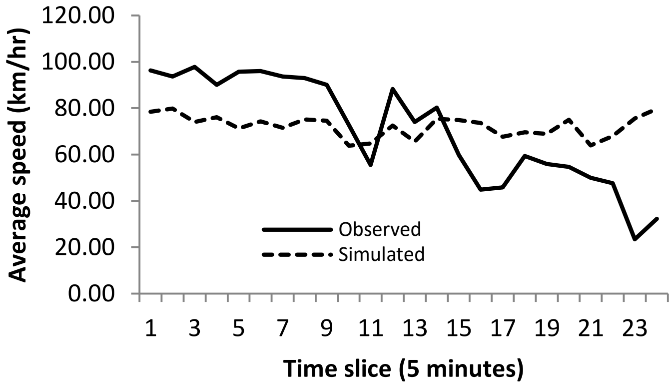


Figure 5.3: Validation - simulated versus observed speed based on data from the M6

5.5 Testing the sensitivity of S-Paramics results for the presence of taper section

In order to find out the effects of the presence of the taper section, three loop detectors within the model were used. These detectors were located at the start of the taper section (Taper detector), at 15 m before the end of taper (A detector) and just after the start of closure (Closure detector), as shown in Figure 5.4. This sensitivity analysis was achieved via two checks. These are, firstly, comparing the modelled flows with the observed data at two positions (start of taper and start of closure) for each lane as well as for all lanes. Secondly, the test was done by investigating the profiles of modelled flow through the transition zone for lane 3 only (i.e. closed lane). All of the three detectors (i.e. Taper, A and Closure detectors) were used in this test.

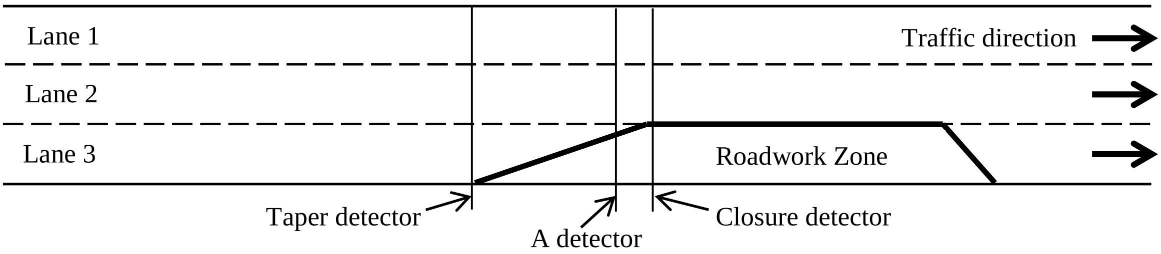


Figure 5.4: Illustration of loop detectors positions

Tables 5.3 and 5.4 summarise the statistical tests results for the M61 and M6 data, respectively. The above-mentioned statistical tests were used.

Table 5.3: Observed versus simulated traffic data based on the M61 data

Detectors' Position	Data type	Lane	RMSE	RMSEP (%)	GEH
Taper	Flow	Lane 1	163 (veh/hr)	16.4	4.6
		Lane 2	237 (veh/hr)	18.9	6.2
		Lane 3	316 (veh/hr)	*	23.5
		All Lanes	72 (veh/hr)	3.3	1.1
Closure	Flow	Lane 1	161 (veh/hr)	16.3	4.5
		Lane 2	157 (veh/hr)	14.1	3.5
		Lane 3	**	**	**
		All Lanes	98 (veh/hr)	4.4	1.5
	Speed	Lane 1	10.3 (km/hr)	11.6	NA
		Lane 2	16.9 (km/hr)	17.9	
		Lane 3	**	**	
		All Lanes	13.6 (km/hr)	14.9	

NA: Not applicable **: Lane 3 is closed for roadwork
*: The denominator in the RMSEP formula is divided by zero (no traffic flow on lane 3)

Table 5.4: Observed versus simulated traffic data based on the M6 data

Detectors' position	Data type	Lane	RMSE	RMSEP (%)	GEH
Taper	Flow	Lane 1	233 (veh/hr)	28.4	6.4
		Lane 2	647 (veh/hr)	35.8	16.3
		Lane 3	456 (veh/hr)	*	25.7
		All Lanes	112 (veh/hr)	5.8	1.6
Closure	Flow	Lane 1	253 (veh/hr)	30.7	7.0
		Lane 2	209 (veh/hr)	11.3	3.9
		Lane 3	**	**	**
		All Lanes	186 (veh/hr)	8.7	2.7
	Speed	Lane 1	18.2 (km/hr)	45.4	NA
		Lane 2	24.6 (km/hr)	64.1	
		Lane 3	**	**	
		All Lanes	22.1 (km/hr)	45.5	

The simulation results based on the M61 data (i.e. Table 5.3) satisfactorily replicate real life conditions. It can be seen from Table 5.3 that values of RMSEP for both flow and speed are around 15% which indicates that the model can reasonably replicate the observed data (as discussed in Section 5.4.1). However, there is a notable difference between the simulated results and the observed data for the M6 case (i.e. Table 5.4), particularly for the speed data. Table 5.4 shows that the values of RMSEP for both flow and speed are higher than 15% (i.e. the RMSEP values around 30% – 45%) which indicates that the model cannot replicate the observed data. This could be attributed to the congested traffic conditions on the M6 roadwork section with the relatively high levels of heavy goods vehicles percentage. Traffic flow was breaking down and dropping down to less than 1600 veh/hr, as shown in Figure 5.1b.

By comparing the statistical test values for flow data at the taper detector with that at the closure detector for both sites, it can be seen from Table 5.3 (representing the uncongested situation) that there is a reasonable close match between both detectors. However, in Table 5.4 (where congested situations prevailed), the closure detector shows lower values than those at the taper detector. This shows that under congested traffic flow condition (i.e. the M6 case shown in Table 5.4), the S-Paramics failed to replicate the observed data. This could be attributed to the insufficient gap sizes available for the subject vehicles to change lanes into, particularly with the very limited lane-changing opportunities due to congestion situations.

Table 5.5 shows the observed and simulated flow for all loop detectors within the transition zone (i.e. Taper, A and Closure Detectors), for both data sets, for lane 3, while Table 5.6 shows the observed and simulated lane utilisation data for all loop detectors within the transition zone (i.e. Taper, A and Closure Detectors), for both data sets, for lane 3. Figure 5.5 shows the observed and the simulated lane utilisation data at the start of the transition zone (i.e. Taper Detector), for both data sets, for the closed lane (i.e. lane 3). The difference between observed and simulated seems high (i.e. around 20%). This may be because the modelled drivers carry on using the closed lane when they are unable to find a suitable gap to merge into the adjacent open lane rather than wait for the opportunity to do so (as also reported by Walker and Calvert, 2015). In addition, Walker and Calvert (2015) reported that the modelled drivers do not distinguish between a temporary traffic management schemes applied at roadworks and the same layout of roadway in normal conditions (i.e. no roadworks), whereas drivers in real-life do make this distinction.

Table 5.5: Flow profile for lane 3 for all loop detectors within the transition zone versus the observed flow for both data sets (M61 and M6)

Data type	Time slice (minutes)	M61 observed flow (veh/hr)	M61 model Flow data (veh/hr)			M6 observed flow (veh/hr)	M6 model Flow data (veh/hr)		
			Taper	A detector	Closure		Taper	A detector	Closure
Flow	0-5	0	312	312	0	24	252	252	0
	5-10	36	264	240	0	144	360	336	0
	10-15	24	276	240	0	24	348	372	0
	15-20	12	312	312	0	12	312	288	0
	20-25	12	372	360	0	72	360	336	0
	25-30	36	348	324	0	24	420	420	0
	30-35	12	372	360	0	36	744	804	0
	35-40	0	408	384	0	84	600	648	0
	40-45	24	228	264	0	72	420	408	0
	45-50	0	432	396	0	60	564	588	0
	50-55	0	384	384	0	36	564	588	0
	55-60	24	384	408	0	96	384	396	0
	60-65	48	240	264	0	72	756	756	0
	65-70	36	252	252	0	36	552	600	0
	70-75	24	312	324	0	48	576	600	0
	75-80	24	324	300	0	60	504	492	0
	80-85	12	312	276	0	12	552	564	0
	85-90	12	348	324	0	72	552	612	0
	90-95	12	312	276	0	72	612	600	0
	95-100	12	348	348	0	48	588	600	0
	100-105	0	348	348	0	84	600	648	0
	105-110	12	300	276	0	72	624	648	0
	110-115	24	312	300	0	72	252	300	0
	115-120	12	348	288	0	14	168	168	0

Table 5.6: Lane utilisation data for lane 3 for all loop detectors within the transition zone versus the observed lane utilisation for both data sets (M61 and M6)

Data type	Time slice (minutes)	M61 observed lane utilisation (%)	M61 model lane utilisation data (%)			M6 observed lane utilisation (%)	M6 model lane utilisation data (%)		
			Taper	A detector	Closure		Taper	A detector	Closure
Lane utilisation	0-5	0	16	16	0	1	12	12	0
	5-10	2	13	12	0	5	14	13	0
	10-15	1	14	12	0	1	14	15	0
	15-20	1	17	17	0	0	13	12	0
	20-25	1	16	16	0	3	15	14	0
	25-30	2	15	14	0	1	16	16	0
	30-35	1	18	18	0	1	25	26	0
	35-40	0	18	17	0	3	22	23	0
	40-45	1	11	12	0	3	15	15	0
	45-50	0	17	16	0	2	19	20	0
	50-55	0	19	19	0	1	19	20	0
	55-60	1	17	19	0	4	15	15	0
	60-65	2	12	13	0	2	24	24	0
	65-70	2	12	12	0	1	19	21	0
	70-75	1	13	14	0	2	19	20	0
	75-80	1	15	14	0	2	18	17	0
	80-85	1	13	12	0	0	18	18	0
	85-90	1	15	14	0	2	18	20	0
	90-95	1	14	12	0	2	21	20	0
	95-100	1	16	16	0	2	18	19	0
	100-105	0	17	17	0	3	20	21	0
	105-110	1	13	12	0	2	20	21	0
	110-115	1	14	14	0	5	13	15	0
	115-120	1	16	13	0	1	8	8	0

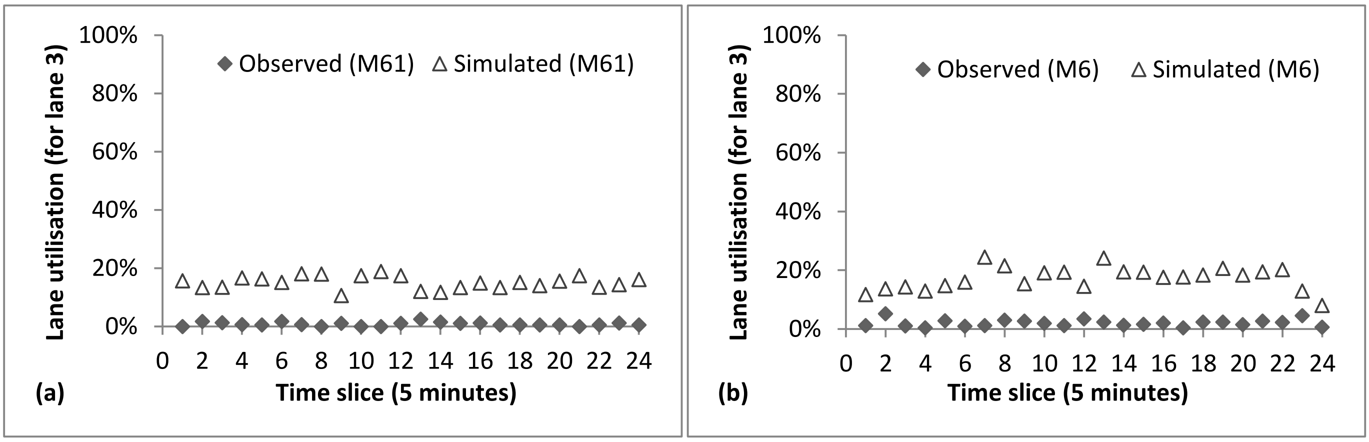


Figure 5.5: Simulated versus observed lane utilisation data at the start of the transition zone for lane 3 for both data sets (a) M61 and (b) M6

It is reasonable to assume that understanding and modelling driver behaviour at roadworks section which may differ from normal roadway sections is not an easy task. However, S-Paramics seems unable to represent the actual behaviour of traffic at roadworks sections, particularly under congested situation. Therefore, more care is needed when modelling such sections.

It is worth mentioning that, during the running of the simulation model under heavy flow conditions, the visual output from S-Paramics suggested that on a number of occasions, vehicles' overlapping on each other has occurred just before the closure (see Figure 5.6). This representation does not seem to be logical. Similar observations have been reported by Al-Jameel (2012). This could be attributed to the ignoring of vehicles' length in the forced lane-changing process calculations in the S-Paramics. Several simulations runs using only one type of vehicles (i.e. Light Goods Vehicle, LGV) with different vehicles' length (i.e. starting from 1 m up to 25 m) for each run was done to find out the effects of vehicle's length on overlapping rates. It was found that runs with short vehicles' length showed less overlapping rates than runs with longer length of vehicles.

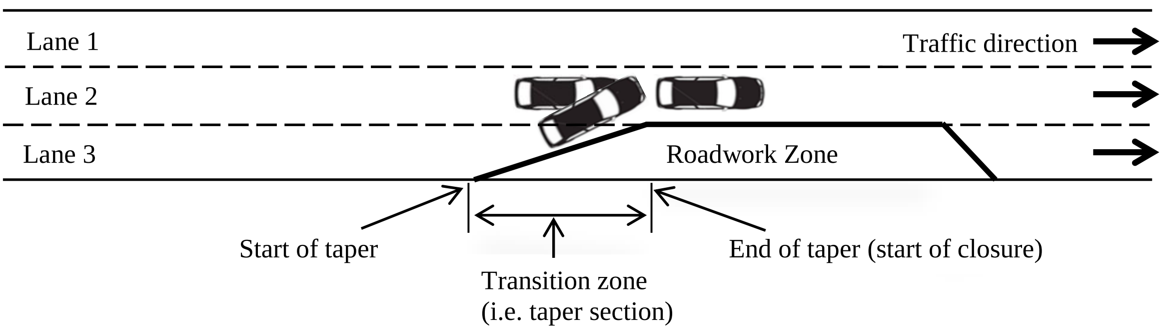


Figure 5.6: Illustration of vehicles' overlapping on each other in the S-Paramics model (i.e. visual representation at the taper)

5.6 Summary

In this chapter, two sets of data from motorway sites were used in order to test the capability of the S-Paramics software (which is widely used in industry) in representing motorway roadwork sections. The S-Paramics software has the ability to represent the behaviour and interaction between individual vehicles on local arterial and regional freeway networks, and also has the ability to simulate different roadway configurations and features. Also, the S-Paramics software provides the users with the options of having several different vehicle types and characteristics. In addition, the users of the S-Paramics software have the option of presenting its output as a real-time visual display. However, the results suggest that the S-Paramics model is not capable of accurately representing traffic behaviour at the taper section (transition zone) which is an important part of the temporary traffic management schemes at motorway roadwork sections.

The model allows for a relatively high number (i.e. around 20% of total traffic) of very late lane changes (i.e. late mergers) at the end of the taper section which does not conform to real life observations. Previous research suggests that late merging may contribute to capacity reduction. Therefore, the increased number of the late mergers within the model may affect the reliability of its outputs in terms of estimating possible capacity reduction and overall delays for roadwork sites. The frequency of those very late mergers increases as the traffic flow increases. The visual display of the S-Paramics does not seem to give an accurate representation of the vehicle movements within the taper section of the closed lane.

In addition, the SIAS Limited (2007) was reviewed in order to find out if the observed driving behaviours at motorway roadwork sections with narrow lanes scheme (as discussed in the previous Chapter) or other driving behaviours at such sections differ from normal motorway section. It was found that the S-Paramics software does not take into consideration the variation in driving behaviours between normal roadway sections and roadworks with narrow lanes sections. All these imply that the S-Paramics software package should be used with caution when modelling roadworks for motorways.

CHAPTER SIX
MODEL SPECIFICATION AND DEVELOPMENT

6.1 Introduction

Due to the lack of capability of the S-Paramics software to appropriately model drivers' behaviour at motorway roadwork sections (as discussed in the previous chapter), a new micro-simulation model for motorway roadwork sections was built from scratch for the purpose of this study. This chapter presents the specification and the structure of the newly developed micro-simulation model. The new model consists of five main sub-models; these are car-following, lane-changing, gap acceptance, lane closure and narrow lanes. Each of these sub-models will be discussed in detail in this chapter.

The microscopic technique was employed in the new model because of the capability of such a technique in representing the interaction between individual vehicles. The development of the new micro-simulation model requires information about basic road geometry together with traffic behaviour at both normal and roadwork sections (as discussed in Chapters 3 and 4) and information about characteristics of drivers and vehicles (as will be discussed later in this Chapter, Section 6.3). It also requires selection/development of suitable algorithms for car-following, lane-changing, gap acceptance, lane closure and narrow lanes sub-models (rules). These rules and characteristics need to be programmed using a suitable programming language.

Compaq Visual FORTRAN (6.5) programming language was used in developing the new micro-simulation model. This programming language was chosen in this study because FORTRAN is one of the widely used programming languages in engineering applications and also engineers have traditionally used it. In addition, this version (i.e. Compaq Visual FORTRAN 6.5) has the ability to provide a visual representation of vehicles' movements and interactions.

6.2 The model structure

Figure 6.1 illustrates the general structure of the newly developed micro-simulation model. The first stage in the structure is to define each driver's/vehicle's characteristics (such as driver's desired speed, driver's reaction time, vehicle's type and length, etc.). Next, vehicles will be generated and assigned at the beginning of the simulated road. The position and speed of the generated vehicles will be updated every scanning time (Δt) for the whole length of the road. The order of dealing with the vehicles during each scanning time is based on their longitudinal positions. The system scans the road at every scanning time (Δt) from the end to the start, including the warm up and cool-off sections. This is undertaken by numbering and renumbering the vehicles in the system at each Δt as shown in Figure 6.2. Then, the simulated data will be collected. The final process is to compare the simulation current time with the assumed simulation period (which is equal to the total simulation time), and the simulation model will be terminated once the simulation period has been reached.

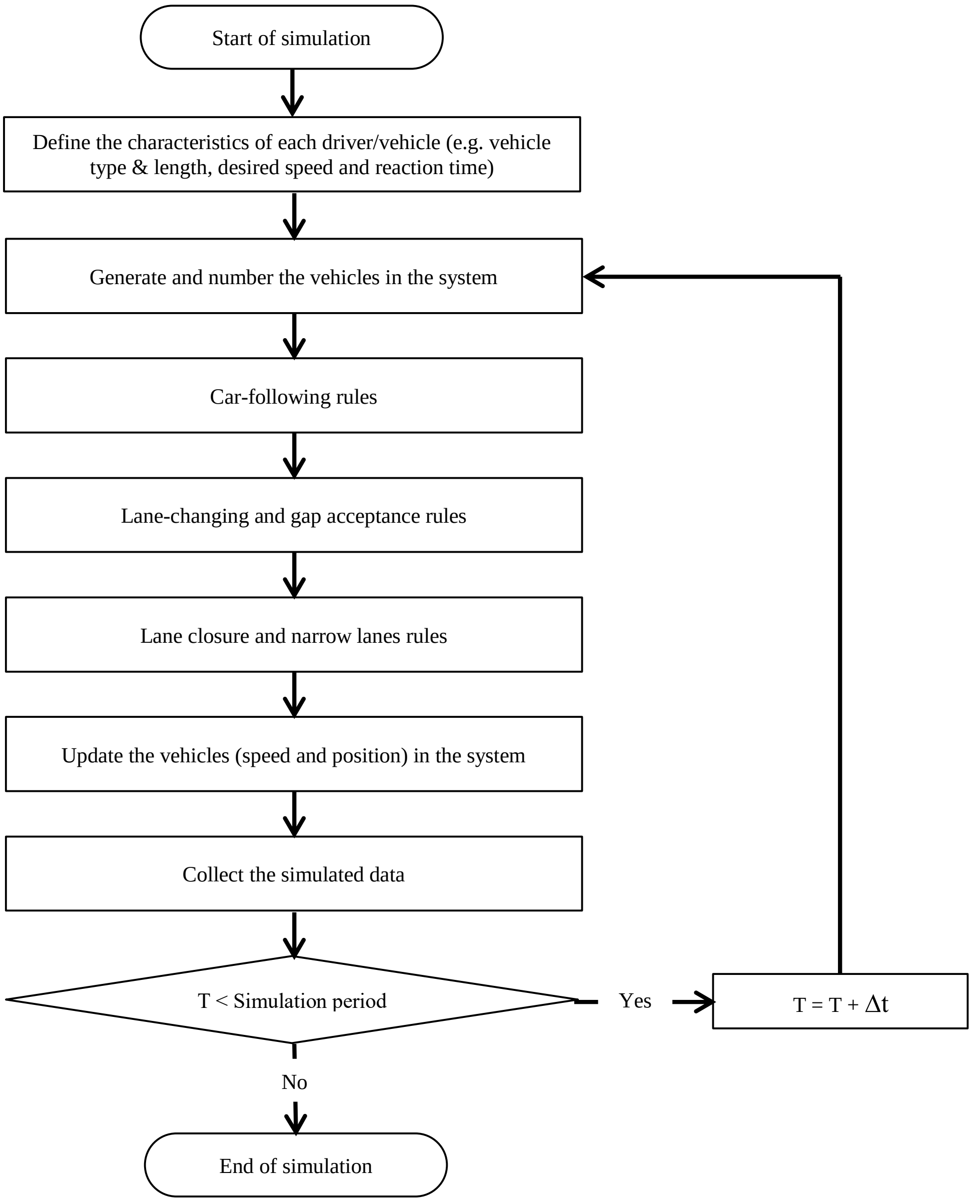


Figure 6.1: General structure of the newly developed micro-simulation model

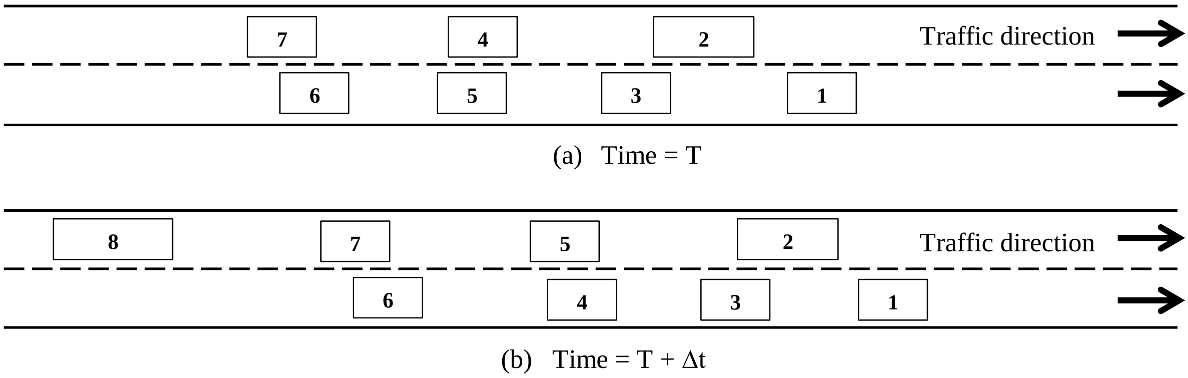


Figure 6.2: (a) Numbering and (b) renumbering the vehicles in the system at each Δt

The time interval at which the elements of the simulation model should be updated is defined as the scanning time (Δt). The determination of the scanning time (Δt) is an important factor in any simulation model. A small scanning time will result in more computer time, whereas a long scanning time may affect the accuracy of the results. Yousif (1993) tested a range of values from 0.1 to 2.0 seconds and suggested a value of 0.5 sec. Many researchers also adopted a value of 0.5 sec as a scanning time to update their simulation models (see for example Purnawan, 2005; Al-Jameel, 2012; Al-Obaedi, 2012; and Alterawi, 2014). Therefore, a scanning time of 0.5 sec was used for this study.

6.3 Drivers' and vehicles' characteristics

The efficiency of any microscopic traffic simulation model depends mainly on the quality of the traffic-flow sub-models (i.e. car-following, lane-changing, gap acceptance, lane closure and narrow lanes) and also depends on the accurate representation of the characteristics of the driver/vehicle units. According to Macadam (2003), the understanding of human drivers and the modelling of their behaviour have a very broad scope. Therefore, in this study, the focus is on the characteristics of the drivers/vehicles which control common activities of driving and its subsequent computer-based modelling. These characteristics of drivers/vehicles are discussed in detail in the following sub-sections.

6.3.1 Vehicle characteristics

6.3.1.1 Vehicle type and length

Several types of vehicles can be found travelling along the motorways ranging from motorcycles to heavy goods vehicles (HGVs). The dimensions and engine capabilities among these vehicles types are different. The length of a vehicle is an important factor which could indicate the type of vehicle and affect the calculations of acceleration/deceleration rates for car-following rules and the estimations of the gaps required for the merging process.

Based on previous empirical observations from UK motorways, El-Hanna (1974) proposed two types of vehicles, namely passenger cars and HGVs. The author reported that the lengths of vehicles are normally distributed for both passenger cars and HGVs with mean and standard deviation as shown in Table 6.1.

Table 6.1: Vehicle types and lengths (source: El-Hanna, 1974)

Vehicle type	Mean (μ)	Standard deviation (σ)
Passenger car	4.2	0.4
HGV	11.2	2.4

The findings by El-Hanna (1974) have been adopted by many researchers including Zia (1992), Zheng (2003) and Wang (2006), whereas Yousif (1993) and Purnawan (2005) adopted the findings by Chin (1983) who found different results with HGVs mean length of 6.8 m. A study carried out by Al-Jameel (2012) based on real traffic data from UK motorways showed that the mean and standard deviation for both passenger cars and HGVs are close to those suggested by El-Hanna (1974). However, Al-Jameel (2012) reported that the lengths of HGVs are not normally distributed.

In this study, only two types of vehicles, namely passenger cars and HGVs, have been adopted in developing the new model. The reasons behind this decision are for simplicity and because the majority of vehicles are either passenger cars or HGVs. Al-Obaedi (2012) investigated vehicle lengths by using the typical manufacturers' data sources and reported that the minimum length for HGVs is 5.6 m. Alterawi (2014) also used a value of 5.6 m to distinguish between passenger cars and HGVs. In this study, this value has been adopted (as suggested by previous researchers), so the developed simulation model considers a vehicle as a HGV when its length is greater than or equal to 5.6 m.

A sample of field data from the Individual Vehicles' raw Data (IVD) consisting of 530,184 vehicles taken from the M25 has been used to investigate vehicles' length. The results revealed that vehicles' length is ranging from 2.52 m to 25.5 m, as shown in Table 6.2 together with the descriptive statistical summary.

Table 6.2: Vehicle lengths based on data from UK motorways (M25) (Site No. 13)

Vehicle type	Mean (m)	Standard deviation (m)	Min. length (m)	Max. length (m)	Sample size
Cars	4.31	0.44	2.52	5.59	461,209
HGVs	11.87	4.59	5.6	25.5	68,975

The results seem in good agreement with El-Hanna (1974) and Al-Jameel (2012). Figures 6.3 and 6.4 show the distributions for passenger car lengths and those for HGVs, respectively.

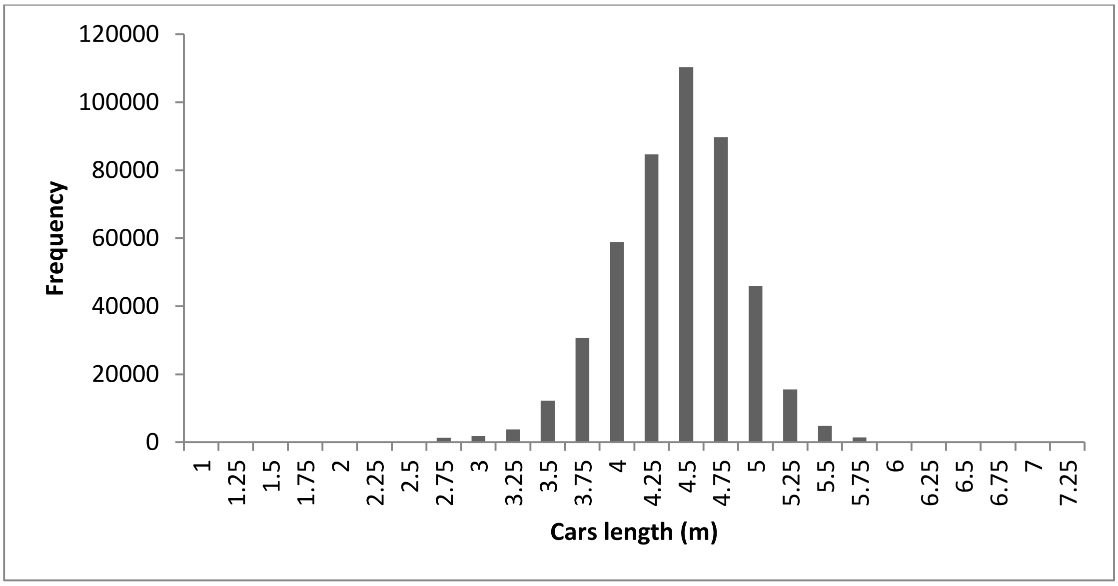


Figure 6.3: Distribution of car lengths based on data from the M25 (Site No. 13)

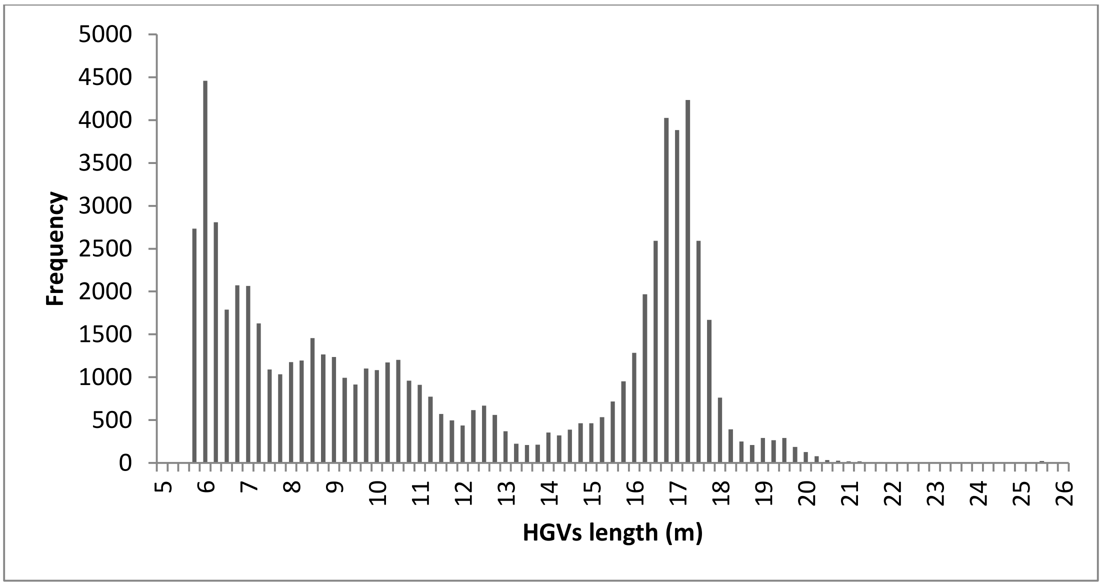


Figure 6.4: Distribution of HGV lengths based on data from the M25 (Site No. 13)

The distribution of cars' length fits a normal distribution as shown in Figure 6.3 and Figure 6.5 which shows the cars' length cumulative distribution. This is consistent with the findings by many previous studies (see for example El-Hanna, 1974; Purnawan, 2005; Al-Jameel, 2012; and Alterawi, 2014). Therefore, in this study, for the generation of passenger car's length the normal distribution is used with the statistical values shown in Table 6.2.

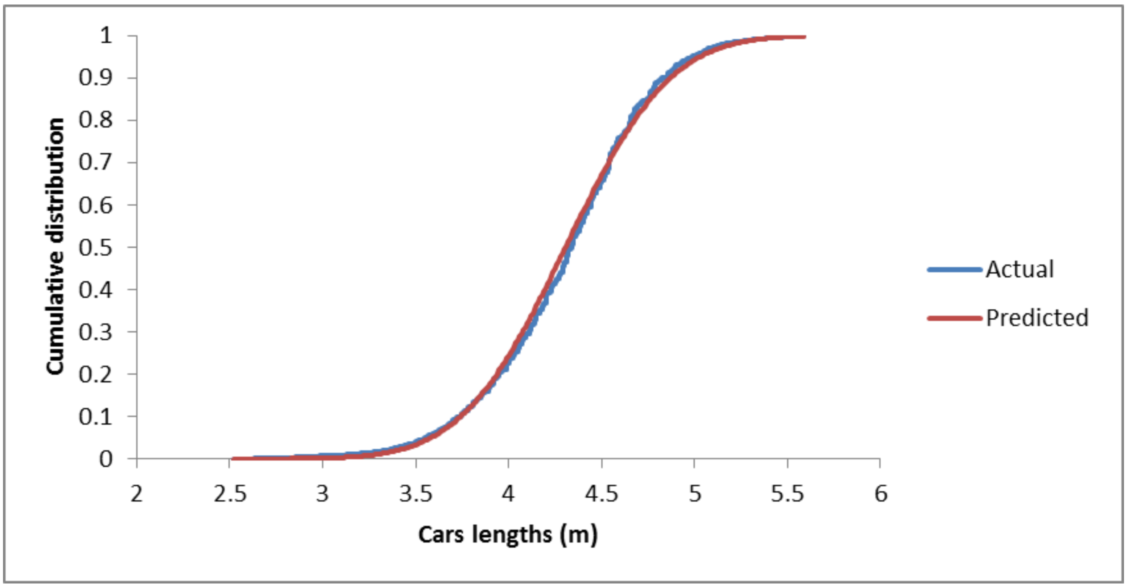


Figure 6.5: Cumulative distribution for car lengths based on data from the M25

It can be seen from Figure 6.4 that the HGVs length distribution is not normally distributed. Therefore, in this study, the HGVs' lengths were obtained from the HGVs cumulative distribution, as shown in Figure 6.6, by generating random numbers. The random numbers were set to be equal to the cumulative distribution as modelled by others (see for example Al-Jameel, 2012; Al-Obaedi, 2012; and Alterawi, 2014).

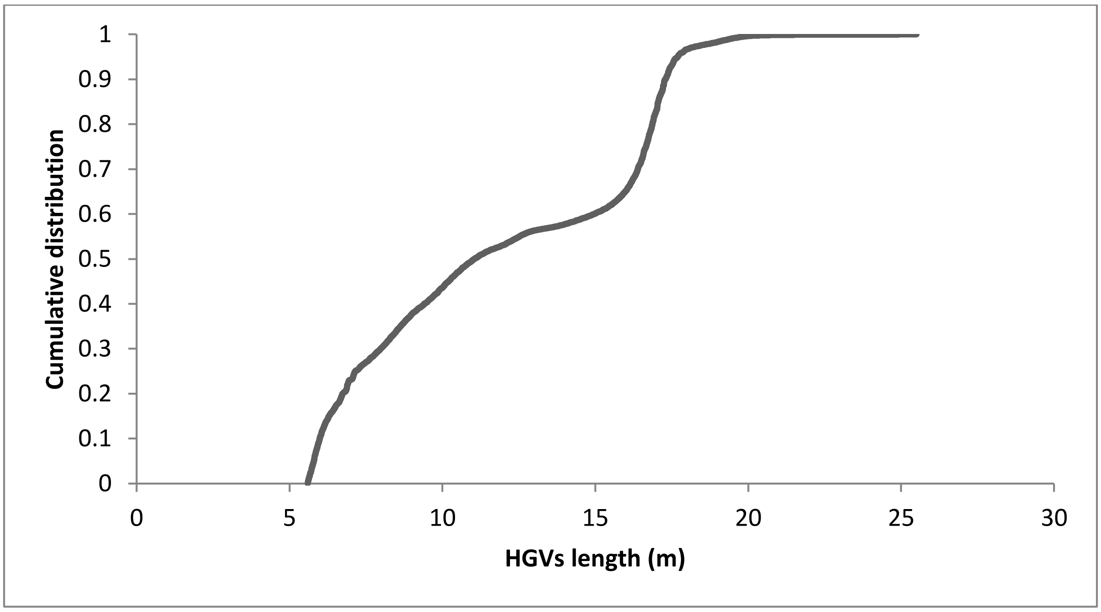


Figure 6.6: Cumulative distribution for HGV lengths based on data from the M25

6.3.1.2 Vehicle acceleration/deceleration rates

The American Traffic Engineering Handbook, ITE (2010) suggested two types of acceleration, namely normal and maximum acceleration/deceleration rates. For the purpose of this study, these two types of acceleration rates, as well as the values of acceleration/deceleration rate used are as proposed by ITE in developing the model, as there is an absence of such data from the UK.

The normal acceleration/deceleration rate (comfortable acceleration) is applied by the drivers to maintain their desired speed, either by slowing down when they exceed the desired speed or accelerating to reach their desired speed. The maximum acceleration/deceleration is applied in other situations (e.g. accelerate to overtake another vehicle or decelerate in urgent situations).

According to the ITE (2010), the values of normal acceleration are 1.1 m/sec^2 for passenger cars and 0.37 m/sec^2 for HGVs, whereas the normal deceleration values are 3.0 m/sec^2 and 1.8 m/sec^2 for cars and HGVs, respectively. Table 6.3 shows the maximum acceleration rates for passenger cars and HGVs, these accelerations represent the vehicles' mechanical abilities under different speed levels. The maximum deceleration rate is assumed as 4.9 m/sec^2. However, the majority of vehicle capabilities in the USA are higher than those in the UK. Therefore, these values were factored down by 75% as suggested by previous researchers such as Yousif (1993), Wang (2006), Al-Jameel (2012) and Alterawi (2014).

Table 6.3: Maximum acceleration rates (m/sec^2) for passenger cars and HGVs (ITE, 1999)

Speed (km/hr)	**0 – 32**	**32 – 48**	**48 – 64**	**64 – 80**	**> 80**
Cars	2.4	2.0	1.8	1.6	1.4
HGVs	0.5	0.4	0.2	0.2	0.1

6.3.2 Driver characteristics

6.3.2.1 Perception reaction time

The driver reaction time is one of the most significant factors that governs the headway value between vehicles and affects the stopping sight distance (minimum distance required for a vehicle to stop before striking an object on the carriageway). The perception reaction time consists of two components: the perception time which is the time period that elapses from seeing the hazard on the carriageway until the driver realises that a brake action is needed, and the reaction time which is the time required by a driver to press the brake pedal (O’Flaherty, 1997). There are several factors affecting the length of the driver reaction time such as driving experience, psychological and physical conditions, age and gender, and the distance to the object (Yousif, 1993; Roess et al., 2004 and Ruhai et al., 2010).

Several researches have studied driver reaction time under different conditions. Johansson and Rumer (1971) used a sample of 321 drivers driving in real traffic to estimate the brake reaction time distribution. They used the term brake reaction time to represent perception reaction time. The drivers were instructed to press the brake pedal straightway after hearing the horn, the brake reaction time is the duration from when the horn was sounded to the instant the driver’s brake light turned on. They recorded the driver reaction time for both alerted and non-alerted (surprised) conditions. The results of the study are shown in Figure 6.7. Johansson and Rumer suggested a correction factor of 1.35 for the non-alerted conditions.

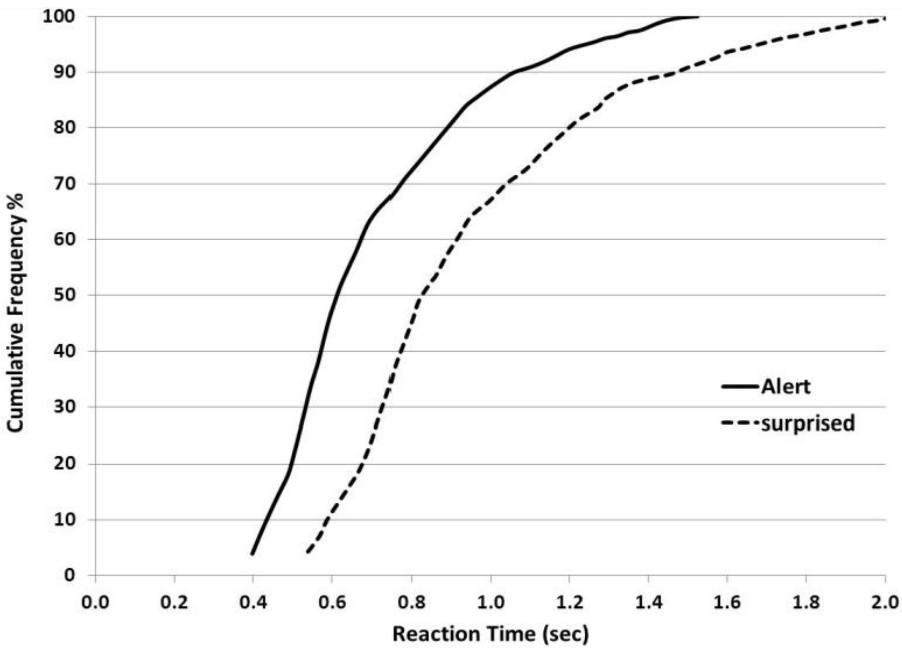


Figure 6.7: Driver reaction time distribution for alerted and surprised conditions (Johansson and Rumer, 1971)

Lerner et al. (1995) used a sample of 56 drivers travelling in real traffic to estimate the distribution of drivers’ reaction time for non-alerted situations. The drivers did not know that they were participating in the experiment. A yellow highway barrel was released (but it was kept within the central reservation) about 200 feet in front of the drivers, when the drivers were travelling at a speed of 40 mph. The reaction time is the duration from when the barrel is released to the instant that the driver applies the brakes. The mean and standard deviation for the reaction time were 1.51, and 0.39 seconds respectively.

For the purpose of this study, drivers' reaction time were obtained from Figure 6.7 cumulative distribution, following many previous researchers such as Benekohal (1986), Yousif (1993), Al-Jameel (2012), Al-Obaedi (2012) and Alterawi (2014).

Congested conditions (i.e. traffic density equal to or exceeding of 37 veh/km) have been used to distinguish between surprised and alerted situations as suggested by the above-mentioned researchers (Benekohal, 1986; Yousif, 1993; Al-Jameel, 2012; Al-Obaedi, 2012 and Alterawi, 2014). The driver is assumed to be in alert mode when he/she drives in congested conditions. At roadwork sections, the drivers are also assumed to be in an alert situation due to the presence of roadworks signs; the drivers will continue to be in an alert situation until passing the end-of-works sign (termination zone).

6.3.2.2 Desired speed

The desired speed represents the speed that is adopted by a driver to reach his/her destination without delay. Following Duncan (1976), Wang (2006), Al-Jameel (2012) and Al-Obaedi (2012) the desired speed has been measured under a free flow condition with flows of less than 300 veh/hr. A sample of field data taken from the IVD resources from two motorways, namely the M25 (four-lane section) and the M42 (three-lane section), were used to measure driver desired speeds as shown in Table 6.4.

Table 6.4: Summary of data collected from IVD resources sites for desired speed

Site No.	Site location	Number of lanes	Date	Duration
13	M25 (J15 – J16)	4	04/05/2002 to 10/05/2002	7 days
14	M42 (J5 – J6)	3	22/08/2002 to 30/08/2002	9 days

The complete days of data as shown in Table 6.4 were filtered manually to exclude the intervals with a flow higher than 300 (veh/hr/lane). Tables 6.5 and 6.6 show typical mean and standard deviation values for the M25 and the M42, respectively, for both cars and HGVs for each lane.

Table 6.5: Desired speeds from the M25 IVD data (Site No. 13)

Lane no.	1		2		3		4	
Vehicle type	Cars	HGVs	Cars	HGVs	Cars	HGVs	Cars	HGVs
Mean speed (km/hr)	112	91	121	102	130	125	138	---
Standard deviation (km/hr)	15.4	9.6	14.6	15.9	15.1	17.5	13.8	---

Table 6.6: Desired speeds from the M42 IVD data (Site No. 14)

Lane no.	1		2		3	
Vehicle type	Cars	HGVs	Cars	HGVs	Cars	HGVs
Mean speed (km/hr)	111	90	121	100	131	---
Standard deviation (km/hr)	17.3	9.5	15.4	15.5	14.8	---

The results reveal that in general the values of desired speeds for all lanes are consistent with those reported by Al-Jameel (2012). Also, the compliance of drivers with the speed limit (i.e. 70 mph equivalent to 112 km/hr) during the free flow condition (with flow less than 300 veh/hr) was very poor. Seventy-five per cent of vehicles were found to be exceeding the speed limit on the M25 and 71% on the M42. These percentages are relatively higher than the 48% that is reported by the Free Flow Vehicle Speed Statistics: Great Britain 2012, (2013). The results also show good agreement in mean speeds between both motorways.

For the purpose of this study, the desired speed for each driver has been generated from a normal distribution, with the statistical values shown in Table 6.5, as suggested by previous studies (e.g. Yousif, 1993; Wang, 2006; Al-Jameel, 2012; Al-Obaedi, 2012; and Alterawi, 2014). In order to include the effects of posted speeds limits, a new parameter called drivers' compliance with speed limit (DCSL%) has been introduced in the developed model. A value of 50% has been adopted for the drivers' compliance with speed limit parameter (DCSL%) as suggested by the Free Flow Vehicle Speed Statistics: Great Britain 2012, (2013).

The process of assigning desired speed for each driver was modelled by generating a random number for each driver; if the generated number is higher than the DCSL% then the driver will be regarded as non-complying with the applied speed limit and will be assigned with a desired speed equal to the generated desired speed from the normal distribution. Otherwise, the driver will be regarded as a complying driver and the applied speed limit (i.e. 70 mph, 60 mph … etc.) will be assigned as a desired speed to that driver. The steps of assigning desired speed are illustrated in Figure 6.8. It is assumed that all drivers enter the simulated section using their assigned desired speeds, and then these speeds will be adjusted once they enter the section according to the car-following rules.

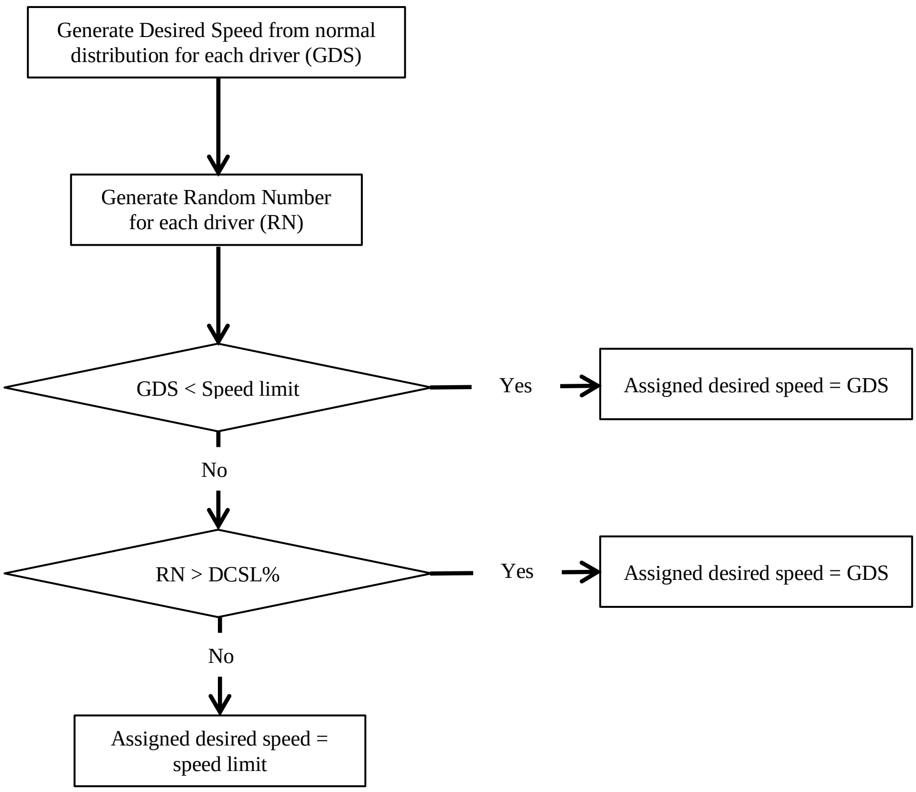


Figure 6.8: Method of assigning driver's desired speed

6.3.2.3 Driver aggressiveness

Driver aggressiveness is another factor that controls the driver's behaviour (e.g. speeds and positions) at the approach to roadwork sections. In this study, based on drivers' reaction time, this factor (i.e. driver aggressiveness) has been classified into two classes. Class 1 represents aggressive drivers whereas class 2 represents the case for non-aggressive drivers. Those drivers with short reaction time (top 20% of drivers) were assumed to be aggressive (i.e. class 1); whereas the others were assumed to be non-aggressive (i.e. class 2). This classification has then been used for the new following vehicle in the target lane (i.e. adjacent open lane) for showing courteous behaviours to those merging from the closing lane, as will be discussed later in this Chapter.

6.4 Car–following rules

The car-following sub-model (rules) governs the interaction between successive vehicles travelling in the same lane. These rules represent the foundation for the vehicles interaction behaviour in the developed micro-simulation model.

The car-following sub-model has been developed based on the assumptions (with some modifications) of the CAR-following SIMulation model (CARSIM) which has been suggested by Benekohal (1986). CARSIM was adopted for the developed micro-simulation model because it has the ability to represent different traffic conditions realistically (free flowing as well as stop and go conditions) so that it helps in achieving a close reflection to the actual situation at roadwork sections. In addition, many previous researches have adopted the CARSIM model (see for example Benekohal, 1986; Yousif, 1993; Purnawan, 2005; Al-Jameel, 2012; Al-Obaedi, 2012; Alterawi, 2014).

Five different situations (accelerations/decelerations) were considered in developing the car-following sub-model (as explained in the following sub-sections). In order to represent the interactions between vehicles realistically and safely, drivers will be assumed to maintain a sufficient distance from their leaders to react safely if any changes occur ahead. The values of these acceleration/deceleration rates are calculated and assigned for each vehicle for every scanning time (Δt). Then, only one acceleration/deceleration rate value (ACC) is selected from the calculated acceleration/deceleration rates to be used in determining the new velocities and positions for each vehicle. At the end of each scanning time, vehicle speeds and locations will be updated using Equations 6.1 and 6.2.

$$VN = Vn + ACC(\Delta t) \qquad \text{Equation 6.1}$$

$$POSN = POSn + Vn(\Delta t) + 0.5(ACC)\Delta t^2 \qquad \text{Equation 6.2}$$

Where:
VN: the updated velocity of vehicle *n* (m/sec), at the end of the current Δt,
POSN: the updated position of vehicle *n* (m), at the end of the current Δt,
ACC: the acceleration/deceleration rate of vehicle *n* (m/sec^2),
Δt: the scanning time (sec) which is equal to 0.5 seconds,
Vn: the current velocity of vehicle *n* (m/sec), and
POSn: the current position of vehicle *n* (m).

6.4.1 Vehicle capability acceleration (ACC_1)

A vehicle type (either a passenger car or a HGV) will be assigned for each vehicle generated in the system. The acceleration/deceleration rate (ACC_1) that will be assigned for the vehicle is affected by the current speed of the vehicle and the vehicle's mechanical ability which, by itself, depends on its type. This rate (i.e. ACC_1) is calculated using Table 6.3.

6.4.2 Desired speed acceleration (ACC_2)

When the generated vehicle is not constrained by a vehicle ahead, the vehicle will be assumed to accelerate/decelerate until reaching its assigned desired speed and then maintain it. The symbol (ACC_2) has been used to represent this condition. The normal acceleration/deceleration values (as discussed in Section 6.3.1.2) are used to measure the value of ACC_2.

6.4.3 Slow moving acceleration (ACC_3)

Under congested conditions, when vehicles are travelling in platoon situations (moving very slowly in a closely-spaced group), the distance between the following and leading vehicle is governed by the buffer space. The buffer space can be defined as the space between two successive vehicles under heavy flow conditions (i.e. platoon situations) as shown in Figure 6.9. Different values of buffer space have been suggested by previous studies as shown in Table 6.7. For the purpose of this study, a value of 1.8 m was assumed for the buffer space, as this value (i.e. 1.8 m) is obtained from the calibration process of the car-following sub-model (as will be discussed later in Section 7.4.1) and is also within the reported limits in the table. The acceleration/deceleration rate used in this situation (ACC_3) is calculated using Equations 6.3 to 6.5.

$$POSL - POSF \geq Llead + BUF \qquad \text{Equation 6.3}$$

By substituting Eq. (6.2) for *POSF* in Eq. (6.3) then,

$$POSL - [POSf \ + Vf(\Delta t) + 0.5(ACC3)\Delta t^2] - Llead - BUF \geq 0.0 \qquad \text{Equation 6.4}$$

By rearranging Eq. (6.4) we get,

$$ACC_3 = \frac{POSL - POSf - Vf(\Delta t) - Llead - BUF}{0.5\Delta t^2} \qquad \text{Equation 6.5}$$

Where:
ACC_3: the acceleration/deceleration rate (m/sec^2) for the slow moving conditions,
POSL: the position of the leading vehicle (m),
POSF and *POSf*: the new and old positions of the following vehicle (m), respectively,
Vf: the velocity of the following vehicle (m/sec),
BUF: the buffer space (m), and
Llead: the length of the leading vehicle (m).

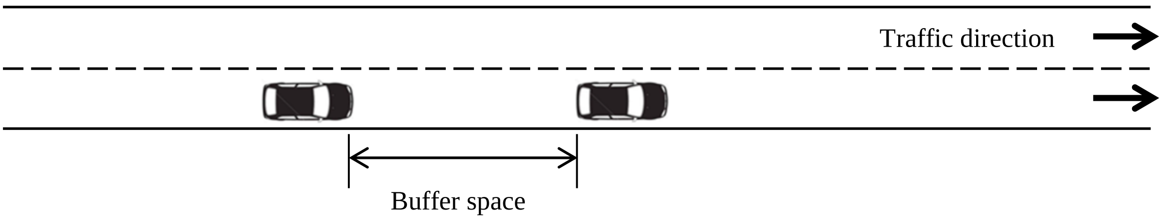


Figure 6.9: Illustration of the safety buffer space

Table 6.7: Summary of previous studies for buffer space

Names and references	Buffer space (m)	Remarks
Benekohal (1986)	0.9 – 3.0	0.9 m was used at high density; elsewhere 3 m was used.
Zia (1992)	3.0	Constant value
Yousif (1993)	1.8	The author used a normal distribution with standard deviation of 1.17 m.
Al-Obaedi (2012)	1.5 – 3.0	1.5 m was used for vehicles travelling on the ramp, while for the main line motorway vehicles 3 m was used.
Al-Jameel (2012)	2.0	Constant value
Alterawi (2014)	1.5	Constant value

6.4.4 Moving from stationary acceleration (ACC_4)

Under congested (platoon) conditions, when the vehicle starts to move from a stopped position, due to the movement of the leading vehicle, it will take a few seconds preparing to move. This delay is called the move-up delay (MUD), and it varies from one driver to another.

Based on real traffic data taken from the M4 at the approach to roadwork sections, Yousif (1993) reported that the MUD differs among drivers in the range of 0.6-4 seconds with an average of 1.8 seconds. Similarly, Al-Obaedi (2012) investigated the MUD using data taken from the M60 for passenger cars only, and found similar findings to those reported by Yousif (1993).

Based on drivers' reaction time, a value of 1 sec as a MUD will be assigned for drivers with a short reaction time (top 20% of drivers) and 2 seconds for the others. These values of the MUD were implemented in this micro-simulation model as suggested by previous researchers, such as Benekohal (1986), Yousif (1993), Al-Jameel (2012) and Al-Obaedi (2012). The acceleration rate values for the move-up delay condition (ACC_4) are 0.42 and 0.21 m/sec^2 for passenger cars and HGVs respectively following Benekohal (1986), Al-Jameel (2012) and Alterawi (2014).

6.4.5 Stopping distance (non-collision criteria) acceleration (ACC_5)

At every scanning time interval, the distance between the following and leading vehicle is calculated to ensure that this distance is sufficient for the follower to stop safely even when the leader stops suddenly. The acceleration/deceleration rate (ACC_5) that satisfies this condition can be measured using the following equations:

$$POSL - [POSf \ + Vf(\Delta t) + 0.5(ACC5)\Delta t^2] - Llead - BUF \ \geq \ Maximum\ of\ Equation\ 6.7\ or\ Equation\ 6.8 \qquad \text{Equation 6.6}$$

$$[Vf + ACC5(\Delta t)]\ Rt \qquad \text{Equation 6.7}$$

$$[Vf + ACC5(\Delta t)]\ Rt + \frac{[Vf + ACC5(\Delta t)]^2}{2MaxDECF} - \frac{VL^2}{2MaxDECL} \qquad \text{Equation 6.8}$$

The solution of the Equations (6.6, 6.7 and 6.8) will consist of two parts, as follows in Equations 6.9 and 6.10. The minimum value of these two equations will be selected to represent the safe distance between the leading and following vehicles.

$$ACC_5 = \frac{POSL - POSf - Vf(\Delta t) - Llead - BUF - Vf(Rt)}{\Delta t(Rt) + 0.5\Delta t^2} \qquad \text{Equation 6.9}$$

$$POSL - [POSf \ + Vf(\Delta t) + 0.5(ACC5)\Delta t^2] - Llead - BUF \geq \ [Vf + ACC5(\Delta t)]\ Rt + \frac{[Vf + ACC5(\Delta t)]^2}{2MaxDECF} - \frac{VL^2}{2MaxDECL} \qquad \text{Equation 6.10}$$

Where:
Rt: the reaction time of the driver (sec),
VL: the velocity of the leading vehicle (m/sec),
MaxDECF: the maximum deceleration rate for the following vehicle (m/sec^2), and
MaxDECL: the maximum deceleration rate for the leading vehicle (m/sec^2).

As mentioned earlier, for every scanning time (Δt), the five accelerations/decelerations rates (i.e. ACC_1, ACC_2, ACC_3, ACC_4 and ACC_5) are calculated and assigned for each vehicle. A unique value for the acceleration/deceleration rate (ACC) is then selected from the calculated accelerations/decelerations rates to update velocities and positions for each vehicle using Equations 6.1 and 6.2. The criteria for selecting the value of (ACC) is as shown in Figure 6.10.

ACC_1: Vehicle capability acceleration
ACC_2: Desired speed acceleration
ACC_3: Slow moving acceleration
ACC_4: Moving from stationary acceleration
ACC_5: Stopping distance (non-collision criteria) acceleration
ACC: Selected acceleration
VF and VL: The velocities of the following and leading vehicle respectively
MaxDEC: Maximum deceleration rate

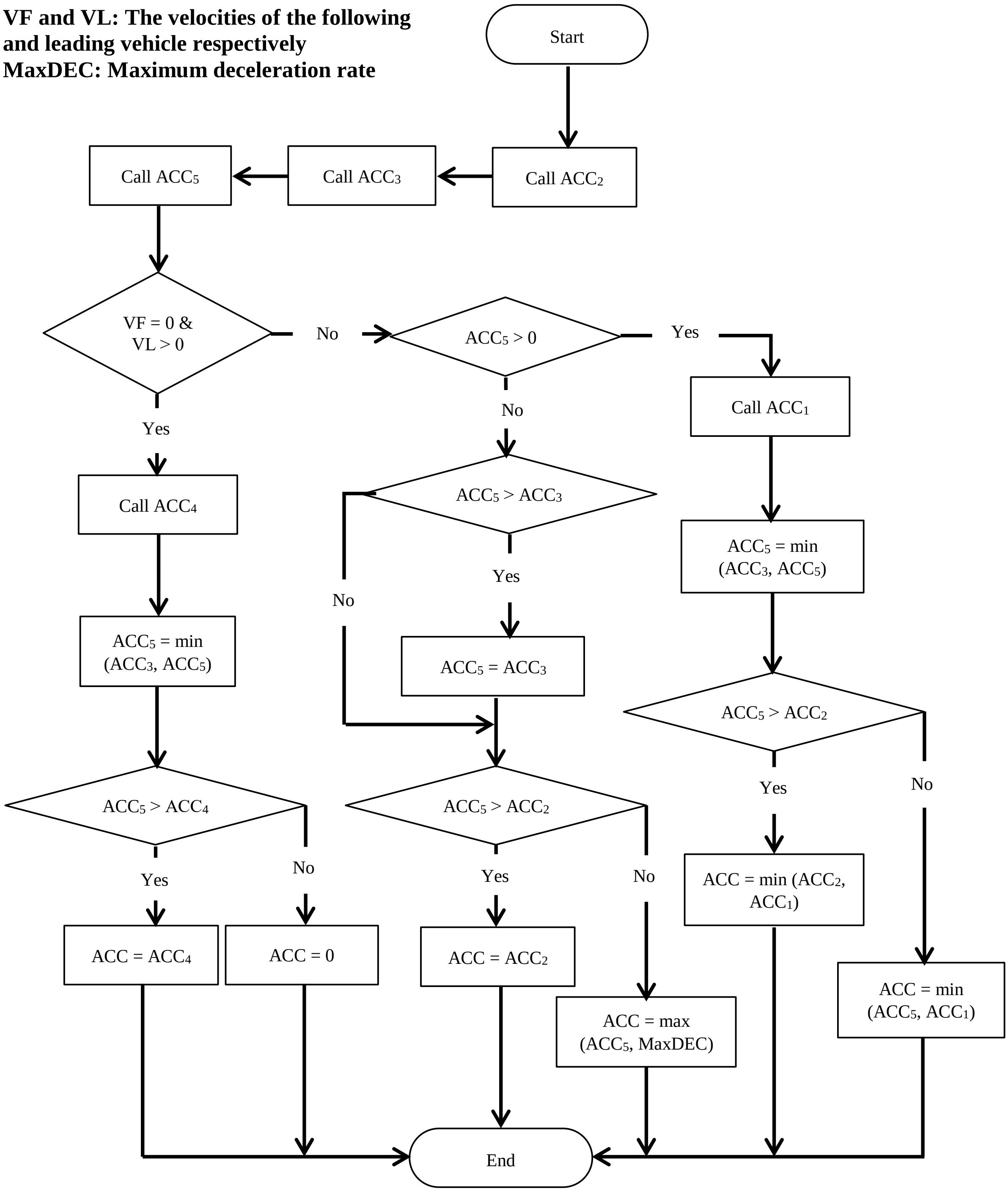


Figure 6.10: The car-following sub-model flow chart

6.5 Lane-changing rules

The lane changing sub-model governs the lateral movements of vehicles from one lane to another. In this study, the lane-changing manoeuvre forms an essential part of the newly developed micro-simulation model and has been classified into two categories: discretionary lane changing (DLC) and mandatory lane changing (MLC). In addition, the MLC was categorised into three types: free, forced, and cooperative. In this study, the DLC will be applied on normal roadway sections and at other situations when the lane-changing manoeuvre is not mandatory, while at the approach to roadwork sections (with the use of lane closures schemes) the MLC will be applied. In this section, the main assumptions that have been made for the DLC and the MLC are discussed in the following sub-sections.

6.5.1 Discretionary lane-changing (DLC)

As mentioned in Section 2.8.2, the DLC is implemented primarily when a driver endeavours to enhance his/her driving conditions, such as speed by overtaking a slower leading vehicle in front or in order to return to his/her original lane after the overtaking process. The drivers' desire to change lane and the basis of lane selection should be identified clearly in order to develop a proper DLC algorithm. The following sub-sections provide further details.

6.5.1.1 DLC toward faster lanes

Generally, drivers might change their lanes toward the faster ones (i.e. right lanes) due to the presence of a slower moving vehicle in front. When a driver feels that after a certain length of time (threshold time, THRT) he/she will be obstructed by a slower leading vehicle, the driver may then try to avoid that slower moving vehicle by moving to a faster lane (Yousif, 1993).

When the driver of vehicle (C) (see Figure 6.11) approaches from behind a slower leading vehicle (L), the driver of C will compare his/her speed with the speed of the leading vehicle (L). If the speed of C is higher than that of L by a value of R (suggested by Ferrari (1989) as R =1040/DVc; where, DVc: is the desired speed of the follower), then the desire of lane-changing is initiated and the driver of C will change to the adjacent faster lane if there are sufficient lead and lag gaps available in that lane and if the lane-changing is beneficial. The availability of the sufficient gaps is controlled by the gap acceptance sub-model, which will be discussed in the next section (Section 6.6). Following Al-Obaedi (2012), the DLC toward faster lane is considered unbeneficial if the distance between the new leading vehicle (L3) and the vehicle C is less than 100 m and the speed of the new leading vehicle (L3) is not higher than that of the leading vehicle (L) by a value of R. Figure 6.11 illustrates the positions of the surrounding vehicles that are involved in the lane-changing process for C.

Otherwise, when the speed of the vehicle (C) is not higher than that of the leading vehicle (L) by a value of R, the driver of C will stay in his/her current lane by slowing down to the speed of the leading vehicle (L), and travels with a speed lower than his/her desired speed.

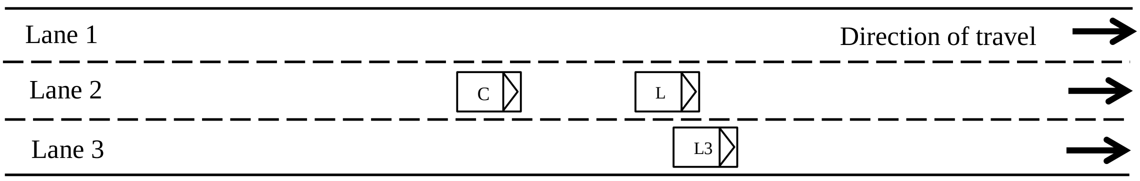


Figure 6.11: Illustration of the surrounding vehicles that affect the lane-changing process for vehicle C (DLC toward faster lane)

The separation time between successive vehicles (TBSVeh) (e.g. between C and L) is calculated, as shown in Equation 6.11, for every vehicle for every scanning time (Δt), then, the calculated TBSVeh will be compared with the threshold time (THRT). The above-mentioned process (i.e. desirability and execution of lane-changing) is initiated only if the TBSVeh becomes ≤ THRT. The value of the threshold time (THRT) parameter would be estimated from the calibration process of the lane changing sub-model, as will be discussed later in Section 7.4.2. Figure 6.12 shows the general structure of the developed rules for the DLC toward faster lanes.

$$TBSVeh = \frac{POSL - POSC - LL}{VC - VL} \qquad \text{Equation 6.11}$$

Where:
TBSVeh: the time between successive vehicles (sec),
POSL: the position of the leading vehicle L (m),
POSC: the position of vehicle C (m),
LL: the length of the leading vehicle L (m),
VC: the velocity of vehicle C (m/sec), and
VL: the velocity of the leading vehicle L (m/sec).

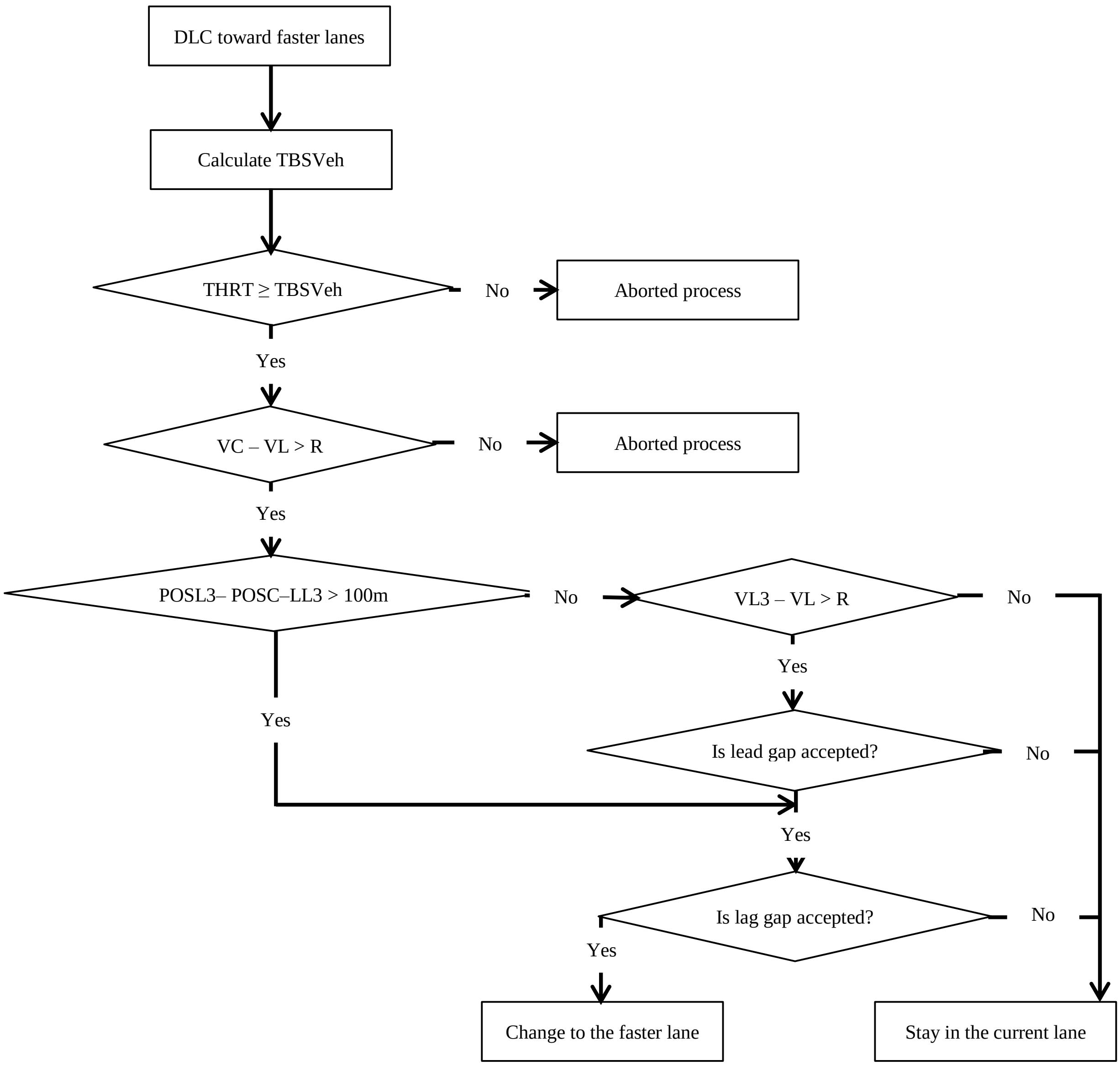


Figure 6.12: DLC toward faster lanes structure

6.5.1.2 DLC toward slower lanes

Drivers might change their lanes to the slower lanes (i.e. left lanes) for the following cases:

Case A: Avoiding obstruction of a faster moving vehicle approaching from behind, and
Case B: After the overtaking manoeuvre, drivers desire to return to their original lane.

Case A:
In situations where the driver of vehicle (C) (see Figure 6.13) is followed by a faster following vehicle (F) within a relatively short distance (threshold distance, THRD) and the driver of C feels that his/her vehicle is obstructing the following vehicle (F), then, the driver of C will desire to change to the adjacent slower lane, if the speed of C is less than that of its follower (F) by a

value of R. This is applicable only when the speed of C is equal or close to its desired speed. The value of the threshold distance (THRD) parameter would be estimated from the calibration process of the lane changing sub-model, as will be discussed later in Section 7.4.2. The decision of estimating the values of the threshold distance (THRD) and the threshold time (THRT) parameters was made due to the difficulties associated with obtaining the values of these parameters from field observations. Figure 6.13 illustrates the threshold distance (THRD) parameter and the positions of the surrounding vehicles that are involved in the lane-changing process for C.

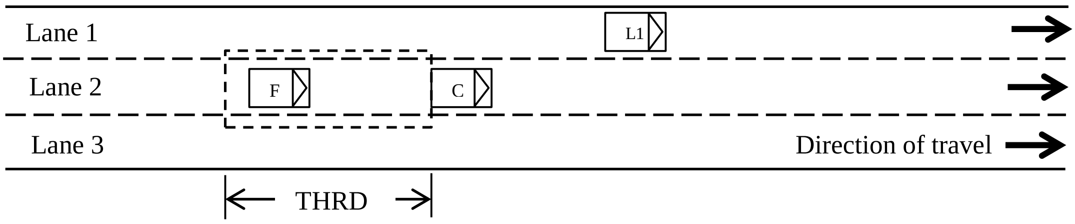


Figure 6.13: Illustration of the THRD parameter and the surrounding vehicles of vehicle C (DLC toward slower lane)

Case B:

An assumption has been made that 80% of drivers would retain their original lanes after overtaking a slower vehicle in the traffic stream, as suggested by Al-Obaedi (2012). This is not applied to drivers who are using the offside lane for overtaking as in such a case it is assumed that all drivers wish to retain their original lanes.

For both cases (A and B), the driver of C will check the situation of the slower lane (i.e. the availability of sufficient gaps and the benefit of lane changing) in order not to be trapped behind a slower leading vehicle (L1) (see Figure 6.13) in that lane. Likewise, the DLC toward slower lane is considered unbeneficial if the new leading vehicle (L1) is within 100 m and the speed of L1 is less than that for C. Figure 6.14 shows the general structure of the developed rules for the DLC toward slower lanes.

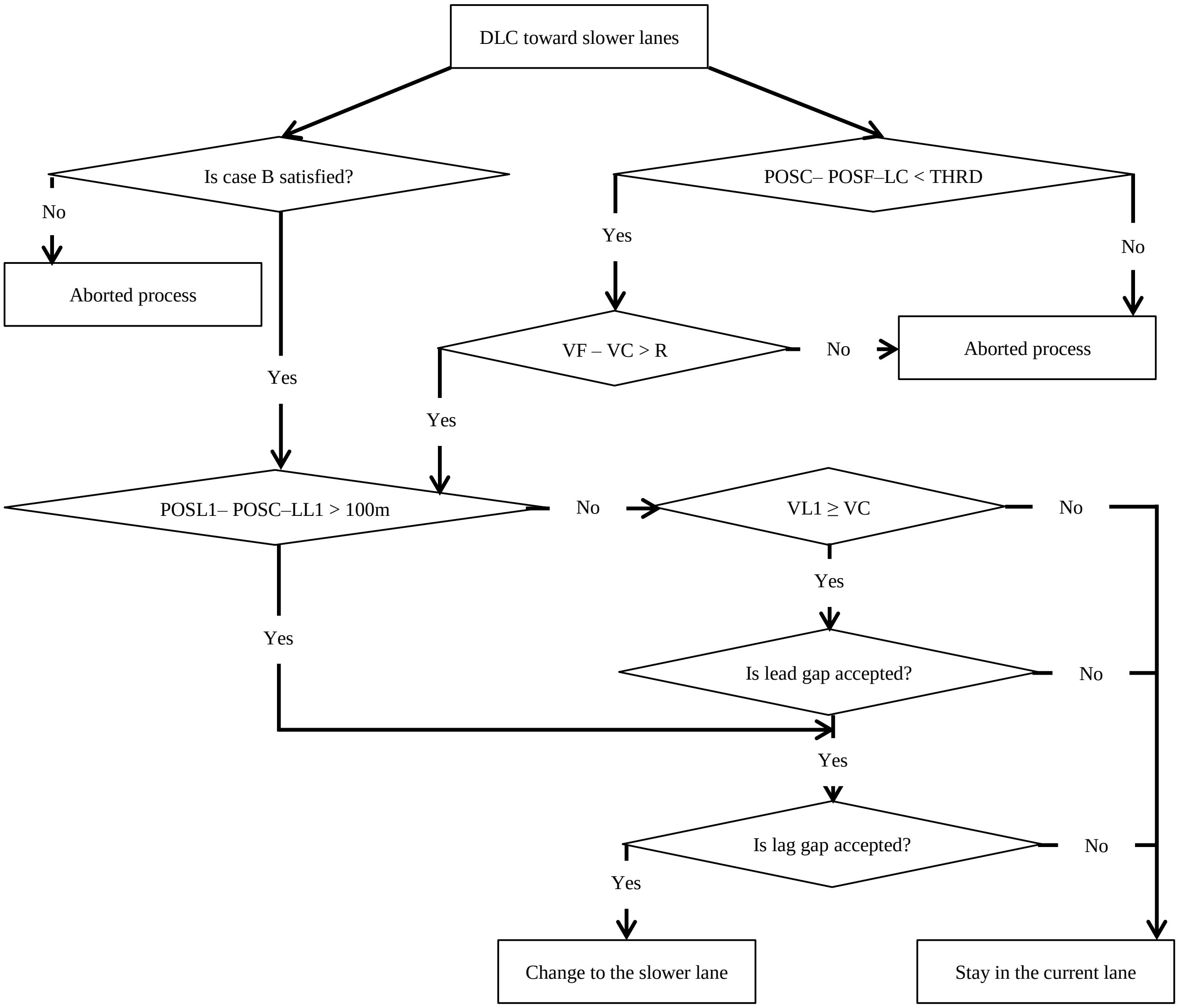


Figure 6.14: DLC toward slower lanes structure

6.5.2 Mandatory lane-changing (MLC)

In this study, the MLC is implemented at the approach to roadwork sections (with the use of lane closures schemes). When drivers approach the lane closure, they will try to change from their closed lane to an adjacent open lane depending on their urgency to perform the lane-changing (merging) manoeuvre (which depends on their distance to the end of the lane, i.e. start of the transition zone), their compliance with posted traffic signs and the courtesy behaviour of drivers in the adjacent open lane. Figure 6.15 illustrates the general structure of developed MLC algorithm for this study.

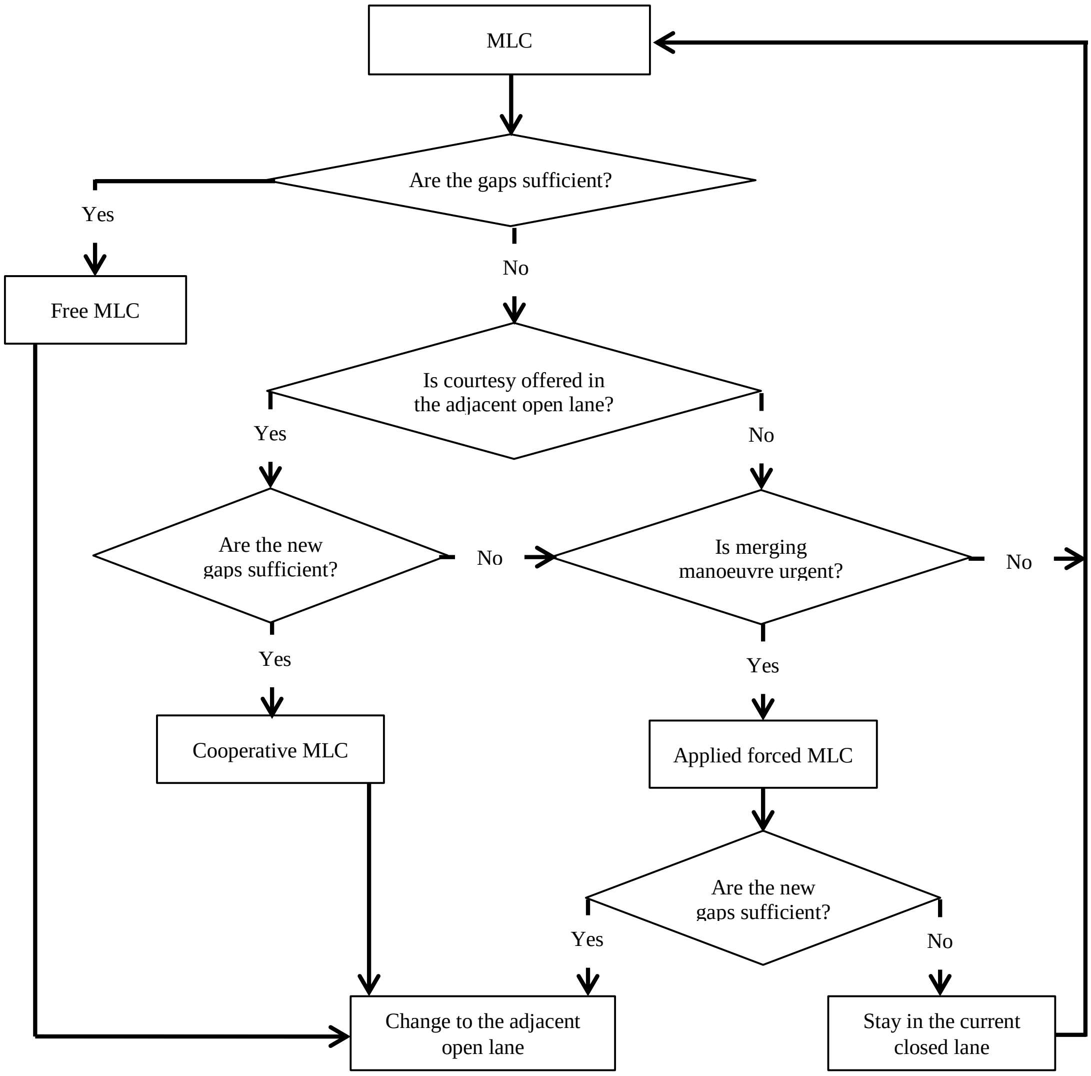


Figure 6.15: The developed MLC structure

For this study, the remaining distance to the end of the lane (as shown in Figure 6.16) is used to represent the urgency of the lane-changing (merging) manoeuvre. A value of 100 m as a remaining distance to the end of the lane was adopted in this simulation model to represent the urgency of the merger. This distance (i.e. 100 m) is within the limit suggested by Rao (2006) who reported that the merger will use the forced lane-changing (merging) manoeuvre when the remaining time to the end of the lane is lower than 10 seconds. In addition, real observations from the M67 site (2 lanes motorway roadwork site with offside lane closure) have shown that most of the observed forced merging manoeuvre cases (i.e. mergers force the new follower in the adjacent open lane) occurred when the mergers were positioned approximately less than 100 m from the end of the lane (i.e. start of the transition zone).

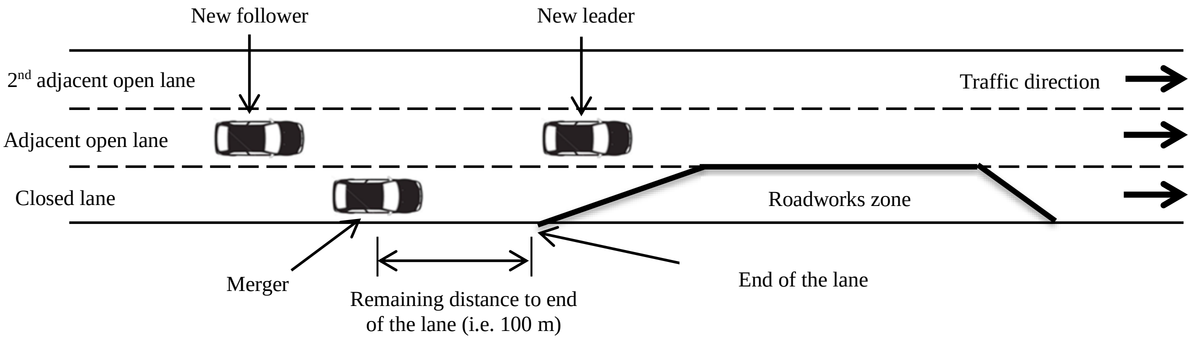


Figure 6.16: Illustration of the urgency of merging manoeuvre

In this simulation model, the merging manoeuvre is considered as a non-urgent manoeuvre if the merger is more than 100 m away from the end of the lane. Otherwise (when the remaining distance of the merger to the end of the lane is lower or equal to 100 m), the merging manoeuvre is considered as an urgent manoeuvre. In such a situation (i.e. urgent manoeuvre), and if the new follower is not offering a courtesy or the offered new gap is not sufficient, the merger would be then forcing the new follower to slow down in order to widen the gap (by using the minimum observed accepted gaps, as will be discussed in Section 6.6).

In this simulation model, the courtesy process in the adjacent open lane consists of two behaviours: cooperative slowing down and cooperative yielding, as discussed in Section 3.7.2. Both behaviours are applicable if there is more than one lane left open for traffic movements at roadwork sections (e.g. 3 or 4 lanes motorway sections with a lane closure). For those sections of roadworks with only one open lane (e.g. 2 lanes motorway section with a lane closure), only the cooperative slowing down is applicable.

The courtesy process is started by sending a courtesy request from a driver (merger) who tries to merge into an adjacent open lane to the new follower in the adjacent open lane if there are no sufficient gaps available in that lane. The new follower will then respond to this request based on his/her driver aggressiveness class (DAGC). If the new follower is class 1 (i.e. aggressive driver), then he/she would ignore the courtesy request, whereas if the new follower is class 2 (i.e. non-aggressive driver), then the new follower will show courteous behaviours to the driver merging from the closed lane. The new follower will slow down to allow the merger to change from his/her closed lane and if the speed reduction is higher than the value of R (suggested by Ferrari (1989) as R = 1040/DVc; where, DVc: is the desired speed of the following driver), then the new follower will apply the DLC manoeuvre and show a cooperative yielding behaviour by moving to the second adjacent open lane (as shown in Figure 6.16) if there is a sufficient gap in that lane.

However, the deceleration rate for the cooperative slowing down is estimated based on the car-following rules with respect to the merger and should not be exceeding the normal deceleration rate (i.e. -3 m/sec^2). Figure 6.17 illustrates the general structure for modelling the courtesy behaviour.

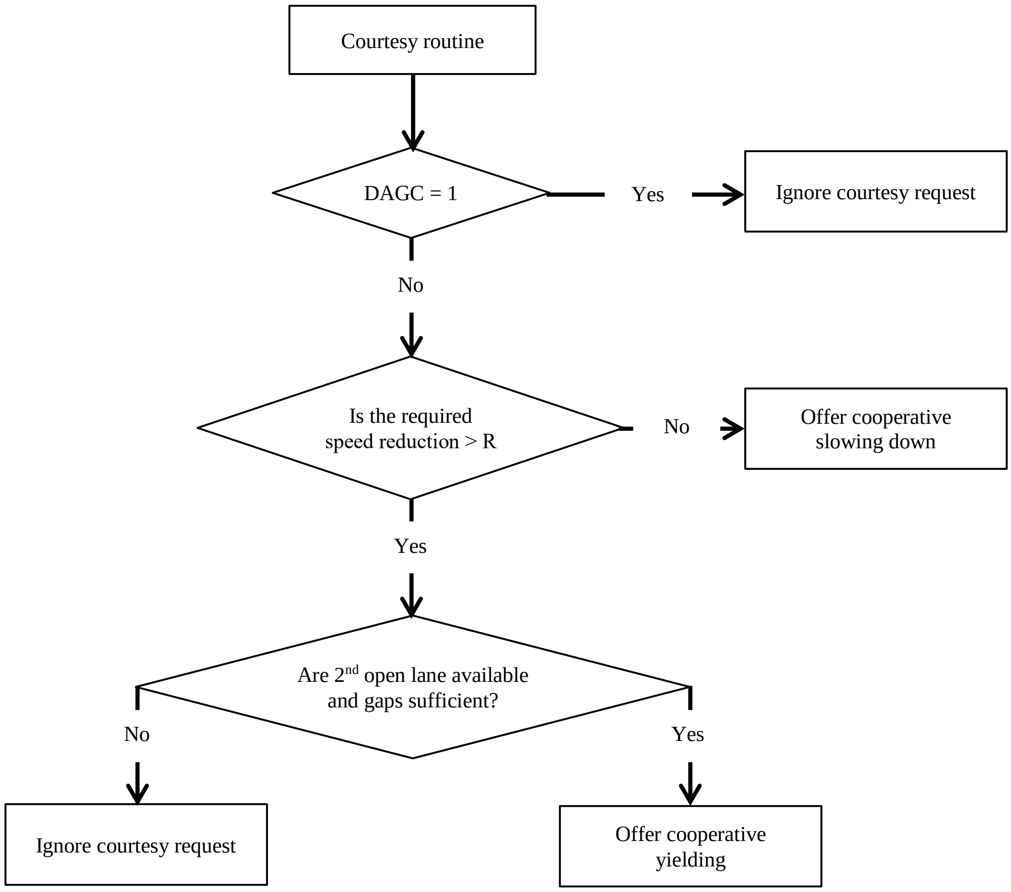


Figure 6.17: Courtesy behaviour structure

6.6 Gap acceptance rules

Basically, the gap acceptance rules are connected to the lane-changing rules. When the desire of lane-changing is initiated, the lane changer (merger) will then look for a safe lane-changing manoeuvre. The safe lane-changing manoeuvre can occur by, firstly, locating the new leading and following vehicles in the target lane, then, selecting available lead and lag gaps with values greater than the corresponding lead and lag (minimum) critical gaps.

As discussed in Sections 2.8.3 and 2.9, the gap acceptance model that has been adopted by Al-Obaedi (2012) which was based on the safety gap acceptance model by Liu (2005) has been adopted in this simulation model. Therefore, Equations 2.6 and 2.7 are applied to measure the lead critical gap and the lag critical gap, respectively, for the DLC manoeuvre.

Yousif (1993), Hidas (2005), Wang (2006), Al-Jameel (2012) and Al-Obaedi (2012) reported that the sizes of the accepted gaps for merge locations (i.e. MLC manoeuvre) are usually lower than those used in DLC manoeuvres. Therefore, Al-Obaedi (2012) used Equations 2.6 and 2.7 but without using the safety buffer space ("BUF" term) and applied a 50% factor to the first term in the equations to calculate the minimum lead and lag gaps for the MLC manoeuvre. This is also adopted in this study. Equations 6.12 and 6.13 show the calculation of lead and lag critical (minimum) gaps that are used for the MLC, respectively. Also, for the cases where the new leader is faster than the merger, a critical lead gap of 1.0 m ($G_{min,lead}$ = 1.0 m) is used as a default value. Also, a default value of 1.0 m is used as a critical lag gap ($G_{min,lag}$ = 1.0 m) when the new follower is slower than the merger, as suggested by Hidas (2002 and 2005) and Al-Obaedi (2012).

$$G_{min,lead} = \frac{Rt(VC)}{2} + Max\left[0, \left(\frac{VC^2}{2MaxDECC} - \frac{VL^2}{2MaxDECL}\right)\right] \qquad \text{Equation 6.12}$$

$$G_{min,lag} = \frac{Rt(VF)}{2} + Max\left[0, \left(\frac{VF^2}{2MaxDECF} - \frac{VC^2}{2MaxDECC}\right)\right] \qquad \text{Equation 6.13}$$

Where:
Rt: the reaction time (sec),
VC: the velocity of the subject vehicle (i.e. merger) (m/sec),
VL: the velocity of the new leader (m/sec),
VF: the velocity of the new follower (m/sec),
MaxDECC: maximum deceleration rate for the merger (m/sec^2),
MaxDECL: maximum deceleration rate for the new leader (m/sec^2), and
MaxDECF: maximum deceleration rate for the new follower (m/sec^2).

For the situation of the urgent MLC manoeuvre, the closed lane driver (i.e. merger) will accept very short gaps to move from the closed lane. According to Gipps (1986), the sense of driver's urgency to change lanes is reflected in the driver's willingness to accept smaller gaps. In the same context, Yousif (1993) reported that the observed lead and lag gaps decrease as the remaining distance to the end of lane decreases. This is consistent with the finding of Nemeth and Rouphail (1983) who reported that late merging at roadwork sections will push drivers to accept very short gaps to merge into the adjacent open lane. Therefore, the critical gaps that are obtained from Equations 6.12 and 6.13 will be compared with the minimum observed accepted gaps which can be obtained from Figure 3.8. Then, the minimum ones will be used as the critical gaps in the simulation model.

6.7 Lane closure rules

In the current simulation model, the lane closure sub-model governs the interactions and behaviours of vehicles at roadwork sections with the use of a lane closure scheme. As mentioned in Section 2.3, the MUTCD (2009) divides the temporary traffic management schemes into four zones (i.e. the advance warning zone, the transition zone, the activity zone, and the termination zone) as shown in Figure 2.1. In addition, the effect of the positions of roadworks signs has been created in this simulation model as suggested by the Traffic Signs Manual (Chapter 8, 2009). Figure 6.18 illustrates the signage layout for roadwork sections at dual carriageways with national speed limits. The following sub-sections describe the behaviours of drivers at each of these four zones.

6.7.1 Advance warning zone

According to the Traffic Signs Manual (Chapter 8, 2009) the decision of lane changing should be taken by drivers who continue to drive on the closed lane once they approach 100 m upstream of the first sign requiring a lane-change decision (i.e. 800 yards sign), as shown in Figure 6.18. Therefore, in this simulation model, the modelled drivers will seek to move to an adjacent open lane when they are less than 900 m from the end of the lane (i.e. start of the transition zone). In this area (i.e. 900 m upstream of the start of the transition zone up to the start of the activity zone) the MLC rules will be applied by drivers who are travelling on the closed lane. While drivers in the adjacent open lane maybe in one of three states:

- offering courtesy by slowing down to increase the gap for the merging vehicle,
- shifting to second adjacent open lane, or
- remaining in the same lane without offering courtesy.

Also, according to the Traffic Signs Manual (Chapter 8, 2009), the temporary speed limit should be applied 50 m in advance of the first sign indicating lane closures (i.e. 800 yards sign), as shown in Figure 6.18. Therefore, the modelled drivers will adapt their speed limit (from the national speed limit (i.e. 70 mph) to the temporary speed limit (i.e. 50 mph)) when they are less than 850 m from the start of the transition zone.

Similarly to the normal roadway sections (as discussed in Section 6.3.2.2), if the modelled drivers are not complying with the posted speed limit, they will start using their roadworks desired speeds which were generated from Figure 3.10 (as discussed in Section 3.7.3) once they pass the first temporary speed limit sign (i.e. 850 m away from the start of the transition zone). Otherwise, if they are complying with the speed limit, the applied temporary speed limit (i.e. 50 mph) will be assigned as a desired speed to those drivers.

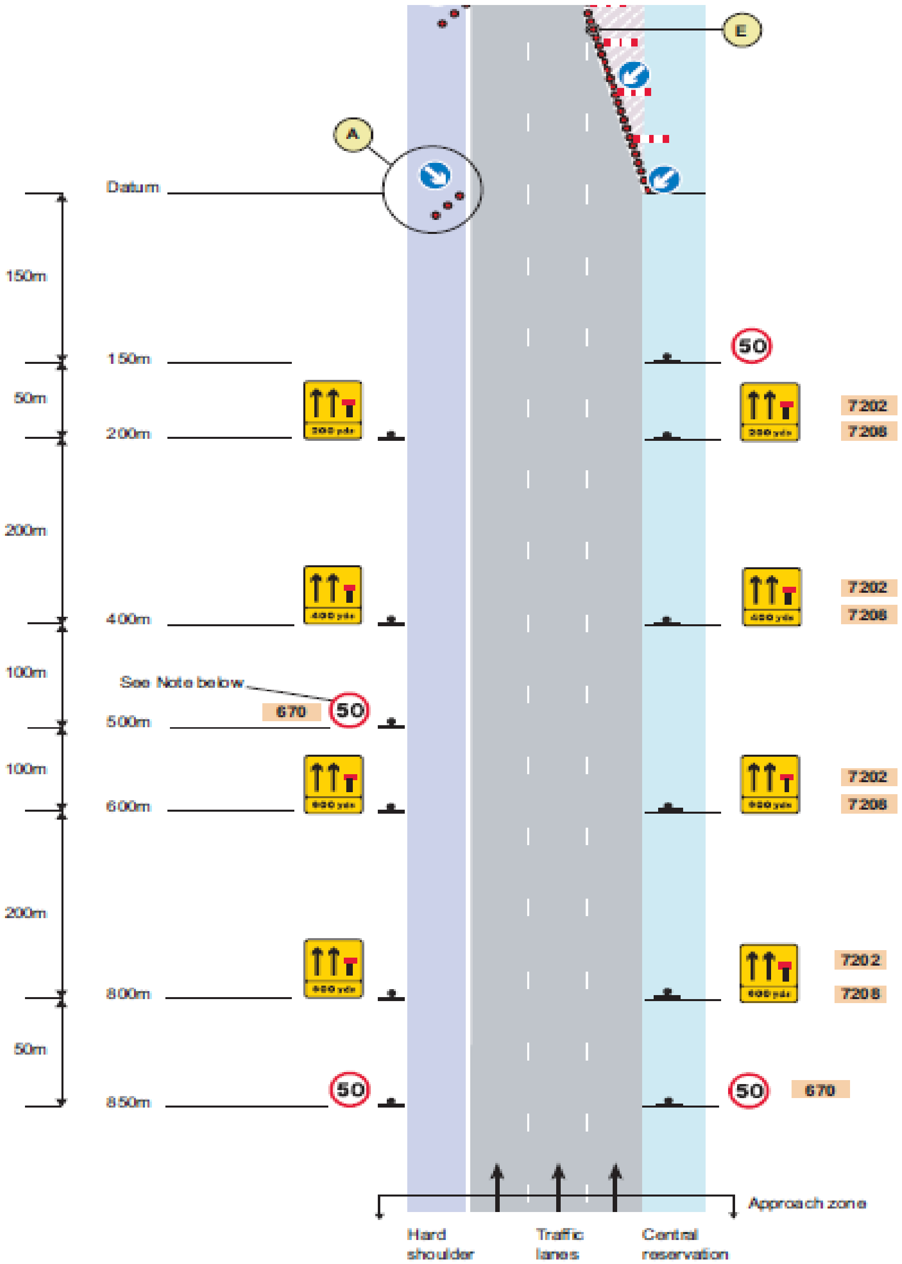


Figure 6.18: Signage layout at roadwork sections (Traffic Signs Manual - Chapter 8, 2009)

6.7.2 Transition zone

As drivers pass the end of the lane, the urgency to change lane is highly increased for those who are still travelling on the closed lane. However, those drivers (who try to merge into an adjacent open lane) will stop at the end of the transition zone if sufficient gaps are not available. Drivers in the adjacent open lane are still in one of the three states: either offering courtesy by slowing down, shifting to second adjacent open lane, or remaining in the same lane without offering courtesy.

6.7.3 Activity zone & termination zone

The activity zone will start after withdrawing the closed lane from the carriageway as shown in Figure 2.1. In this zone, all vehicles have moved from the closed lane to the adjacent open lane. Therefore, the MLC rules (which were applied by drivers on the closed lane) and the courtesy behaviours (which were applied by drivers in the adjacent open lane) are aborted in this zone and beyond. The termination zone is located at the end of the activity zone, where the road layout returns to its normal condition (normal driving condition is restored, such as national speed limit).

6.8 Narrow lanes rules

The narrow lanes scheme requires narrowing the width of existing lanes only, without withdrawing any lane from the carriageway. Therefore, the MLC rules and the courtesy behaviours are not applied by drivers who drive on roadwork sections with a narrow lanes scheme.

The observed behaviours associated with narrow lane sections as described in Chapter 4 (i.e. avoiding behaviour when passing/overtaking HGVs) have been integrated within the developed micro-simulation model. The lane repositioning before passing HGVs behaviour was not integrated within the developed model since it is believed that this behaviour mainly affects the safety levels of traffic which is out of the scope of the developed model. However, the avoiding behaviour when passing/overtaking HGVs splits into: avoiding passing HGVs on the adjacent lane and avoiding passing HGVs on the same lane. The main assumptions that have been made for both behaviours of avoiding passing HGVs are discussed in the following sub-sections.

6.8.1 Avoiding passing HGVs on adjacent lane

As discussed in Section 4.4.1, field observations have shown that a relatively high number of observations of drivers following a HGV travelling on adjacent lanes, avoid passing the HGV even when their lane is clear from vehicles. The percentage of these drivers (who prefer following the HGV on adjacent lane, FDAL%) was found to be around 47%, for the M6 site. In the current simulation model, this behaviour has been modelled by generating a random number (RN) for each driver. The driver is regarded as an avoider if the generated number (RN) is equal to or lower than the percentage of avoiders on the adjacent lane (FDAL%), otherwise he/she will be regarded as a passer.

When the driver of vehicle C (see Figure 6.19) approaches from behind a HGV on the adjacent lane and if the driver of C is considered as a passer (i.e. FDAL% < RN), he/she will continue interacting (accelerate/decelerate) with his/her current leader (L) in the current lane and ignoring the presence of the HGV. Otherwise, if the driver of C is considered as an avoider (i.e. FDAL% ≥ RN), then he/she will start interacting with the HGV on the adjacent lane in order to keep following that HGV. The acceleration/deceleration rate that is applied by the avoider (C) is the minimum of A1 (which is the acceleration/deceleration rate with respect to current leader (L) in the current lane) and A2 (the acceleration/deceleration rate with respect to the HGV in the adjacent lane), as shown in Figure 6.19. It should be noted that each of Al and A2 are obtained from the car-following rules that were discussed in Section 6.4. The process of modelling the avoiding passing HGVs in the adjacent lane on narrow lanes sections is illustrated by the flowchart in Figure 6.20. This process is applicable while drivers are travelling in transition and activity zones where the lanes are narrowed. Before or after these zones (where normal lane width is restored) this process is not applicable.

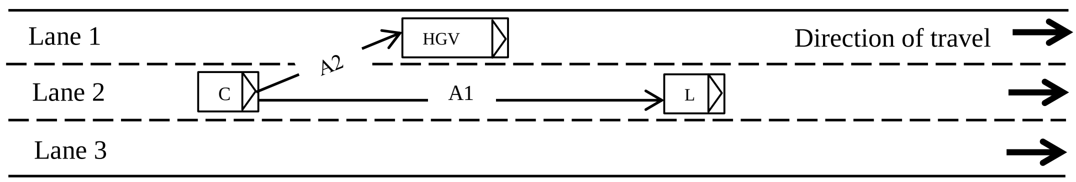


Figure 6.19: Illustration of the calculation of acceleration rates for avoiders

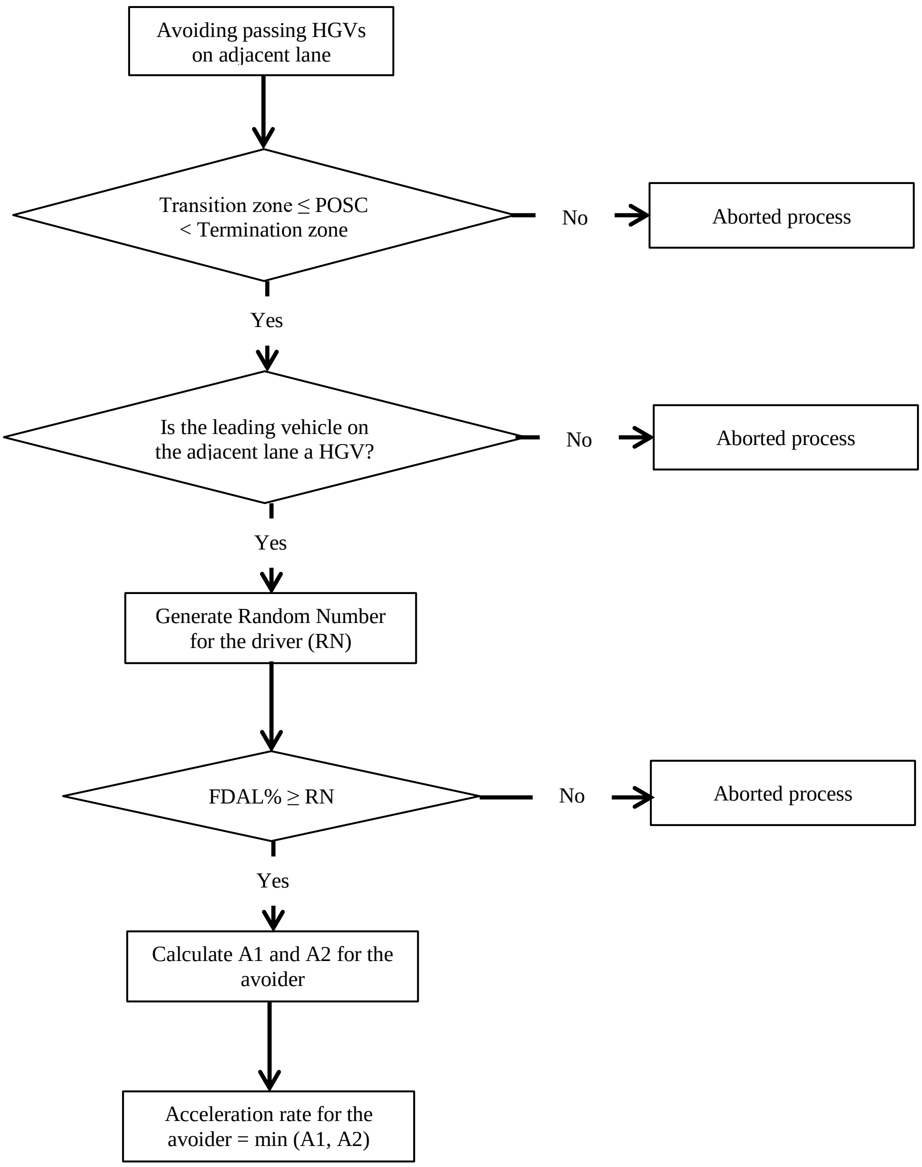


Figure 6.20: Flow chart for modelling the "avoiding" of passing HGVs on adjacent lane

6.8.2 Avoiding passing HGVs on same lane

The second behaviour of the avoiding behaviour when passing/overtaking HGVs is avoiding overtaking HGVs on the same lane. As discussed in Section 4.4.3, the percentage of drivers who prefer staying in the same lane driving behind a HGV and following it even if they have the opportunity to overtake (FDSL%) was not measured due to the shortage of observed section length from the video footage. Therefore, the value of the FDSL parameter would be estimated from the calibration process of the narrow lanes sub-model, as will be discussed later in Section 7.4.4. Likewise, this behaviour (i.e. avoiding overtaking HGVs on the same lane) has been modelled by generating a random number for each driver. The driver is regarded as an avoider if the generated number is equal to or lower than the percentage of avoiders on the same lane (FDSL%), otherwise he/she will be regarded as a passer. The avoider (C) will stay in his/her current lane driving behind his/her leading HGV and refuse any desire of overtaking the HGV even if the new leading vehicle (L2) is far away and the lane-changing manoeuvre is beneficial (DLC toward faster lanes), as shown in Figure 6.21. The process of modelling the avoiding of overtaking HGVs on the same lane is illustrated by the flowchart in Figure 6.22. Likewise, this process is applicable while drivers are travelling in transition and activity zones where the lanes are narrowed. Before or after these zones (where normal lane width is restored) this process is not applicable.

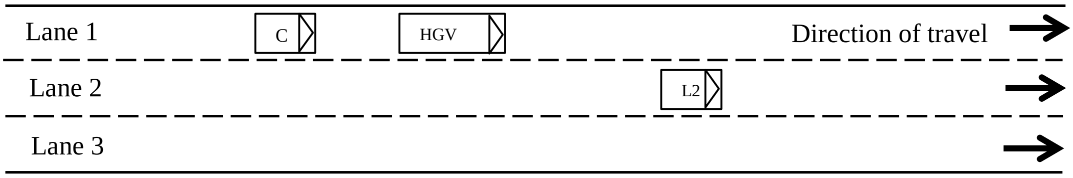


Figure 6.21: Illustration of the surrounding vehicles for the avoider (vehicle C)

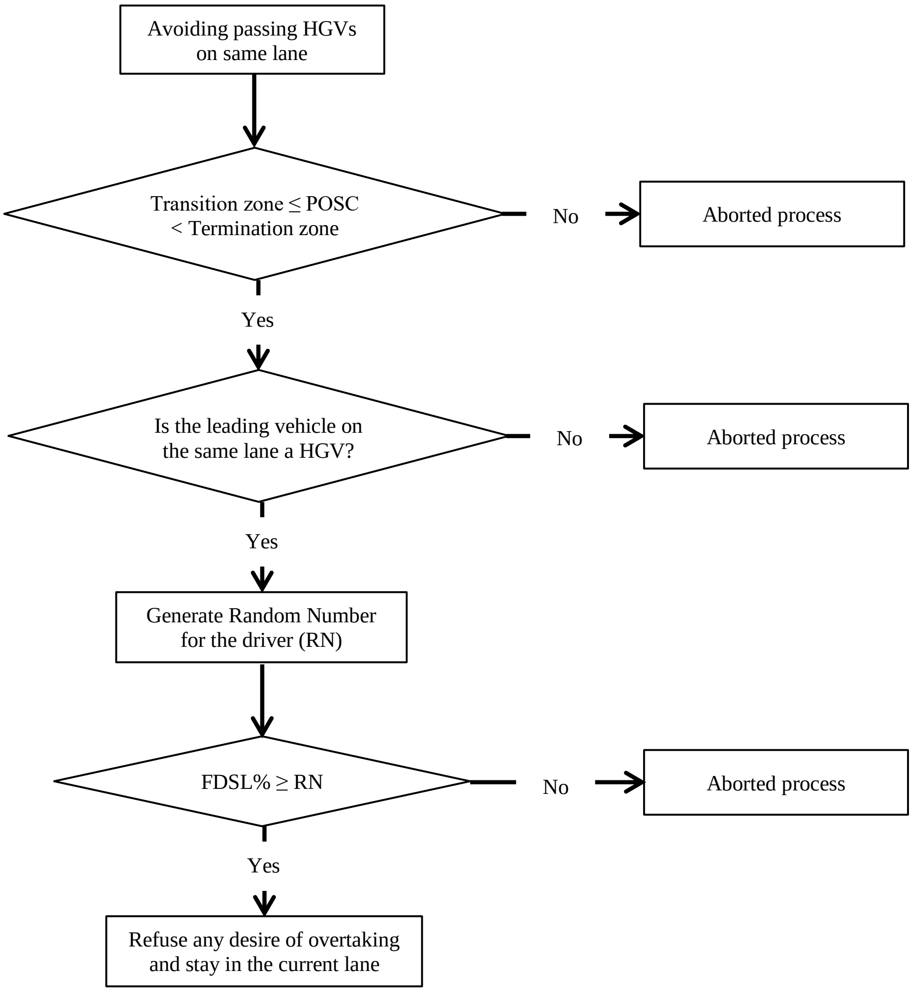


Figure 6.22: Flow chart for modelling the “avoiding” of overtaking HGVs on the same lane

6.9 Other characteristics of the developed model

Other characteristics were added in the newly developed micro-simulation model, such as warm-up and cool-off sections which have been introduced (500 m each) at the beginning and termination points of the simulated section, respectively. The purpose of having such sections for the warm-up section, is to eliminate the unsteady conditions during the start of the simulation model, whereas for the cool-off section, it is to prevent the effect of traffic behaviour changing abruptly due to the exiting of vehicles from the simulated section. In both of these sections, the simulation outputs are ignored. Several simulation studies have adopted the value of 500 m for these sections (i.e. warm-up and cool-off sections), see for example Zia (1992), Yousif (1993), Purnawan (2005) and Alterawi (2014).

Warm-up and cool-off periods have also been introduced (5 minutes each) in the current simulation model at the start and the end of the simulation period. The simulation outputs are also ignored in these periods. The purpose of having a warm-up period is to ensure that some vehicles have crossed the total length of the simulated section to ensure a steady condition of the traffic behaviour, whereas the purpose of the cool-off period is the same as previously reported for the cool-off section.

The simulated section is divided into a number of sub-sections (i.e. data collection points) in order to collect the data from the model. The number and locations of these sub-sections can be varied, and the interval of the unit length where the sub-sections are located can be easily changed through the input file.

6.10 The developed model output

The output of the developed micro-simulation model consists of two levels of output data. These are: first, micro output data which gives detailed information such as vehicle position, speed and acceleration/deceleration rate, and spacing between vehicles, and second, macro output data which consists of traffic flows, average speeds and delays.

6.11 The developed model capabilities

The model is designed in order to test the effect of different temporary traffic management schemes that are applied at motorway roadwork sections (i.e. lane closure and narrow lanes schemes) on system capacity and delay. In addition, the effects of various parameters (i.e. HGVs%, section length, speed limits and drivers' compliance with the speed limit) on system capacity and delay were also tested. Furthermore, all related parameters are easily changed in the input file in order to assess the effect of applying different values.

6.12 Summary

This chapter described the development of the newly developed micro-simulation model for motorway roadwork sections. The developed model consists of five sub-models (i.e. car-following, lane changing, gap acceptance, lane closure and narrow lanes rules) which were also described in detail in this chapter. These rules have been developed with the help of real observations from UK motorway sites as well as some related previous studies.

- The car-following sub-model has been developed based on the assumptions of the CAR-following SIMulation model (CARSIM) which has been suggested by Benekohal (1986).
- The lane-changing sub-model has been classified into two categories, DLC and MLC. The DLC is applied on normal roadway sections and at other situations when the lane changing manoeuvre is not mandatory, while at the approach to roadwork sections (with the use of lane closures schemes) the MLC will be applied. In addition, the MLC was categorised into: free, forced and cooperative.
- The gap acceptance sub-model that has been adopted by Al-Obaedi (2012) which was based on the safety gap acceptance model by Liu (2005) has been adopted in this simulation model.
- The lane closure sub-model has been developed in order to govern the interactions and behaviours of drivers at roadwork sections with the use of a lane closure scheme. The cooperative behaviours of drivers (i.e. slowing down and yielding) were integrated in this sub-model.
- The narrow lanes sub-model has been developed to govern the interactions and behaviours of drivers at roadwork sections with the use of a narrow lanes scheme. The observed driving behaviours from narrow lanes sites (i.e. avoiding passing HGVs) were integrated in this sub-model.

The following chapter will describe the verification, calibration and validation processes of this developed micro-simulation model using field data taken from different motorway sites.

Limitations identified in the current chapter: the development of the new micro-simulation model has been based on data taken from selected UK motorway roadwork sites. More data from other parts of the country as well as other countries would make the newly developed micro-simulation model more comprehensive to include the effect of any variations in driving behaviours.

CHAPTER SEVEN
MODEL VERIFICATION, CALIBRATION AND VALIDATION

7.1 Introduction

The newly developed model (as referred to in the previous chapter) should be assessed and tested by comparing its outputs with real traffic data before applying it to evaluate the existing TTMSs. Three processes were adopted in assessing the performance of the developed model; these are verification, calibration and validation. These processes are dependent and repetitive as suggested by May (1990) and Al-Obaedi (2012) since any discovered errors may require adjusting the model's assumptions and/or parameters. Figure 7.1 shows a typical structure for the verification, calibration and validation process to be applied for any simulation model.

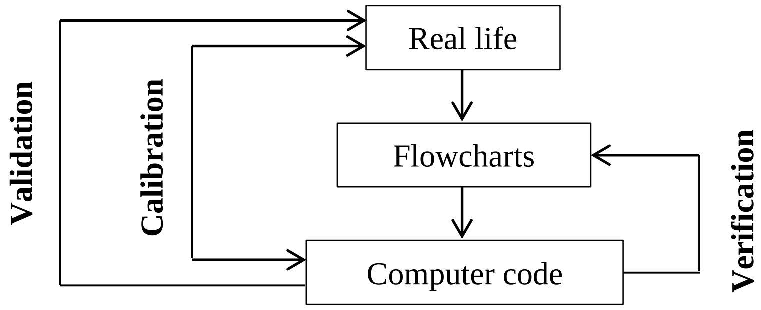


Figure 7.1: Micro-simulation model verification, calibration and validation processes (May, 1990)

In this chapter, the statistical tests and the three processes of assessing the performance of the developed model are discussed in details in the following sections.

7.2 Statistical tests

For the purpose of the calibration and validation processes, several statistical tests were used. In addition to the previously described tests in Chapter 5 (i.e. RMSE, RMSEP and GEH), three new statistical tests have also been used to test the goodness-of-fit between observed and simulated results. These are the Theil's inequality coefficient (U), the Theil's mean difference (Um) and the Theil's standard deviation difference (Us). All of these tests are extensively used in calibration and validation processes of traffic simulation models (see for example Wang, 2006; Al-Jameel, 2012; Al-Obaedi and Yousif, 2012; and Alterawi, 2014). Their equations are given in Equations 7.1 to 7.3.

- ***Theil's Inequality Coefficient (U):***

The Theil's inequality coefficient (U) measures how well simulated results are close to corresponding observed values. The U value is bounded between 0 and 1; with a value of 0 representing a perfect fit, and a value of 1 represent the worst possible fit (Wang, 2006). This test is considered to be more efficient than the RMSE or RMSEP (Al-Obaedi, 2012). It can be determined by the following equation (Wang, 2006):

$$U = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i)^2} + \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i)^2}} \qquad \text{Equation 7.1}$$

Where,
n: number of time intervals,
x_i: observed data at time interval i, and
y_i: simulated results at time interval i.

- ***Theil's mean difference (Um):***

The Theil's mean difference (Um) represented in Equation 7.2 measures the difference between the mean values. The Um value is between 0 and 1 with a lower value giving a better fit (Wang, 2006).

$$Um = \frac{(\mu x - \mu y)^2}{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad \text{Equation 7.2}$$

Where,
μx: the mean of the observed data, and
μy: the mean of the simulated data.

- ***Theil's standard deviation difference (Us):***

The Theil's standard deviation difference (Us) represented in Equation 7.3 measures the degree of variability of the simulated results compared with observed data by comparing standard deviation values (Alterawi, 2014). The Us value is also between 0 and 1.

$$Us = \frac{(\sigma x - \sigma y)^2}{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \qquad \text{Equation 7.3}$$

Where,
σx: the standard deviation of the observed data, and
σy: the standard deviation of the simulated results.

According to Alterawi (2014), satisfactory model results will be achieved if (U) is lower than 0.3. According to the Design Manual for Roads and Bridges (1996), the GEH should be ≤ 5 for the link flow to be satisfactory. These thresholds, along with other measures, are monitored throughout the calibration/validation process to ensure acceptable model quality.

7.3 Verification process

The verification process could be defined as the procedure of checking the accuracy of translation of proposed flowcharts and assumptions into a computer code. This could be achieved by observing the animation of the developed model and the simulation outputs to check if they are logical under several input parameters without the use of real data (Wang, 2006; Al-Jameel, 2012 and Alterwai, 2014).

In this study, the model verification process has been achieved at earlier stages of the model development by observing the animation, checking the model outputs (for example vehicle length distribution, headway distribution, travel time, desired speed, lane utilisation, etc.) and debugging the program code for any errors or illogical behaviour. A typical screenshot from the developed model run is as shown in Figure 7.2.

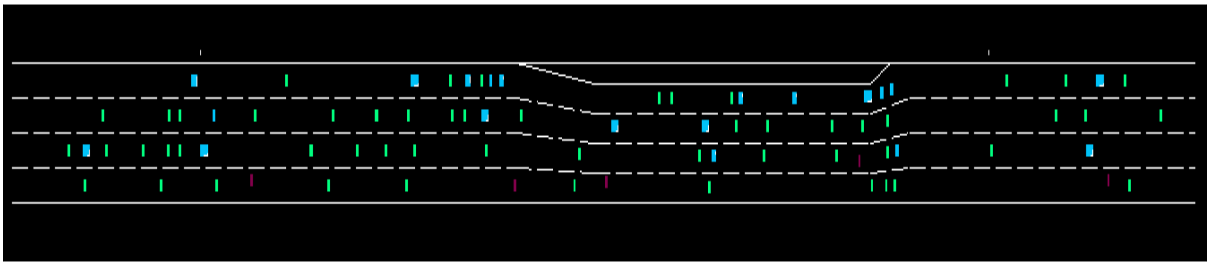


Figure 7.2: Typical screenshot from the newly developed micro-simulation model (narrow lanes roadworks section)

By investigating the distributions of simulated desired speed and passenger cars length, it was found that the distributions of both desired speed and cars' length are approximately the same as normal distribution as shown in Figure 7.3. This is similar to what was expected (as assumed in generating of these distributions). Likewise, it was found that the shifted negative exponential distribution fits the distribution of the simulated headways (as shown in Figure 7.4); this is the same as assumed for generating these headways. In addition, several characteristics (e.g. traffic composition, vehicles' travel time, reaction time, etc.) and rules (e.g. car-following, lane changing, lane closure and narrow lanes) were tested against the logical behaviour. See for example, Figure 7.5 which shows the simulated lane utilisation results for a three lanes normal motorway section. The simulation results were gathered at a location 1000 m after the end of the warm up section. The verification results proved that the newly developed model provided results as expected.

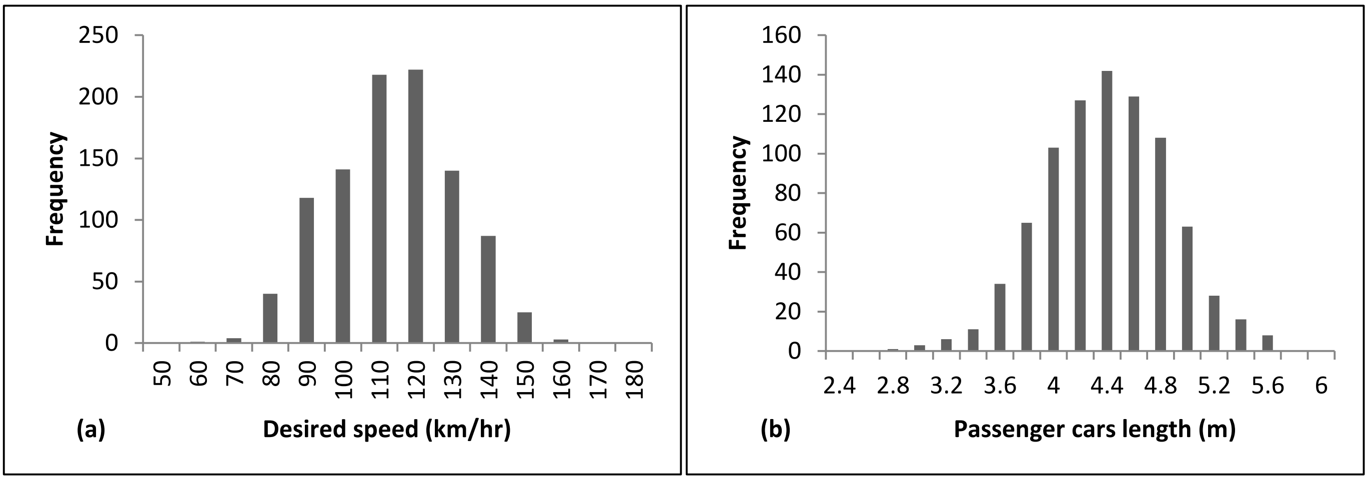


Figure 7.3: Verification - simulated (a) desired speed distribution (b) passenger cars length distribution

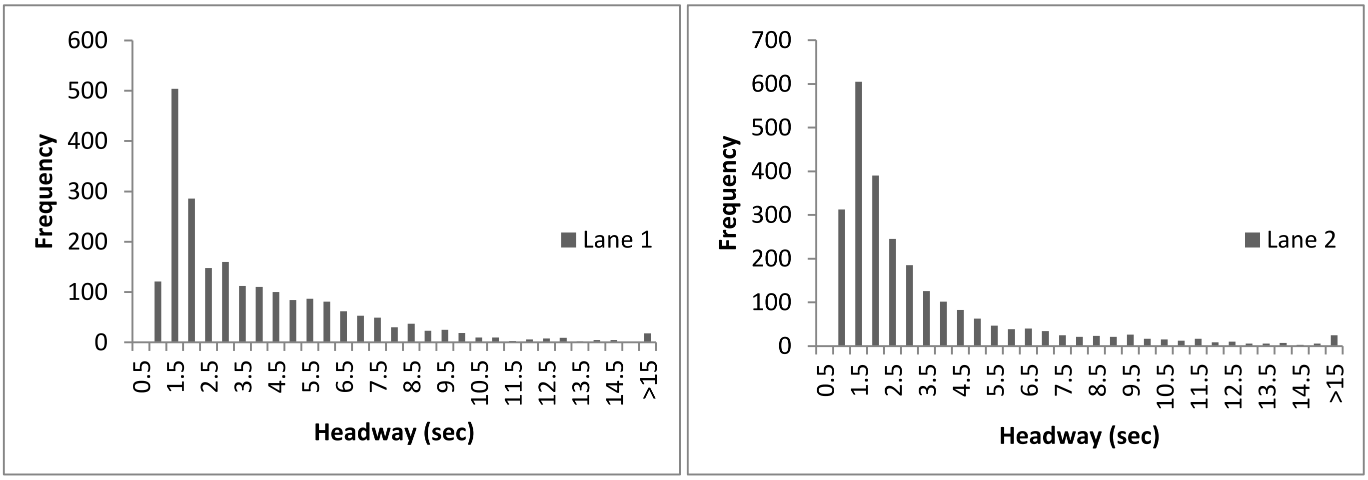


Figure 7.4: Verification - simulated headway distribution for a 2-lane normal motorway section

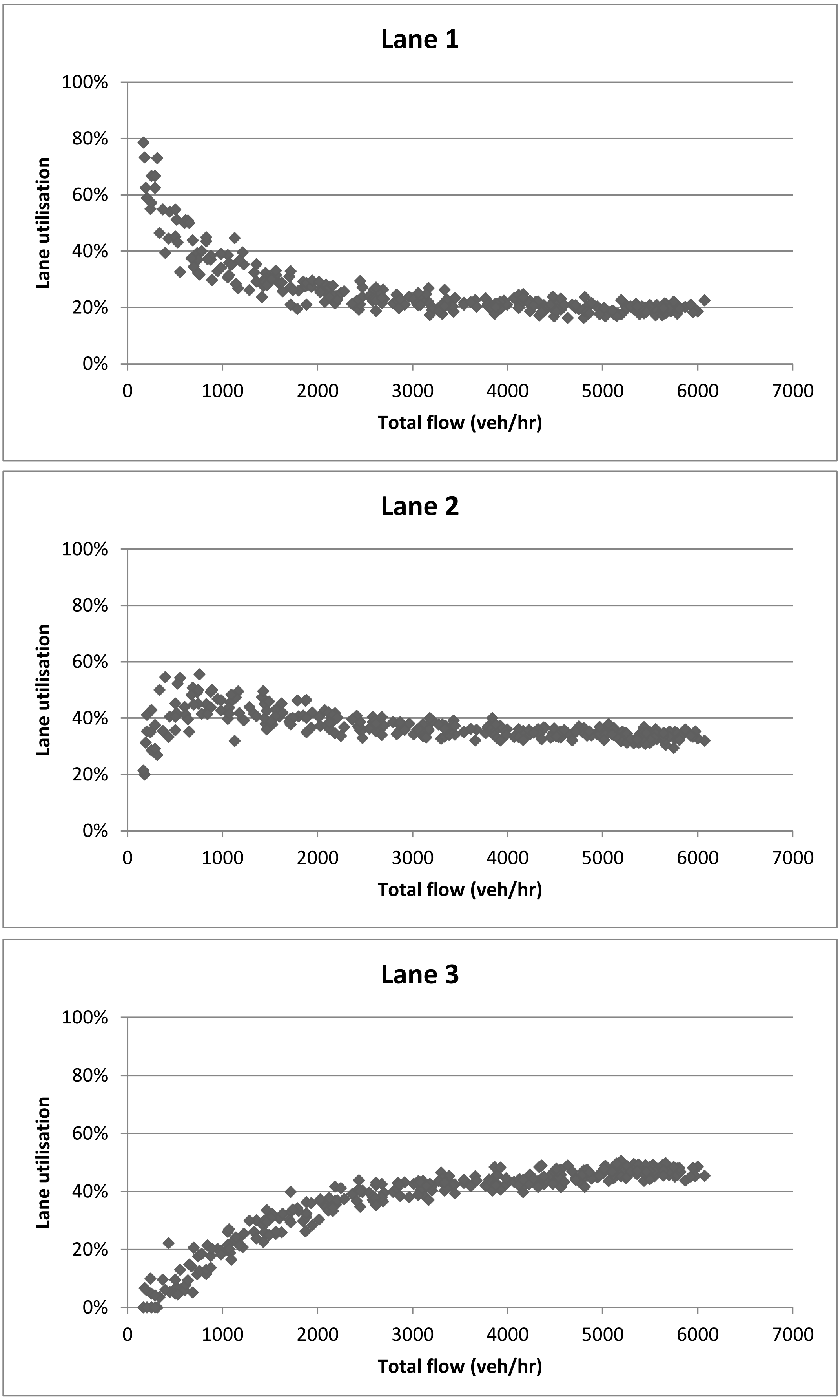


Figure 7.5: Verification - simulated lane utilisation results for a 3-lane motorway section

The sensitivity of simulation results to the variation in the random number seeds used has also been tested. Figure 7.6 shows the simulation results for five simulation runs for the same input data but with different seeds. The simulation results (i.e. flow, average speed and average delay) were collected at the end of the roadwork zone (for a 2-lane motorway section with an inside lane closure and a total length of the simulated section of 5000 m). One hour of simulation time (excluding the periods of warm-up and cool-off) is used for each run. It can be seen from Figure 7.6 that the using of different seeds has no significant effect on the results.

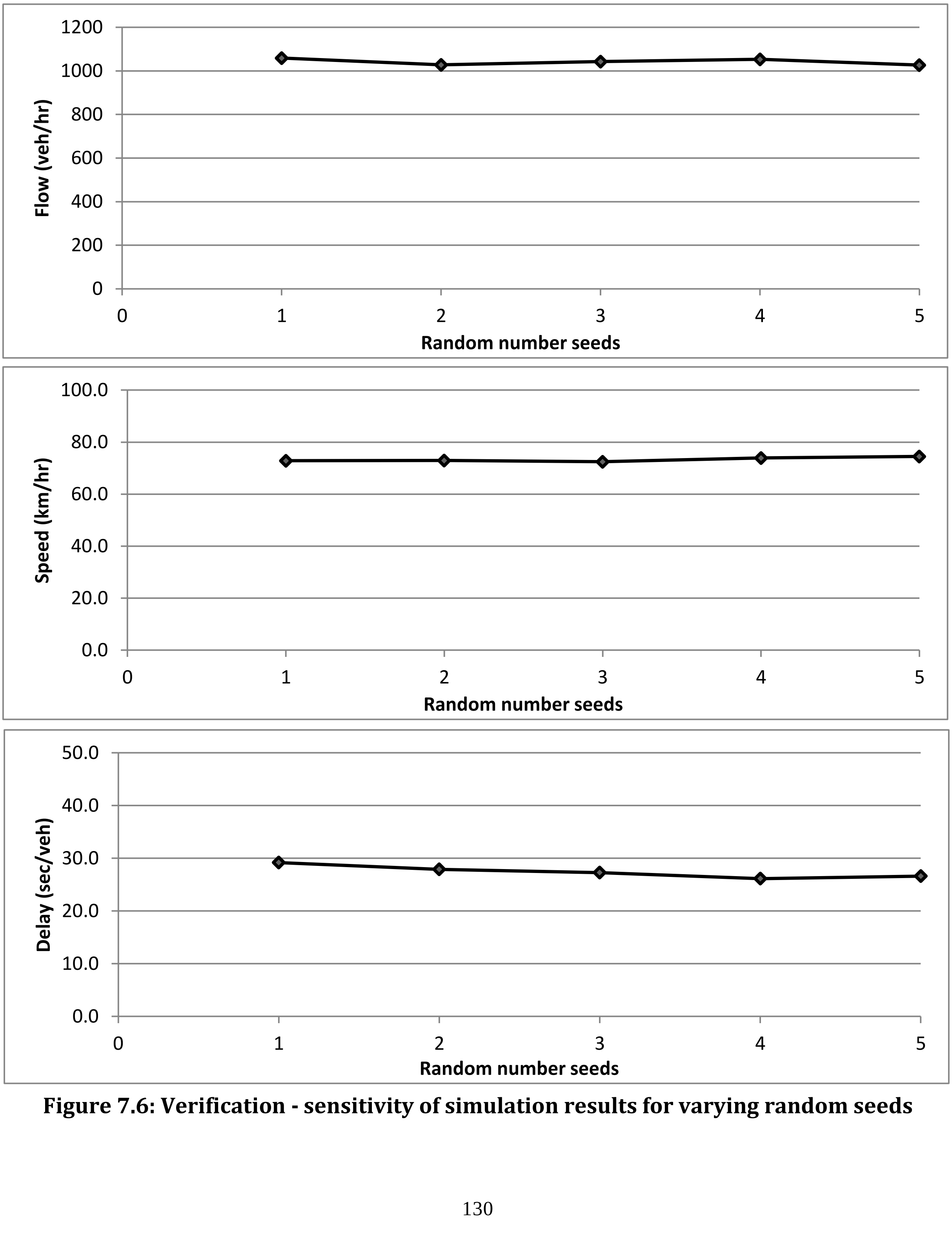


Figure 7.6: Verification - sensitivity of simulation results for varying random seeds

7.4 Calibration process

According to Liu and Wang (2007), the model calibration process can be defined as the process of adjusting model parameters in order to achieve a closer fit between observed and simulated results. In the current study, the model calibration process has been achieved by performing several simulation runs (i.e. several iterations). During these iterative processes, the model parameters/rules were adjusted in order to achieve the closer fit between the simulated and observed data. Therefore, the results presented in this section represent the best results that could be obtained based on several runs. In this section, the calibration process for car-following, lane changing, lane closure and narrowing lanes sub-models are described in details in the following sub-sections.

7.4.1 Calibration of the car-following sub-model

For the purpose of calibration of the developed car-following sub-model, field trajectory data that was collected by the Robert Bosch GmbH Research Group has been used in this study. This data was gathered by using an instrumented vehicle to record the relative speed and space headway between the instrumented vehicle and the leading vehicle (i.e. the vehicle immediately in front). The trajectory data is taken from Panwai and Dia (2005) (based on a single lane road in Stuttgart, Germany) and is characterised as follows:

- Three stop-and-go conditions.
- A range of speed between 0 and 60 km/hr.
- The duration of the test is 300 seconds for a distance of 2.5 km.

The reason behind using this field trajectory data is that the gathering of such data (which covers different traffic conditions) needs extensive resources and this is out of the scope of the current study due to time and resources limitations. In addition, such data is very limited or unpublished in the UK.

Panwai and Dia (2005) used this trajectory data to evaluate the car-following behaviour of many well-known micro-simulation models such as S-Paramics, VISSIM and AIMSUN. For the purpose of this evaluation, two statistical tests (RMSE and EM, Error Metric) have been used by Panwai and Dia (2005) to compare the simulated clear spacing between the leader and the follower with the observed data. The results of the tests with the newly developed micro-simulation model are presented in Table 7.1. The Error Metric (EM) test can be expressed by the following equation (Panwai and Dia, 2005):

$$EM = \sqrt{\sum \left(\log \frac{Y}{X}\right)^2} \qquad \text{Equation 7.4}$$

Where,
X & Y: the observed and simulated space headway, respectively.

Table 7.1: Performance of the car-following sub-model in the selected traffic simulation models (Panwai and Dia, 2005)

Statistical test	AIMSUN (v4.15)	VISSIM (v3.70)		PARAMICS (v4.1)	The developed simulation model
		Wiedemann 74	Wiedemann 99		
EM	2.55	4.78	4.50	4.68	**3.19**
RMSE (m)	4.99	5.72	5.05	10.43	**4.97**

As discussed in Section 6.4, the developed car-following sub-model has been based on a safety criterion. Therefore, and following Alterawi (2014), the safety buffer space between successive vehicles and the driver's reaction time are considered the main parameters influencing the car-following behaviour. The developed simulation model has been run several times to select the optimum values of the buffer space and the driver's reaction time. A range of values starting with 0.5 sec and ending with 2.2 sec have been tested for the driver's reaction time, whereas for the buffer space the tested values are ranging from 0.8 m to 3.5 m. The results of the initial simulation run (i.e. buffer space = 0.8 m and reaction time = 0.5 sec) revealed that the values of RMSE and EM are 7.37 m and 6.29, respectively, whereas the best results have been obtained by using an optimum buffer space value of 1.8 m and an optimum reaction time of 1.4 sec, the values of RMSE and EM for the best results are 4.97 m and 3.19 respectively. Figure 7.7 shows the best results when comparing the observed and simulated clear spacing between the leading and the following vehicles.

Figure 7.7 shows good agreement between the simulated and the observed clear spacing between the follower and the leader. Furthermore, it can be seen from Table 7.1 that the developed simulation model is the second best model after AIMSUN (with a very small difference) in terms of the representation of the leader-follower relationships on the basis of this test conditions.

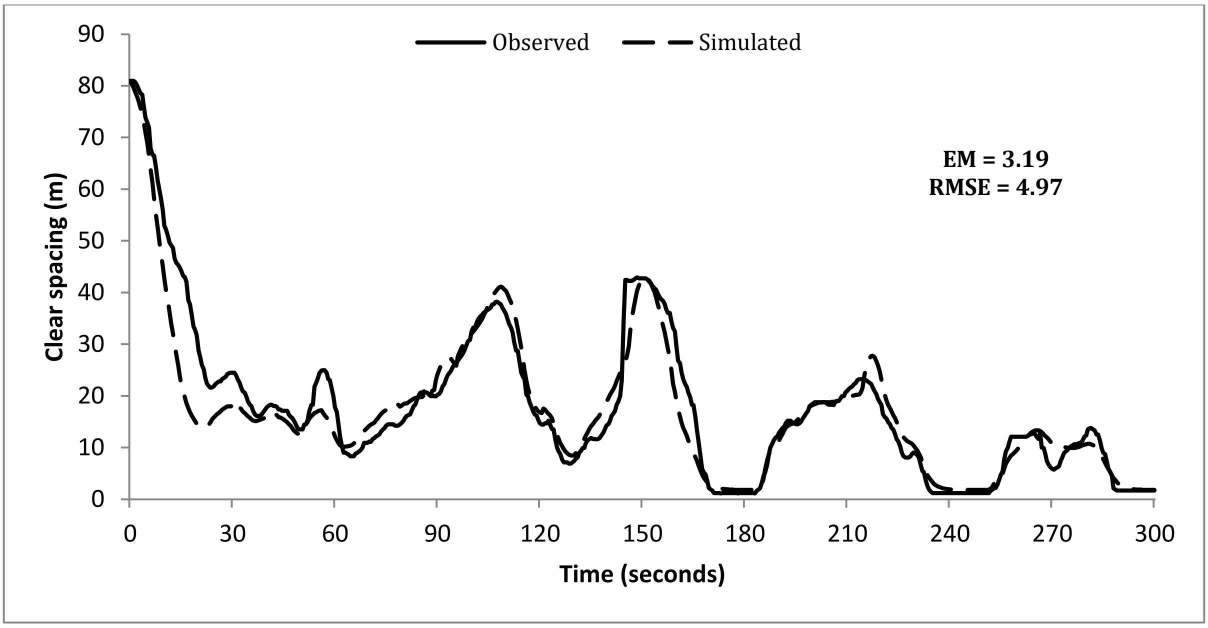


Figure 7.7: Calibration - simulated versus observed clear spacing based on data from Panwai and Dia (2005)

7.4.2 Calibration of the lane changing sub-model

Following Zia (1992), Yousif (1993), McDonald et al. (1994), Al-Jameel (2012) and Al-Obaedi (2012) the frequency of lane changes data has been used in calibrating the developed lane changing sub-model. For the purpose of this calibration, several sets of published field data (for 2 and 3 lanes normal sections) have been used.

As discussed in Section 6.5, several parameters can influence the lane changing behaviour. In this study, the threshold time (THRT) and threshold distance (THRD) parameters were considered as the most important parameters affecting the lane changing behaviour. Therefore, a sensitivity analysis has been carried out to test the effect of these parameters on the frequency of lane changing. Several simulation runs were implemented using different values of the threshold time (ranging from 5 sec to 50 sec) and threshold distance (from 25 m to 250 m) to get the best results. After several iterations, it was then decided to use a combination of THRT and THRD values [(5sec, 50m), (10sec, 75m), (15sec, 100m), (20sec, 125m), (25sec, 150m), (30sec, 175m) and (35sec, 200m)] rather than using arbitrary values. This is in order to represent these parameters logically and reasonably since some runs have provided nearly the same results even if the differences in the parameters THRT and THRD values are high between these runs. For example, the result of one run which was based on values of 5 sec for THRT and 200 m for THRD is nearly similar to that of another run with 35 sec for THRT and 50 m for THRD, as shown in Figure 7.8.

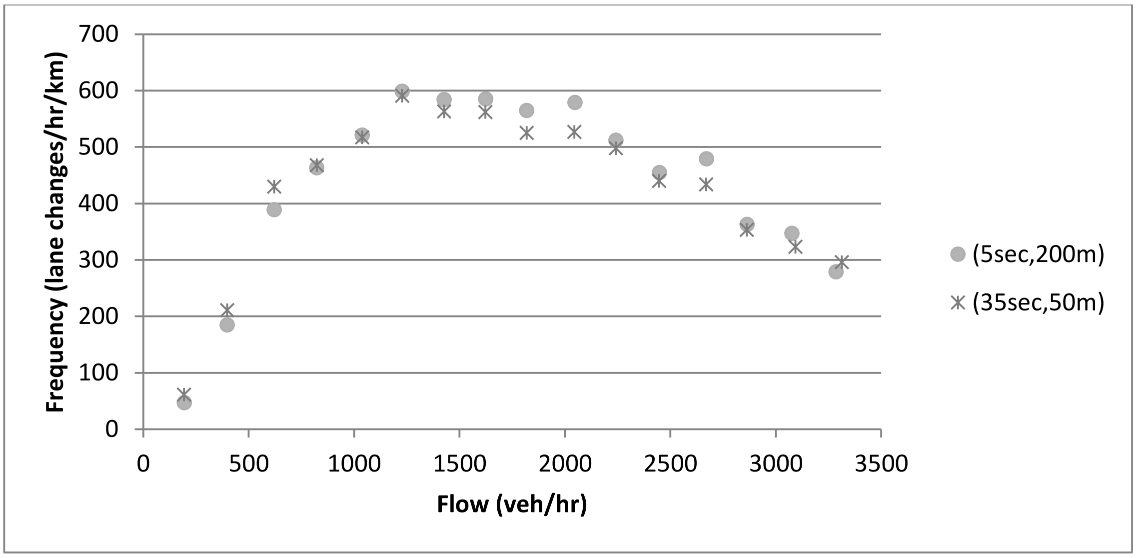


Figure 7.8: Calibration - simulated lane changing frequency for a 2-lanes normal motorway section under arbitrary values of THRT and THRD

Therefore, the proposed combinations of THRT and THRD [i.e. (5sec, 50m), (10sec, 75m), (15sec, 100m), (20sec, 125m), (25sec, 150m), (30sec, 175m) and (35sec, 200m)] have been used in calibrating the developed lane changing sub-model. Figure 7.9 shows the results (i.e. simulated lane changing frequency) of some simulation runs (using high, low and average values of combination of THRT and THRD) since showing the results of all runs may be unhelpful and confusing. The simulation results have been collected from the mid-section (1000 m length) of a 5000 m simulated road length (normal motorway section with 2 lanes). Flow rates up to 4000 veh/hr with 15% HGV have been used for this test.

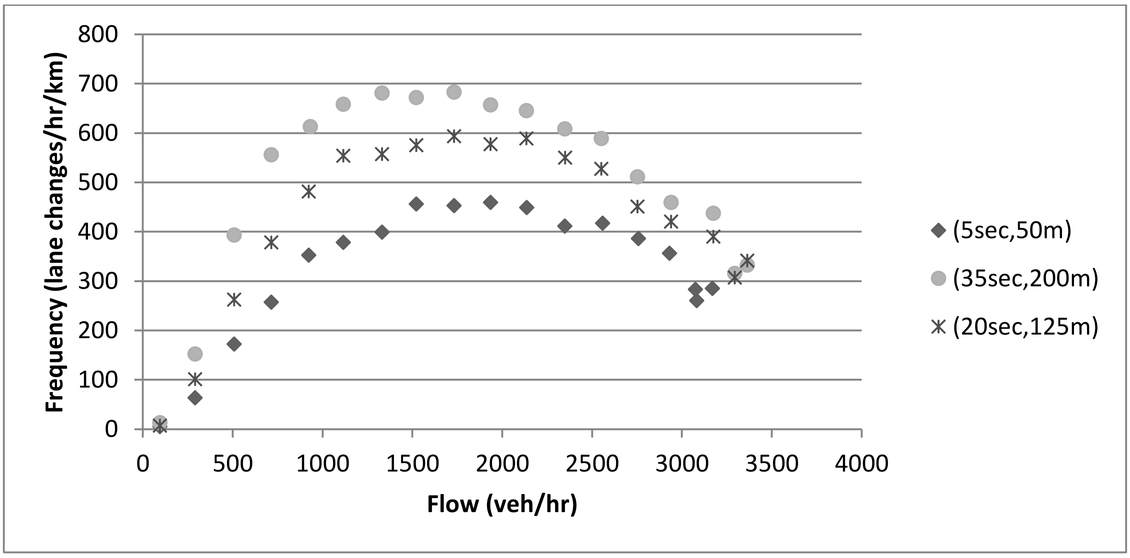


Figure 7.9: Calibration - simulated lane changing frequency for a 2-lanes normal motorway section under high, low and average values of THRT and THRD

7.4.2.1 Two lanes section

For the purpose of comparing the simulated results with field data, two sets of field data gathered by Yousif (1993) and by Sparman (1979) have been used due to the shortcomings of the collected data from the M602 (as discussed in Section 3.6.1.3). The Sparman's data is taken from Al-Jameel (2012). Several iterations were implemented using the proposed combinations of THRT and THRD values (i.e. (5sec, 50m), (10sec, 75m), (15sec, 100m) …etc.) in order to get a closer fit between the actual and simulated data. The simulation run with values of 15 sec for THRT and 100 m for THRD was found to produce the best match with the actual data as shown in Figure 7.10.

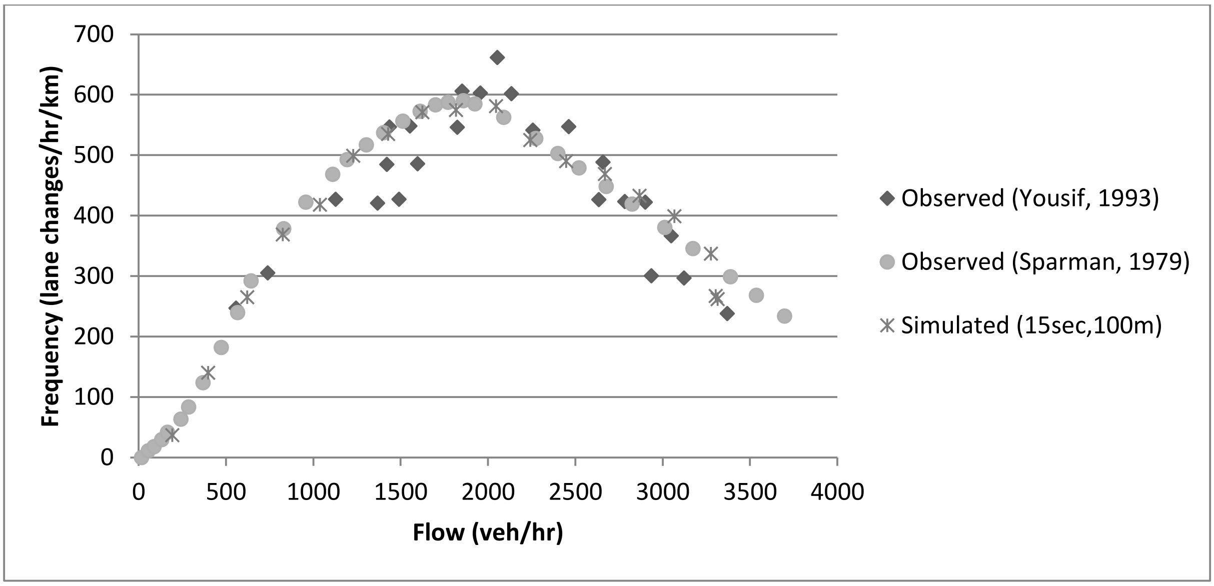


Figure 7.10: Calibration - simulated versus two sets of observed lane changing frequency data for a 2-lanes normal sections

7.4.2.2 Three lanes section

A published field data by Yousif (1993) was used for the calibration purposes of the three lanes normal section due to the shortcomings of the field data collected from the M60 (as discussed in Section 3.6.1.2). Likewise, several iterations were carried out using the proposed combinations of THRT and THRD. It was found that the run with values of 25 sec for THRT and 150 m for THRD yield the best match between the actual and simulated data as shown in Figure 7.11. Flow rates up to 6000 veh/hr with 15% HGV have been used in testing the simulation model for the three lanes normal motorway section.

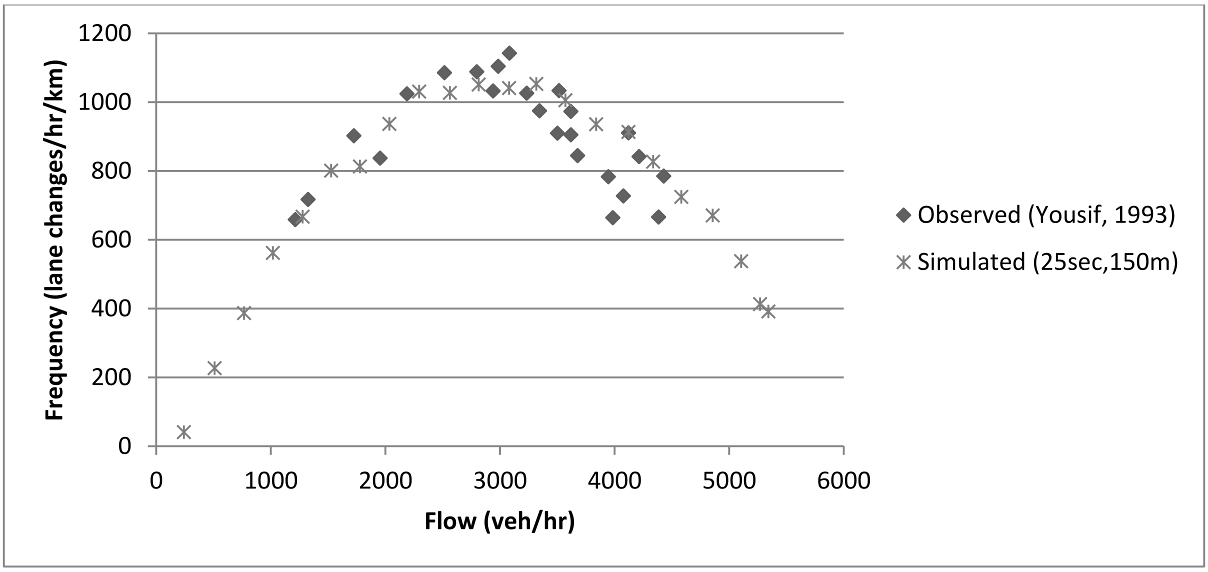


Figure 7.11: Calibration - simulated versus observed lane changing frequency data for a 3-lanes normal sections

Based on several simulation results, it was found that the proposed combinations of THRT and THRD with values ranging from 15 sec to 25 sec for the THRT parameter and from 100 m to 150 m for the THRD parameter yield reasonable results when compared with the observed data for both two and three lanes sections. Therefore, it was decided to adopt values of 20 seconds for the THRT parameter and 125 metres for the THRD parameter for the purpose of this study. In addition, these adopted values of THRT and THRD parameters are in good agreement with those reported by Yousif (1993) and Al-Obaedi (2012).

7.4.3 Calibration of the lane closure sub-model

The calibration of the developed lane closure sub-model has been achieved in order to minimise the number of early merged drivers as the field observations have suggested. This is in order to make sure that the simulation model correctly replicates the traffic behaviour at lane closure sections.

As discussed in Section 6.7.1, the modelled drivers (who drive on a closed lane) were directed to merge into an adjacent open lane once they approached the first signs indicating changing lane due to the presence of lane closure ahead. The simulation results showed that the modelled drivers merge much earlier in the approaching section which is not consistent with the real observations and data from field surveys. The real observations from the M67 site (2 lanes motorway with offside lane closure) revealed that a number of drivers using the lane to be closed change lanes within a relatively short distance from the start of the transition zone, and some change lane within the transition zone itself. Therefore, the lane closure rules/assumptions were modified in order to obtain a more realistic result from the simulation model. This has been achieved via two steps. These are, firstly, reducing the required distance (which is 900 m from the start of the transition zone, as suggested by the Traffic Signs Manual (Chapter 8, 2009) for dual carriageways with national speed limits) to initiate the desire of lane changing due to the presence of lane closure. Secondly, introducing a percentage of drivers who are not complying with the merging signs in order to allow for some drivers to proceed further on their closed lane. This has been modelled by generating a random number (C8) for each driver travelling on the closed lane. The driver will be regarded as non-complying with those merging signs and proceeding with driving on his/her current closed lane if the generated number is equal or lower than the percentage of non-complying drivers (N-CD%). Otherwise, he/she will be regarded as a complying driver and looking for suitable gaps in order to merge into an adjacent open lane. This process is then repeated every scanning time (Δt) until the subject driver merges into an open lane. The flowchart presented in Figure 7.12 illustrates the process of modelling the non-complying drivers with merging signs.

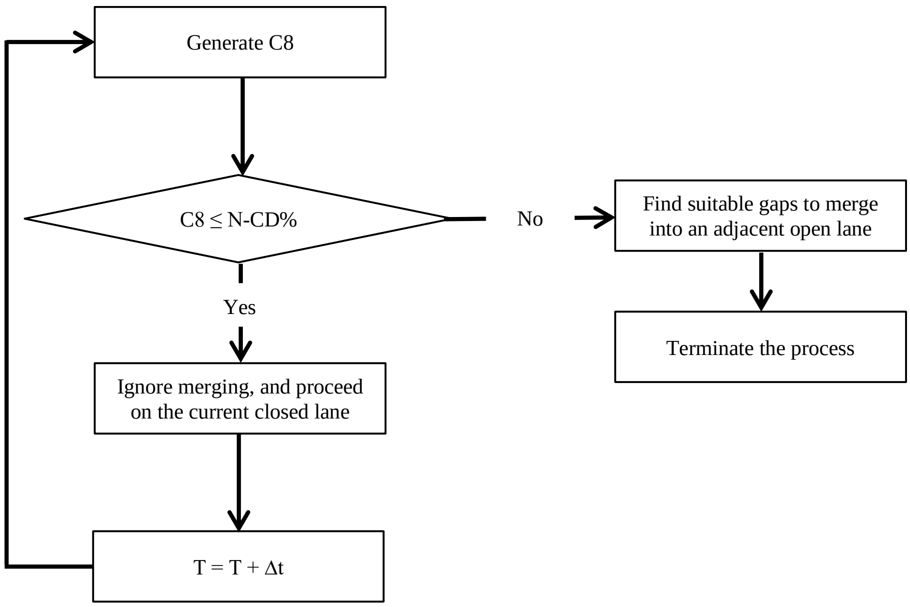


Figure 7.12: Method of modelling non-complying drivers with merging signs

In order to find out the optimum percentage of non-complying drivers (N-CD%) and the optimum distance required to initiate the desire of lane changing (D2LC), three sets of field data which cover a wide range of traffic flow conditions have been used. For free traffic conditions two sets of published field data collected from the A4232 and the M4 by Yousif (1993) have been used, whereas for congested traffic conditions a historic data from the M6 Site No. 16 (see Section 5.3.1) has been used. The reasons for using such historic data are because these have been made available to this study and they (the two data sets by Yousif) covered the traffic movements for a very long section which extend for more than 1 mile. In addition, the reason for using the M6 (Site No. 16) data is because it represents congested situations and also to compare the simulation results obtained from the newly developed micro-simulation model with those obtained from the S-Paramics software since the M6 data was used in testing the S-Paramics software (see Section 5.5; Table 5.6 and Figure 5.5).

➢ ***Data set 1 (A4232):***

Yousif (1993) collected lane utilisation data from the A4232 site using camcorders. The A4232 site consists of 2 lanes with inside lane closure. The length of the observed section covered by the camcorders is about 1 mile showing traffic movements from the 1 mile sign to the end of the transition zone. The lane utilisation data was extracted (by Yousif, 1993) at several sections upstream the activity zone (at positions of 1 mile, 800 m, 600 m, 400 m and 200 m upstream the transition zone and also at the start of the transition zone and at the end of the transition zone). Figure 7.13 shows the observed lane utilisation data compared with the simulation results for the early merging assumptions (before adopting N-CD% and D2LC parameters). The observed traffic characteristics reported by Yousif (1993) (total traffic flow = 700 veh/hr with 14% HGV) were adopted in running the simulation model.

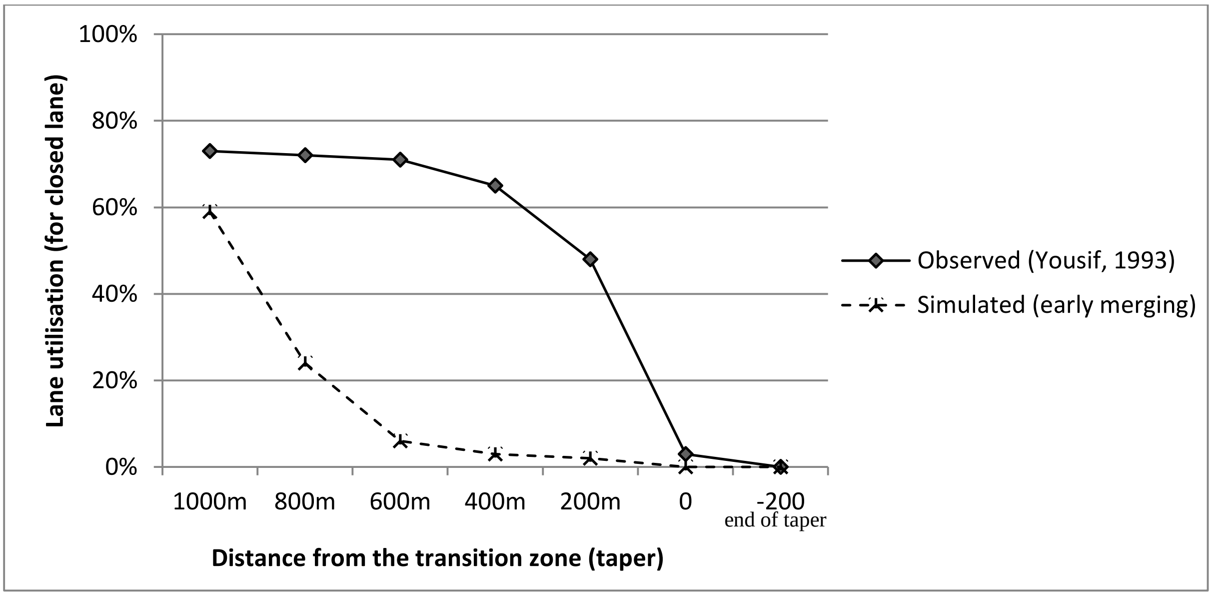


Figure 7.13: Simulated (early merging) versus observed lane utilisation data from the A4232

Several simulation runs have been implemented using different values of N-CD% and D2LC (distance required to initiate the desire for lane changing) in order to obtain best results.

The best fit between the simulated and observed data has been achieved for the use of values of 95% for the N-CD% parameter and 600 m for D2LC parameter, as shown in Figure 7.14.

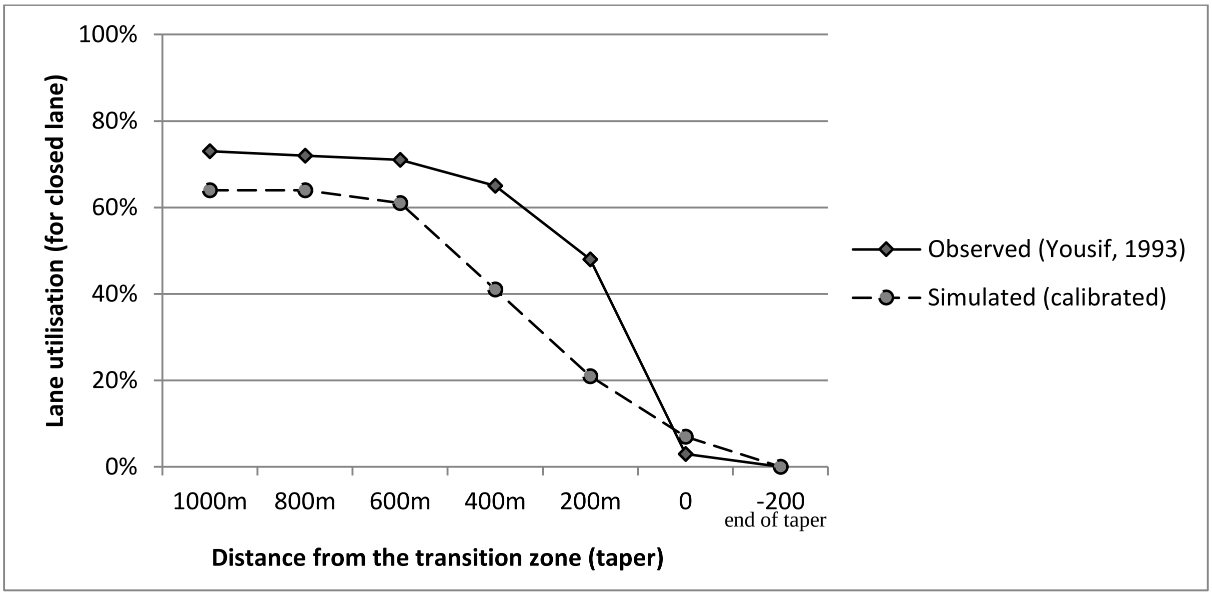


Figure 7.14: Calibration - simulated (calibrated, N-CD%=95% & D2LC=600m) versus observed lane utilisation data (A4232)

- ***Data set 2 (M4, J29 – J32):***

The M4 site is a two lanes motorway roadwork section with inside lane closure. Yousif (1993) collected data on lane utilisation using two camcorders to cover the section from the position of the 800 yards sign to the start of the transition zone. Figure 7.15 shows the observed versus the simulated lane utilisation results for both early merging assumption (before adopting N-CD% and D2LC parameters) and the calibrated one (after adopting N-CD% and D2LC parameters). Likewise, the use of 95% for the N-CD% and 600 m for the D2LC produced better results based on several simulation runs. The same characteristics as reported by Yousif (1993) for the M4 site (i.e. total flow = 1300 veh/hr with 8% HGV) were adopted in the simulation model.

It can be seen from Figure 7.15 that the simulated lane utilisation result for early merging assumptions is lower than the observed lane utilisation data. This could be because the modelled drivers under the early merging assumptions merge much earlier in the approaching section, whereas after adopting the N-CD% and the D2LC parameters with values of 95% for the N-CD% and 600 m for the D2LC parameters, respectively, the simulation result were then started to get closer to the observed data, as shown in the figure (i.e. simulated (calibrated)).

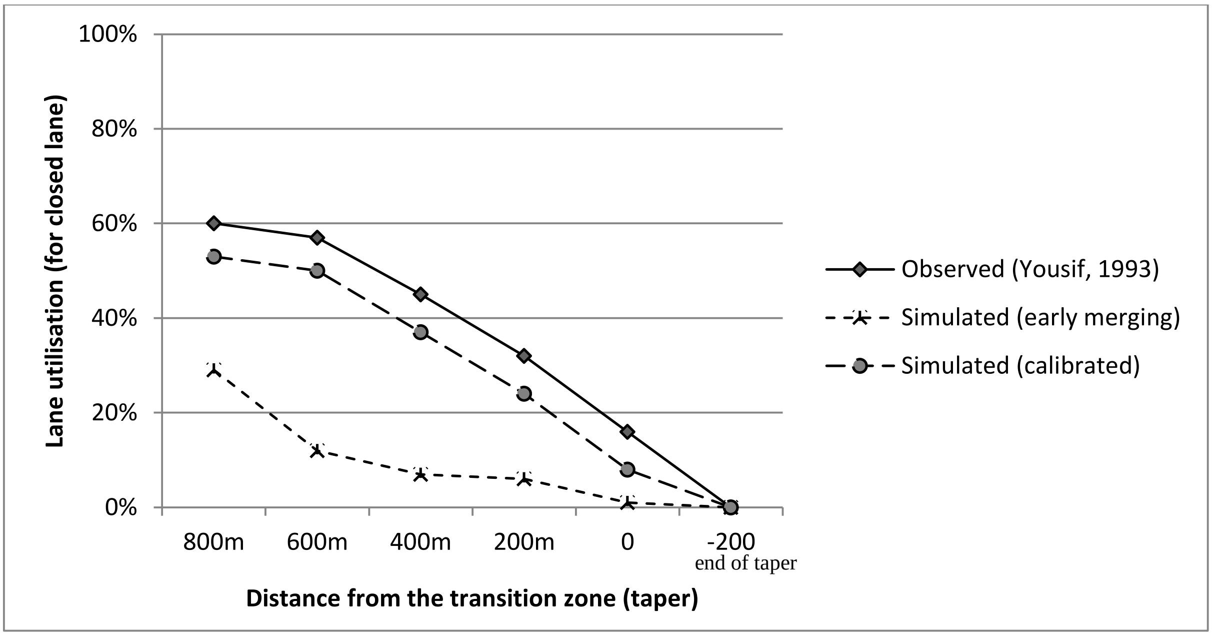


Figure 7.15: Calibration - simulated (early merging and calibrated, N-CD%=95% & D2LC=600m) versus observed lane utilisation data (M4)

➢ ***Data set 3 (M6, J14 – J15, Site No. 16):***

A three lanes motorway roadwork site with offside lane closure from previous studies has been made available and used to extract field traffic data. The available footage (see Table 5.1, Site No. 16) shows the traffic movements at the start of the transition section. The lane utilisation data was extracted from the start of the transition section for every 5 minutes interval. The total flow rates and the percentage of HGVs were extracted (from the footage) from the start of the transition section and was then used as input data for the newly developed model at the start of the simulated section. Figure 7.16 shows the observed versus the simulated (N-CD% = 95% and D2LC = 600 m) lane utilisation data at the start of the transition zone for the closed lane (i.e. offside lane).

Figure 7.16 shows that the percentage of lane utilisation is higher for the simulation results compared with the actual observed data. This could be due to the high percentage of N-CD% (i.e. 95%) used in running the simulation model. As traffic flow increases, the availability of opportunities to merge into an open lane decreases due to the congested situations. This could lead drivers on the closed lane to utilise any available opportunity to merge. Therefore, the N-CD% and D2LC parameters were modified in order to obtain best results. Based on several simulation runs, it was found that values of 30% for N-CD% and 800 m for the D2LC produced better results. The simulation results using these parameters values (i.e. N-CD% = 30% and

D2LC = 800 m) are compared with the observed actual data from the M6 as shown in Figure 7.17 which shows very close match between the simulated and observed data.

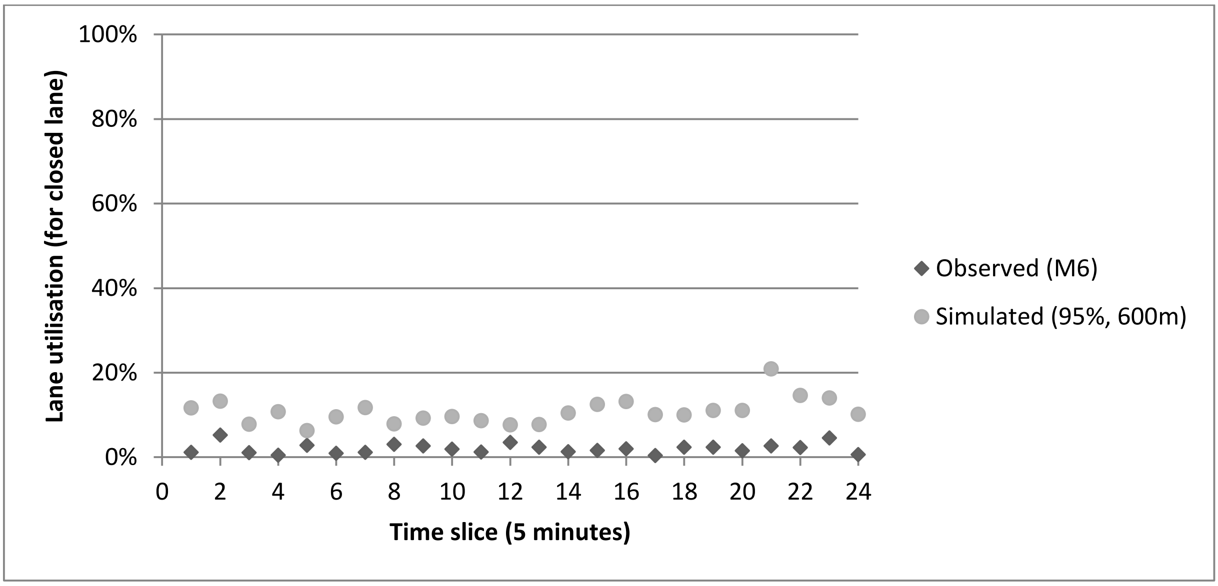


Figure 7.16: Calibration - simulated (N-CD%=95% & D2LC=600m) versus observed lane utilisation data (M6) at the start of the transition section

Figure 7.17 also shows the simulated lane utilisation data by using the S-Paramics software. It can be seen from Figure 7.17 that the simulation results obtained from the newly develop model (i.e. Simulated 30%, 800m) replicate the observed data from the M6 better than those obtained from the S-Paramics software (S-Paramics results).

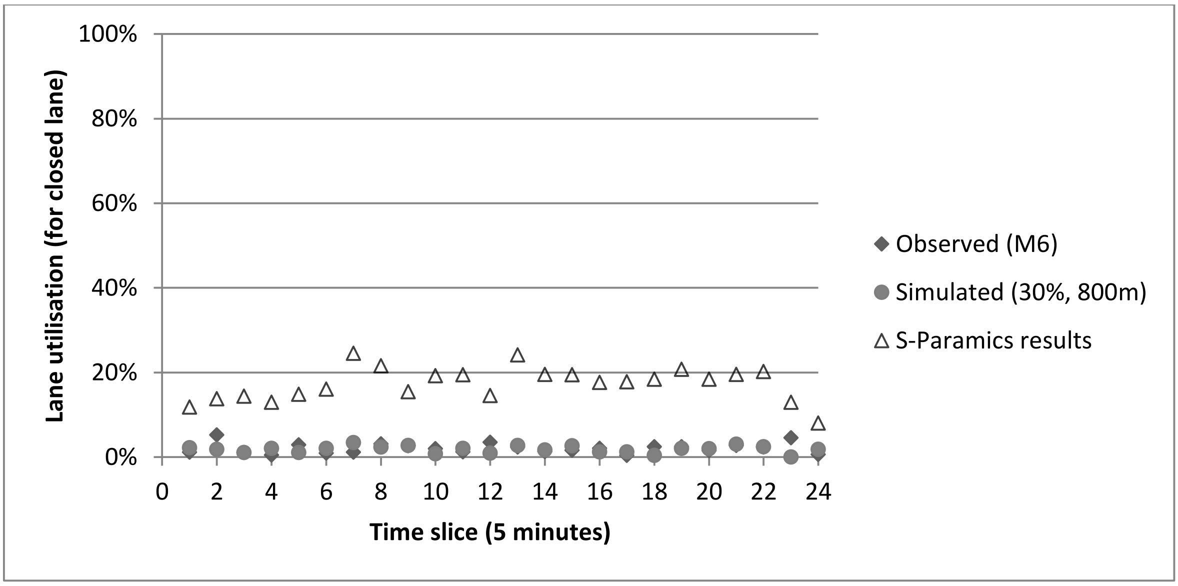


Figure 7.17: Calibration - simulated (N-CD%=30% & D2LC=800m) versus observed lane utilisation data (M6) at the start of the transition section

Based on the simulation results presented in Figures 7.13 to 7.17, it was decided to adopt values of N-CD% = 95% and D2LC = 600 m for the simulation model under free to moderate traffic flow conditions, whereas under heavy traffic flow conditions, values of 30% for the N-CD% and 800 m for the D2LC should be adopted.

7.4.4 Calibration of the narrow lanes sub-model

The FDSL parameter (as described in Section 6.8.2) is a percentage of drivers who prefer staying in the same lane driving behind a HGV and following it with a gap even if they have the opportunity to overtake. As discussed in Section 4.4.3, the (FDSL) parameter was not measured due to the shortage of observed section length from the video footage. Therefore, the calibration of the developed narrow lanes sub-model has been utilised to estimate the FDSL parameter.

The calibration process has been carried out by conducting a sensitivity analysis for the FDSL parameter to test its effect on traffic flow and time headway distributions. Therefore, two types of field data (i.e. traffic flow and headway) were extracted from the M6 (J31 – J32) site (Site No. 3) and were then used for the purpose of this calibration. The M6 motorway site consists of 4 lanes with narrow lanes applied as a TTMS. The hard shoulder and part of lane 1 were closed for roadworks. Around three and a half hours of video footage were recorded from 11:40 to 15:20 on Sunday the 31st of August 2014 (more details about this site in terms of its location, geometric design and other characteristics were shown in Section 4.3). The field data was extracted in 5 minutes interval at the start of the narrowing lanes section (i.e. start of the activity zone). Several simulation runs were implemented using different values of the FDSL parameter in order to get a closer fit between the observed and simulated data. The corresponding input values as gathered from the M6 site (e.g. the total flow and the percentage of HGVs) were adopted. Figure 7.18 shows the simulated and observed traffic flow data for each 5 minutes interval for the M6 site. Table 7.2 shows the corresponding statistical goodness of fit tests for the traffic flow data.

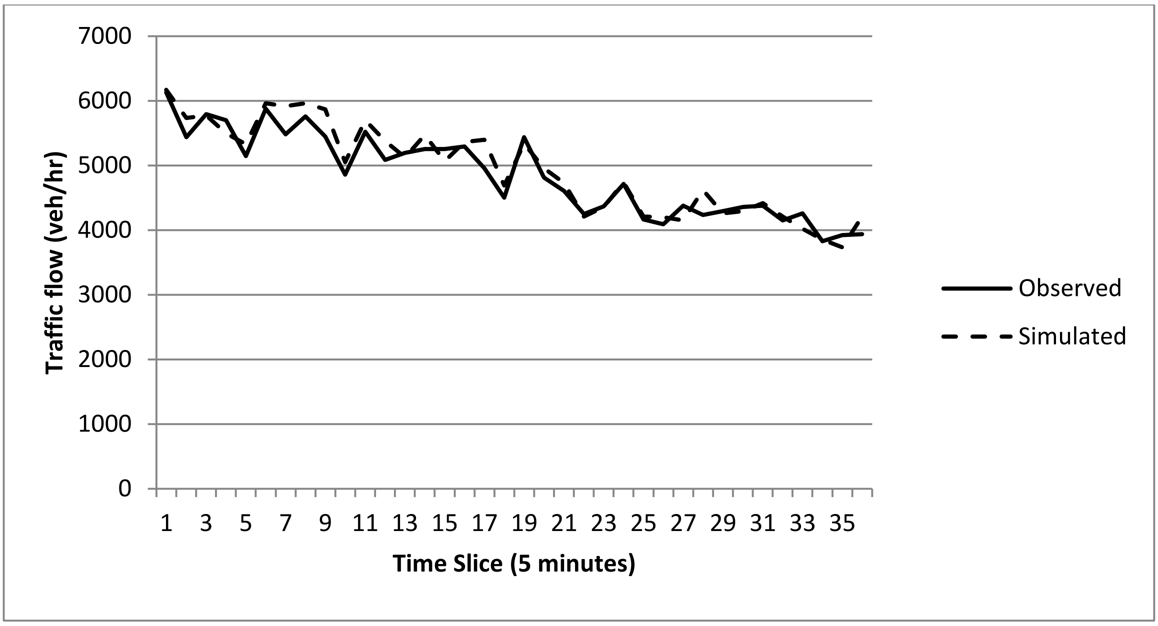


Figure 7.18: Calibration - simulated versus observed traffic flow data (M6, J31 – J32)

Table 7.2: Calibration - statistical tests for the simulated flow based on data from the M6

Statistical tests	RMSE	RMSEP	GEH	U	U_m	U_s
Flow	204 (veh/hr)	4.19%	0.83	0.021	0.175	0.082

It can be seen from Figure 7.18 that the simulated traffic flow is in good agreement with the real observed data. It can also be seen from Table 7.2 that all the six statistical tests results for traffic flow data are satisfactory. The table shows that the value of GEH test is only 0.83 which indicates a good performance of the developed model.

Figure 7.19 compares the observed with the simulated cumulative distribution of headway for each lane of the M6 site. The non-parametric Kolmogorov-Smirnov (K-S) hypothesis statistical test was used (at the 5% level of significance) in testing whether there is a significant difference between the observed and the simulated headway cumulative distributions. The K-S test compares the maximum difference (D_{max}) between the two cumulative distributions with the critical value (D_{cr}) which can be obtained from the K-S tables or as shown in Equation 3.8. The results are reported in Table 7.3.

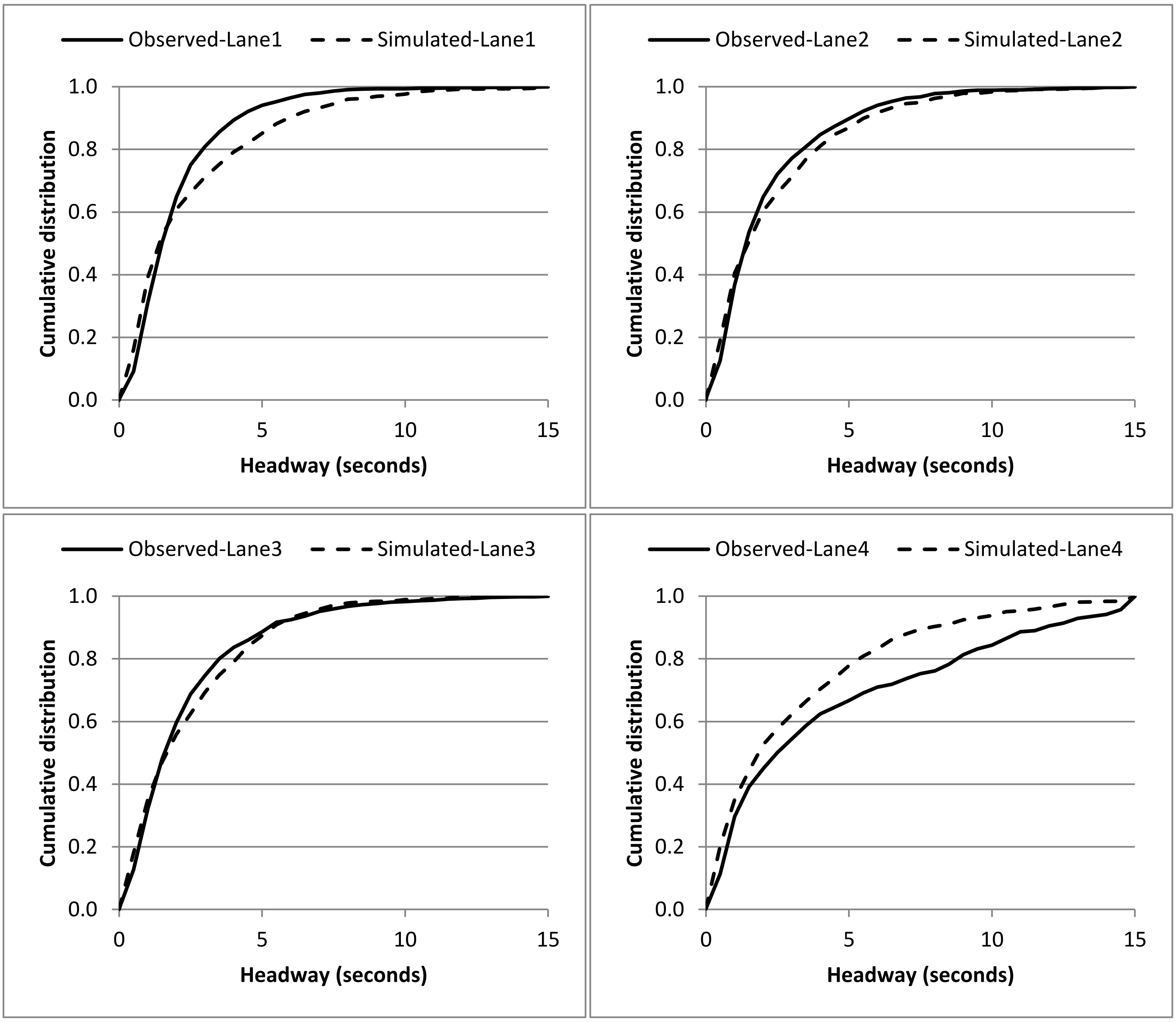


Figure 7.19: Calibration - simulated versus observed cumulative distribution of headways in lanes 1, 2, 3 and 4 on the M6

Table 7.3: Calibration – K-S test results for the simulated headway distributions based on data from the M6

Lane no.	**1**	**2**	**3**	**4**
$\mathbf{D_{max}}$	0.103	0.064	0.062	0.143
$\mathbf{D_{cr}}$	0.061	0.064	0.063	0.091
Accept ($D_{cr} > D_{max}$)	No	Yes	Yes	No

It can be seen from Figure 7.19 and Table 7.3 that the simulation results for lanes 2 and 3 seem to be in good agreement with the observed data, whereas for lanes 1 and 4, the simulation results showed that there is a significant difference in the distributions of time headway when compared to the observed data. Different shift values (in the shifted negative exponential distribution, in the simulation model) were adopted (i.e. 0.1 to 1.0 with an increment of 0.1 seconds) in an attempt to enhance the results. However, no good enhancement has been reached.

The results of the sensitivity analysis showed that the FDSL parameter has a negligible effect on both traffic flow and headway distribution results. This could be due to the low percentage of heavy vehicles on the M6 site (which was only 7% HGVs). However, for simplicity, a value of 50% was assumed for the FDSL parameter, for the purpose of this study. It is worth mentioning here that the effect of FDSL parameter on traffic behaviour may differ from other sites, of roadworks with narrow lanes scheme, with high HGVs%. Therefore, field data from such sites (i.e. narrow lanes with high HGVs%) are required.

7.5 Validation process

In the previous section, the main four components of the newly developed micro-simulation model (i.e. car following, lane changing, lane closure and narrow lanes) were calibrated and tested using several sets of field data. As a final check, the whole simulation model was then validated using data collected from other sites to those used in the calibration process. Park and Schneeberger (2003) and Al-Obaedi (2012) define the model validation as the process of testing the accuracy of the whole micro-simulation model against real data before using the model in further applications.

Park and Schneeberger (2003) cite Milam and Choa (2001) reporting that the model validation process could be achieved by comparing the simulated traffic flow data with that gathered from the field. In this study, the comparison between simulated and real traffic data is mainly based on comparing the flow, speed and lane utilisation data.

In this study, the model validation process has been divided into two categories (i.e. those with normal roadway sites and those with roadworks). The following sub-sections provide further details.

7.5.1 Model validation under normal roadway conditions

Several data sets from motorways with 2, 3 and 4 lanes under different levels of flows (i.e. from free flow to congested situations) have been used to validate the newly developed micro-simulation model, under normal roadway conditions. These were used to provide the input data for the developed model and also to compare traffic characteristics from the field with those predicted by the model.

7.5.1.1 Four lanes section

Two sets of data taken from the M25 (J15–J16, Individual Vehicle Data, IVD) were used for the purpose of validating the developed model. These two sets were selected to represent peak and off-peak periods, as shown in Table 7.4. The traffic field data was collected and averaged for every 5 minutes interval. The corresponding input values as extracted from the site (e.g. the total flow and the percentage of HGVs) were used at the start of the simulated section, which was a 5000 m in length. The simulation results were collected at the mid-length section (i.e. 2500 m from the start of the simulated section).

Table 7.4: Validation – M25 data sets details

Site No.	Data set No.	Site location	Number of lanes	Traffic condition	Date	Time	Duration
13	1	M25 (J15-J16)	4	Peak	Wednesday 08/05/2002	07:00 – 10:00 a.m.	3 hours
	2	M25 (J15-J16)		Off-peak	Saturday 11/05/2002	20:45 – 23:45 p.m.	3 hours

- ***Comparison with data set 1:***

Figures 7.20 and 7.21 show the observed and simulated traffic flow and speed data, respectively, for each 5 minutes interval. While, Figure 7.22 compares the simulated and observed lane utilisation data by considering each lane separately. The results of the statistical goodness-of-fit tests for the traffic flow and speed for the 5 minutes interval are reported in Table 7.5.

Figures 7.20 to 7.22 suggest good agreement of the simulation results with the real observed data. In addition, the statistical test results shown in Table 7.5 confirm the validity of the developed model for such traffic flow conditions. The table shows that the values of RMSEP for both flow and speed are lower than 15% which indicates that the newly developed model can reasonably replicate the chosen set of observed data, for the set of parameters used in running the model.

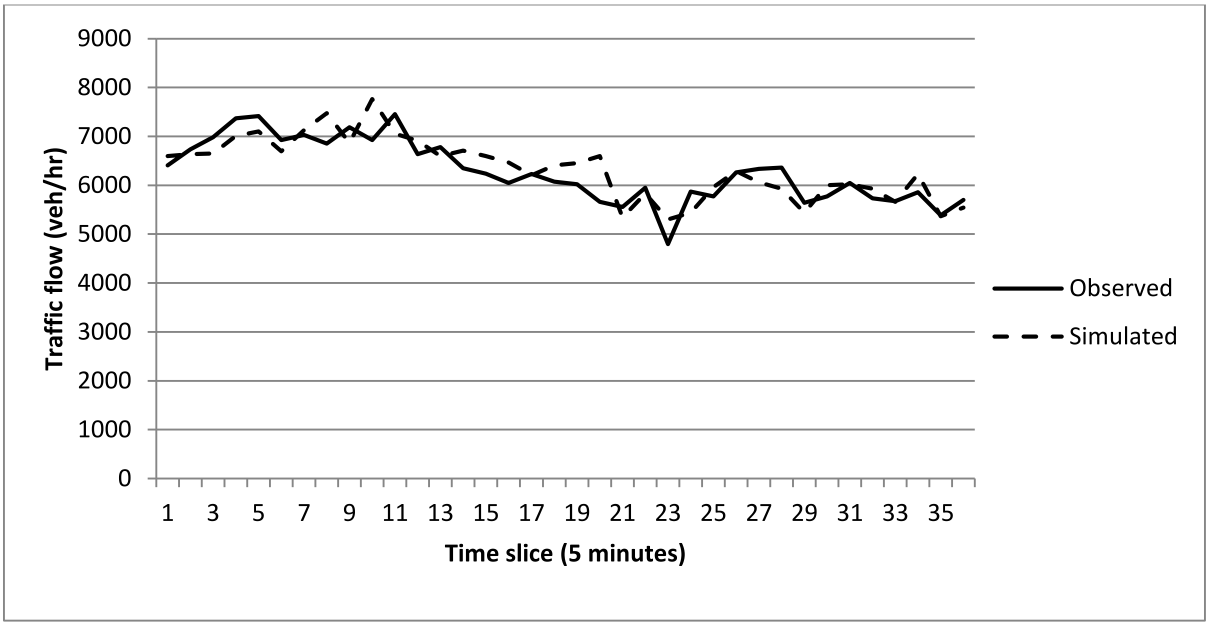


Figure 7.20: Validation - simulated versus observed traffic flow data (M25, data set 1)

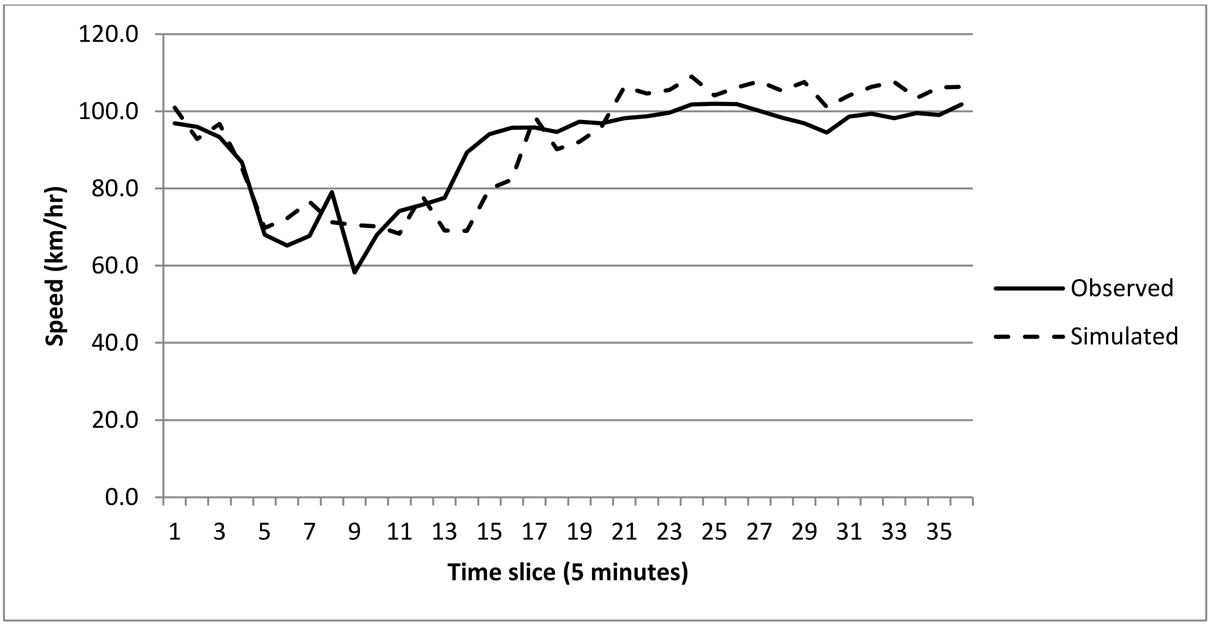


Figure 7.21: Validation - simulated versus observed speed data (M25, data set 1)

Table 7.5: Validation - statistical tests for the developed model based on data from the M25 (data set1)

Statistical tests	RMSE	RMSEP	GEH	U	U_m	U_s
Flow	358 (veh/hr)	5.8 %	1.29	0.028	0.030	0.000
Speed	7.6 (km/hr)	8.9 %	--	0.041	0.053	0.094

--: The Department for Transport (1996) suggested using the GEH test for testing the flow data.

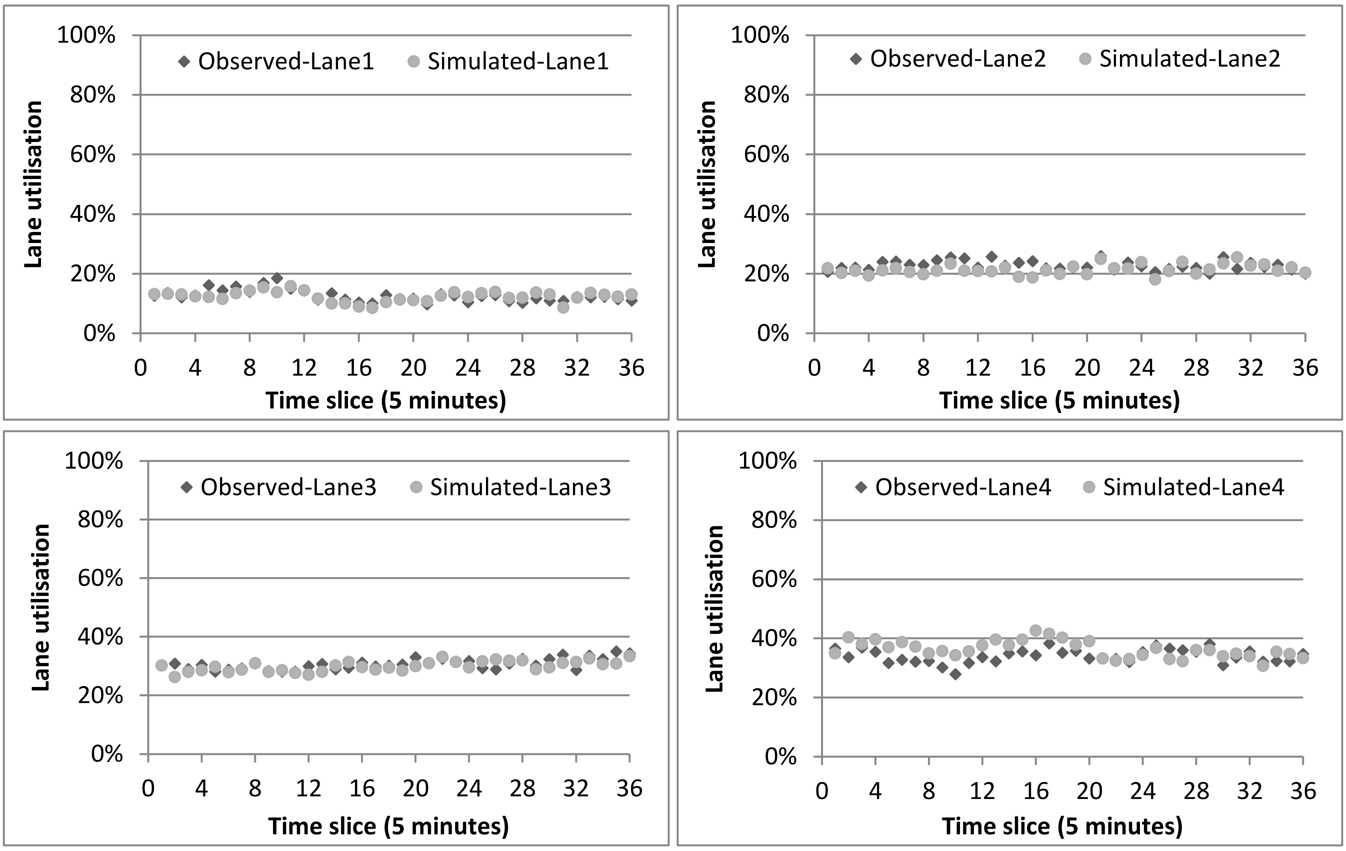


Figure 7.22: Validation - simulated versus observed lane utilisation data for lanes 1, 2, 3 and 4 on the M25 (data set 1)

➢ ***Comparison with data set 2:***

The data set 2 was taken from the M25 (IVD) in the off-peak period (from 8:45 p.m. to 11.45 p.m.). Figures 7.23 to 7.25 show the comparison (for every 5 minutes interval) between the simulated and the observed flow, speed and lane utilisation data respectively, whereas the statistical goodness-of-fit tests results are presented in Table 7.6.

It can be seen from Figures 7.23 to 7.25 that the simulation results are in good agreement with the real observed data. It can also be seen from Table 7.6 that the statistical tests results are within the acceptable limits. The table shows that the values of U, which measures the overall error, for both flow and speed are very small (under 0.3) which indicates a good correlation.

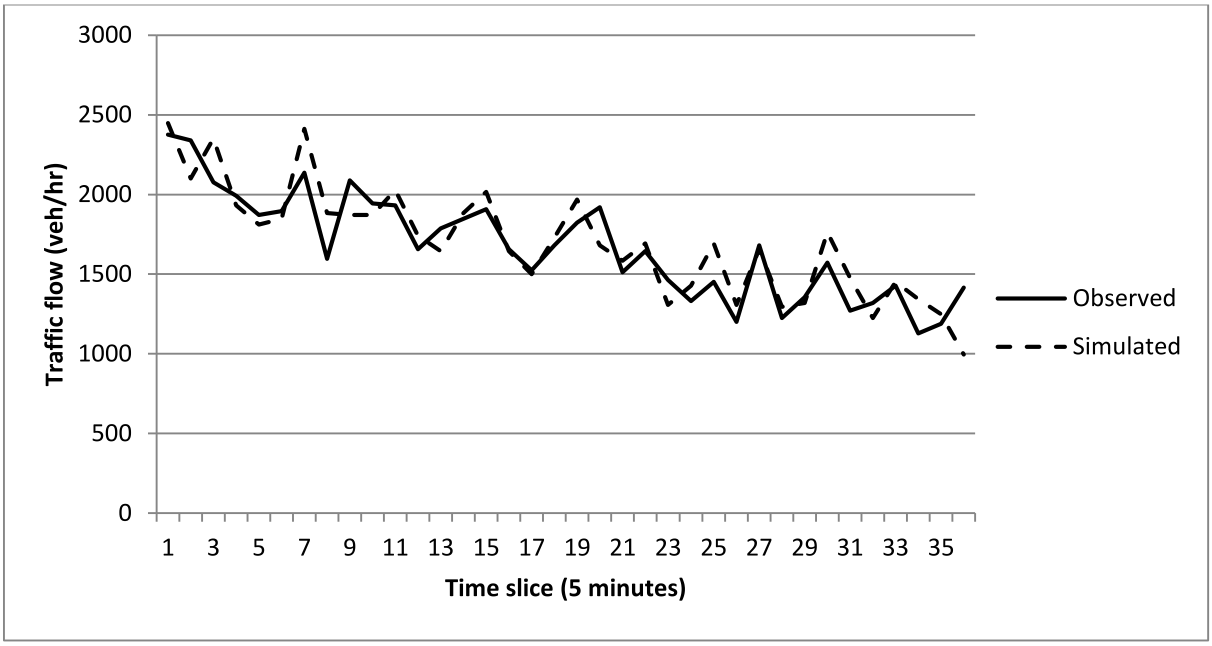


Figure 7.23: Validation - simulated versus observed traffic flow data (M25, data set 2)

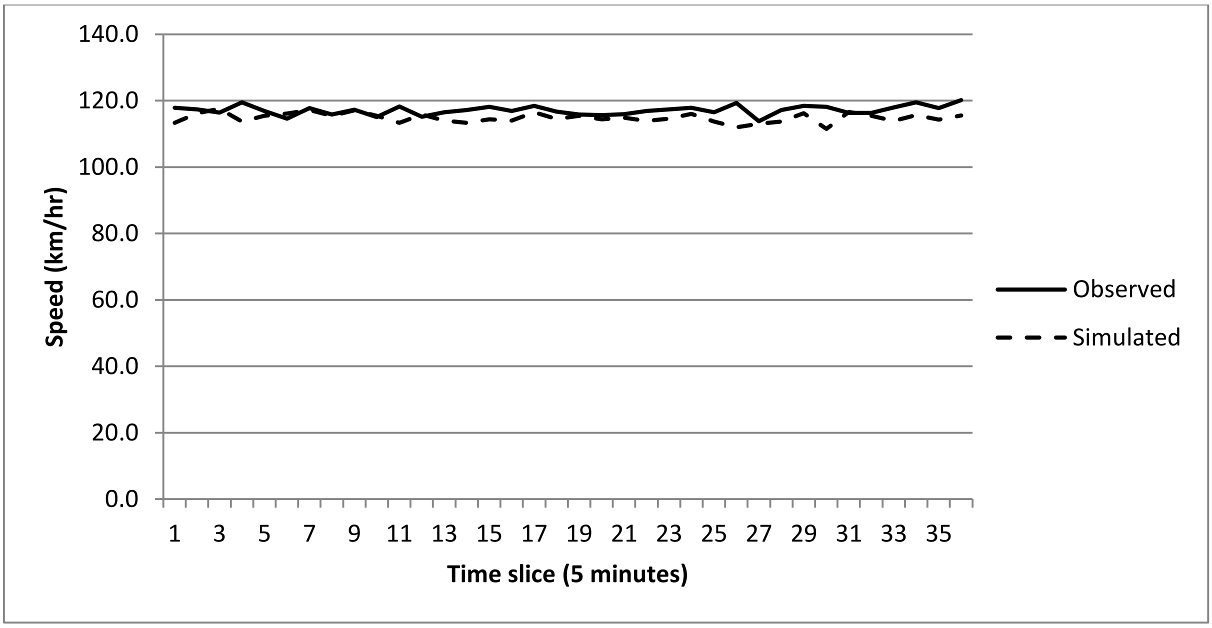


Figure 7.24: Validation - simulated versus observed speed data (M25, data set 2)

Table 7.6: Validation - statistical tests for the developed model based on data from the M25 (data set 2)

Statistical tests	RMSE	RMSEP	GEH	U	U_m	U_s
Flow	160 (veh/hr)	10.1 %	1.15	0.047	0.025	0.007
Speed	3.1 (km/hr)	2.6 %	--	0.013	0.540	0.000

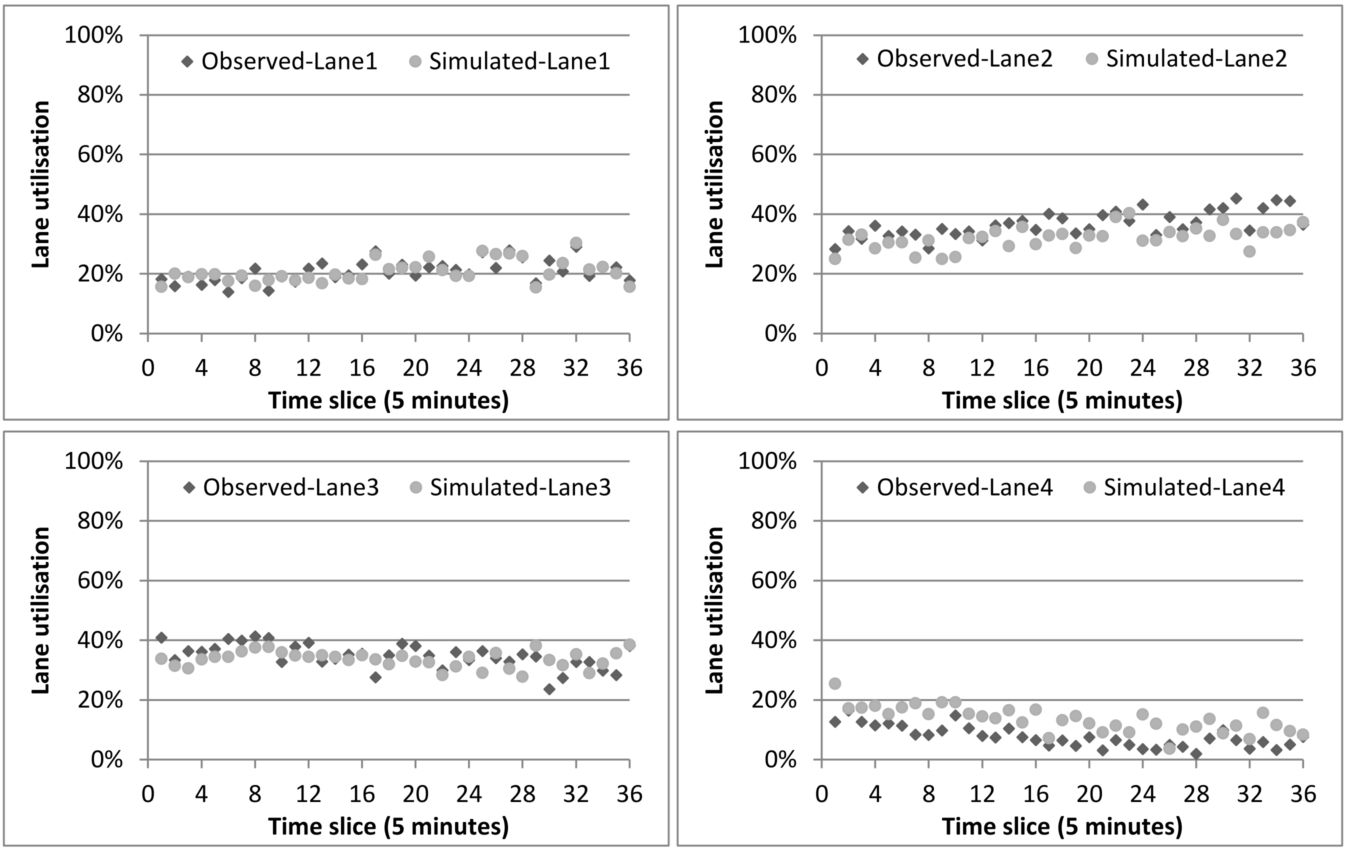


Figure 7.25: Validation - simulated versus observed lane utilisation data for lanes 1, 2, 3 and 4 on the M25 (data set 2)

7.5.1.2 Three lanes section

One data set taken from the M42 (J5–J6, Individual Vehicle Data, IVD) was used in validating the developed model. The M42 (J5-J6) site is a three lanes normal motorway section. Table 7.7 provides further details about the M42 site. Likewise, the field data and the simulation results were also averaged for every 5 minutes interval. Figures 7.26 to 7.28 show the comparison between the simulated and the observed flow, speed and lane utilisation data, respectively, whereas the statistical goodness-of-fit tests results are presented in Table 7.8.

Table 7.7: Validation – M42 data set details

Site No.	Site location	Number of lanes	Date	Time	Duration
14	M42 (J5 – J6)	3	Friday 06/09/2002	09:45a.m. – 12:45p.m.	3 hours

It can be seen from Figures 7.26 to 7.28 that the simulation results are in good agreement with the real observed data. Moreover, the statistical tests show a good agreement between the simulated and field data as indicated in Table 7.8.

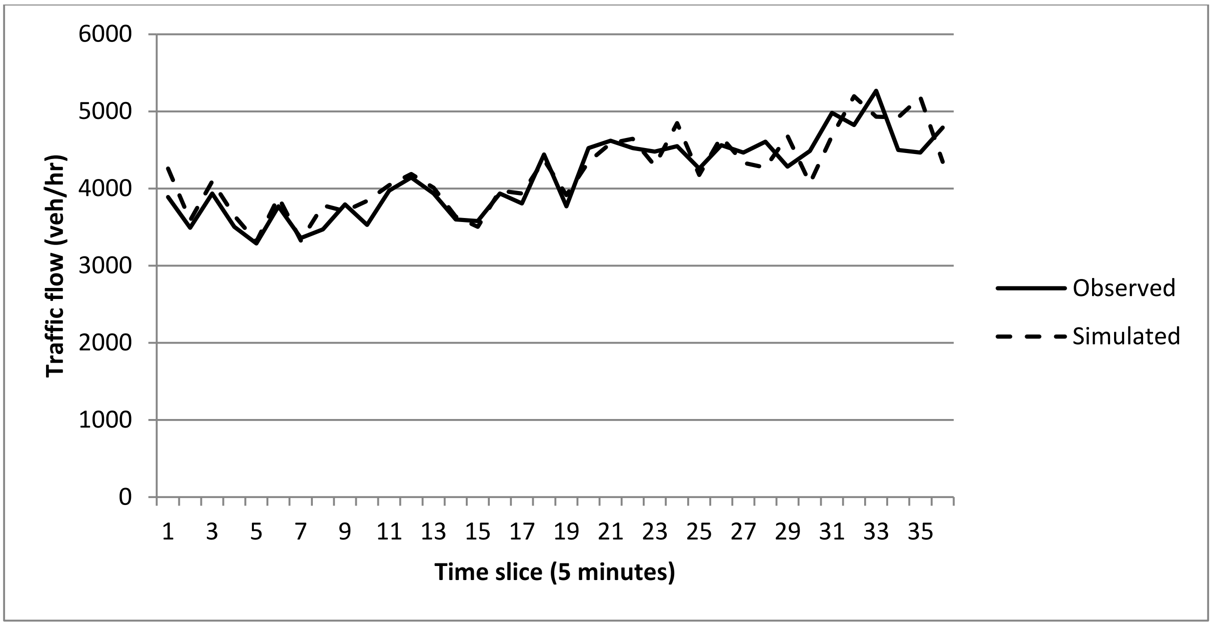


Figure 7.26: Validation - simulated versus observed traffic flow data (M42)

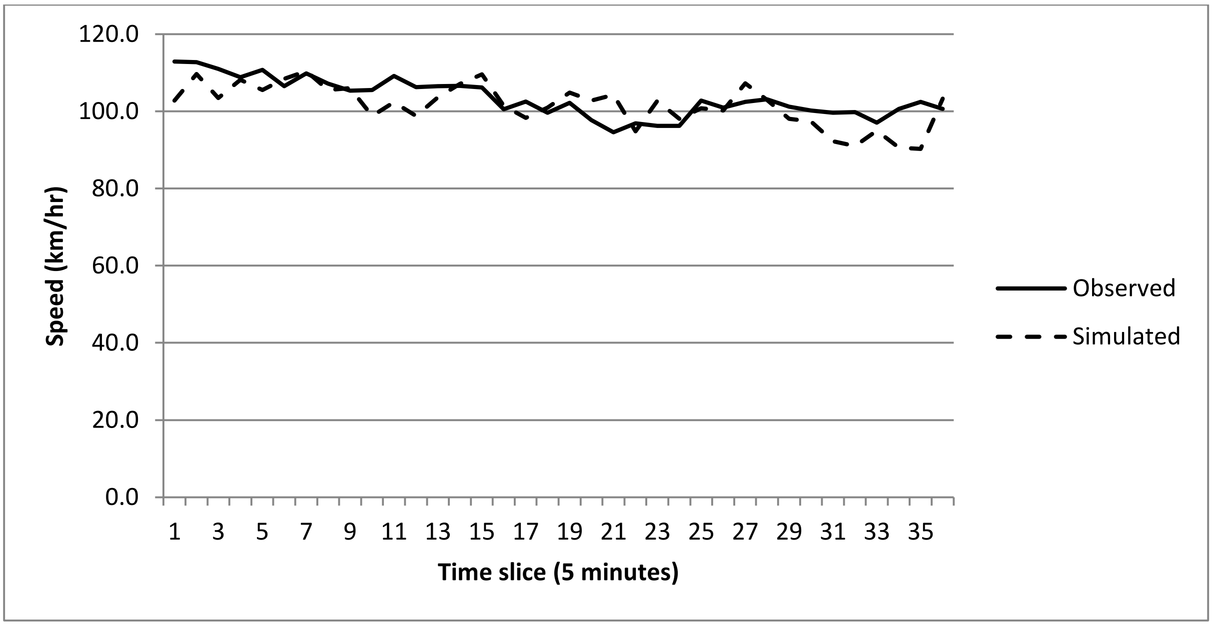


Figure 7.27: Validation - simulated versus observed speed data (M42)

Table 7.8: Validation - statistical tests for the developed model based on the M42 data

Statistical tests	RMSE	RMSEP	GEH	U	U_m	U_s
Flow	256 (veh/hr)	5.9 %	1.10	0.030	0.038	0.002
Speed	5.3 (km/hr)	5.1 %	--	0.026	0.118	0.011

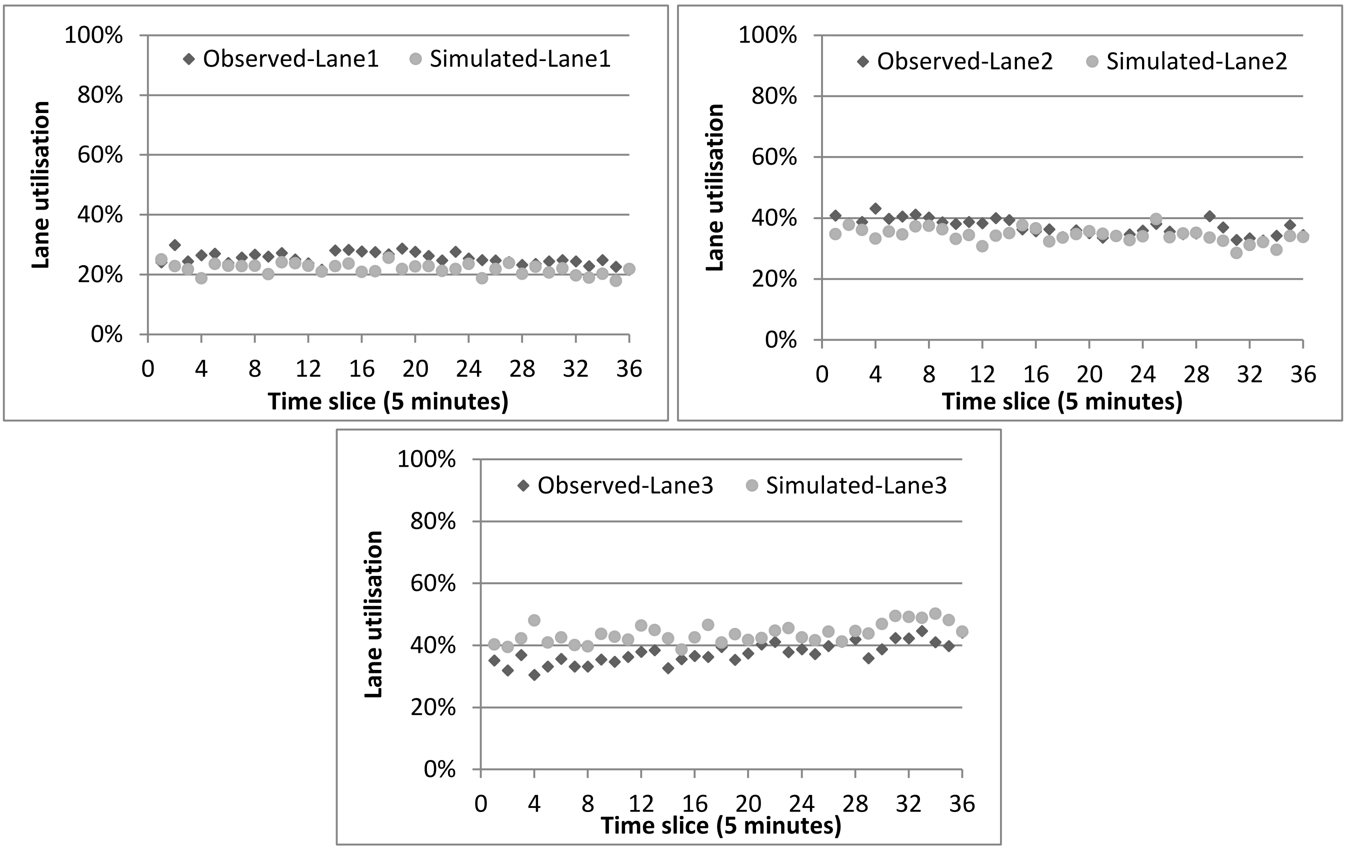


Figure 7.28: Validation - simulated versus observed lane utilisation data for lanes 1, 2 and 3 on the M42

7.5.1.3 Two lanes section

For the purpose of validating the developed model for section with 2 lanes, field data was collected using camcorders from the M602 (J2–J3). Table 7.9 shows the details of the field data. The M602 (J2–J3) site is a two lanes normal motorway section. The traffic flow data was collected and averaged for every 5 minutes interval. By applying similar inputs for the developed model, the model shows a good agreement with the field data as shown in Figures 7.29 and 7.30 which show the comparison between the simulated flow and lane utilisation with the observed data. The statistical goodness-of-fit tests between the simulated and the actual flow data are presented in Table 7.10. This table shows that the results are within the acceptable limits.

Table 7.9: Validation – M602 data set details

Site No.	Site location	Number of lanes	Date	Time	Duration
10	M602 (J2 – J3)	2	Tuesday 18/11/2014	09:35 – 11:45 a.m.	130 minutes

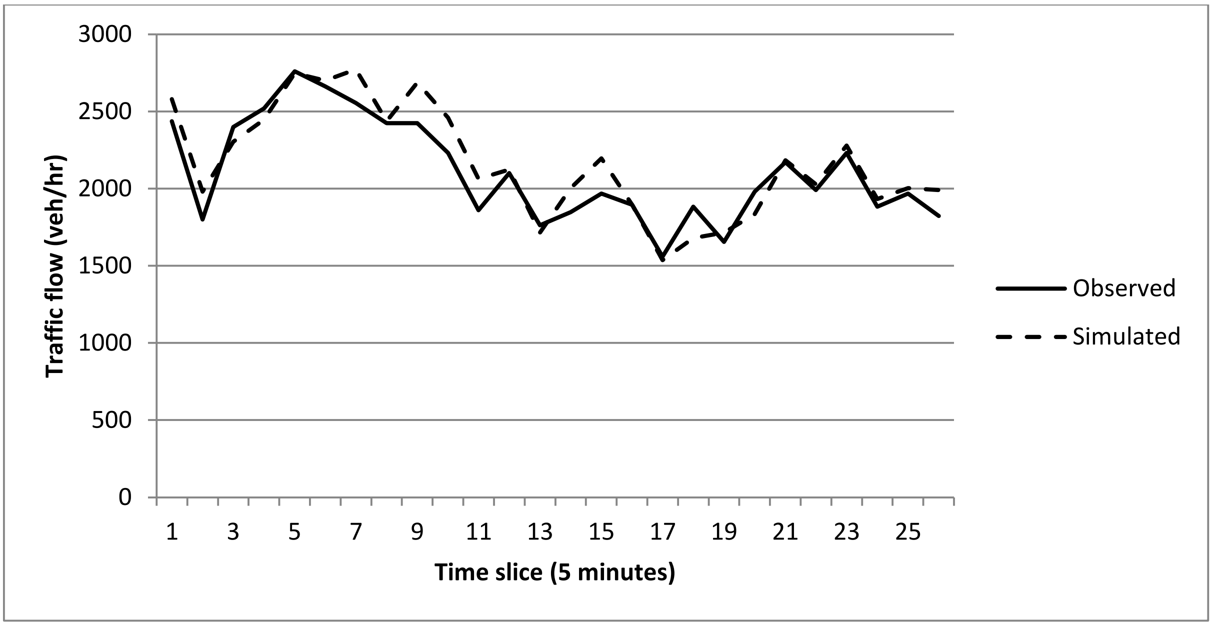


Figure 7.29: Validation - simulated versus observed traffic flow data (M602)

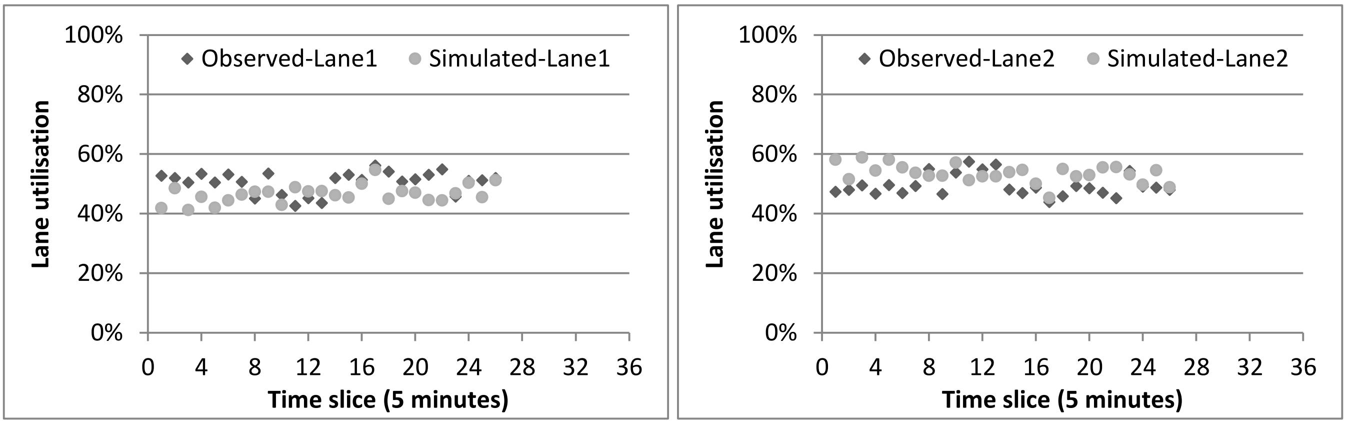


Figure 7.30: Validation - simulated versus observed lane utilisation data for lanes 1 and 2 on the M602

Table 7.10: Validation - statistical tests for the developed model based on the M602 data

Statistical tests	RMSE	RMSEP	GEH	U	U_m	U_s
Flow	133 (veh/hr)	6.4 %	0.83	0.031	0.188	0.040

7.5.1.4 Summary

The simulation results, in general, reveal a good agreement between the simulated and the actual data (e.g. The U for the flow and speed measurements did not exceed 0.1). This indicates that the newly developed model can reasonably describe the observed data from normal roadway sections in terms of replicating flow, speed and lane utilisation. In next section, the newly developed micro-simulation model will be validated against field data collected from roadworks sections.

7.5.2 Model validation under roadworks conditions

For the purpose of validating the developed model under roadworks conditions, two roadworks sites were used. These two sites were selected to represent lane closure and narrow lanes situations, as shown in Table 7.11. A similar procedure to that used for the model validation under normal roadway conditions was adopted for model validation at roadworks sites. Flow, speed and lane utilisation data were collected from field surveys and compared with those predicted by the developed model. The description of the roadworks sites and the outputs of the developed model will be described in details in the following sub-sections.

Table 7.11: Validation – summary of the selected roadworks sites details

Site No.	Site location	Traffic direction	Number of lanes	Type of section	Speed limit	Date	Time
2	M67 (J2-J3)	Westbound	2 lanes	Lane closure	50 mph	Saturday 21/06/2014	11:20 – 14:55
6	M62 (J18-J19)	Eastbound	3 lanes	Narrow lanes	50 mph	Sunday 15/03/2015	11:30 – 13:30

7.5.2.1 Lane closure section

Field data was collected by using camcorders from the M67 (J2-J3) site for the purpose of validating the developed model at roadworks section operated by lane closure scheme. The M67 site consists of 2 lanes with offside lane (i.e. lane 2) closure applied as a TTMS. Figure 7.30 shows an illustration of the M67 roadwork site layout.

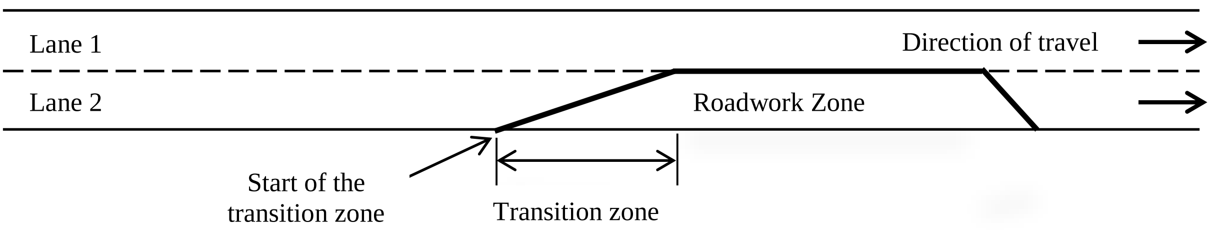


Figure 7.31: Illustration of the M67 roadwork site layout

The field traffic flow, speed and lane utilisation data were extracted at the start of transition zone by playing back the video footage. The field data was then averaged for every 5 minutes interval. The corresponding input values as extracted from the site (e.g. the total flow and the percentage of HGVs) was used at the start of the simulated section. The simulation results were collected at the start of the simulated transition zone. Figure 7.32 illustrates the layout of the simulated section.

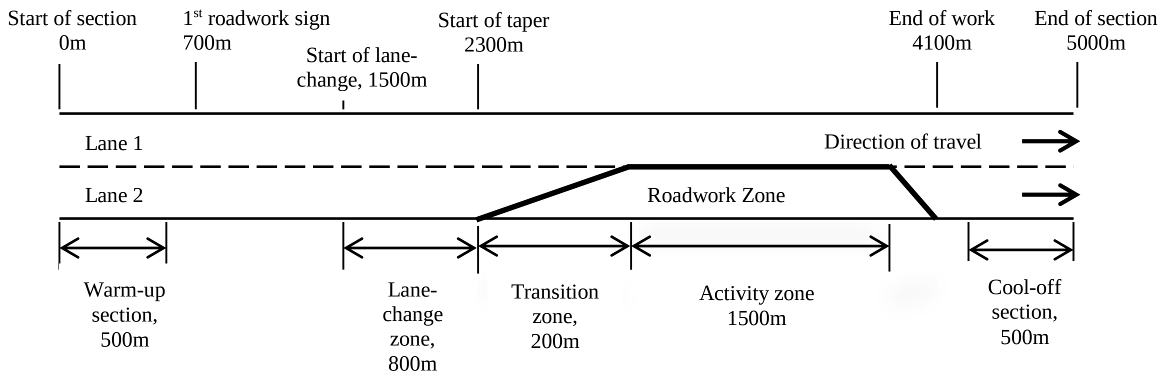


Figure 7.32: Illustration of the simulated section layout (based on the M67 site)

Figures 7.33 and 7.34 show the observed and simulated traffic flow and speed data, respectively, for each 5 minutes interval. While Figure 7.35 shows the simulated and observed lane utilisation data at the start of the transition zone for each lane separately. The statistical goodness-of-fit tests for the traffic flow and speed are reported in Table 7.12.

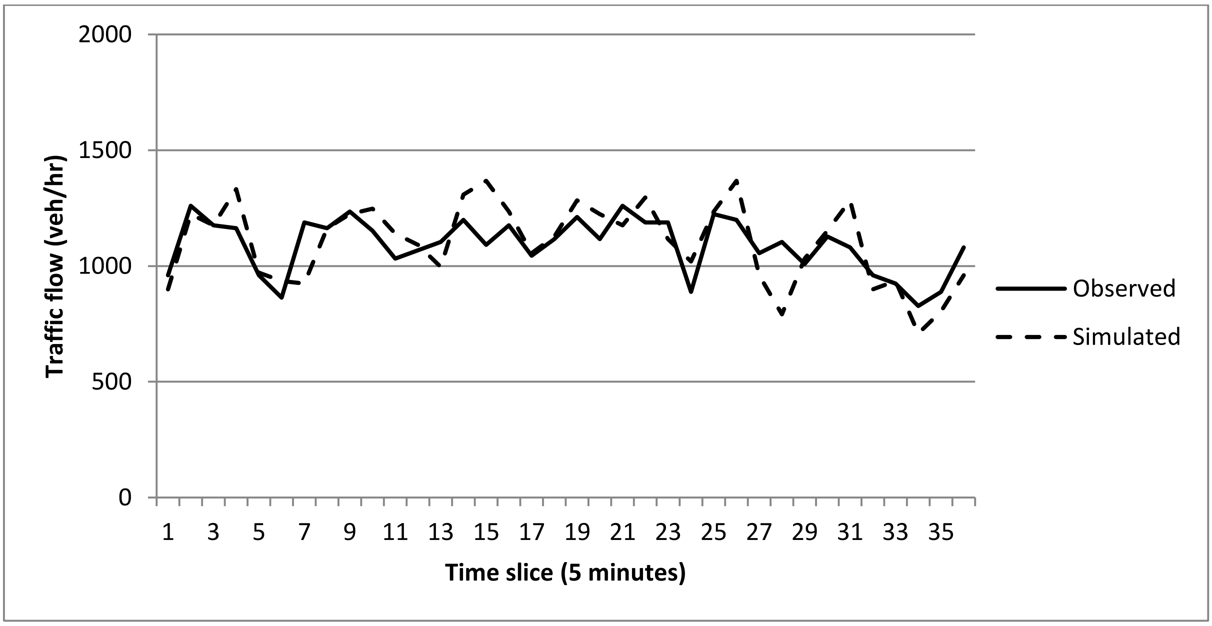


Figure 7.33: Validation - simulated versus observed traffic flow data (M67, lane closure)

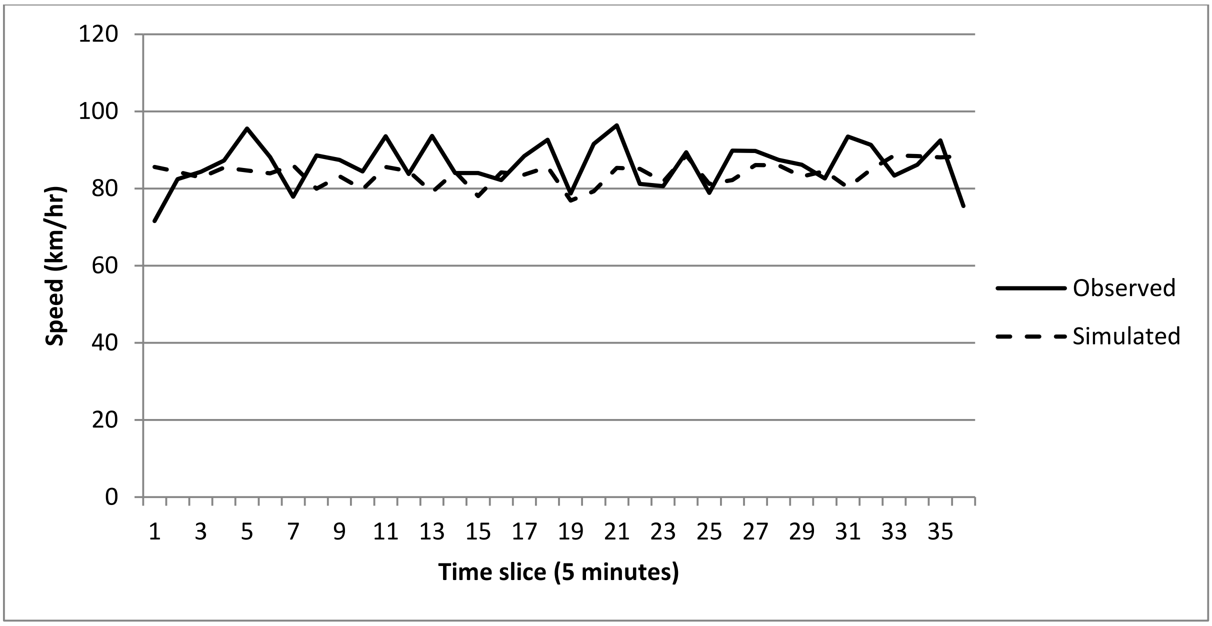
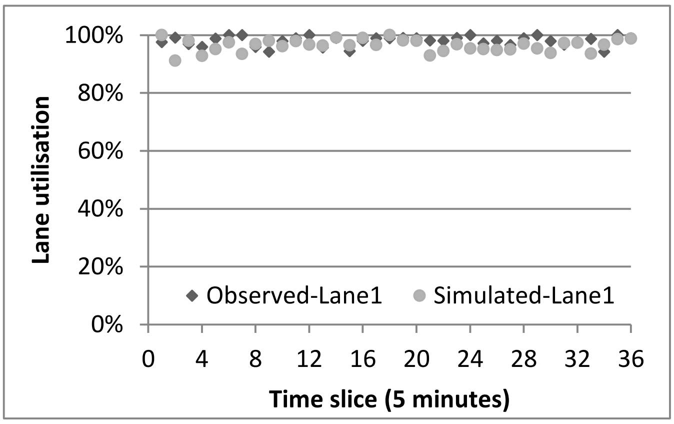


Figure 7.34: Validation - simulated versus observed speed data (M67, lane closure)



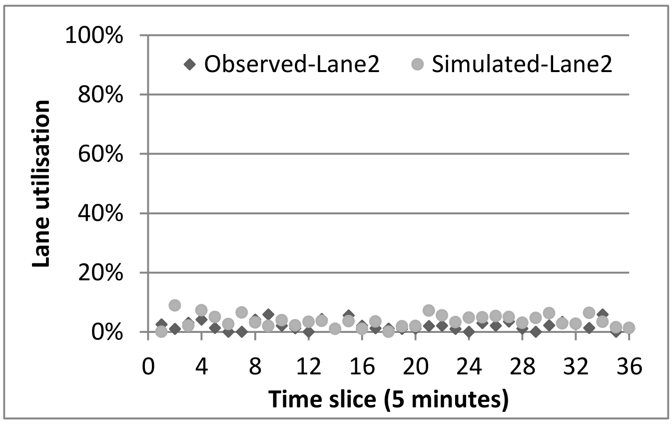


Figure 7.35: Validation - simulated versus observed lane utilisation data for lanes 1 and 2 on the M67 (lane closure)

Table 7.12: Validation - statistical tests for the developed model based on the M67 data

Statistical tests	RMSE	RMSEP	GEH	U	U_m	U_s
Flow	118 (veh/hr)	10.9 %	1.05	0.054	0.008	0.213
Speed	6.9 (km/hr)	8.1 %	--	0.041	0.115	0.159

It can be seen from Figures 7.33 to 7.35 that the simulation results are in good agreement with the real observed data. It can also be seen from Table 7.12 that the statistical tests results are within the acceptable limits.

7.5.2.2 Narrow lanes section

For the purpose of validating the developed model at narrow lanes roadworks section, field date collected from the M62 (J18-J19) was used. The M62 site is a 3 lanes motorway with narrowing lanes applied as a TTMS (see Section 4.3, for more details about this site). Likewise, the input data and the analyses were averaged for every 5 minutes interval. The simulation results were collected at the mid-length section (the length of the simulated section was 5000 m). Figures 7.36 and 7.37 show the comparison between the observed and the simulation results for flow and speed data, respectively. While, the comparisons between the simulated and observed lane utilisation data for each lane of the M62 site are presented in Figure 7.38. The statistical goodness-of-fit tests for the traffic flow and speed are reported in Table 7.13.

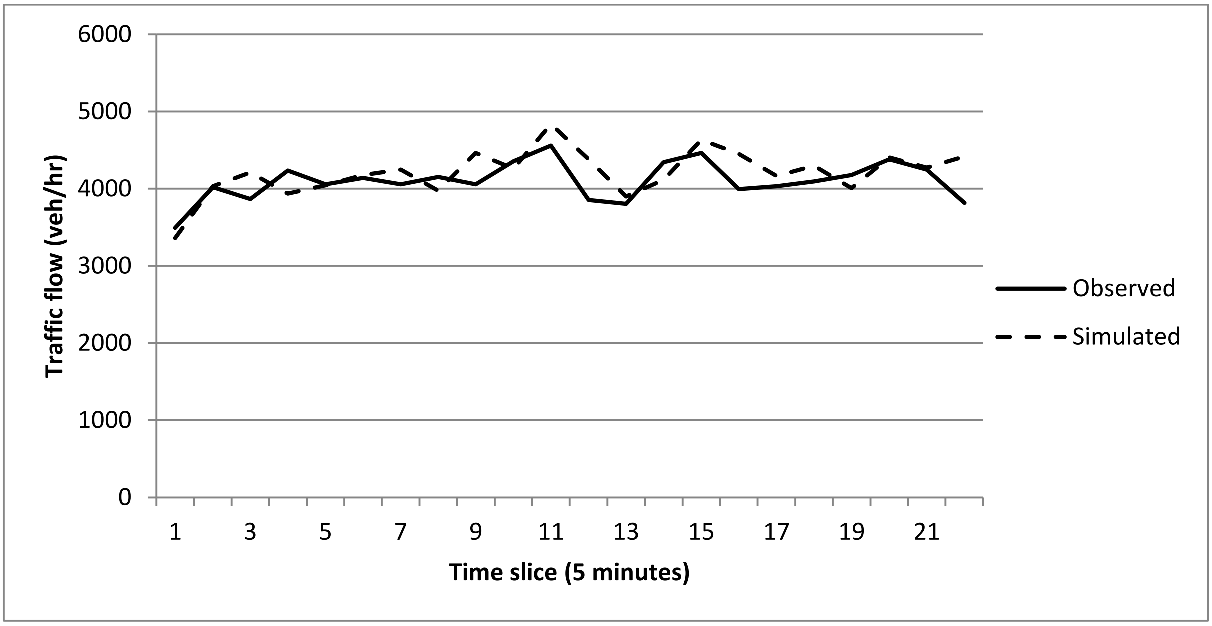


Figure 7.36: Validation - simulated versus observed traffic flow data (M62, narrow lanes)

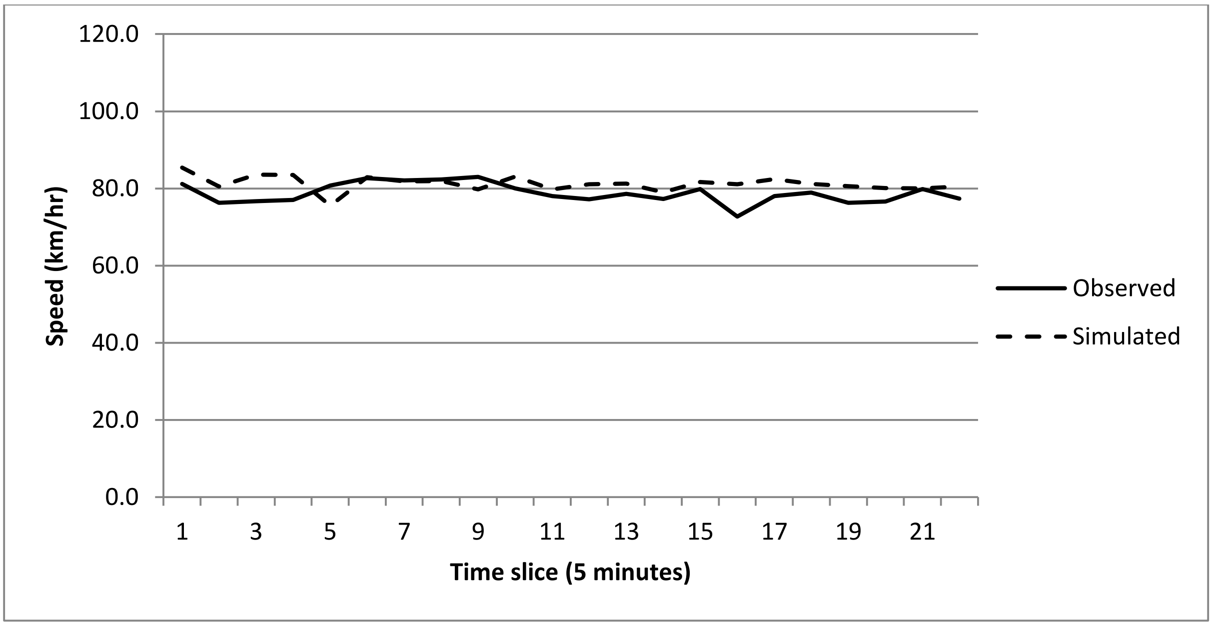


Figure 7.37: Validation - simulated versus observed speed data (M62, narrow lanes)

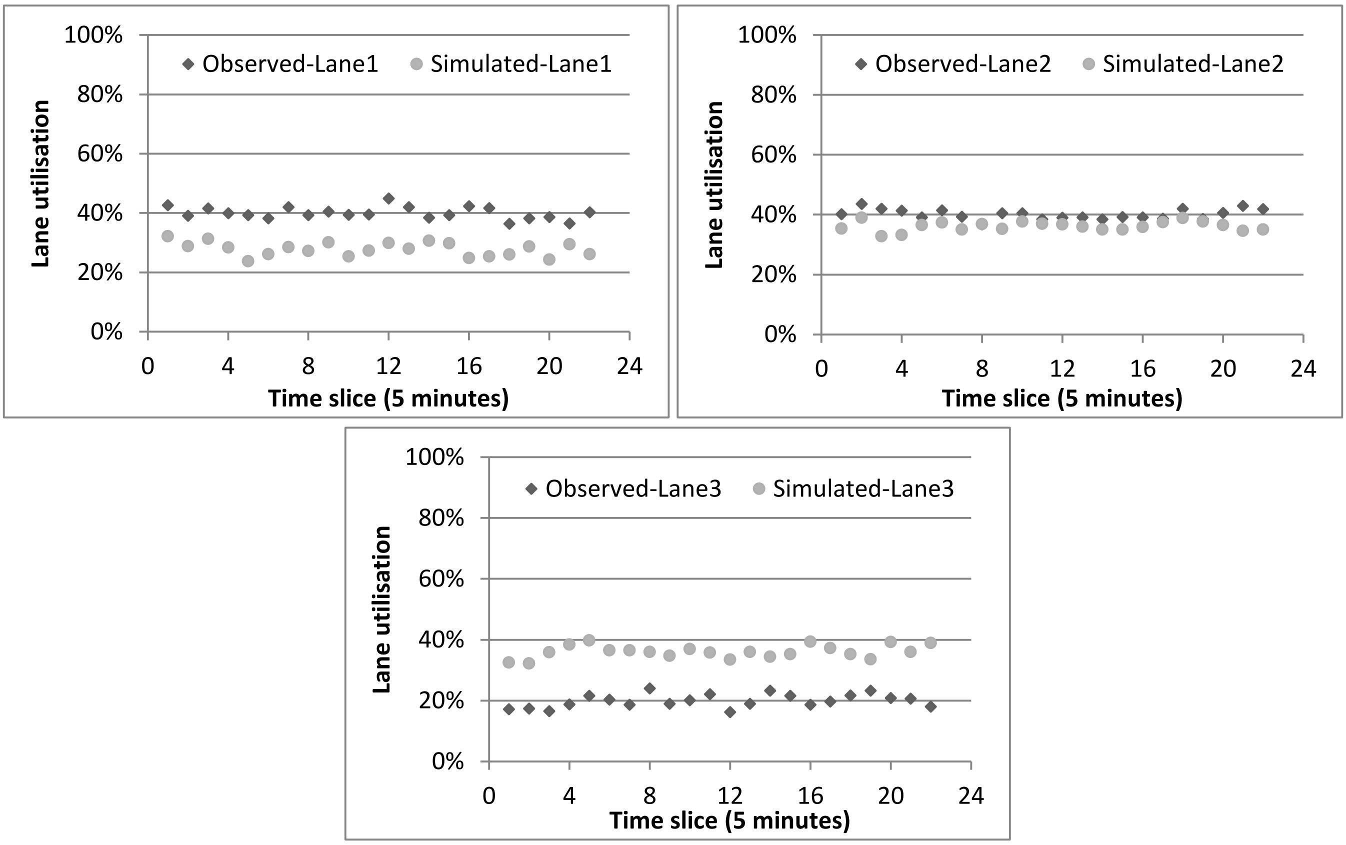


Figure 7.38: Validation - simulated versus observed lane utilisation data for lanes 1, 2 and 3 on the M62 (narrow lanes)

Table 7.13: Validation - statistical tests for the developed model based on the M62 data

Statistical tests	RMSE	RMSEP	GEH	U	U_m	U_s
Flow	267 (veh/hr)	6.7 %	1.19	0.032	0.164	0.038
Speed	3.9 (km/hr)	5.1%	--	0.025	0.389	0.022

Figures 7.36 and 7.37 together with the statistical tests shown in Table 7.13 indicate that the simulation results are in good agreement with the real observed data. However, Figure 7.38 shows that the observed and simulated lane utilisation data are not close to a good match, particularly for lane 1 and lane 3. This difference could be due to the location of the M62 site. The observed section for the M62 site was located before around 300 metres from an exit to a service station and a local area (i.e. Whittle Lane, Heywood). This may explain the reasons for observing the actual drivers have been using lane 1 more than those predicted by the model.

It can be concluded that the simulation results for both sites (the M67 lane closure section and the M62 narrow lanes section) are in good agreement with the real observed data. This consistency can be proved by statistical test results for both flow and speed which are satisfactory for all tests as they are within the limits (e.g. the U for the flow and speed measurements did not exceed 0.1 and the RMSEP for the flow and speed did not exceed 15%). This indicates that the newly developed model can reasonably describe the observed data from roadworks sections (lane closure and narrow lanes TTMSs) in terms of replicating flow, speed and lane utilisation.

7.6 Summary

The current chapter presented the verification, calibration and validation processes that have been achieved for the developed model with using published and observed data. The main points of this chapter can be summarised as follows:

- The verification process has been achieved for the developed micro-simulation model by observing the animation of the model and the simulation outputs. The verification results showed that the developed model performs logically and as expected (after making several improvements and debugging any errors).
- The calibration process has been achieved for the main four components of the developed micro-simulation model (i.e. car following, lane changing, lane closure and narrow lanes) using several sets of field data. The simulation results were compared with the corresponding field data. The calibration results, in general, showed good agreement between the observed field data and those obtained from the developed model.
- The current model contains several parameters; some of these parameters have been obtained directly either from the observed data or from the literature, whereas others have been obtained from the model itself. This was achieved by performing several simulation runs using different values of the parameter, then comparing the simulated with observed data to choose the most appropriate values that achieved the closest match between the observed and simulated results.
- The validation process has been achieved for the whole simulation model (under normal and roadworks sections) using different sets of field data to those used in the calibration process. The validation results were within acceptable limits which confirm the validity of the developed model. Therefore, the newly developed model has been applied to evaluate the efficiency of TTMSs and also to test the effect of different scenarios on the traffic conditions at roadworks sections, as will be discussed in the following Chapter.
- Limitations identified in this chapter: the low percentage of heavy good vehicles on the collected data from roadwork sections with narrow lanes such as the M6 site

(HGVs% = 7%) affects the calibration process of the developed narrow lanes sub-model (see Section 7.4.4). Therefore, field data from motorway roadwork sites with the use of a narrow lanes scheme with high HGVs% are required.

CHAPTER EIGHT
MODEL APPLICATIONS

8.1 Introduction

In the previous chapter, the verification, calibration and validation processes of the newly developed micro-simulation model were discussed. It is revealed that the developed micro-simulation model is reliable enough to be used for further applications. In this chapter, the newly developed micro-simulation model is applied to evaluate the efficiency of different TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure) at motorway roadwork sections. The effect of various traffic parameters (i.e. HGVs%, section length and speed limits) on traffic performance (i.e. capacity and average vehicles delay) were also studied using the developed micro-simulation model.

8.2 The effect of TTMSs on traffic performance for different HGVs%

It is believed that the different types of temporary traffic management schemes (TTMSs) applied at motorway roadwork sections have different effects on sections capacity, safety and delay. Previous simulation studies have considered the effect of the side of lane closure (i.e. which side to be closed) on site capacity (see for example Hunt and Yousif, 1994). However, no simulation study has been found in the literature to deal with the effect of using narrow lanes as a TTMS.

The developed micro-simulation model has been used to study the effect of different TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure) on traffic performance under different HGVs% for a typical length of motorway including a roadwork section. Figure 8.1 shows a typical road layout (for a 3-lanes motorway section with offside lane closure) which is used as a default section for this test.

Two measures of performance were used for the purpose of this test and throughout this chapter. These are capacity and average vehicles delay which are widely used to describe the traffic performance in many previous studies (see for example Zia, 1992; Yousif, 1993; Al-Jameel, 2012; Weng and Meng, 2013; and Alterawi, 2014). As discussed in Section 2.6, the capacity can be defined as the maximum throughput that can be achieved; the throughput is the number of vehicles passing the roadwork section during a given time period, whereas the delay can be defined as the difference between the journey time of a vehicle travelling along a certain section and the journey time when travelling along that section using the desired speed. The average vehicles' delay is calculated by dividing the total delay of all vehicles over the total number of vehicles (in sec/veh).

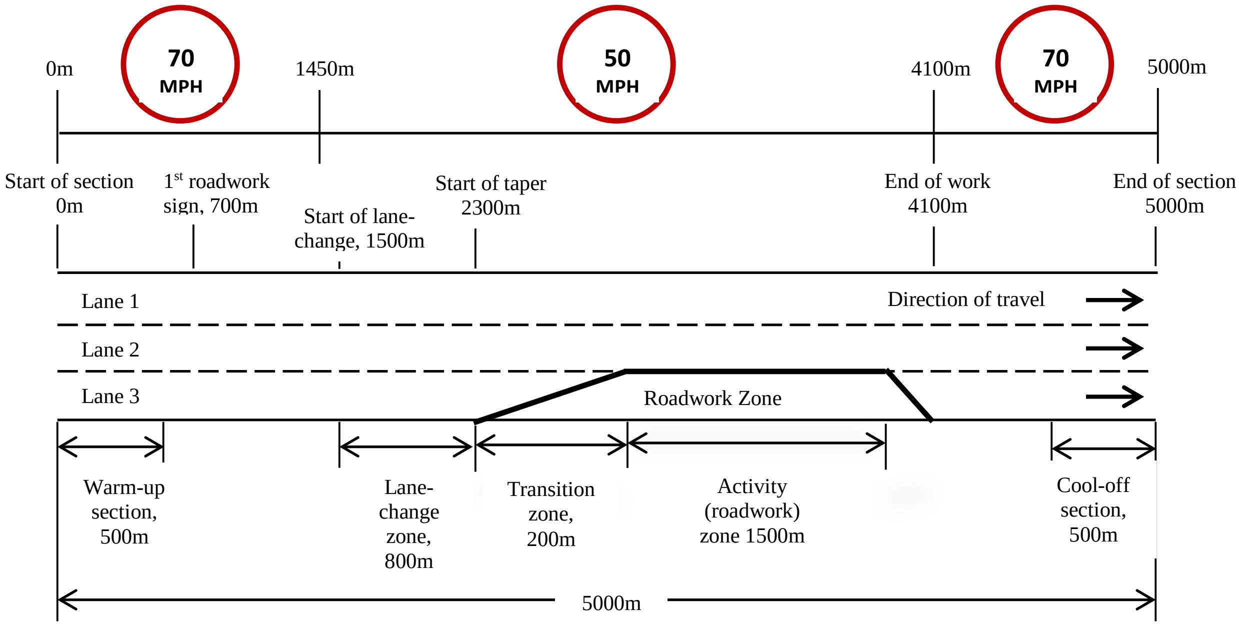


Figure 8.1: Typical layout used in testing the effect of different TTMSs

For this test, narrow lanes, offside lane closure and inside lane closure schemes were tested. Various HGVs percentages were also tested (HGVs of 0% - 30% with 5% increment). The effect of different TTMSs for motorway roadwork sections with 2, 3 and 4 lanes under different levels of traffic flows (i.e. from free flow to congested situations) will be discussed in the following sub-sections. The simulation results (i.e. capacity and average vehicles delay) were analysed at the end of the roadwork zone where the road layout returns to its normal condition. One hour of simulation time (excluding the periods of warm-up and cool-off) is used for each run of the simulation. Over 1200 simulation runs were conducted for this test (i.e. the effect of different TTMSs on traffic performance under different HGVs%).

8.2.1 Two lanes section

Table 8.1 lists the main parameters that were used to test the effect of TTMSs on section capacity and average vehicles delay for a motorway roadwork section with 2 lanes. All other vehicle's/driver's characteristics were kept fixed. Figure 8.2 shows schematic layouts of the tested 2-lanes motorway sections with roadworks.

Table 8.1: Parameters used in testing the effect of TTMSs on capacity and average delay (2-lanes roadwork section)

Number of lanes	**TTMSs**	**HGVs (%)** (increment)	**Flow rates (veh/hr)** (increment)	**Whole section length (m)**	**Roadwork zone length (m)**	**Roadwork speed limit (mph)**
2	- Offside closure - Inside closure	0 – 30 (5)	250 - capacity (250)	5000	1500	50

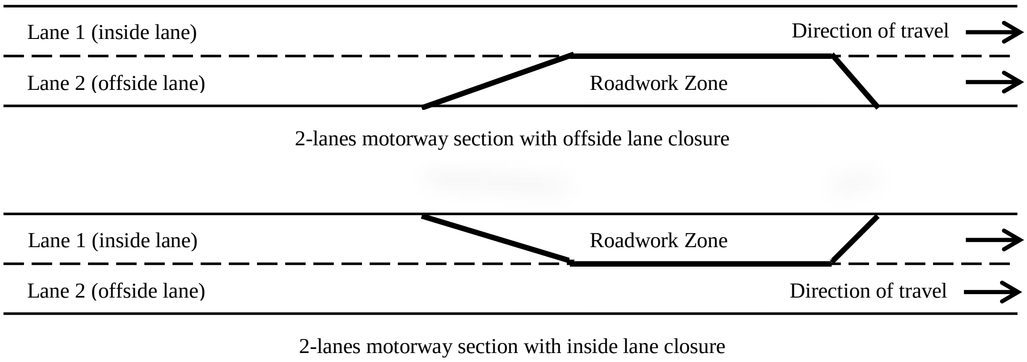


Figure 8.2: Schematic layouts of the tested 2-lanes motorway roadwork sections

It should be noted that for Table 8.1 and Figure 8.2 the simulated roadwork section was used for both the offside and inside lane closures as a TTMSs without using narrow lanes, due to unavailability of data from sites with narrow lanes schemes on a 2 lanes motorway roadwork sections (possibly due to section width shortage). It can also be seen from Table 8.1 that the input flow rates for successive runs of the simulation was increased from 250 veh/hr up to the section capacity with an increment of 250 veh/hr. When the simulated section reaches its capacity, the generated vehicles were not all able to enter the simulated section due to the car-following rules which are based on maintaining a safe distance between vehicles on the same lane, as discussed in Section 6.4.

8.2.1.1 Effect of TTMSs on section capacity

Figure 8.3 shows the effect of TTMSs (i.e. offside and inside lane closure schemes) on section capacity for different HGVs%. The simulation results presented in Figure 8.3 are based on the average results for three simulation runs with different random numbers' seeds. However, the sensitivity of simulation results to the variation in the random number seeds was found to be insignificant (see Section 7.3). Therefore, the simulation results (for the following sections) were based on one simulation run for each case which will help in reducing the number of simulation runs significantly.

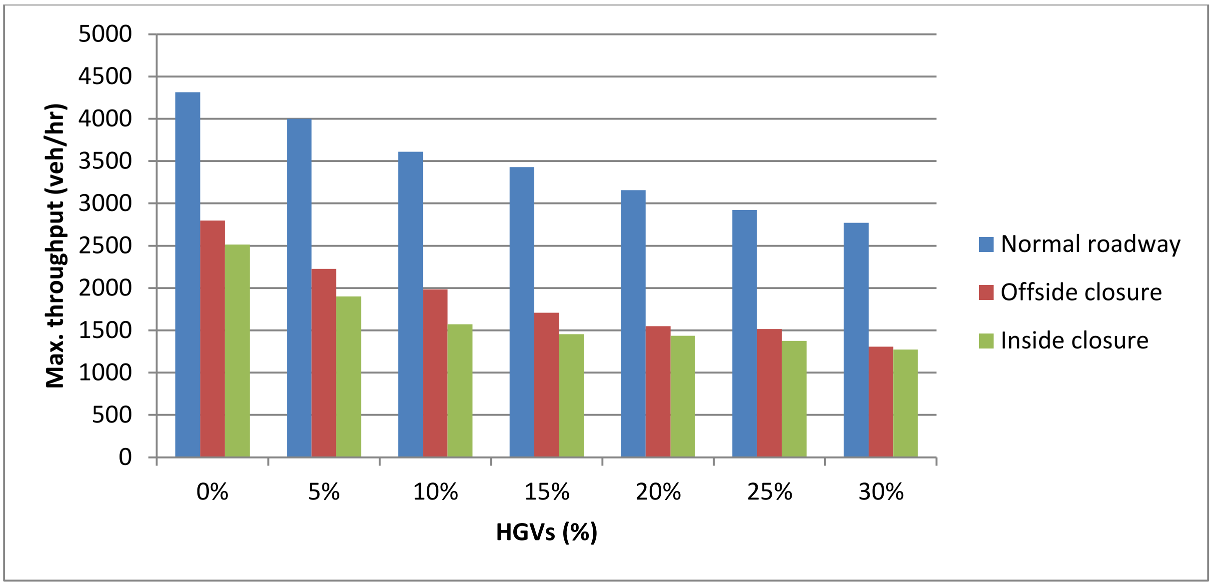


Figure 8.3: Effect of TTMSs on 2-lanes roadwork sections capacity for different HGVs%

It can be seen from the figure that the maximum section throughput (capacity) is generally higher for the case of the offside lane closure layout compared with the inside lane closure layout. This could be due to the variation of HGVs% between both lanes (the inside lane carries more HGVs than the offside lane). When the inside lane is closed, the HGVs and other slow moving vehicles that are travelling on the inside lane are required to merge into the offside lane which carries faster moving vehicles. This could be difficult for the HGVs due to their lower acceleration capabilities (Yousif, 1993). This could cause some traffic turbulences which could affect the section capacity. This finding (i.e. roadwork sections with offside lane closures having capacity higher than those with inside lane closures) could be the reason for having offside lane closure being the most commonly used layouts in practice.

It can also be seen from Figure 8.3 that the maximum section throughput (capacity) achieved for roadwork section with offside lane closure for a traffic composition of 15% HGVs is around 1700 veh/hr. This was found to be consistent with the findings of Matthews (1984), as discussed in Section 2.6.1.

8.2.1.2 Effect of HGVs% on section capacity

Figure 8.3 shows also the effect of different HGVs percentages on section capacity for both normal and roadwork sections. As the percentage of HGVs increases, the section capacity decreases from about 2500 veh/hr (for roadwork section with inside lane closure scheme) at 0% HGVs to around 1270 veh/hr at 30%. This is approximately 50% reduction in capacity which could be attributed to the longer lengths of HGVs resulting in an increase in headways and hence reduction in capacity. Also, HGVs have lower acceleration capabilities and lower desired speeds than those of passenger cars (as discussed in Section 6.3.2.2). Table 8.2 summarises the effect of different HGVs% on the capacity of 2 lanes motorway for both normal and roadwork sections.

Table 8.2: Effect of HGVs% on the capacity of normal and roadwork sections (2-lanes)

Type of section	Section capacity (veh/hr)		Reduction in capacity (%)
	0% HGVs	30% HGVs	
Normal roadway section	4314	2769	36
Roadwork with offside lane closure	2796	1307	53
Roadwork with inside lane closure	2515	1273	49

8.2.1.3 Effect on average vehicles delay

Figure 8.4 shows the effect of flow rates for various HGVs% for different TTMSs on average vehicles delay. The figure indicates that as traffic flow increases, the average delay increases. The average delay increases sharply when the inflow is approaching the maximum section throughput (capacity). When the inflow exceeds the roadwork section capacity, queues started to develop (at the start of the roadwork zone) leading to an increase in the driver's journey time and hence an increase in delay.

It should be noted that, for the case of normal roadway section (when all lanes are open for traffic movements), the sharp increase in the average vehicles delay would not be possible, because, as mentioned earlier, when the simulated section reaches its capacity, the generated vehicles were not all able to enter the simulated section due to the car-following rules. This means that the inflow cannot exceed the section capacity. However, for the cases of roadwork section with inside or offside closures (i.e. when a lane is withdrawn from the roadway), the sharp increase in the average vehicles delay would occur when the inflow exceeds the roadwork section capacity. This is because the section located before the roadwork (which has two lanes open for traffic movements) can accommodate more vehicles than that for roadwork section (which has only one lane open for traffic movements, see Figure 8.2). This leads to the occurrence of queues and hence the sharp increase in the delay as a result, due to the inflow being higher than the outflow (throughput).

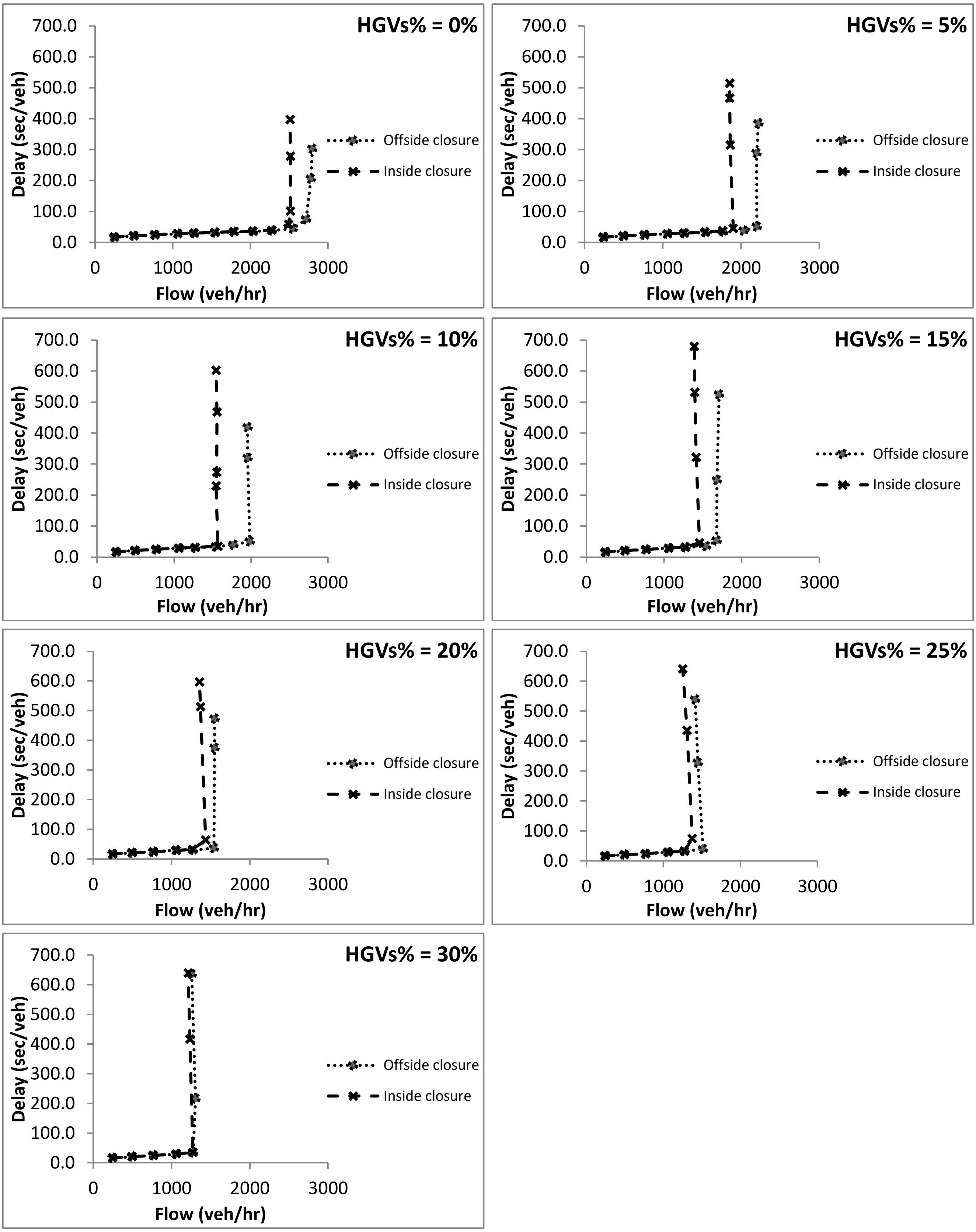


Figure 8.4: Effect of flow rates, HGVs% and TTMSs on average delay for 2-lanes motorway roadwork sections

It can be seen from Figure 8.4 that, when the inflow is lower than the roadwork section capacity, there are no significant differences in the average vehicles delay between the offside lane closure and the inside lane closure layouts. However, when the inflow exceeds the section capacity, in general, the average vehicles delay has increased for the inside lane closure layout compared with that of the offside lane closure layout, for the same input flows. This could be due to what has been discussed in Section 3.6.2 that HGVs need more time to perform lane changing manoeuvres than passenger cars and due to the fact that higher proportions of HGVs are travelling on the inside lane (i.e. closed lane) which have to merge into the offside lane. This could lead to an increase in vehicles' journey time further and hence increase the average vehicles delay.

8.2.1.4 Summary

Table 8.3 summarises the effect of TTMSs (i.e. offside and inside lane closure schemes) on reducing section capacity of 2 lanes motorway roadwork sections for different HGVs%. It can be seen from Table 8.3 that the reduction in capacity has increased for the inside lane closure scheme compared with that of the offside lane closure scheme for all of the HGVs%. Table 8.3 also summarises the percentage of capacity gained when using the offside lane closure scheme instead of using the inside lane closure scheme.

Table 8.3: Effect of TTMSs on capacity of 2-lane roadwork sections for different HGVs%

TTMSs	Reduction in Capacity (%)						
	0% HGVs	**5% HGVs**	**10% HGVs**	**15% HGVs**	**20% HGVs**	**25% HGVs**	**30% HGVs**
Offside lane closure scheme	35	44	45	50	51	48	53
Inside lane closure scheme	42	52	57	58	55	53	54
Gaining in capacity (%) (resulting from using the offside closure scheme instead of using the inside closure scheme)							
The use of offside closure scheme	7	8	12	8	4	5	1

It can be seen from Table 8.3 that the gaining in capacity when using the offside lane closure scheme instead of using the inside lane closure scheme, in general, was around 8%. In addition, it can be seen from Figure 8.4 that the average vehicles delay (the sharp increase in the average vehicles delay) has increased by around 150 seconds when using inside lane closure compared with that of the offside lane closure scheme. Based on these simulation results, it can be concluded that the offside lane closure scheme has performed better than the inside lane closure in terms of maintaining section capacity and with lower average vehicles delay. However, sometimes site conditions may necessitate the closure of the inside lane because of certain requirements on site.

8.2.2 Three lanes section

Table 8.4 lists the main parameters that were used to test the effect of different TTMSs on section capacity and average vehicles delay for a motorway roadwork section with 3 lanes. Likewise, all other vehicle's/driver's characteristics were kept fixed. Figure 8.5 shows schematic layouts of the tested 3 lanes motorway sections with roadworks.

Table 8.4: Parameters used in testing the effect of TTMSs on capacity and average delay (3-lanes roadworks section)

Number of lanes	**TTMSs**	**HGVs (%)** (increment)	**Flow rates (veh/hr)** (increment)	**Whole section length (m)**	**Roadwork zone length (m)**	**Roadwork speed limit (mph)**
3	- Narrow lanes - Offside closure - Inside closure	0 – 30 (5)	250 - capacity (250)	5000	1500	50

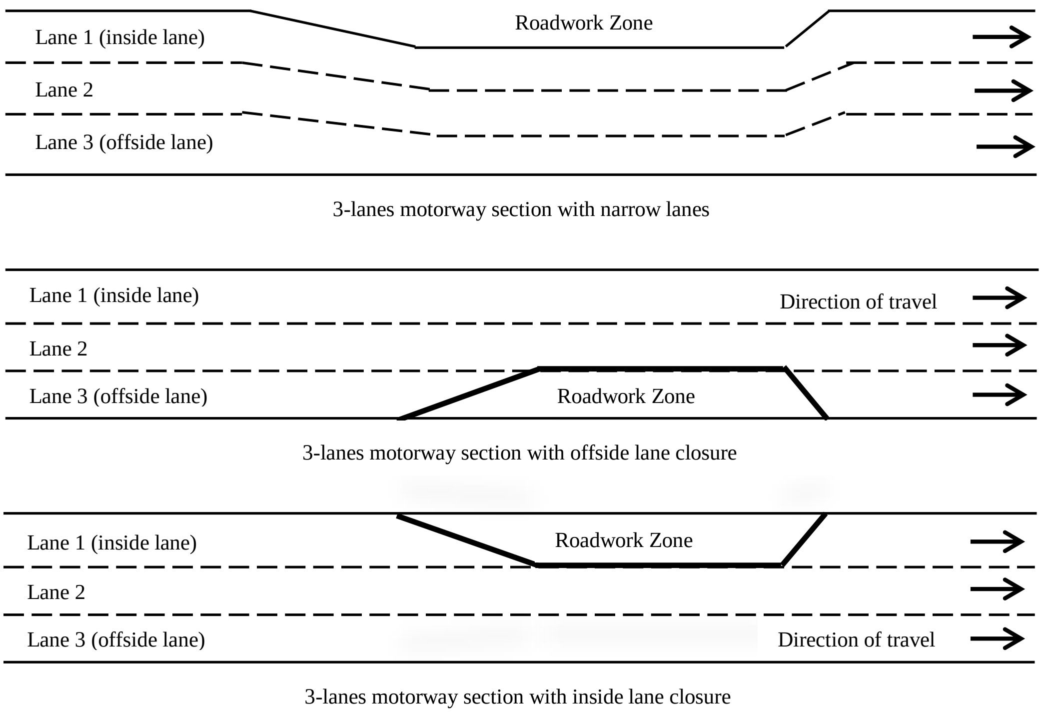


Figure 8.5: Schematic layouts of the tested 3-lanes motorway roadwork sections

8.2.2.1 Effect of TTMSs on section capacity

Figure 8.6 shows the effect of different TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure) on section capacity for different HGVs%. It can be seen from the figure that, when the HGVs% is lower or equal to 25%, the maximum section throughput (capacity) has not decreased for the use of the narrow lanes layout compared to the normal roadway section (i.e. no roadworks). When the HGVs% is increased to 30%, the section capacity has decreased for the case of the narrow lanes layout compared to the normal roadway section.

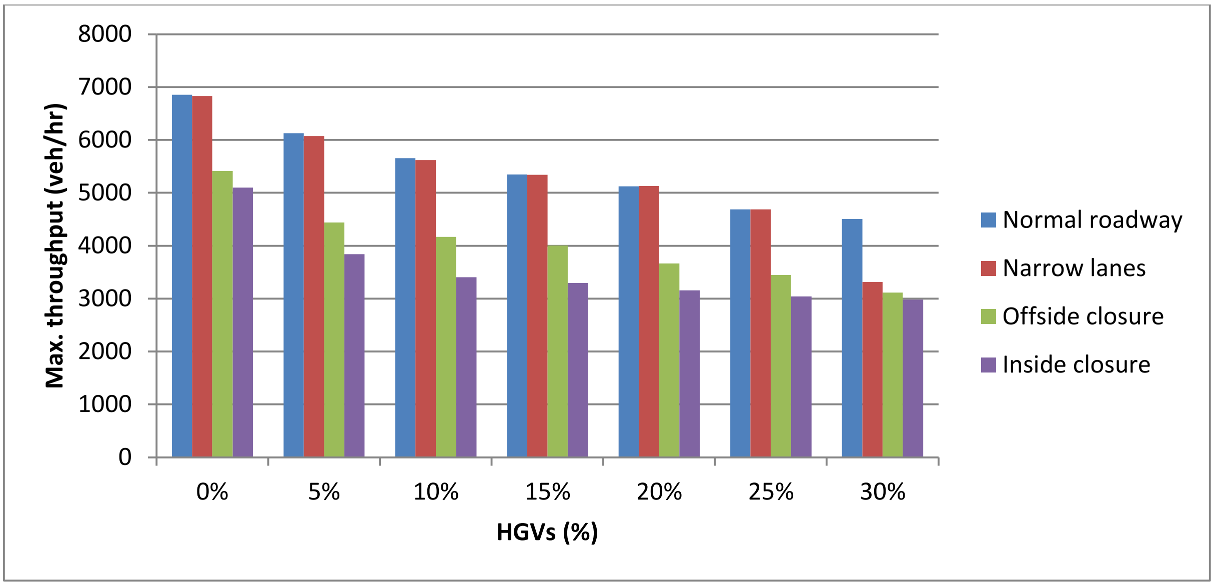


Figure 8.6: Effect of TTMSs on 3-lanes roadworks section capacity for different HGVs%

As the HGVs% increases, the effect of narrow lanes on driving behaviours (i.e. avoiding passing HGVs on the same lane and on the adjacent lane, as discussed in Chapter 4) increases. At high percentages of HGVs, the number of avoiders (drivers who prefer to keep following HGVs rather than overtaking them) also becomes higher. Those avoiders will block other drivers behind preventing them from overtaking and forcing them to drive below their desired speeds. This could lead to an increase in the speed differences between drivers at the approach to roadwork sections. This disturbance in traffic flow may lead to flow breakdown and explain the reasons for observing the drop in section capacity for the use of the narrow lanes layout at 30% of HGVs.

Also, it can be seen from Figure 8.6 that for the case of the offside lane closure layout, section capacity is higher than that for the inside lane closure layout. This is consistent with the results presented in Section 8.2.1.1 for the 2 lanes motorway roadwork section.

8.2.2.2 Effect of HGVs% on section capacity

Figure 8.6 also shows the effect of different HGVs percentages on section capacity for both normal and roadwork sections. As the percentage of HGVs increases, the section capacity decreases from around 5400 veh/hr (for roadwork section with offside lane closure scheme) at 0% HGVs to about 3100 veh/hr at 30% with approximately 40% reduction in capacity. Table 8.5 summarises the effect of different HGVs% on the capacity of 3 lanes motorway for both normal and roadwork sections.

Table 8.5: Effect of HGVs% on the capacity of normal and roadwork sections (3-lanes)

Type of section	Section capacity (veh/hr)		Reduction in capacity (%)
	0% HGVs	30% HGVs	
Normal roadway section	6855	4507	34
Roadwork with narrow lanes	6827	3314	51
Roadwork with offside lane closure	5415	3112	43
Roadwork with inside lane closure	5101	2982	42

8.2.2.3 Effect on average vehicles delay

Figure 8.7 shows the effect of the flow rates, HGVs% and TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure) on average vehicles delay for 3 lanes motorway roadwork sections. When the offside or inside lane closure layouts are implemented, the figure indicates that as traffic flow increases, the average delay increases. The average delay increases sharply when the inflow exceeds the maximum roadwork section throughput (capacity).

It can also be seen from Figure 8.7 that, when the narrow lanes layout is implemented, the average vehicles delay increases slightly as traffic flow increases; this is when the adopted HGVs% equals to or is lower than 25%. When the HGVs% is increased to 30%, the average vehicles delay increases sharply as the inflow exceeds the section capacity. Therefore, it can be concluded that the sharp increase in the average vehicles delay is strongly influenced by the HGVs%.

It should be noted here that, for the cases of normal roadway section or roadwork section with narrow lanes (with HGVs% ≤ 25%, for 3-lane sections), the sharp increase in the average vehicles delay would not be possible, see Figure 8.7. This is because, as mentioned earlier in Section 8.2.1.3, the inflow cannot exceed the section capacity. Also, as shown in Figure 8.6, the section capacity has not decreased for the use of the narrow lanes layout with HGVs% ≤ 25% compared to the normal roadway section. However, for the cases of roadwork section with inside/offside closures or narrow lanes with HGVs = 30%, the sharp increase in the average vehicles delay would occur (when the inflow exceeds the roadwork section capacity).

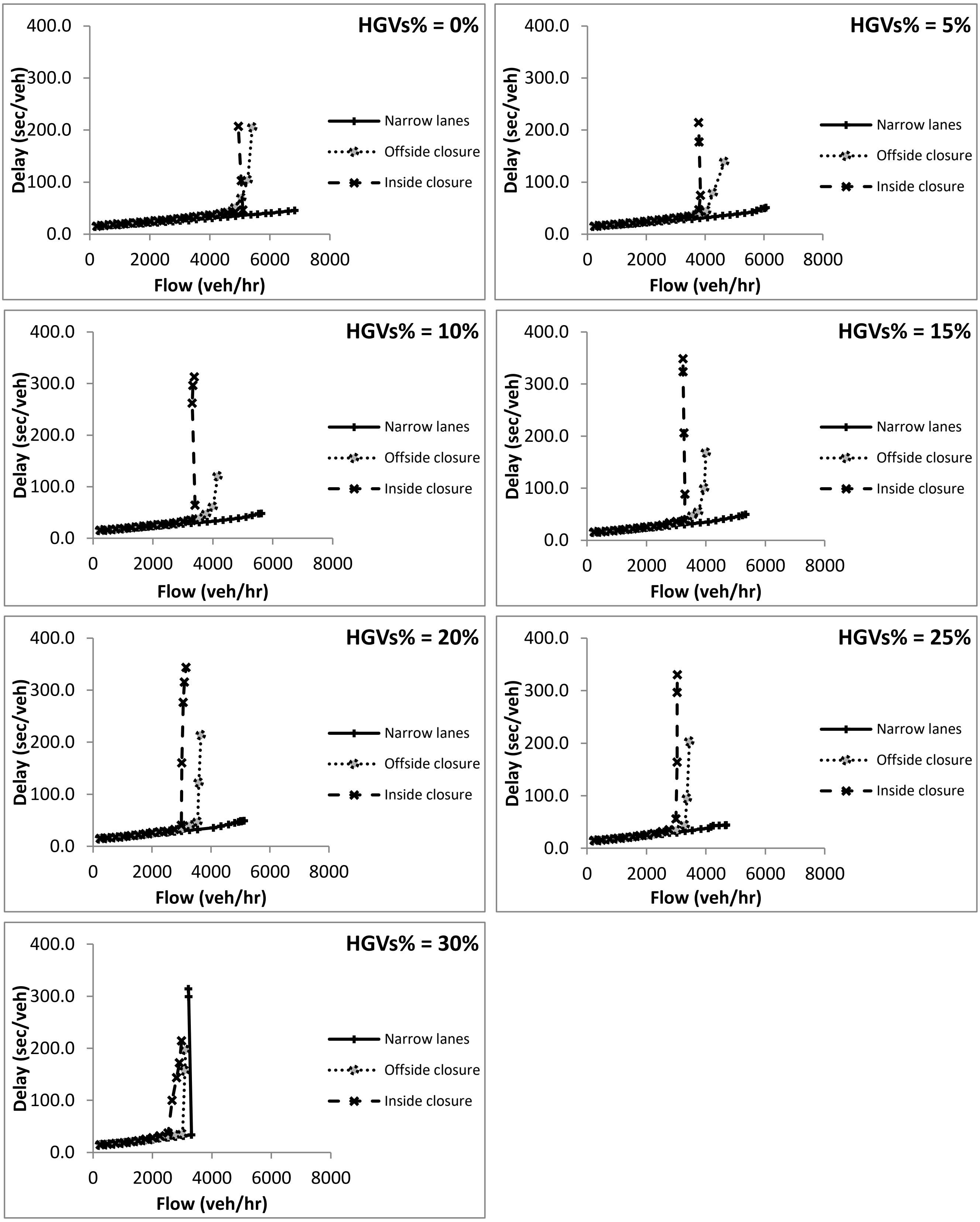


Figure 8.7: Effect of flow rates, HGVs% and TTMSs on average delay for 3-lanes motorway roadwork sections

Observations from the developed simulation model animation have shown that, at high traffic flows associated with high HGVs% (i.e. 30% or possibly higher), queues started to develop at the start of the roadwork zone. The movement of traffic through the roadwork zone (i.e. narrow lanes) was found to be intermittent (not continuous and moving in platoons), as shown in Figure 8.8. Such intermittent movements which were observed from the developed model through the narrow lanes zone were also observed on site. This intermittent movement could be attributed to the presence of a number of slowing moving drivers of HGVs and their avoiders who block other drivers behind them and force them to slowing down too. This leads to the loss of available spaces through narrow lanes zone which could lead to a reduction in section throughput. This situation (i.e. intermittent movement) in addition to the disturbance in traffic stream at the approach to roadwork section (due to the relative difference in speeds amongst motorists) could lead to flow breakdown.

Chitturi and Benekohal (2005) studied the effect of lane width on speeds of passenger cars and HGVs based on data collected from motorway roadwork sites with narrow lanes scheme. The results showed that the free-flow speeds of HGVs were statistically lower than the free-flow speeds of cars, even though the applied temporary speed limit was the same for both passenger cars and HGVs. In addition, the reduction in the free-flow speeds of HGVs was greater than the reduction in the free-flow speeds of cars. Furthermore, they reported that this reduction in the speed of HGVs affected the performance of the traffic stream in the roadwork sections.

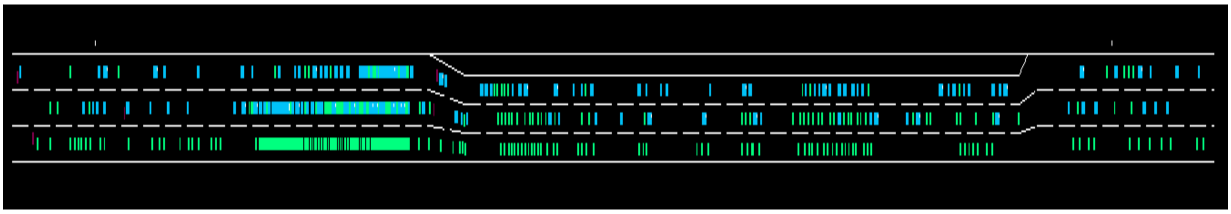


Figure 8.8: Typical screenshot from the developed simulation model (3-lanes motorway roadworks section with narrow lanes scheme at high flows and high HGVs%)

8.2.2.4 Summary

Table 8.6 summarises the effect of TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure schemes) on reducing section capacity of 3 lanes motorway roadwork sections for different HGVs%. Also, it shows the percentage of capacity gained when using the narrow lanes scheme instead of using the offside lane closure scheme. It should be noted here that the narrow lanes scheme was compared to the offside lane closure scheme since the offside lane closure scheme performed better than the inside lane closure scheme, as shown in Table 8.6. The table also shows the percentage of capacity gained when using the offside lane closure scheme instead of using the inside lane closure scheme.

Table 8.6: Effect of TTMSs on capacity of 3-lane roadwork sections for different HGVs%

TTMSs	Reduction in Capacity (%)						
	0% HGVs	**5% HGVs**	**10% HGVs**	**15% HGVs**	**20% HGVs**	**25% HGVs**	**30% HGVs**
Narrow lanes scheme	0	1	0	0	0	0	26
Offside lane closure scheme	21	28	26	25	28	26	31
Inside lane closure scheme	26	37	40	38	38	35	34
Gaining in capacity (%) (resulting from using the narrow lanes scheme instead of using offside lane closure scheme)							
The use of narrow lanes scheme	21	27	26	25	28	26	5
Gaining in capacity (%) (resulting from using the offside lane closure scheme instead of using inside closure scheme)							
The use of offside lane closure	5	9	14	13	10	9	3

It can be seen from Table 8.6 that, in general, there is a relatively high percentage in gained capacity when using the narrow lanes scheme instead of using the offside lane closure scheme when the HGVs percentage is ≤ 25%. This is in the region of about 25%. However, this capacity gain drops down to 5% when HGV% is increased to 30%. In addition, it can be seen from Figure 8.7 that the average vehicles' delay has decreased by around 150 seconds for the use of narrow lanes scheme compared with that of the offside lane closure scheme, when the HGVs ≤ 25%. It can also be seen from Table 8.6 that the gaining in capacity when using the offside lane closure scheme instead of using the inside lane closure scheme was, in general, around 10%. Additionally, it can be seen from Figure 8.7 that the average vehicles delay has increased by around 150 seconds for the inside lane closure scheme compared with that of the offside lane closure scheme. Based on these simulation results, it can be concluded that narrow lanes scheme performed better than both the offside and inside lane closure schemes in terms of maintaining section capacity and average vehicles delay up until the percentage of HGVs is 25%. After that, when the HGVs% becomes higher (i.e. 30%), the performance of the all tested TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure schemes) are nearly similar. Therefore, it may be argued that the use of narrow lanes scheme as a TTMS at 3 lanes motorway roadwork sections is not recommended when the expected HGVs% is higher than 25% for high traffic demands, since for HGVs% = 30% the gaining in capacity is only 5% (see Table 8.6) and the average vehicles delay, when using the narrow lanes scheme, is higher than both the offside and inside lane closure schemes by around 100 seconds (see Figure 8.7). It is also believed that some driving behaviours at narrow lanes sections are unsafe (as discussed in Sections 4.4.2 and 4.5).

8.2.3 Four lanes section

Table 8.7 lists the main parameters that were used to test the effect of different TTMSs on section capacity and average vehicles delay for a motorway roadwork section with 4 lanes. Likewise, all other vehicle's/driver's characteristics were kept unchanged. Figure 8.9 shows schematic layouts of the tested TTMSs that applied at 4 lanes motorway roadwork sections.

Table 8.7: Parameters used in testing the effect of TTMSs on capacity and average delay (4-lanes roadworks section)

Number of lanes	**TTMSs**	**HGVs (%)** (increment)	**Flow rates (veh/hr)** (increment)	**Whole section length (m)**	**Roadwork zone length (m)**	**Roadwork speed limit (mph)**
4	- Narrow lanes - Offside closure - Inside closure	0 – 30 (5)	500 - capacity (500)	5000	1500	50

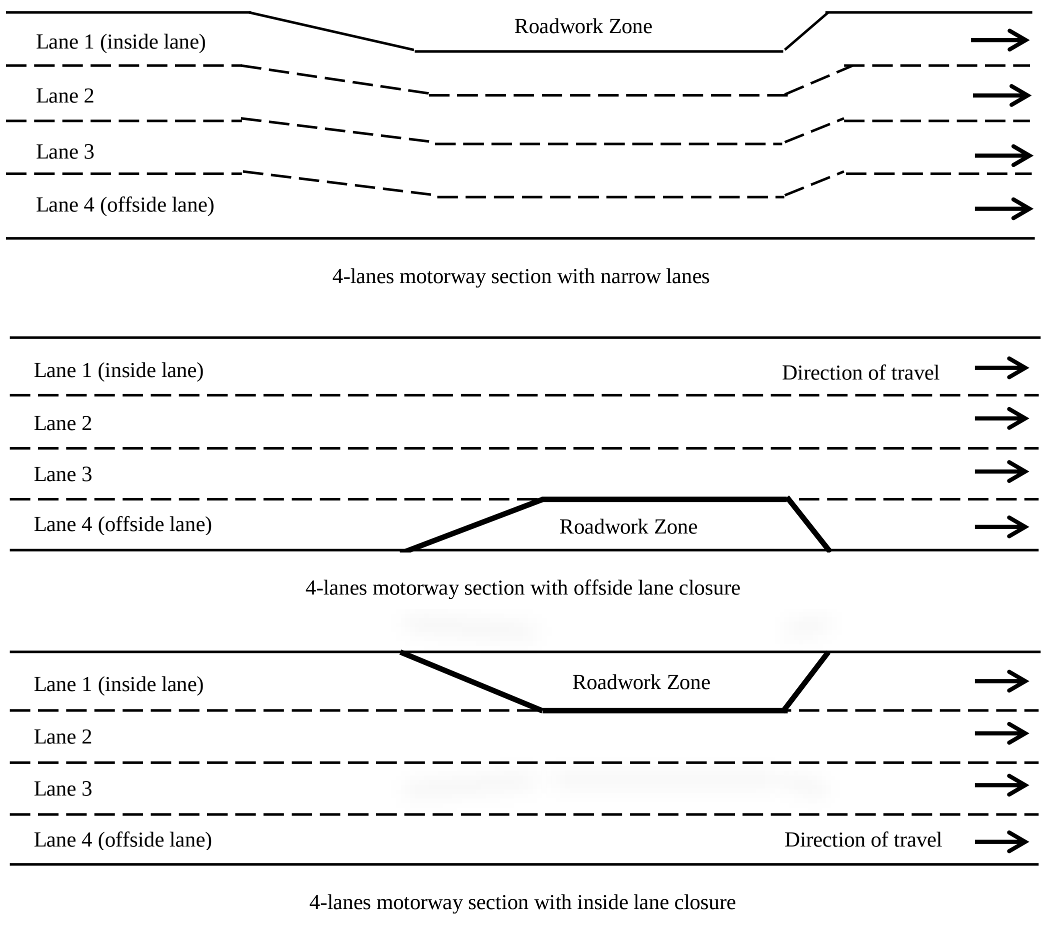


Figure 8.9: Schematic layouts of the tested 4-lanes motorway roadwork sections

It should be noted that for Table 8.7, the increment of input flow rates used for successive runs was increased. Normally an incremental value of 500 veh/hr is used until the section reaches its capacity, then a smaller increment was used (e.g. 250 veh/hr or even 100 veh/hr). This is to minimise the required numbers of simulation runs.

8.2.3.1 Effect of TTMSs on section capacity

Figure 8.10 shows the effect of different TTMSs on section capacity for different HGVs%. It can be seen from the figure that (when the HGVs% is ≤ 20%) the section capacity has not decreased for the use of the narrow lanes layout compared to the normal roadway section. After that, when the HGVs% reaches 25% or over, the section capacity has started decreasing for the use of the narrow lanes layout compared to the normal roadway section. It can also be seen from Figure 8.10 that the section capacity for the offside lane closure layout is slightly higher than that for the inside lane closure layout. This is consistent with the results presented in Sections 8.2.1.1 and 8.2.2.1.

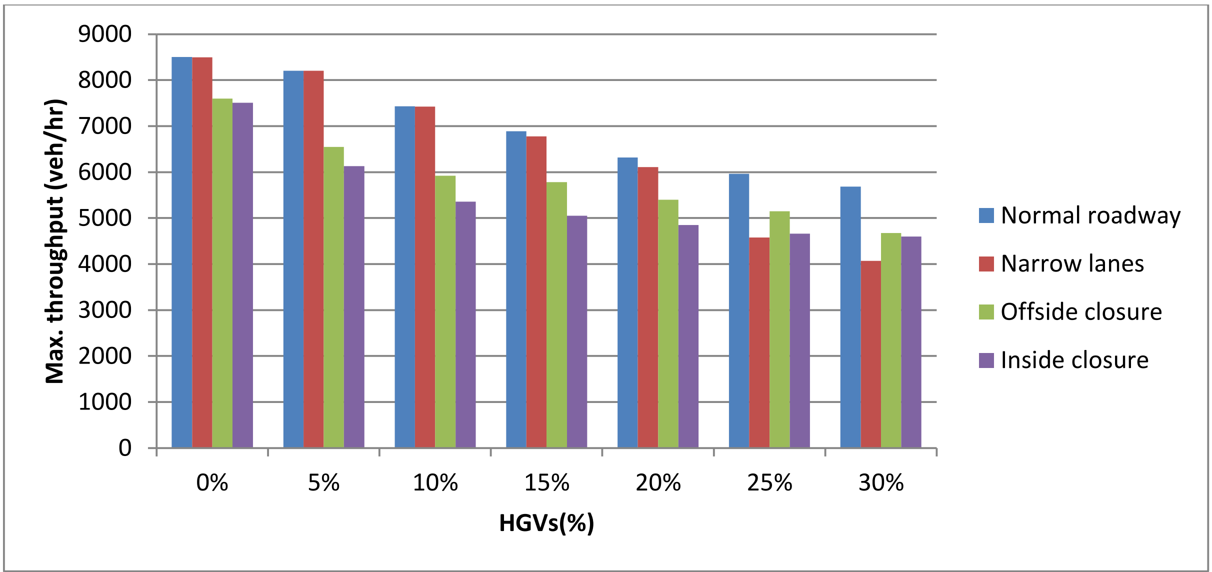


Figure 8.10: Effect of TTMSs on 4-lanes roadworks section capacity for different HGVs%

8.2.3.2 Effect of HGVs% on section capacity

Figure 8.10 also shows the effect of different HGVs percentages on section capacity for both normal and roadwork sections. Likewise, as the percentage of HGVs increases, the section capacity decreases. This is consistent with the results presented in Sections 8.2.1.2 and 8.2.2.2. Table 8.8 summarises the effect of different HGVs% on the capacity of 4 lanes motorway for both normal and roadwork sections.

Table 8.8: Effect of HGVs% on the capacity of normal and roadwork sections (4-lanes)

Type of section	Section capacity (veh/hr)		Reduction in capacity (%)
	0% HGVs	30% HGVs	
Normal roadway section	8502	5687	33
Roadwork with narrow lanes	8497	4073	52
Roadwork with offside lane closure	7597	4675	38
Roadwork with inside lane closure	7509	4597	39

8.2.3.3 Effect on average vehicles delay

Figure 8.11 shows the effect of the flow rates, HGVs% and TTMSs on average vehicles delay for 4 lanes motorway roadwork sections. Likewise, when the offside or inside lane closure layouts are implemented, the figure indicates that as traffic flow increases, the average delay increases. The average delay increases sharply when the inflow exceeding the section capacity. It can also be seen from Figure 8.11 that, when the narrow lanes layout is implemented, the average vehicles delay increases slightly as traffic flow increases, when the HGVs% is ≤ 20%. When the HGVs% is ≥ 25%, the average vehicles delay increases sharply as the inflow exceeds the section capacity.

It should be noted here that, for the cases of normal roadway section or roadwork section with narrow lanes (with HGVs% ≤ 20%, for 4-lane sections), the sharp increase in the average vehicles delay would not be possible, see Figure 8.11. This is because, as mentioned earlier in Section 8.2.1.3, the inflow cannot exceed the section capacity. Also, as shown in Figure 8.10, the section capacity has not decreased for the use of the narrow lanes layout with HGVs% ≤ 20% compared to the normal roadway section. However, for the cases of roadwork section with inside/offside closures or narrow lanes with HGVs ≥ 25%, the sharp increase in the average vehicles delay would occur (when the inflow exceeds the roadwork section capacity).

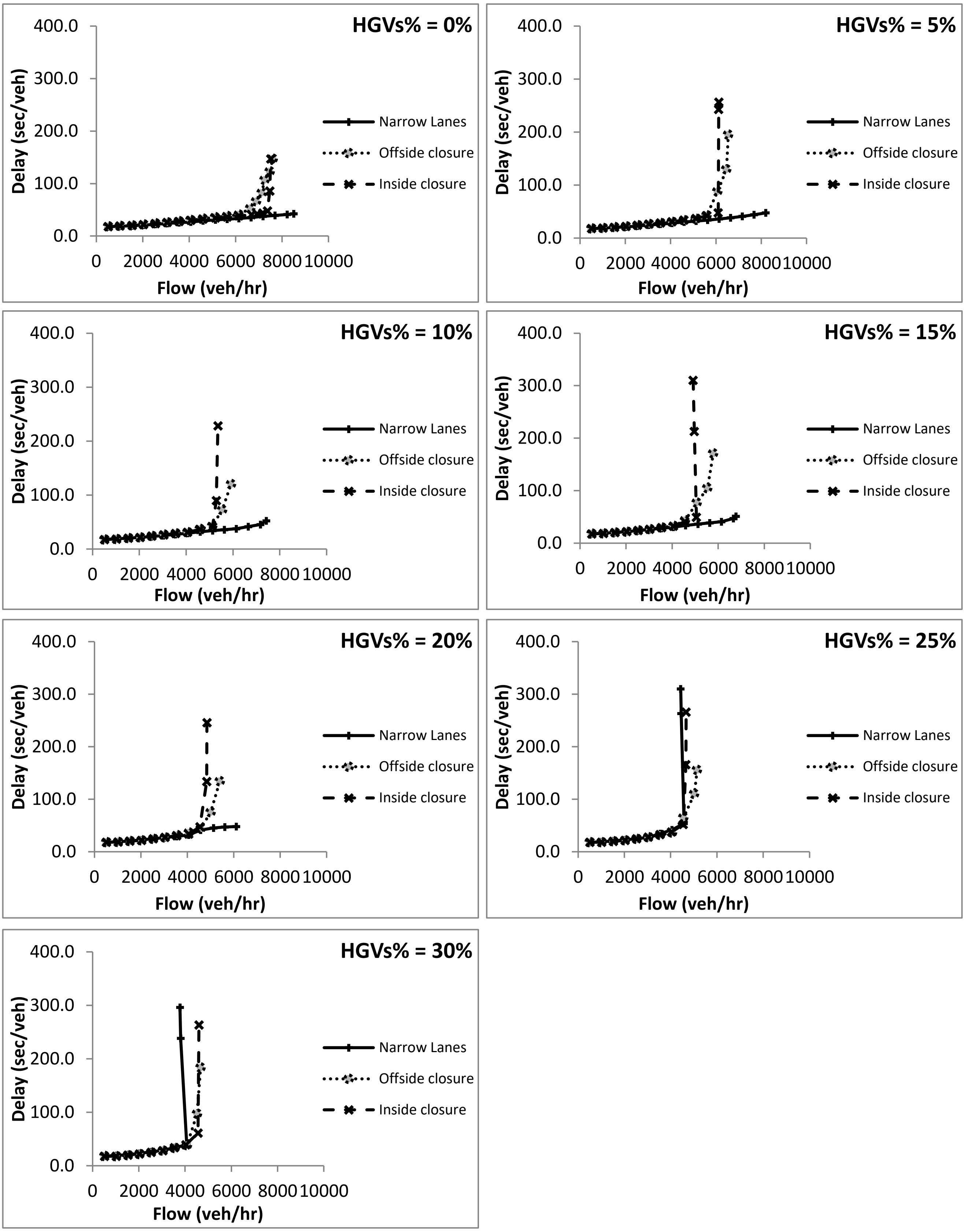


Figure 8.11: Effect of flow rates, HGVs% and TTMSs on average delay for 4-lanes motorway roadwork sections

Comparing Figure 8.7 for the 3 lanes section with Figure 8.11 for the 4 lanes section case, the use of narrow lanes as a TTMS has resulted in a sharp increase in the average vehicles delay when the HGVs% is ≥ 30% in the case of 3 lanes compared with ≥ 25% for 4 lanes. This difference could be attributed to the proportions of HGVs% distributed among the lanes. For the 3 lanes section, typical values for HGVs lane utilisation at traffic flow = 3000 veh/hr and at HGVs% = 30% are 70% and 30% for lane 1 (i.e. inside lane) and lane 2 respectively (based on the lane utilisation models suggested by Yousif et al., 2013a). The HGVs are unevenly distributed between lanes 1 and 2, whereas for the 4 lanes section, typical values for HGVs lane utilisation at traffic flow = 4000 veh/hr and at HGVs% = 30% are 45%, 38% and 17% for lane 1, 2 and 3, respectively. The HGVs on 4 lanes section may provide more avoiders than the 3 lanes section since the HGVs on 4 lanes section are distributed nearly evenly among the lanes unlike the 3 lanes section (where 70% of HGVs are using lane 1).

8.2.3.4 Summary

Table 8.9 summarises the effect of TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure schemes) on reducing section capacity of 4 lanes motorway roadwork sections for different HGVs%. Also, it shows the percentage of capacity gained when using the narrow lanes scheme instead of using offside lane closure scheme when HGVs% ≤ 20%. It also shows the percentage of capacity gained when using the offside lane closure scheme instead of the narrow lanes scheme when the HGVs% is ≥ 25%. Furthermore, it shows the percentage of capacity gained when using the offside lane closure scheme instead of the inside lane closure scheme.

Table 8.9: Effect of TTMSs on capacity of 4-lane roadwork sections for different HGVs%

TTMSs	Reduction in Capacity (%)						
	0% HGVs	**5% HGVs**	**10% HGVs**	**15% HGVs**	**20% HGVs**	**25% HGVs**	**30% HGVs**
Narrow lanes scheme	0	0	0	2	3	23	28
Offside lane closure scheme	11	20	20	16	14	14	18
Inside lane closure scheme	12	25	28	27	23	22	19
Gaining in capacity (%) (resulting from using narrow lanes scheme instead of using offside closure, HGVs% ≤ 20%)							
The use of narrow lanes scheme	11	20	20	14	11	--	--
Gaining in capacity (%) (resulting from using offside closure scheme instead of using narrow lanes, HGVs% ≥ 25%)							
The use of offside closure scheme	--	--	--	--	--	9	10
Gaining in capacity (%) (resulting from using the offside lane closure scheme instead of using inside closure scheme)							
The use of offside closure scheme	1	5	8	11	9	8	1

It can be seen from Table 8.9 that, in general, the gaining in capacity when using the narrow lanes scheme instead of using the offside lane closure scheme and when the HGVs is ≤ 20% is around 15%. In addition, it can be seen from Figure 8.11 that the average vehicles delay has decreased by around 120 seconds for the use of narrow lanes scheme compared with that of the offside lane closure scheme when the HGVs is ≤ 20%, whereas when the HGVs% becomes ≥ 25% the use of offside lane closure scheme compared with that of the narrow lanes scheme has increased section capacity by around 10% (see Table 8.9) and has preserved the average vehicles delay by around 140 seconds (see Figure 8.11). It can also be seen from Table 8.9 that the gaining in capacity when using the offside lane closure scheme instead of using the inside lane closure scheme was, in general, around 8%. Additionally, it can be seen from Figure 8.11 that the average vehicles delay has increased by around 100 seconds for the use of the inside lane closure scheme compared with that of the offside lane closure scheme. Based on these simulation results, it can be concluded that, the narrow lanes scheme performed better than both the offside and inside lane closure schemes in terms of maintaining section capacity and average vehicles delay up to an expected HGVs% of around 20%, whereas after that when HGVs% becomes ≥ 25%, the offside lane closure scheme performs better than narrow lanes scheme. Therefore, the use of narrow lanes scheme as a TTMS at 4 lanes motorway roadwork sections is not recommended when the expected HGVs% is higher than 20% associated with high traffic demand.

8.3 Effect of roadwork zone length on traffic performance for different HGVs%

The developed micro-simulation model has also been used to study the effect of roadwork zone lengths on traffic performance (i.e. capacity and average vehicles delay). For this test, various lengths of roadwork zone were tested (roadwork zone lengths ranging from 1500 m to 4500 m with 1500 m increment). Various flow rates with various HGVs% were also tested. The following sub-sections provide further details about the effect of roadwork zone lengths on the traffic performance for motorway roadwork sections with 2, 3 and 4 lanes operated by using different TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure). Over 500 simulation runs were used to test the effect of roadwork zone lengths on traffic performance.

8.3.1 Narrow lanes scheme

Table 8.10 lists the main parameters that were used to test the effect of different lengths of roadwork zone on section capacity and average vehicles delay for motorway roadwork sections with 3 and 4 lanes operated by using narrow lanes scheme. All other vehicle's/driver's characteristics were kept unchanged.

Table 8.10: Parameters used in testing the effect of roadwork zone lengths on capacity and average delay (narrow lanes scheme)

Number of lanes	TTMSs	HGVs (%) (increment)	Flow rates (veh/hr) (increment)	Whole section length (m) (increment)	Roadwork zone length (m) (increment)	Roadwork speed limit (mph)
3	- Narrow lanes	5 – 30 (5)	500 – capacity (500)	5000 – 8000 (1500)	1500 – 4500 (1500)	50
4			1000 – capacity (1000)			

It should be noted that for this test the increment of input flow rates used for successive runs was increased, as shown in Table 8.10. This is to minimise the required numbers of simulation runs. Also, it is worth mentioning here that, a value of 500 m was firstly used as an increment for the roadwork zone length. However, the simulation results reveal that such little increment had a little effect on the traffic performance, therefore and in order to cover a long distance of roadwork zones and also in order to minimise the required simulation runs, it was decided to use a value of 1500 m.

8.3.1.1 Three lanes section

Figure 8.12 shows the effect of roadwork zone lengths on the capacity of a three lanes motorway roadwork section (with the use of narrow lanes scheme), under different HGVs%. The figure indicates that the different lengths of the roadwork zone adopted in the test have no significant effect on section capacity.

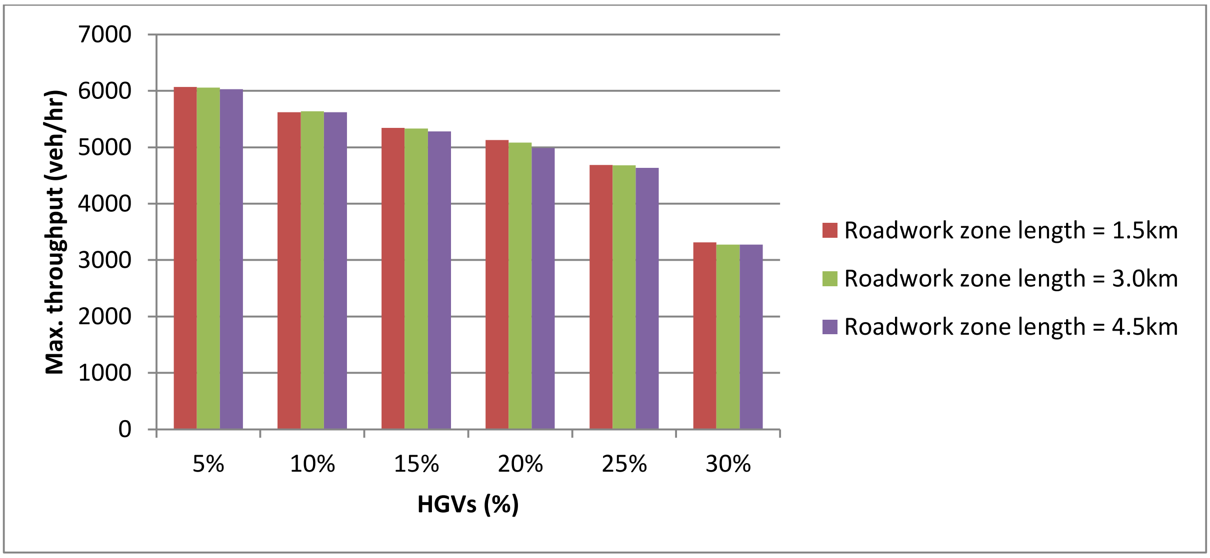


Figure 8.12: Effect of roadwork zone lengths on 3-lanes section capacity (narrow lanes)

Figure 8.13 shows the effect of different roadwork zone lengths on the average vehicles delay for a three lanes motorway roadwork (with the use of narrow lanes scheme) section under different flow rates and HGVs%. It can be seen from the figure that, as expected, there is an increase in the average vehicles delay as roadwork zone length increases.

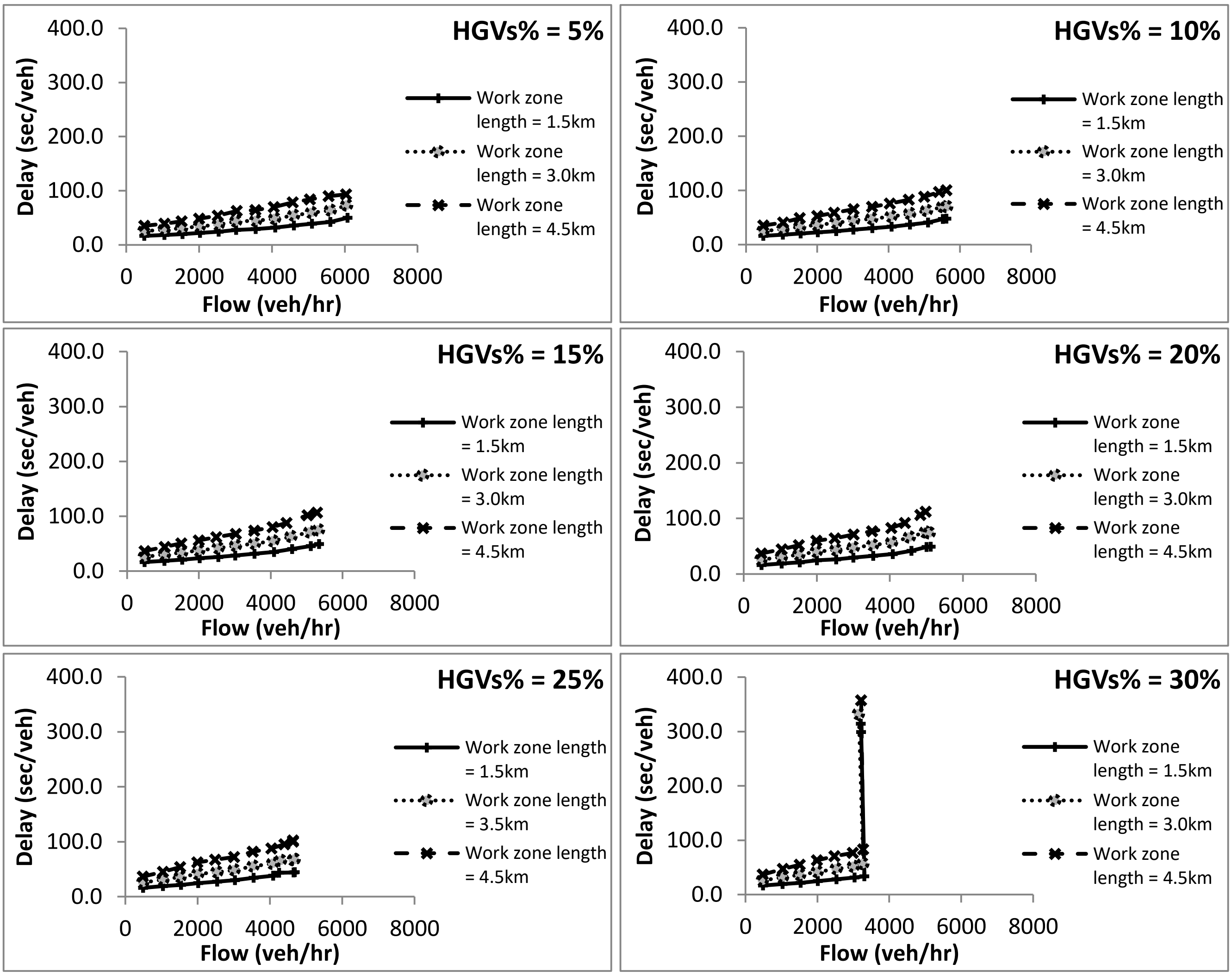


Figure 8.13: Effect of roadwork zone lengths on average delay for 3-lanes motorway roadwork section with narrow lanes

8.3.1.2 Four lanes section

Figure 8.14 shows the effect of different roadwork zone lengths on the capacity of a four lanes motorway roadwork section (with the use of narrow lanes scheme), under different HGVs%. Likewise, the figure indicates that the different lengths of the roadwork zone adopted in the test have no significant effect on section capacity.

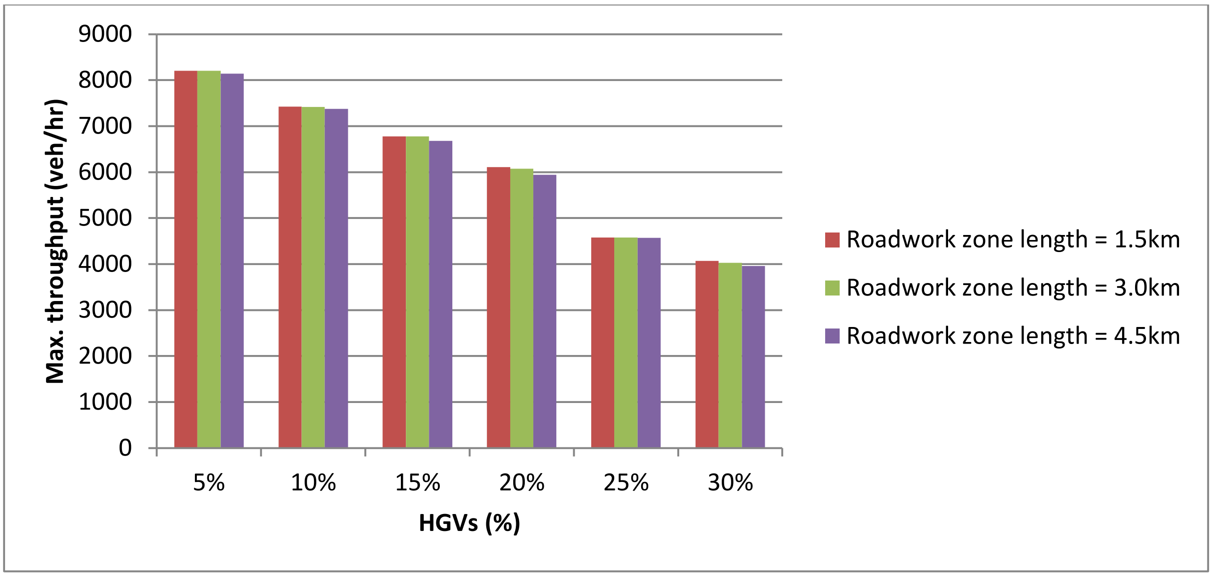


Figure 8.14: Effect of roadwork zone lengths on 4-lanes section capacity (narrow lanes)

Figure 8.15 shows the effect of different roadwork zone lengths on the average vehicles delay for a four lanes motorway roadwork (with the use of narrow lanes scheme) section under different flow rates and HGVs%. Likewise, the figure indicates that there is an increase in the average vehicles delay as roadwork zone length increases.

8.3.2 Offside and inside lane closure schemes

For the purpose of this application, the developed simulation model has also been used to study the effect of roadwork (with the use of offside/inside lane closure scheme) zone lengths on the traffic performance. Likewise, various roadwork zone lengths were tested (from 1500 m up to 4500 m with an increment of 1500 m). Various flow rates with a chosen 15% of HGVs were also tested.

As mentioned in Section 8.2.2, the sharp increase in the average vehicles delay for roadwork sections with the use of narrow lanes scheme is strongly influenced by the HGVs%. Therefore, in the previous sub-section (i.e. Section 8.3.1), different HGVs% were tested, whereas the sharp increase in the average vehicles delay for roadwork sections with the use of offside or inside lane closure scheme is influenced by the flow rates (as described in Section 8.2.1). Therefore, in the current subsection, only a 15% of HGVs was chosen.

Table 8.11 lists the main parameters that were used to test the effect of different roadwork zone lengths on section capacity and average vehicles delay for motorway roadwork sections with 2, 3 and 4 lanes operated by using offside/inside lane closure scheme. Likewise, all other vehicle’s/driver’s characteristics were kept unchanged.

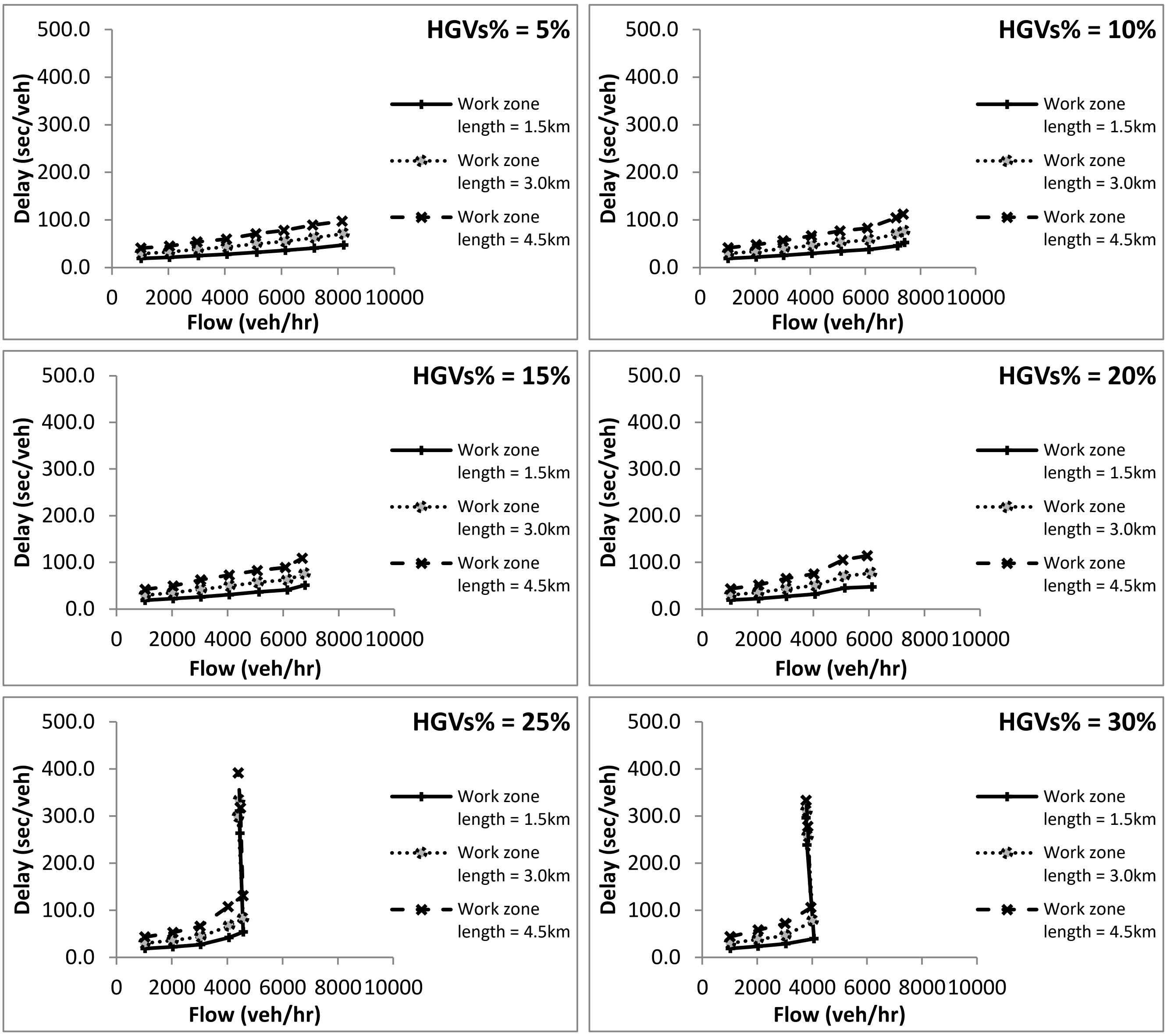


Figure 8.15: Effect of roadwork zone lengths on average delay for 4-lanes motorway roadwork section with narrow lanes

Table 8.11: Parameters used in testing the effect of roadwork zone lengths on capacity and average delay (offside/inside lane closure schemes)

Number of lanes	**TTMSs**	**HGVs (%)**	**Flow rates (veh/hr)** (increment)	**Whole section length (m)** (increment)	**Roadwork zone length (m)** (increment)	**Roadwork speed limit (mph)**
2	- Offside closure - Inside closure	15	500 – capacity (500)	5000 – 8000 (1500)	1500 – 4500 (1500)	50
3			500 – capacity (500)			
4			1000 – capacity (1000)			

8.3.2.1 Two lanes section

Figure 8.16 shows the effect of different roadwork zone lengths on the capacity of a two lanes motorway roadwork section (with the use of offside/inside lane closure schemes), for a 15% of HGVs. It can be seen from the figure that the maximum throughputs (capacity) for the different lengths of roadwork zone tested are not significantly different.

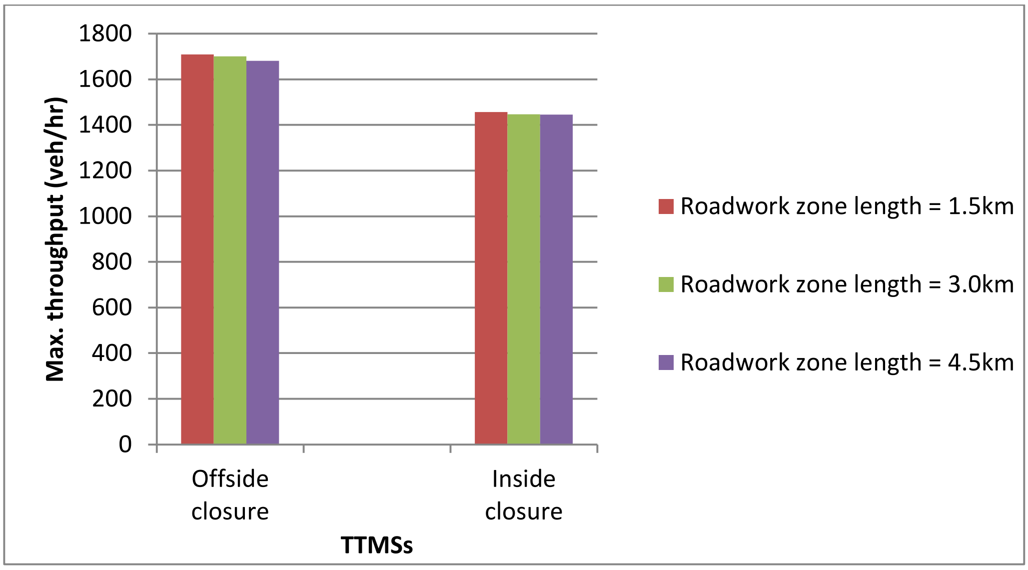


Figure 8.16: Effect of roadwork zone lengths on 2-lanes section capacity (lane closures)

Figure 8.17 shows the effect of different roadwork zone lengths on the average vehicles delay for a two lanes motorway roadwork (with the use of offside and inside lane closure schemes) section under different flow rates with 15% of HGVs. It can be seen from the figure that there is a slight increase in the average vehicles delay as the length of roadwork zone increases (for the same input flow) for both offside and inside lane closure schemes. The average vehicles delay increases sharply when the inflow is exceeding the section capacity.

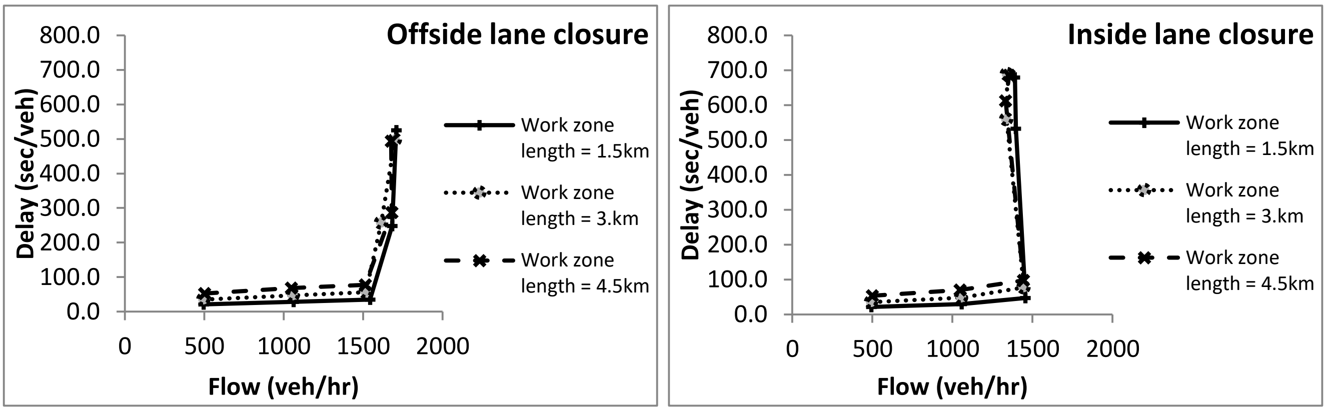


Figure 8.17: Effect of roadwork zone lengths on average delay for 2-lanes motorway roadwork section with offside/inside lane closure

8.3.2.2 Three lanes section

Figure 8.18 shows the effect of different roadwork zone lengths on the capacity of a three lanes motorway roadwork section (with the use of offside and inside lane closure schemes), for a 15% of HGVs. Likewise, the figure indicates that the different roadwork zone lengths adopted in the test have no significant effect on section capacity.

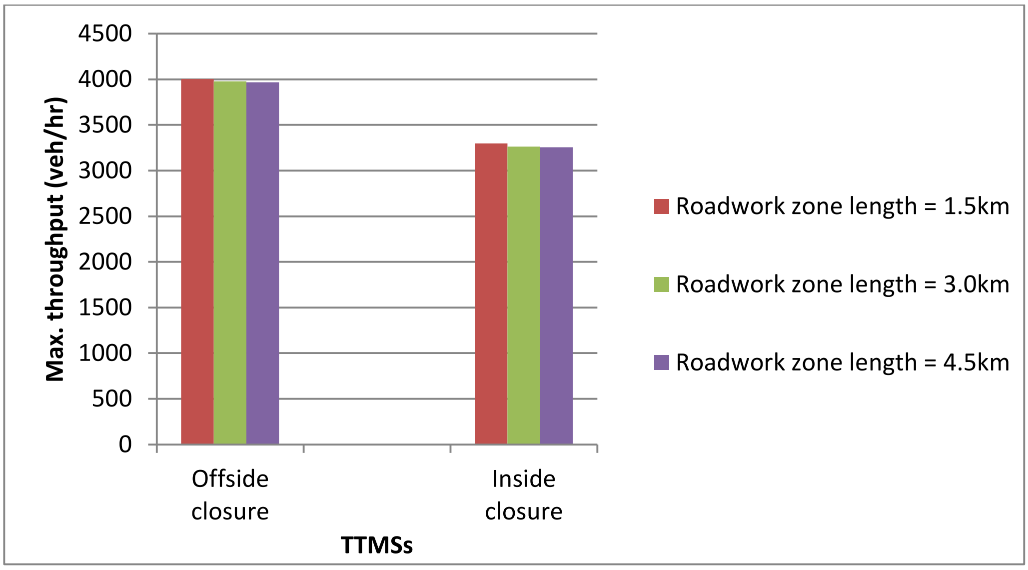


Figure 8.18: Effect of roadwork zone lengths on 3-lanes section capacity (lane closures)

Figure 8.19 shows the effect of different roadwork zone lengths on the average vehicles delay for a three lanes motorway roadwork (with the use of offside and inside lane closure schemes) section under different flow rates with 15% of HGVs. Likewise, the figure indicates that there is a slight increase in the average vehicles delay as the length of roadwork zone increases (for the same input flow) for both schemes (i.e. offside and inside lane closure schemes). The average vehicles delay increases sharply when the inflow is exceeding the section capacity.

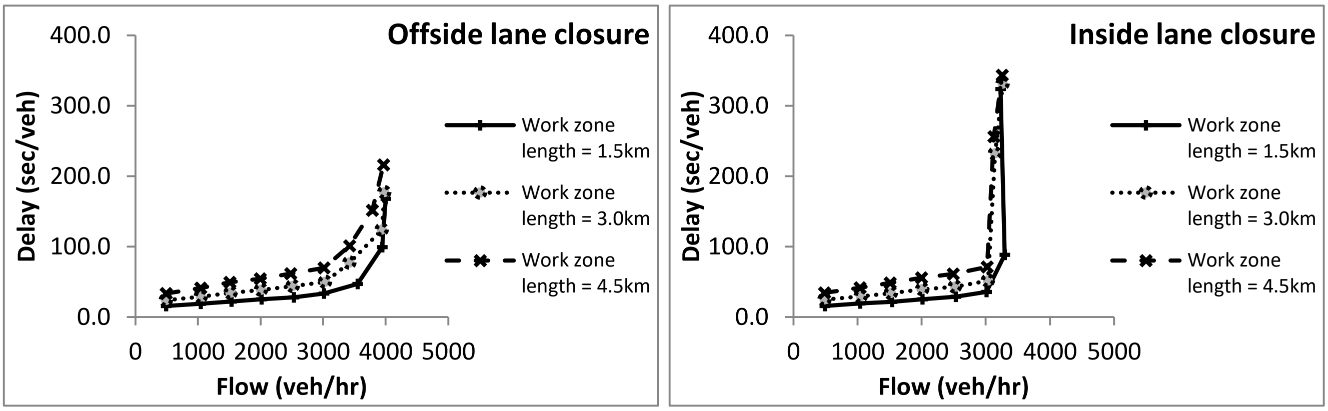


Figure 8.19: Effect of roadwork zone lengths on average delay for 3-lanes motorway roadwork section with offside/inside lane closure

8.3.2.3 Four lanes section

Figure 8.20 shows the effect of different roadwork zone lengths on the capacity of a four lanes motorway roadwork section (with the use of offside and inside lane closure schemes), for a 15% of HGVs. Likewise, the figure indicates that the different roadwork zone lengths adopted in the test have no significant effect on section capacity.

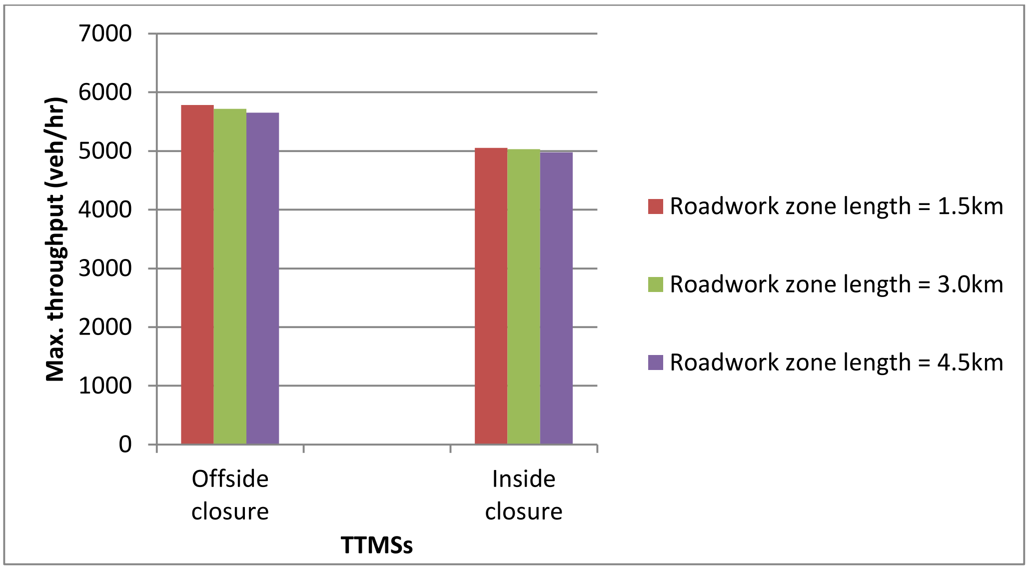


Figure 8.20: Effect of roadwork zone lengths on 4-lanes section capacity (lane closures)

Figure 8.21 shows the effect of different roadwork zone lengths on the average vehicles delay for a four lanes motorway roadwork (with the use of offside and inside lane closure schemes) section under different flow rates with 15% of HGVs. Likewise, the figure indicates that there is a slight increase in the average vehicles delay as the length of roadwork zone increases (for the same input flow) for both offside and inside lane closure schemes. The average vehicles delay increases sharply when the inflow is exceeding the section capacity.

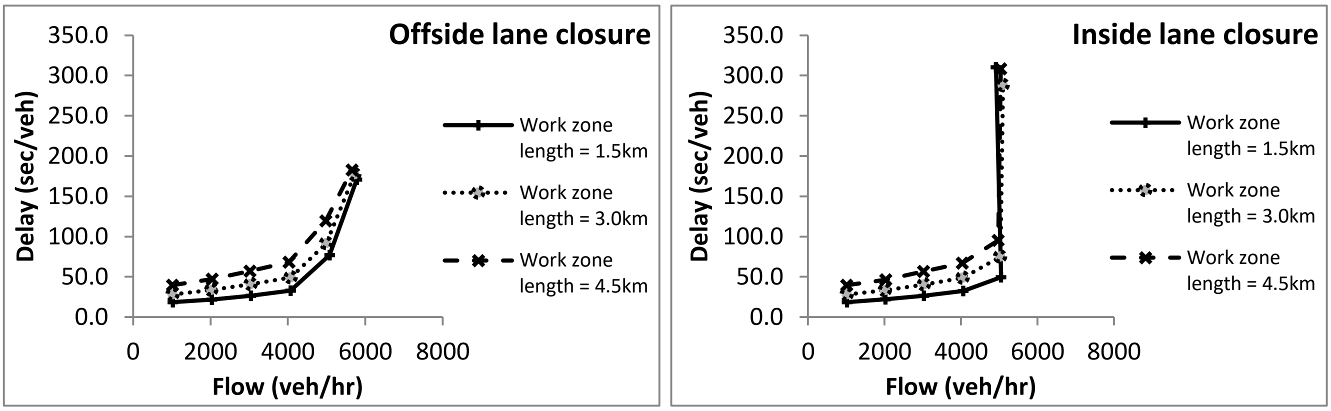


Figure 8.21: Effect of roadwork zone lengths on average delay for 4-lanes motorway roadwork section with offside/inside lane closure

8.3.3 Summary

Based on the simulation results for this test, it can be concluded that the different lengths of the roadwork zone adopted in the test have no significant effect on section capacity. This was found to be consistent with the findings of Yousif (1993) and Weng and Meng (2015). It can also be concluded that the capacity of motorway roadwork sections is not dependent on the length of the roadwork zone but it depends on HGVs%, number of lanes and the type of TTMSs applied.

The simulation results for this test have also revealed that the increasing of roadwork zone length affects average vehicles delay. For the same input flow and HGVs% used, as the length of roadwork zone increases, the average vehicles delay increases. This is also consistent with the findings by Yousif (1993). The simulation results (presented in Figures 8.13, 8.15, 8.17, 8.19 and 8.21) show that the average vehicles delay has increased by around 15 sec for every increment of the roadwork zone length (i.e. 1500 m), for the same input flow and HGVs%.

8.4 Effect of temporary speed limit applied at roadworks on traffic performance

According to Geistefeldt (2011), the purpose of using variable speed limits on heavily trafficked motorway sections is to increase road safety and to harmonise traffic flow and hence influence motorway capacity by reducing the variation in speeds amongst motorists.

In this section, the developed model has been used to study the effect of the application of different temporary speed limits at roadwork section on traffic performance. Various temporary speed limits were tested (speed limit of 35 mph – 50 mph with 5 mph increment). Table 8.12 lists the main parameters that were used to test the effect of different temporary speed limits applied at roadwork sections on section capacity and average vehicles delay. All other vehicle's/driver's characteristics were kept unchanged. In order to include the effects of temporary speeds limits, an assumed value of 50% was adopted as a percentage of drivers who are complying with those temporary speed limits.

Table 8.12: Parameters used in testing the effect of speed limits applied at roadwork sections on capacity and average delay

<table>
<tr><th>Number of lanes</th><th>TTMSs</th><th>HGVs (%)</th><th>Flow rates (veh/hr)</th><th>Whole section length (m)</th><th>Roadwork zone length (m)</th><th>Roadwork speed limit (mph) (increment)</th></tr>
<tr><td>4</td><td>- Narrow lanes</td><td>25 and 30</td><td>5500</td><td rowspan="2">5000</td><td rowspan="2">1500</td><td rowspan="2">35 – 50
(5)</td></tr>
<tr><td>3</td><td>- Offside closure</td><td>15</td><td>4500</td></tr>
</table>

8.4.1 Narrow lanes scheme

The reduction of speed limit upstream the roadwork zone could lead to the reduction in the variation of speed amongst drivers. This could lead to alleviating the turbulence in driving behaviour (associated with the use of narrow lanes scheme) which could be considered as the main reason for the flow breakdown at such sections.

Figure 8.22 shows the effect of temporary speed limits applied at roadwork section (with assuming that 50% of drivers are complying with those limits) on the capacity of a four lanes motorway roadwork section using narrow lanes scheme, for input flow rate = 5500 veh/hr and under 25% and 30% of HGVs, while Figure 8.23 shows the effect of the temporary speed limits on the average vehicles delay.

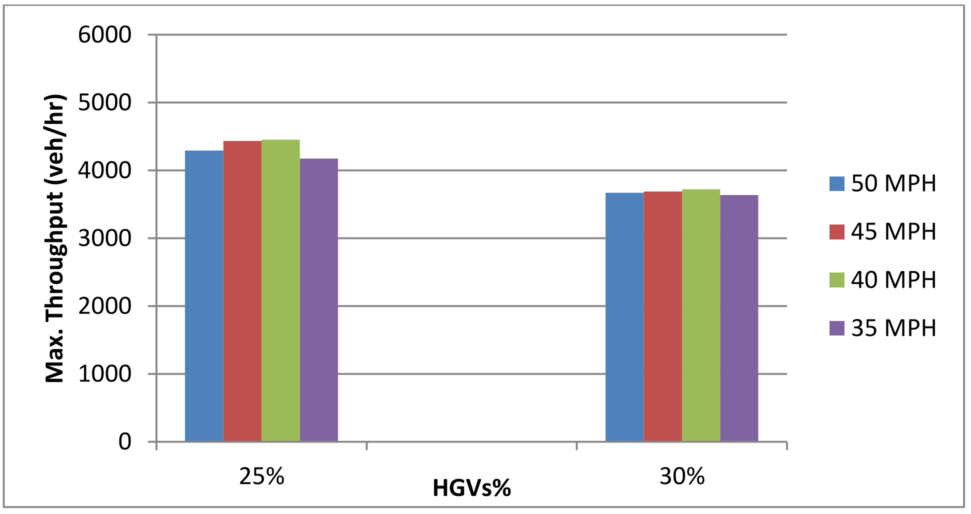


Figure 8.22: Effect of roadwork speed limits (with 50% complying with speed limits) on 4 lanes section capacity (narrow lanes)

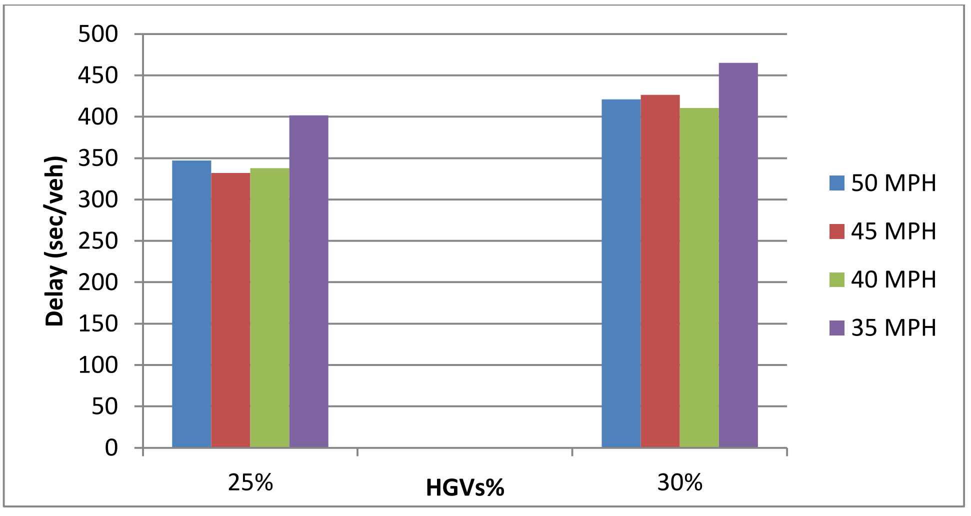


Figure 8.23: Effect of roadwork speed limits (with 50% complying with speed limits) on 4 lanes section delay (narrow lanes)

It can be seen from the figures that, for both percentages of HGVs (i.e. 25% and 30%), the use of lower values of temporary speed limits seems to be ineffective in terms of increasing the throughput and decreasing the average vehicles delay.

An attempt was made by assuming that all drivers are complying with the applied temporary speed limit (i.e. 100% complying). Although, this attempt seems to be unrealistic since the field surveys have shown that very little percentages of drivers were observed to comply with the applied speed limit (as described in Section 3.7.3). However, this attempt was made in order to test the effect of drivers' compliance with the applied speed limits on the traffic performance. The simulation results for this attempt are presented in Figures 8.24 and 8.25 which show the effect of temporary speed limits applied at roadwork section on the capacity and average delay, respectively, for a four lanes motorway roadwork section using narrow lanes scheme, for input flow = 5500 veh/hr and under 25% and 30% of HGVs.

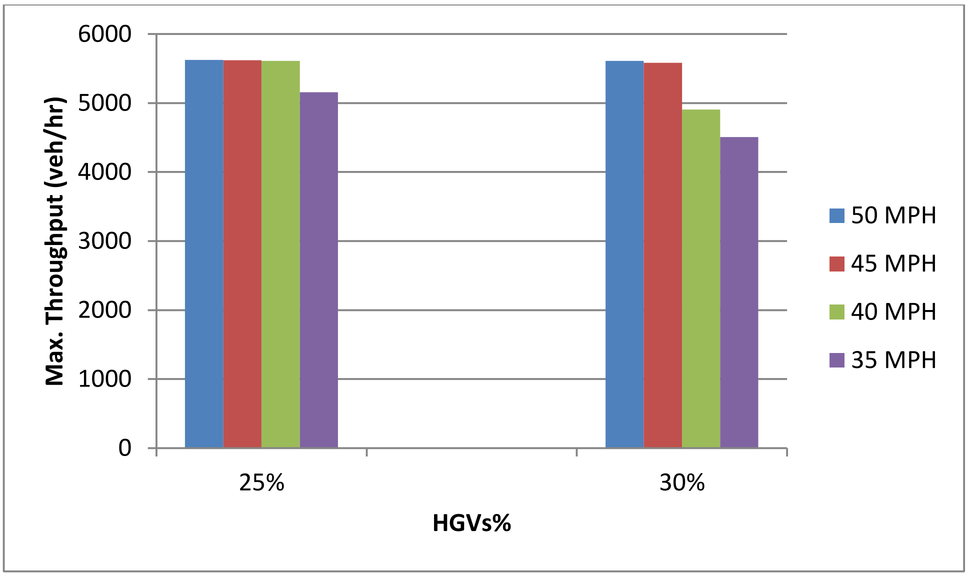


Figure 8.24: Effect of roadwork speed limits (with 100% complying with speed limits) on 4 lanes section capacity (narrow lanes)

By comparing the simulation results presented in Figures 8.22 and 8.23 (i.e. 50% complying) with those presented in Figures 8.24 and 8.25 (i.e. 100% complying), it can be concluded that the drivers' compliance with the temporary speed limits applied at roadwork sections has a significant effect on the traffic performance. The figures indicate that the section capacity has increased and the average delay has decreased for the adoption of 100% drivers' compliance with temporary speed limits (for all the speed limits tested) compared with the adoption of 50% drivers' compliance. Therefore, extra enforcement measures (such as placing more visible speed cameras with sending fines to those who are breaking the speed limits) should be taken on sites to make sure that all or the vast majority of drivers are complying with the posted speed limits. Also, based on these simulation results (presented in Figures 8.22 to 8.25), it can be concluded that the application of low temporary speed limits (such as 35 mph) at roadwork sections seems to be unnecessarily since it does not enhance the traffic performance (i.e. capacity and average vehicles delay).

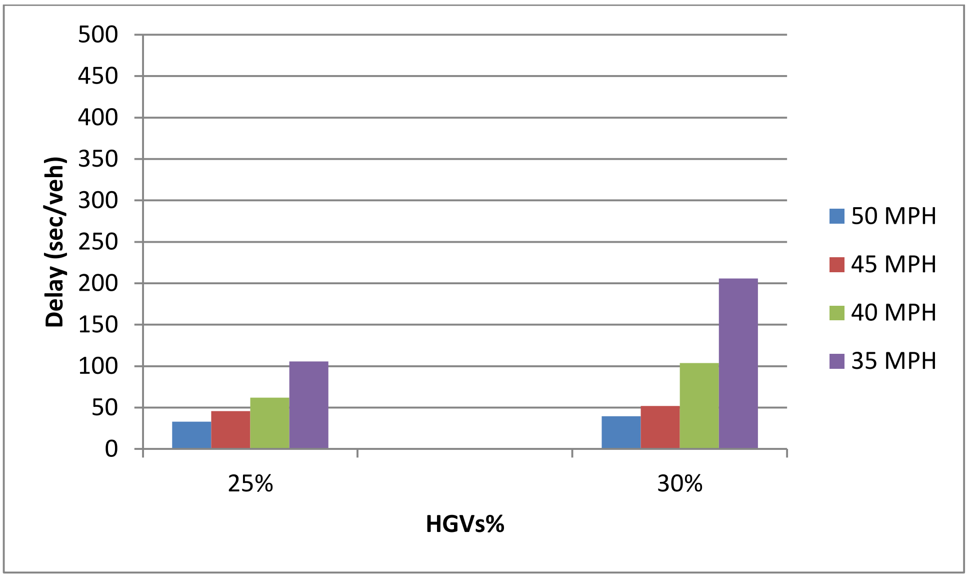


Figure 8.25: Effect of roadwork speed limits (with 100% complying with speed limits) on 4 lanes section delay (narrow lanes)

8.4.2 Lane closure scheme

As stated earlier, the reduction of speed limit upstream the roadwork zone could lead to the reduction in the variation of speed amongst drivers. This could lead to facilitating the merging process (i.e. MLC manoeuvre) by reducing the required gaps, as discussed in Section 2.8.3.

For the purpose of this test, values of 50% and 100% were assumed for the drivers' compliance with the applied speed limits. Figure 8.26 shows the effect of temporary speed limits applied at roadwork section (for both 50% and 100% of drivers' compliance) on the capacity of a three lanes motorway roadwork section (with the use of offside lane closure scheme), under a 15% of HGVs for input flow rate = 4500 veh/hr, while, Figure 8.27 shows the effect of the temporary speed limits on the average vehicles delay.

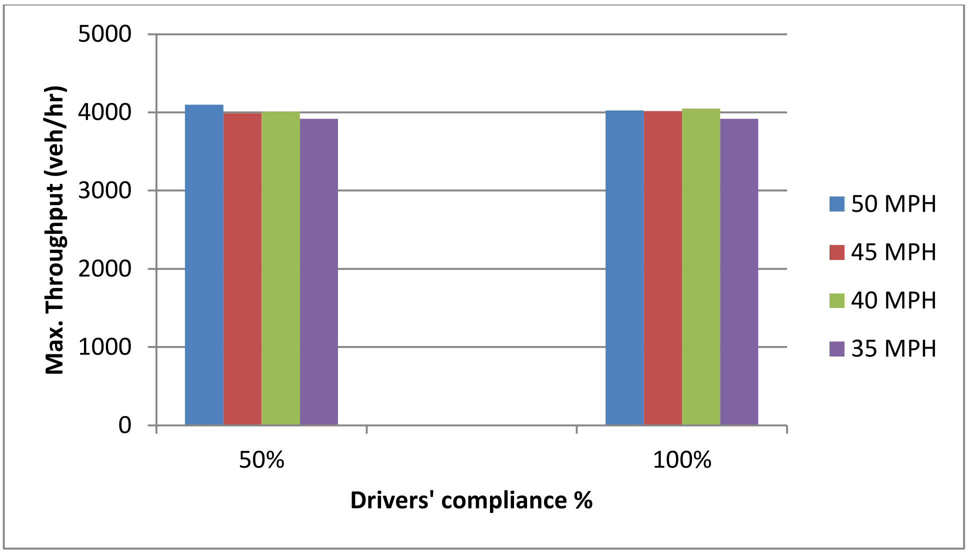


Figure 8.26: Effect of roadwork speed limits on 3-lanes section capacity (lane closure)

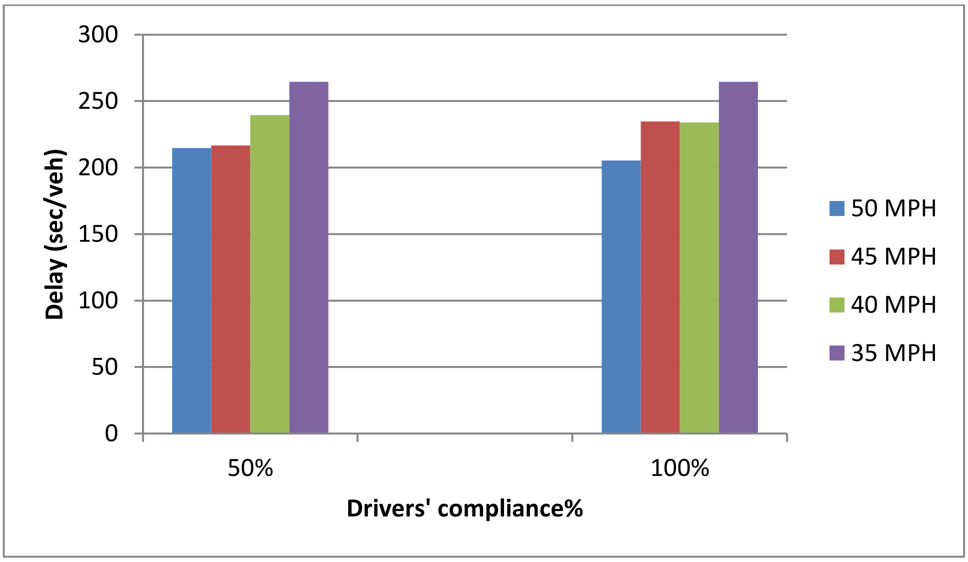


Figure 8.27: Effect of roadwork speed limits on 3-lanes section delay (lane closure)

Figures 8.26 and 8.27 indicate that the application of different temporary speed limits at roadwork sections (with the use of offside lane closure scheme) for both percentages of drivers' compliance (i.e. 50% and 100%) seems to be ineffective in terms of increasing the throughput and decreasing the average vehicles delay. This could be due to the fact that the simulated roadwork section (i.e. 3-lane section with offside lane closure, 2 lanes were left open for traffic movements and one lane was closed for roadwork) has reached its capacity (with about 4000 veh/hr) and any enhancement for the section capacity might not be possible. According to previous literature, it was found that the maximum throughput for each open lane that can be achieved at motorway roadwork sections is around 2000 veh/hr/lane. In addition, at such high traffic flow (when there are insufficient gap sizes available for the closed lane drivers to merge), the closed lane drivers (mergers) will depend on the courtesy of drivers in the adjacent open lane in order to merge into the adjacent open lane. If such courteous behaviour is not offered, the mergers might be stuck in the closed lane and cannot change lanes to the adjacent open lane.

8.4.3 Summary

Based on the simulation results for this test, it can be concluded that a stricter speed limit compliance should be imposed on motorway roadwork sections with the use of narrow lanes TTMS in order to maintain higher section capacity and reduced delays. The simulation results (presented in Figures 8.22 to 8.25) show that the assumed 100% compliance with the speed limit has increased the section capacity by around 1250 veh/hr and has reduced the average vehicle delay by around 300 seconds. Also, the application of very low temporary speed limits (such as 35 mph) at roadwork sections seems to be unnecessarily since such low speed limit may influence traffic performance negatively. The simulation results show that the use of 35 mph as a speed limit (with the use of 100% compliance) has reduced the section capacity by 500 – 1000 veh/hr (see Figure 8.24) and increased the average vehicles delay by 50 – 100 seconds (see Figure 8.25), compared to other assumed speed limit values such as 50 mph.

8.5 Estimation of capacity of motorway roadwork sections

In the previous sections, several factors that could affect the maximum section throughput (capacity) of motorway roadwork sections (such as HGVs%, type of TTMSs, roadwork zone length and speed limits) were tested using the newly developed micro-simulation model. The simulation results reveal that the capacity of motorway roadwork sections is affected by HGVs%, number of lanes and the type of TTMSs implemented. Following the identification of these factors, a multiple regression analysis was carried out between the identified factors and the capacity using the statistical program SPSS, version 20. This regression analysis was carried out based on the simulation results presented in Section 8.2. Equation 8.1 shows the results from the regression analysis, which describes the relationship between the maximum section throughput (capacity) and the identified factors (i.e. number of lanes, HGVs% and type of TTMS implemented).

$$Capacity = 846.3 + 1794.0(Lanes) - 5935.9(HGVs\%) - 488.0(Narrow) - 1237.3(Offside) - 1673.9(Inside) \qquad \text{Equation 8.1}$$

Where:
Capacity: the maximum throughput (capacity) of motorway roadwork sections (veh/hr),
Lanes: the number of lanes of motorway (i.e. 2, 3 or 4),

HGVs%: the percentages of Heavy Goods Vehicles (decimal, i.e. 0.15 for 15%),
Narrow: the implementation of narrow lanes as a TTMS (1 if true and 0 if false),
Offside: the implementation of offside lane closure as a TTMS (1 if true and 0 if false), and
Inside: the implementation of inside lane closure as a TTMS (1 if true and 0 if false).

The coefficient of determination (R^2) value of the regression analysis is 0.94 which indicates a strong relationship between the dependent variable (i.e. capacity) with the other independent variables (i.e. number of lanes, HGVs% and type of TTMS implemented). According to Equation 8.1, as the values of HGVs% increases, the capacity decreases. In addition, as the number of lanes increases, the capacity increases as well. The equation also shows that the coefficient for inside lane closure (*Inside*) variable is lower than that for the offside lane closure (*Offside*) variable which means that the section capacity decreases further for the use of the inside lanes closure scheme compared with the use of the offside lane closure scheme. These effects seem to be consistent with the description of how these variables affect the capacity of motorway roadwork sections as discussed in Section 8.2. However, the main limitation of Equation 8.1 is that the equation suggests that there is reduction in capacity for the use of narrow lanes scheme even at low HGVs%. This is not consistent with the simulation results from the developed simulation model (as described in Section 8.2) which shows that the reduction in capacity for motorway roadwork sections with the use of narrow lanes scheme occurred at high HGVs% (i.e. ≥ 30% for 3 lanes section and ≥ 25% for 4 lanes section). Therefore, it can be suggested that, at low HGVs% (i.e. < 25% for 3 lanes section and < 20% for 4 lanes section) and when the narrow lanes scheme is implemented, a value of zero can be used for the "*Narrow*" variable. Also, it should be noted that the use of narrow lanes scheme at 2-lanes motorway section may not be compatible with the equation since such a case is not considered in the regression analysis.

8.6 Estimation of average delay of motorway roadwork sections

Based on the simulation results presented in Section 8.2 (which are based on roadwork zone length = 1500 m), multiple regression analysis was also used to estimate average vehicles delay. It should be noted that for this regression analysis the cases when traffic flow exceeds section capacity (when the average vehicles delay increases sharply) are not included. At such cases (i.e. when traffic flow exceeds section capacity), queues are often formed and as a result, the computed average delay becomes very high and it depends on the period of time for which the simulation continues. Therefore, only those cases of traffic flows that are lower than the section capacity are considered in this regression analysis. Equation 8.2 shows the results from the regression analysis, which describes the relationship between the average vehicles delay and number of lanes, HGVs% and type of TTMS implemented.

$$Delay = 10.1 - 5.8(Lanes) + 0.006(Flow) + 12.6(HGVs\%) + 18.7(Narrow) + 21.7(Offside) + 21.6(Inside) \qquad \text{Equation 8.2}$$

Where:
Delay: the average vehicles delay (sec/veh), and
Flow: the traffic flow of motorway section (veh/hr).

The coefficient of determination (R^2) value of the regression analysis is 0.82 which indicates a good relationship between the dependent variable (i.e. delay) with the other independent variables (i.e. number of lanes, HGVs% and type of TTMS implemented). It can be seen from Equation 8.2 that the coefficients for the inside lane closure (*Inside*) and the offside lane closure (*Offside*) variables are nearly similar. Therefore, an attempt to simplify the regression equation for the average delay was carried out by using one variable (which was called "*Closure*") to represent both the inside lane closure and the offside lane closure variables, as shown in Equation 8.3.

$$Delay = 10.3 - 5.9(Lanes) + 0.006(Flow) + 12.8(HGVs\%) + 18.6(Narrow) + 21.6(Closure) \qquad \text{Equation 8.3}$$

Where:
Closure: the implementation of offside lane closure or inside lane closure as a TTMS (1 if true and 0 if false).

An attempt to include the effect of roadwork zone lengths on the regression analysis for the average delay was carried out (as shown in Equation 8.4) based on the simulation results presented in Sections 8.2 and 8.3. It should be noted that the applied length for this analysis ranges from 1500 m to 4500 m.

$$Delay = -10.7 - 6.9(Lanes) + 0.007(Flow) + 22.3(HGVs\%) + 0.012(Lrw) + 19.1(Narrow) + 22.6(Closure) \qquad \text{Equation 8.4}$$

Where:
Lrw: the length of roadwork zone (m).

The value of R^2 for this regression analysis is 0.88 which indicates a good relationship between the dependent variable (i.e. delay) with the other independent variables. However, the main limitation of Equation 8.4 is that the applied roadwork zone length is ranging from 1500 m to 4500 m. Therefore, Equation 8.4 should only be used for roadwork zone length within this range. The summary of the statistical results for all the equations (i.e. Equations 8.1 to 8.4) are shown in Appendix (A).

8.7 Summary

This chapter presented the application of the newly developed micro-simulation model in testing the efficiency of different TTMSs applied at motorway roadwork sections. The effects of various parameters (i.e. HGVs percentage, roadwork zone length, temporary speed limit and drivers' compliance with the speed limit) on traffic performance were also tested and presented in the current chapter. The most important findings can be summarised as follows:

- The use of offside lane closure scheme seems to perform better in terms of capacity and delay than the use of inside lane closure scheme for 2, 3 and 4 lanes motorway roadwork sections. The simulation results showed that the gaining in capacity when using the offside lane closure scheme instead of using the inside lane closure scheme was around 8%, for 2, 3 and 4 lanes sections. In addition, the average vehicles delay has decreased by around 150 seconds for the use of the offside lane closure scheme compared with that of the inside lane closure scheme.
- The presence of HGVs has a large impact on reducing section capacity for both normal and roadwork sections with different TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure schemes) and with different numbers of lanes (i.e. 2, 3 and 4 lanes). The simulation results showed that, as the percentage of HGVs increases, the section throughput decreases.
- Under low traffic demand (when the flow of a 3 lanes motorway roadwork section is under 3000 veh/hr and the flow of a 4 lanes motorway roadwork section is under 4000 veh/hr), the use of narrow lanes schemes seems to perform better in terms of capacity and delay than both offside and inside lane closure schemes. While under high traffic demand associated with high HGVs percentage (i.e. HGVs% > 25% for 3 lanes section and HGVs% > 20% for 4 lanes section), the use of narrow lanes scheme is not recommended and it was found that the use of offside lane closure scheme becomes the favourite option.
- The length of roadwork zone has a very marginal impact on throughput of motorway roadwork sections with different TTMSs (i.e. narrow lanes, offside lane closure and

inside lane closure schemes) and with different numbers of lanes (i.e. 2, 3 and 4 lanes), whereas the length of roadwork zone has influenced the average vehicles delay. The simulation results showed that, as the length of roadwork zone increases, the average vehicles delay increases. The results have shown that the average vehicles delay has increased by around 15 seconds for every increment of the roadwork zone length (i.e. 1500 m), for the same input flow and HGVs%.

- Applying different temporary speed limits have not influenced the traffic performance. The simulation results showed that drivers' compliance with the temporary speed limits applied at roadwork sections (with the use of narrow lanes scheme) has a significant influence on the traffic performance in terms of increasing throughput and decreasing average vehicles delay. The simulation results showed that the assumed 100% compliance with the applied speed limit has increased the section capacity by around 1250 veh/hr and has reduced the average vehicle delay by around 300 seconds. Therefore, a stricter speed limit compliance may need to be imposed on motorway roadwork sections in order to enhance section capacity and reduce delay and also to maintain safety levels (since this will lead to a reduction in the variation in speeds amongst motorists).
- Limitations identified in this chapter: the newly developed micro-simulation model has not been applied to test the effect of changing the layout of TTMSs on traffic performance, for example increasing/decreasing the length of the transition zone or lane change zone (see Figure 8.1).

CHAPTER NINE
CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

As discussed in Section 1.2, the main aim of this study is to evaluate the efficiency of different temporary traffic management schemes (TTMSs) at motorway roadwork sections by developing a new traffic micro-simulation model. Also, the newly developed model will be used as a tool to investigate different factors (i.e. effect of HGVs%, roadwork zone length, temporary speed limit and drivers' compliance with the speed limit) that could affect traffic performance (i.e. capacity and average vehicles delay) of roadwork sections. The aim of the study was achieved by means of eight research objectives. The first objective was the identification of the important factors of the modelling concept and the limitations of previous models and was achieved by conducting a comprehensive literature review. The second and third objectives were to collect and analysis field traffic data from several motorway roadwork sections with different TTMSs as well as from normal motorway sections with 2, 3 and 4 lanes in order to gain a better understanding into traffic behaviours and also to use the data in developing, calibrating and validating the new micro-simulation model. The fourth objective was to test the validity of the S-Paramics (an industry standard traffic software) in representing motorway roadwork sections. The fifth objective was the developing of a new traffic micro-simulation model (using a Visual Compact Fortran programing language) that is capable of representing motorway roadwork sections. The sixth objective was to verify, calibrate and validate the newly developed micro-simulation model to make sure that the new model is reliable enough to be used for further applications. The seventh objective was the application of the new model to evaluate the efficiency of different TTMSs at motorway roadwork sections and also to test the effect of various traffic parameters (i.e. HGVs%, roadwork zone length and speed limits) on traffic performance (i.e. capacity and average vehicles delay). The eighth objective was to developing and recommending regression models to estimate section capacity and delay based on the simulation results. The following sections summarise the key findings related to each research objective of the study.

- Objective 1: The literature has shown that the microscopic simulation approach allows the users some flexibility in representing changes in parameters affecting traffic behaviour and road layouts with relative ease, unlike other approaches such as mathematical models. Also, it is proven to be more effective in representing traffic behaviour at complicated traffic situations such as the case of roadwork sections (see Sections 2.7 and 2.8). Therefore, the microscopic simulation approach has been adopted in this study. The literature has also shown that there is a lack of research in studying motorway roadworks operated by using narrowing lanes.

- Objectives 2 & 3: Real traffic data from 17 UK motorway sites (from four different sources) have been collected and analysed (see Chapters 3 and 4). The data was used in developing, calibrating and validating the newly developed micro-simulation model. Different factors have been analysed based on results from real observations from motorway roadwork sites including drivers' compliance with the applied speed limits (the results showed that 83% of drivers are not complying with the applied speed limit), drivers' courtesy behaviour (the results showed that 12% of drivers are offering cooperation by slowing down) and accepted gap values (the results showed that the minimum observed lead and lag gaps for the M67 site were about 0.2 and 0.4 seconds, respectively) (see Section 3.7). Traffic behaviour at roadwork sections with narrow lanes has been investigated based on real observations, since the use of narrow lanes, as one of the TTMSs at UK motorway roadworks, has become very common in recent years. Field observations suggest that the behaviours for UK drivers on narrowing lanes could be divided into two discernible patterns in the presence of heavy goods vehicles (HGVs). These are "avoiding" passing/overtaking HGVs and lane "repositioning" while passing/overtaking an HGV (see Chapter 4). The results revealed that around 30% - 50% of drivers who were following a HGV on the adjacent lanes were observed to be "avoiding" passing HGVs (see Section 4.4.1) and around 70% - 80% of drivers were observed to be doing lane repositioning when approaching from behind a HGV in the adjacent lane HGVs (see Section 4.4.2).

- Objective 4: The S-Paramics micro-simulation software (which is widely used in industry) has been tested to model roadwork sections at motorway using two sets of real data. The results showed that the S-Paramics software suffers from certain limitations. It is not capable of accurately representing traffic behaviour at the transition zone which is an important part of the TTMSs (see Chapter 5). The difference between the observed and simulated data is about 20% (see Tables 5.5 and 5.6 and Figure 5.5). This has led to the development of a new micro-simulation model to estimate traffic capacity and delay and to represent traffic behaviour at motorway roadwork sections.

- Objective 5: The newly developed micro-simulation model for motorway roadwork (and for normal sections) has been based on car-following, lane changing and gap acceptance and lane closure rules, together with the newly developed narrow lanes algorithms. These rules and algorithms have been developed based partly on previous studies as well as other real observations from UK motorway sites as described in this study (see Chapters 3, 4 and 6). The new micro-simulation model has taken into account driver's courtesy behaviour at the approach to roadwork sections (with the use of lane closure scheme) since this behaviour is found to be predominant on UK roads (see Sections 2.8.2, 3.7.2 and 6.5.2). The observed behaviours from sites with narrow lanes sections have been also taken into account in the development of the micro-simulation model (see Section 6.8).

- Objective 6: The developed micro-simulation model has been calibrated and validated using field data. The results suggest that the developed model could acceptably represent real traffic situations (see Chapter 7).

- Objective 7: The newly developed micro-simulation model has been applied to evaluate the efficiency of different TTMSs (i.e. narrow lanes, offside lane closure and inside lane closure) at motorway roadwork sections. The effect of various traffic parameters (i.e. HGVs percentage, roadwork zone length, temporary speed limit and drivers' compliance with the speed limit) on traffic performance (i.e. capacity and average vehicles delay) have also been studied using the developed micro-simulation model (see Chapter 8). The main findings from this research objective can be summarised as follows:

    - The simulation results have revealed that the use of offside lane closure scheme seems to perform better in terms of capacity and delay than the use of inside lane closure scheme for 2, 3 and 4 lanes motorway roadwork sections (see Section 8.2). The simulation results showed that the gaining in capacity when using the offside lane closure scheme instead of using the inside lane closure scheme was around 8%, for 2, 3 and 4 lanes sections. In addition, the average vehicles' delay has decreased by around 150 seconds for the use of the offside lane closure scheme compared with that of the inside lane closure scheme (see Sections 8.2.1.4, 8.2.2.4 and 8.2.3.4).

- The simulation results have also revealed that, under low traffic demand (when the flow of a 3 lanes motorway roadwork section is under 3000 veh/hr and the flow of a 4 lanes motorway roadwork section is under 4000 veh/hr), the use of narrow lanes scheme seems to perform better in terms of capacity and delay compared with the case of using either offside or inside lane closure schemes. However, under high traffic demands associated with high percentages of HGVs (i.e. HGVs% > 25% for 3 lanes sections and HGVs% > 20% for 4 lanes sections), the use of narrow lanes scheme is not recommended and the use of offside lane closure scheme becomes the favourite option (see Section 8.2).

- The simulation results have also revealed that the presence of HGVs has a large impact on reducing section capacity for both normal and roadwork sections with different TTMSs and with different numbers of lanes. The simulation results have shown that, as the percentage of HGVs increases, the section throughput decreases (see Section 8.2).

- The effect of roadwork zone length on traffic performance (i.e. capacity and average vehicles delay) has also been studied using the newly developed micro-simulation model. The simulation results have shown that, for the tested roadworks zone lengths, this length has a very marginal impact on the throughput of motorway roadwork sections using different TTMSs and with different numbers of lanes (i.e. 2, 3 and 4 lanes), whereas this length has influenced the average vehicles' delay. The simulation results suggest that, as the length of roadwork zone increases, the average vehicles delay increases. The simulation results have shown that the average vehicles' delay has increased by around 15 seconds for every increment of the roadwork zone length (i.e. 1500 m), for the same input flow and HGVs% (see Section 8.3).

- The effect of temporary speed limits on traffic performance has been studied using the newly developed simulation model. The simulation results show that applying different temporary speed limits have no significant effect on traffic performance. The simulation results suggest that drivers' compliance with the temporary speed limits applied at roadwork sections with narrow lanes has a significant influence on traffic performance in terms of increasing throughput and decreasing average vehicles delay. The simulation results showed that for the assumed 100% compliance with the applied speed limit, this has increased the section capacity by around 1250 veh/hr and has reduced the average vehicle delay by around 300 seconds. Therefore, a stricter speed limit compliance may need to be imposed on motorway roadwork sections in order to enhance section capacity and reduce delay and also to maintain safety levels since this may lead to a reduction in speed differentials amongst motorists (see Section 8.4).

- Objective 8: Regression analysis has been carried out based on the simulation results (which are obtained from the newly developed micro-simulation model) in order to provide equations for use in estimating section capacity and delay. These regression equations have been developed based on several parameters such as flow rates, percentage of HGVs, number of lanes, type of TTMSs implemented and roadwork zone length (see Sections 8.5 and 8.6).

9.2 Recommendations and further research

- Based on field observations from motorway roadwork sections with narrow lanes, it appears that the reduction in lane width is the main cause of the lane "repositioning" behaviour in the presence of HGVs (see Section 4.4.2). The data analysis showed that the lane "repositioning" percentage for the inside lane (i.e. lane 1) is equal to zero. This is because the inside lane has a width equal to 3.25 m, whereas the width of other lanes is equal to 3.0 m (see Tables 4.6, 4.7, 4.8 and 4.10). This behaviour is believed to be unsafe and could potentially lead to an increase in the rate of traffic accidents. Therefore, this study recommends that the lane width could be reduced to 3.25 m as an absolute minimum where HGVs are expected. The second cause of lane "repositioning" behaviour is the speed of drivers. The data analysis showed that the offside lane (i.e. lane 4) and lane 3 have very high percentages of lane "repositioning" (see Tables 4.6, 4.7, 4.8 and 4.10). This could be attributed to the relatively high speed of drivers who were driving on lanes 3 and 4 compared to those who using lanes 1 and 2. Therefore, this study recommends a lowering of the speed limits to, for example, 40 mph and with stricter compliance when narrow lanes are implemented. The simulation results obtained from the newly developed micro-simulation model showed that the use of

40 mph as a temporary speed limit has values of traffic performance (i.e. capacity and delay) similar to those of using 50 mph as a temporary speed limit (see Figures 8.22 and 8.23). However, further empirical investigation to find out the impact of this proposed reduction in speed limits on traffic performance is required. This recommendation of reducing the speed limits is in agreement with a similar recommendation by Harb (2009).

- Based on the simulation results obtained from the newly developed micro-simulation model, this study recommends that the use of narrow lanes scheme as a TTMS at 3 lanes motorway roadwork sections is not recommended when the expected HGVs% is > 25% associated with high traffic demand, alternatively the offside lane closure scheme could be used (see Section 8.2.2.4); in addition, this study recommends that the use of narrow lanes scheme as a TTMS at 4 lanes motorway roadwork sections is not recommended when the expected HGVs% is higher than 20% associated with high traffic demand, alternatively the offside lane closure scheme could be used (see Section 8.2.3.4).

- Due to the limited research devoted to studying motorway roadworks with narrow lanes (see Section 4.5), empirical studies in investigating the effects of the use of narrow lanes on site safety and capacity are highly needed, particularly for sites with relatively high percentages of HGVs. These empirical studies are needed to find out the feasibility of using narrowing lanes as a TTMS at motorway roadwork sections since the main reason behind using narrow lanes is to improve section capacity. Detailed information on driving behaviours at motorway roadwork sections with narrowing lanes is also needed to inform and enhance the assumptions made in the development of the current micro-simulation model.

- It should be noted that this study has concentrated on data taken from several UK motorway roadwork sites (see Section 6.12). In order to apply or validate the recommended regression equations from this study for use in other countries, more data may be needed from these countries to validate the assumptions made in the micro-simulation model before use.

References

Ahie, L. M., Charlton, S. G. and Starkey, N. J. (2015). The role of preference in speed choice, Transportation Research: Part F, 30, 66–73.

Ahmed, K. (1999). *Modelling drivers' acceleration and lane changing behaviour*. (PhD Thesis), Massachusetts Institute of Technology, USA.

Alberti, C.F, Shahar, A. and Crundall, D. (2014). Are experienced drivers more likely than novice drivers to benefit from driving simulations with a wide field of view?. Transportation Research: Part F, 27, 124–132.

Al-Jameel, H. A. E. (2012). *Developing a simulation model to evaluate the capacity of weaving sections.* (PhD Thesis), University of Salford, Salford, UK.

Allpress, J. A. and Leland Jr, L. S. (2010). Reducing traffic speed within roadwork sites using obtrusive perceptual countermeasures. Accident Analysis and Prevention, 42(2), 377–383.

Al-Obaedi, J. T. S. (2012). *Development of micro-simulation model for motorway merges with ramp metering*. (PhD Thesis), University of Salford, Salford, UK.

Al-Obaedi, J. and Yousif, S. (2012). Microsimulation model for motorway merges with ramp-metering controls. IEEE, Transactions on Intelligent Transportation Systems, 13(1), 296-306.

Alterawi, M. T. (2014). *Development of a micro-simulation model to evaluate shuttle-lane roadwork Operations*. (PhD Thesis), University of Salford, Salford, UK.

Aycin, M. (2001). *Development of a Car-following Model to Simulate Driver and Autonomous Intelligent Cruise Controlled Vehicular Traffic Flow*. (PhD Thesis), University of Illinois, USA.

Bai, Y., Finger, K. and Li, Y. (2010). Analysing motorists' responses to temporary signage in highway work zones. Safety Science, 48, 215–221.

Barceló, J. (Ed.) (2010). Fundamentals of traffic simulation. International Series in Operations Research & Management Science, 145, Springer, New York.

Barceló, J. and Casas, J. (2005). Dynamic network simulation with AIMSUN. Simulation Approaches in Transportation Analysis: Recent Advanced and Challenges, pp 57-98, Springer, 2005. DOI: 10.1007/0-387-24109-4_3

Bekhor, S., Lotan, T., Gitelman, V. and Morik, S. (2013). Free-flow travel speed analysis and monitoring at the national level using global positioning system measurements. American Society of Civil Engineers (ASCE), Journal of Transportation Engineering,139(12), 1235-1243.

Bella, F. (2005). Validation of a driving simulator for work zone design. Transportation Research Record No.1937. TRB, 136-144.

Benekohal, R. F. (1986). *Development and validation of a car following model for simulation of traffic flow and traffic wave studies at bottleneck*. (PhD dissertation), the Ohio state university, USA.

Benekohal, R. and Treiterer, J. (1988). CARSIM: Car-following model for simulation of traffic in normal and stop-and-go conditions. Transportation Research Record, 1194, 99-111.

Bertini, R., Lindgren, R. and Tantiyanugulchai, S. (2002). Draft application of PARAMICS simulation at a diamond interchange. Research Report PSU-CE-TRG-02-02, Portland State University.

Bourne, N., Gillan, W., Notley, S. O., Taylor, N. and Webster, D. (2008). A review of literature on the nature of the impact of roadworks on traffic movement and delay. Transport Research Laboratory, TRL PPR 348, Crowthorne.

Brackstone, M. and McDonald, M. (1999). Car following: a historical review. Transportation Research: Part F, 2(4), 181-196.

Brackstone, M., McDonald, M. and Wu, J. (1998). Lane changing on the motorway: Factors affecting its occurrence, and their implications. 9th International Conference on Road Transport Information and Control. No. 454, 160-164.

Branston, A. (1976). Models of single lane time headway distributions. Transportation Science, 10(2), 125-148.

Burghout, W. (2004). *Hybrid microscopic-mesoscopic traffic simulation*. (PhD dissertation), Royal Institute of Technology, Sweden.

Butcher, L. (2009). Lorry sizes and weights. Business and Transport, Standard Note: SN/BT/654.

Butcher, L. (2013). Roads: Speed Limits. Business and Transport, Standard Note: SN468.

Cao, S., Qin, Y., Zhao, L. and Shen, M. (2015). Modeling the development of vehicle lateral control skills in a cognitive architecture. Transportation Research: Part F, 32, 1–10.

Cassidy, M. J. and Han, L. D. (1993). Proposed model for predicting motorist delays at two lane highway work zones. American Society of Civil Engineers (ASCE), Journal of Transportation Engineering, 119(1), 27-41.

Chang, G. and Kao, Y. (1991). An empirical investigation of macroscopic lane-changing characteristics on uncongested multilane freeways. Transportation Research: Part A, 25(6), 375-389.

Charlton, S. G., Starkey, N. J., Perrone, J.A. and Isler, R.B. (2014). What's the risk? A comparison of actual and perceived driving risk, Transportation Research: Part F, 25, 50–64.

Chen, E. and Tarko A. (2014). Modeling safety of highway work zones with random parameters and random effects models. Analytic Methods in Accident Research, 1, 86-95.

Chin, H. C. (1983). *A computer simulation model of traffic operation at roundabouts*. (PhD Thesis), University of Southampton, UK.

Chien, S. and Schonfeld, P. (2001). Optimal work zone lengths for four-lane highways. American Society of Civil Engineers (ASCE), Journal of Transportation Engineering, 127(2), 124-131.

Chien, S., Tang, Y. and Schonfeld, P. (2002). Optimizing work zones for two-lane highway maintenance projects. American Society of Civil Engineers (ASCE), Journal of Transportation Engineering. 128(2), 145-155.

Chitturi, M. & Benekohal, R. (2005). Effect of lane width on speeds of cars and heavy vehicles in work zones. Transportation Research Record: Journal of the Transportation Research Board, No. 1920, Transportation Research Board of the National Academies, Washington, D.C., 2005, 41–48.

Chitturi, M. V. and Benekohal, R. F. (2007). Passenger car equivalents for heavy vehicles in work zones. 87th Transportation Research Board Annual Meeting, TRB.

Choudhury, C. (2007). *Modelling driving decision with latent plans*. (PhD Dissertation), Massachusetts Institute of Technology, USA.

Cohen, S. (2004). Using the hard shoulder and narrowing lanes to reduce traffic congestion. Proceedings of the 12th IEE International Conference Road Transport Information & Control, London, April 2004. Conference Publication No. 501, 149-153.

Coutton-Jean, C., Mestre, D.R., Goulon, C. and Bootsma, R. J. (2009). The role of edge lines in curve driving. Transportation Research: Part F, 12, 483–493.

Department for Transport (1996). Design Manual for Roads and Bridges (DMRB), Volume 12, Section 2, Part 1, London: HMSO. Available at: http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol12/section2.htm Accessed 22nd November 2014.

Department for Transport (2003). Traffic Signs Manual, Chapter 5 (Road Marking), Available at: https://www.gov.uk/government/publications/traffic-signs-manual Accessed 05th January 2015.

Department for Transport (DfT, 2005). Design Manual for Roads and Bridges (DMRB), Vol. 9, Section 3, Part 1, HD 20/05. Available at: http://www.dft.gov.uk/ha/standards/dmrb/vol9/section3/hd2005.pdf Accessed 02nd December 2013.

Department for Transport (2009). Traffic Signs Manual, Chapter 8, Part 1. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/128759/traffic-signs-manual-chapter-08-part-01.pdf Accessed 8th December 2014.

Department for Transport (DfT, 2013). Free Flow Vehicle Speed Statistics: Great Britain 2012. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/209104/free-flow-vehicle-speeds-2012.pdf Accessed 15th February 2015.

Driving Standards Agency (DSA) (2000). The Official Theory Test for Car Drivers and Motorcyclists.

Duncan, G. I. (1995). PARAMICS wide area microscopic simulation of ATT and traffic management. 28th ISATA Conference, Stuttgart, Germany.

Duncan N. C. (1976). Rural speed-flow relations. Transportation and Road Research Laboratory, LR 705.

Duret, A., Ahn, S. and Buisson, C. (2012). Lane flow distribution on a three-lane freeway: General features and the effects of traffic controls. Transportation Research: Part C, 24, 157–167.

Elghamrawy, T. M. (2011). *Optimizing work zone practices for highway construction projects*. (PhD Dissertation), University of Illinois, USA.

El-Hanna, F. (1974). *An evaluation of highway intersection gap acceptance metering system*. (PhD thesis), University of Bradford, UK.

European Commission (2000). Final report for publication of the SMARTEST (Simulation Modelling Applied to Road Transport European Scheme Test). Contract No: RO-97-SC.1059, Coordinator: ITS, University of Leeds, UK. http://www.its.leeds.ac.uk/projects/smartest/finrep.PDF Accessed 6th September 2014.

European Union Road Federation (ERF) (2007). Safety on motorway work zones. Brussels Programme Centre of the International Road Federation (IRF), Discussion Paper, September 2007.

Federal Highway Administration (2004). Traffic congestion and reliability: linking solutions to problems, Cambridge Systematics, Inc.

Federal Highway Administration (2009). Manual on Uniform Traffic Control Devices for streets and highways (MUTCD). Washington, D.C.

Ferrari, P. (1989). The effect of driver behaviour on motorway reliability. Transportation Research: Part B, 23(2), 139-150.

Freeman, M., Mitchell, J. and Coe, G. A. (2004). Safety performance of traffic management at major motorway roadworks. Transport Research Laboratory, TRL 595, Crowthorne.

Gazis, D., Herman, R. and Rothery, W. (1961). Nonlinear follow-the-leader models of traffic flow. Research Laboratories, General Motor Corporation, Warren, Michigan, 545-567.

Geistefeldt, J. (2011). Capacity effects of variable speed limits on German freeways. Proceedings of the 6th International Symposium on Highway Capacity and Quality of Service, TRB, Stockholm, Procedia Social and Behavioural Sciences, 16, 48-56.

Gillard, S. J., Wilson, A., Slip, J., Kenington, P. B. and Thompson, L. (2008). Technology for variable speed limits for roadworks. Road Transport Information and Control (RTIC) and ITS United Kingdom Members' Conference, IET, Manchester, UK.

Gipps, P. G. (1981). A behavioural car-following model for computer simulation. Transp. Res. Board, 15B (2), 105-111.

Gipps, P. G. (1986). A model for the structure of lane changing decisions. Transp. Res. Board, 20B (5), 403-414.

Greenshields, B. (1935). A study of traffic capacity. Highway Research Board, 10(1), 448-477.

Ha, D., Aron, M. and Cohen, S. (2012). Time headway variable and probabilistic modelling. Transportation Research: Part C, 25, 181–201.

Hall, F. L. (1987). An Interpretation of Speed-Flow-Concentration Relationships using Catastrophe Theory. Transportation Research: Part A, 21A (3), 191-201.

Hall, J. W. and Rutman, E. W. (2003). Work zone safety: Analysis of crashes. Speeds, and traffic flow during the reconstruction of the I-25/I-40 interchange. Report No: NM00SAF-01, University of New Mexico.

Harb, R. (2009). *Safety and operational evaluation of dynamic lane merging in work zones*. (PhD Dissertation), University of Central Florida, Orlando, Florida.

Hayes, M. R., Taylor, P. J. and Bowman, H. C. R. (1994). A study of the safety performance of major motorway roadwork layouts. Transport Research Laboratory (TRL), Project Report PR 81, Crowthorne.

Hayter, A. (2002). Probability and statistics for engineers, 2nd Edition, Duxbury Thomson Learning, USA.

Helly, W. (1959). Simulation of bottlenecks in single lane traffic flow. In Proceedings of the Symposium on Theory of Traffic Flow, Research Laboratories, General Motors, 207-238. New York: Elsevier.

Heydecker, B. and Addison, J. (2011). Analysis and modelling of traffic flow under variable speed limits. Transportation Research: Part C, 19(2), 206-217.

Hidas, P. (2002). Modelling lane changing and merging in microscopic traffic simulation. Transportation Research: Part C, 10, 351-371.

Hidas, P. (2005). Modelling vehicle interactions in microscopic simulation of merging and weaving. Transportation Research: Part C, 13, 37- 62.

Highways Agency (2005). Drivers urged to take care to protect road workers at risk; HA-052-05. Available at: http://www.speedcheck.co.uk/pdf/General_HA_Road_workers_safety_052-05.pdf Accessed 15th February 2015.

Hollander, Y. and Liu, R. (2008). The principles of calibrating traffic microsimulation models. Springer, Transportation, 35(3), 347-362. doi: 10.1007/s11116-007-9156-2.

Hourdakis, J., Michalopoulos, P. and Kottommannil, J. (2003). Practical procedure for calibrating microscopic traffic simulation models. Transportation Research Record, 1852, 130-139.

Hunt, J. G., Griffiths, J. D., Moses, T. S. and Yousif, S. Y. (1991). A study of traffic capacity through the various features of motorway roadworks. Transport Road Research Laboratory, TRRL CR 283, Crowthorne.

Hunt, J. G. and Yousif, S. Y. (1990). Merging behaviour at roadworks. PTRC 18th Summer Annual Meeting, University of Sussex, UK.

Hunt, J. G. and Yousif, S. Y. (1994). Traffic capacity at motorway roadworks – effects of layout, incidents and driver behaviour. Proc. Second International Symposium on Highway Capacity, Akcelik, R. (ed.), 1, 295–314.

Institute of Transportation Engineering ITE (1999). Traffic Engineering Handbook, 5th Edition, USA.

Institute of Transportation Engineering ITE (2010). Traffic Engineering Handbook, 6th Edition, USA.

Jeon, M., Walker, B. N. and Yim, J. (2014). Effects of specific emotions on subjective judgment, driving performance, and perceived workload. Transportation Research: Part F, 24, 197–209.

Jiang, X. and Adeli, H. (2003). Freeway work zone traffic delay and cost optimisation model. American Society of Civil Engineers (ASCE), Journal of Transportation Engineering. 129(3), 230-241.

Jiang, X. and Adeli, H. (2004). Object-oriented model for freeway work zone capacity and queue delay estimation. Computer-Aided Civil and Infrastructure Engineering, 19, 144-156.

Jin, W. (2010). A kinematic wave theory of lane-changing traffic flow. Transportation Research: Part B, 44, 1001-1021.

Johansson, G. and Rumer, K. (1971). Drivers' brake reaction times. Human Factors, 13(1), 23-27.

Kazzaz, A. S. (1998). *Speed-flow-density analysis near the taper zone within motorway roadworks*. (MSc Dissertation), University of Salford, UK.

Kathmann, T. and Cannon, R. (2000). The use of active speed warning signs. Proceedings of the ICE - Transport, 141(2), 67-77.

Khattak, A., Khattak, A. and Council, F. (2002). Effects of work zone presence on injury and non-injury crashes. Accident Analysis and Prevention, 34(1), 19–29.

Khodayari, A., Kazemi, R., Ghaffari, A. and Braunstingl, R. (2011). Design of an improved fuzzy logic based model for prediction of car following behaviour. Proceedings of the 2011 IEEE International Conference on Mechatronics, April 13-15, 2011, Istanbul, Turkey.

Kim, T., Kim, T. and Kim, H. (2013). A decision-making framework to evaluate traffic control strategies on freeway work zone. International Journal of Control and Automation, 6(2), 45-52.

Knoop, V.L., Duret, A., Buisson, C. and Arem, B. (2010). Lane distribution of traffic near merging zones influence of variable speed limits. In: Proceedings of the 13th International IEEE Conference on Intelligent Transportation Systems, Madeira Island, Portugal, 19–22 September 2010, 485–490.

Kometani, E., and Sasaki, T. (1959). Dynamic behaviour of traffic with a nonlinear spacing-speed relationship. In Proceedings of the Symposium on Theory of Traffic Flow, Research Laboratories, General Motors, 105-119. New York: Elsevier.

Leduc, G. (2008). Road traffic data: collection methods and applications. European Commission, Joint Research Centre (JRC) (47967), Institute for Prospective Technological Studies, Spain.

Lee, G. (2006). *Modelling gap acceptance in freeway merges*. (MSc thesis), Department of Civil and Environmental Engineering, MIT, USA.

Lee, J. and Park, B. (2010). Lane flow distributions on basic segments of freeways under different traffic conditions. Transportation Research Board, TRB 89th Annual

Meeting, 10-14. Washington, DC. Meeting Compendium of Papers DVD, Paper #10-1947.

Lerner, N., Huey, R., McGee, H. and Sullivan, A. (1995). Older driver perception-reaction time for intersection sight distance and object detection, Report FHWA-RD-93-168, Federal Highway Administration, U.S Dept. of Transportation, Washington, DC.

Leutzbach, W. (1968). Introduction to the Theory of Traffic Flow. pp. 143-146.

Li, Z., Liu, H. and Li, J. (2010). A calibration and validation procedure for microscopic simulation model. 13th International IEEE, Annual Conference on Intelligent Transportation Systems, Madeira Island, Portugal, September 19-22, 2010.

Lighthill, M. J. and Whitham, G.B. (1955). On kinematic waves: II. A theory of traffic flow on long crowded roads. Proceedings of the Royal Society 229A, 317–345.

Lines, C. J. (1981). The effect of motorway signals on traffic behaviour. Transport Road Research Laboratory TRRL, Supplementary Report 707, ISSN 0305-1315, Crowthorne.

Liu, R. (2005). The DRACULA dynamic traffic network microsimulation model. Simulation Approaches in Transportation Analysis: Recent Advanced and Challenges, 23-56, Springer, 2005. DOI: 10.1007/0-387-24109-4_2

Liu, R. and Wang, J. (2007). A general framework for the calibration and validation of car-following models along an uninterrupted open highway. Mathematics in Transport: Selected Proc. Of the 4th IMA Int. Conf. on Mathematics in Transport, Elsevier, Oxford, UK, 111-123.

London First (2012). Road sense: balancing the costs and benefits of road works. Report developed by Ernst & Young, AECOM, Colin Buchanan.

Lv, W., Song, W., Liu, X., and Ma, J. (2013). A microscopic lane changing process model for multilane traffic. Physica A (392), 1142–1152.

Macadam, C. C. (2003). Understanding and modeling the human driver. Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility, Vol. 40, Nos.1-3, 101-134.

Mahoney, K. M., Porter, R. J., Taylor, D. R., Kulakowski, B. T. and Ullman, G. L. (2006). Design of construction work zones on high-speed highways. Transportation Research Board, TRB, Final Report for NCHRP Report 581. Washington, DC.

Mannering, F. and Washburn, S. (2012). Principles of highway engineering and traffic analysis, 5th Edition, Wiley Global Education, USA.

Matthews, DH (1984). Traffic management for major roadworks on dual carriageways. Proceedings of the Planning and Transport Research and Computation (PTRC), 12th Summer Annual Meeting Seminar L, University of Sussex, July 1984, pp. 239–254, London.

Marczak, F., Daamen, W. and Buisson, C. (2013). Key variables of merging behaviour: empirical comparison between two sites and assessment of gap acceptance theory. 20th International Symposium on Transportation and Traffic Theory (ISTTT 2013), Procedia - Social and Behavioral Sciences, 80, 678–697.

Marlow, M. and Coombe, R. D. (1989). A study of the safety of major motorway roadworks in 1987. Transport Road Research Laboratory, TRRL, Research Report, RR 223, Crowthorne.

Marlow, M., Coe, G. A. and Evans, R. (1992). Modified contra-flow layouts for major maintenance: narrow lane and tidal flow operation. Transport Research Laboratory, TRL Research Report 332, Berkshire.

May, A. (1990). Traffic flow fundamental. Prentice Hall, Englewood Cliffs, New Jersey.

McCoy, P. T. and Mennenga, D. J. (1998). Optimum length of single-lane closures in work zones on rural four-lane freeways. Transportation Research Record 1650, Transportation Research Board, National Research Council, Washington DC., 55-61.

McDonald, M., Brackstone, M. and Jeffery, D. (1994). Data requirements and sources for the calibration of microscopic motorway simulation models. Proceeding of Vehicle Navigation and Information Systems Conference, 233-238.

Memmott, J. L. and Dudek, C. L. (1984). Queue and cost evaluation of work zones (QUEWZ). Transportation Research Record 979, Transportation Research Board, National Research Council, Washington, DC., 12-19.

Milam, R. T. and Choa, F. (2001). Recommended guidelines for the calibration and validation of traffic simulation models. 8th TRB Conference on the Application of Transportation Planning Methods, pp 179-187, 22-26 April 2001, Corpus Christi, Texas.

Moriarty, K. D., Collura, J., Knodler, M., Ni, D. and Heaslip, K. (2008). Using simulation models to assess the impacts of highway work zone strategies; case studies along interstate highways in Massachusetts and Rhode Island. TRB 2008 Annual Meeting.

Morris, B., Boddington, K., Notley, S. and Rees, T. (2010). External Factors Affecting Motorway Capacity. Transport Research Laboratory, TRL, Published Project Report, PPR534, Crowthorne.

Nassrullah, Z. and Yousif, S. (2015). Modelling motorway roadworks using S-Paramics. Paramics Microsimulation Workshop dated the 16th of June, 2015, Manchester, UK.

Nemeth, Z. A. and Rouphail N. M. (1983). Traffic control at freeway work sites. Journal of Transportation Engineering, 109(1), 1-15.

Nordaen, T. and Rundmo, T. (2009). Perceptions of traffic risk in an industrialised and a developing country. Transportation Research: part F, 12(1), 91-98.

O'Flaherty, C.A. (1997). Transport planning and traffic engineering. 1st Edition, Arnold, UK.

Olstam, J., and Tapani, A. (2004). Comparison of car-following models. Swedish National road and Transport Research Institute, Report VTI meddelande 960A, Sweden.

Oner, E. (2011). Approximated headway distributions for non-signalized and signalized freeway entrance ramps. Procedia Social and Behavioural Sciences, 20, 381–389.

Panwai, S. and Dia, H. (2005). Comparative evaluation of microscopic car-following behaviour. IEEE, Transactions on Intelligent Transportation Systems, 6(3), 314- 325.

Paolo P. and Sara, D. (2012). Driving speed behaviour approaching roadwork zones on two-lane rural roads. SIIV - 5th International Congress - Sustainability of Road Infrastructures, Procedia - Social and Behavioral Sciences 53 (2012), 672–681.

Papageorgiou, M., Papamichail, I., Spiliopoulou, A. D. and Lentzakis, A. F. (2008). Real-time merging traffic control with applications to toll plaza and work zone management. Transportation Research: Part C, 16, 535-553.

Park, B. and Schneeberger, J. D. (2003). Microscopic simulation model calibration and validation: Case study of VISSIM simulation model for a coordinated actuated signal system. Transportation Research Record 1865, paper no. 03-2531, pp. 185-192. DOI: 10.3141/1856-20.

Pratt, J. M. (1996). *An investigation into the causes of personal injury accidents at selected roadwork and non-roadwork motorway sites in Cheshire*. (MSc Dissertation), University of Salford, UK.

Purnawan. P. (2005). *Developing of traffic micro-simulation for on-street parking facilities*. (PhD thesis), University of Salford, Salford, UK.

Racha, S., Chowdhury, M., Sarasua, W. and Ma, Y. (2008). Analysis of work zone traffic behaviour for planning applications. Transportation Planning and Technology, 31(2), 183-199. doi: 10.1080/03081060801948175.

Rao, A. (2006). *Modelling anticipatory driving behaviour*. (MSc thesis), Department of Civil and Environmental Engineering, MIT, USA.

Roess, R. P., Prassas, E. S. and McShane, W. R. (2004). Traffic engineering. 3rd Edition, Pearson Education, Inc., New Jersey, USA.

Ruhai, G., Weiwei, Z. and Zhong, W. (2010). Research on the driver reaction time of safety distance model on highway based on fuzzy mathematics. International Conference on Optoelectronics and Image Processing, IEEE, 978-0-7695-4252-2/10. DOI 10.1109/ICOIP.2010.

Salter, R. J. and Hounsell, N. B. (1996). Highway traffic analysis and design. 3rd Edition, MacMillan Press Ltd, UK.

Schonfeld, P. and Chien, S. (1999). Optimal work zone lengths for two-lane highways. American Society of Civil Engineers (ASCE), Journal of Transportation Engineering, 125(1), 21-29.

SIAS Limited (2007). S-Paramics 2007 reference manual. Edinburgh, UK.

Sinclair, M. (2010). Vulnerability at road construction sites, South Africa. Proceedings of the 29th Southern African Transport Conference (SATC 2010), Pretoria, South Africa.

Slinn, M., Matthews, P. and Guest, P. (2005). Traffic Engineering Design; Principles and Practice; Second edition. Elsevier Butterworth-Heinemann Linacre House, Jordan Hill, Oxford OX2 8DP.

Sparmann, U. (1978). Spurwechselvorgan auf Zweispurigan BAB-Richtungsfahrbahnen. Forschung StraBenbau und StraBenverkehretechnik, Heft 263.

Sultan, B. and McDonald, M. (2001). The lane changing process: Data analysis and modelling behaviour. Traffic Engineering + Control, 43(5), 202- 207.

Summersgill, I. (1985). Safety performance of traffic management at major roadworks on motorways in 1982. Transport Road Research Laboratory, Research report 42, Crowthorne.

Tahaa, M. A. and Ibrahim, L., (2012). Traffic simulation system based on fuzzy logic. Procedia Computer Science, 12, 356–360.

Tarko, A. P. and Venugopal, S. (2001). Safety and capacity evaluation of Indiana lane merge system. Joint Transportation Research Program Final Report FHWA / IN / JTRP – 2000 / 19. Purdue University, West Lafayette, Indiana.

Toledo, T. (2007). Driving behaviour: models and challenges. Transport Reviews: A Transnational Transdisciplinary Journal, 27(1), 65-84. doi: 10.1080/01441640600823940.

Toledo, T., Choudhury, C.F. and Ben-Akiva, M.E. (2005). A lane-changing model with explicit target lane choice. TRB 2005 Annual Meeting CD-ROM.

Tolle J. E. (1976). Vehicular headway distributions: testing and results. Transportation Research Board, 576, 56-64.

Transportation Research Board (2000). Highway Capacity Manual (HCM), Washington, DC.

Transportation Research Board (2010). Highway Capacity Manual (HCM), Washington, DC.

Walck, C. (1996). Hand-book on statistical distributions for experimentalists, Particle Physics Group, University of Stockholm.

Walker, G. and Calvert, M. (2015). Driver behaviour at roadworks. Applied Ergonomics, 51, 18-29.

Wang, J. (2006). *A merging model for motorway*. (PhD Thesis), University of Leeds, Leeds, UK.

Warner, H.W. and Aberg, L. (2008). Drivers' beliefs about exceeding the speed limits. Transportation Research: Part F, 11, 376–389.

Weng, J. and Meng, Q. (2011). Modeling speed-flow relationship and merging behavior in work zone merging areas. Transportation Research: Part C, 19, 985-996.

Weng, J. and Meng, Q. (2013). Estimating capacity and traffic delay in work zones: An overview. Transportation Research: Part C, 35, 34-45.

Weng, J. and Meng, Q. (2015). Incorporating work zone configuration factors into speed-flow and capacity models. Journal of Advanced Transportation, 49 (3), 371–384. doi: 10.1002/atr.1277.

Weng, J. and Yan, X. (2016). Probability distribution-based model for work zone capacity prediction. Journal of Advanced Transportation, 50 (2), 165–179. doi: 10.1002/atr.1310.

Wood, R. Sexton, B. and Rillie, I. (2010). Speed compliance in overnight roadworks. Transport Research Laboratory, TRL, Project Report CPR875, 710 (387) HTRL, Crowthorne.

Yang, Q., and Koutsopoulos, H. N. (1996). A microscopic traffic simulator for evaluation of dynamic traffic management systems. Transportation Research: Part C, 4(3), 113-129.

Yousif, S. Y. (1993). *Effect of lane changing on traffic operation for dual-carriageway roads with roadworks*. (PhD. Thesis), University of Wales College of Cardiff, UK.

Yousif, S. (2002). Motorway Roadworks: Effects on Traffic Operations. Journal of Highways and Transportation, 49(4), April 2002. (ISSN 0265 - 6868).

Yousif, S. and Hunt, J. (1995). Modelling lane utilisation on British dual-carriageway roads: effects on lane-changing. Traffic Eng. Control, 36(12), 680–687.

Yousif, S., Al-Obaedi, J. and Henson, R. (2013a). Drivers' lane utilization for UK motorways. American Society of Civil Engineers (ASCE), Journal of Transportation Engineering, 139(5), 441-447.

Yousif, S., Alterawi, M. and Henson, R. (2013b). Effect of road narrowing on junction capacity using microsimulation. American Society of Civil Engineers (ASCE), Journal of Transportation Engineering, 139(6), 574-584.

Zarean, M. (1987). *Development of a simulation model for freeway weaving sections*. (PhD Dissertation), the Ohio State University, USA.

Zhang, L., Cai, S., Zhang, Y. and Zhang, M. (2010). Comparison of lane changing algorithms between NGSIM and CORSIM. IEEE, Vehicular Technology Conference (VTC 2010-Spring), IEEE 71st.

Zheng, P. (2003). *A microscopic simulation model of merging operation at motorway onramps.* (PhD Thesis), University of Southampton, UK.

Zia, F. F. (1992). *Traffic operation at merges on motorways and dual carriageways*. (PhD Thesis), University of Wales, Cardiff, UK.

References from the web

The Chartered Institution of Highways and Transportation. Lower maximum speed proposed for part of the M1, January 8, 2014. Available from: http://www.ciht.org.uk/en/media-centre/news.cfm/Lower-Speed-Proposed-For-M1 Accessed 16th January 2014.

The National Work Zone Safety Information Clearinghouse. Fatalities in Motor Vehicle Traffic Crashes by State and Work Zone (2012). Available from: http://www.workzonesafety.org/crash_data/workzone_fatalities/2012

www.infrastructure-intelligence.com/article/dec-2014/highways-england-sets-out-its-%C2%A315bn-plan-five-year-post-agency-spending (accessed on 25/10/2015 – Article dated 10/12/2014 on “Highways England five year post-Agency spending”.

Appendix A: Summary of the statistical results for capacity and delay equations

A.1 Capacity

Table A.1: Statistical summary of capacity model (Equation 8.1)

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.967[a]	.935	.930	484.419

a. Predictors: (Constant), Inside Closure, HGVs Percentages, Lanes No., Narrow Lanes, Offsie Closure

Table A.2: Coefficients of the capacity model (Equation 8.1)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	846.331	246.430		3.434	.001
	Lanes No.	1794.074	70.519	.751	25.441	.000
	HGVs Percentages	-5935.930	437.106	-.387	-13.580	.000
	Narrow Lanes	-487.957	163.663	-.101	-2.981	.004
	Offsie Closure	-1237.250	139.840	-.303	-8.848	.000
	Inside Closure	-1673.917	139.840	-.410	-11.970	.000

a. Dependent Variable: Max Throughput

A.2 Delay

Table A.3: Statistical summary of delay model (Equation 8.2)

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.904[a]	.817	.816	5.06471

a. Predictors: (Constant), Inside Closure, HGVs (%), Lanes No., Offsie Closure, Total Flow (veh/hr), Narrow Lanes

Table A.4: Coefficients of the delay model (Equation 8.2)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	10.075	.940		10.723	.000
	Lanes No.	-5.811	.286	-.341	-20.348	.000
	Total Flow (veh/hr)	.006	.000	.858	47.614	.000
	HGVs (%)	12.626	1.834	.107	6.884	.000
	Narrow Lanes	18.674	.531	.725	35.174	.000
	Offsie Closure	21.745	.552	.814	39.380	.000
	Inside Closure	21.587	.558	.796	38.687	.000

a. Dependent Variable: Delay (sec/veh)

Table A.5: Statistical summary of delay model (Equation 8.3)

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.899[a]	.809	.808	5.17949

a. Predictors: (Constant), Lane Closure, HGVs (%), Lanes No., Total Flow (veh/hr), Narrow Lanes

Table A.6: Coefficients of the delay model (Equation 8.3)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	10.320	.960		10.750	.000
	Total Flow (veh/hr)	.006	.000	.858	46.528	.000
	Lanes No.	-5.873	.292	-.344	-20.105	.000
	HGVs (%)	12.805	1.876	.108	6.827	.000
	Narrow Lanes	18.615	.544	.723	34.196	.000
	Lane Closure	21.614	.512	.915	42.184	.000

a. Dependent Variable: Delay (sec/veh)

Table A.7: Statistical summary of delay model (Equation 8.4)

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.937[a]	.878	.877	7.03494

a. Predictors: (Constant), Lane Closure, HGVs (%), Lanes No., Works Length (m), Total Flow (veh/hr), Narrow Lanes

Table A.8: Coefficients of the delay model (Equation 8.4)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-10.750	1.247		-8.620	.000
	Lanes No.	-6.888	.357	-.228	-19.287	.000
	Total Flow (veh/hr)	.007	.000	.622	49.157	.000
	HGVs (%)	22.306	2.352	.105	9.484	.000
	Works Length (m)	.012	.000	.641	54.675	.000
	Narrow Lanes	19.147	.712	.470	26.907	.000
	Lane Closure	22.615	.682	.560	33.162	.000

a. Dependent Variable: Delay (sec/veh)