UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE & MATHEMATICS

School of Civil Engineering and the Environment

The design and operation of motorway diverge areas

by

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Thesis for the degree of Doctor of Philosophy

April 2004

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
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Doctor of Philosophy
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An efficiently designed diverge area, where drivers can leave a motorway, will allow exiting traffic to leave the mainline as easily and as quickly as possible without disrupting other traffic wishing to continue on the mainline. The design process for motorway diverges was established in the 1970's, and has remained largely unchanged since then. In the meantime, traffic conditions and operations have changed significantly, and new diverge layouts have had to be introduced. This situation has prompted the research described in this thesis, which has concerned a critical evaluation of traffic operations and design procedures at motorway diverges, to identify the key issues concerned and to recommend new improved design procedures where appropriate.

A historical review of standards for motorway diverges in the UK was carried out along with a critical review of the diverging flow-region diagram, used by UK traffic engineers as a tool to select the most appropriate diverge layout. Further reviews looked at driving behaviour at motorway diverges, and the results from video trials into the effectiveness of the new Ghost Island diverge layout to reduce swooping (drivers cutting into the slip road from lanes 2 or 3 in order to leave the mainline), which has been installed at several UK motorway interchanges. This was supplemented by a questionnaire survey asking drivers their views of the new layout at the M27/M3 diverge.

SISTM (SImulation of Strategies for Traffic on Motorways) was selected as a suitable microscopic model to further evaluate existing and alternative diverge layouts in terms of their capacity and associated operations. After a preliminary exercise and extensive initial testing of the program, four layouts (Taper, Parallel, Taper lane drop and the Ghost Island) were modelled in order to carry out a theoretical comparison within SISTM.

The results showed that the throughput at the diverge (sum of the flow on the slip road and the mainline after the diverge) was maximised when the utilisation of the mainline lanes before the diverge was as equally used as possible. This was related to the type of layout and whether it provided the exiting driver with any lane and/or exit choice. The Ghost Island and Parallel layouts were both shown to operate well with high throughputs over a wide range of diverging percentages (0% - 60%), both providing a degree of exit choice to drivers. The Taper and Taper lane drop layout, offered no such choice, and were only suited to a smaller range of diverging percentages (0% - 30% and 30% to 50% at capacity flow levels respectively). Additional results regarding lane utilisations, average speeds, lane changes and journey times/speeds provided useful information concerning the operation and potential safety of each layout.

Limitations to the SISTM model were identified with possible enhancements suggested. In addition, measures to improve the capacity and/or the lane distribution near the diverge were examined, such as installing a hard shoulder running lane, real time road markings and the use of variable speed limits.

Conclusions included a design process flowchart containing a toolkit of measures to improve the operation and capacity of the diverge. Recommendations included making the Ghost Island diverge layout (with or without a lane drop) a standard design layout with its ability to reduce swooping and potentially improve throughput. In addition, field trials should be carried out to assess measures such as real time road markings in their effectiveness in trying to optimise the lane distribution on the mainline before the diverge.

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ACKNOWLEGEMENTS

The author would like to thank a number of people/organisations for their help during this PhD research. I would like to thank my supervisor, Dr Nick Hounsell for his guidance and advice throughout the three years; EPSRC for providing the financial support to carry out this research; the Highway Agency for their permission to use SISTM for the modelling work; Ewan Hardman (TRL) for his advice with regard to the use of SISTM; TRL for their permission to use the research material from the anti-swooping trials; the five traffic engineers who provided input with regard to the diverging flow-region diagram; the 54 individuals who took part in the questionnaire survey and Dr Mark Brackstone, Dr Pengjun Zheng, Dr Beshr Sultan and Dr Birendra Shrestha (all from the Transportation Research Group, University of Southampton) for their respective input and help. I would also like to thank the support from my family; my wife Jan, my mother and my brother Stephen. I would finally like to dedicate this thesis to my late father, Dr DT Wall, who encouraged and helped me enormously in my general education, particularly at school.

CHAPTER 1

INTRODUCTION

1.1 Background

Fast, safe and efficient communications are a prerequisite for any nation's prosperity. In a compact, densely populated country such as the UK, motorways have proved to be a safe and effective means of providing short and predictable journey times, over long distances. Great Britain's motorway network is having to cope with ever increasing traffic volumes, increased congestion and delay. The motorway network accounts for 3,500 kilometres (2,031 miles), less than 1% of the total length of British roads but carries 20% of all traffic. Traffic on motorways has been growing particularly quickly, rising by 56% between 1987 and 1997 to 95.4 billion vehicle-kilometres, reflecting increases in motorway length as well as traffic flow (National Statistics 2001).

A diverge is the area of the motorway where drivers can leave the main carriageway. An efficiently designed diverge will allow traffic to leave the mainline as easily and as quickly as possible, without disrupting other traffic wishing to continue on the mainline. The design of the diverge should "permit the driver to perform his driving task with a minimum of discomfort, indecision and frustration … where poor judgement is not penalised too greatly" (Taylor and Raymond 1974).

There are two basic types of diverge layout recommended in the latest Standard TD22/92 (Department of Transport 1992a). These are the Taper diverge and the Parallel diverge (see Figure 1.1).

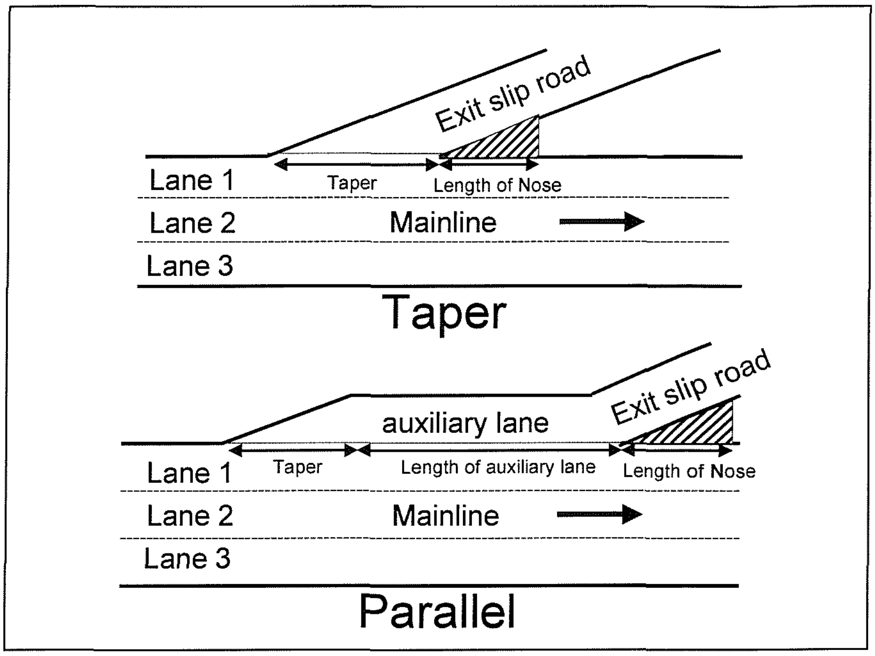


Figure 1.1: Two basic types of diverge layout

With the Taper diverge, drivers wishing to leave the motorway should stay in lane 1 prior to the diverge and then move directly into the exit slip road. Drivers leave the mainline at a flat angle on a direct path, reducing the amount of driver steering control. With the Parallel diverge, drivers wishing to leave the motorway should stay in lane 1 and then move into the auxiliary lane that feeds into the exit slip road. An auxiliary lane (or a parallel lane) provides extra capacity, reducing the risk of traffic blocking back onto the main carriageway. It also helps facilitate the positioning of the driver leaving the mainline and acts as a speed-change lane, enabling drivers to make the necessary change of speed from the mainline to the exit slip road.

These two types of layout can be associated with a lane drop or double lane drop (Parallel layout only). A lane drop occurs when the number of lanes downstream of the diverge is less than the number of lanes upstream of the diverge. This is as a result of the inside mainline lane(s) feeding into the exit slip road. Lane drops are only usually provided when there is a high diverging percentage or when there is a high merging percentage requiring a lane gain upstream of the diverge. There may also be policy, layout or economic reasons for their use.

With the increasing traffic flows on the UK's motorway network, diverges are having to cope with an increasing volume of traffic wishing to leave the mainline. It is an important area of the motorway whose efficient operation depends on a design that has a high capacity and encourages good driving behaviour.

High cost measures, such as adding new traffic lanes to existing motorways to increase capacity, carry an economic and environmental 'price'. Various low cost measures have therefore been used to improve capacity and driver behaviour at diverges such as various lane separation markings and the new "tiger-tail" Ghost Island layouts. The latest Standard for motorway diverges, TD22/92 "The Layout of Grade-Separated Junctions" (Department of Transport 1992a and 1992b), is over 10 years old and is based on research which was undertaken in the 1970's. It therefore needs updating with alternative and improved diverge layouts. Since that time, there have been significant changes in traffic conditions and in evaluation methodologies which have led to improved design procedures for other elements of the road infrastructure. This situation has suggested a clear need for the research described in this thesis, which seeks to provide new understandings of motorway diverge operations and improved design procedures as appropriate.

1.2 Objectives

The objectives of the research have been to:

1. Review the current design practices for motorway diverges, comparing the situation in the UK with similar countries overseas.
2. Develop a methodology for the evaluation of existing and alternative diverge layouts.
3. Assess existing and alternative diverge layouts with regard to their capacity and associated operation.
4. Recommend enhancements to the microscopic model SISTM.
5. Produce recommendations for the design of diverges.

1.3 Methodology and contents

This PhD thesis reports on the objectives of the research. Chapter 2 contains a critical review of design standards for motorway diverges in the UK and equivalent standards in other countries around the world with similar network and infrastructure conditions. A review of driving behaviour at motorway diverges is contained in Chapter 3. This includes the "anti-swooping trials" that were carried out by the author whilst working at the Transport Research Laboratory (TRL) between 1995 and 2000. It also contains the results of a questionnaire survey of drivers' reactions to the new Ghost Island diverge layout installed at the M27/M3 eastbound, one of the trial sites used in the TRL work. Chapter 4 contains a review of motorway microscopic simulation models with a critical look at SISTM, and the reasons why it was selected as a suitable model for the purpose of this research. A preliminary modelling exercise of part of the M27 undertaken using SISTM is discussed in Chapter 5. Chapter 6 contains an initial assessment of SISTM by the use of a number of tests on a number of different parameters, in order to check that the program's results are an accurate representation of reality. The setting up and testing of the different diverge layouts being modelled is discussed in Chapter 7. Chapters 8 and 9 contain the modelling results from SISTM; throughput, speed and lane utilisation results in Chapter 8 with journey time and lane changing results in Chapter 9. Chapter 10 is a discussion of some of the implications of the results on measures that could improve the capacity and/or the lane distribution of the mainline before the diverge. Chapter 11 contain the conclusions and recommendations. Appendix A shows the questionnaire form used to ask drivers their reactions to the new layout at the M27/M3 diverge. Appendix B contains results from the preliminary modelling exercise. Appendices C and D contain sample SISTM input and output files respectively used in the modelling work. Following the Appendices is a glossary and a list of references.

CHAPTER 2

STANDARDS FOR MOTORWAY DIVERGES

2.1 Historical background

The Romans introduced the idea of a national road system to Britain in the first century, in order for military purposes of conquest and linking important centres of trade. Similarities still exist between the main roads in existence in 200 AD and the present-day UK motorway network. Pressure for the construction of a system of motorways mounted as they were seen to be, potentially, a network of roads exclusively for motor traffic, designed for the needs of the country as a whole. This followed the construction of motorways in countries like the USA, Germany and Italy in the 1920's and 1930's. However, it was not until December 1958 that the first length of road constructed as a motorway was opened to the public. This was the 8 mile long Preston by-pass, part of the now M6 in Lancashire (Charlesworth 1984). Their purpose was to provide safe, fast and reliable communication between the main centres of the UK. They were to supplement the existing road network, providing access to the motorway at reasonable intervals via connecting roads.

2.2 The use of standards

Standards are technical specifications issued by Government in order to provide requirements for the design of new roads and junctions. These standards are mandatory for work on trunk roads or motorways in the UK and have been updated at regular intervals over the last 40 years, in particular to cope with the large increase in traffic flows. They have also needed to change in order to cater for new levels of vehicle and driver performance, as well as address any safety concerns. New standards are often just minor amendments to the existing standards. Some of the changes have been due to a need for further clarification, as the previous standard lacked the required detail or definition.

Standards may need to be 'relaxed' in order for a new road to be built in difficult circumstances e.g. very hilly terrain. Many standards contain a 'desired minimum' and an 'absolute minimum'. Behavioural studies have shown that there is a considerable margin below the desired minimum standards before safety is significantly reduced (Simpson and Kerman 1982). A relaxation from the desired minimum may be necessary if the economic or environmental cost cannot be justified. Departures (going beyond the absolute minimum) require authorisation from the Department's headquarters. Relaxations or departures should not compromise safety but may reduce driving comfort.

Once it was decided to design and build motorways, the then Ministry of Transport had to decide on standards of layout and construction to be used. In doing so, they have drawn on research from the Transport and Road Research Laboratory (now the Transport Research Laboratory or TRL).

2.3 Standards for motorway diverges in the UK

Ever since the first motorway was opened to the public in the UK in 1958, the standards for their construction have evolved over the years. Table 2.1 lists the most important standards for motorway diverges to be published in the UK over the last 40 years.

Table 2.1: Selected UK standards for motorway diverges

Standard Title and Number	Government Department responsible	Year published
Layout of Roads in Rural Areas	Ministry of Transport	1968
Technical Memorandum on design flows for motorways and all-purpose roads (H6/74)	Department of the Environment	1974
Technical Memorandum on rural motorway to motorway interchanges – single lane links (H17/75)	Department of the Environment	1975
Technical Memorandum on design of rural motorway to motorway interchanges – merging and diverging lanes (H18/75)	Department of the Environment	1975
Highway Link Design (TD9/81)	Department of Transport	1981
Layout of Grade-Separated Junctions (TD22/86)	Department of Transport	1986
Layout of Grade-Separated Junctions (TD22/92 and TA48/92)	Department of Transport	1992
The Design of Major Intersections (TD39/94)	Department of Transport	1994

2.4 Research background to the diverging flow-region diagram

2.4.1 Introduction to the diverging flow-region diagram

The latest UK standard, setting out the layout requirements for diverges, is entitled "The Layout of Grade-Separated Junctions" and is commonly known as TD22/92 (Department of Transport 1992). TD22/92 recommends five diverge layout types. These are the Taper diverge, Parallel diverge, Taper diverge with lane drop, Parallel diverge with lane drop and Parallel diverge with a double lane drop. Figure 2.1 shows these five different layouts.

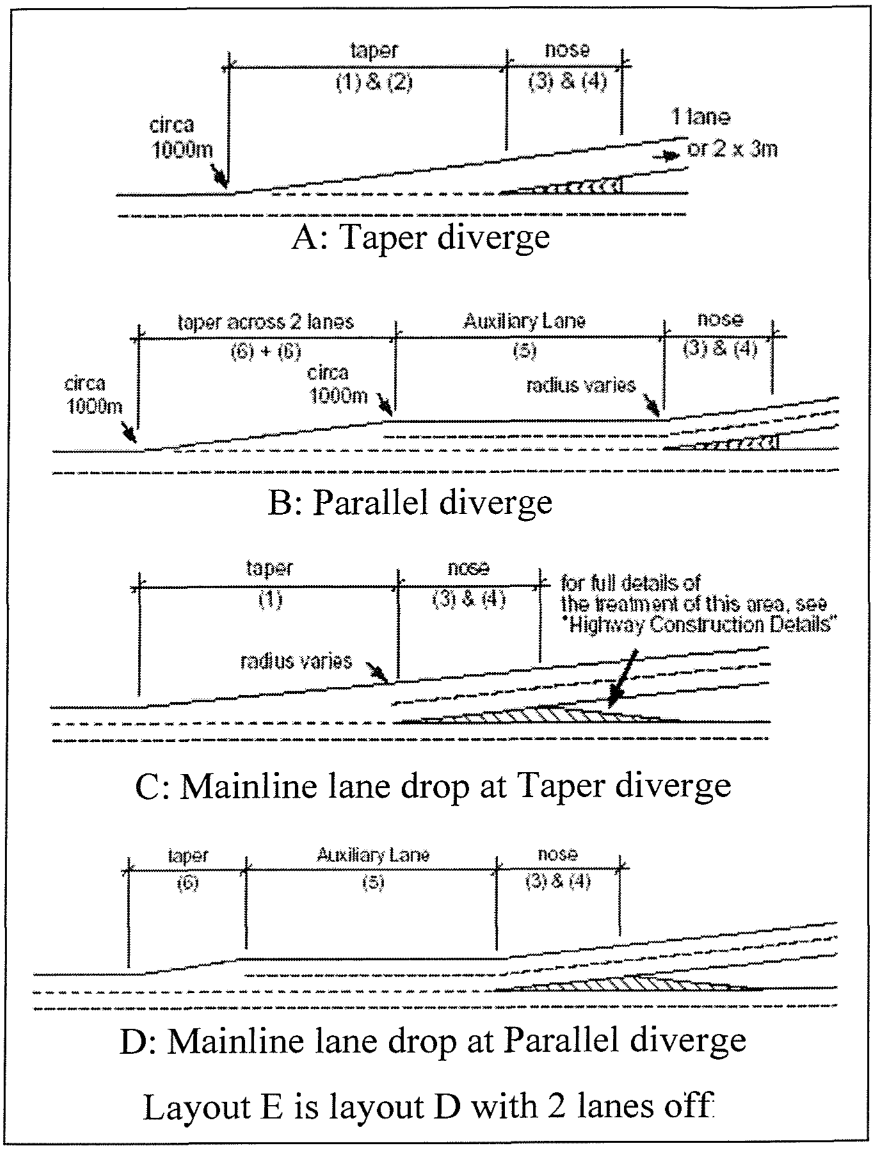


Figure 2.1: Different diverging layouts taken from TD22/92

In order for traffic engineers to choose the correct diverge layout for a specific site, the Standard TD22/92 provides traffic engineers with a diverging flow-region diagram, recommending the different diverge layouts for varying combinations of mainline and diverging flows (see Figure 2.2). The traffic engineer needs to select the 30th highest combination of predicted hourly flows expected in the 15th year of operation. The 30th highest combination is used as it is assumed that there is very low seasonal variation on the motorway in the predicted hourly flows. The flows selected, therefore, do not represent the most congested operating conditions but do cater for the majority of periods.

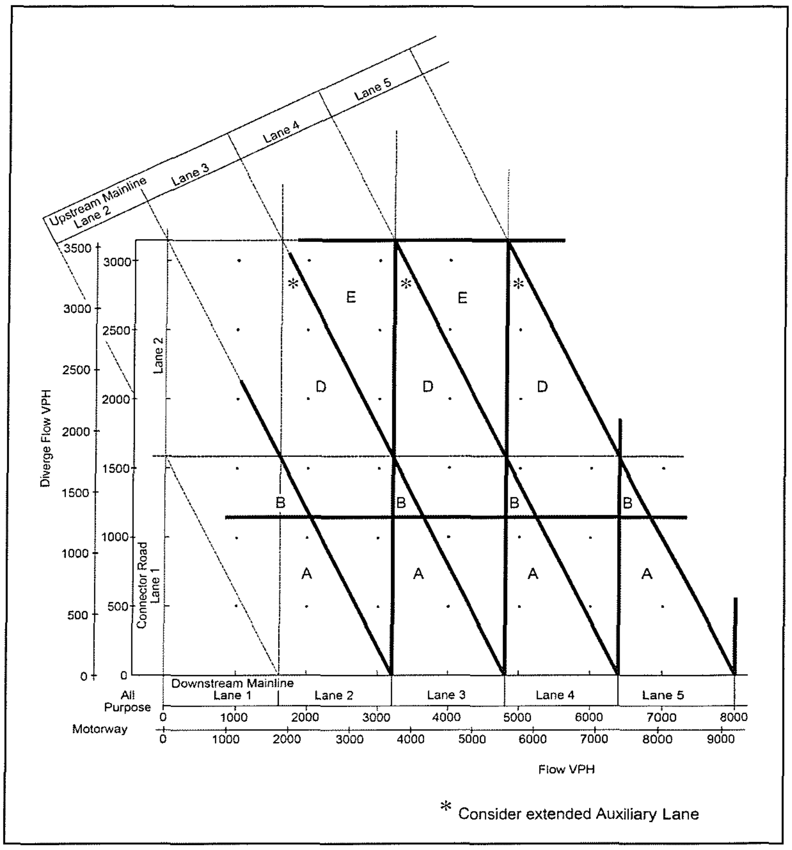


Figure 2.2: The diverging flow-region diagram from TD22/92

The standard TD22/92 also contains a merging flow-region diagram. Section 2.4.2 describes how the diverging flow-region diagram was derived from the merging flow-region diagram (with extra limits for the merging diagram). The concepts behind the two manoeuvres are very different with merging involving gap acceptance but diverging involving a manoeuvre at a free flowing exit. It is not clear the justification for deriving these two diagrams in a similar way except for the fact that the diagrams are selecting layouts from a traffic flow perspective rather than an operational, behavioural or safety perspective.

There are six types of merge recommended in TD22/92, labelled A to F in the regions of the diagram. The six types of merge are as follows:

A: Taper merge

B: Parallel merge

C: Ghost Island merge

D: Taper merge with lane gain

E: Ghost Island merge with lane gain

F: Ghost Island merge with double lane gain

The Ghost Island merge (layout C) is not labelled on the diagram as it is only used when mainline design flows are light, there are three or more mainline lanes or the merging flow exceeds the capacity of one lane.

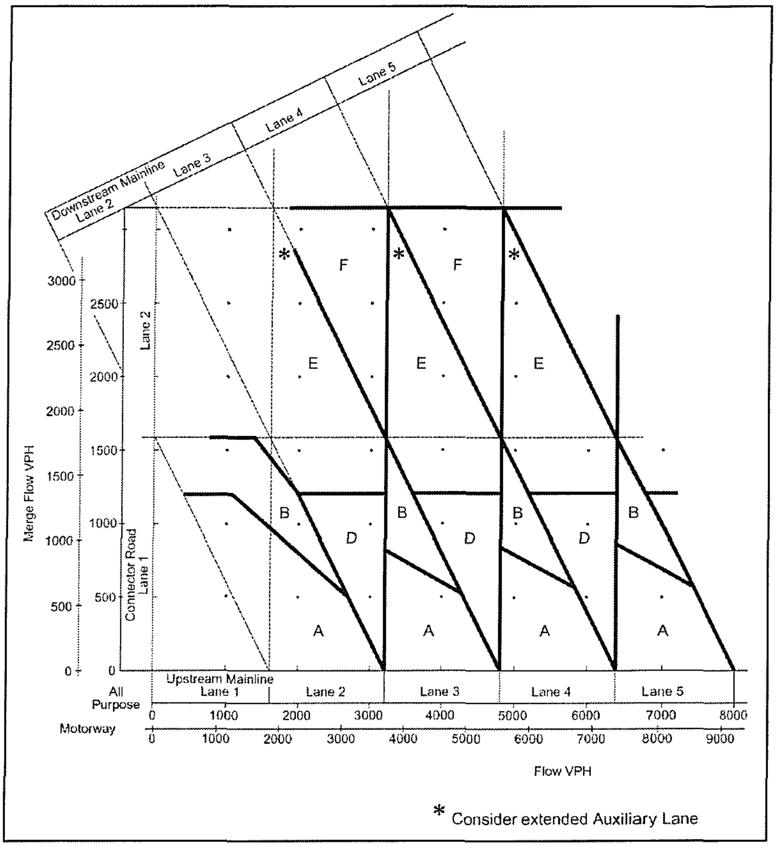


Figure 2.3: The merging flow-region diagram from TD22/92

The use of a flow-region diagram is not unique to the selection of diverges and merges. In the Departmental Standard TD42/95 entitled "Geometric Design of Major/Minor Junctions" (Department of Transport 1995), traffic engineers are recommended to use a flow-region diagram in the selection of the type of major/minor priority junction to install. Traffic engineers need to know the two-way annual average daily flow (AADT) on the major and minor road at the priority junction in order to find the appropriate region on the diagram. If there is a high seasonal variation or intense peaks in the traffic flow, the traffic engineer needs to select an appropriate peak hour flow (e.g 200th highest combined hourly flow which assumes a high seasonal variability).

With a low minor flow, a simple priority junction is recommended but with a high minor flow, a roundabout is recommended. The Standard states that the diagram "gives the starting point for junction choice ... but other factors need to be considered before a final decision is made" (Department of Transport 1995). The use of the diagram would normally be followed by producing a more detailed design (deciding upon the various geometric parameters) which would be supported by using the macroscopic simulation computer program ARCADY (for roundabouts) or PICADY (for priority junctions). This is an important principle for the diverging flow-region diagram which is a useful tool but can never be used to make the final decision exclusively. The traffic engineer needs to use his/her common sense and experience, particularly in borderline situations. Modelling work can also be beneficial in confirming the most suitable diverge layout in terms of throughput, journey times and lane changes. Figure 2.4 shows the "flow-region" diagram for major/minor junctions.

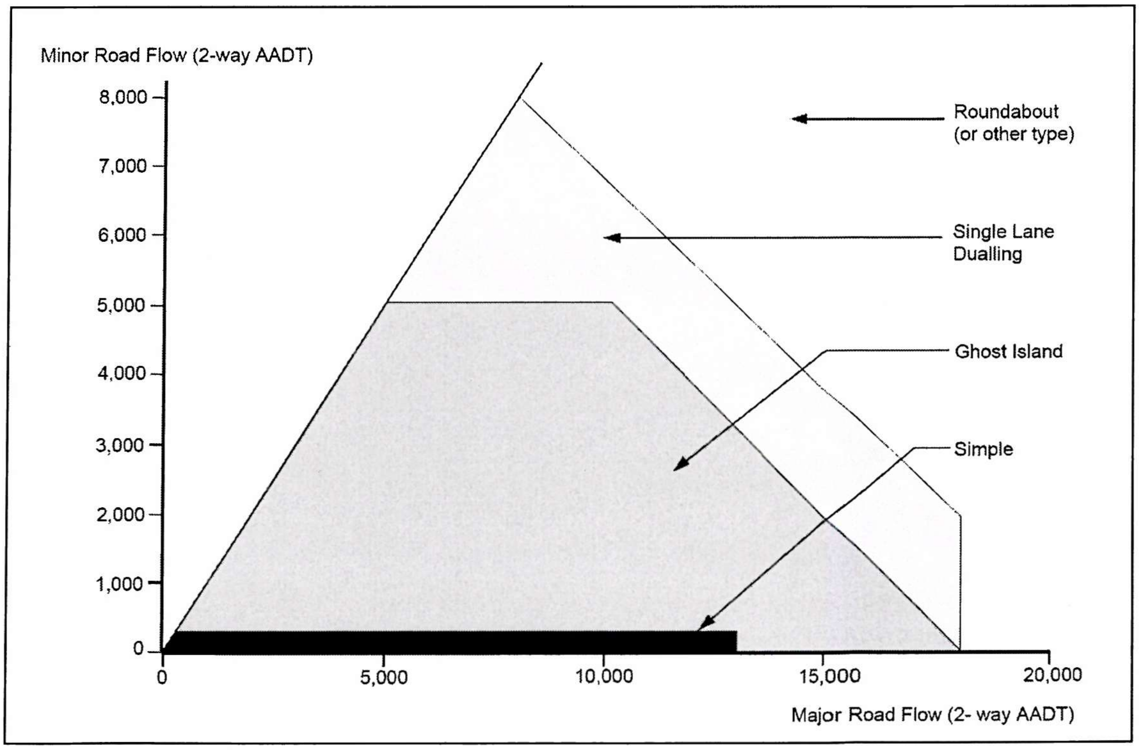


Figure 2.4: Major/minor priority junction "flow-region diagram" from TD42/95

2.4.2 Research carried out in the 1970's

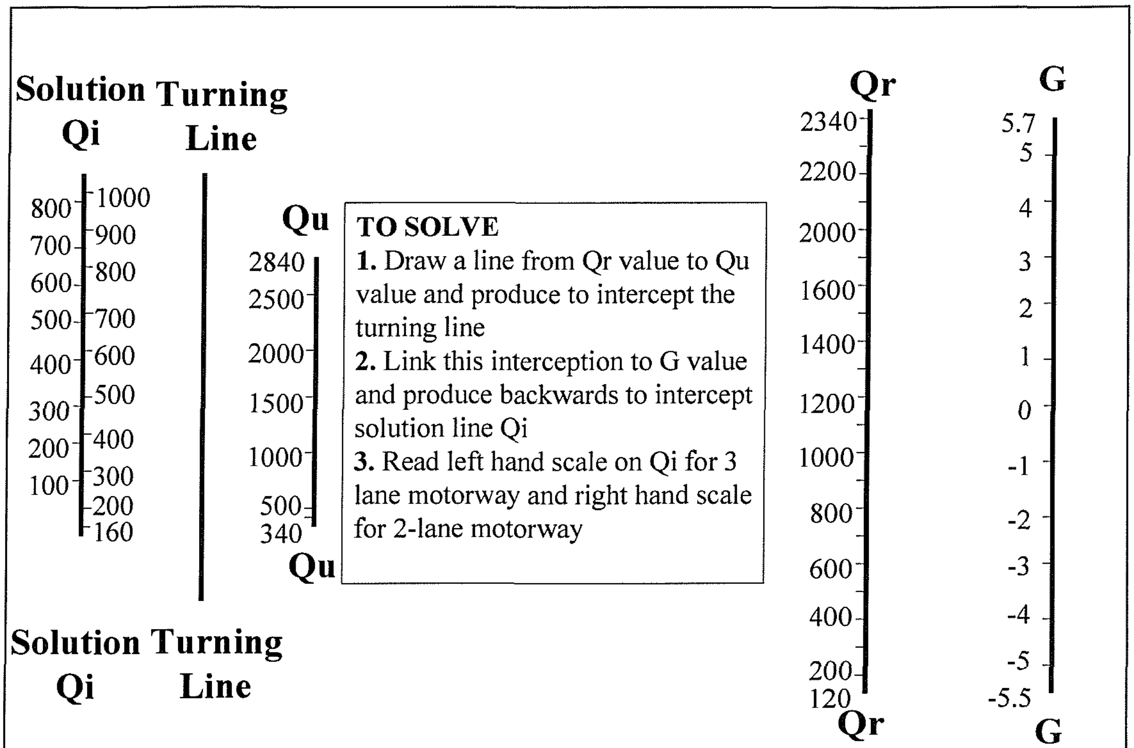
Much of the research background to the diverging flow-region diagram was carried out in the 1970's in the form of various motorway merging trials. Due to the high dependence on the USA for data on merging and diverging behaviour, a study was initiated in the UK at a number of urban motorway sites in 1972 (Berresford and Sneddon 1972; Sneddon 1976). This enabled equations to be produced by multiple linear regression to calculate the upstream lane 1 flow. After numerous attempts, the most acceptable regression for the inside lane flow was:

$Qi = 493 + 0.36Qu - 0.14Qr - 19G - 183N$ where

Qi is the upstream inside lane flow
Qu is the total upstream flow
Qr is the slip road flow
G is the relative gradient (slip road grade – motorway grade, uphill positive)
N is the number of motorway lanes (either 2 or 3)

The equation was based on 67 three-minute observation periods at four different sites. Statistical tests gave an R^2 value of 0.85. Subsequent t-tests indicated that Qu was significant at the 1% level with all other variables significant at the 0.1% level. The equation shows a dependence of the inside lane flow on the slip road flow, indicating that many mainline vehicles move into the outer lanes to allow easier access for merging vehicles as well as minimising their own journey time. The equation also showed the dependency of inside lane flow on relative gradient, showing that with good visibility (uphill gradient and downhill slip road), there would be a higher inside lane flow. These equations provide a knowledge of the ultimate inside lane capacity rather than a working design value which is more important in the design process.,

Nomographs accompanied the equations to make calculating the inside lane flow easier. Figure 2.5 shows a nomograph to help to calculate the inside lane flow.



$$Qi = 127 + 0.36Qu - 0.14Qr - 19G \text{ (2 lane motorway)}$$
$$Qi = -56 + 0.36Qu - 0.14Qr - 19G \text{ (3 lane motorway)}$$

Figure 2.5: A nomograph to help to calculate the inside lane flow Qi (from Berresford and Seddon 1972)

The study continued in 1973 so that the number of merging sites being analysed could be increased (Sneddon 1976). The formula for the inside lane flow was revised and included a slip road gradient term which was a better fit to the UK sites than the one in the Highway Capacity Manual (Highway Research Board 1965). A new set of nomographs accompanied the revised equation.

Building on this research, the Warwickshire Sub-Unit of the Midland Road Construction Unit produced a new set of motorway merge design flow-region diagrams for a Department of the Environment Working Party. These were based on practices in the USA as described in the Highway Capacity Manual, showing maximum traffic flow levels for different levels of service. They suggested much higher flow levels than those recommended in the previous Standard entitled "Layout of Roads in Rural Areas" published in 1968 (Ministry of Transport et al 1968). The diagrams were modified by TRL (Burrow 1976) and then incorporated into Technical Memorandum H18/75 (Department of the Environment 1975b), which gave advice regarding the design of merging and diverging layouts.

The diagram was to be used in the early stages of design to see which layout was likely to be most appropriate for the given downstream mainline and diverging flows. Within a given region of the diverging flow-region diagram, a tick indicated which of the nine diverging layout configurations were suitable (see Table 2.2). A method of compensating for variations in the traffic composition and for the effect of gradients was also included. Comparisons made with recorded flow measurements showed that the new design flows were realistic. Figure 2.6 shows the diverging flow-region diagram from H18/75 with the motorway scale added from TD22/86 (Department of Transport 1986). TD22/86 was the first standard that assigned a different maximum design flow value for a lane on an all-purpose road than that on a motorway. The flow-region diagram in TD22/86 is otherwise identical to the one in H18/75.

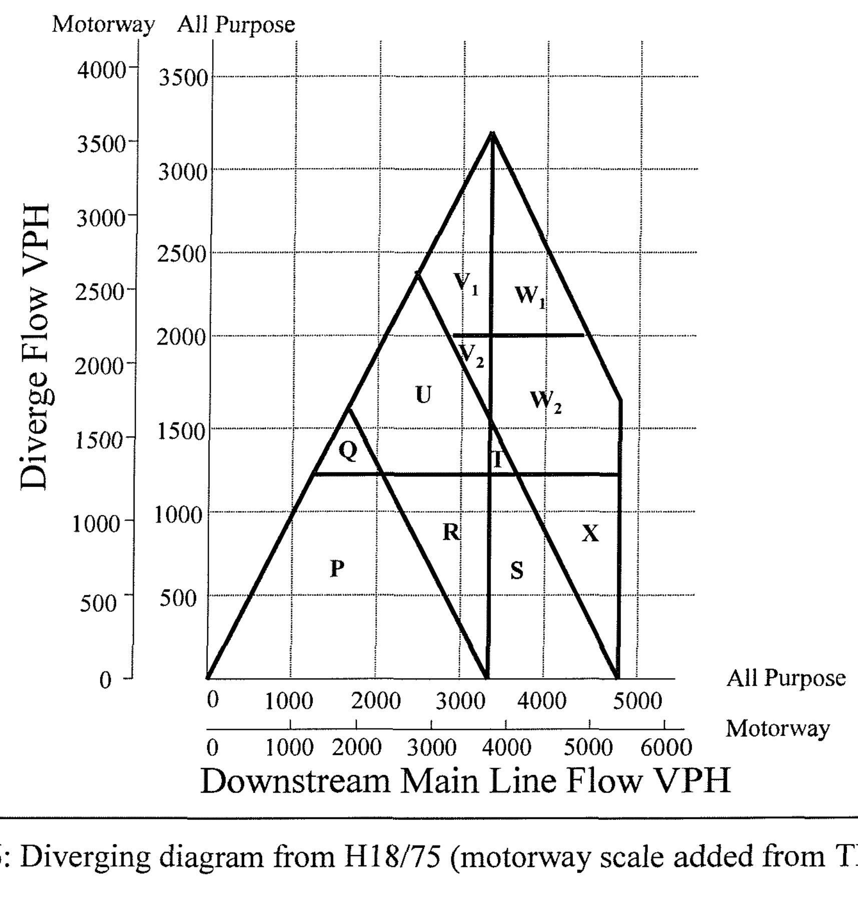


Figure 2.6: Diverging diagram from H18/75 (motorway scale added from TD22/86)

Table 2.2: Diverging lane types applicable to flow-regions in Figure 2.6

Diverging lane types		1	2	3	4	5	6	7	8	9
Number of lanes	Upstream mainline	2	2	3	3	3	4	3	4	4
	Link (slip lane)	1	2	1	2	2	2	1	1	2
	Downstream mainline	2	2	3	2	3	3	2	3	2
Flow Region	P	√	√	√	√	√	√	√	√	√
	Q	X	√	X	√	√	√	X	X	√
	R	X	X	√	√	√	√	√	√	√
	S	X	X	√	X	√	√	X	√	X
	T	X	X	X	X	√	√	X	X	X
	U	X	X	X	√	√	√	X	X	√
	V	X	X	X	X	X	√	X	X	√
	W	X	X	X	X	X	√	X	X	X
	X	X	X	X	X	X	√	X	√	X

2.4.3 Derivation of the diverging flow-region diagram

The derivation of the diverging flow-region diagram from TD22/92 is shown below in Figures 2.7 – 2.10, one 'level' at a time. It is set out in a similar way to the derivation of the merging flow diagram (Burrow 1976). However the phrase "upstream of the merge" is replaced with "downstream of the diverge".

1. The main carriageway downstream flow (i.e. after the diverge takes place) is subject to a limit of 1800 veh/hr per lane.

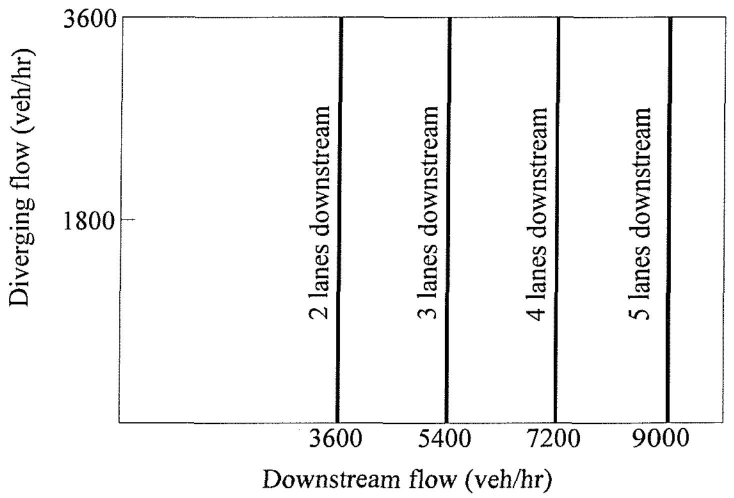


Figure 2.7: Main carriageway downstream flow limits

2. The diverge flow is limited to 1800 veh/hr per lane, except that a flow of 1350 veh/hr should be used for a single lane link. The lower design flow value for a single link is thought to be due to the fact it provides no overtaking opportunities which can result in platoons of exiting vehicles following an HGV or slow moving car.

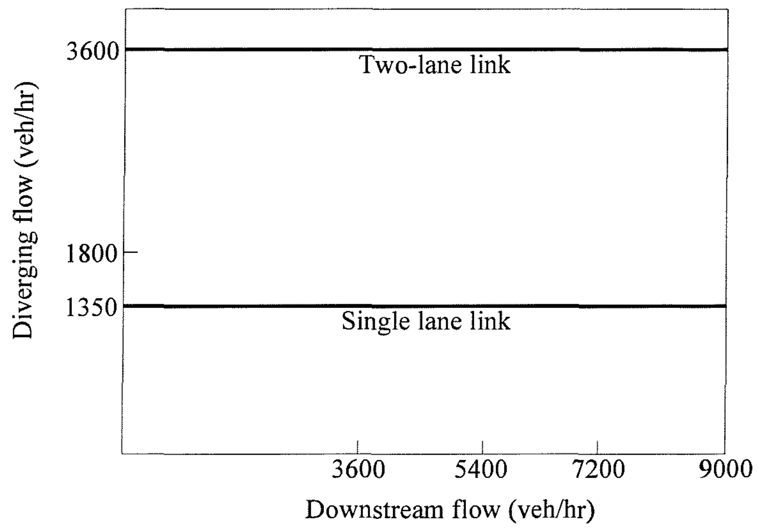


Figure 2.8: Exit flow limits

3. The upstream total diverge flow (which is then divided between the diverging and mainline downstream flow) is restricted to 1800 veh/hr per lane.

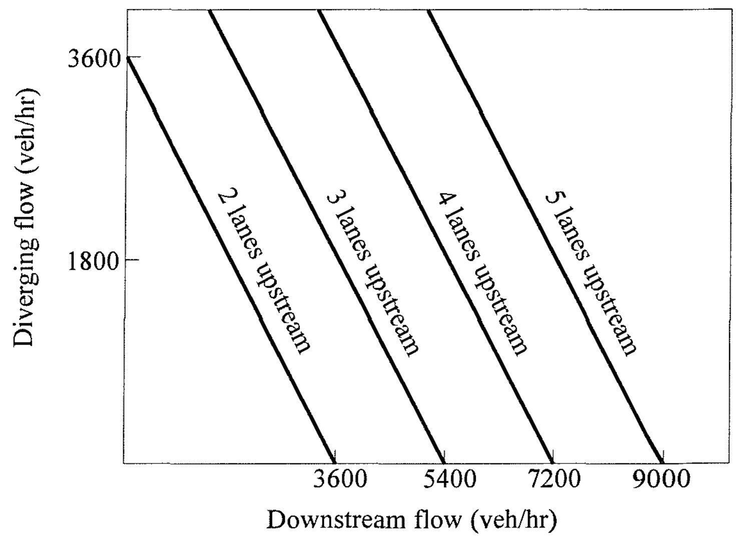


Figure 2.9: Upstream total diverge flow limits

4. The diverging flow must be no more than twice the downstream mainline flow (i.e. the diverging percentage has to be less than 67%).

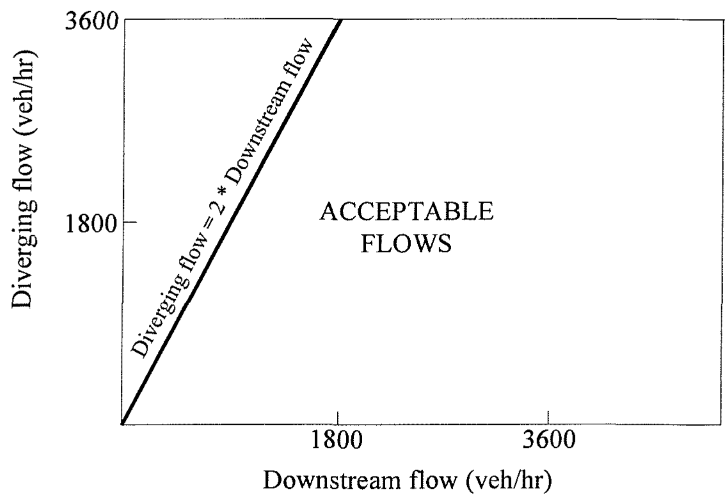


Figure 2.10: Additional downstream main carriageway flow limit

5. The limits are combined into one diagram, restricted to 2, 3, 4 or 5 lanes downstream and a single or two-lane link (Figure 2.2 shows the completed diverging diagram from TD22/92).

2.4.4 Corrections to flow due to percentage of HGVs and gradients

The diverging and mainline downstream mainline flows used in the diverging flow-region diagram are based upon a standard traffic composition and gradient. The standard composition was defined to be 15% HGVs and up to 1% uphill. To establish the mainline gradient, the average gradient of a 1km section is used 0.5km either side of the diverge or merge nose. The merge/diverge connector gradient is the average of the 0.5km section before/after the nose.

Many studies have shown how gradient can have an effect on the capacity and the average speed (for example Lin 1981). Corrections for non-standard compositions are given in Table 2.3 below. The effects of this correction under adverse conditions (e.g. a high proportion of HGVs and/or a steeper uphill gradient than 1%), result in the predicted traffic flows being increased before being plotted on the diagram. It is not known what original source or research was used to obtain these correction factors.

Table 2.3: Corrections for differing HGV proportions and gradients from H18/75

Percentage correction to predicted flow								
Gradient on mainline	Percentage heavy vehicles on link or mainline being considered							
	5	10	15	20	25	30	35	40
Downhill, level & up to 1% uphill	- 8	- 4	0	+ 4	+ 8	+12	+ 16	+ 20
Over 1% and up to 2%	+2	+ 6	+ 10	+ 14	+ 18	+ 22	+ 26	+ 30
Over 2% and up to 3%	+ 12	+ 16	+ 20	+ 24	+ 28	+ 32	+ 36	+ 40

For every 1% increase in uphill gradient, the flow needs to be increased by 10% in order to compensate for the loss in capacity. With every 5% increase in the percentage of HGVs, the flow needs to be increased by 4% to compensate for the loss in capacity.

For TD22/86 and TD22/92, the flow corrections due to gradient and the percentage of HGVs were changed slightly from H18/75 (see Table 2.4).

Table 2.4: Corrections for differing HGV proportions and gradients from TD22/92

%HGVs	Mainline gradient		Merge connector gradient		
	< 2%	> 2%	< 2%	2% – 4%	> 4%
5	-	+ 10	-	+ 15	+ 30
10	-	+ 15	-	+ 20	+ 35
15	-	+ 20	+ 5	+ 25	+ 40
20	+ 5	+ 25	+ 10	+ 30	+ 45

For gradients on the mainline above 2%, the flow needs to be increased by 5% with every 5% increase in the percentage of HGVs, in order to compensate for the loss in capacity. For mainline gradients less than 2%, the flow only needs to be corrected by 5% once the HGV percentage reaches 20%.

This new table simplifies the original table in H18/75 by dividing the mainline gradient into just two categories (under 2% or over 2%) rather than three categories as before. It also has only four HGV percentage categories, with the maximum being 20% rather than the original eight categories with a 40% maximum in H18/75.

These corrections to the flow due to the percentage of HGVs and uphill gradient show that these two factors are very important in the choice of diverge layout to install. These factors will be investigated in more detail in the modelling work in Chapters 6 and 8.

2.5 Interchange (major diverge) layouts

2.5.1 Introduction

The PhD project has mainly focussed on the diverge layouts recommended in TD22/92 (Department of Transport 1992a) along with the new Ghost Island layouts (see Chapter 3). This section looks at some major diverge layouts (or interchanges) that are either recommended at major interchanges, used already or proposed as a possible alternative layout for the future.

2.5.2 Recommended UK interchange (major diverge) layouts

In the UK, there are three layouts recommended for major diverges in the Standard TD39/94 (Department of Transport 1994). These layouts are shown in Figure 2.11. The layouts are as follows:

1. Major Parallel double lane drop with 3 slip lanes leaving a 5-lane mainline.
2. Major Parallel lane drop with 3 slip lanes leaving a 4-lane mainline.
3. Major diverge between two interchange links (diverging traffic leaves the mainline at the same point but then makes a subsequent decision whether to go left or right).

All of these layouts are recommended for use at major motorway-to-motorway interchanges with a mainline of at least 4 lanes. Major diverges of this kind can have problems with turbulence, as weaving can occur between slow and fast moving vehicles. There can also be problems with a large number of vehicles moving from the mainline to the slip lanes or visa versa for the whole length of the auxiliary lane. The installation of the new Ghost Island layout at major interchanges could improve the operation of each of these three layouts by regulating the exiting traffic into two orderly streams (see Chapter 3). It would also stop weaving between the slip lanes and the mainline and potentially dangerous last minute manoeuvres.

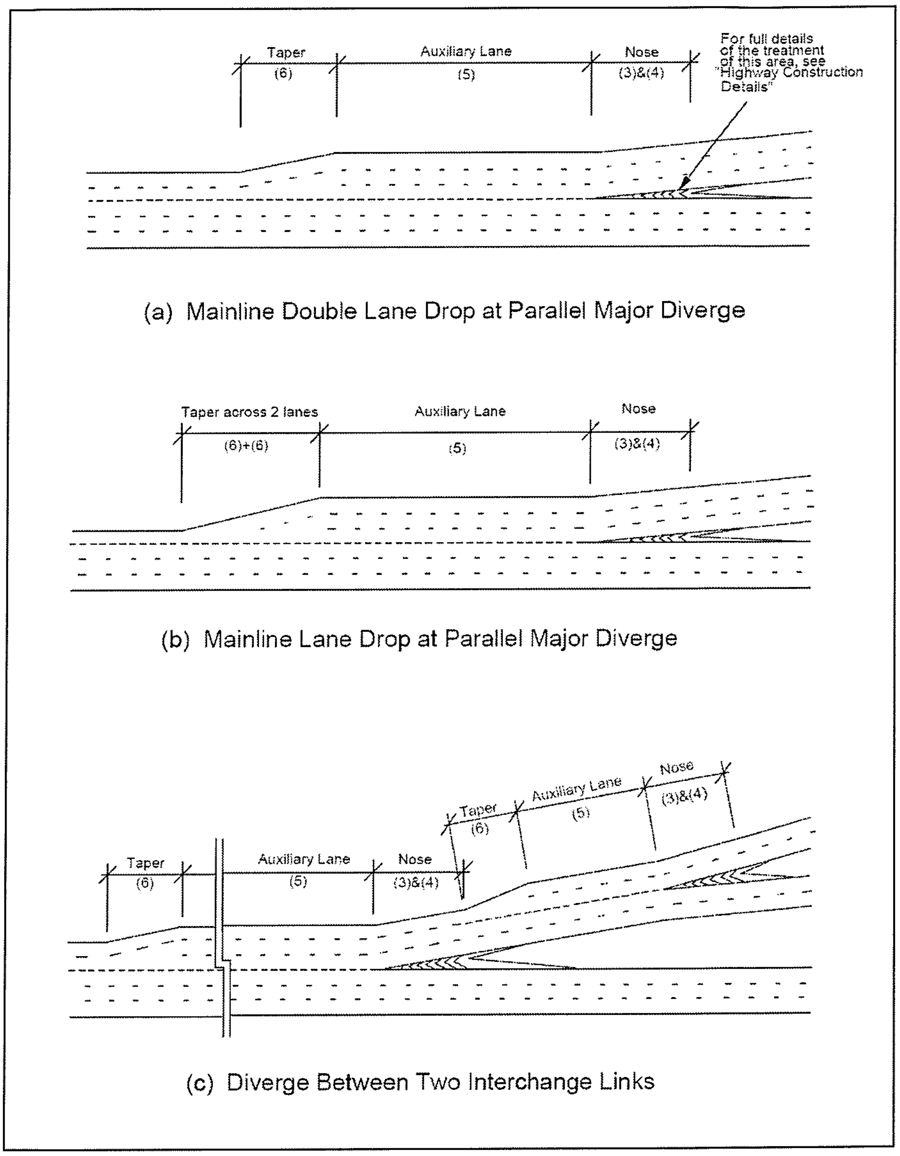


Figure 2.11: Recommended interchanges (or major diverges) from TD39/94

2.5.3 The major fork layout

This layout usually occurs at major interchanges where there are two equally important destinations with a diverging percentage of over 40% (Taylor and Raymond

1974). It occurs at a variety of major interchanges in the UK including the M275/M27 northbound near Portsmouth which forks to either the M27 westbound or the A27 eastbound. Another example is the A27/A1(M) near Portsmouth. Before this interchange, the mainline has four lanes with lanes 1 and 2 heading to the A1(M) and lanes 3 and 4 continuing on the A27. Drivers wishing to stay on the A27 need to be in lanes 3 or 4 and so may need to lane change twice in order to be correctly positioned for their required destination. This layout is a type of double lane drop with approximately 50% forking left and right respectively. This layout can cause potentially hazardous conditions, with faster vehicles needing to weave past slow moving vehicles in order to reach their required destination. Care must therefore be taken when considering the installation of such a design.

There can be a particular problem for slow moving HGVs with this type of layout and in order to cater for this, traffic engineers in California have designed a special major fork layout which has a right-exiting (left-exiting in the UK) left-turn (right-turn in the UK) lane for HGVs. This is shown in Figure 2.12 (Taylor and Raymond 1974).

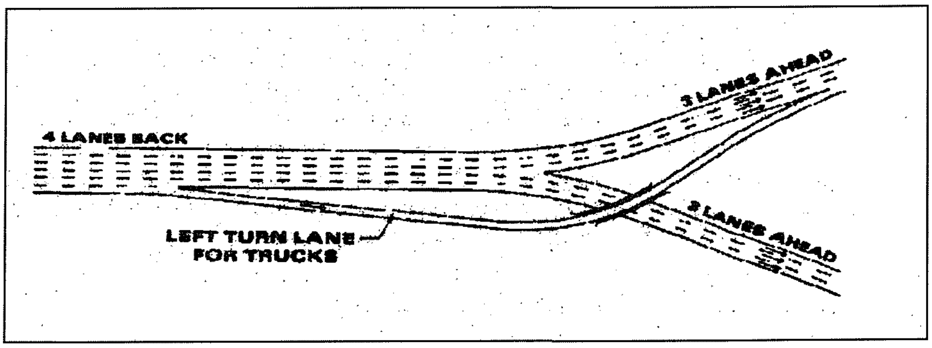


Figure 2.12: Major fork layout with lorry lane, California

Figure 2.13 shows a proposed major fork layout in Hamburg, Germany which was adapted from an existing fork layout (Meinefeld and Schnuell 1990). The mainline has 3 lanes, with drivers now able to use the middle lane to go either left or right. This provides lane choice to the driver, improving the lane distribution on the mainline before the fork and reducing the number of necessary lane changes. This layout could be improved further by the use of hatching and directional arrows in the middle lane which could regulate drivers more effectively and reduce the number of potentially dangerous last minute lane changes.

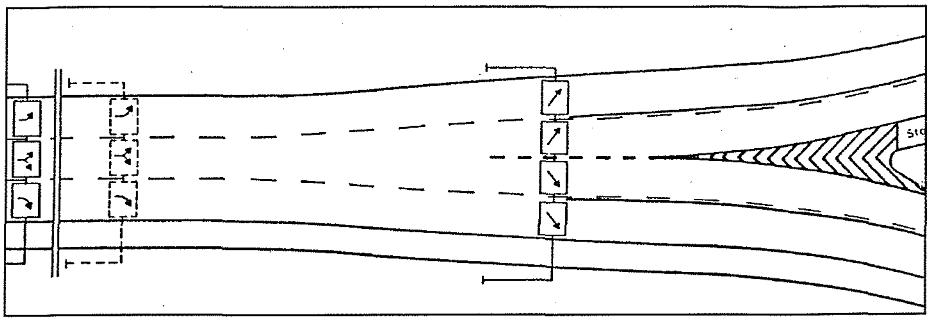


Figure 2.13: Proposed major fork layout, Hamburg

2.5.4 Left/right diverge layout

With a mainline of four lanes or more, many lane changes may be required for diverging vehicles to leave the mainline resulting in turbulence. One possible solution suggested was a diverge layout which allows vehicles to leave the mainline from the inside lane to slip lane 1 and from the outside lane to slip lane 2. Lane changing would be reduced but there would be extra structural costs as well as potential operating problems (as with the layout in Figure 2.12). Drivers would have to become familiar with the new signing, layout and road markings for it to be considered a feasible option. This is particularly true of faster vehicles using the outside lane to leave the mainline as there would be an abrupt design speed change from the mainline to a slip road with a low radius. This left/right diverge layout is shown in Figure 2.14 (Stanton 1992).

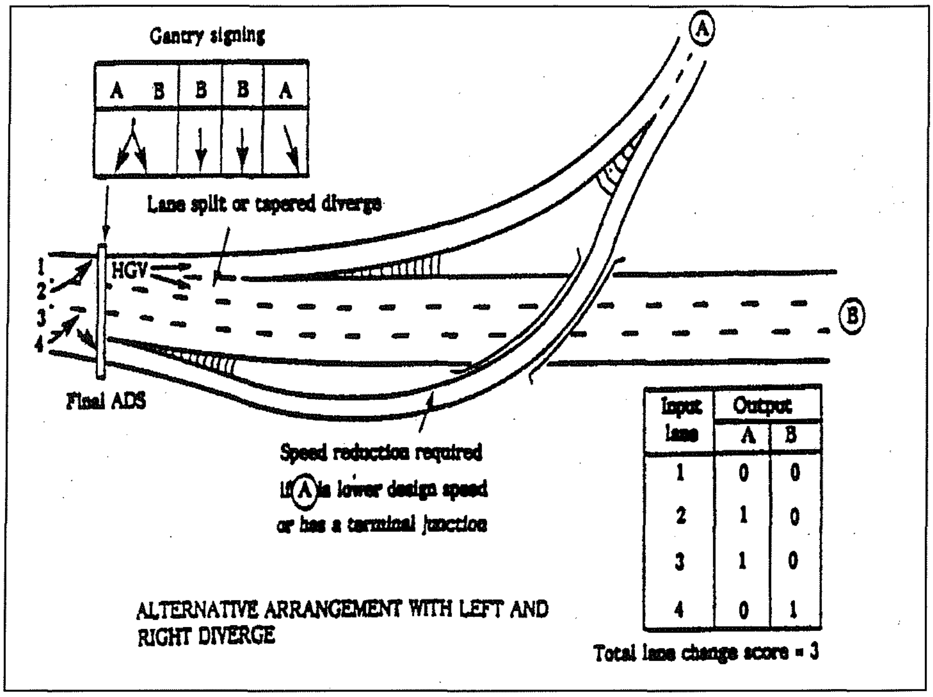


Figure 2.14: Left/right diverge layout

2.6 Comparison of diverge geometric parameters

2.6.1 Comparison between different UK Standards

A comparison was made of the geometric parameters for diverges recommended in H18/75, TD22/86 and TD22/92. Table 2.5 compares the principle diverge layout parameters for the Standards H18/75, TD22/86 and TD22/92.

Table 2.5: Comparison of diverge layout parameters for three UK Standards

	H18/75	TD22/86	TD22/92
Length of taper (Taper single/double link) (m)	185	-	170 (1 lane) 185 (2 lanes)
Length of taper (Parallel single/double link) (m)	90 (1 lane) 185 (2 lanes)	-	75 (1 lane) 150 (2 lanes)
Length of taper (Taper lane drop) (m)	185	-	170
Length of taper (Parallel lane drop) (m)	90	-	75
Length of auxiliary lane (m)	200 (min)	200 (min)	200 (min) up to 600m if necessary
Length of Nose (m)	80 100 (lane drop)	80	80
Taper for Nose	1:15 min	1:15 min	1:15 min
Taper angle of diverging lane (Taper double link)	1:25	1:25	-
Taper angle of diverging lane (Parallel double link)	1:25	1:20	-
Taper angle of diverging lane (Taper lane drop)	1:50	1:45	-
Taper angle of diverging lane (Parallel lane drop)	1:25	1:20	-
Maximum total exit width (m)	9	9	9.6
Minimum loop radii (m)	-	75	75

- A blank entry denotes that no figure for that geometric parameter was provided in that particular Standard. It is assumed that the figure from the previous Standard would still be used in the updated Standard.

These geometric parameters have showed a slight 'tightening' of values over time. The general tendency has been towards more compact designs with less generous values. Changes made have tended to be relatively minor and probably came about as a result of increased traffic flows, improved vehicle performance or changes in driver behaviour.

2.6.2 Comparison between different UK diverging flow-region diagrams

The diverging flow-region diagram has been changed from the one contained within Standard H18/75 to the one in Standard TD22/92. TD22/86 contains exactly the same diagram as H18/75 except that a motorway scale has been added, assigning higher maximum hourly flow values to lanes on motorways as opposed to lanes on all-purpose roads. These maximum hourly flow values have been increased from those in H18/75 to those in TD22/86 and TD22/92. H18/75 and TD22/86 recommend layout configurations (i.e. number of upstream lanes, number of slip lanes and the number of downstream lanes) whereas TD22/92 recommend diverge types (e.g. Taper). These differences in the diverging flow-region diagram are shown in Table 2.6 below.

Table 2.6: Parameters from the diverging flow-region diagrams

	H18/75	TD22/86	TD22/92
Number of diverge layouts	9 configurations	9 configurations	5 types
Maximum number of lanes on main carriageway	3 lanes	3 lanes	5 lanes
Maximum hourly flow on single link road (veh/hr)	1200	1350	1350
Maximum hourly flow for a two lane link (veh/hr)	3200	3600	3600
Maximum hourly flow for a mainline lane (veh/hr)	1600	1800	1800

In order to do an accurate comparison of the diverging flow-region diagrams in H18/75 and TD22/92, alterations have been made so that the regions in both diagrams refer to diverge layout configurations. In addition, the diagram in TD22/92 has been restricted to three downstream lanes, the same number as in H18/75. Figures 2.15 and 2.16 show the altered diagrams. In the H18/75 diagram, it has been assumed that for each region of the diagram, the cheapest option would generally be installed (i.e. the one with fewest upstream, slip and downstream lanes). For example, all nine configurations are possible for installation in region P (see Figure 2.6) but the cheapest option would be two upstream lanes, one slip lane and two downstream lanes (2-1-2).

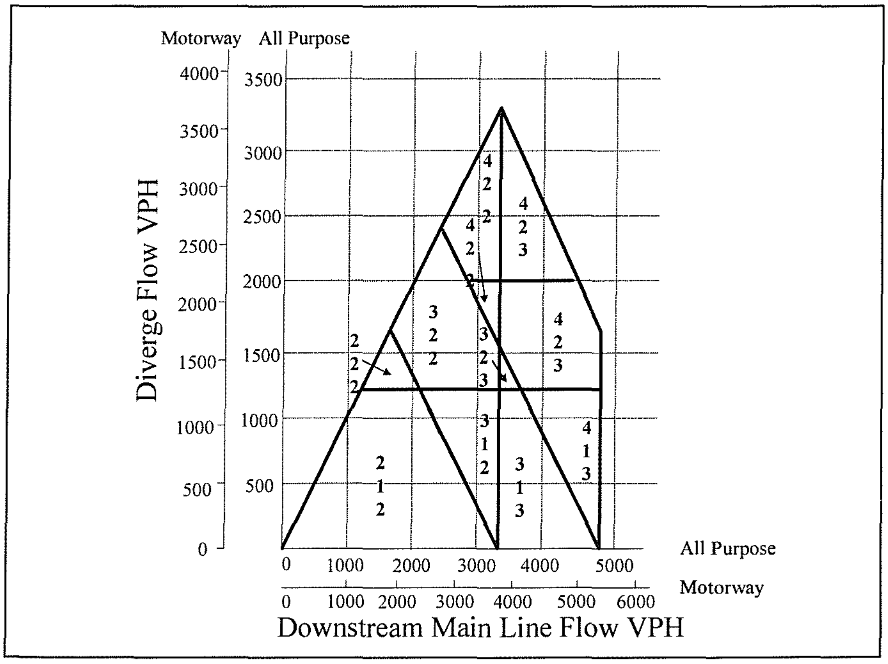


Figure 2.15: Altered diverging flow-region diagram from H18/75

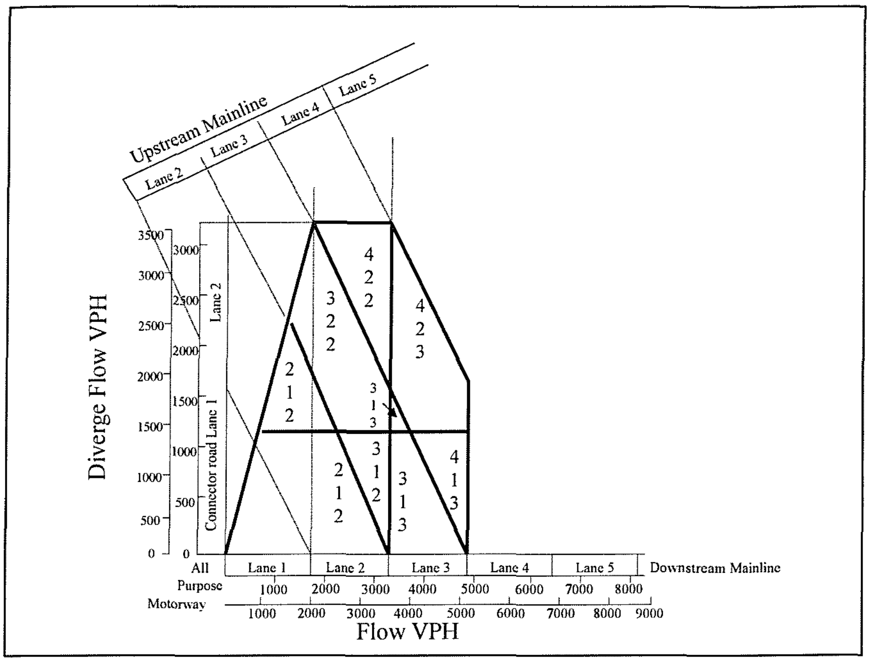


Figure 2.16: Altered diverging flow-region diagram from TD22/92

The two flow-region diagrams are very similar to each other. The recommended configuration in each region of the diagram corresponds almost exactly (see Figures 2.9 and 2.10). There are, however, a few differences which include:

- In H18/75, one of the limits was that the diverging flow must be less than the downstream flow (i.e. a diverging percentage less than 50%). In TD22/92, twice the diverging flow must be less than the downstream mainline flow (i.e. the diverging percentage must be less than 67%). It is probable that this limit changed due to an increasing number of diverges which had high diverging percentages (i.e. greater then 50%), particularly motorway-to-motorway interchanges. Ghost Island drop layouts now allow exiting drivers to move into the slip road directly from lane 1 or lane 2, thus catering for a higher diverging percentage.

- In H18/75, the layout configuration is what is important (e.g 2-1-2), whereas with TD22/92 it is the layout type (Taper or Parallel).

- In H18/75, a mainline lane has a maximum design flow of 1600 veh/hr whereas in TD22/92, it is 1800 veh/hr, Also, a single link has a capacity of 1200 veh/hr in

H18/75 which has increased to 1350 veh/hr in TD22/92. It is unclear whether empirical evidence was used to increase these design flow values. It is thought these figures were updated due to changes in traffic flows, speeds and behaviour over time.

Again, the differences are minor and reflect the evolving nature of the standards as traffic flows, vehicle performance and driver behaviour change over time.

2.6.3 Comparison between different selected European countries' Standards

A recent study for the European Union compared the road design features of motorway diverges in selected EU countries (Steinbrecher 1994). There were a lot of common design principles between countries but differences were also found. Table 2.7 shows some of the diverge parameters for selected EU countries.

Table 2.7: Diverge parameters for selected EU countries

Country	Diverge type (Taper/Parallel)	Length of auxiliary lane (m)	Length of taper (m)
Germany	Parallel	190	60
France	Parallel[(1)] Taper	>1000	250 150
UK	Parallel[(1)] Taper	200 (min)	75 150
Netherlands	Parallel	150	100
Portugal	Parallel[(1)] Taper	>400	75 110
Belgium	Parallel	80	120
Ireland[(2)]	Parallel	145	75
Denmark	Taper	-	100
Spain	Parallel	220	(incl.)

[(1)] In the case of a two-lane exit slip road.

[(2)] The design standard used in Ireland was RT165 Geometric design guidelines – motorway interchanges (Environmental Research Unit 1982) but since January 2001 has been superseded by an amended version of the UK standard TD22/92. This has been done by the use of an Addendum (National Roads Authority 2000) in order that the Standard suits Irish conditions and practice.

The geometric values for the UK in Table 2.7 are generally within the range of values for the other selected EU countries. In the UK and France, auxiliary lanes are only recommended for two lane exit slip roads. The length of the auxiliary lane for all the EU countries is generally above 145m with the exception of Belgium whose standard is 80m. Denmark is the only country without Parallel diverges and therefore auxiliary lanes. However, the Danish guidelines do provide for a sufficient length for drivers to de-accelerate in before reaching the minimum curve radius.

Safety is a major consideration in the production of geometric standards; little reliable evidence has been found in the literature of a link between design standards and safety for motorway diverges. It is not altogether surprising therefore that variations in standards exist between the various EU countries.

2.7 Design standards in other Countries

2.7.1 USA

Design standards for motorways in the UK and elsewhere have been greatly influenced by research in the USA. A number of roads of motorway type, with grade-separation and interchanges, were been built in the USA in the 1930's. These early motorways became an excellent resource for observation and research purposes. Two important publications followed in the 1960's that were the basis for future American Association of State Highway Officials (AASHO) design policies. These were "The Highway Capacity Manual" (Highway Research Board 1965) and "A Policy on Geometric Design of Rural Highways" (American Association of State Highway Officials 1965).

The Highway Capacity Manual replaced the original Manual published in 1950. Its purpose was to provide empirical and theoretical information on highway capacity, which would aid traffic engineers in the assessment of existing facilities. It has been used as a basis for highway capacity research around the world including Finland, Hungry, India, Israel, Japan, Poland, South Africa, China, Denmark, Germany and Norway (ARRB 1994; Road Directorate 1998).

Ramps (slip roads) are primarily recommended to be used with freeways (motorways). Various geometric layouts are also discussed for both on-ramps (merging traffic) and off-ramps (diverging traffic). A successful diverge will be able to:

- Prevent long queues forming in lane 1 upstream of the diverge
- Provide an efficient design for the diverging area
- Provide sufficient capacity at the end of the slip road to avoid exit blocking

An important term in the Highway Capacity Manual is "level of service" which is defined to be "a qualitative measure of the effect of a number of different factors, which include speed and travel time, traffic interruptions, freedom to manoeuvre, safety, driving comfort and convenience and operating costs". It is used to assess the operating conditions of a particular stretch of road. There are six levels of service from 'A' (free flow) to 'F' (forced flow). Table 2.8 shows the six levels of service with their respective load factor (or saturation factor).

Table 2.8: Levels of service

Level of service	Traffic flow description	Load factor
A	Free flow	0.0
B	Stable flow	≤ 0.1
C	Stable flow	≤ 0.3
D	Approaching unstable flow	≤ 0.7
E	Unstable flow	≤1.00
F	Forced flow	N/A

These flows are then compared with the limiting flows for a given level of service to check their acceptability. For the diverge to operate at a particular level of service, the upstream, downstream and diverging flows must be within their respective limits.

The latest Highway Capacity Manual (Transportation Research Board 2000) defines the level of service for a particular stretch of road using three performance measures; density (passenger cars per km per lane), speed (mean passenger car speed) and volume to capacity ratio. These parameters indicate how well the traffic flow is being accommodated by a particular stretch of road.

2.7.2 Australia

Highway capacity was first mentioned in the 1930's in Australian literature. By the 1950's, a wide variety of research was being undertaken into capacity related areas in Australia. Much transport research has been encouraged by co-operation between the National Association of Australian State Road Authorities (NAARSA that later became Austroads in 1989) and the Australian Road Research Board (ARRB). Over the years, Australia has drawn heavily from the USA's Highway Capacity Manual, with most requirements taken directly from them (including those for motorway diverges). Research in Australia has tended to concentrate on areas where the USA standards are unsuitable for Australian conditions.

New standards for motorways (freeways in Australia) were published in 1972 (National Association of Australian State Road Authorities 1972). As with present UK standards, it made a distinction between inner urban and suburban motorways. It also contained desirable, intermediate, restricted and minimum standards for the various geometric parameters. These were often determined by the topography of the area, allowing more flexibility where the terrain was hilly. Taper and Parallel diverges were both recommended. However, Parallel diverges (with auxiliary lanes) were thought to provide a safer, controlled diverge area with drivers having to make a definite lane change to enter the auxiliary lane.

The current standards published in 1984 (National Association of Australian State Road Authorities 1984) are due to be updated again soon. It was published to assist traffic engineer's to plan and design grade-separated interchanges in both urban and rural areas. Rigid design parameters are not imposed due to the wide variety of locations where interchanges are required. Typical examples of single and two-lane exit ramps are illustrated with similar geometry to the 1972 publication.

2.7.3 Canada

Research in Canada into highway capacity and levels of service on motorways has been ongoing since the 1970's. Research from the USA influenced standards in Canada but since the 1970's, Canadian research has provided input into the 1985 and 1994 Highway Capacity Manual's. Geometric design standards for roads were first considered by a committee in 1958, leading to the first 'Manual of Geometric Design Standards for Canadian Roads', published in 1963. It provided planning and design standards for road authorities across Canada. Various revisions have been made over the years, with the previous Standard been published in 1986 (Roads and Transportation Association of Canada 1986). This publication contains a whole chapter on interchange design, including the concepts of lane balance and a basic number of lanes (similarly expressed in the USA and UK standards).

The 1986 Standard has been revised and replaced by a new design Standard published in 1999 (Transportation Association of Canada 1999), although the advise given regarding exit ramps is virtually unchanged. When an interchange design is proposed, a number of factors are assessed to determine whether to install a Taper or Parallel design. These include traffic flows, safety issues, topography, highway classification and the economic cost. The length of the auxiliary lane depends on the distance required for de-acceleration after the vehicle has left the mainline. This is dependent on the design speed of the highway and the control speed of the ramp.

The key to Canadian design is maintaining uniformity by selecting consistent types of design features along a route or within a regional area. This will then help to improve driver understanding, behaviour and safety.

2.7.4 Sweden

The USA Highway Capacity Manual has been very influential on Swedish design standards. However, the capacity analysis in the USA publication was eventually considered to be inconsistent with observed traffic behaviour in Sweden. This led to the Swedish Road Administration completing a research and development project in the 1970's that led to the publication of the first Swedish Highway Capacity Manual in 1978 (Peterson et al 1978; McLean 1983; Hansson and Bergh 1988). It consistently predicted higher road capacities than the USA publication.

Swedish motorway diverges are mainly of the Taper design due to the first generation of Swedish standards (influenced by German designs) from the mid 1970's. The present Standard, Road Design 94 (Swedish National Road Administration 1994), introduced Parallel diverges and recommended their use when there are high traffic flows and when the exit is hidden from view (e.g. by a bridge or a bend in the road). Lane drops are used particularly when it is costly to maintain a high number of lanes along a whole route (the new E4 motorway through Stockholm has now 6 mainline lanes).

2.8 Critical review of the UK diverging flow-region diagram

2.8.1 Introduction

This section provides a critical review of the UK diverging flow-region diagram, given an understanding of its derivation and the review of other practices in other similar countries. The review has included the following:

- Checking that the diverging (and merging) flow-region diagrams are logical.
- Recommending improvements to the diagram itself which includes comments from five practicing traffic engineers.

This review, therefore, focuses on the detail of the diagram rather than whether the concept of the diagram is appropriate.

2.8.2 Checking the logic of the flow-region diagrams

The recommended layouts, for various downstream (upstream) mainline and diverging (merging) flows within the diverging (merging) flow-region diagram, were checked to see if they progress in a logical way. This was shown to be the case by:

1. Increasing the downstream (upstream) mainline flow with a constant diverging (merging) flow - the configuration for the diverge changes by adding an extra upstream lane and then adding an extra downstream lane. This process is repeated as the downstream mainline flow is increased (e.g. 2-1-2 to 3-1-2 to 3-1-3 to 4-1-3). This seems logical because as the downstream mainline flow increases (with the diverging flow constant), more capacity is needed both upstream and downstream of the diverge. The Taper diverge is only recommended when the diverging flow does not exceed the capacity of one slip lane. Table 2.9 shows how the configurations and layout types change for the diverging flow-region diagram.

Table 2.9: Diverging layouts and configurations with an increasing mainline flow

Configuration Layout type Reference letter	2-1-2 Taper A	3-1-2 Taper LD C	3-1-3 Taper A	4-1-3 Taper LD C
Configuration Layout type Reference letter	2-2-2 Parallel B	3-2-2 Parallel LD D	3-2-3 Parallel B	4-2-3 Parallel LD D
Configuration Layout type Reference letter	3-3-2 Parallel LD D	4-2-2 Parallel DLD E	4-2-3 Parallel LD D	5-2-3 Parallel DLD E

A similar process was carried out for the merging flow-region diagram (see Figure 2.3), increasing the upstream mainline flow and keeping the merging flow constant. Again, the configuration changes by adding an extra upstream lane and then adding an extra downstream lane. The Taper merge is also only recommended when the merging flow does not exceed the capacity of one slip lane. Table 2.10 shows how the configurations and layout types change for the merging flow-region diagram.

Table 2.10: Merging layouts and configurations with an increasing mainline flow

Configuration Layout type Reference letter	2-1-2 Taper A	3-1-2 Taper LG D	3-1-3 Taper A	4-1-3 Taper LG D
Configuration Layout type Reference letter	2-1-2 Taper A	2-1-2 Parallel B	3-1-2 Taper LG D	3-1-3 Taper A
Configuration Layout type Reference letter	2-1-2 Parallel B	3-1-2 Taper LG D	3-1-3 Parallel B	4-1-3 Taper LG D
Configuration Layout type Reference letter	2-1-2 Parallel B	3-2-2 Ghost Island LG E	3-2-3 Parallel B	4-2-3 Ghost Island LG E
Configuration Layout type Reference letter	3-3-2 Ghost Island LG E	4-2-2 Ghost Island DLG F	4-2-3 Parallel LG E	5-2-3 Ghost Island DLG F

2. Increasing the diverging (merging) flow with a constant downstream (upstream) mainline flow - the diverge configuration changes by adding an extra upstream mainline lane and then adding an extra exit slip lane. Again this process is repeated as the diverging flow increases (e.g. 2-1-2 to 3-1-2 to 3-2-2 to 4-2-2). This seems logical because as the diverging flow increases (with the downstream mainline flow constant), more capacity is needed both upstream of the diverge and on the exit slip road. As the diverging flow increases, the layout recommended in the diagram provides more and more capacity for exiting drivers. As the diverging flow exceeds the capacity of one slip lane, it is recommended that a Taper layout is replaced by a Parallel layout which provides more capacity at the exit. As the diverging flow increases further, a Parallel lane drop is recommended with the possibility of increasing the length of the auxiliary lane if necessary. For very high diverging flows, a Parallel double lane drop can be installed. Table 2.11 shows how the configurations and layout types change for the diverging flow-region diagram.

Table 2.11: Diverging layouts and configurations with an increasing diverging flow

Configuration Layout type Reference letter	2-1-2 Taper A	3-1-2 Taper LD C	3-2-2 Parallel LD D	4-2-2 Parallel DLD E
Configuration Layout type Reference letter	2-1-2 Taper A	2-2-2 Parallel B	3-2-2 Parallel LD D	4-2-2 Parallel DLD E
Configuration Layout type Reference letter	3-1-3 Taper A	4-1-3 Taper LD C	4-2-3 Parallel LD D	5-2-3 Parallel DLD E

With an increasing merging flow with the upstream mainline flow constant, more capacity for merging vehicles is provided by progressing from a Taper merge to a Parallel merge. For higher merging flows, a lane gain (or double lane gain) is recommended as part of a Ghost Island style layout. This is equivalent to the Parallel layout in the diverging flow-region diagram. Table 2.12 shows how the configurations and layout types change for the merging flow-region diagram.

Table 2.12: Merging layouts and configurations with an increasing diverging flow

Configuration Layout type Reference letter	2-1-2 Taper or Parallel A or B	3-1-2 Taper LG D	3-2-2 Ghost Island LG E	4-2-2 Ghost Island DLG F
Configuration Layout type Reference letter	3-1-3 Taper or Parallel A or B	4-1-3 Taper LG D	4-2-3 Ghost Island LG E	5-2-3 Ghost Island DLG F

The diverging and merging flow-region diagrams were constructed in a similar way (as explained in section 2.4.2) with the diverging diagram evolving from the merging one. The two diagrams are therefore similar in many ways and have shown to be logical in their progression from one layout/configuration to another with increasing mainline or diverging/merging flows. The Ghost Island merge (no lane gain, lane gain and double lane gain) is a recommended layout in TD22/92. There is a Parallel merge but the Ghost Island lane gain and double lane gain is recommended instead of similar Parallel layouts. At present, the latest Standard does not include any Ghost Island diverge layout (see Chapter 3). These layouts, however, could replace the Parallel diverges in a similar way as in the merging diagram.

2.8.3 Possible improvements to the diverging flow-region diagram

The views of five traffic engineers who use the diagram on a regular basis were sought in order to investigate its strengths and weaknesses, and how it could be improved. The engineers were Stephen Pollock (Road Services, Northern Ireland), Martin Price (Mott Macdonald), Mike Slinn (MVA), John Border (Arup) and Bob Marlow (WS Atkins). The diagram was now being used almost exclusively as a design tool for an evaluation of existing motorway diverges, rather than for newly proposed diverges. Layout problems at existing diverges often only become apparent with a combination of very high traffic flows and poor driver behaviour.

The following comments about the diverging diagram divide into two sections; firstly improvements that could be carried out easily and quickly and secondly improvements that may require further research.

Improvements that could be carried out easily and quickly are mainly presentational and include making sure that:

- The diagram is properly labelled and referenced with a more accurate axes.
- The diagram shows more clearly the diverging flow ranges which apply to an extended auxiliary lane.
- There is an accompanying diagram depicting how type ‘E’ layouts (Parallel double lane drop) should be configured.
- The diagram could be produced in the form of a computer program, helping the user to plot points more accurately.

Improvements that may require further research include:

- **Adopting a more realistic design flow value**

Many traffic engineers use a design flow of 2000 veh/hr per lane for a motorway rather than the lower figure of 1800 veh/hr in TD22/92. The scale on the diagram could easily be modified to adopt a more realistic design flow based on current working flows.

- **Providing additional advice in border line decisions**

When plotting data points on the diagram, it is quite common to find that some will appear on the border of two or three different regions of the diagram. This is a particular problem when the data point is within a region designated for a type 'B' diverge (Parallel diverge) as these regions are clearly smaller than the error margin of the data commonly used. Traffic data recommending region 'B' may lead to the traffic engineer having to consider the six adjacent regions in the diagram to check if they could provide more suitable layouts. Given the changing nature of traffic flows over time, a layout in a particular region needs to be easily adaptable in order to convert it into the layout recommended for the adjacent region(s) in the diagram.

Converting some layout types to another layout type may not be possible if the acquiring of land is needed due to the problems of cost, availability of land (if part of the hard shoulder is not to be used) and environmental concerns (e.g. converting a Taper into a Parallel). More advice within the Standard could help engineers choose the most suitable layout to adopt in more borderline situations.

- **Providing additional advice where the recommended layout is impractical**

At some sites, the recommended number of upstream, downstream and exit lanes may be impractical due to restrictions on land take, environmental considerations or economic reasons. It would be useful if the Standard provided additional advice concerning the best layout possible given certain practical limitations at the site.

As the diagram is mainly used to re-assess existing diverge layouts, it can be difficult to know how to plot points where the provision does not match the demand. For example, there may be a diverge with a predicted downstream mainline flow of 2500 veh/hr on an existing 3-lane motorway, or where 3 lanes needs to be provided for other reasons.

- **Providing additional advice about the use of lane drops**

Layout types ‘C’, ‘D’ and ‘E’ involve dropping a lane(s) at the diverge, with the lane(s) normally gained again at the merge. Lane drops are only usually provided when there is a high diverging proportion or when there is a high merging proportion requiring a lane gain upstream of the diverge. There may also be policy, layout or economic reasons for their use. Additional advice in the Standard concerning the use of lane drop type diverges would help engineers decide if their use is appropriate for a particular exit. The incorrect use of a lane drop type diverge could cause problems both for mainline and diverging traffic.

- **Extending the diagram so it can cater for mainlines of more than 5 lanes**

With the proposed widening of the M25 and other motorways, the diagram may need to be extended to cater for a mainline of more than 5 lanes. The diagram (as derived in section 2.4.3) can be easily extended to cater for more lanes. However, diverging can become very problematic with mainlines of 6 or more lanes due to the increase of the number of lane changes necessary and the subsequent “turbulence” which it creates. Alternative diverge layouts may need to be considered which can cope more adequately with these situations.

- **Modifying the diagram to include the new “tiger-tail” Ghost Island diverge**

Since the production of the diagram, a lot of research work has been carried out at the TRL into the effectiveness of the new “tiger-tail” Ghost Island diverge layout (with and without a lane drop) (see Chapter 3). They have been shown to be successful at three UK motorway diverges in reducing the number of potentially dangerous last minute lane changes, as well as regulating the traffic flow into two orderly streams of traffic (Wedlock et al 2001). They are particularly recommended where there is a high diverging proportion (i.e. above 40%), poor lane discipline, a high number of potentially dangerous last minute lane changes and a need to increase the capacity of the exit (Highways Agency 1998). The diagram could be redrawn to provide regions where the Ghost Island diverge (with or without a lane drop) would be the recommended diverge type.

- **Providing advice regarding the length of the auxiliary lane**

TD22/92 states that the auxiliary lane in the Parallel layout should be a minimum of 200m and up to 600m if necessary. More exact advice is given to traffic engineers in the USA as to what the desired deceleration length should be based on the design speed and average running speed of the motorway as well as the design speed and average running speed of the exit curve (Koepke 1993). Further advice such as this would aid traffic engineers in the UK select the most suitable auxiliary lane length for a particular junction.

- **Checking the assumed capacity of the auxiliary lane**

The Taper diverge (layout A) is used only where the diverging flow is less than or equal to 1350 veh/hr on motorways. The parallel diverge (layout B) uses an auxiliary lane as an addition to the Taper diverge and is used where the diverging flow is between 1350 veh/hr and 1800 veh/hr on motorways. This suggests that the auxiliary lane can cater for an additional 450 veh/hr independent of its length (which is normally a minimum of 200m). There may need to be more research carried out to calculate the extra capacity the auxiliary lane provides (with different lengths of auxiliary lane) as well as its affect on queuing traffic from the exit.

- **Checking the relationship between the diverging and downstream mainline flow**

In H18/75, one of the limits requires that the diverging flow is always less than the downstream mainline traffic flow (i.e. a diverging percentage less than 50%). However, in TD22/92, this limit requires that twice the diverging flow is always less than the downstream flow (i.e. a diverging percentage less than 67%). There is, therefore, an inconsistency between H18/75 and TD22/92. The question is whether this new limit is valid and what happens in situations where this is not the case. This limit has probably been amended to cater for the increasing number of junctions (particularly motorway-to-motorway interchanges) with high diverging flows above 50%.

2.8.4 Discussion regarding the diverging flow-region diagram

The diverging flow-region diagram has been shown to be a useful tool for providing a preliminary indication of which diverge layout is most suitable for a given set of downstream mainline and diverging flows. These flows are also corrected for gradients and HGV percentage within the traffic composition (see Chapter 6 for a more detailed assessment of both gradient and HGV percentage). However, according to the diagram, these are the only factors which affect the capacity of the diverge and the subsequent choice of layout.

In using the diagram, traffic engineers can only select the layout and not alter any of the geometric parameters associated with that layout (with the exception of the auxiliary lane which must be at least 200m in length). In practice, these geometric parameters (such as taper length, angle of slip road to mainline and length of auxiliary lane) may well affect the capacity of the diverge. This differs from the design of other junctions such as traffic-signalled junctions or roundabouts where the geometric parameters are typically adjusted in order to obtain a RFC (Ratio of Flow to Capacity) value of no higher than 0.85. There is the advantage of having a consistent design for diverges across a motorway or dual-carriageway network but this can reduce the flexibility of the traffic engineer to try and cope with varying traffic levels. A more detailed study could establish whether these parameters do affect capacity and if so establish relationships which could be incorporated into a microscopic traffic motorway model.

Driving behaviour is also considered to have an affect on capacity. Diverge layouts which experience frequent lane changes in the exiting vicinity can operate less efficiently and therefore below expected capacity. This, again, is not catered for in the flow-region diagram although the type of layout may give some indication of the expected lane changes necessary for exiting vehicles. Again, a detailed study looking at how the relationship between layout type, lane changes and capacity would provide useful information in the design stage of a diverge.

2.9 Summary

In order to evaluate the existing diverge layouts recommended in the latest standard, a historical review has been carried out concerning the evolving nature of standards for diverges in the UK and other countries, along with a critical review of the diverging flow-region diagram which is used by engineers to select the most appropriate diverge layout.

Ever since the first motorway was opened to the public in the UK in 1958, the standards for their construction have evolved over the years. Standards are technical specifications issued by Government in order to provide requirements for the design of new roads. There is often some flexibility within the standards, particularly if the economic or environmental cost can not be justified.

Interchanges (or major diverge layouts) have also been examined. This includes those already recommended in the UK as well as alternative layouts that are used already at certain sites or that are proposed as possible designs for the future. This includes the major fork diverge where there are two equally important destinations with a diverging percentage of over 40%, and the left/right diverge layout which proposes a slip lane to the left and the right of mainlines of at least four lanes.

The standards for motorway diverges in the UK have been updated at regular intervals and the main publications have been assessed. Most changes have been minor as a results of changes to traffic flow, driver behaviour or vehicle performance. The main standards for motorway diverges have been reviewed along with a derivation of the diverging flow-region diagram contained in the latest Standard TD22/92. A comparison has been made to see how the geometric parameters recommended for diverges have changed over the years and how they compare with other EU countries.

Research carried out in the USA led to "The Highway Capacity Manual" and "A Policy on Geometric Design of Highways and Streets", which formed the basis for the USA standards. These publications have greatly influenced standards in the UK and many other countries world-wide. In addition, research work leading to the development of standards for motorway diverges for Australia, Canada and Sweden have also been examined.

A critical review has been carried out of the diverging flow-region diagram. The following four conclusions were reached.

- The diverging (and merging) flow-region diagram provides traffic engineers with a useful design tool for a preliminary indication of the most suitable layout. Common sense as well as the experience of the traffic engineer is also essential in the decision process, particularly in borderline situations.
- The recommended layouts, for various downstream mainline and diverging flows within the diagram, seemed to progress in a logical way.
- Improvements could be made to the diagram immediately to make it a more effective tool for traffic engineers (e.g. producing the diagram in the form of a computer program). More research could bring about further improvements to the diagram (e.g adapting the diagram to include the "tiger-tail" Ghost Island diverge).
- Some of the assumptions made in the construction of the diagram could be explained and justified in more detail within the Standard.

CHAPTER 3

DRIVING BEHAVIOUR AT DIVERGES

3.1 Introduction

The latest Standard TD22/92 contains five recommended diverge layouts which are selected from a traffic flow perspective using the diverging flow-region diagram. There are also operational, behavioural and safety issues that also need to be considered when designing diverges. These, at present, are not currently covered in TD22/92.

This chapter, therefore, contains a literature review of research into driving behaviour at motorway diverges and how the layout or type of diverge can affect such behaviour. The review includes an assessment of the new Ghost Island diverge layout which is an alternative layout to the types recommended in the latest Standard TD22/92. Section 3.2 looks at three studies in the UK, USA and Sweden respectively which have looked at different aspects of driving behaviour at diverges. Section 3.3 contains a review of the research undertaken by TRL for the Highways Agency, between 1995 and 2000.

The TRL research investigated low cost measures to reduce a potentially hazardous form of driver behaviour known as 'swooping' at motorway diverges. Swooping has been defined to be vehicles moving directly from lanes 2 or 3 of the mainline to exit at a diverge, typically within 500m of the diverge point. Two cost effective methods were used to combat swooping. These were:

- New lane separation markings.
- New 'Ghost Island' diverge layouts.

Swooping was thought to occur at diverges which had high turning flows or where queuing on the slip road was common during the peak periods. Work within the TRL study included:

- Design of new markings including simulator and test track trials.
- Design of appropriate signing for the schemes.

Within the TRL study, six diverges have had anti-swooping measures installed and monitored. Lane separation markings were installed at three sites; the Dartford Tunnel (no 'before' study was carried out), the M27 J3 and the M6 J6. The new Ghost Island diverge layout was installed at three sites: the M20/M26, the M6 J4a and the M27/M3.

3.2 Previous research on driving behaviour at diverges

A literature review was carried out to investigate previous research into driving behaviour at motorway diverges other than the TRL work. It was discovered that a lot of work had been carried out at merges, with the diverge being included as part of a more general study of the merge area. However, many of the studies highlighted problems which a better design may of helped to overcome such as last minute lane changes (including swooping) and an unequal lane distribution on the mainline and slip road.

3.2.1 Driving behaviour at grade-separated junctions

A video study was carried out at 30 grade-separated junctions in England in order to provide a behavioural and analytical database (Stanton 1992). Stanton highlighted a number of different types of driving behaviour that were common in the diverge area from the video study. These included lane 1 dominance prior to exit, late entry to lane 1 for exiting vehicles and mainline vehicles changing from lane 1 to lane 2 particularly when there is a lane drop.

The study also suggested alternative diverge layouts that could help to control the traffic movements and so reduce the number of lane changes (see section 2.5.4).

3.2.2 Driving behaviour at exit gore areas

A study was carried out looking into the erratic behaviour of drivers at exit gore (or nose) areas (Taylor and McGee 1972 and 1973). This behaviour included stopping, reversing, slowing up suddenly and last minute double lane changes in the gore area. Results showed that factors leading to such behaviour were due to one or more of the following:

- Driver related (breakdown in his/her decision making process)
- Poor geometric layout
- Poor signing and or road markings.

A subsequent study in Israel investigated the installation of soft plastic bollards at exit gore areas in order to help to reduce erratic vehicle manoeuvres at the diverge and regulate the traffic streams more effectively (Hakkert and Gitelman 1998). It was thought that the installation of the bollards could have reduced the number of accidents by 11% at exit gore areas. Trials showed that the installation of these bollards reduced erratic manoeuvres by 60% in the daytime and 65% at night resulting in the recommendation that they should be installed at all exit gore areas.

3.2.3 Driving behaviour at Taper and Parallel diverges

A study in Sweden looked at the advantages and disadvantages of Taper (called a Wedge in Sweden) and Parallel diverge layouts in relation to traffic flows and road safety issues (Ringhagen 1976). The study monitored the accident rates at four Parallel and six Taper diverges. Results showed that drivers tended to adjust their diverging behaviour to the exit design. This was seen at the Parallel sites with the auxiliary lanes being used by the vast majority of drivers. However, at one of the Taper diverges, a relatively large proportion of drivers used part of the hard shoulder to leave the motorway as the exit had a short exit entrance located on a right hand bend.

The accident rate at the diverge was far higher on the exit slip road than on other parts of the diverge area. The most frequent accidents were single vehicle ones where a vehicle left the road. The exit slip road is an area where possible safety improvements could be made. There was, however, no statistically significant difference in the accident rates for Taper as opposed to Parallel diverges. It was thought that the introduction of an auxiliary lane at certain Taper diverges (converting them to a Parallel diverge), would improve the safety and accessibility of the exit for drivers.

3.3 The TRL anti-swooping trials

This section summarises the anti-swooping studies that have been carried out by TRL for the Highways Agency between 1995 and 2000 (Wedlock, Peirce and Wall 2001) to investigate measures to reduce this potentially hazardous form of driver behaviour known as 'swooping' at motorway diverges. The work is divided into two sections: lane separation marking and Ghost Island diverges.

3.3.1 Anti-swooping lane separation markings

Mr. Robert Key MP, whilst Minister for Roads, requested that measures to control and reduce swooping should be investigated. In response to this, the Highways Agency commissioned TRL to investigate possible measures to discourage the practice of swooping.

It was thought that the introduction of a new carriageway marking between lanes 1 and 2 in the vicinity of the diverge area would reduce the occurrence of swooping. It was hoped that this would be a relatively simple and cost effective solution to this problem.

Three types of carriageway marking were trialled. These were:

- Double white line marking at the Dartford Tunnel (Harrison 1996)

- Solid white line at the M27 J3 westbound (Wall 1996a)
- Diamond markings at the M6 J6 (Wedlock 2000)

The double white line marking (dashed on the nearside and continuous on the offside) installed at the Dartford Tunnel did not prevent the occurrence of swooping. As no 'before' survey was carried out, an evaluation of the effectiveness of the marking was not possible. As there was no associated signing explaining the meaning of the marking, drivers may have been unclear about their expected behaviour in its vicinity. The solid white line that was installed on the M27 J3 was also found to be unsuccessful in reducing the occurrence of swooping. This may have been due to the fact that it was installed as a stand-alone measure, with no associated signing to inform drivers of its meaning and their subsequent expected behaviour. There was also a problem at this site with the capacity of the slip road, leading to queues of slow moving traffic in slip lane 1/lane 1.

In contrast, the diamond markings installed on the M6 J6 were found to be successful in reducing the occurrence of swooping. The reduction in the number of swoopers of 58% was associated with an increase in the throughput of the mainline by 12%. It is not clear whether there was a direct link between swooping and throughput but swooping at this site was known to have caused a capacity bottleneck where the two slip lanes merged into one lane. It was thought that the publicity campaign on TV and radio, along with the presence of signing informing drivers of the new markings, helped to reduce the level of swooping at the site. These diamond markings have been used as an anti-swooping measure in a subsequent study at the A40/A406 diverge, near the Hanger Lane gyratory (URS 2002). Their presence had some limited effect in moving swoopers further upstream and reducing their overall numbers.

3.3.2 'Tiger-tail' Ghost Island diverge layouts

3.3.2.1 Background

High proportions of swooping manoeuvres carried out by diverging traffic may indicate that the diverge layout is not operating optimally. Factors effecting the number of swooping manoeuvres at a diverge include the diverging proportion and the capacity of the slip road.

Following the success of the Ghost Island merge layout at improving merging performance at a number of locations on the motorway network, it was decided to trial the installation of a Ghost Island diverge at locations where specific problems had been identified. It is of worth noting that the operation and mechanism of the Ghost Island merge differs in some respects to that of the Ghost Island diverge layout. With the merge, both entry lanes are equally useable in joining the mainline whereas with some Ghost Island diverges, drivers need to use the appropriate slip lane in order to be correctly positioned to go to a particular destination at a subsequent diverge on the slip road. With the Ghost Island merge, drivers may choose to use the second slip lane also in order to avoid slower moving traffic in slip lane 1. Using slip lane 2 can enable drivers to join the mainline earlier and move quicker into lane 2, avoiding having to merge into a stream of traffic comprised not just of mainline traffic but also of merging traffic from slip lane 2. With the Ghost Island diverge, drivers may use the second exit in order to avoid slow moving traffic in lane 1 and/or slip lane 1.

It was hoped that the new layout would improve driver behaviour and as a result improve the performance of the diverge both on and off the mainline. The first Ghost Island diverge layout to be installed on a UK motorway diverge was at the M3/M25 (northbound and southbound) in 1993. The idea came out of discussions between the Department of Transport, Surrey County Council and Surrey Police in order to reduce the accident risk at the junction. It was a lane drop design and seemed to operate efficiently with noticeably less queuing in lane 1 (no detailed assessment of this site was carried out) and demonstrated how the diverge could be designed more effectively.

The "tiger-tail" Ghost Island diverge layout was subsequently installed at three further sites in the UK. These were:

- M20/M26 near Wrotham near Kent (Wall 1996b; Wall et al 1997)

- M6 J4a near Birmingham (Wedlock 1999)
- M27/M3 near Southampton (Wall and Peirce 2000)

3.3.2.2 The M20/M26

The first 'before' and 'after' video survey was carried out at the M20/M26 interchange at Wrotham, in Kent in 1995, during the morning peak period. The diverging area was approximately 1 km long with two slip lanes leading to the M26 alongside the three mainline lanes of the M20. The diverge was, therefore, of a Parallel type but with two auxiliary lanes. There was considerable weaving between slip lanes 1 and 2 and the mainline, with considerable speed differentials between vehicles. This provided ample opportunity for the swooping manoeuvre. Figure 3.1 shows the 'before' M20/M26 survey site.

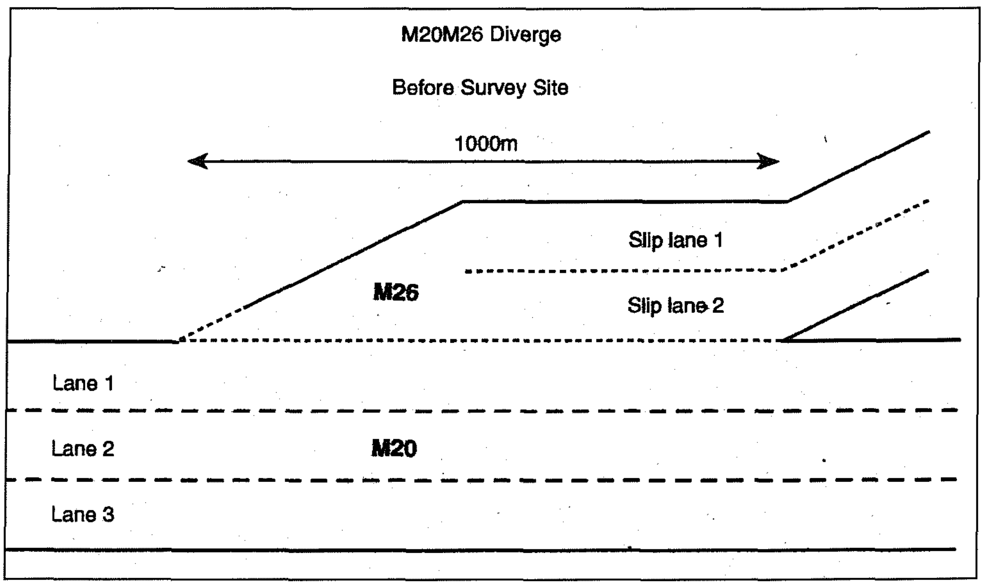


Figure 3.1: The M20/M26 'before' survey site

A new layout combining an auxiliary lane with a tiger-tailed marked ghost island was designed to allow easier departure from lane 2 of the mainline, without the need for a last minute swoop. This marked ghost island would replace the offside auxiliary lane. It was also hoped that the movement of diverging traffic would be regulated into a safer and more orderly stream. In order to leave the mainline in the new layout (see Figure 3.2), vehicles needed to be in lane 1 and use either the first exit to join slip lane 1 or second exit to join slip lane 2.

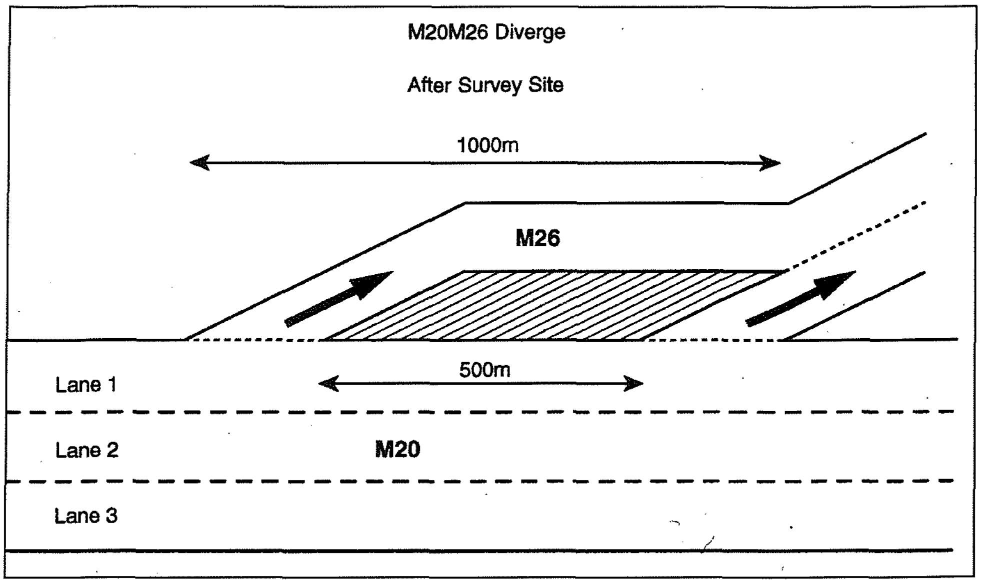


Figure 3.2: The M20/M26 'after' survey site

The average number of swoopers decreased significantly in the 'after' survey from an average of 709 to 239 swoopers per hour, despite a small increase in traffic flow. The difference in the average was statistically significant at the 1% level using a t-test. The remaining number of swoopers in the 'after' survey, were concentrated at the two exit points (90% of all swoopers) with a noticeable proportion of drivers crossing the ghost island markings (an average of 94 vehicles an hour).

The relatively large number of swoopers at the first exit was thought due in part to the lack of a vertical sign clearly showing drivers that there was another opportunity to leave the mainline. This could also explain why drivers crossed the ghost island markings in order to leave the mainline. After the installation of the ghost island markings, slip lane 1 was found to carry about 440 vehicles per hour more than slip lane 2.

A second 'before' and 'after' video survey was carried out in 1997. The layout remained unchanged from the original 'after' survey in the first trial. The purpose of the second trial was to evaluate what effect installing a new vertical sign, explaining the new layout to drivers, had on swooping and the numbers crossing the ghost island markings. The new vertical sign showed drivers that in order to leave the mainline they needed to be in lane 1, and that there were two equally usable exits (see Figure 3.11).

Between the first and second trial, swooping had again fallen considerably (from 239 to 120 vehicles an hour) as well as vehicles crossing the ghost island markings (from 94 to 23 an hour), presumably due to drivers' increased familiarity with the layout. These were much greater decreases than the 10% reduction in the total traffic flow observed. The new trial showed a marginal increase in swooping (120 to 148 per hour), but no change in vehicles crossing the ghost island markings (remaining at 23 an hour). This minor increase in swooping needed to be considered in the context of a 10% increase in flow between the second 'before' and 'after' surveys. Following the Ghost Island diverge installation, the flows in the slip lanes were unbalanced (slip lane 1 with 61% and slip lane 2 with 39% of diverging traffic). By the time the new sign was introduced, these slip lane flows had evened out at 54% and 46%, presumably due to driver familiarity. In the 'after' survey, the slip lane flows were at 53% and 47%, showing that the sign had made little additional effect.

The results for both trials were for peak period operation, when most drivers were very familiar with the junction layout; the fact that both swooping and ghost island violations had dropped significantly between the first 'after' and the second 'before' survey indicated that increased familiarity had improved driver behaviour. Although the installation of the sign had no noticeable effect in the AM peak period, it was not unreasonable to assume that drivers unfamiliar with the layout will be assisted by the new sign, reducing the perceived need to swoop and/or cross the ghost island markings.

Overall, the trial was a success. Swooping was substantially reduced and the exit now ran in a more orderly fashion than before, with lower speeds on both slip lanes. It was expected that the combination of the new layout with the new vertical sign would result in a more equal balance of flow between the two slip lanes, as well as reducing swooping and the numbers crossing the ghost island markings. Vehicles essentially now leave the mainline either by slip lane 1 or slip lane 2, and having once entered a lane, they remain in it until away past the diverge area. Photographs of the 'before' and 'after' layouts at the M20/M26 are shown in the Highways Agency's Toolkit (Highways Agency 1998) as an example of an anti-swooping marking.

3.3.2.3 The M6 J4a

Following the success of the trials of the Ghost Island diverge layout at the M20/M26 intersection in reducing the occurrence of swooping, other sites were identified which could possibly benefit from these measures. The M6 J4a site was suggested by the Highways Agency as such a site as it had high traffic flows and a significant diverging proportion. The original 'before' layout was a Parallel diverge.

A 'before' and 'after' video survey was carried out in November 1997 and October 1998 respectively for the evening peak period using seven video cameras (Wedlock 1999). The new Ghost Island layout was installed in June 1998. Figures 3.3 and 3.4 show the 'before' and 'after' layouts. Figure 3.5 is a photograph depicting the start of the ghost island markings at the M6 junction 4a.

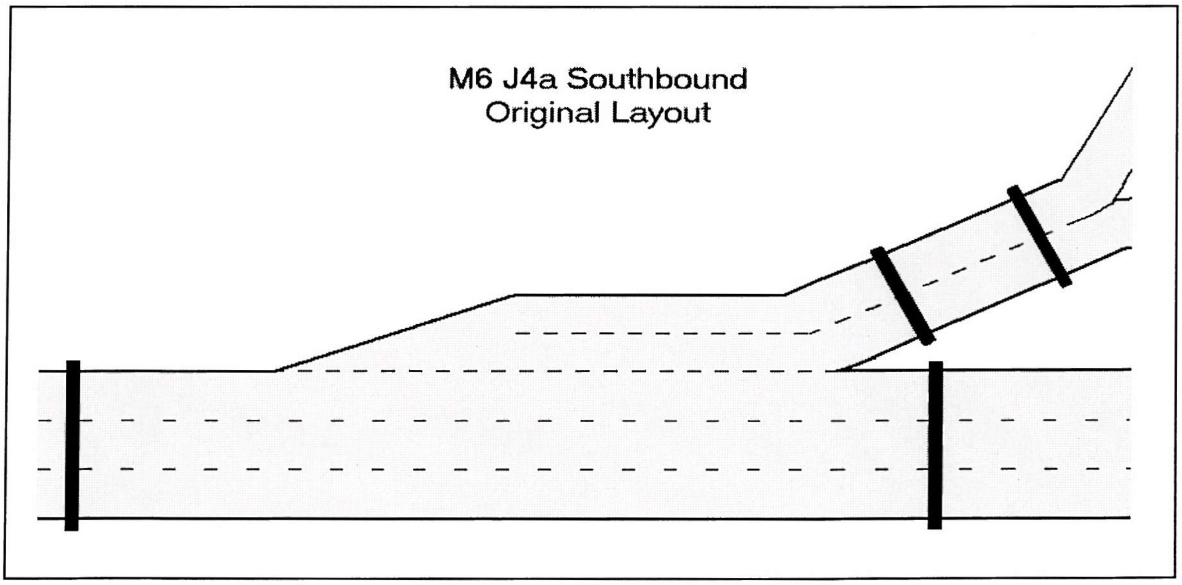


Figure 3.3: The 'before' M6 J4a survey site

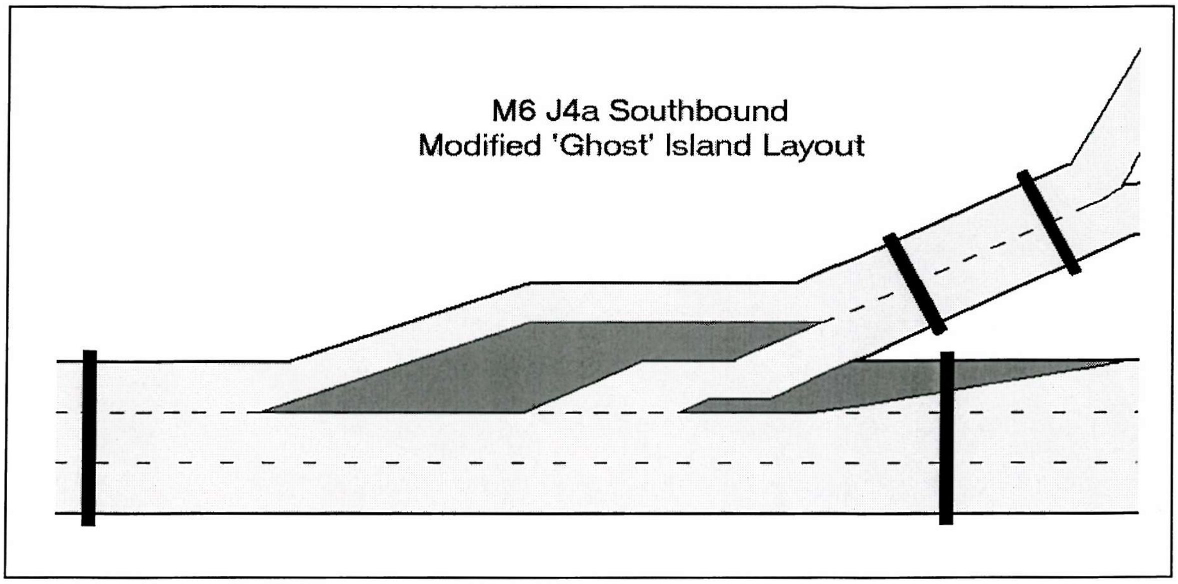


Figure 3.4: The 'after' M6 J4a survey site

Figure 3.5: The start of the Ghost Island layout at the M6 junction 4a

In the 'before' survey, it was found that during the evening peak hour, 47% of traffic diverged at the junction. This meant that lane 1 could not provide the required capacity for the exiting traffic and so there was a high occurrence of the practice of swooping, especially during the peak hour, when 14% of exiting vehicles performed swooping manoeuvres. Over 50% of the swooping manoeuvres occurred once the slip road had sufficient width for two lanes of traffic. Also, flow breakdown occurred on the slip road that caused queues of slow moving traffic to form, which on occasions extended back onto the mainline.

Due to the above reasons, it was decided that the most appropriate Ghost Island layout would incorporate a lane drop, but in order not to reduce the capacity of the mainline this lane was regained immediately after the diverge had ended (economic reasons may also of been prevalent in the decision to stay with 3 mainline lanes after the diverge). The existing large diverge area allowed the ghost island markings to be introduced with little impact on the hard shoulder of the diverge area. As well as modifying the diverge layout, the signing at 1 mile, ⅔ mile and ⅓ mile was altered informing drivers of the new layout.

In the 'after' survey, it was found that the level of swooping had fallen by 77% despite increases in vehicle flow of 4% during the survey period and 12% during the peak hour. The new layout effectively allowed the driver to retain the perceived personal benefits of swooping, but without the safety hazards to other drivers associated with last minute lane changing. A new vertical sign was also installed at the site informing drivers of the new layout (see Figure 3.11).

After the survey, the second exit was under utilised with only 22% of diverging vehicles using it. This means that once the marked ghost island had ended, there were a large number of lane changing manoeuvres on the slip road. Also, there were approximately 25 vehicles an hour crossing the ghost island markings. It was hoped that as drivers become more familiar with the new layout (as at the M20/M26), the two exits would become more equally utilised, along with a reduction in the number of vehicles crossing the ghost island markings.

3.3.2.4 The M27/M3

A 'before' and 'after' video survey was carried out on the M27/M3 eastbound diverge during the morning peak period, near Southampton, in November 1998 and June 2000 respectively. In between the two surveys, a "tiger-tail" Ghost Island lane drop layout was installed at the site. Figures 3.6 and 3.7 show the 'before' and 'after' survey site at the M27/M3 eastbound diverge. The new layout replaced the previous Taper lane drop layout.

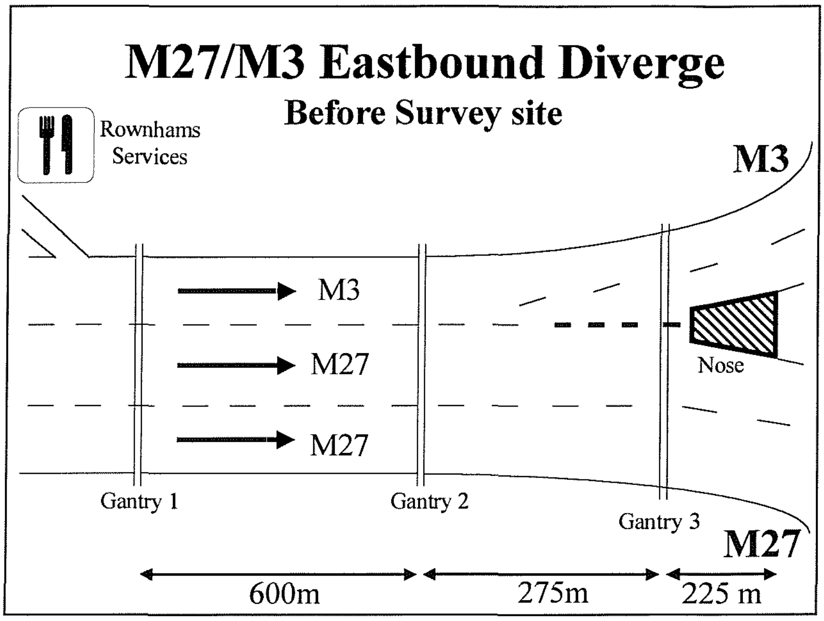


Figure 3.6: The 'before' survey site

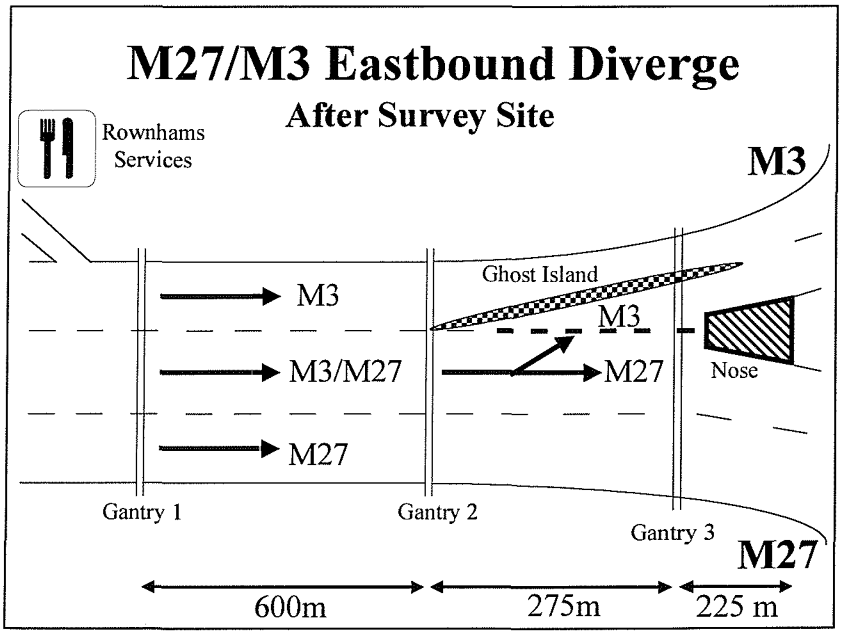


Figure 3.7: The 'after' survey site

With the 'before' layout, vehicles wishing to diverge onto the M3 needed to be in lane 1. It was estimated that about 50% of traffic diverged onto the M3. This meant that lane 1 could not provide the required capacity for the exiting traffic. This resulted in queues of slow moving traffic in some of the peak periods along with a high occurrence of swooping (defined at a lane drop to be vehicles moving into the slip road directly from lane 3, within 1500m from the exit, in order to leave the mainline). There were also a number of potentially dangerous manoeuvres (defined to be sudden lane changes into or out of the slip road/lane within 1100m of the exit, including swooping). It was hoped that the installation of the new Ghost Island layout would allow easier departure onto the M3 from lane 1 and lane 2, reducing the need of drivers to swoop. It was also hoped that the movement of diverging traffic would be regulated into two orderly streams.

New gantry and vertical signing (shown in Figure 3.11), informing drivers of the new layout, were also installed. With the new layout, vehicles wishing to diverge onto the M3 needed to be in either lane 1 and use the first exit to join slip lane 1, or lane 2 and use the second exit to join slip lane 2. Vehicles wishing to continue on the M27 still needed to be in either lanes 2 or 3.

Swooping at the diverge decreased significantly from an average of 69 to 44 swoopers per hour (approximately a 36% reduction). Although the level of swooping observed at the site was relatively low compared to, for example the M20/M26 diverge, this was still an encouraging result. Potentially dangerous manoeuvres decreased significantly from an average of 399 to 81 an hour (an 80% reduction). The new Ghost Island layout was particularly successful in reducing the number of these potentially dangerous manoeuvres by regulating the diverging flow into two orderly streams, eliminating many potential conflict opportunities.

The average number of vehicles crossing the nose reduced from 3 to 1 vehicles an hour. A small number of drivers crossed the ghost island markings (an average of 17 an hour which is less than 0.8%) and changed from either slip lane 1 to slip lane 2 (8 vehicles an hour) or slip lane 2 to slip lane 1 (9 vehicles an hour). These numbers were expected to reduce to close to zero once drivers were more familiar with the new layout.

The average number of vehicles changing from the slip road/slip lane 1 to slip lane 2 reduced dramatically from 835 to just 8 vehicles per hour. In the 'before' survey, there was potential conflict between vehicles changing from the slip road/slip lane 1 to slip lane 2 (835 vehicles per hour) and those vehicles changing from lane 2 to slip lane 2 (215 vehicles per hour). Changing from lane 2 to slip lane 2 in the 'before' layout was not illegal but could still be dangerous. This potential conflict involving last minute departures from lane 2 was almost eliminated in the 'after' survey. Drivers were now able to change safely from lane 2 to slip lane 2 and did so in increased numbers (1022 vehicles per hour compared to 215 vehicles per hour in the 'before' survey).

Overall, the trial was a success. Swooping and potentially dangerous manoeuvres were substantially reduced, with the exit running in a more orderly fashion and with lower average speeds on both slip lanes. Vehicles now leave the mainline by either slip lane 1 (from lane 1) or slip lane 2 (from lane 2) and having once entered a slip lane, remain in it until away from the diverge vicinity.

3.4 Questionnaire survey concerning the M27/M3 diverge

3.4.1 Results of the questionnaire survey

As part of this PhD study, a preliminary questionnaire survey was subsequently designed and carried out to obtain subjective data concerning drivers' reactions to the new Ghost Island layout at the M27/M3 diverge (see Appendix A). This was to complement the objective data already collected from the video survey.

The questionnaire was carried out on 54 drivers between November 2000 and March 2001, asking for their views on the newly installed layout. The majority of the 54 drivers filled in a questionnaire form, with only 3 drivers answering the questions orally. All the drivers taking part were known by the author and familiar with the diverge and had no vested interest in the success or otherwise of the scheme (e.g. from the HA or TRL). The results of the questionnaire are set out in Tables 3.1 to 3.18.

Table 3.1: Age of drivers

18 - 30	31 - 40	41 - 50	51 – 60	Over 60
9 (17%)	11 (20%)	18 (33%)	9 (17%)	7 (13%)

Table 3.2: Sex of drivers

Male	Female
42 (78%)	12 (22%)

Table 3.3: How long have you been driving for ?

Less than 1 year	1 – 5 years	6 – 10 years	Over 10 years
0 (0%)	3 (6%)	5 (9%)	46 (85%)

Table 3.4: How often do you drive on motorways ?

Every week day	About once a week	About once every two weeks	About once a month	Less than once a month
19 (35%)	16 (30%)	4 (7%)	10 (19%)	5 (9%)

Table 3.5: How often do you drive past the M27/M3 eastbound junction ?

Every week day	About once a week	About once every two weeks	About once a month	Less than once a month
15 (28%)	14 (26%)	6 (11%)	10 (19%)	9 (16%)

Table 3.6: When do you normally drive past the M27/M3 eastbound junction ?

AM peak (06:30 – 09:30)	PM peak (16:00 – 19:00)	Off-peak (any other time)
24 (44%)	16 (30%)	31 (57%)

N.B. 41 drivers ticked 1 box, 9 drivers ticked 2 boxes and 4 drivers ticked 3 boxes. 30 drivers (56%) had driven through the junction during a peak period.

Table 3.7: Do you normally stay on the M27 or leave the M27 to join the M3 ?

Stay on the M27	Join the M3	Both equally
16 (30%)	31 (57%)	7 (13%)

Table 3.8: Did you notice any changes to the M27/M3 junction layout since April 2000 ?

No	Don't remember	Yes
3 (5%)	10 (19%)	41 (76%)

BEFORE CHANGES

Table 3.9: Did you experience any problems at the M27/M3 eastbound junction before April 2000 (before the new layout was installed ?)

No	Yes
15 (29%)	37 (71%)

N.B. 2 drivers gave no answer. Percentage figures are, therefore, of those drivers who answered.

Table 3.10: If yes were they:

Long, slow moving queues in lane 1 leaving the M27 for the M3	Dangerous last minute lane changes	Slow moving lorries in lane 2
27 (73%)	28 (76%)	19 (35%)

N.B. Drivers were encouraged to tick more than 1 box if appropriate.

Other comments included:

Slow moving traffic (e.g. lorries) joining the M27 from Rownhams Service area can cause problems in the diverge area. Drivers can be trapped in lane 1 when wishing to remain on the M27. Many drivers keep in lane 3 in order to avoid queues/congestion in the diverge area.

Table 3.11: When wishing to join the M3, before the new layout was installed, did you normally :

Stay in lane 1 and join slip lane 1 well before the exit (manoeuvre A)	Stay in lane 2 change into slip lane 2 near the exit (manoeuvre B)
36 (69%)	16 (31%)

N.B. 2 drivers gave no answer. Percentage figures are, therefore, of those drivers who answered.

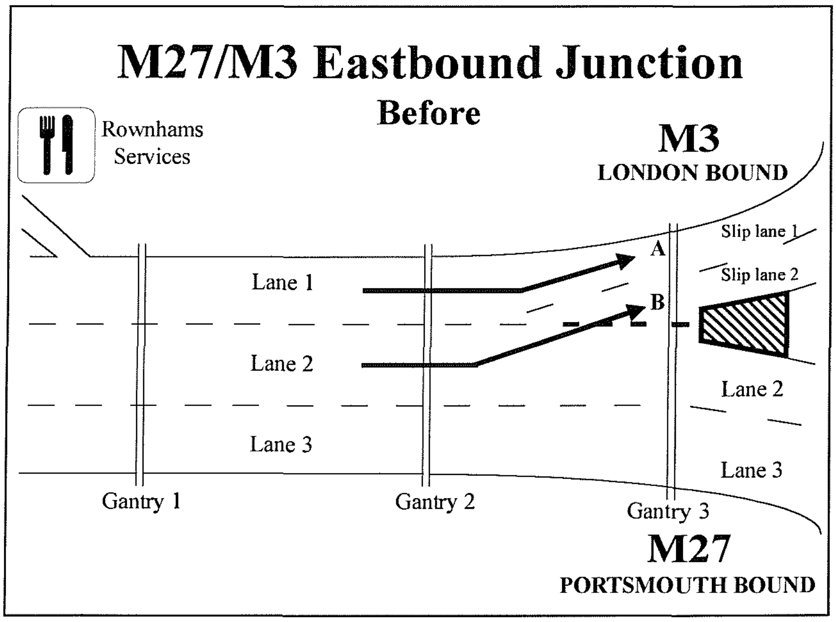


Figure 3.8:The 'before' M27/M3 manoeuvres A and B

AFTER CHANGES

Table 3.12: Do you think the new layout is better than the old layout in terms of

	Yes	No	Same	No answer
Smoother traffic flow (less congestion/queues)	39 (78%)	2 (4%)	9 (18%)	4
Easier access to the M3	39 (76%)	4 (8%)	8 (16%)	3
Less last minute dangerous lane changes	33 (70%)	10 (21%)	4 (9%)	7
Less driver stress	22 (45%)	10 (20%)	17 (35%)	5

N.B. Percentage figures are of those drivers who answered.

Table 3.13: Comments about the new layout

'Best thing they ever did'.
Taken a potentially dangerous driving manoeuvre in the 'before' layout and made it much safer recognised movement.
Many dangerous lane changes now take place from lane 3 to lane 2 to the second exit.
Many drivers keep in lane 1 for fear of missing the second exit.
Second exit is at a sharp angle – a lane narrowing measure ?

Table 3.14: When wishing to join the M3, after the new layout was installed, do you normally

Stay in lane 1 and join slip lane 1 well before the exit (manoeuvre A)	Stay in lane 2 change into slip lane 2 near the exit (manoeuvre B)
23 (43%)	30 (57%)

N.B. 1 driver stated that they did both manoeuvres equally as often.

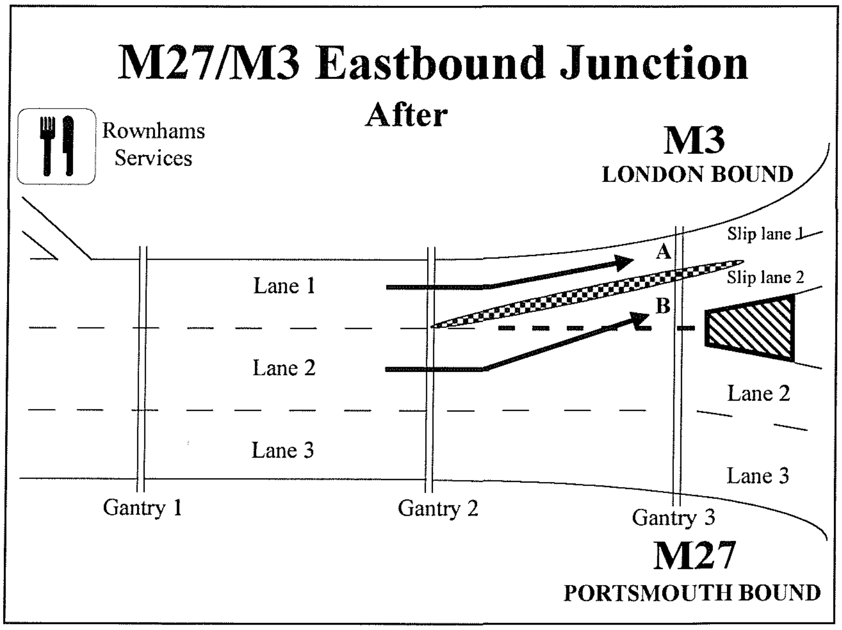


Figure 3.9:The 'after' M27/M3 manoeuvres A and B

Table 3.15: Have you noticed the new sign informing drivers of the new layout (as in Figure 3.10) ?

Yes	No
49 (91%)	5 (9%)

Table 3.16: Do you think the new sign adequately informs drivers of the new layout ?

Yes	No
40 (75%)	13 (25%)

N.B. 1 driver gave no answer.

Table 3.17: Comments about the new sign

When overtaking, lorries in lane 1 can obscure the sign. The sign could have included a junction number (i.e. 4) and destinations on the end of each arrow. Two arrows to the M3 on the sign can be a bit confusing – is one M3 northbound and the other M3 southbound?

Table 3.18: Other comments about driving on this stretch of motorway

This section of motorway is an accident hotspot. There has been roadwork's here making driving hazardous. VMS signs are often not working. The diverge area needs more mainline lanes. The traffic lights on the previous slip road are awful.

3.4.2 Conclusions from the questionnaire survey

The drivers who took part in the questionnaire survey were mainly male (78%), represented a good cross-section of age-groups, were mainly experienced drivers (85% had been driving for at least 10 years) who were generally used to driving on motorways (65% drove on a motorway at least once a week). A majority of the drivers (54%) drove past the M27/M3 eastbound diverge at least once a week and so were familiar with the layout. Also, a majority of the drivers (56%) drove through the junction during a peak period, thereby experiencing the diverge area at its most congested. Most of the drivers (57%) stated that they would normally join the M3 rather than continue on the M27.

76% of the drivers noticed a change in the layout of the diverge area with 71% stating that they had experienced problems before the changes were made to the layout. The main problems were long, slow moving queues in lane 1 (73%) and last minute dangerous lane changes (76%), both of which the new layout was designed to minimise. Before the changes to the layout, 31% (16 drivers) stated that in order to join the M3, they went directly from lane 2 into slip lane 2 which was a potentially dangerous manoeuvre. This proportion almost doubled to 57% after the changes to the layout, but now this manoeuvre was a safe and recognised movement. This increase was statistically significant at the 1% level using a paired t-test. There were 12 drivers who originally used the first exit but who now used the second exit to join the M3. Only one driver originally used the second exit and now preferred to use the first exit (although it is not known why). All the other drivers in the survey preferred to use the same exit with both the 'before' and 'after' layouts. This, therefore, showed an increase in the number of drivers in the survey who now preferred to use the second exit in order to join the M3.

In the Highways Agency Toolkit (Highways Agency 1998), the 'tiger-tail' Ghost Island diverge is recommended as an anti-swooping marking to smooth the exit flow. It states that it is suitable at diverges where there is:

- Poor driver discipline or
- Traffic congestion due to insufficient exit capacity or
- A large number of drivers making potentially dangerous last minute lane changes (including swooping) in order to make a late exit.

The Toolkit lists the benefits of the "tiger-tail" Ghost Island diverge as being:

- Discouraging dangerous last minute lane changes (including swooping)
- Smoothing traffic flow (less queues/congestion)
- Reducing driver stress
- Increasing exit capacity

These benefits (apart from the last one that would require modelling work and/or video data) were incorporated into the questionnaire to see if drivers experienced such improvements at the M27/M3 eastbound diverge. The vast majority of the drivers stated that the new layout had smoothed traffic flow (78%) and reduced last minute lane changes (76%) as well providing easier access to the M3 (70%). However, only

45% of the drivers stated that the new Ghost Island layout had helped to reduce driver stress (a parameter that can be difficult to define and measure accurately). This may be due to the fact that the diverge is a lane drop layout and remained as such despite the changes made. The 43% of drivers who stated that they usually stay on the M27 would have experienced little change, as they still needed to be in lane 2 or 3 in order to remain on the mainline. Many drivers also commented that there were still last minute lane changes from lane 3 to the second exit indicating that these potentially dangerous manoeuvres had not been eliminated completely.

91% of drivers noticed the new vertical sign, informing drivers of the new layout. The vast majority (75%) of the drivers felt it was satisfactory but several improvements were suggested. These included adding the destinations (e.g. Portsmouth or London) and a junction number (i.e. 4) to the sign. There were, in fact, two of these vertical signs as well as three gantry signs directing drivers into the correct lane for the appropriate destination. However, the sign could have been improved if the destinations and junction number had of been included.

Overall, drivers thought that the new layout did improve the safety and operation of the diverge area. They experienced smoother flow, a reduction in last minute lane changes and easier access to the M3. This subjective information complemented the objective 'before' and 'after' video data which also concluded that the new layout improved the safe operation of the diverge area (Wall and Peirce 2000).

3.5 Locations of existing Ghost Island diverges

Table 3.19 contains a list of all known Ghost Island diverges in the UK, along with other details about the site.

Table 3.19: List of known Ghost Island diverge layouts in the UK (* TRL monitored sites)

	Date installed	'before' layout type	'after' layout type	Number of lanes on mainline 'before'	Number of lanes on mainline 'after'	Do the two exit lanes separate for two different motorway destinations?	Reasons for the introduction of the scheme
M3/M25 M3 J2 Northbound and Southbound	1993	Taper lane drop	Ghost island lane drop	3	3	Yes	Long queues in lane 1 due to high diverging traffic. In order to reduce accidents
M23/M25 M23 J8 Northbound	1995	Taper lane drop	Ghost Island lane drop	3	3	Yes	Reduce accidents by encouraging better driver lane discipline
M20/M26* M20 J3	1995	Parallel with two auxiliary lanes	Ghost Island	3	3	No (but need to be left hand lane to turn off on the A20 to Wrotham)	High occurrence of swooping
M6/M61 M6 J30 Southbound	1995	Taper	Ghost Island lane drop	3	4	No	Part of a widening scheme from M6 J30 to J32. capacity problems
M6 J4a* Southbound	1998	Parallel	Ghost Island lane drop	3	3	Yes	Swooping and capacity problems with long queues in lane 1
M40/M42 M42 J3a Southbound	1999	Taper lane drop	Ghost Island lane drop	3	3	No	Swooping and capacity problems
M5 J31 (M5/A30/ A38)	1999	Taper	Ghost Island lane drop	3	3	No	Part of the 'solar eclipse' traffic management measures
M27/M3* M27 J4 Eastbound and Westbound	2000	Taper lane drop	Ghost Island lane drop	3	3	No	Swooping and capacity problems with long queues in lane 1
M62/M621 M62 J27 Eastbound	2000	Taper	Ghost Island	3	3	No but need to be in left hand slip lane for A62 or A650	Improve capacity with 4% uphill gradient and 25% HGVs
M6/M5 M6 J8 Southbound	2001	Taper	Ghost Island lane drop	3	3	No	Improve capacity

N.B. Two other recent sites are the M60/M61 (M60 J15) and the M1/M69 (M1 J21). Also, all Ghost Island lane drop layouts listed in the table regained the mainline lane either immediately after the diverge or at the subsequent merge.

All of the Ghost Island diverge layouts in the UK, listed in Table 25, have so far been installed at motorway-to-motorway interchanges, where there are high turning proportions and no flow restriction at the end of the slip road.

Significant modifications in driver behaviour have been recorded at each of the three Ghost Island diverges which have been assessed by TRL. This has resulted in a reduction in the number of swooping manoeuvres at all three sites (66% at the M20/M26, 80% at the M6 J4a and 39% at the M27/M3). Potentially dangerous manoeuvres were also measured at the M27/M3 and reduced by 80%. There was also a higher throughput for through traffic at the M6 J4a (up 12% during the peak hour). Given the success of the Ghost Island diverge in the video trials, it has been recommended that these new designs should be confirmed as standard diverge layouts (Wedlock, Peirce and Wall 2001).

They have also been recommended for installation in the USA (Tignor 1999) where the Ghost Island diverge has been described as "an innovative pavement marking pattern which separates multiple lanes by using a wide painted buffer, reducing turbulence and improving operations as traffic leaves a mainline". The research team concluded that the "tiger-tail Ghost Island diverge would have great potential value for use on freeways in the USA".

3.6 Guidelines for installing Ghost Island diverges

The Ghost Island diverge layout is currently a departure from standard and requires approval for its installation from the relevant Overseeing Organisation. Authorisation is also required for non-standard signing which includes vertical and gantry signing. Ghost Island diverges have been particularly effective at improving driver behaviour and traffic flow at junctions with high diverging proportions i.e. 1600 vehicles an hour. Depending on the space available and the required mainline capacity, the Ghost Island diverge can be installed at Taper or Parallel diverges with or without a lane drop. The installation of a Ghost Island at a standard Parallel or Taper diverge may require the use of part of the hard shoulder in order to create space for the ghost island markings. If there is a shortage of space to install the ghost island markings or the hard shoulder could not be used, the installation of the diamond markings may be a more suitable option. Figure 3.10 (from Wedlock, Peirce and Wall 2001) shows examples of recommended layouts for the new Ghost Island diverges developed from a Taper, a Parallel and a Taper lane drop layout. These designs could be incorporated into the new standards.

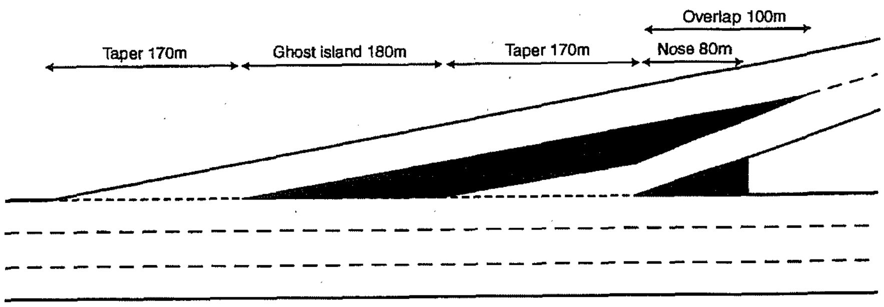


Figure A1 'Ghost' Island diverge developed from an existing TD 22/92 layout 'A' (Taper diverge)

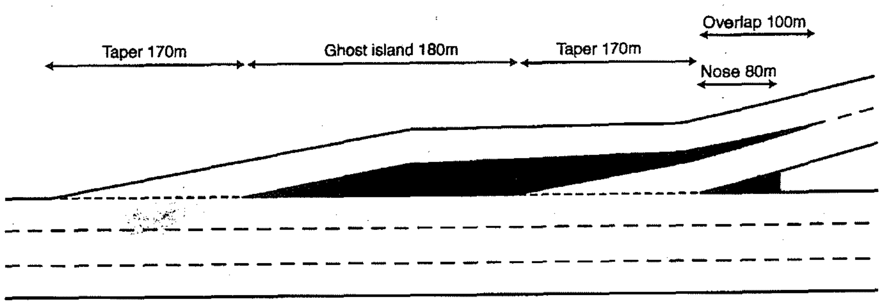


Figure A2 'Ghost' Island diverge developed from an existing TD 22/92 layout 'B' (Parallel diverge)

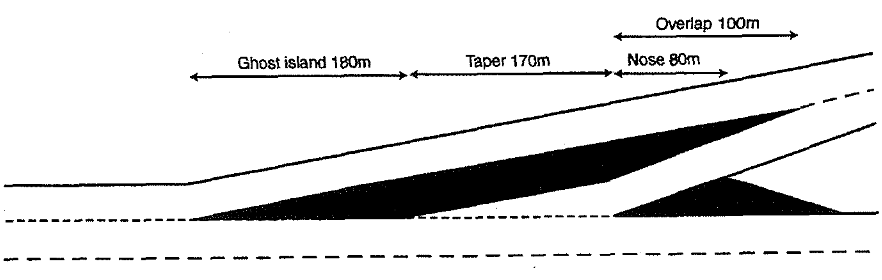


Figure A3 Lane drop 'Ghost' Island diverge developed from an existing TD 22/92 layout 'C' (Mainline lane drop at taper diverge)

Figure 3.10: Recommended layouts for Ghost Island diverges

The vertical sign associated with the new Ghost Island layout should inform drivers of their expected behaviour at the diverge. The main objective of the sign should be to inform the driver of the existence of the second exit and whether the two exits are equally useable or separate for two different destinations. The questionnaire survey at the M27/M3 showed drivers felt that the vertical sign could be more informative if it contained destinations (motorway and place name) and a junction number (as at the M6 J4a and the M42 J3a). Figure 3.11 shows the three vertical sign designs for the TRL trial sites.

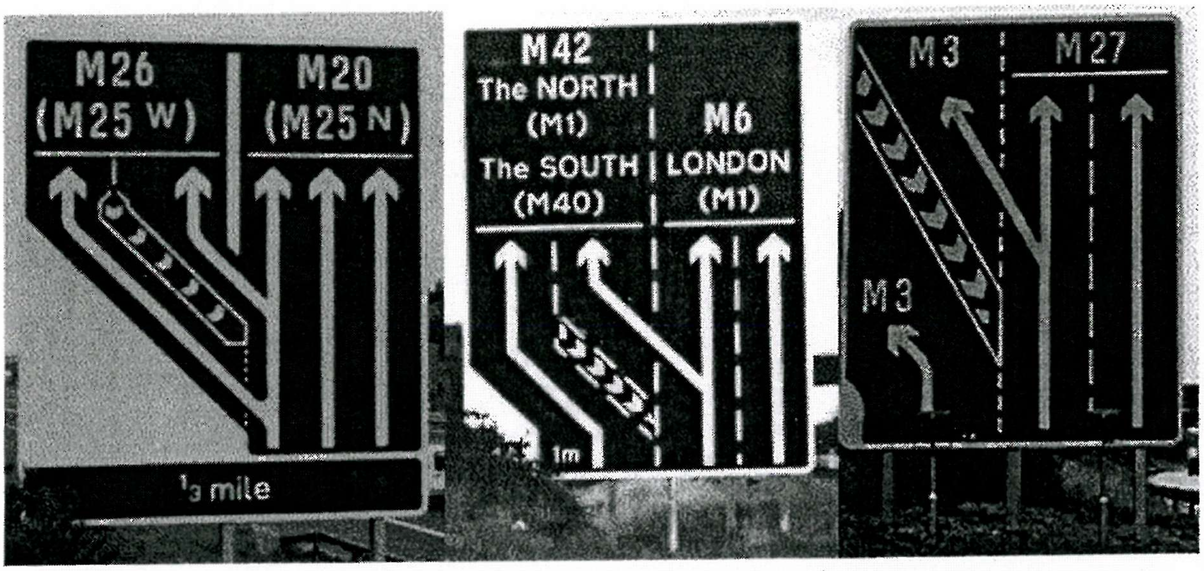


Figure 3.11: Vertical sign designs for the three TRL trial sites

3.7 Discussion regarding Ghost Island diverges

This section has shown the importance of driving behaviour of exiting vehicles on the successful or otherwise operation of the diverge. The video trials and the questionnaire survey have shown the success of the Ghost Island diverge in reducing swooping and other potentially dangerous manoeuvres. This is thought to have had a subsequent benefit on improving capacity by its ability to regulate the exiting flow into two orderly streams of traffic.

In order to evaluate this layout and variants of it in more detail, a microscopic simulation computer program is needed to model it and assess its performance and compare it with other diverge layouts. It has been recommended to be installed at diverges where there is either a high occurrence of swooping or where there is a high diverging percentage (above 40%). In reality, a high diverging percentage may lead to a high occurrence of swooping. The microscopic modelling work would be able to assess more exactly the mainline and diverging flows for diverging percentages for which it is best suited. This information could then be used to further enhance the design requirements and recommendations in an updated and revised Standard.

3.8 Summary

This chapter contains a literature review of research into driving behaviour at motorway diverges and how the layout or type of diverge can affect such behaviour. It also examines the new Ghost Island diverge layout, an alternative layout to the types recommended in the latest Standard TD22/92.

Three previous studies looking at driving behaviour near the diverge were examined. The first was a UK video study which identified several types of driver behaviour at diverges which were common e.g. lane 1 dominance and late entry into lane 1. The second was a USA study looking at erratic driving behaviour at the Nose or Gore, which included stopping, reversing and last minute double lane changes. The third was a Swedish study looking into driving behaviour and accident rates at both Taper and Parallel type diverges.

A review has also been carried out of the research undertaken by TRL for the Highway Agency between 1995 and 2000, to reduce the occurrence of swooping at the diverge. Swooping has been defined to be vehicles moving directly from lanes 2 or 3 of the mainline into the slip road, in order to leave the mainline, typically within 500m of the diverge point. Two methods were used to combat swooping. These were:

- New lane separation markings
- New 'Ghost Island' diverge layouts

Within the TRL study, six diverges have had anti-swooping measures installed and monitored. Lane separation markings were installed at three sites; the Dartford Tunnel (no 'before' study was carried out), the M27 J3 and the M6 J6.

The "tiger-tail" Ghost Island diverge layout was installed at three sites; one with a lane drop (M27/M3), one with a twin auxiliary lane (M20/M26) and one where an auxiliary lane layout was converted into a "tiger-tail" lane drop layout (M6 J4a). In all three cases, significant reductions in the average number of swooping manoeuvres per hour were recorded; 66% at the M20/M26, 80% at the M6 J4a and 39% at the M27/M3. The Ghost Island diverge layout was also successful in regulating the flow into two orderly streams of traffic at all three sites.

To complement the video data from the TRL study, a questionnaire was carried out on 54 drivers between November 2000 and March 2001, asking for their views on the newly installed Ghost Island diverge layout at the M27/M3. Overall, drivers thought that the new layout did improve the safety, operation and control of the diverge area. They experienced smoother flow, a reduction in last minute lane changes and easier access to the M3.

A further evaluation of this layout using a microscopic model should help to assess at which mainline and diverging flows it is best suited. Given the success of the Ghost Island diverge in the video trials and the questionnaire survey, it has been recommended that these new designs should be confirmed as standard diverge layouts.

CHAPTER 4

REVIEW OF MICROSCOPIC MODELS

4.1 Introduction

A microscopic simulation is a computer program designed to model traffic at the level of an individual vehicle. Simulated vehicles move through a simulated network dependent on a number of parameters such as geometry, driver behaviour, vehicle characteristics, gap acceptance, car following and lane changing behaviour. These software packages are becoming an increasingly important tool for the development of various traffic control strategies. They give traffic engineers a "bird's eye" view of the traffic within the network and an opportunity to try out various techniques, without any disruption to real traffic.

A microscopic model needs to work on the macroscopic and microscopic level in order to replicate observed driving behaviour in urban areas or on motorways. The microscopic level is how the vehicles and drivers interact with each other at a particular point in time. The macroscopic level is the effect these individual vehicles and drivers have on the traffic as a whole in terms of parameters such as speed and flow. For example, poor lane changing on a microscopic level may lead to a reduction in speed on a macroscopic level.

These packages can be used to evaluate the effectiveness of various traffic management strategies (e.g. a new diverge layout), forecast the effect of incidents and possible interventions (e.g. VMS signs) and carry out a traffic impact assessment for expected changes in traffic flow.

A microscopic model will be used in this research to evaluate various existing and alternative diverge layouts in terms of their capacity and associated operation, as discussed in chapters 2 and 3. The modelling work will be able to provide important information regarding the capacity and operation of diverges that the diverging flow-region diagram, the video trials or questionnaire survey could not such as individual vehicle data concerning speed, lane changes and journey times. It will also enable each of the layouts to be tested to assess the range of mainline and diverging flows they are best suited for. This chapter, therefore, contains a review of microscopic simulation models, with an explanation about why the microscopic model SISTM was chosen as a suitable tool for this research work.

4.2 Features of microscopic simulation models

A recent study (Institute of Transport Studies, University of Leeds 2000) compiled a list of 57 existing microscopic simulation software models, most of which are research tools. The models were categorised into five categories depending on the traffic situation they were intended to model, i.e. Urban, Motorway (or Freeway), Combined Urban and Motorway (or Freeway), Automated Highway Systems (AHS) or Other.

Features common to all the models include:

- Vehicles are moved through the network in time-steps (typically 1-second intervals). Three models use event based intervals models (FLEXSYT-II, SIGSIM and SIMNET).
- Car following, lane changing and gap acceptance laws are used to govern vehicle movements along road links.
- The number of vehicles using the network is defined by specifying origin-destination (O-D) data. Some of the programs have an assignment model.
- Most of models display an animation of the vehicles moving around the network.

Respondents to a survey on microscopic traffic models highlighted the most important requirements for the user (Halcrow Fox 2001a and 2001b). The microscopic models which are currently available (including SISTM) would not necessarily satisfy all these requirements. SISTM has been shown to have some limits in its functionality when modelling diverges (see Chapter 10) and has scope to be made more user-friendly. The requirements were:

- Functionality – their ability to model a wide range of situations e.g incidents or roundabouts.
- Outputs – range of results available in terms of efficiency, safety and environmental factors.
- ITS modelling ability – their ability to model new technologies such as ramp metering or dynamic route management.
- User friendliness – ideally providing a graphical user interface for input, editing and presentation of results.
- Execution speed – run times several times faster than real time.
- High performance quality – providing the user with calibrated default parameter values which have been extensively validated with real data.

4.3 Comparison of the microscopic motorway models

Table 4.1 compares the functionality of the Combined Urban and Motorway models (Institute of Transport Studies, University for Leeds, 2000).

Table 4.1: Functionality of the Combined Urban and Motorway micro-simulation models (from Institute for Transport Studies, University of Leeds, 2000)

	AIMSUN2	CORSIM	FLEXSYT-II	INTEGRATION	MELROSE	MICROSIM	MITSIM	Paramics	PLANSIM-T	TRANSIM	VISSIM
ITS Functions modelled											
Ramp metering	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Freeway flow control		✓	✓	✓	✓		✓	✓			✓
Incident management	✓	✓	✓	✓			✓	✓			
Variable message signs	✓			✓			✓	✓	✓		
Dynamic route guidance	✓			✓	✓	✓	✓	✓	✓		
Automatic debiting & toll plazas	✓		✓	✓	✓		✓	✓			
Adaptive cruise control					✓						
Automated highway system					✓			✓	✓		
Autonomous vehicles					✓						
Probe vehicles				✓	✓		✓	✓	✓		✓
Vehicle detectors	✓		✓	✓	✓		✓	✓			✓
Objects & phenomena modelled											
Weather conditions							✓	✓			
Commercial vehicles		✓	✓	✓	✓		✓	✓	✓	✓	✓
Incidents	✓	✓	✓	✓			✓	✓			✓
Public transport vehicles	✓	✓	✓	✓				✓	✓	✓	✓
Traffic calming measures			✓	✓			✓	✓			✓
Queue spill back	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Weaving	✓	✓	✓	✓	✓		✓	✓	✓		✓
Roundabouts	✓	✓	✓	✓			✓	✓	✓		✓
Other properties											
Runs on a PC	✓	✓	✓	✓			✓				✓
Graphical Presentation of Results	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 4.2 compares the functionality of the Motorway micro-simulation models (from Institute of Transport Studies, University for Leeds, 2000)

Table 4.2: The functionality of the Motorway micro-simulation models (from Institute of Transport studies, University of Leeds, 2000)

	Autobahn	FREEVU	FRESIM	MIXIC	SISTM
ITS Functions modelled					
Co-ordinated traffic signals	✓				
Adaptive traffic signals	✓				
Ramp metering	✓		✓		✓
Freeway flow control	✓		✓	✓	✓
Incident management	✓		✓		
Zone access control	✓				
Variable message signs	✓				✓
Dynamic route guidance	✓				
Parking guidance	✓				
Automatic debiting & toll plazas	✓				
Adaptive cruise control	✓			✓	
Automated highway system	✓			✓	
Autonomous vehicles	✓			✓	
Probe vehicles	✓	✓			
Vehicle detectors	✓	✓	✓		✓
Objects & phenomena modelled					
Weather conditions	✓			✓	
Commercial vehicles	✓		✓		✓
Incidents	✓		✓		✓
Public transport vehicles			✓		
Queue spill back	✓	✓	✓		
Weaving	✓	✓	✓	✓	✓
Other properties					
Runs on a PC	✓	✓	✓	✓	✓
Graphical Presentation of Results		✓	✓	✓	✓

Most of the motorway models found in Table 4.2 concern themselves with replicating the various geometric parameters on the motorway as well as catering for ramp metering, speed control and VMS signs. The FREEVU model has been developed to specifically assess the impact of trucks on freeway operations. The German model AUTOBAHN allows a mix of traffic equipped with different automatic speed control systems to be modelled. However, along with MIXIC, it has only been calibrated with data from German Autobahns or on a driving simulator. FRESIM allows vehicles to react to static warning signs at the roadside. SISTM, developed for the Highways Agency by TRL, is discussed in detail in section 4.6.

Limitations of the packages on offer include difficulty in modelling very congested situations (as lane changing and gap acceptance behaviour can be very different) and often a requirement for further calibration and validation of the model. Practical problems of running such software can include long run-times, a requirement for multiple runs to obtain more reliable results, limited graphical output and the need to collect a wide range of geometric and traffic demand data.

4.4 Driving behaviour within microscopic models

4.4.1 Different methods used

To accurately model the driving behaviour within a microscopic model (car-following and lane changing behaviour), three different methods have been used. These are:

- **Neural network** – this method tries to simulate the functionality of the human brain. The neural network obtains data from the outside world which is fed through the network and produces an output (Lyons 1995).

- **Fuzzy logic** - this is a superset of Boolean logic that has been extended to cater for the concept of partial truth (i.e. truth values between "completely true" and "completely false"). Driver's decisions are therefore based on a set of "fuzzy" rules developed through experience (Kikuchi and Chakroborty 1993).

- **Mathematical equations** – This method is used widely in a large number of models to represent the driving decision process. Equations are derived which are then calibrated and validated using real data for a wide range of situations.

4.4.2 Mathematical car following models

There have been three main mathematical models used to replicate car following. These are:

- **Safety based** – this is a collision avoidance model developed by Gipps (Gipps 1981) where the driver of a following vehicle selects a speed to insure that even if the vehicle ahead stops suddenly, no collision will take place. This method is used by SISTM and is discussed in more detail in section 4.6.3.

- **Action point** – This model was developed by Michaels and Cozan (Michaels and Cozan 1963) and makes the assumption that drivers recognise their distance from the vehicle ahead by its changes in relative size as they approach it. They can also recognise the relative velocity through changes in the visual angle subtended by the vehicle ahead.

- **Scores and thresholds** – this model was developed at the General Motors Laboratory in Detroit (Chandler, Herman and Montroll 1958) and assumes that the acceleration of a vehicle is determined by the driver reactions to speed differences and relative distance.

4.4.3 Previous lane changing studies

The lane changing logic within microscopic models controls the lateral movement of vehicles on the mainline. As the decision process is complex, it can be difficult to replicate within a model. This process affects the lane distribution of the mainline. There is evidence that lane changing is the manoeuvre that causes more accidents on motorways than any other (Jeffcoate 1969).

Previous research has been carried out to examine this process in more detail, but mainly at a macroscopic level with point or area based observations allowing for the collection of lane changing rates and lane utilisations for a particular point or area of the mainline. These studies have examined the relationships between lane changing rates, flows and speeds. They have, however, provided little in the way of a derivation of lane changing rules.

A study in Germany (Sparmann 1979) assessed lane changing rates on a 1km section of the two-lane German motorway, with the use of detectors placed every 100m on both lanes. The results were based on microscopic data for 2000 lane changes and macroscopic values for 11000 lane changes. The research discovered that as the vehicle flow increased the lane changing rate increased rapidly at first, but then increased less proportionality until it reaches a maximum value of 600 lane changes/hr/km at a flow of 2000 veh/hr. As the traffic flow increased further, the lane changing rate decreased. The shape of the graph was determined by the demand for and supply of lane changing opportunities. As the flow increased, the demand for lane changes increased; the possibility to do so however decreased. Beyond a flow of 2000 veh/hr, this possibility was restricted. Drivers were also found to accept a smaller critical gap when leaving lane 1 for lane 2 than changing from lane 2 to lane 1. This behaviour led to an unequal lane distribution.

An American study investigated the macroscopic lane-changing process on uncongested multi-lane freeways, looking in particular at the inter-relationships between the traffic conditions and the lane changing frequency and fraction at two sites (Chang and Kao 1991). Results from the study showed that there was a high correlation between headway (mean and variance), speed, density ratios between neighbouring lanes and the lane changing rate (and fraction).

Another American study, based on field data from a 6-lane freeway in Chicago, considered the frequency and pattern of lane changing as well as the mechanics of the manoeuvre itself (Worrall and Bullen 1970). Results showed lane changing to be a random event in the traffic flow, subject to large variations at any point in space or time. The study agreed with Sparmann's finding regarding the lane changing rate rising with increasing flow and then decreasing. At first, drivers changed lanes to make progress through the traffic which became increasingly congested by these lane changes. As the traffic density increased, drivers became increasingly unable to make lane changes due to the decreasing number of suitable gaps. Three other key observations were:

1. The time taken to change lane varied between 2 seconds (at a flow of 1500 veh/hr/lane and at 65 kph) to 3.5 seconds (at a flow of 300 veh/hr/lane and at 125 kph).
2. There was no noticeable relationship between the size of gaps accepted in the target lane and the density in that lane.
3. The accepted headways tended to increase as the speed of the manoeuvre increased. It was thought that there was likely to be some dependence on either the lead or lag gap in an individual lane change, but not both. Average observed values in seconds were 1.1 to 2.9 in total, and 0.2 to 0.7 and 0.3 to 0.6 in lead and lag times respectively.

Research in the area of the accepted gap size was carried out by Pahl (Pahl 1972a and Pahl 1972b) at three freeway sites in the Los Angeles area. The sites consisted of an 8-lane, 6-lane and 4-lane freeway, each with a diverge and an upstream mainline section. Aerial data was used to determine the average spatial and time sizes of the accepted gaps and the lag gaps accepted by exiting vehicles as they approached the exit. For exiting vehicles, these accepted gaps reduced in size as they got nearer to the exit by reducing the lag gap. The study confirmed the general size of these gaps with their totals reducing from 6.0 to 3.7 seconds as the flow increased and lag gaps reducing from 2.7 seconds to 1.8 seconds. The study also showed how exiting vehicles changed lane more frequently to the right (or left in the UK) and mainline vehicles changed lane more frequently to the left (or the right in the UK). After the exit, these mainline vehicles were shown to move back to the rightmost lane (or the leftmost in the UK).

A more recent study looked at 2000 lane changes and found no relationship between headways (lead or lag) and the speed or relative speed of the vehicles involved (McDonald, Brackstone and Jeffrey 1994).

4.4.4 Mathematical lane changing models

Measurements of the parameters describing the lane changing process require a large data collecting exercise as a large number of variables which have influence over the process have to be measured at the same time. Given the relatively small number of empirical lane changing studies described above, it is unsurprising to note that the lane changing logic within microscopic models has been based mainly on certain well held beliefs regarding the decision making process, with little experimental calibration.

In microscopic models, three different mathematical models are used. These are:

- Safety based
- Action point
- Scores and thresholds

4.4.4.1 Safety based

This approach makes sure that any lane changing which takes place does so subject to a set of safety criteria. If a driver can not reach a speed that is within a set amount of his desired speed, then he will try to lane change. The driver's decision is dependent on how much the rear vehicle has to brake in order to avoid a collision. An example of this model is the Gipps model (Gipps 1981). The deceleration rates are compared with those used in the Gipps car following model to make sure the rear vehicle does not have to brake unacceptability hard. This maximum desirable deceleration rate can be increased where there is a particular need for drivers to be in a certain lane. This model can have limitations in that the driver does not show an increased desire to change lanes when he is behind a slower vehicle or enable the user to know when he will change lanes. It also has limitations in very congested situations where drivers 'force' their way into their destination lane, with drivers willing to accept this behaviour in these conditions.

4.4.4.2 Action point

This model was developed by Sparmann (Sparmann 1978) and later incorporated into the MISSION model (Leutzbach and Wiedemann 1986), which has been calibrated with real data from German motorways. The model represents human estimation of distances and speed differences in lane changing decisions. Two thresholds defined represent the distances at which it is possible to detect the approach of a vehicle in a neighbouring lane, based on the size of the relative velocities and changes in distance. These thresholds are also affected by the lane, lane type and type of lane change being considered.

Although these factors define a range (within which a vehicle must fall for it to be considered to make a lane change), they do not describe the conditions for which drivers actually would change lanes (e.g. gap size and speed difference). It is therefore assumed that these decisions are sampled from a normal or uniform distribution.

4.4.4.3 Scores and thresholds

This method potentially offers the most straightforward way with which to model the many factors affecting lane choice. In summary a driver's desire to change lane is modelled from the stimulus he feels from a range of scaled factors. Once compiled, these stimuli are compared against threshold values. If exceeded, the driver will change lane assuming the rear vehicle does not have to decelerate by more than a set amount. It is used within the SISTM model and is explained in more detail in section 4.6.4.

4.5 Model requirements for this research project

In order to model the capacity and safety of various diverge layouts, the tool used within this research project must have the following characteristics:

- Be adapted to model a range of diverge layouts including types with auxiliary lanes, lane drops, ghost island markings and slip roads with a variety of lanes.
- Be able to model vehicles individually so that individual results concerning parameters such as speed, journey time and lane changes can be obtained at

specific points before, on and after the diverge. Also, flows for particular time periods need to be obtained at specific points before, on and after the diverge.

- Be able to model differing diverging percentages leaving the mainline.
- Contain well established and researched lane changing and car following logic
- Be calibrated and validated against a wide range of observed data from various UK motorways.

There are a number of macroscopic motorway models which represent the movement of vehicles in quantities (flow, average speed and density) rather than individually. The SIMAUT model (Morin et al 1991) and the META model (Wang et al 2001) are examples of two such models. However, the assumption of traffic flow behaving in a similar way to a fluid negates the fact that traffic flow is composed of the movement of individual vehicles. These models have therefore not been seen to be as suitable for use during this research project as the microscopic models, which would provide individual vehicle results including speed, journey time and lane changing.

The modelling review resulted in the microscopic simulation computer program SISTM (TRL 2001a, 2001b and 2001c) being selected as a suitable tool to assess the effectiveness of various diverge layouts within this research program. A detailed review of the program SISTM is contained within the next section (section 4.5). It has been selected for the following reasons (although limitations in its use were subsequently found and are discussed in Chapter 10):

- It has been used within TRG (Transportation Research Group of the University of Southampton) on a number of projects including a recent project entitled "Access Control" commissioned by the Highways Agency. It has also been used by TRL on a number of related motorway projects for the Highways Agency (Hardman 1996; Harbord 1995; Hardwood 1993 and Hardman et al 1996).
- It has the ability to model diverges with or without lane drops. It can also be adapted to model Ghost Island diverges with two exit points.
- It can cater for motorways of up to six lanes. Diverging behaviour can therefore be assessed for motorways with a various number of mainline lanes.

- It has been carefully validated and calibrated using data from various UK motorways and provides the user with default parameter values.
- It produces a wide variety of output data including flow, speed, journey time and lane changing information at specific points/areas before, on and after the diverge by the use of psuedo-detectors.
- It has an awareness and aggression factor for drivers that may be useful when assessing drivers' reactions to different diverge layouts.
- Various road management strategies can be implemented such as the introduction of VMS signing (or other signing) and the imposition of variable speed limits.
- It is a non-commercial product and is therefore free for academic use subject to agreement.
- It is well documented in English.

4.6 SISTM

4.6.1 Introduction

SISTM (SImulation of Strategies for Traffic on Motorways) is a microscopic simulation computer program, developed by the Transport Research Laboratory (TRL) for the Highways Agency (HA), to model motorways of up to 6 lanes.

The role of the model was clearly defined by TRRL (now TRL) for Wootton Jeffreys Consultants in August 1988. It was "to aid in assessing the potential benefits of strategies employed to improve the flow of traffic on congested multi-lane motorways" (Wootton Jeffreys 1990). The job specification also stated "that it should be used to assess congested motorways" (Wootton Jeffreys 1990).

Individual vehicles and their interactions are modelled such that it can replicate in detail the behaviour of congested motorways. The program can model up to 99km of carriageway, with a maximum number of vehicles on the network at any one time of 9,600. It can cater for 39 links on the motorway, 10 origin zones and 10 destination zones (i.e. 9 merging and 9 diverging slip roads) and up to 8 vehicle classes. The normal simulation period adopted is 3 hours and 10 minutes, based on 5 minute time slices. The O/D matrix is designated into 5 minutes time slices across the modelled period. The program operates on a fixed time increment of 5/8ths second. This time is used in the driver's reaction time algorithms as the minimum response time for a driver.

SISTM can be used as a tool to help in the design and evaluation of traffic management measures designed to reduce motorway congestion. It is a very transparent model in the way it allows users to change the vast majority of input values (see Appendix C). A real time coloured animated representation of the vehicles on the network is shown on the computer display during the simulation. A variety of data is produced from up to 99 pseudo detectors that show speed, flow, occupancy, time headways and lane changing stimuli for each lane.

The program has been developed over the last 15 years for the Highways Agency with version 1.0 released in July 1990, at the end of the first contract with Wootton Jeffreys Consultants. This version was then delivered for the first time to TRL. A Windows version of the main simulation program appeared with version 4.3 in May 1997. The latest version, 5.3, was released in July 2001 with additional ramp metering features.

4.6.2 Modelled vehicle behaviour in SISTM

In the model, each vehicle is seen as a combination of both a vehicle with fixed performance characteristics (e.g. length and braking rate) and a driver who has choices about how to use the performance of the vehicle. The driver can be seen as responding to stimuli around him. In the model, vehicles are generated and given performance parameters that constrain how the driver can use the vehicle. Drivers are also given attributes and are then paired with vehicles.

SISTM represents driving behaviour according to eight awareness and aggression bands. Factors such as gap acceptance, acceleration, maximum speed, likelihood of a lane change and size of headway are parameters that vary according to these two parameters (Druitt 1998). Two distributions based on drivers awareness and aggression has proved sufficient to include the majority of drivers' behaviour. Druitt states that "behind the randomness of the traffic flow, lies a complex order based on simple rules of car following, gap acceptance and vehicle kinematics (e.g. size, acceleration/deceleration and the ability to change lane)". These two parameters, aggressiveness and awareness, are used to produce distributions of desired speed and indirectly headway. Lane changing is controlled using a lane changing stimulus which can be user-defined to specify the desire to change lanes. Drivers are allowed to accept an unsafe headway temporarily when changing lanes to allow smoother merging to take place when a driver has to move into a particular lane.

The SISTM control file contains P values (parameters), T values (thresholds) and F values (factors) which control the behaviour of vehicles via the car following and lane changing algorithms. The program uses a combination of P, T and F values to model vehicle behaviour. The dependencies between these values are complex.

Many of these values have been derived from an iterative process of changing the values and then observing the modelled behaviour (Wootton Jeffreys 1992).

4.6.3 Car following logic

The main assumption of the model is that the decision of the driver will be made at the end of a given reaction time. This reaction time is equal to the chosen epoch length. The vehicle/driver therefore will have responded to the driver in front in the previous epoch. The current epoch length in SISTM is $5/8^{th}$ second.

The car following algorithm is a fundamental component of the model and describes the movement of individual vehicles within a platoon. Models developed in the 1960's assumed that a following driver adjusts speed according to stimuli perceived from the leading vehicle. This proved to be unsatisfactory in the full flow range experienced on traffic networks. The Gipps model (Gipps 1981), developed in the early 1980's was based on collision avoidance. It assumes that drivers follow a leading vehicle at a safe distance (i.e. a distance allowing them to stop without collision should the driver ahead come to a sudden stop). In practice, many drivers do not leave as large as gap between themselves and the car ahead as the Gipps model assumes. Also, the behaviour of drivers is not entirely dependent on the vehicle ahead.

Drivers can anticipate and alter their behaviour by looking at the traffic further upstream. SISTM uses a modified Gipps car following algorithm.

In order that collision avoidance occurs within the model, vehicles must adopt a speed that is consistent with the vehicle ahead. Each vehicle class has an associated acceleration rate, which are allocated into 4 ranges of desired speed. This speed is calculated so that if the car in front brakes at the maximum rate, the vehicle behind will not collide into it. These braking rates are inputs in the data file. There are in fact four braking rates in SISTM; the maximum desired, the perceived maximum, the acceptable maximum lead and the acceptable maximum lag braking rates. The acceptable lead and lag braking rates can be seen as the 'comfort' braking rate of vehicles.

Vehicles will always try and accelerate to their desired speed. The desired speed is entered as a distribution. The rate of acceleration depends on the vehicles attributes, the perceived change of speed of the vehicle in front (represented by parameter P8), other vehicles wishing to move into a gap in front of the current vehicle and the speed change of vehicles in adjacent lanes. Also, speed friction (the relative speed at which vehicles pass adjacent lanes) may cause a change in speed. P12, P13 and P14 determine this relative speed for overtaking vehicles, passing vehicles on a merge slip road and undertaking vehicles respectively.

Vehicles are assigned lanes at the start of the network according to two parameters; P21 representing the mean speed of the vehicles and P22 representing the width of the speed band (for 3 lanes or more). For example if P21 = 110kph and P22 = 20kph then for desired speed V:

2 lanes	V <= 110kph	Lane 1
	V > 110kph	Lane 2
3 lanes	V <= 100kph	Lane 1
	100 < V <= 120kph	Lane 2
	V > 120kph	Lane 3

4.6.4 Lane changing logic

All vehicles are checked for lane changing possibilities in order to monitor their progress through the motorway network. The algorithm has a three stage sequence of decisions and two possible stages of action. The 'T' and 'F' parameters within the control file are applied to these tests. The algorithm is an iterative process.

4.6.4.1 Decision 1 – Lane changing possibility

SISTM determines whether a vehicle wishes to merge or diverge. If so, it then determines whether the lane change is to the left or the right. It is also checks that the manoeuvre is permitted. The parameter T3 reduces weaving by ensuring that a certain time period elapses before a vehicle can change back into the lane it has just moved out of (normally 8 seconds).

4.6.4.2 Decision 2 – Lane changing desire

In order for a vehicle to change lane, it must generate a desire or score that is measured through a +ve or –ve stimulus. Scoring is an integral part of the SISTM model and causes vehicles to have stimulus to change lanes, merge or diverge. The effects of the scores are dependent on threshold values within the control file. At a diverge, there are four specific points, only two with a lane drop. The scores are normally in ascending order e.g. 10, 20, 50 and 100. Additional scoring for diverges are implemented with signing (normally 1000m, 500m and 100m from the diverge point). This enables the user to influence the behaviour of diverging vehicles prior to the diverge. The total stimulus is

F1 * positive right hand speed advantage – F2 * positive left hand speed advantage (if aggressiveness > T4)

The positive right/left speed advantage is calculated for each vehicle in each epoch. It compares the vehicles current speed against the speed that it could achieve in the lane to the vehicles left or right. Special stimulus can be added to the total stimulus if the vehicle wishes or is forced to move out of its current lane, or if the total stimulus alone would force it into a lane that it will shortly have to leave. For example, at a merge or diverge, there would be an additional factor of

+F4*merge score
-F5*lane drop/diverge score
+F5*move banned vehicle class out of lane score
+F5*dedicated O-D lane score.

The total stimulus (negative or positive) is then compared to threshold values T9 (to go left and a –ve value) and T10 (to go right and a +ve value). If the total stimulus (plus the special stimulus if appropriate) is above either of these thresholds, then the vehicle will desire to change lane.

The current default values in the control file for these parameters are:

F1 = 15	T4 = 6
F2 = 4	T5 = 2
F3 = 4	T8 = 31
F4 = 4	T9 = -89
F5 = 2	T10 = 90
F6 = 100	

These default values have been calibrated through an iterative process using real data. F1 (factor for right hand speed advantage) is considerably higher than F2 (factor for left hand speed advantage). This encourages vehicles to overtake rather than undertake, thus replicating observed behaviour.

4.6.4.3 Decision 3 - Lane changing opportunity

Once a vehicle has a desire or stimulus to change lane, SISTM calculates whether there is such an opportunity. This assessment is performed through calculating the effect the vehicle will have on the lead and lag vehicle in the lane it wishes to move into. The lead and lag headways are based on the maximum and minimum lead and lag braking rates. If these are unacceptable, then the vehicle will not change lane. This situation is only changed if the stimulus exceeds thresholds T16 and T17 (defaults as 120 and –120), indicating that the vehicle is desperate to change lane. These thresholds need to be higher than T9 and T10. If the vehicle passes these tests then it will change lane (action 1). If the vehicle has sufficient stimulus, it will speed match to find a gap (action 2).

This lane changing logic in SISTM can lead to problems with regards to some vehicles not reaching their correct destination (see section 7.2.4). Vehicles wishing to diverge are identified within the network and colour coded in the visual display. This is particularly useful in helping the user to check that vehicles are reaching their correct destination.

4.6.5 Aggressiveness and awareness

Awareness and aggression are the two behavioural characteristics of drivers. Each vehicle is assigned an awareness and aggressiveness number between 1 and 8. Awareness is an arbitrary number used to decide how the driver responds to the behaviour of other traffic. A more aware driver would be more likely to move back into the left hand lane after overtaking, let a vehicle out from the slip road and be more courteous and knowledgeable. Aggression is also an arbitrary parameter that is used to decide the desired headway and lane changing/gap acceptance of the particular driver, from the desired speed distribution. An aggressive driver is one who would be more likely to change lanes and have a higher desired speed. Table 4.3 (Wootton Jeffreys 1990 and 1992) shows the expected driving behaviour for low medium and high levels of awareness and aggression.

Table 4.3: Likely driving behaviour for different levels of awareness and aggression

		Aggressiveness		
		Low	Medium	High
Awareness	Low	Slow driver, Lane hogging, 'Sunday driver'	Tired normal driver	Reckless driver in a hurry
	Medium	Normal driver in no hurry, Holiday behaviour	'Normal' behaviour	Normal driver in a hurry – Friday PM behaviour
	High	Experienced driver in no hurry	Experienced driver in normal conditions	Very experienced driver, e.g AM or experienced driver in a hurry

4.6.6 Calibration and validation

The original model was calibrated on data from the 3 lane M27 in 1991 (Hardman and Taylor 1992). In most cases, the parameter values were assumed to be fixed. The model was later extended to cater for motorways of up to 5 lanes and to allow some of the parameters to be user defined rather than fixed values. Vehicle data in time periods of 5 minutes from the M25 (between J12 and J13) and the M20 (between J8 and J7) were used to validate the model for 4 and 5 lane carriageways. As a result of the new validation exercise, three major changes to the parameters were made. These were:

- An increased braking rate of 5.2 km/hr/sec was adopted.
- Drivers would only notice a higher speed change of 5 km/hr rather than 2 km/hr.
- An improved simulation of queuing behaviour resulting from changes to the lane changing algorithms.

The validation exercise showed that SISTM reproduced the flow/time profile accurately but its predicted speeds fell earlier than the actual speeds observed on the M25. A similar exercise on the M20 showed an accurate representation of the speed/flow data, although some of the speeds were slightly higher than observed. A further validation exercise of SISTM used vehicle data collected in 1-minute intervals. SISTM had more problems replicating the flow behaviour for the 1-minute intervals than for the 5-minute intervals, particularly in replicating shockwaves. The original model had assumed that shockwaves do not occur as a result of lane changes whereas in reality they can do so. It is also unclear exactly how much specific validation of the driving behaviour near the diverge area was carried out

4.6.7 Input data required

A variety of input is required to run SISTM. This includes:

- Vehicle data (lengths of vehicles, acceleration and braking rates, effects of gradients)
- Desired speed distributions

- Detailed geometry of the motorway system (e.g. number of mainline and slip lanes, gradients, type of merge/diverge layouts with or without a lane drop and the location of signs)
- Traffic demand data in 5 or 15-minute intervals entered by the user as an origin-destination matrix.
- Traffic management measures in force.

The following data is requested by SISTM but it has no effect on the simulation:

- Environmental conditions
- Radii of curvature of bends in road
- Lane widths
- Vehicle widths
- Presence of hard shoulder
- Angle of slip road lanes to main carriageway

4.7 Summary

This chapter contains a review of microscopic simulation models. A microscopic model will be used in this research to evaluate various existing and alternative diverge layouts in terms of their capacity and associated operation. The modelling work will provide important information regarding the capacity and operation of diverges that the diverging flow-region diagram, the video trials or questionnaire survey could not such as individual vehicle data concerning speed, lane changes and journey times. It will also enable each of the layouts to be tested to assess the range of mainline and diverging flows they are best suited for. An explanation is given as to why the microscopic model SISTM was chosen as a suitable tool for this research work.

A microscopic simulation is a computer program designed to model traffic at the level of an individual vehicle. Simulated vehicles move through a simulated network dependent on a number of parameters such as geometry, driver behaviour, vehicle characteristics, gap acceptance, car following and lane changing behaviour. These software packages are becoming an increasingly important tool for the development of various traffic control strategies (e.g. variable speed limits and the introduction of

VMS signs). They give traffic engineers a “bird’s eye” view of the traffic within the network and an opportunity to try out various techniques without any disruption to real traffic.

Microscopic simulation models can be categorised into five categories depending on the traffic situation they were intended to model, i.e. Urban, Motorway, Combined Urban and Motorway, Automated Highway Systems (AHS) or Other. The Combined Urban and Motorway and Motorway models have then been compared in relation to a number of criteria.

The tool used within this research must have various characteristics which include the ability to model various diverge layouts and slip road of various numbers of lanes, as well as the ability to obtain individual vehicle parameters such as speed, journey time and lane changes for a specific point/area before, on or after the diverge. There are a number of macroscopic motorway models which represent the movement of vehicles in quantities (flow, average speed and density) rather than individually. However, these models have not been thought to be as suitable for use for this research work as the microscopic models.

The driving behaviour (car following and lane changing logic) within microscopic models was reviewed, assessing the strengths and weaknesses of the various approaches. Previous empirical lane changing studies were also reviewed to determine their impact on the development of the lane changing logic within the models. It was discovered that the lane changing logic within microscopic models has been based mainly on certain well held beliefs regarding the decision making process, with little experimental calibration.

SISTM was seen to be a good microscopic simulation package for motorway networks and selected for use during this research project. It has been selected for a number of reasons including the fact it has been extensively calibrated and validated using observed data from UK motorways. It can also be adapted to model a range of diverge layouts including the Ghost Island diverge with two exit points. SISTM also produces a wide variety of output data including flow, speed, journey time and lane changing information. A detailed analysis of this package was carried out including its car following and lane changing logic, its practical usage, data requirements and its validation and calibration.

CHAPTER 5

A PRELIMINARY MODELLING EXERCISE IN SISTM

5.1 Introduction

In order to become familiar with SISTM and its capabilities, a preliminary exercise was carried out on a section of the M27. This work was part of a TRG project for the Highways Agency entitled "Development of an Access Control Methodology" (TRG 2002). SISTM was to be used as a microscopic model to assess various access control strategies, including ramp metering.

The network to be modelled was the M27 westbound carriageway upstream of Junction 8 to downstream of Junction 5, during the morning peak period (07:00 – 09:30). This included three junctions each with a merge and a diverge. The modelled section of the M27 was a 3-lane carriageway except for the stretch between J8 and J7 which was a 4-lane carriageway. All slip road merges and diverges had 2 slip lanes.

5.2 Setting up the model

SISTM is actually a suite of computer programs. QVNET is used first to define the basic structure of the network in terms of links and nodes. SISQV is then used to add further information to the basic network. SIMENT is the main interactive data entry program defining the vehicle and driver characteristics, the network geometry, any traffic management measures and the origin-destination demand flows. SIMDAT checks the data in SIMENT to make sure it is correct and produces an interim file. SIMCNT is another interactive data entry program which defines the driver behaviour and the type of output required by the user. Finally, SIMRUN is the main simulation program. Figure 5.1 shows the network depicted in the SISQV screen, as modelled in SISTM.

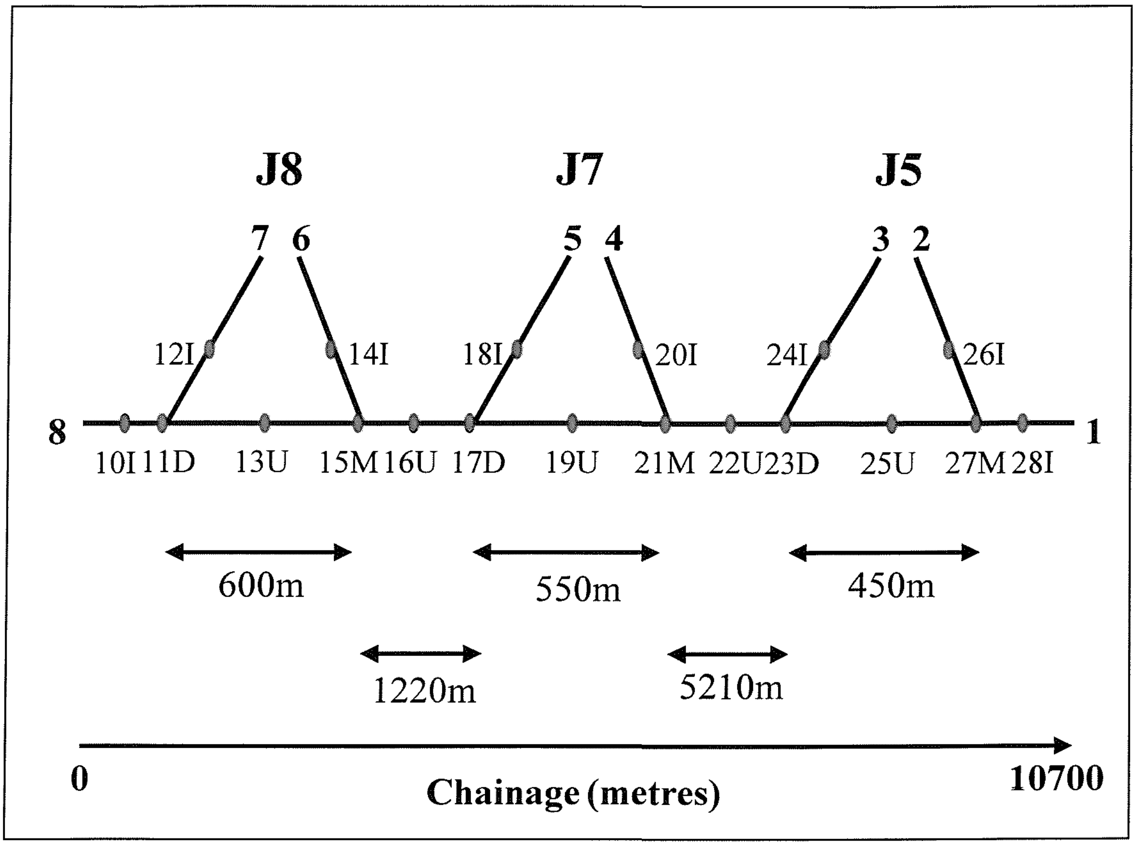


Figure 5.1: Modelled network in SISTM

There are 27 nodes in the model. These are:

- 4 origin nodes (8, 6, 4 and 2)
- 4 destination nodes (7, 5, 3 and 1)
- 3 diverge nodes (11, 17 and 23 denoted by a D)
- 3 merge nodes (15, 21 and 27 denoted by an M)
- 8 interface nodes representing the upstream/downstream limits of the node (10, 12, 14, 18, 20, 24, 26 and 28 denoted by an I)
- 5 Unclassified nodes (13, 16, 19, 22 and 25 denoted by a U) used as an interface node between a diverge and a merge node.

Each node is defined by a series of chainages (or distances) in metres from the origin. These geometric measurements were obtained from various maps and drawings in order to obtain an accurate model. Appendices C and D contain sample SISTM input and output files respectively.

5.3 Traffic demand data

The demand flow data had to be entered into SISTM in the form of an origin-destination table. The flow data obtained from the MIDAS loops had been entered into a macroscopic route assignment model CONTRAM which then provided predicted origin-destination flow data. The data was split between two vehicles classes; light vehicles and heavy goods vehicles (HGVs). HGV's were only about 1% of the overall traffic composition which was low compared to the standard composition in TD22/92 (Department of Transport 1992a). However, for the purpose of this preliminary exercise, this was not important as further consideration of how the traffic composition affects capacity is discussed in detail in Chapters 6 and 8.

It is recommended in SISTM to have at least two categories of each vehicle class. This is because SISTM can only generate one vehicle per vehicle class per origin-destination movement per second. The CONTRAM data was therefore modified to produce a new origin-destination table with four vehicle classes. This data was then entered into SISTM. These origin-destination tables are shown in Tables B.1 and B.2 in Appendix B.

5.4 Psuedo-detectors in SISTM

In order to obtain average speeds and flows at various strategic points on the mainline and the slip roads, psuedo-detectors were installed within the model. The demand origin-destination flows did not indicate what the precise link flows would be for a particular time period. The average speeds varied according to the positioning of the pseudo-detectors. The slowest point on the mainline was generally just downstream of the merge. Ten detectors were installed, one on each of the six slip roads (D1, D2, D5, D6, D9 and D10) and four on the mainline (D3, D4, D7 and D8). Detectors D3 and D4 covered four mainline lanes. Figure 5.2 shows the location of these detectors within the model.

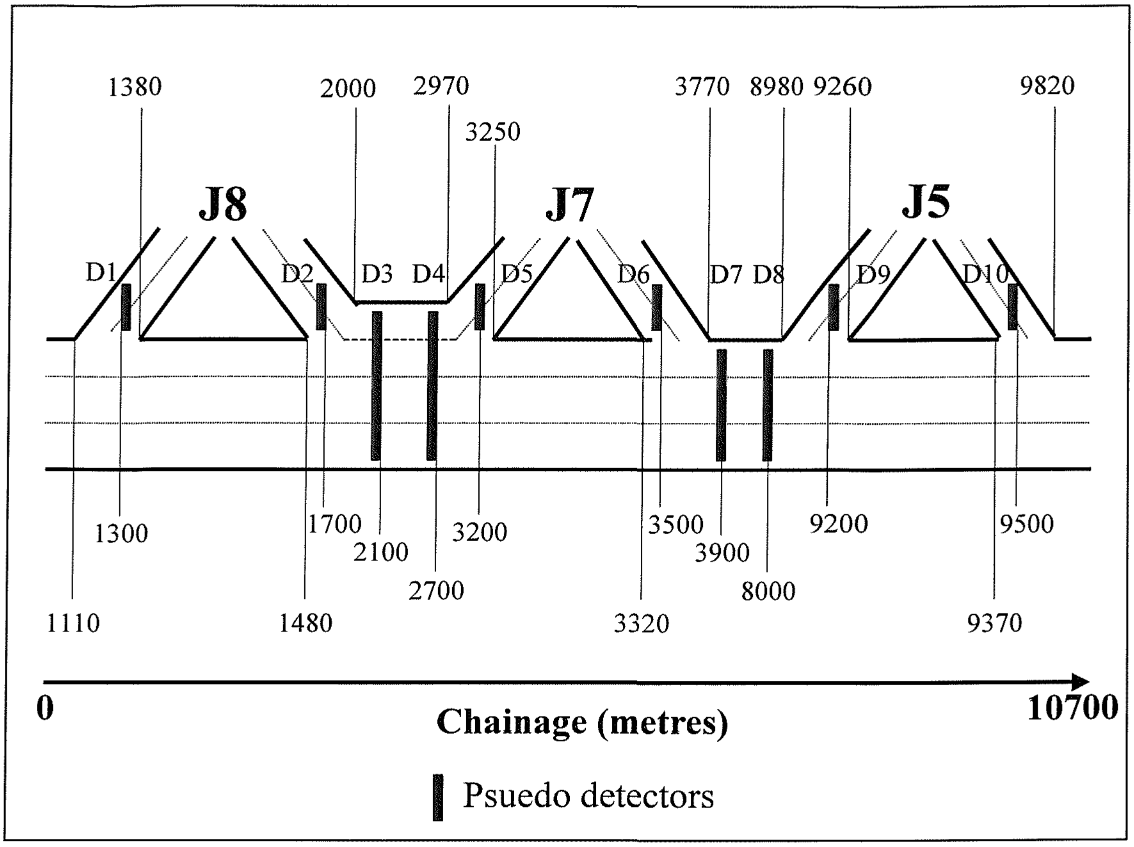


Figure 5.2: Location of psuedo-detectors in the M27 SISTM model

5.5 Results from SISTM

5.5.1 Introduction

This preliminary modelling exercise was helpful in making sure that SISTM was used in such a way as to obtain the most reliable results possible. Several runs were carried out with different random seed numbers in order to reflect the random nature of the traffic. A warm up time of at least 10 minutes was required to fill the motorway network up with traffic. The results obtained from SISTM were average speeds and vehicle flows from the 10 pseudo-detectors as well as journey times for three specific routes. These are shown in section 5.5.2 and 5.5.3.

5.5.2 Flow and speed results

The detailed flow and speed results are contained in Appendix B. Tables B.3 and B.4 show the average speed (kph) and the total flow (veh) respectively over the modelled period. Table B.5 shows the total flows as in Table B.4 but as rates per hour.

The average speeds on the mainline remained high (i.e. between 95 – 105 kph). This is expected as the vehicle flows used in the model were generally within capacity. The time period with the highest flows overall was 07:30 – 07:45. Figure 5.3 shows a pictorial representation of the speed and flow results from the 10 pseudo-detectors.

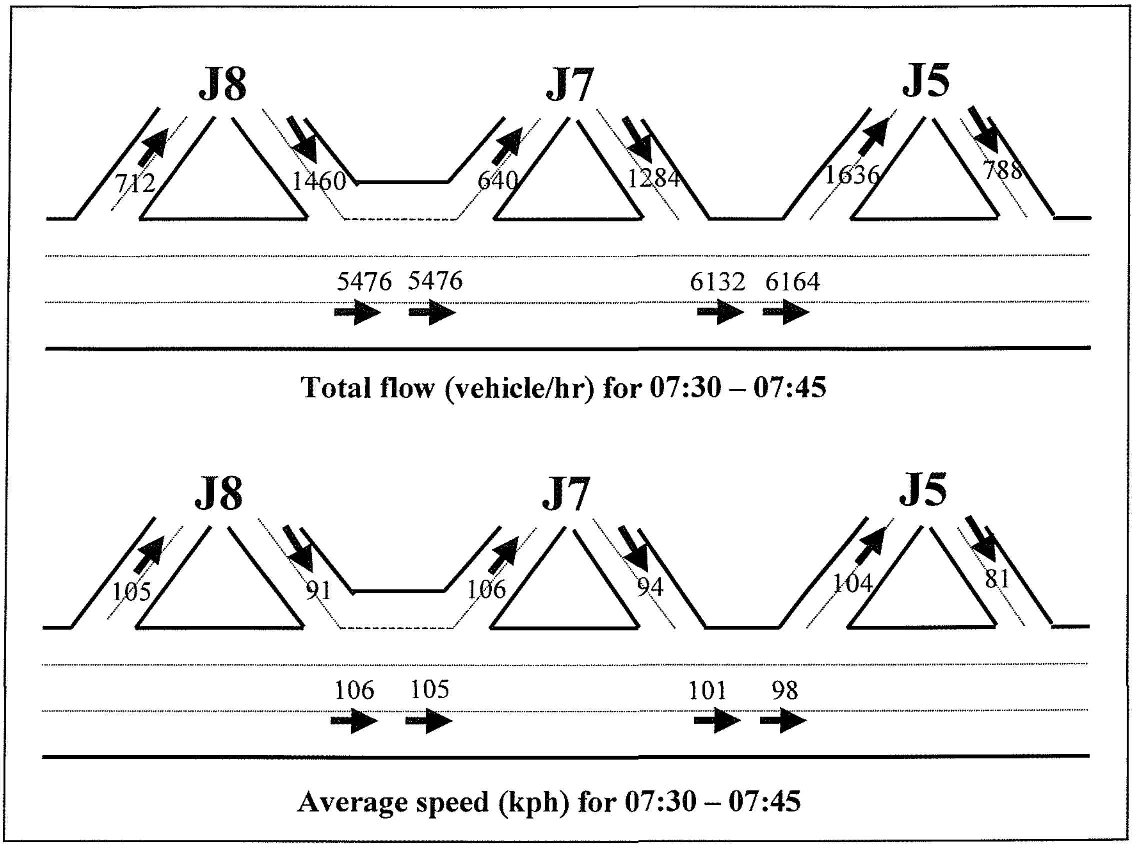


Figure 5.3: Total flows and average speeds for 07:30 - 07:45

The average speeds on the merging slip road were generally higher in slip lane 2 than slip lane 1. SISTM models the merging slip road in a similar way to the mainline with the same lane changing and car following logic applied. Vehicles will only use slip lane 2 to overtake slower vehicles in slip lane 1. After overtaking, they will return to slip lane 1. As the demand flows are well within capacity, there is a much higher proportion of vehicles using slip lane 1 as opposed to slip lane 2. It is important to note that the slip lane distribution was not being modelled in this exercise. Exit blocking which may occur at peak periods was also not being modelled.

The average speed at the start of the exit slip road was normally slightly higher in slip lane 1 than slip lane 2 (or similar). In SISTM, when a vehicle wishes to leave the mainline, it is unaware of the fact that there are two exit slip lanes. The second slip lane is only used if the vehicle misses the first exit by either not being in lane 1 early enough or by a vehicle in lane 1 blocking access to the first slip lane. This means vehicles using the second exit will have had to reduce speed in order to find a gap in lane 1 in which to change lane. As the exiting demand flows in this exercise were well within capacity, there was a much higher proportion of vehicles using slip lane 1 as opposed to slip lane 2 (as with the merging slip roads).

5.5.3 Journey time results

SISTM can provide journey times for specific origin-destination movements and/or from and to specified chainages. Journey times for three different routes were collected by SISTM both for light vehicles and HGVs. The three routes were as follows:

J1: Start of Junction 8 to the exit point of Junction 5 (from chainage 1480m to 8980m)
J2: Start of Junction 7 to the exit point of Junction 5 (from chainage 3320m to 8980m)
J3: Start of the mainline to the end of the mainline (chainage 0m to 10700m)

The three routes are shown in Figure 5.4.

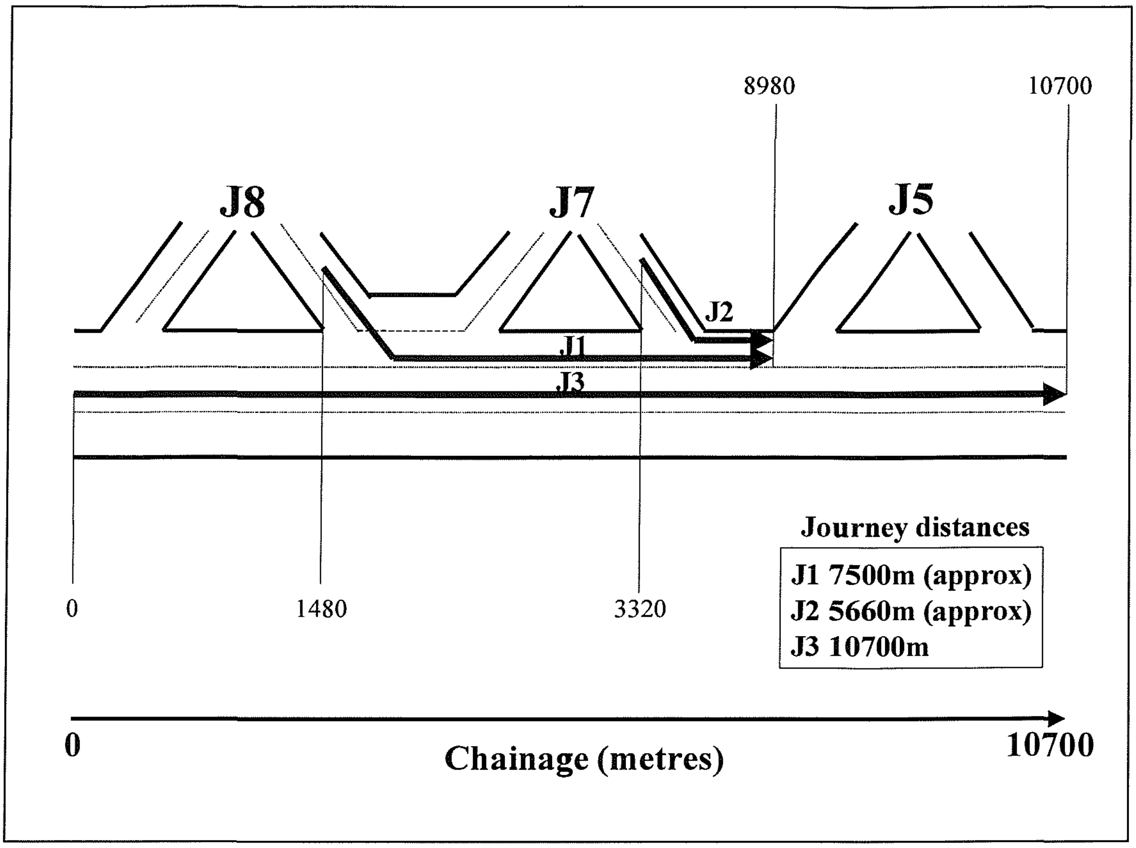


Figure 5.4: Three routes analysed in SISTM

Table 5.1 shows the average journey times for J1, J2 and J3 for light vehicles and HGVs respectively. The light vehicles were on average travelling 13 kph faster than the HGVs (101 kph compared to 88 kph). but a bigger sample of HGVs would have improved the reliability of the results.

Table 5.1: Average journey times for routes J1, J2 and J3

	Light vehicles		HGVs	
	Average journey time (secs)	Number of vehicles sampled	Average journey time (secs)	Number of vehicles sampled
J1	204	768	235	3
J2	271	766	350	1
J3	375	841	432	11
Overall	286 (101kph)	2375	387 (88 kph)	15

5.6 Summary

In order to become familiar with SISTM and its capabilities, a preliminary exercise was carried out on a section of the M27. This work was part of a TRG project for the Highways Agency entitled "Development of an Access Control Methodology". SISTM was used as a microscopic model to assess various access control strategies, including ramp metering. The network to be modelled was the M27 westbound carriageway upstream of Junction 8 to downstream of Junction 5, during the morning peak period (07:00 – 09:30).

This preliminary modelling exercise showed that SISTM has a wide capability and provides a wide range of output data. The flow, speed and journey time results appeared realistic and found a basis for a more detailed testing/validation exercise described in the next chapter.

CHAPTER 6

INITIAL TESTING OF SISTM

6.1 Introduction

Before using SISTM to model various diverge layouts to assess their throughput and operation, it was first necessary to check that the output from the program was sensible and realistic when either validated with real data (when available) or checked to see it was a logical expectation. Noticeable differences between observed and modelled data can then be noted and assessed to see how critical they are. The modelling work can then be carried out in areas where the model is giving good and reliable results.

In order to check that the results from SISTM are similar to observed results, a set of tests were carried out at a Taper diverge. A Taper lane drop diverge was also used to look at lane changes on the mainline. The model used was based on Junction 5 westbound on the M27, near Southampton. Pseudo-detectors were installed within the model at various places in order to obtain information regarding speed and flow. Unless stated otherwise, a mainline demand flow of 6500 veh/hr was used as this has been shown to generate a detector flow that causes congested conditions but not flow breakdown (see Figure 6.1). A diverging percentage of 30% was used as this corresponded to the proportion leaving the mainline at Junction 5 of the M27 in the morning peak period. The traffic composition was set at 85% light vehicles and 15% heavy vehicles with 0% gradient on the mainline. Where real data had been available, a comparison was made of the observed and modelled results.

A series of tests were devised in order to give an assessment of the results from SISTM over a wide range of different situations. The tests cannot prove that the driving behaviour in SISTM is correct as only the results are being compared. However, the tests themselves provide a good indication of the way SISTM performs, the output it gives and how particular parameters have an effect on the throughput and operation of the diverge.

The tests have focused on the following areas:-

1. Speed/flow relationship.
2. Lane utilisation.
3. Average speed and its distribution.
4. Gradient on the mainline and the slip road.
5. Vehicle composition (percentage of HGVs).
6. Lane changes.

6.2 Speed/flow relationship

6.2.1 Introduction

The speed/flow relationship within SISTM was investigated to see if it accurately represented real data from the M27. For these tests, the HGV percentage was 0% in order to achieve a homogeneous flow. There is no assumed speed/flow relationship or curve in SISTM as it is modelling microscopic behaviour. In order to clarify this relationship, two tests were carried out. These looked at the relationships between the:

- Detector flow and average speed (for each mainline lane)
- Demand flow and detector flow

6.2.2 Detector flow and average speed (for all lanes and each lane)

For the first test, the relationship between the total detector flow and the average speed on the link between J7 and J5 was examined. A pseudo-detector was placed about 1km upstream of the J5 exit. It showed that once the total flow reached about 6500 veh/hr, there was a noticeable drop in the average speed for all lanes (see Figure 6.1). Figure 6.2 shows the detector flow against average speed for lane 1, lane 2 and lane 3 respectively. It also shows a sharp drop in speed for each lane (particularly lane 3) once the flow reaches about 2200 veh/hr.

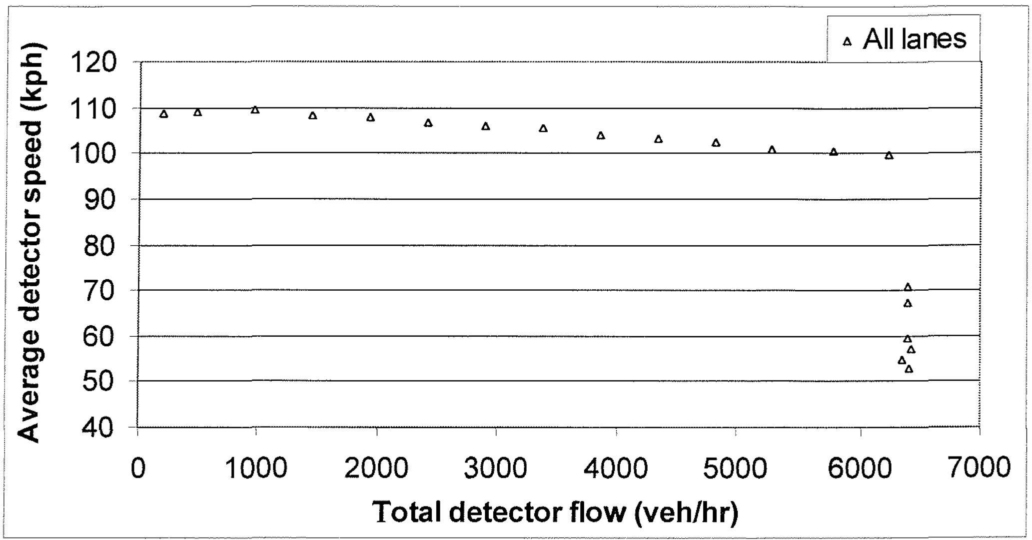


Figure 6.1: Mainline detector flow against average speed for the mainline lanes

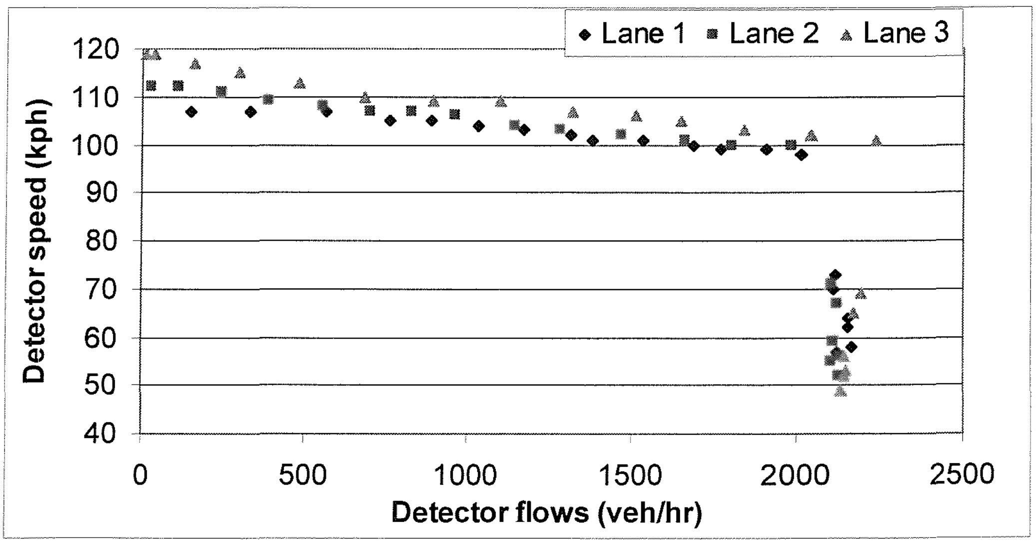


Figure 6.2: Detector flows against average speeds for the mainline lanes

The speed-flow results from SISTM were compared with observed speed-flow results from Midas loops on the M27 for all mainline lanes between J7 and J5. Figure 6.3 below shows the two sets of results plotted on the same graph so they can be easily compared.

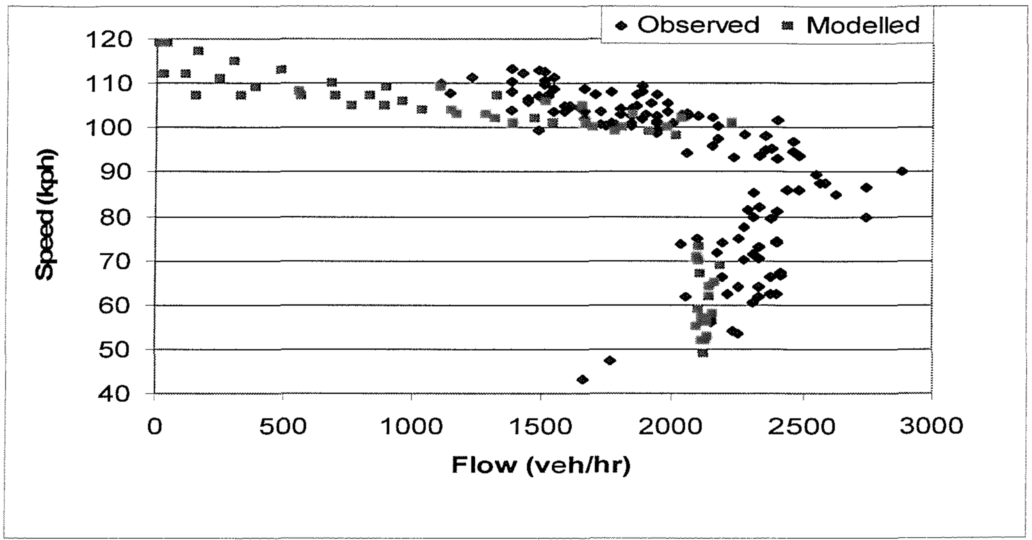


Figure 6.3: The observed and modelled speed-flow results on the M27

The observed and modelled results match reasonably well but differences do occur. The observed flows do not go below 1000 veh/hr as they were taken from Midas loops during the morning peak period. The flow started to noticeably decrease at about 2200 veh/hr per lane from the Midas data (from Figure 6.3) but this figure can change with a different section of motorway with different geometry (e.g gradient and horizontal alignment) as well as different weather conditions and percentage of HGVs. A small proportion of the Midas data is at flows in excess of 2500 veh/hr. This seems very high and may be due to the inductive loops over counting the flow. With SISTM, a mechanistic model, the mainline flow noticeably decreased at a similar figure to the Midas data of about 2200 veh/hr per lane. SISTM does have difficulty in replicating conditions after flow breakdown but the speed-flow curve produced by the model are similar to the ones contained within the Highway Capacity Manual as shown in Figure 6.4 (Transportation Research Board 2000).

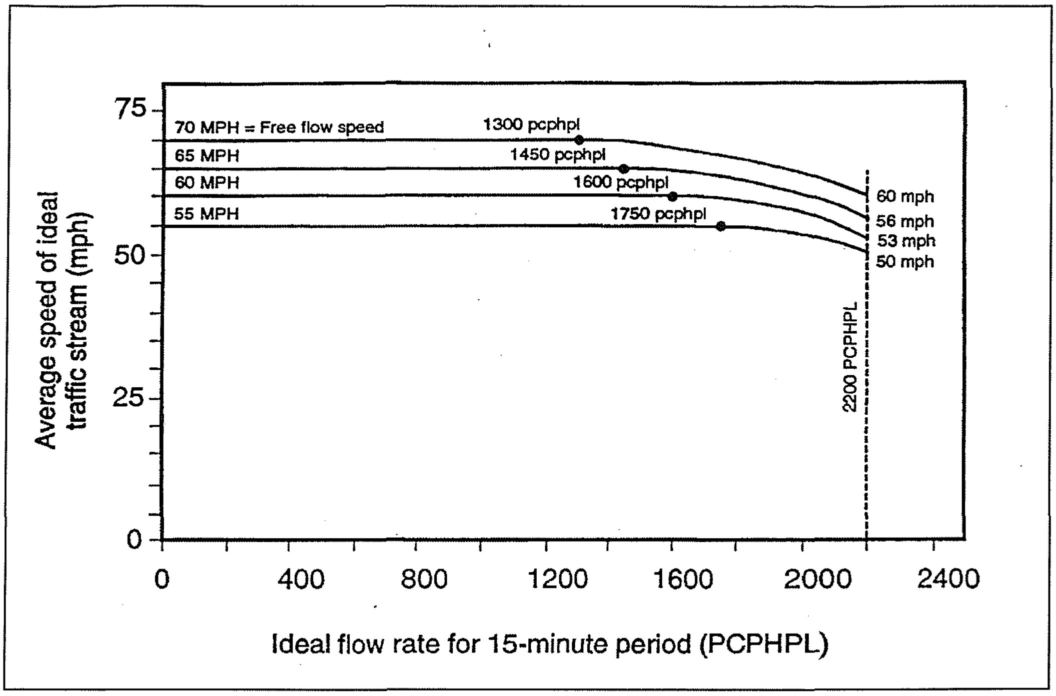


Figure 6.4: Highway Capacity Manual speed-flow curves for basic freeway sections

6.2.3 Demand flow and detector flow

For the third test, an investigation was carried out on the same 3-lane carriageway between J7 and J5 to clarify the relationship between the demand flow and the actual detector flow. This showed an approximately linear relationship between the demand flow and the actual detector flow until the capacity of the mainline was reached (see Figure 6.5). However, for demand flows of about 6500 veh/hr and above, the detector flow remained at between 6400 – 6600 veh/hr, the modelled capacity limit for the 3-lane carriageway. This is as expected.

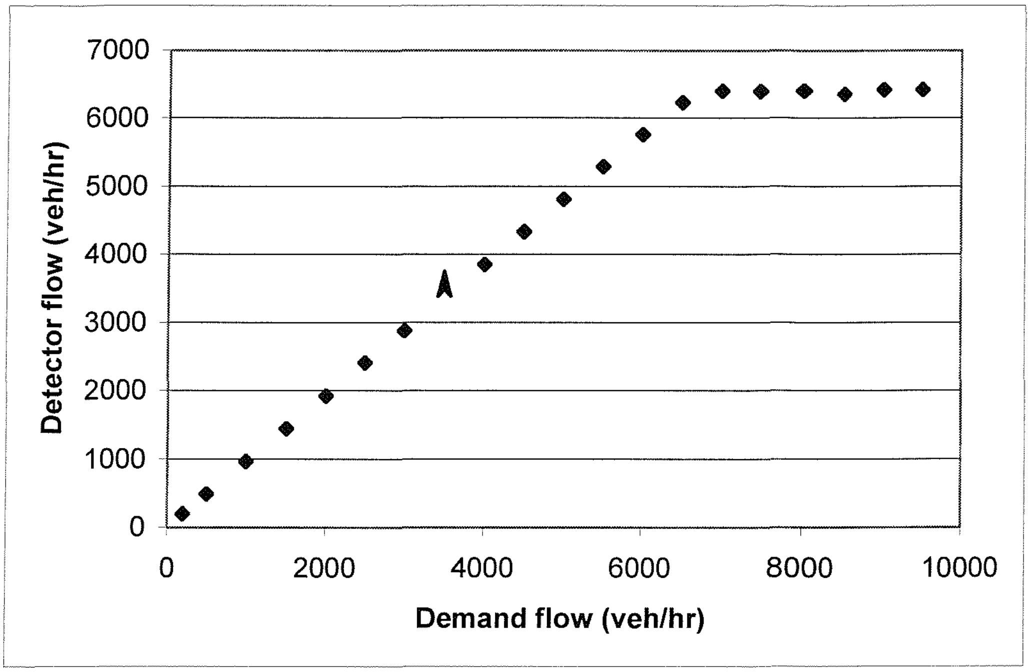


Figure 6.5: The relationship between demand flow and actual detector flow

6.3 Lane utilisation

6.3.1 Introduction

Lane utilisation is defined as the proportion or percentage of vehicles using each of the mainline lanes or slip lanes. It is an important measure particularly in relation to a diverge as normally drivers wishing to exit the mainline need to be in lane 1 prior to the slip road. The utilisation of lane 1 in particular can vary according to flow, distance to the diverge and the diverging percentage. Three tests have been carried out in order to investigate lane utilisation. These looked at the relationship between :

- Mainline flow and the lane utilisation
- Distance from diverge and the lane utilisation
- Diverging percentage and the lane utilisation on the mainline and slip road

6.3.2 Lane utilisation with increasing mainline flow

The first test was carried out to see how the utilisation of each individual lane on the mainline varied as the mainline flow increased.

A psuedo-detector was placed on the mainline approximately 2km from the diverge. The demand flow was increased by 1000 vehicles per hour on each run. For each demand flow, the percentage of vehicles using each lane was recorded and plotted in Figure 6.6. The x-axis shows the detector flow, 2km upstream of the diverge.

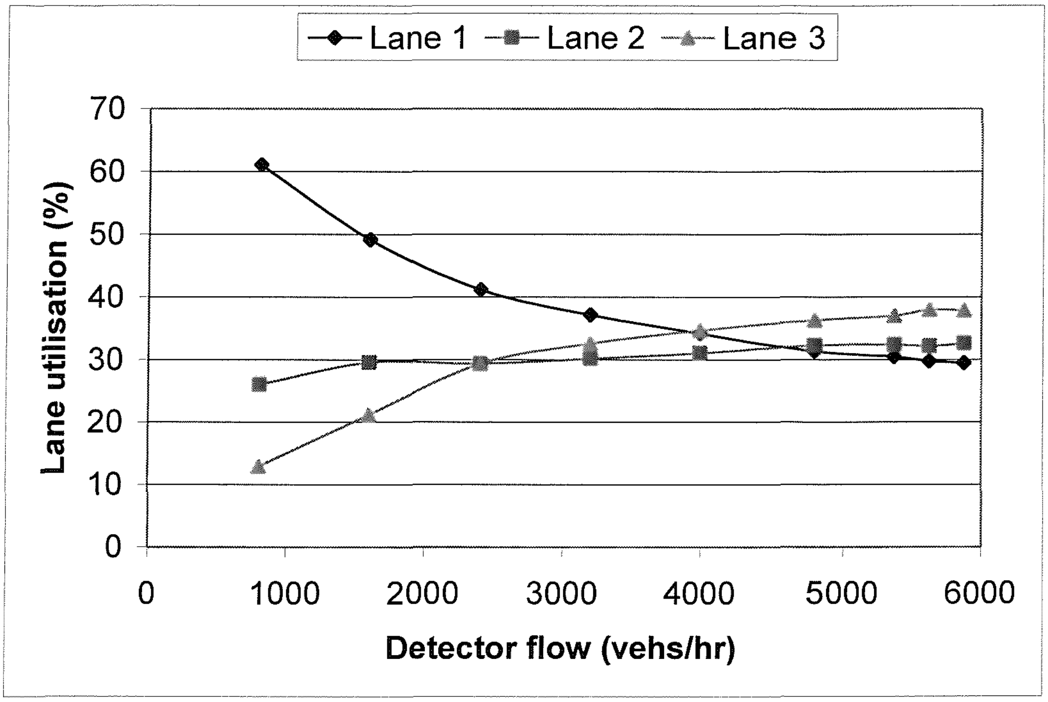


Figure 6.6: Lane utilisation of the mainline with increasing flow

The lane utilisation results from SISTM were compared with results from a recent lane changing study which assessed the lane utilisation on the 3-lane mainline of the M27 between junctions 11 and 12 (Brackstone, McDonald and Wu 1998). Figure 6.7 shows the lane utilisation of each of the mainline lanes on the M27 against vehicle flow.

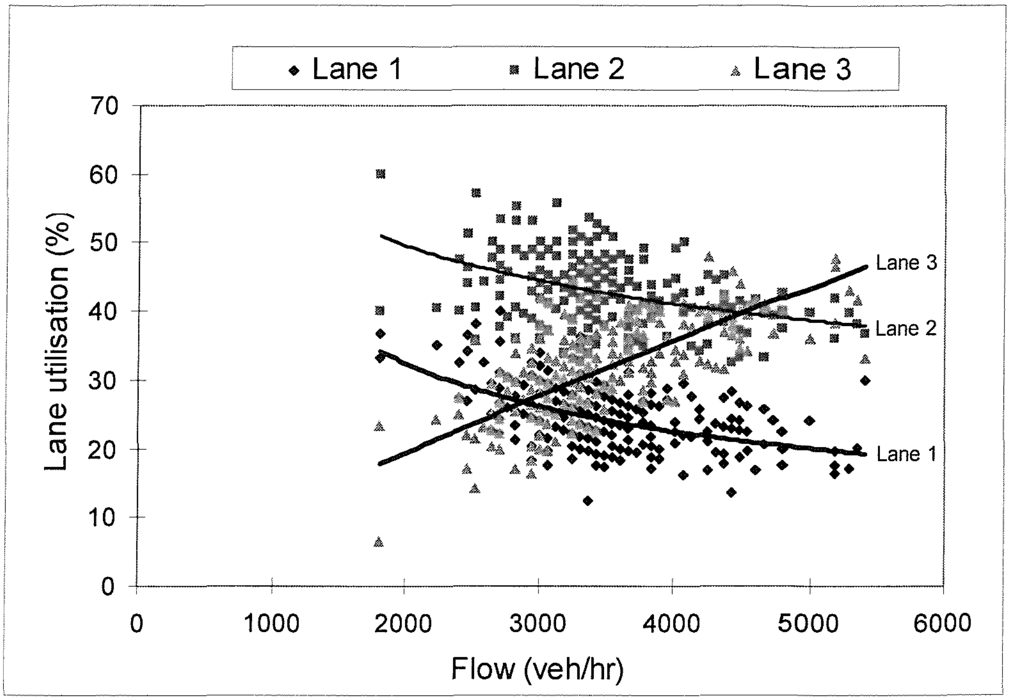


Figure 6.7: Lane utilisation of the mainline of the M27

In the Highway Code (Road Safety Directorate/Driving Standards Agency 2001), rule 238 states that "You should drive in the left-hand lane if the road ahead is clear. If you are overtaking a number of slower moving vehicles, it may be safer to remain in the centre or outer lanes until the manoeuvre is completed rather than continuously switching lanes. Return to the left-hand lane once you have overtaken all the vehicles or if you are delaying traffic behind you."

With low flows, the majority of drivers in SISTM used lane 1 as there is far less traffic to overtake and this behaviour is recommended in The Highway Code and replicated within the model. As the flow increased, the utilisation of lane 1 decreased as the utilisation of lanes 2 and 3 increased. With the higher mainline flow, many vehicles use lane 2 or 3 in order to overtake slower moving traffic in lane 1. Data from the M27 showed that lane 2 had a higher lane utilisation than lane 1, even at lower flows. Another study looking at driver's lane changing behaviour found that driver's staying in lane 2 (lane hogging) was a common practice (Yousif and Hunt 1995). It is therefore unrealistic for SISTM to assume that all drivers will return to lane 1 after overtaking. Enhancements to the lane changing logic in this regard would improve the accuracy of SISTM.

6.3.3 Lane utilisation with decreasing distance to diverge

The second test was carried out to see how the lane utilisation of lane 1 varied as the distance to the diverge decreased.

For a Taper diverge, drivers needed to be in lane 1 prior to the diverge in order to enter the slip road and leave the mainline. This meant that any exiting drivers in lanes 2 or 3 wishing to leave the mainline had to change lanes prior to the diverge. For this test, nine pseudo-detectors were placed on the mainline of the model before and after the diverge area in 300 metre intervals. Figure 6.8 shows a graph of how the lane utilisation changed for the individual mainline lanes as the distance to the diverge decreased. It showed how the utilisation for lane 1 increased within 600m of the diverge (to about 38%) as exiting vehicles position themselves into this lane in order that they can leave the mainline. In this test, exiting vehicles received extra stimulus to change lanes to the left at 500m, 300m and 100m prior to the exit. After the diverge, the utilisation of lane 1 decreased to about 33% as exiting vehicles had now left the mainline and were therefore not using lane 1. This test showed how lane 1 can have a very high utilisation prior to the diverge which can then drop noticeably just after the diverge. In Figure 6.8, negative distances are before the diverge and positive distances are after the diverge.

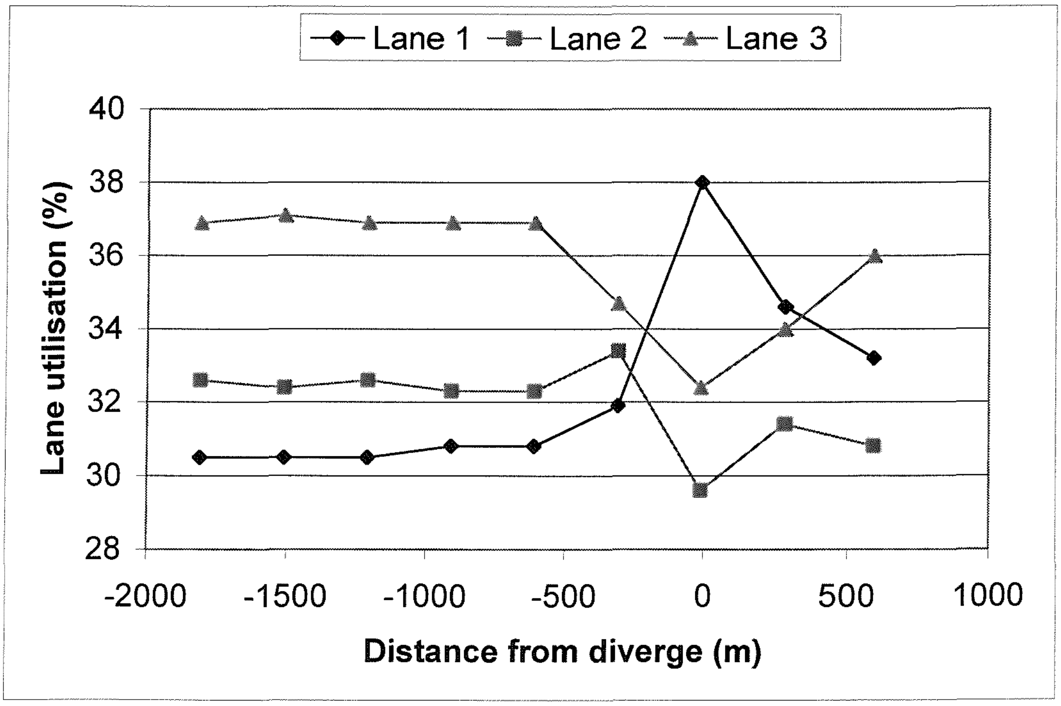


Figure 6.8: Lane utilisation approaching the diverge

The trends in Figure 6.8 are all logical and confirm expectations even though the absolute values can not be validated against real data in this case. This is because Midas loops are normally positioned much less frequently at 500m before the diverge and/or 500m after the merge.

6.3.4 Lane utilisation with increasing diverging percentages

The third test was carried out to see how the lane utilisation of lane 1 varied as the diverging percentage increased.

This test used one psuedo-detector on the mainline just prior to the start of the diverge and one on the slip road. The diverging percentage was changed from 0% to 60%. The lane utilisations were recorded for all the individual mainline lanes and plotted in Figure 6.9.

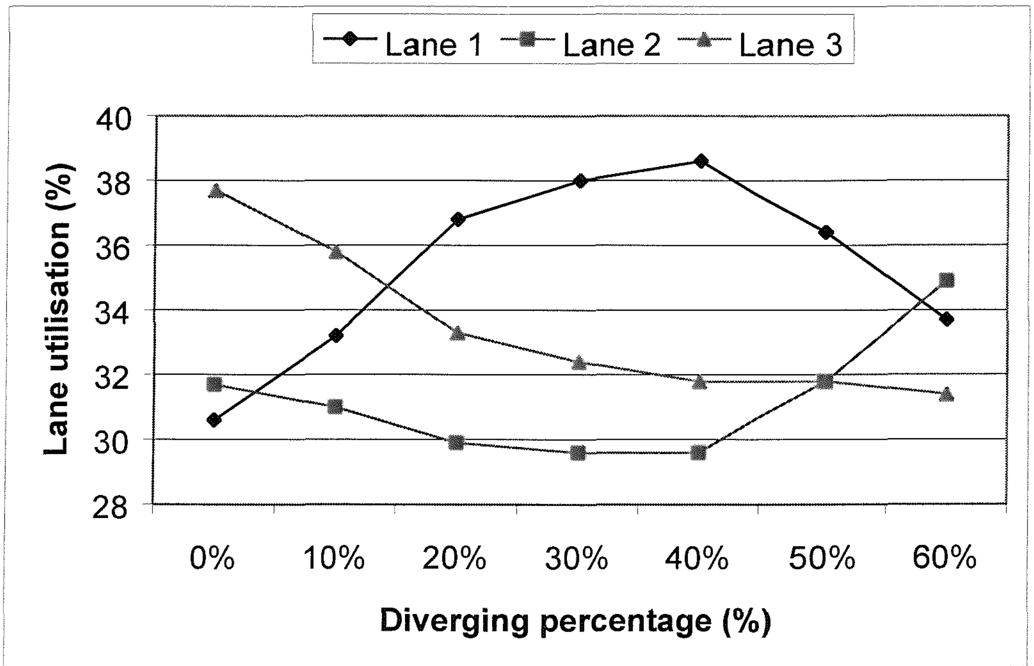


Figure 6.9: Lane utilisation with varying diverging percentages

The graph in Figure 6.9 shows that as the diverging percentage increased, the utilisation of lane 1 increased. However, when the diverging percentage reached 40%, lane 1 was at capacity and could not hold any more vehicles. At this point, the utilisation of lane 2 started to increase, having to cater for an increased number of diverging vehicles which cannot enter lane 1. As the diverging percentage increased, the utilisation of lane 3 decreased as less and less vehicles continued on the mainline.

It is very difficult to find real data to compare with Figure 6.9 as a particular diverge normally has a much smaller range of diverging percentages from day to day, or at different times of the day. However, the results seem to be sensible and showed how the utilisation of lane 1 is affected by the diverging percentage.

Figure 6.10 shows the lane utilisation of the slip lanes with varying diverging percentages.

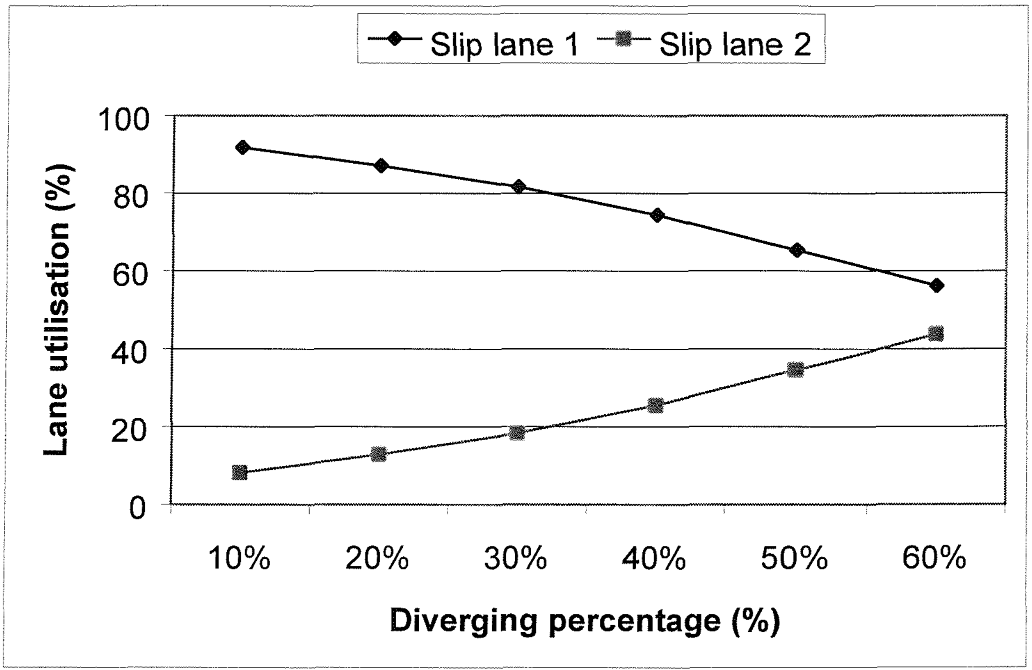


Figure 6.10: Slip lane utilisations with varying diverging percentages

The graph in Figure 6.10 shows that as the diverging percentage increased, the utilisation of slip lane 1 decreased whilst the utilisation for slip lane 2 increased. As explained in Chapter 5, vehicles in SISTM are unaware of the fact that there are two slip lanes at the exit, so that slip lane 2 can be under utilised compared to real data. As the diverging percentage increased, the slip lanes became more equally used. Results from the TRG Access Control Project (discussed in Chapter 5) showed that 3172 vehicles (approximately 28% diverging percentage) used the slip road on Junction 5 of the M27 between 07:15 – 09:30 (see Table B.5). Of those, 2377 used slip lane 1

(75%) and 795 used slip lane 2 (25%). These results correspond reasonably well to the graph in Figure 6.10 although the mainline flow was only on average just above 5000 veh/hr compared to a demand flow in SISTM of 6500 veh/hr.

6.4 Average speed near the diverge and its distribution

6.4.1 Introduction

Average speed on the mainline prior to the diverge gives a good indication of how efficiently the diverge is able to deal with exiting vehicles without disruption to the mainline. When approaching the diverge, average speeds might be expected to drop due to lane changing, deceleration and 'congestion' near the exit. Two tests have investigated the following:

- Average speed and distance from the diverge
- Speed distribution for all lanes on the mainline

6.4.2 Average speed approaching the diverge

The first test was carried out to investigate how the average speed in each lane varied as the distance to the diverge decreased. This test corresponded to the test in section 6.3.3 investigating how the lane utilisation varied approaching the diverge. The results were plotted in Figure 6.11.

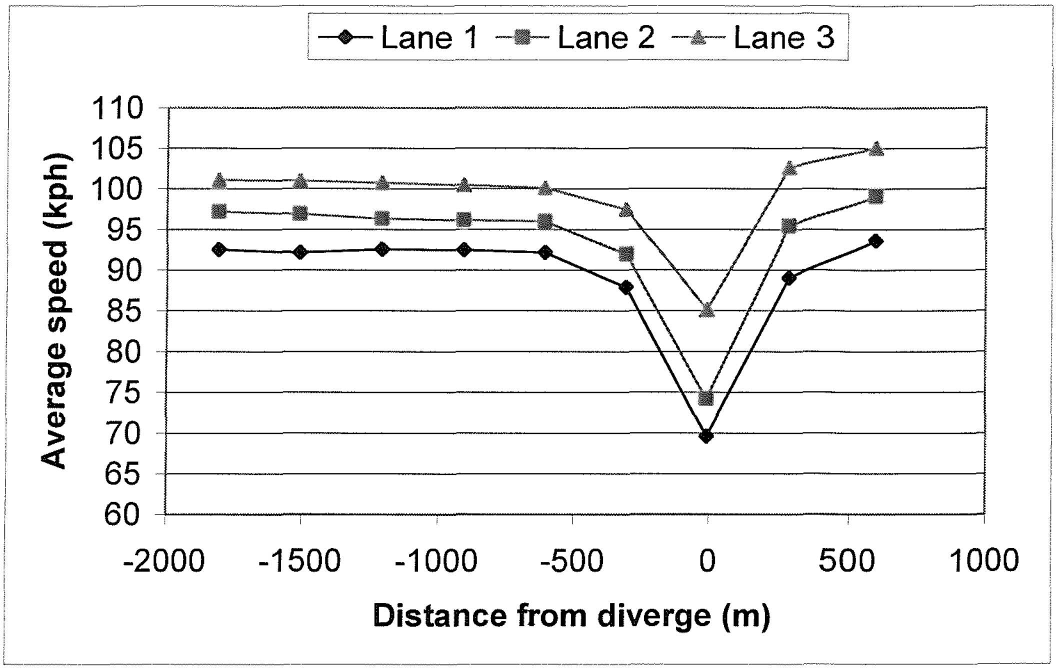


Figure 6.11: Average speed approaching the diverge

It can be seen from Figure 6.11 that the average speeds for all of the mainline lanes remained reasonably constant until about 600m from the diverge due to the scoring and threshold system within SISTM (see section 4.6.4). These speeds then decreased to a minimum at the diverge and then increased again after the diverge. The decrease in average speed was most noticeable for lane 1 and least noticeable for lane 3. As stated in section 6.3.3, it was very difficult to check this result with real data but it seemed to be providing a sensible result. The apparent significant decrease in lane 3 may be due to the high demand flow of 6500 veh/hr in the model, coupled with the reasonably high diverging proportion (30%). Exiting drivers in lane 3 may still be looking for gaps in lane 2 and then lane 1 near to the diverge in order to leave the mainline.

6.4.2 Speed distribution on the mainline

A second test was carried out to check that SISTM was generating a realistic distribution of speeds for each lane of the mainline. A pseudo-detector was placed about 2km before the diverge to record average speeds for each minute within a five hour period. The results have been plotted in a frequency distribution histogram shown in Figure 6.12.

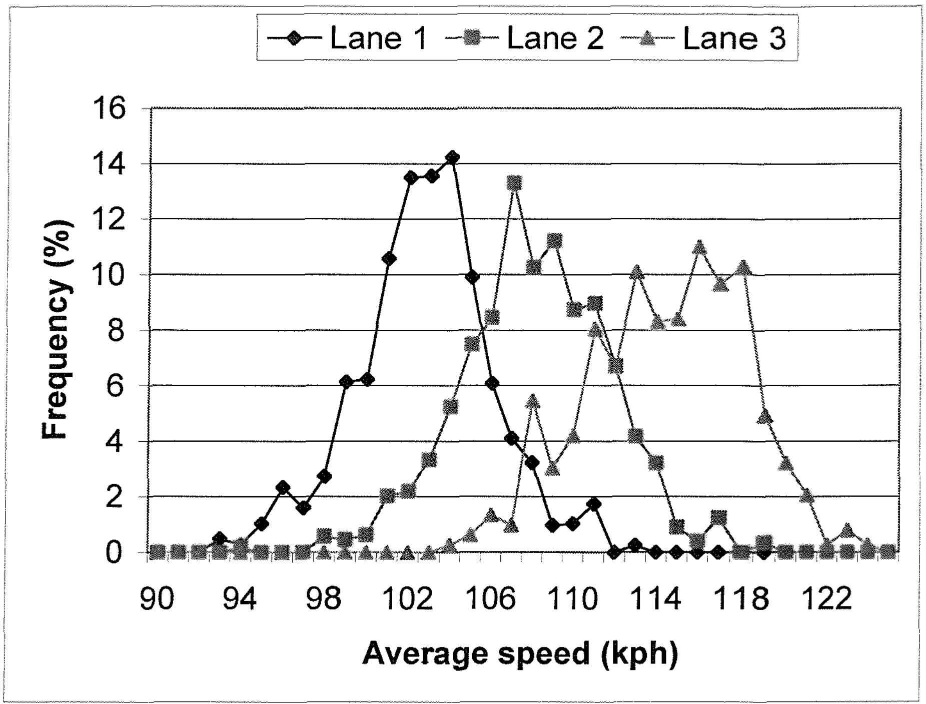


Figure 6.12: Frequency distribution histogram of speeds within the SISTM model

The speed distribution SISTM produced for each lane, shown in Figure 6.12, seemed to be reasonable and sensible. The speed distribution for each lane overlapped with the previous lane's distribution progressively, with higher speeds and a higher range of speeds. The speed distribution of each lane approximates to a normal distribution which would be typical of free-flowing conditions.

6.5 The effect of gradient and percentage of HGVs

6.5.1 Introduction

The gradient of the mainline and the slip lane and the percentage of HGVs are expected to affect average vehicle speeds. In the latest standard TD22/92, corrections to the downstream mainline and diverging flows are made for uphill gradients and percentages of HGVs (see Table 2.4). These parameters are not dealt with individually but instead a factor is applied to a combined mainline gradient (below or above 2%) and HGV percentage (5%, 10%. 15% or 20%). For example, with gradients on the mainline above 2%, the flow needs to be increased by 5% with every 5% increase in the percentage of HGVs, in order to compensate for the loss in capacity. For mainline gradients less than 2%, the flow only needs to be corrected by

5% once the HGV percentage reaches 20% (see section 2.4.4 for further details). It is not known the research for which these figures are based on and therefore how accurate these correction factors are.

Recent research analysed vehicle speeds on rural highways in New Zealand of gradients of up to 10% (Bennett and Dunn 1994). The study found a relationship between used power and gradient. The speed of a vehicle at any point in time was dependent on its limiting speed and its acceleration/deceleration. On steep uphill gradients (over 5%), the acceleration rate was governed by the power-to-weight ratio (which varies considerably between cars and HGVs). On low/moderate uphill gradients (0% – 5%), drivers used less power than was available and so the acceleration was governed by driver behaviour.

Various tests were carried out in SISTM to investigate how effectively SISTM models gradient and the percentage of HGVs in terms of their effect on the flow and speed. This would see whether SISTM's results matched those factors from TD22/92. The tests investigated the relationships between the following:

- Average mainline speed and uphill mainline gradient
- Average slip road speed and uphill slip road gradient
- Average mainline speed and percentage of HGVs
- Mainline flow and percentage of HGVs

SISTM allows the user to input a value for the gradient of between -15% and +15%, even though the model has only been validated for gradients up to 3%. A downhill (or negative) gradient has no effect on the results. For completeness, the gradient in these tests was altered between 0% and 10%. However, it would be impossible to validate the results for this range as the maximum desirable uphill gradient on a motorway mainline in the UK is 3% (the absolute maximum is 4%) (Department of Transport 1981 and 1993).

6.5.2 Average mainline speed with a varying uphill mainline gradient

The first test carried out was to see how the uphill gradient of the mainline affected the average speed on the mainline. The gradient of the mainline 1km before the diverge was altered from 0% to 10% and a pseudo-detector placed just before the diverge. The average speed was recorded and shown in Figure 6.13.

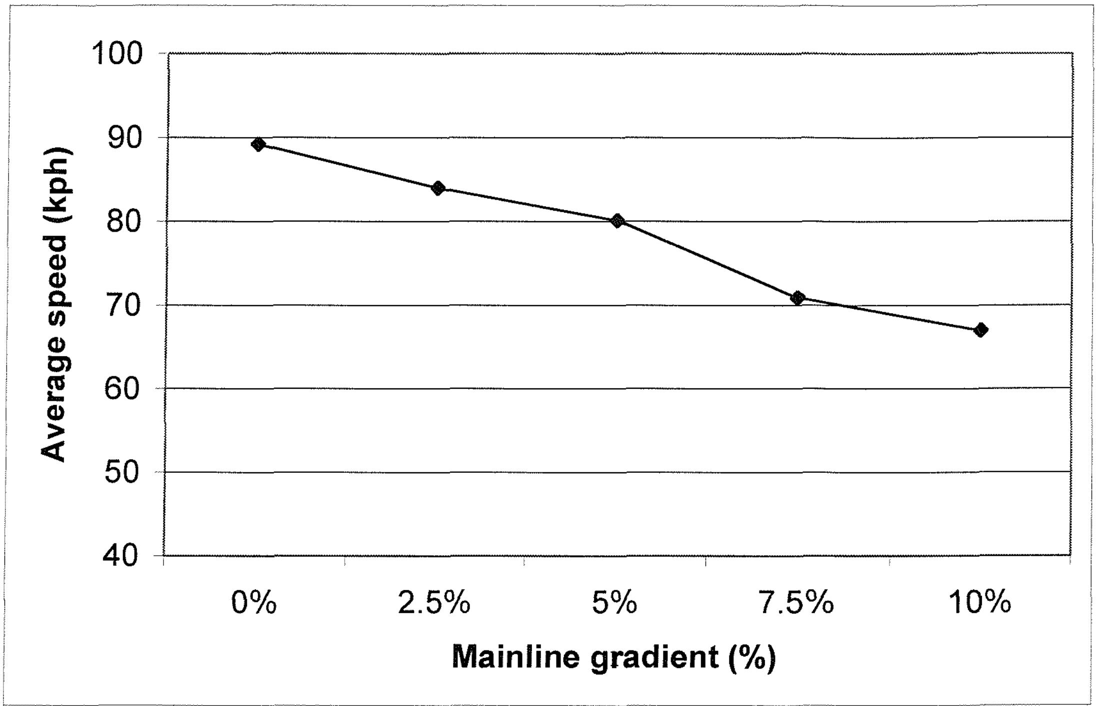


Figure 6.13: Average speed over all lanes with a varying gradient

Figure 6.13 showed how the average speed decreased as the mainline gradient increased. In SISTM, gradients have no effect on the speeds of light vehicles; for HGVs there is a 5kph reduction in desired speed for each 1% increase in gradient. The reduction in acceleration is 0.36km/hr/s for each 1%. The graph shows that there is approximately a 2kph decrease in speed for every 1% increase in gradient.

A simulation program has been written to predict the speed of any vehicle type travelling along an uphill stretch of a rural highway in New Zealand (Bennett and Dunn 1994). The speeds predicted compared favourably with real data. Figure 6.14 shows a graph of limited speed against uphill gradient for various vehicle types (PC – passenger cars; PC+TRL – passenger cars towing; LCV – light commercial vehicle; MCV – medium commercial vehicle; HCV – heavy commercial vehicle). For cars, the graphs showed little change in limiting speed until the gradient was about 3%, at which point it decreased its limiting speed by about 3kph per 1% increase in gradient. For heavy vehicles, the limiting speed dropped by about 5kph for every 1% increase in gradient. SISTM does not take into account the power-to-weight ratio, only a reduction in the maximum acceleration rate for each vehicle type. Further research, calibration and validation would be necessary to enhance SISTM's ability to accurately model the effect of gradient on the speed of different vehicle types.

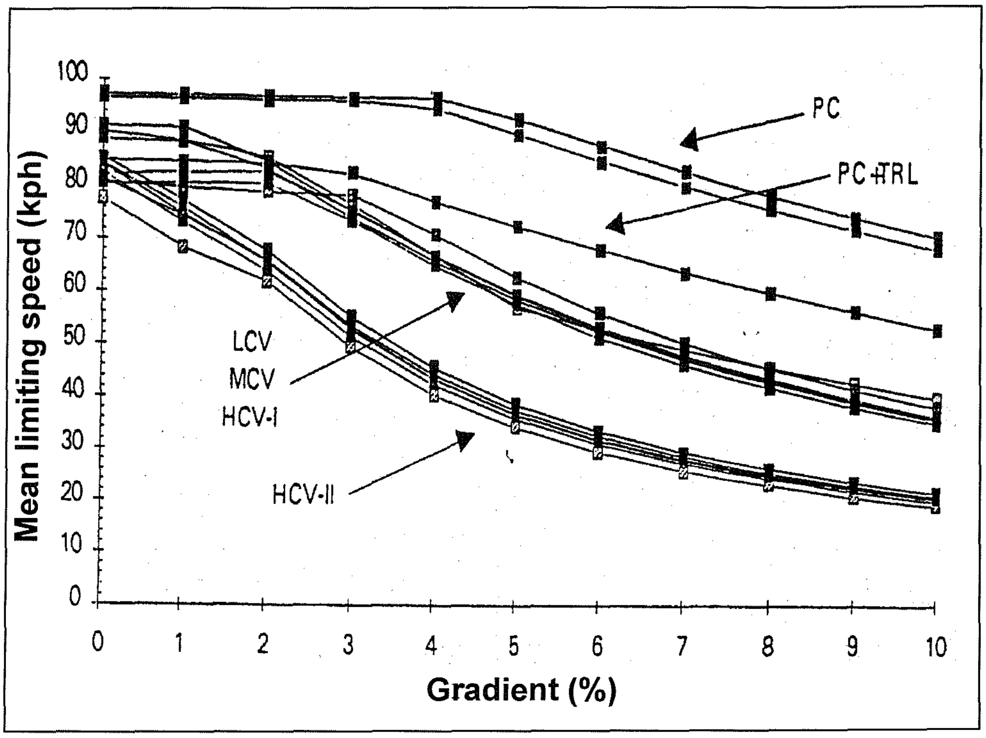


Figure 6.14: Mean limiting speed (mph) against gradient (%)

Tests were also carried out in SISTM to see if the length of the mainline for which the gradient was applicable affected the average speed of the mainline. Various runs showed that this parameter did not affect the results which in reality would not happen. A long stretch of mainline with an uphill gradient would have a greater effect on the average speed of the mainline than a much shorter stretch, and may also affect the type of diverge layout that should be selected. The correction factors in TD22/92 only focus on the mainline gradient and not on the length for which it applies. It is recommended, however, that a Parallel diverge should replace a Taper diverge if the mainline has an uphill gradient of >3% (or a downhill gradient of <-3%) for longer than 1.5km prior to the start of the exit. SISTM also showed no noticeable reduction in detector flow for an increased mainline gradient (as gradient had no effect on light vehicles). This result may be reasonable given that drivers often increase their acceleration rate in order to maintain their speed, compensating for the uphill gradient. This result, however, does not agree with the correction factors in TD22/92 and more research would be needed to validate the true relationship between gradient and flow. The modelling work described in Chapters 8 and 9 have assumed that there is no gradient on the mainline.

6.5.3 Average slip road speed with a varying uphill slip road gradient

The second test looked at the relationship between the uphill gradient of the slip road and the average speed on the slip lanes. A pseudo-detector was installed on the slip road. The slip road gradient was varied from 0% to 10% to see how this affected the average speed on the slip road (the maximum uphill gradient for UK motorway connector roads is 6%) (Department of Transport 1992a). The results are shown in Figure 6.15.

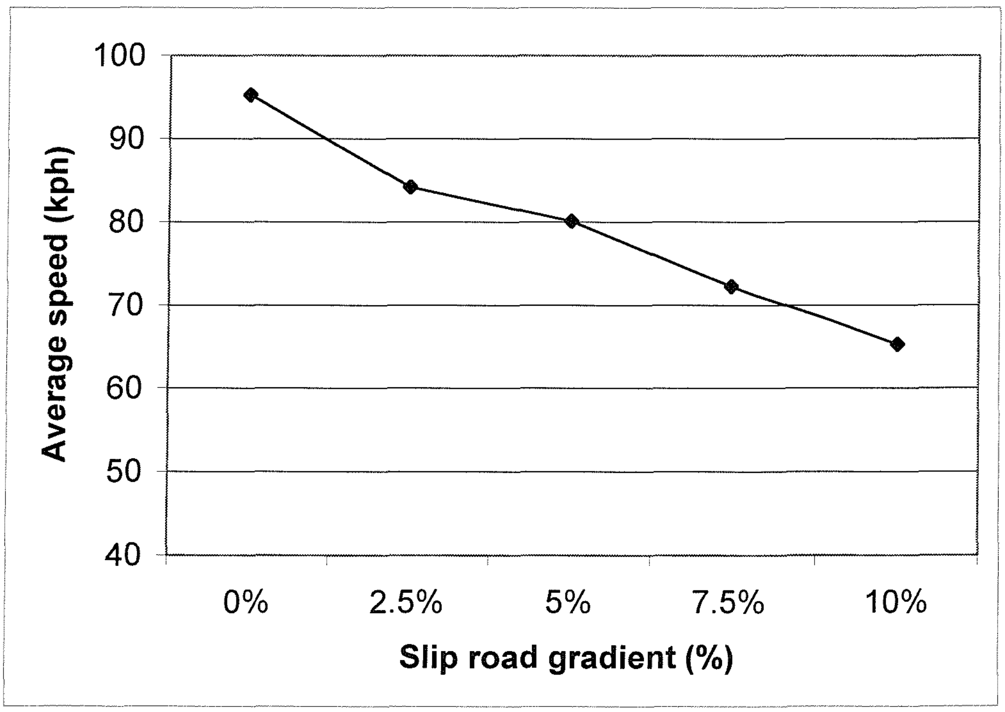


Figure 6.15: Average speed on the slip road with a varying slip road gradient

Figure 6.15 shows that the average speed on the slip road decreased by about 3 kph for every 1% increase in slip road gradient. This is a higher decrease to that in section

6.5.2 for the effect on speed of altering the mainline gradient (2 kph for every 1% increase). There was, however, no noticeable decrease in detector flow.

It can be seen from these tests that SISTM has some problems in replicating the effect of gradient on both speed and flow. The gradient parameter had no effect in reducing the speed of light vehicles, and the gradient length parameter seemed to have little if any effect at all. This is a limitation of the model as gradient can be an important factor in the selection of the most appropriate diverge layout (see section 10.2.2.4 for further discussion).

6.5.4 Average speed and flow and the percentage of HGVs

SISTM allows different vehicle classes to be modelled. The main two are light vehicles and heavy goods vehicles, each vehicle class having its own set of vehicle attributes such as length, width, maximum acceleration and desired speed. A third test was carried out to see how the percentage of HGVs within the traffic composition affected the mainline speed. A pseudo-detector was placed approximately 2 km from the diverge to record the mainline speed. Figure 6.16 shows the results.

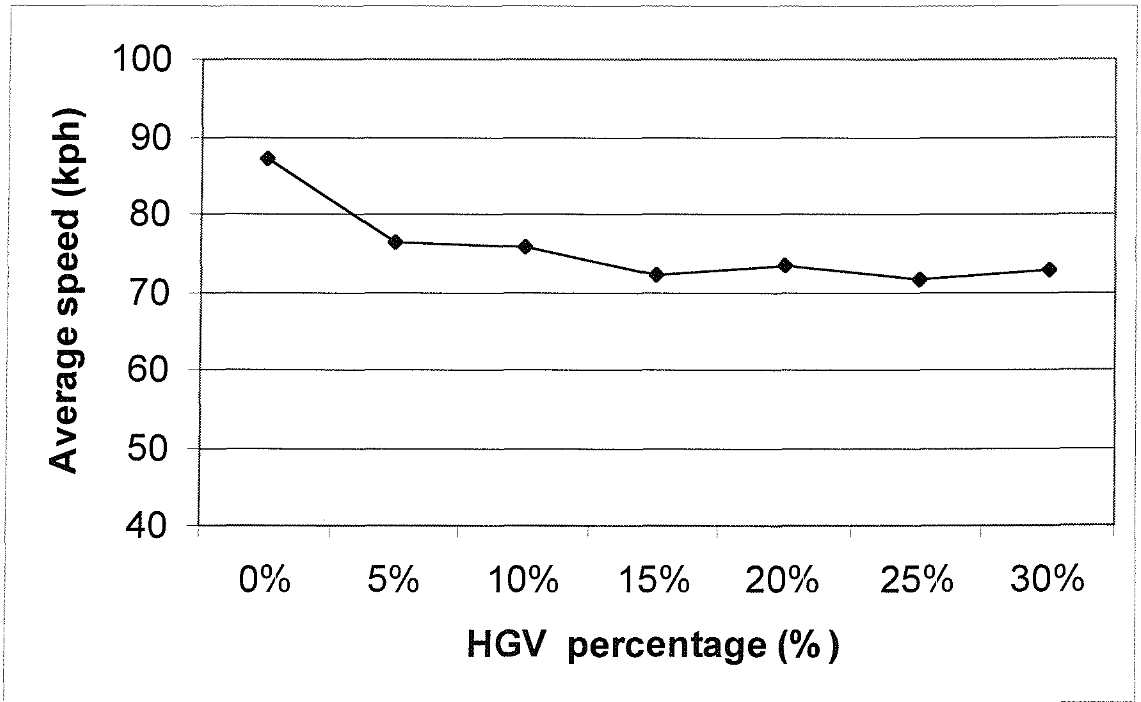


Figure 6.16: The average mainline speed with a varying HGV percentage

The graph shows how the average speed decreased as the percentage of HGVs increased. This reduction in speed does not happen in a linear way, having a bigger effect when the HGV percentage was lower. As soon as the HGVs were introduced into the traffic composition, the light vehicles were delayed and needed to change lane more often in order to obtain their desired speed in the new situation. For each 5% increase in the percentage of HGVs, the relative percentage increase in this proportion decreased which could explain its diminishing effect on the average speed (for example an HGV percentage increase from 5% to 10% is a 100% relative increase whereas 25% to 30% is only a 20% relative increase).

Data from the pseudo-detector also showed how the flow changed as the percentage of HGVs increased. The results are shown in Figure 6.17.

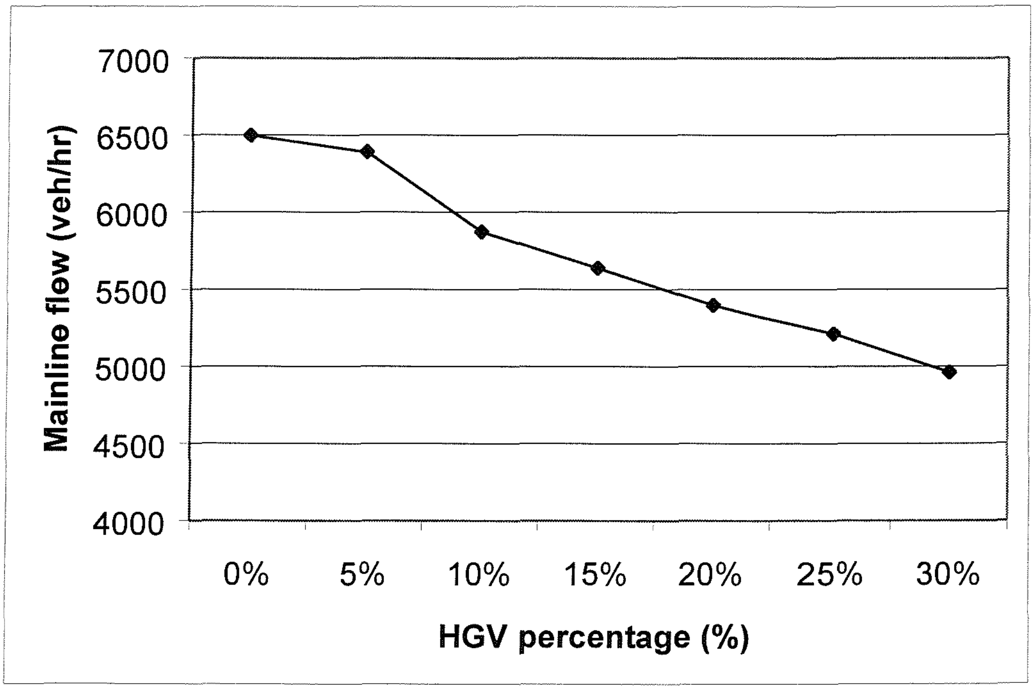


Figure 6.17: The mainline flow with a varying HGV percentage

Further calculations from Figure 6.17 show that the passenger car unit (pcu) factor for an HGV is 2.0 (e.g. at 20% HGVs, the flow is approximately 5400 veh/hr which is composed of 4320 cars and 1080 HGVs. The pcu factor for an HGV is therefore (6500 – 4320)/(1080) which is approximately equal to 2.0). TD22/92 recommends that the flow should increase by 5% for every 5% increase in HGVs for mainline gradients over 2%. For mainline gradients under 2% (as in this test), the flow is unaltered except increased by 5% when the HGV percentage is 20%. However, SISTM is telling us that at 0% gradient, an HGV has a pcu factor of 2.0 requiring an adjustment in the flow.

The SISTM result (shown in Figure 6.17) seems a logical one but is different to the correction factors used in TD22/92. It is not clear where the research that formed the basis for these correction factors came from (shown in Table 2.4). These factors seem to have been simplified for ease of use by traffic engineers as they all progress in a linear way and are all multiples of five percent. Further research would be needed in order to validate these correction factors so that the effect of the percentage of HGVs on the flow can be accurately compensated for. It is an important parameter when selecting the most appropriate diverge layout and more discussion of this effect is covered in Chapter 8.

6.6 Lane changes near the diverge

6.6.1 Introduction

Lane changes occur on all parts of the mainline mainly in order for vehicles to overtake slower vehicles in that lane. When approaching a Taper diverge, drivers wishing to exit the motorway needed to be in lane 1 in order to leave the mainline. However, at a Taper lane drop, vehicles wishing to stay on the mainline needed to be in lanes 2 or 3. Lane changing can therefore become very frequent in the area just before the diverge. Two tests were carried out to investigate the following:

- Lane changes to the left approaching a Taper diverge
- Lane changes to the right approaching a Taper lane drop diverge

6.6.2 Lane changes to the left at a Taper diverge

The first test was carried out to investigate how the numbers of lane changes to the left varied approaching a Taper diverge. SISTM can output lane changing results for up to five different sections of the motorway network. In this test, five 300m sections of the mainline were specified on the approach to the diverge. The sections were 1500m – 1200m, 1200m - 900m, 900m – 600m, 600m - 300m and 300m – 0m from the diverge. The lane changing results for each section were recorded and shown in Figure 6.18.

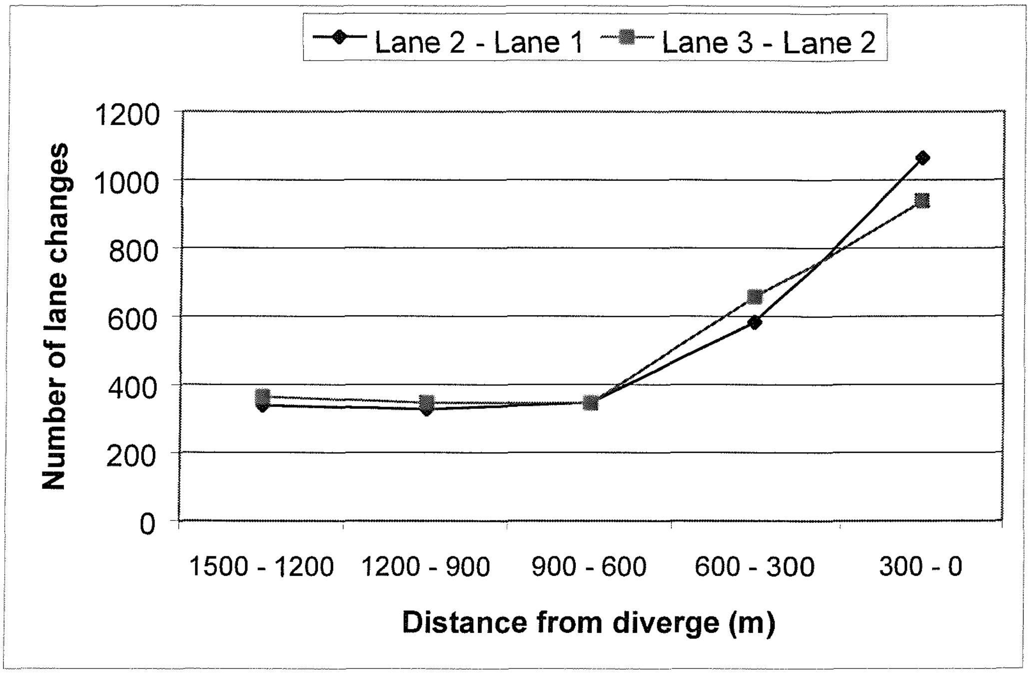


Figure 6.18: Number of lane changes to the left approaching a Taper diverge

At the Taper diverge, drivers wishing to leave the mainline needed to be in lane 1 prior to the exit in order to leave the mainline. As expected, the number of lane changes to the left increased sharply as the vehicles were within 600m of the diverge. This is due to the scoring and threshold system in SISTM (as described in section 4.6.4). This result was consistent with TRL video studies at various diverges where lane changes to the left increased as the distance to the diverge decreased (Wedlock, Peirce and Wall 2001).

6.6.3 Lane changes to the right at a Taper lane drop diverge

The second test was carried out to see how the numbers of lane changes to the right varied approaching a Taper lane drop diverge. As in the first test, the lane changes were recorded in five 300m sections approaching the diverge. In this situation, drivers wishing to continue on the mainline (70% of the traffic) needed to be in lane 2 or lane 3. The results were plotted in Figure 6.19.

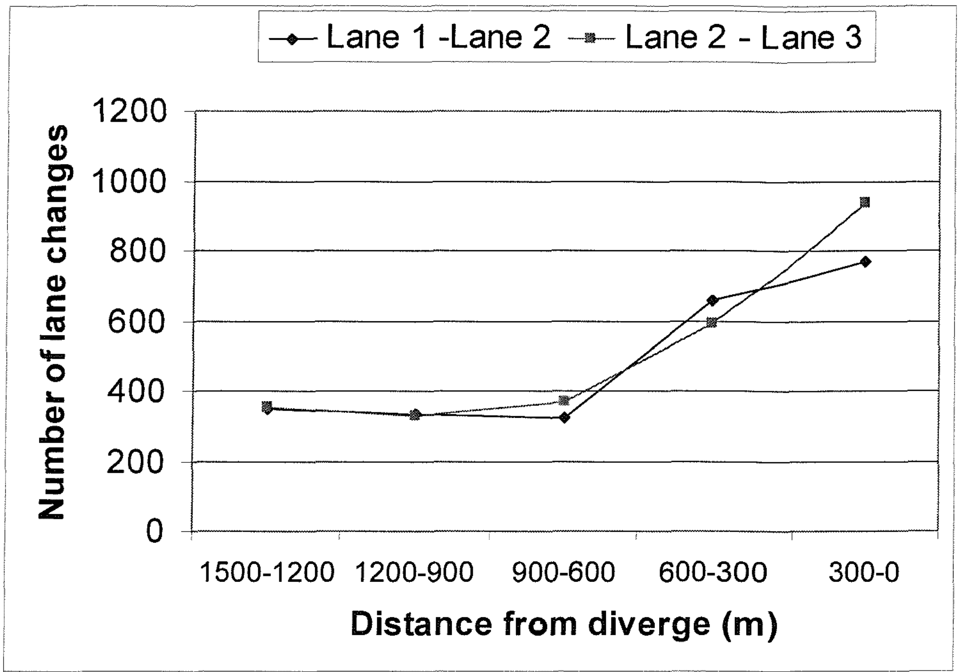


Figure 6.19: Lane changes to the right approaching a Taper lane drop diverge

As in Figure 6.18, the lane changes to the right remained reasonably constant until about 600m from the exit. This is again due to the scoring and threshold system which gives stimuli to mainline vehicles in lane 1 so that they change into lane 2 or lane 3 in order to remain on the mainline. This again is consistent with TRL video studies at lane drop diverges where lane changes out of lane 1 increased as the distance to the diverge decreased (Wedlock, Peirce and Wall 2001).

6.6 Summary

The tests that have been carried out in this chapter have given a good assessment of SISTM over a wide range of different situations. These tests have given a measure of confidence for further modelling work as well as highlighting some limitations of the program. The model has already been extensively validated and calibrated by TRL for the Highways Agency using data from various motorways in the UK and therefore is expected to be a useful tool in modelling various diverge layouts in order to assess their capacity and operation.

A comparison between the results from SISTM and the correction factors used for mainline gradients and percentage of HGVs in TD22/92 was made. The correction factors seemed to have been simplified for use by traffic engineers due to their linear progression in multiples of five percent. The factors also represent a combined figure for the mainline gradient and HGV percentage.

SISTM did have some problems in replicating the effect of gradient, in particular the length over which the gradient applies. This is an important factor in the design and selection of diverges and can be used to justify a Parallel rather than a Taper layout. This parameter, however, does not effect the correction factors. Results also showed that the gradient had no noticeable effect on the flow which is not consistent with the correction factors. It did however have a noticeable effect on average speed. Further research would be needed to validate the effect of gradient (and the length over which it applies) on mainline flow.

SISTM showed that an HGV has an approximate pcu value of 2.0 and therefore had an effect on the mainline flow which seemed a logical result. The correction factors in TD22/92 recommended that the flows should be increased by 5% for every 5% increase in HGV percentage, but only at a mainline gradient of over 2%. Further research would validate the true relationship between percentage of HGVs and mainline flow.

SISTM also had problems in areas such as replicating post-flow breakdown. However, it is thought that the modelling work focussing on the capacity of the exit will not be affected significantly by these differences. Results that have differed noticeably from the observed data have been noted and either explained and/or closely monitored in the modelling work, to make sure they have no significant effect on the results. Given the theoretical nature of the comparison of the capacity of various diverge layouts, any differences will apply generally to all the layouts modelled.

CHAPTER 7

SETTING UP AND TESTING THE MODELS IN SISTM

7.1 Introduction

The modelling work carried out in this research project, using the computer program SISTM, is designed to assess various diverge layouts in terms of their:

- Throughput (sum of the flow on exit and mainline after the diverge)
- Impact on lane changes (which can influence efficiency and safety)
- Performance (as reflected by average journey times)

The simulation results are then used to contribute to the development of recommendations regarding the choice of diverge layouts in different situations.

7.2 Modelling diverge layouts in SISTM

7.2.1 Introduction

In order to begin the modelling work, an assessment of which diverge layouts could be modelled was made. In the latest standard TD22/92 (Department of Transport

1992), there are five recommended layouts for the UK (as discussed in chapter 2). These are as follows:

- Taper
- Parallel
- Taper lane drop
- Parallel lane drop
- Parallel double lane drop

There are also two additional alternative diverge layouts (discussed in Chapter 3) which are as follows:

- Ghost Island
- Ghost Island lane drop

Further layouts could also be envisaged from findings in this research which could be evaluated subject to the modelling results from these 'standard' designs.

With any microscopic simulation computer program, more than 1 run with different random seeds is necessary in order to account for the random nature of the driving behaviour.

7.2.2 Setting up the models

Models were set up in SISTM for all seven diverge layouts. The models represented a 3-lane main carriageway of 6km with the diverge starting at just over 5km (modelled on the mainline stretch on the M27 westbound between Junctions 7 and 5). The geometric dimensions of the various layouts are shown schematically in Figures 7.1, 7.2 and 7.3 and are taken from Government Standard TD22/92 (Department of Transport 1992a) or "A review of anti-swooping trials" (Wedlock, Peirce and Wall 2001). With the exception of the two Ghost Island layouts (see below), all the other diverge layouts were modelled with a double link.

SISTM models the diverge as a Taper layout (with or without a lane drop) but other diverge layouts were set up by an adaptation of the program. Figure 7.1 shows a SISTM representation of the Taper and Taper lane drop layouts (Figure 2.1 in Chapter 2 shows the Taper and Taper lane drop layouts from TD22/92).

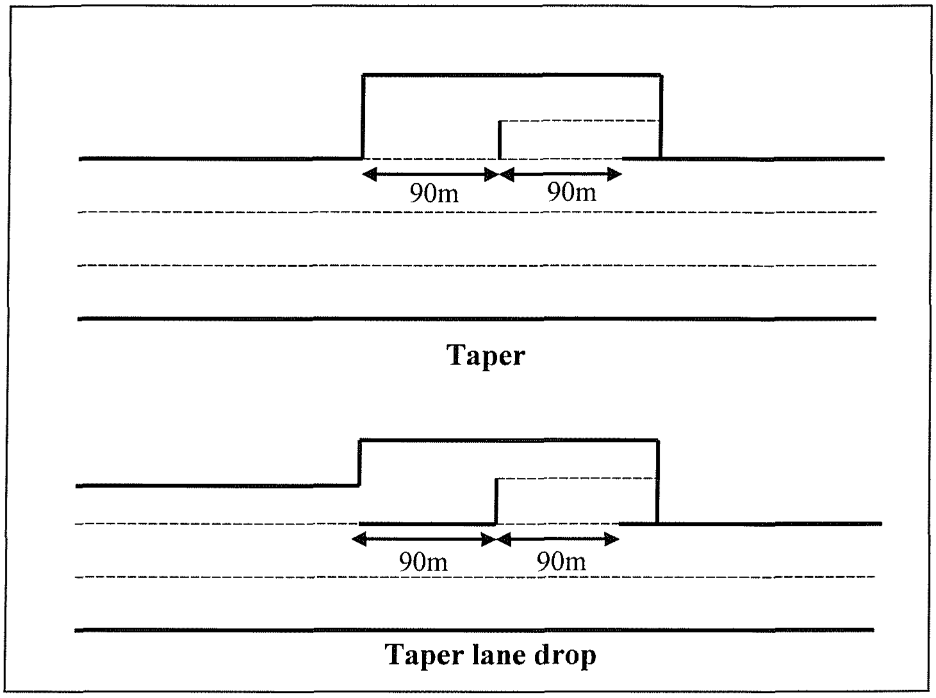


Figure 7.1: Taper and Taper lane drop layouts represented in SISTM

For the Parallel diverge, a lane gain node was added at least 200m prior to the exit in order to represent a single auxiliary lane. This extra lane was then dropped at the exit where it feeds traffic into the two exit slip lanes. Figure 7.2 shows how SISTM represents the Parallel and Parallel lane drop layouts (see Figure 2.1).

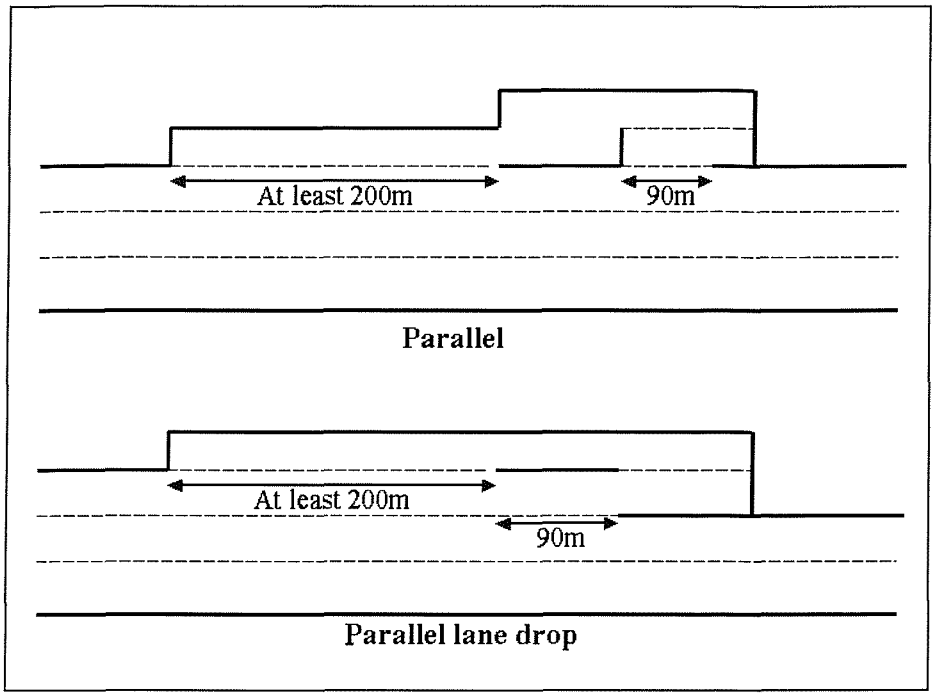


Figure 7.2: Parallel and Parallel lane drop layouts represented in SISTM

The Ghost Island layout was represented by two closely spaced single link diverges. The origin-destination flow table can be used to determine the proportion of exiting vehicles using each exit. Figure 7.3 shows how SISTM represents the Ghost Island and Ghost Island lane drop layouts (Figures 3.2 and 3.7 show examples of these layouts).

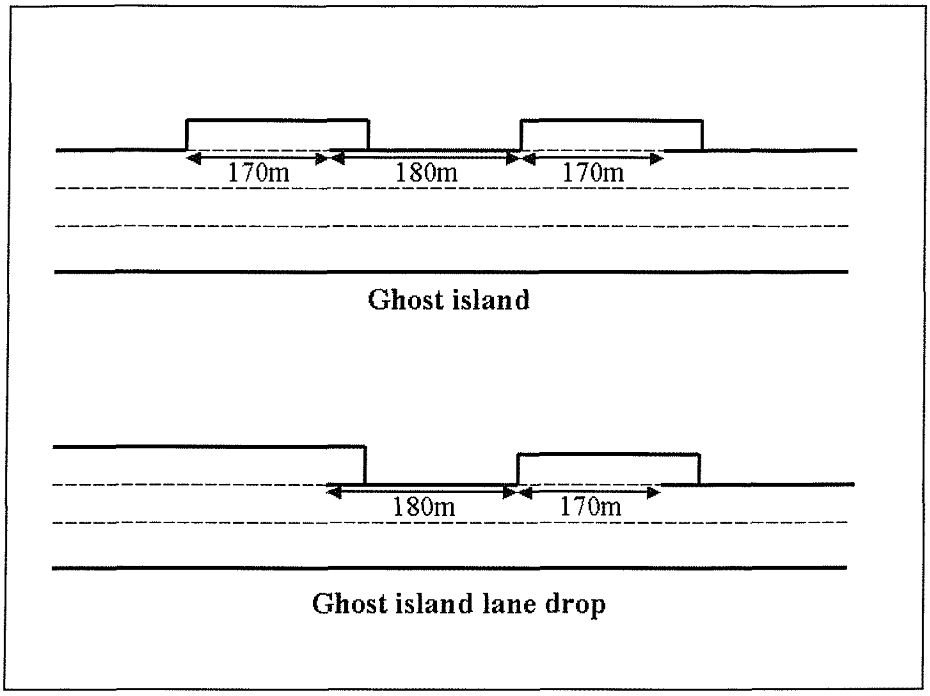


Figure 7.3: Ghost Island and Ghost Island lane drop layouts represented in SISTM

SISTM can only generate a maximum demand flow of 3600 veh/hr per vehicle class per origin-destination movement. In order for the program to be able to model scenarios with high demand flows and distinguish between mainline and exiting vehicles, six vehicle classes were used for each model (for the Ghost Island layout there were seven classes). Figure 7.4 shows the vehicles classes used with their respective origin-destination movements (L and H represent light and heavy vehicle classes respectively).

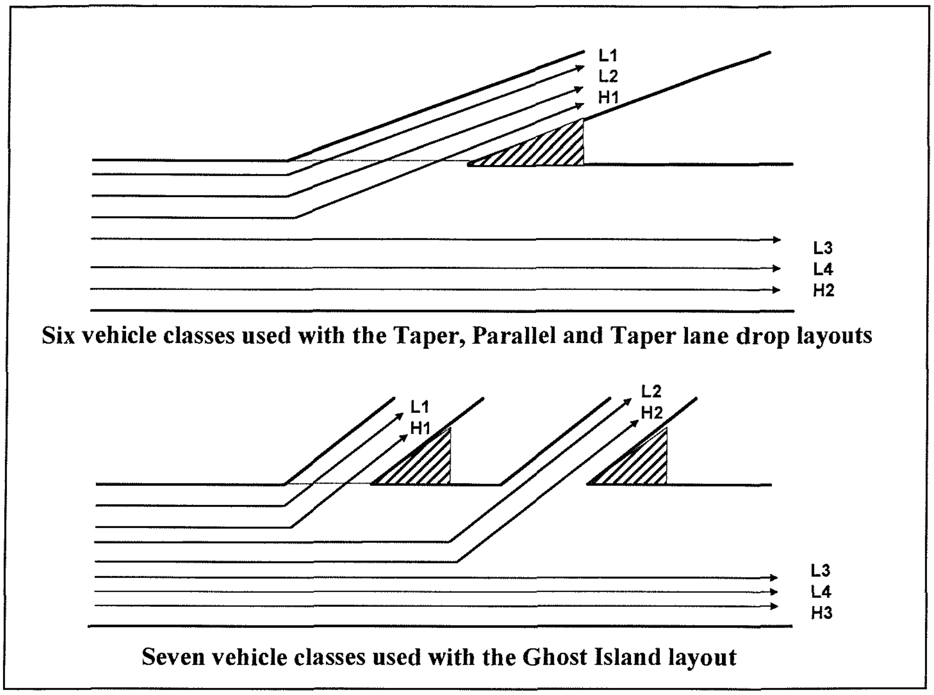


Figure 7.4: Vehicles classes used in the SISTM modelling work

In order to check that SISTM was modelling these seven layouts correctly, two tests were carried out on each layout. These were:

1. Checking the number of incorrect destinations associated with each layout
2. Checking that the general driving behaviour for each diverge was realistic

7.2.3 Initial testing of the models for incorrect destinations

The models were initially tested to check that vehicles were correctly travelling to their required destination. In practice, there are probably a small number of drivers who may be forced to go on to an incorrect destination. This could occur, for example, in peak flow conditions if a driver could not find a suitable gap in lane 1 in which to move into and was forced to continue on the mainline (or unable to change lane out of lane 1 on a lane drop).

The number of incorrect destinations was recorded from the SISTM NETWORK output file for all layouts. Simulation runs were carried out for each layout with 0%, 30% and 60% diverging from the mainline. The demand flow and the percentage of

HGVs for each run was 6000 veh/hr and 15% respectively with a 400m auxiliary lane for the Parallel layout.

Table 7.1 shows the percentage of incorrect destinations for the seven layouts. The numbers in the table represent an average figure for five runs. In addition, extra runs for the lane drop layouts were carried out at 10%, 20%, 40% and 50% in order to determine the range of diverging percentages for each layout where this error was seen to be negligible (i.e. no higher than 5% was considered to be a practical value to use with SISTM even though this figure was higher than desired).

Table 7.1: The numbers and percentage of incorrect destinations for varying diverging percentages for the seven diverge layouts

	Diverging percentage			Diverging range where incorrect destinations < 5%
Layout type	0%	30%	60%	
Taper	0 (0%)	13 (0.2%)	151 (2.7%)	0% - 60%
Parallel	0 (0%)	1 (0.02%)	107 (1.8%)	0% - 60%
Ghost island	0 (0%)	102 (1.7%)	313 (5.2%)	0% - 60%
Taper lane drop	1037 (17.3%)	82 (1.4%)	93 (1.6%)	20%* - 60%
Parallel lane drop	902 (15.0%)	79 (1.3%)	1234 (20.6%)	20%* - 30%
Ghost island lane drop	1049 (17.5%)	529 (8.8%)	361 (6.0%)	None
Parallel double lane drop	1496 (25.0%)	84 (1.4%)	77 (1.3%)	30% - 60%

* At 20%, the percentage of incorrect destinations for the Taper lane drop and the Parallel lane drop were 3.4% and 1.0% respectively.

Table 7.1 showed that for the three layouts not associated with a lane drop (Taper, Parallel and Ghost Island), the percentage of incorrect destinations was always below 5% (usually well below this figure). However, the other four layouts associated with lane drops had a percentage of incorrect destinations ranging from 15% to 25% at certain diverging percentages. However, the Taper lane drop layout produced much more accurate results within a diverging range of 20% - 60%.

All vehicles in SISTM theoretically should reach their intended destination with the appropriate use of scores. Attempts were made at reducing the number of incorrect destinations for these four layouts by altering the signing information (their location and scores) as well as experimenting with the use of dedicated and/or banned lanes. However, the number of incorrect destinations for the remaining three lane drop layouts still remained at an unacceptable level. It was discovered, by watching the simulation run, that the driving behaviour at these three lane drop layouts did not behave realistically. With low diverging flows, many drivers wishing to remain on the mainline were forced to leave the main carriageway as no suitable gap in lane 1 could be found in time. In reality, these occurrences are thought to be rare, as drivers would not want the prospect of a long detour. Instead, some vehicles may queue in lane 1 until a suitable gap into lane 2 can be found. Alternatively, they may force their way into lane 1 or be given a gap by a driver in lane 1.

SISTM, however, does not replicate this behaviour. Vehicles continue to travel at a reasonable speed and if no suitable gap can be found then they will continue on to an incorrect destination. Also for similar reasons at higher diverging flows, some drivers wishing to leave the mainline could not find a suitable gap in which to change lanes into lane 1 and so were forced to stay on the mainline. This also led to a high proportion of drivers travelling to an incorrect destination. As a result of these initial tests, the Parallel lane drop, the Parallel double lane drop and the Ghost Island lane drop were eliminated from further modelling work.

7.2.4 Further testing of the driving behaviour within each model

Further testing of the remaining four models (Taper, Parallel, Ghost Island and Taper lane drop) was carried out to check whether vehicles were behaving in a realistic way near the exit in terms of their lane choice and lane changes. Any obviously incorrect driving behaviour could be observed by watching SISTM's visual display of the simulation. The Taper and Ghost Island layouts seemed to be modelled well within SISTM as did the Taper lane drop layout for a restricted range of diverging percentages (20% - 60%). However, closer examination of the Parallel layout showed that there were problems in replicating this type of exit accurately within SISTM.

As described in section 7.2.2, the Parallel layout was modelled by installing a lane gain node in order to represent the auxiliary lane. This lane was then dropped at the exit. As the simulation was run, it was possible to see many mainline vehicles moving into the auxiliary lane and then out of it again within a very short time (represented by the dashed line in the top picture in Figure 7.4). In order to rectify this incorrect behaviour, the auxiliary lane was made into a dedicated lane for exiting vehicles only, stopping mainline vehicles from entering it and then leaving it again before the exit. The implementation of a dedicated lane solved this problem but created another problem.

Upon further closer study, it was discovered that all exiting vehicles entered the auxiliary lane at the start of its existence, unless unable to do so (represented by the dashed line in the bottom picture in Figure 7.5). In practice, many exiting vehicles would enter the auxiliary lane at other places, particularly if the lane was long or the exiting vehicle was travelling quickly and wanted to avoid being held up by a slow moving vehicle. Given the fact that 15% of the exiting traffic were HGVs, platoons of cars following an HGV or a slow moving car were common within the auxiliary lane. As the lane increased in length (over 400m), journey times for exiting vehicles actually increased as they were having to follow an HGV or a slow moving car for a longer period of time with no possibility of overtaking.

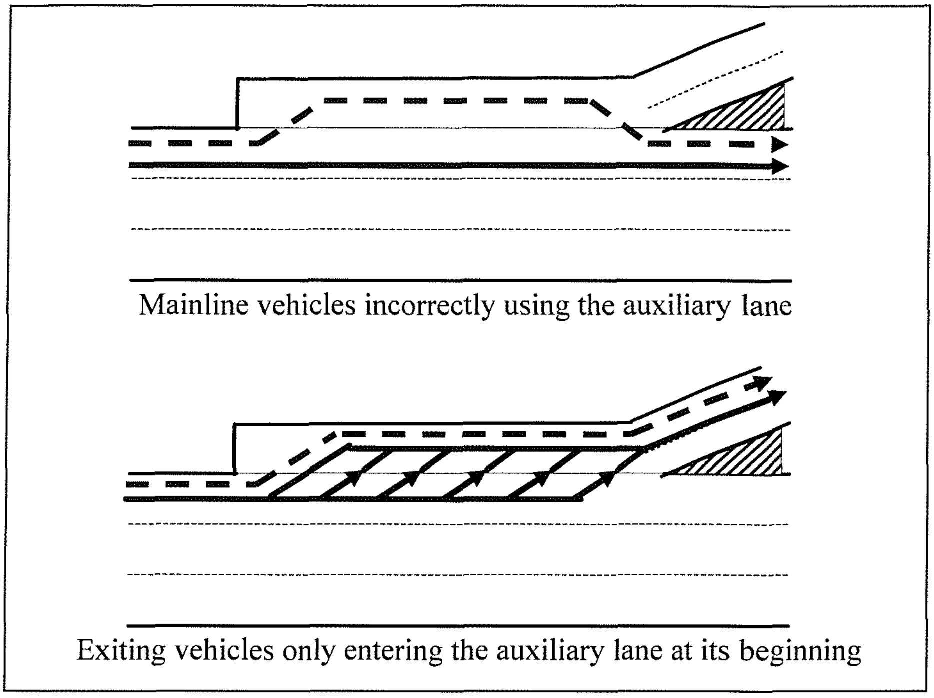


Figure 7.5: Problems with driving behaviour for the Parallel diverge in SISTM

Given these observations regarding the Parallel layout, it was thought that the results from SISTM regarding average speed, lane utilisation, lane changes and journey times would be inaccurate. However, it was thought beneficial to look at the throughput results for this layout (as it would be an under-estimation rather than an over-estimation) in order to see how an auxiliary lane effected the throughput of a diverge layout.

7.3 Summary

SISTM has been used to set up seven different diverge layouts. A rigorous testing of each layout within the program has shown that SISTM had some problems replicating certain aspects of driving behaviour, particularly at diverges with lane drops and/or auxiliary lanes. Results from SISTM for these layouts have thought to be unreliable and therefore have been eliminated from further study.

The testing process of each layout within SISTM has been shown to be a very important process in the modelling work. The program has been used to model other types of diverges not explicitly catered for within the program. It may appear to model these different layouts satisfactorily by adapting certain parameters, but on closer examination fail to replicate driving behaviour accurately.

It has been decided that the modelling work would therefore focus on the three layouts that SISTM modelled accurately (i.e. Taper, Ghost Island and Taper lane drop). In addition, the Parallel layout would also be modelled purely to obtain results regarding its throughput and lane utilisation.

CHAPTER 8

MODELLING RESULTS: CAPACITY AND SPEED

8.1 Introduction

In order to obtain results regarding the maximum throughput of each layout, it was necessary for SISTM to generate a very high demand flow in order that the mainline would be running at capacity. The three layouts (Taper, Ghost Island and Taper lane drop) were tested with a demand flow of 8000 veh/hr, a figure way above the capacity of the 3-lane mainline, in order to obtain throughput results with their associated lane utilisation and average speeds. Checks were made to make sure that flow breakdown did not occur before the diverge (see section 10.2.3.1). In addition, a fourth layout (the Parallel diverge) would also be modelled purely to obtain throughput results for a layout with an auxiliary lane.

8.2 Throughput results

8.2.1 Introduction

The throughput is the sum of the total flow per unit time on the slip lanes and the mainline after the diverge, measured in vehicles per hour. The capacity is the maximum flow or throughput per unit time for a particular lane or carriageway, measured in vehicles per hour. Figures 8.1 and 8.2 show the throughput and capacity parameters for each of the four layouts.

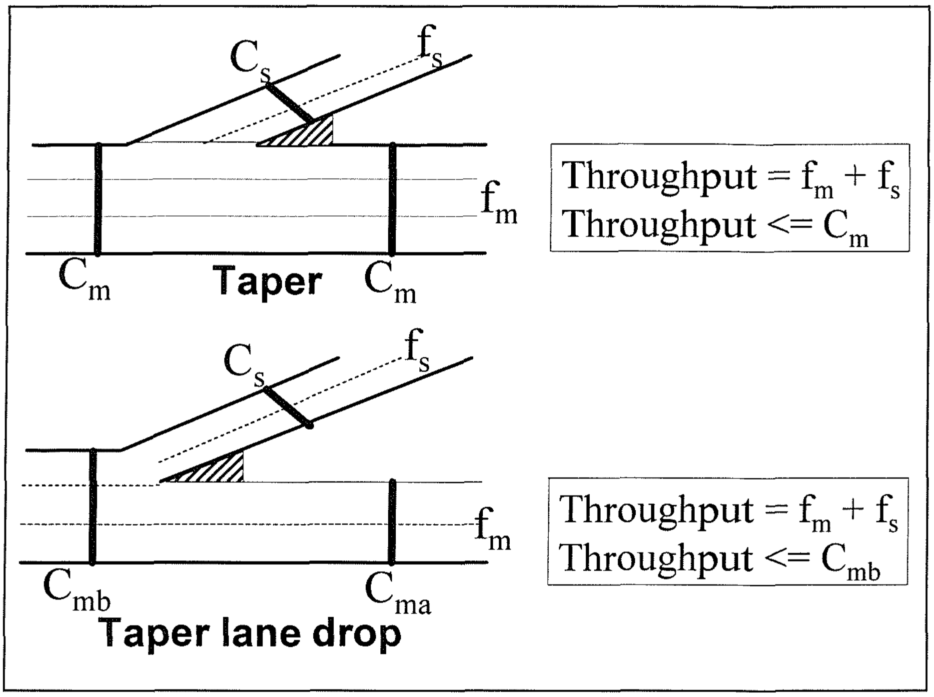


Figure 8.1 Throughputs and capacities for the Taper and Taper lane drop layouts

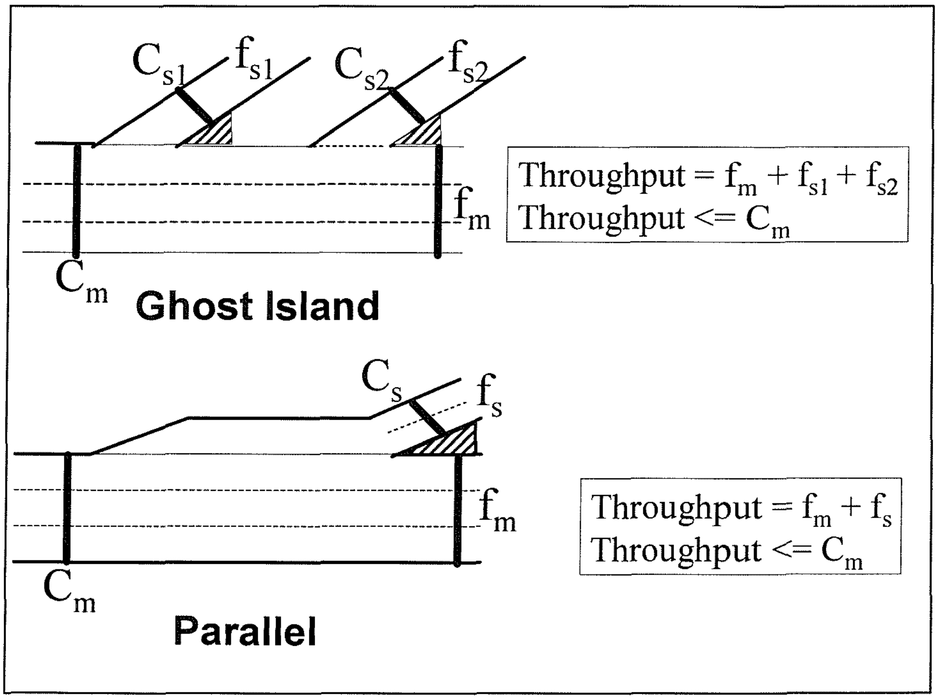


Figure 8.2 Throughputs and capacities for the Ghost Island and Parallel layouts

The notation used in Figures 8.1 and 8.2 is as follows:

C_m: Capacity of the mainline
C_{mb}: Capacity of the mainline before the diverge for the Taper lane drop
C_{ma}: Capacity of the mainline after the diverge for the Taper lane drop
C_s: Capacity of the slip road
C_{s1}: Capacity of slip lane 1 for the Ghost Island diverge
C_{s2}: Capacity of slip lane 2 for the Ghost Island diverge
f_{ma}: Flow on the mainline after the diverge
f_s: Flow on the slip road
f_{s1}: Flow on the first exit slip lane for the Ghost Island
f_{s2}: Flow on the second exit slip lane for the Ghost Island

The maximum throughput for each layout can be no higher than the capacity of the 3-lane mainline before the diverge (C_m or C_{mb} with the Taper lane drop layout). This is appropriately 6600veh/hr in SISTM (2200veh/hr per lane).

There can also be two additional constraints on the maximum throughput depending on the type of layout and its diverging percentage. These are:

1. **Capacity of the two slip lanes** - the two slip lanes have a combined capacity within SISTM of approximately 4400 veh/hr (this figure may be lower for the Taper and Taper lane drop layouts due to the model under utilising slip lane 2). If the number of exiting vehicles exceeds this number (i.e a diverging percentage of at least 70% at capacity levels) then the maximum throughput would be reduced. This can also be dependant on the capacity of lane 1 (Taper and Taper lane drop layouts) and/or the auxiliary lane (Parallel layout) that feeds the slip lanes. The Ghost Island layout, having two exit points, also has a combined slip lane capacity of 4400 veh/hr but divides the exiting flow into two streams easing the pressure on lane 1. A very high diverging percentage of over 70% would be very unlikely in practice.

2. **Capacity of the mainline after the diverge** - there are only two mainline lanes after the Taper lane drop diverge, restricting the flow on this section of the mainline (a capacity limit of approximately 4400 veh/hr). If the straight-ahead mainline traffic exceeds this number (i.e a diverging percentage of under 30% at capacity flow levels) then the maximum throughput will be reduced.

A well designed diverge, allowing exiting vehicles to leave the mainline easily without causing disruption to the straight ahead traffic, will enable the mainline flow to approach this maximum capacity (C_m or C_{mb} for the Taper lane drop layout), thus increasing the throughput at the diverge. This maximum capacity will only be reached at high flows and when the mainline lanes are utilised in an optimal way (normally equally used).

There are two factors that enable the lane utilisation of the individual mainline lanes to be more equal before the diverge and therefore maximise throughput at the diverge. This is particularly important in high mainline and diverging flow situations. These are:

1. **Mainline lane choice** – Does the exiting driver have a choice of mainline lanes to use in order to be correctly positioned to leave the mainline? For example, with the Taper layout drivers need to be in lane 1 prior to the diverge in order to move into the exit slip road providing no lane choice. However with a Ghost Island lane drop, drivers may use lane 1 and come off at the first exit point or stay in lane 2 and leave the mainline at the second exit point.

2. **Mainline exit choice** – Does the exiting driver have to leave the mainline at a particular point or have a choice of exit points or an area in which to choose from? For example, the Taper layout has one particular point at which drivers must leave the mainline. However, with the Parallel layout, drivers can move into the auxiliary lane at any point along its length. Also, with a Ghost Island layout, drivers have a choice of two exit points.

Mainline lane choice and exit choice are related as exit choice enables drivers to decide when and where to leave the mainline, and so have flexibility about which lane to be in before the diverge and when they need (if necessary) to change lanes. If exiting vehicles have to be in lane 1 prior to the diverge, then the mainline lanes will not be utilised in an optimal way. However, when drivers have a choice of lanes or exit points/auxiliary lane available, the driver has more flexibility and the mainline before the diverge can be utilised much more effectively. This does not mean that drivers should be given complete freedom of all available road space but they should be regulated with the help of signing and road markings into an orderly stream of exiting traffic.

8.2.2 Throughput and lane utilisation results

For each of the four layout types modelled, a demand flow way above the capacity of the 3-lane mainline of 8000 veh/hr was generated in SISTM in order to assess the throughput of each layout. The demand data was entered in a detailed way giving origin-destination flows for each vehicle class separately for various time slices. The demand flow of 8000 veh/hr was the highest possible demand flow that could be used in all runs (with different diverging and HGV percentages) whilst keeping within the 3600 veh/hr figure.

The demand flow was increased to 8000 veh/hr in several easy steps in order to try to replicate the build-up of traffic in a more realistic way. Psuedo-detectors were installed 500m before the diverge, on the slip road and 500m after the diverge. This provided important data regarding vehicle flows and speeds before, on and after the diverge. The throughput of each layout was measured for varying diverging percentages (0% - 60% for Taper, Ghost Island and Parallel layouts; 20% - 60% for Taper lane drop layout). For this scenario, the two exits for the Ghost Island layout were set up to be equally used. The Parallel layout was modelled with an auxiliary lane of 400m. The throughput results are shown in vehicles per hour (with 85% light and 15% heavy vehicle composition) in Figure 8.3.

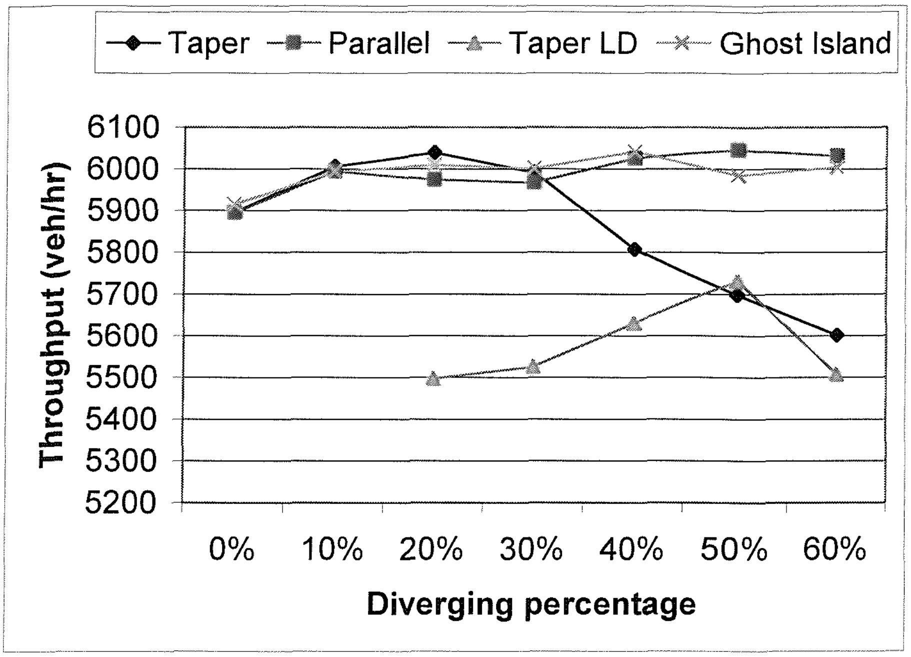


Figure 8.3: Throughput results for the four layouts with 15% HGVs

For the Taper layout, the throughput increased to a maximum value at 20% diverging and then started to decrease. Once the diverging percentage went above 20%, lane 1 could no longer provide sufficient capacity for all the exiting traffic and lane 1 (and lane 2) became full of slower moving traffic as the exit struggled to cope with the higher diverging demand. This was due to the fact that exiting vehicles, in order to leave the mainline, had no lane choice but needed to be in lane 1 prior to the exit, so they could move into the slip road and leave the mainline.

Intuitively, it may have been expected that the maximum throughput would occur when there is no diverging traffic (i.e. 0%). Figure 8.4 shows the lane utilisation for the individual mainline lanes against diverging percentage for the Taper layout. It shows that the three lanes are most equally utilised with 30% diverging percentage, which corresponds approximately to the maximum throughput value at 20%. This could also be due in part to the fact that when there is exiting traffic, more efficient use is made of the available road space at the junction (the two slip lanes being used as well as the three mainline lanes).

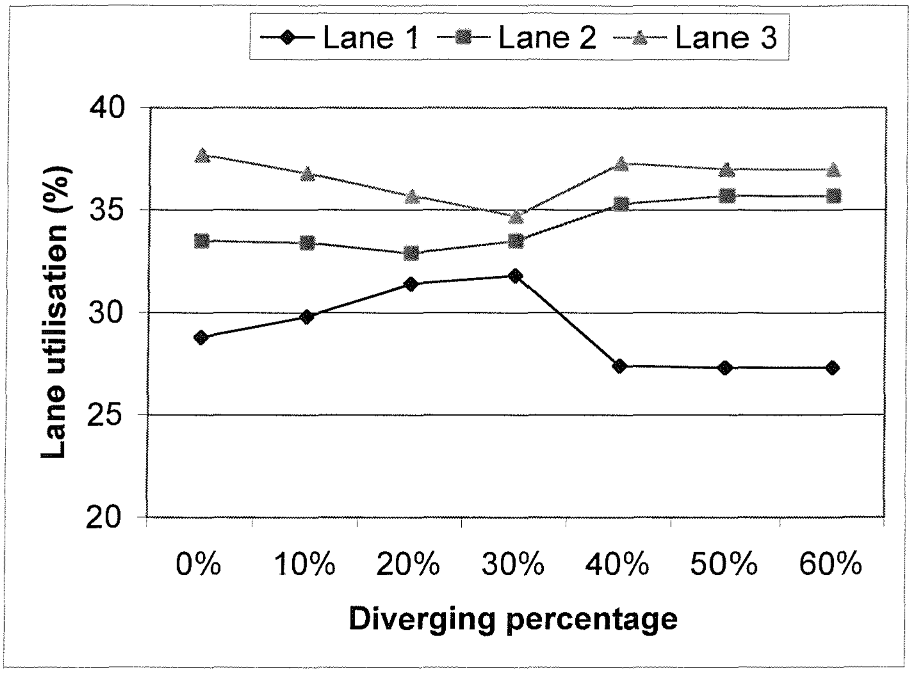


Figure 8.4: Lane utilisation 500m before the Taper diverge

For the Taper layout, the lane utilisation for lane 1 started to decrease beyond 30% diverging, unable to cope with any more traffic. Chapter 9 contains lane utilisation results for a more typical flow, below the capacity of the mainline.

For the Parallel layout, the throughput increased between 0% and 10% diverging and then remained reasonably constant. At a wide range of diverging percentages (0% - 60%), this layout was able to produce a high throughput.

As explained in Chapter 7, SISTM is not able to model the Parallel layout accurately and the throughput results would be an under estimation as exiting vehicles enter the single auxiliary lane at its beginning (if possible) with no overtaking allowed. This leads to platoons of vehicles following an HGV or a slow moving car in the auxiliary lane, increasing journey times particularly for exiting vehicles.

Even with the problems SISTM had at modelling this type of layout, the results showed that the presence of an auxiliary lane enables the exit to provide more capacity and to operate more efficiently. In reality, the auxiliary lane helps drivers become more aware of the diverge by providing a prolonged opportunity to leave the mainline early. Drivers still have no lane choice, as they need to be in lane 1 prior to entering the auxiliary lane. However, they do have some exit choice by being able to leave the mainline and join the auxiliary lane within the length of the lane and not just at a particular point. This enables more flexibility in when to move into lane 1 and leave the mainline.

Figure 8.5 shows the lane utilisation for the individual mainline lanes against diverging percentage for the Parallel layout. It shows that the three lanes are most equally utilised with about 50% diverging percentage, which corresponds to the maximum throughput value.

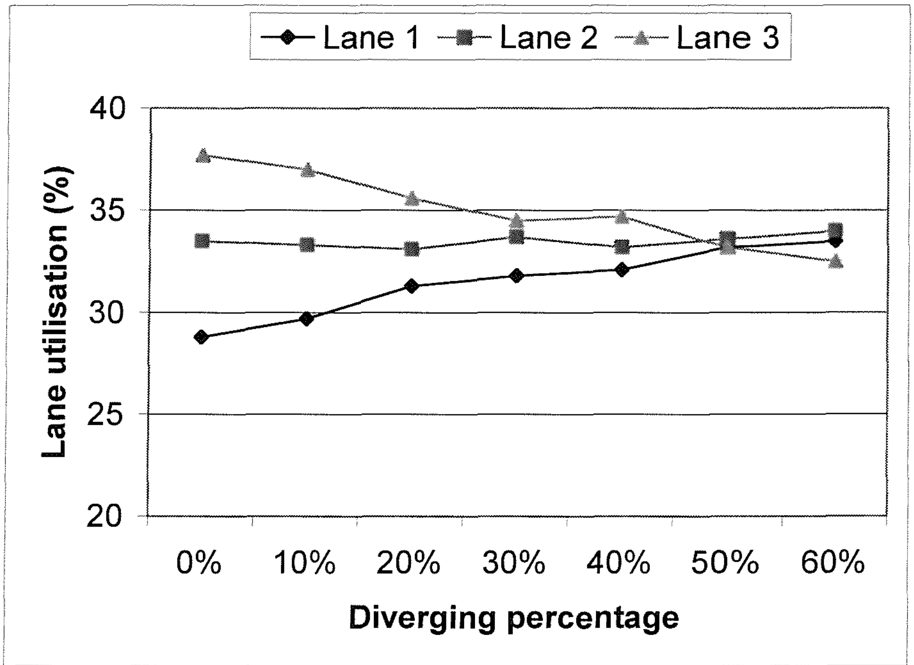


Figure 8.5: Lane utilisation 500m before the Parallel diverge

The Parallel layout is a "half way house" between a Taper layout, that has no lane or exit choice, and a Ghost Island layout that has both. The auxiliary lane has other benefits, acting as a speed change lane for exiting vehicles. It also provides extra capacity at the exit, reducing the likelihood of traffic queuing from the end of the exit and blocking back onto the mainline. This result is consistent with findings from research in the USA which recommend multi-exit Parallel layouts (with an auxiliary lane between 450m and 750m) where the diverging flow exceeds the capacity of 1 slip lane (Taylor and Raymond 1974).

For the Ghost Island layout, the throughput increased between 0% and 10% diverging and then remained reasonably constant with minor fluctuations. Even with a high diverging percentage, this layout was still able to produce a high throughput. Exiting traffic had a choice of which exit to use with only those vehicles wishing to use the first slip lane needing to be in lane 1 prior to the diverge. Exiting vehicles intending to use the second exit did not need to be in lane 1 prior to the first slip lane, having an extra period of time in which to move into lane 1 prior to the second slip lane. Both slip lanes (modelled as single links in SISTM) were equally utilised and coped well with the high numbers of diverging vehicles.

Figure 8.6 shows how the lane utilisation for the individual mainline lanes before the Ghost Island diverge converged to being more equally utilised as the diverging percentage increased. This explains how the throughput was high even at high diverging percentages.

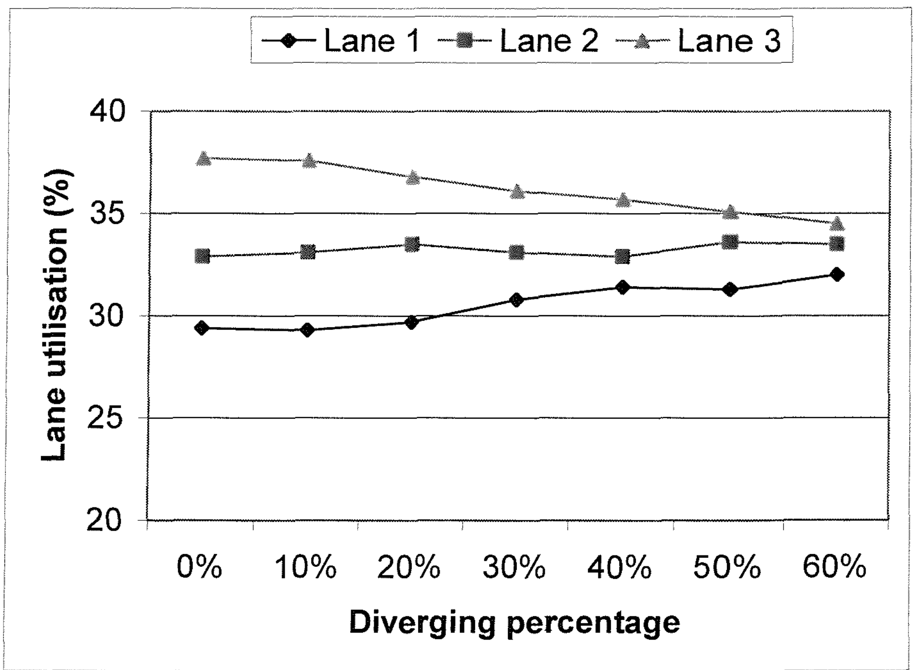


Figure 8.6: Lane utilisation 500m before the Ghost Island diverge

For the Taper lane drop layout, the throughput increased between 20% and 50% diverging (reaching a peak at 50%) and then started to decrease. As with the Taper layout, exiting vehicles needed to be in lane 1 which is then dropped and became the slip road. At a diverging percentage of above 50%, lanes 1 and 2 were full of slower moving traffic as exiting vehicles, not already in lane 1, needed to find a suitable gap into that lane in order to leave the mainline. The throughput for this layout is noticeably lower than the other two layouts (particularly for diverging percentages lower than 50%) as a lane is dropped at the exit, leaving only two mainline lanes after the diverge.

Figure 8.7 shows the lane utilisation of the individual mainline lanes before the Taper lane drop diverge. It showed that the utilisation of the mainline lanes converged to becoming more equally used as the diverging percentage increased.

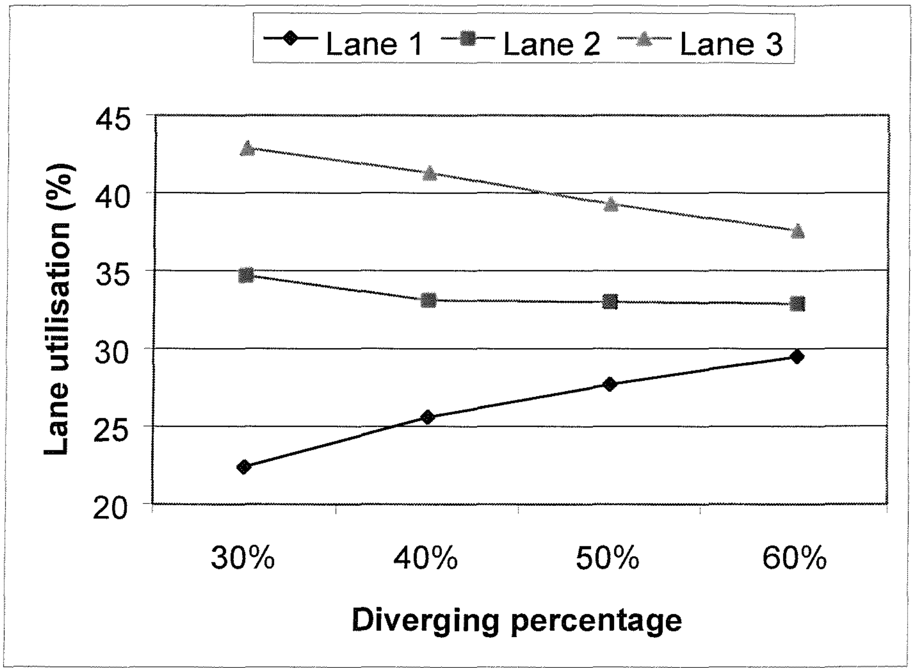


Figure 8.7: Lane utilisation 500m before the Taper lane drop

Figure 8.8 divides the throughput for the Taper layout into the 'mainline after' flow and the slip road flow. It shows how the exiting flow increased and the mainline flow after the diverge decreased, with an increased diverging percentage. There was a similar pattern for the other layouts.

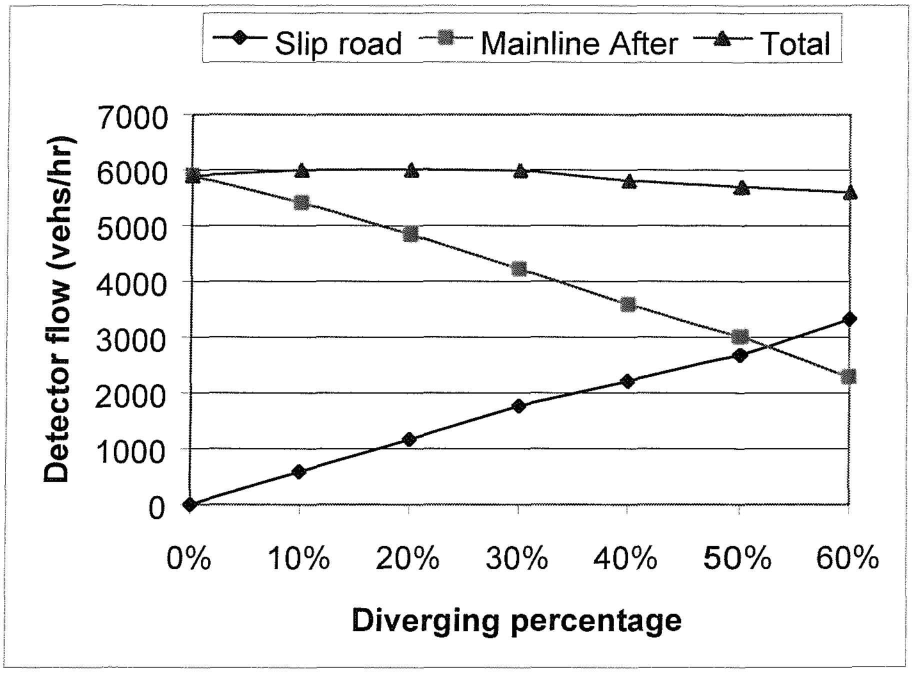


Figure 8.8: Slip road and mainline flow after the diverge for the Taper layout

Overall, the results showed that the both the Parallel and the Ghost Island layouts had a consistently high throughput for a large range of diverging flows (0% - 60%). Both layouts offered exiting drivers flexibility as to when they needed to be in lane 1 and when to leave the mainline. This improved the utilisation of the mainline lanes before the diverge, contributing to a higher throughput.

However, the Taper and Taper lane drop layouts struggled to cope with higher diverging percentages beyond 20%-30% and 50% respectively. Both layouts offered no lane or exit choice, with drivers having to be in lane 1 prior to the exit and leave the mainline at a particular point. The Taper lane drop had the lowest throughput in part due to the presence of only two mainline lanes after the exit.

It has been shown that there is a connection between lane and exit choice and how efficiently the mainline lanes are being utilised prior to the exit. This in turn affects the throughput results. Lane utilisation is a factor which needs to be taken into account in the decision making process for the selection of the most suitable diverge layout.

8.2.3 Throughput and traffic composition

The throughput results in section 8.2.2 were for a 15% HGV percentage. In SISTM, HGVs are only permitted to use lanes 1 and 2, which complies with UK motorway regulations. With high diverging percentages and a high HGV percentage, the demand for lane 1 (and lane 2) can exceed its capacity causing slow moving traffic before the exit. It is therefore thought that the percentage of HGVs can have a noticeable effect on the throughput at the diverge given their size, weight and average speed.

In order to quantify the effect of the percentage of HGVs on the throughput of each layout, further simulation runs were carried out with varying HGV percentages (i.e. 0%, 5% and 25% HGVs). Figure 8.9 shows the throughput results for each of the four layouts with 0% HGVs. The shape of the throughput profile for each layout remained similar to those in Figure 8.3 but with much higher throughput values for all four layouts of between about 10% and 15%. Figure 8.10 shows how the throughput profile varies with different HGV percentages using the Taper diverge as an example. The effect of increasing the percentage of HGVs within the traffic composition is not linear (as already shown in Chapter 6, section 6.5.4), having a more noticeable effect at lower proportions.

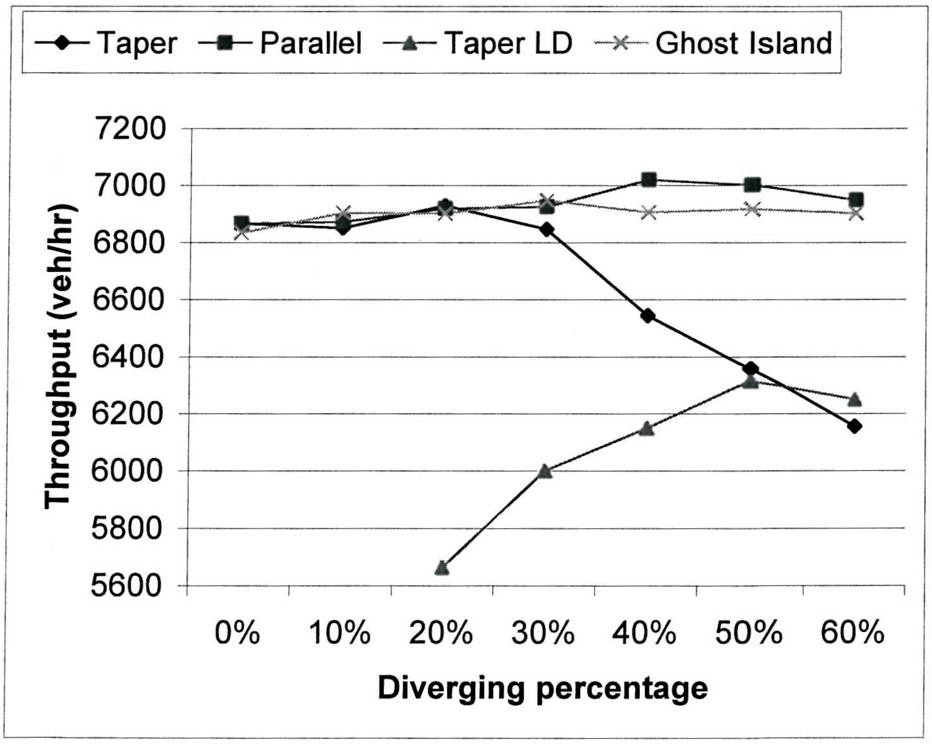


Figure 8.9: Throughput results for the four layouts with 0% HGV

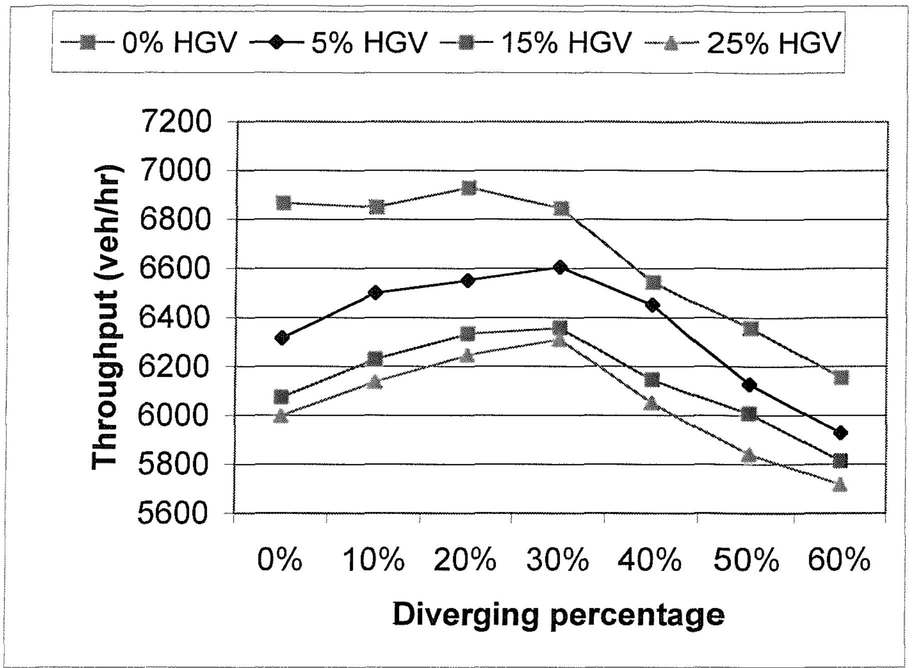


Figure 8.10: Throughput at the Taper diverge with different HGV percentages

In order to investigate these throughput results further, an additional comparison was made of the standard deviation of the utilisation of the three mainline lanes before the diverge for 0% HGVs and 15% HGVs. The standard deviation of the mainline utilisations was thought to be a good indication of how equally (and therefore optimally) the mainline lanes were being used 500m before the diverge. The results are shown in Table 8.1.

Table 8.1: Standard deviations of the mainline lane utilisations before the diverge

	Taper		GI		Parallel		Taper LD	
Diverging (%)	15% HGV	0% HGV	15% HGV	0% HGV	15% HGV	0% HGV	15% HGV	0% HGV
0%	4.45	1.69	4.17	1.97	4.45	1.69	-	-
10%	3.50	1.14	4.15	1.18	3.65	1.61	-	-
20%	2.18	0.91	3.55	1.21	2.16	0.64	7.46	12.69
30%	1.46	0.70	2.66	0.83	1.39	1.21	10.32	8.71
40%	5.23	1.27	2.18	0.51	1.31	1.15	7.85	4.31
50%	5.27	0.99	1.91	0.87	0.23	1.82	5.81	2.25
60%	5.27	1.15	1.26	0.12	0.76	0.90	4.07	1.59

The results in Table 8.1 show the standard deviation of the utilisation of the mainline lanes were much lower with 0% HGVs. This helps to explain why the throughput values are much higher when there are no HGVs present and how a high HGV and diverging percentage can reduce the throughput noticeably (see the Taper and Taper lane drop layout results for high diverging percentages). The only exception in the results was for the Taper lane drop with 20% diverging. With 0% HGVs, lane 1 had a utilisation of only 18% compared to 25% when there were 15% HGVs. This can highlight the ease at which light vehicles can accept smaller gaps when changing lane, particularly when moving out of lane 1 in order to avoid the lane drop. In contrast, HGVs need much longer gaps in order to lane change due to their size and lower average speed.

The throughput results recorded in this chapter are in vehicles per hour as SISTM records the flow data in this way. This is consistent with TD22/92 (Department of Transport 1992a) where flows are recorded in vehicles per hour but are then adjusted by the correction factors according to the percentage of HGVs. In OSCADY (a program for optimising the signal timings and calculating the capacity of signal-controlled junctions), flows are entered into the program in vehicles per hour and then converted into passenger car units per hour (pcu/hr) according to the vehicle type composition. HGVs and cars are given a pcu value of 2.3 and 1.0 respectively (Binning 1998).

HGVs are restricted to using lane 1 or 2 on the motorway (as modelled in SISTM). Preliminary modelling in SISTM to restrict HGVs to lane 1 only showed that it reduced the throughput with a correspondingly more unequal lane distribution before the diverge. This may be a beneficial measure when there is a high proportion of HGVs within the traffic composition, with a noticeable proportion of them wishing to leave the mainline.

8.2.4 Further investigation of the Ghost Island diverge

8.2.4 .1 Exit usage

An investigation was carried out on the Ghost Island layout to see how the throughput of the junction was affected by varying the utilisation of the two exit slip lanes. This was carried out for two main reasons. These were:

1. The throughput results (in section 7.3.2.1) may be influenced by the fact that vehicles within SISTM do not know about the presence of the second slip lane in a double slip lane exit (see section 6.3.4). This effects the utilisation of the second slip lane in the Taper, Taper lane drop and Parallel layouts and hence their throughput results. The Ghost Island layout is unaffected in this regard as it is comprised of two closely spaced single lane exits, enabling the user to determine the proportion of diverging traffic using each exit point. Given the fact that even at relatively high diverging flows only up to 30% of exiting vehicles use the second slip lane (see Figure 8.20 and 8.21), a fairer comparison between the four layouts may occur when the utilisation of the slip lanes are similar (throughput results for the Ghost Island layout in section 7.3.2.1 were based on the two exit slip lanes being used equally).

2. From previous video studies at Ghost Island diverges, there tended to be an initial unequal usage of the two exits with a larger proportion of diverging vehicles using the first exit (Wedlock et al 2001). This normally changed over time to a more equal usage of each exit point, as drivers got more familiar with the new layout (SISTM is unable to model familiarity). It is important to see whether the Ghost Island layout still performs well when there is unequal usage of the two slip lanes.

3. There are some Ghost Island diverges where the slip lanes separates shortly after the exit into two different destinations (e.g. M3/M25 northbound where drivers take the first exit for Heathrow Airport and the second exit for Gatwick Airport). Slip lane usage can be therefore dependant on destination as well as driver preference.

Further simulation runs were carried out to assess the throughput of the Ghost Island layout with unequal usage of the two exit slip lanes. The diverging percentage was varied from 10% to 60% with the percentages of diverging traffic using the first and second exit respectively set at 90%-10%, 80%-20%, 70%-30% and 60%-40%. The throughput results are shown in Figure 8.11.

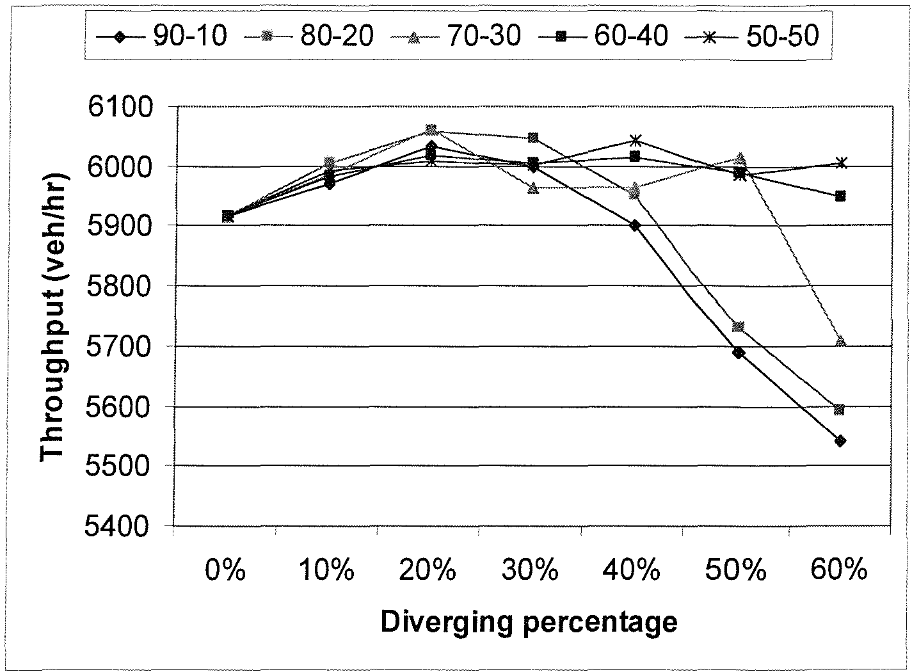


Figure 8.11: Throughput at a Ghost Island diverge with unequal usage of slip lanes

The more exiting vehicles that can leave the mainline at the first exit enables easier access to the second exit for the remaining diverging traffic. However, there is a capacity limit for the first exit and slower moving traffic in lane 1 prior to this exit can occur when there is a high number of exiting vehicles using it. Also, the more exiting vehicles wishing (or needing) to use the first exit reduced their lane and exit choice, causing more disruption to the mainline traffic.

The results showed that for low diverging percentages (up to 20%), the throughput remained similar whatever the usage of the slip lanes. At these low diverging percentages, unequal exit usage was not as important as the first exit slip lane still had the necessary capacity for the exiting traffic wishing to use it. However, when the diverging percentage was above 40%, there was a noticeable reduction in throughput for the 90%-10%, 80%-20% and 70%-30% exit usage scenarios. This reduction in throughput was most noticeable when the exit usage was most unequal (i.e. 90%-10%) with slip lane 1 being more and more unable to cope. There was also a reduction in the throughput for the 60%-40% scenario when the diverging percentage rose above 50%. However, the 50%-50% scenario was relatively constant between 20% and 60% diverging, with no noticeable reduction in throughput.

Figure 8.12 shows the standard deviation of the 3 lane utilisations for varying diverging percentages for each of the five different exit percentage splits. It shows how as the diverging percentage increased, the standard deviation of the lane utilisations for the 50%-50% and 60%-40% cases decreased. For the 70%-30%, 80%-20% and 90%-10% cases, the standard deviation decreased but then increased again with higher diverging percentages. This was because the utilisation of the mainline lanes prior to the diverge became more unequal, when there was a high diverging percentage and a more unequal use of the slip lanes for the exiting vehicles. In particular, the utilisation of lane 1 started to fall, unable to cope with any more exiting traffic. This, again, is reflected in the lower throughput values for the higher diverging percentages particularly for the 90%-10% and 80%-20% scenarios.

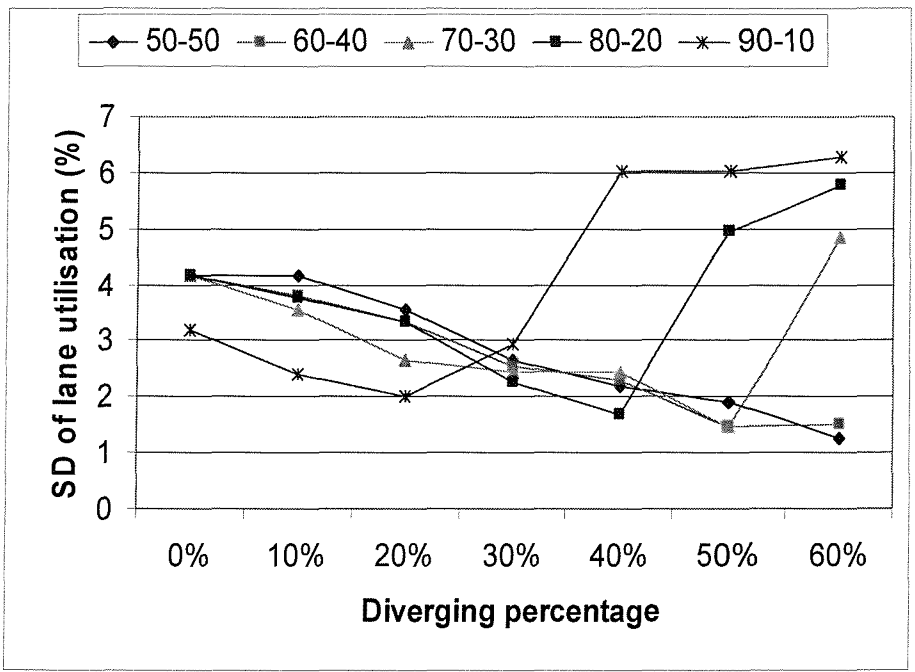


Figure 8.12: Standard deviation of the lane utilisations against diverging percentage

It would be interesting to see if drivers over time find the optimal exit split for a particular Ghost Island layout, with its unique and possibly varying diverging percentage. This would not always be an equal use of the two exits. Drivers can tend to use the motorway in such a way as to reduce their own personal travel time by, for example, changing to a 'faster' lane rather than optimise the lane usage of the mainline, thus reducing the overall travel time for all drivers.

These results seem realistic and show that even with an uneven usage of each exit of up to 80%-20% (which is unlikely in reality), the throughput of the Ghost Island remained higher than the Taper and the Taper lane drop layouts, particularly at high diverging percentages (over 30%). They are, however, still lower than the throughput results for the Parallel layout.

8.2.4.2 Exit spacing

A further investigation was carried out on the Ghost Island layout to see whether the distance between the two exit slip lanes (or exit spacing) effected the throughput. The exit spacing is important as it helps to separate and regulate the diverging flow into two orderly streams of traffic with the help of the marked ghost island. The recommended distance is 180m (Wedlock, Peirce and Wall 2001) but this distance was varied from 100m to 1000m, in 100m intervals. The diverging percentage was fixed at 50%. Figure 8.13 shows the throughput results.

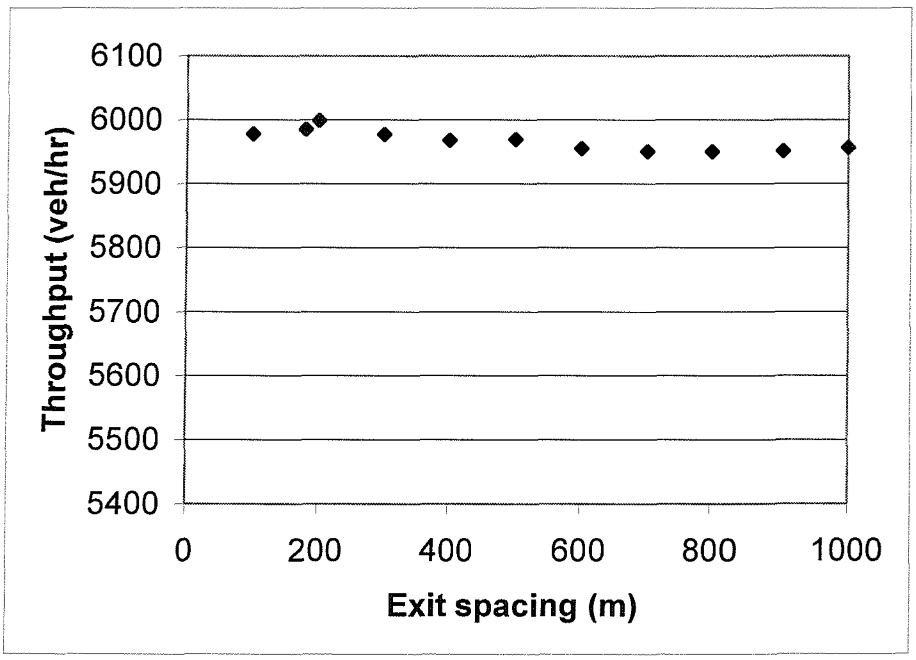


Figure 8.13: Throughput at a Ghost Island diverge with a varying exit spacing

The results show that increasing the exit spacing had no noticeable effect on the throughput of the diverge. The utilisation of the individual mainline lanes before the diverge varied slightly between 100m and 400m, before staying constant between 500m and 1000m. Once the exit spacing was above 500m, diverging traffic leaving at the second exit had plenty of time to change into lane 1 after the first exit and leave the mainline. The Ghost Island layout is modelled as two single link separate diverges in SISTM and so there are two scoring systems to cater for the two exits. With a longer exit spacing (above 500m), exiting vehicles leaving at the second exit will be given no stimulus to change lanes until much nearer their exit resulting in these vehicles having no effect on the lane utilisation before the first exit. In reality, vertical signing before the first exit would inform drivers of the presence of two exits of the Ghost Island diverge, along with information concerning which lane they should be in. Driver's reactions to these directional signs and subsequent behaviour can not be modelled within SISTM but can be an important factor in the behaviour of drivers (Wedlock et al 2001).

A longer exit spacing could have benefits in allowing exiting vehicles to leave the mainline early at the first exit, causing less disruption to the mainline traffic. However, long queues of slow moving traffic on the first slip lane can occur when a platoon of vehicles follows an HGV or a slow moving car, with the ghost island markings preventing overtaking opportunities.

8.3 Average speeds results

8.3.1 Introduction

Average speeds on the mainline and the exit slip road were automatically collected by the pseudo-detectors, and give an indication of the efficiency and operation of the diverge. These speeds were collected at three different positions before, on and after the diverge. These were:

- Mainline 500m before the diverge
- Slip road
- Mainline 500m after the diverge

8.3.2 Average speeds on the mainline before the diverge

Average speeds on the mainline before the diverge are an important indication of the efficient way the diverge is operating at enabling exiting traffic to leave the mainline, causing as little disruption to other traffic as possible. Figures 8.14 show the average speed for the mainline 500m before the diverge for the three layouts.

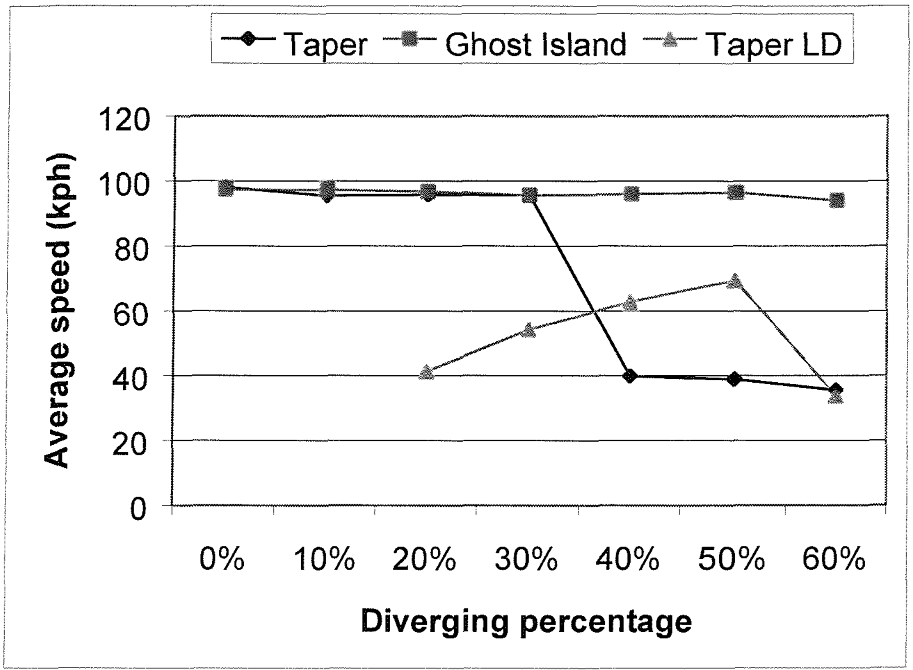


Figure 8.14: Average mainline speeds 500m before the diverge

For the Taper layout, the average speed on the mainline before the diverge dropped noticeably at 40% diverging. The utilisation of lane 1 had risen to a peak at 30% diverging to about 33% of the mainline traffic, which corresponded to the maximum throughput. Given that the flow levels were at capacity, lane 1 could not cope with any more exiting traffic and at 40% diverging percentage, queues of slow moving traffic were present in lanes 1 and 2.

For the Ghost Island layout, the average speed before the diverge remained relatively constant until 50% diverged, when it started to decrease slightly. This average speed would have been lower with an unequal use of each exit.

For the Taper lane drop layout, average speeds before the diverge increased from 20% to 50% diverging and then started to decrease. Initially, speeds increased as there were more exiting vehicles, with lane 1 being much better utilised. However, at 50% diverging, the exit struggled to cope with such a high number of diverging vehicles with the result being slower moving traffic in lanes 1 and 2.

8.3.3 Average speeds for each lane on the mainline before the diverge

In order to obtain more detailed information about the operation of each layout, the average speed before each of the diverge layouts were split into average speeds for each of the three mainline lanes. Figures 8.15, 8.16 and 8.17 show how the average speeds for each lane on the mainline 500m before the diverge for the Taper, Ghost Island and Taper lane drop layouts respectively.

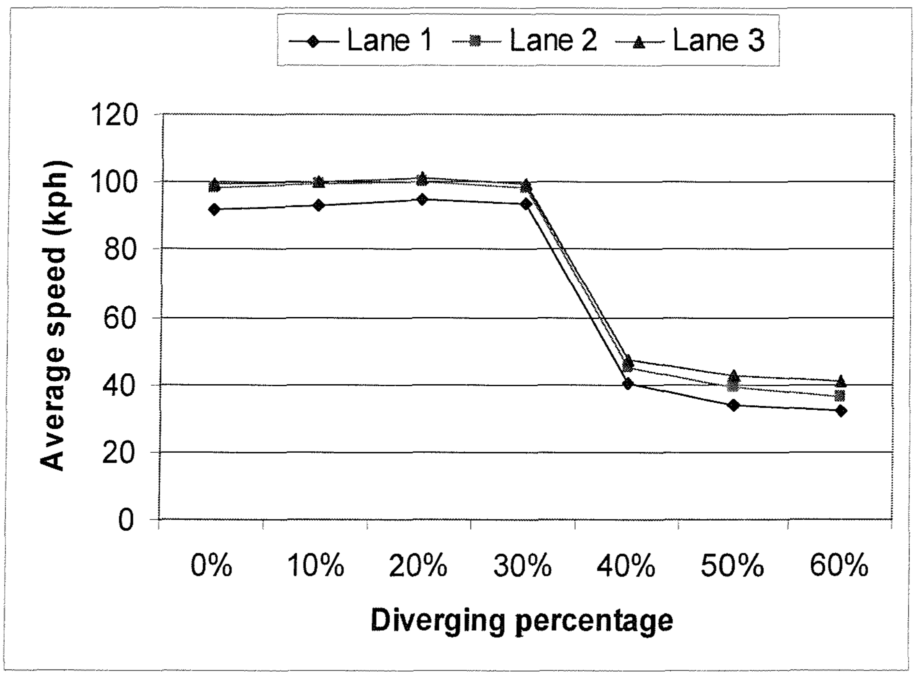


Figure 8.15: Average speeds 500m before the Taper layout

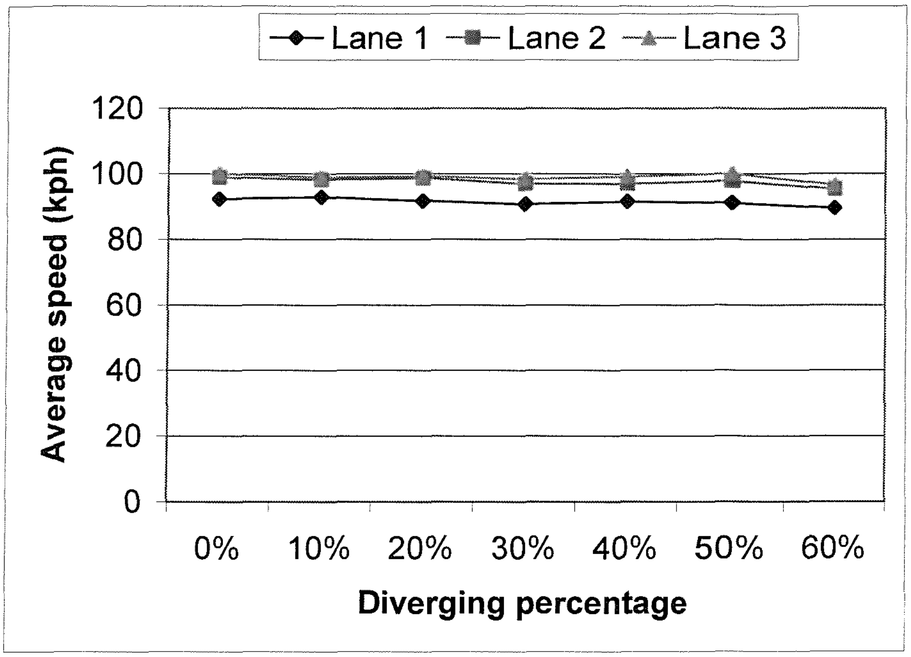


Figure 8.16: Average speeds 500m before the Ghost Island layout

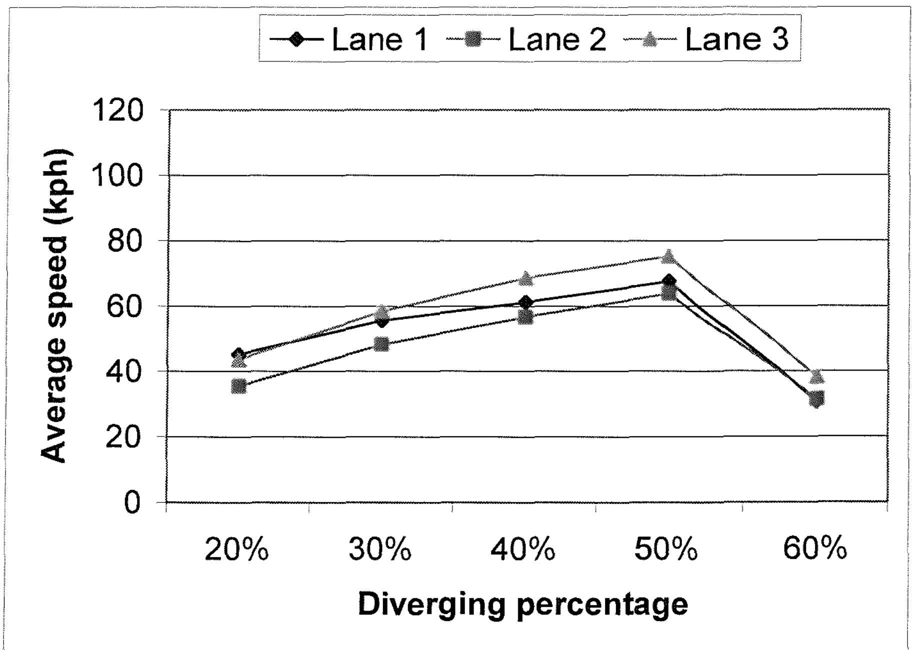


Figure 8.17: Average speeds 500m before the Taper lane drop layout

These three figures showed how lane 1 remained the slowest lane for the Taper and Ghost Island layouts, whereas lane 2 was the slowest lane for the Taper lane drop layout. Even at 500m from the Taper diverge, the mainline was effected as lane 1 became full of slow moving traffic once the diverging percentage rose above 40%. All three lanes showed a reasonably similar reduction in speed which is probably due to the fact that all 3 lanes were very congested. It is likely that, in reality, lane 3 would probably show the smallest reduction in average speed, but this may be due to either the logic of SISTM and/or the fact that very high mainline flows were being used in the model. For the Taper lane drop, lane 2 became full of slow moving traffic particularly as the diverging percentage rose above 50%, with exiting traffic in lane 2 trying to find a gap to change into lane 1. The Ghost Island layout, however, coped well even with high diverging flows, and saw a slight reduction in average speed at 50% diverging.

8.3.4 Average speeds on the slip road

Average speeds on the slip roads were the highest for the Ghost Island layout which saw only a gradual reduction as the diverging flows increased (see Figure 8.18). Average speeds for the Taper and Taper lane drop layouts dropped noticeably at 30% and 50% diverging percentage respectively, showing how the exit was struggling to cope with high diverging flows. Part of the reason, however, may be due to the way SISTM models the slip lanes with slip lane 2 being under utilised for the Taper and Taper lane drop layouts (see Figures 9.4 and 9.5). The Ghost Island layout was not affected in this way.

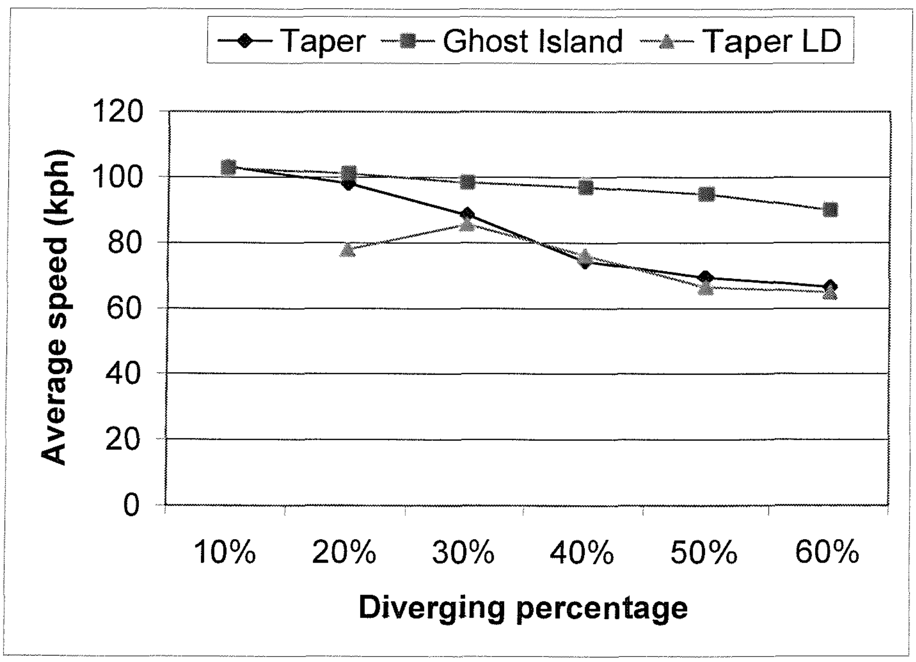


Figure 8.18: Average slip road speeds for each layout

8.3.5 Average speeds on the mainline after the diverge

Average speeds on the mainline after the diverge for all three layouts increased as the diverging percentage increased (see Figure 8.19). This corresponded to a decrease in the remaining mainline traffic. Average speeds for the Taper lane drop layout were noticeably lower than the other two layouts, due mainly to the fact that there were now only two mainline lanes as opposed to three mainline lanes for the other layouts.

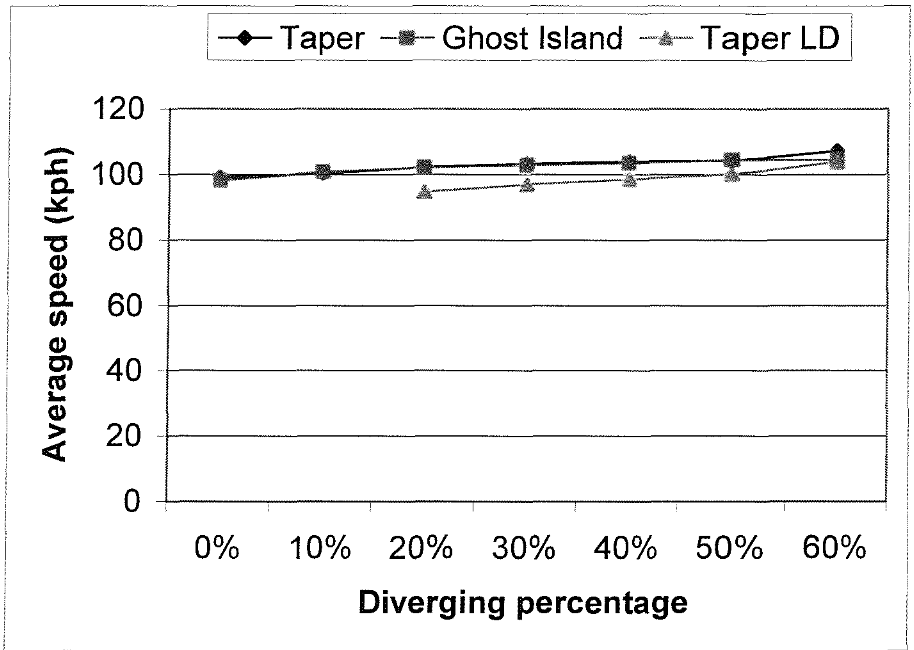


Figure 8.19: Average mainline speeds 500m after the diverge

8.4 Summary

The modelling work in this chapter has been carried out to assess the throughput and operation of various diverge layouts using a very high demand flow. SISTM, a microscopic simulation computer program has been used to provide useful information regarding throughput, average speed and lane utilisation.

The modelling work has shown that the capacity of the different diverge layouts modelled varied according to various factors such as the utilisation of the mainline lanes before the diverge, which mainly depended on their ability to provide lane and exit choice to drivers. The maximum throughput for each layout normally occurred when the lane distribution before the diverge was as optimal as possible. Drivers can tend to use the motorway in such a way as to reduce their own personal travel time by, for example, changing to a 'faster' lane frequently rather than optimise the lane usage of the mainline, thus reducing the overall travel time for all drivers.

The Taper and Taper lane drop layouts provided no lane or exit choice and were shown to be only suitable for situations where the diverge had a limited range of diverging flows. With high diverging flows, these Taper and Taper lane drop layouts experienced a noticeable drop in average speed on the mainline before the exit at 30% and 50% respectively.

The Ghost Island and Parallel layouts performed much better then the Taper layouts, having high throughput values and average speeds even at high diverging percentages. The throughput at the Ghost Island layout was reduced when there was an unequal use of the two exit points with a more unequal use of the mainline lanes before the diverge. It still however performed well at the full range of diverging percentages up to an 80%-20% use of the two exit points. An increase in the exit spacing had no noticeable effect on the throughput. The two exits points in the Ghost Island layout and the auxiliary lane in the Parallel layout were seen to be beneficial as they provided drivers with more flexibility with regard to exit choice, enabling the mainline lanes before the diverge to be more equally and therefore optimally utilised.

The percentage of HGVs in the traffic composition was also seen to be an important factor in the throughput of the diverge. The effect was not linear, having a greater effect in reducing the throughput at lower HGV percentages. The introduction of HGVs into the traffic composition also resulted in a more unequal use of the mainline lanes before the diverge.

Overall, SISTM has provided useful information concerning the throughput of each layout and has shown how the lane distribution before the diverge is an important factor which is related to lane and exit choice.

CHAPTER 9

OTHER MODELLING RESULTS

9.1 Introduction

This chapter contains modelling results for a more typical demand flow of 5000veh/hr (well below the capacity of the 3-lane mainline). This enables the diverge layouts to be evaluated in typically busy but not congested operating conditions. The results for the three diverge layouts are split into three sections. These are:

- lane utilisations
- lane changing rates
- journey times/speeds

It was hoped that the modelling results associated with this flow would provide additional information concerning the potential safety and operation of each layout.

9.2 Lane utilisation results

9.2.1 Introduction

Lane utilisation, as defined in section 6.3, is the proportion or percentage of vehicles using each of the mainline lanes or slip lanes. It is an important parameter particularly near diverges. Figures 8.1, 8.2, 8.3 and 8.4 in the Chapter 8 showed the lane utilisation for the individual mainline lanes just before the diverge for a very high demand flow. These were used to assess the throughput results. In this section, lane utilisation for the individual mainline lanes before and after the diverge (as well as for the slip lanes) were investigated for each layout, for a more typical demand flow of 5000veh/hr.

9.2.2 Lane utilisation before the diverge

Figures 9.1, 9.2 and 9.3 show the lane utilisation for the individual mainline lanes 500m before the diverge for the Taper, Ghost Island and the Taper lane drop layouts respectively. The results for the Taper and Ghost Island layouts were similar, with the utilisation of lane 1 increasing and lane 3 decreasing with an increased diverging percentage. The exception to this was the utilisation of lane 2, which increased for the Taper diverge but decreased for the Ghost Island diverge. As the diverging flow increased, more vehicles needed to be in lane 1 prior to the exit. At low diverging flows, lane 3 was the most used lane, enabling drivers to avoid slower moving exiting vehicles in lane 1 (and possibly lane 2). Figure 9.1 differs to Figure 8.4 (lane utilisation for the Taper layout with a very high demand flow of 8000 veh/hr) in that lane 1 is able to cope with the diverging flow and hence its utilisation increases between 0% and 60%.

For the Taper lane drop, lane 3 was the most utilised lane, particularly at lower diverging percentages. Lane 1 was the least utilised lane but its utilisation rose between 30% and 60% diverging. With high diverging percentages, the utilisation of lane 3 decreased with exiting traffic moving into lanes 1 and 2 in order to leave the mainline, resulting in the mainline lanes being reasonably equally used.

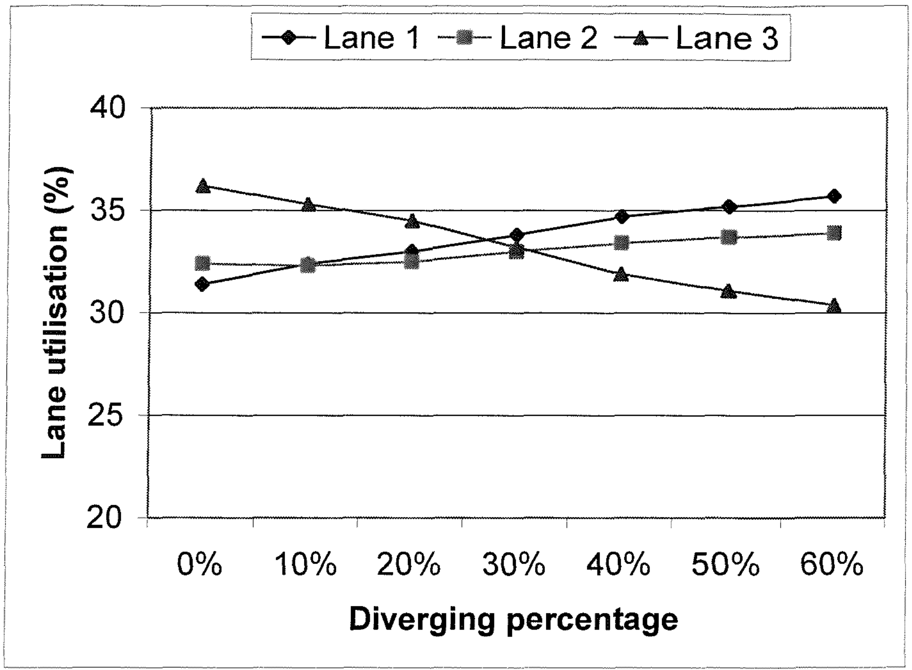


Figure 9.1: Utilisation of mainline before the Taper diverge

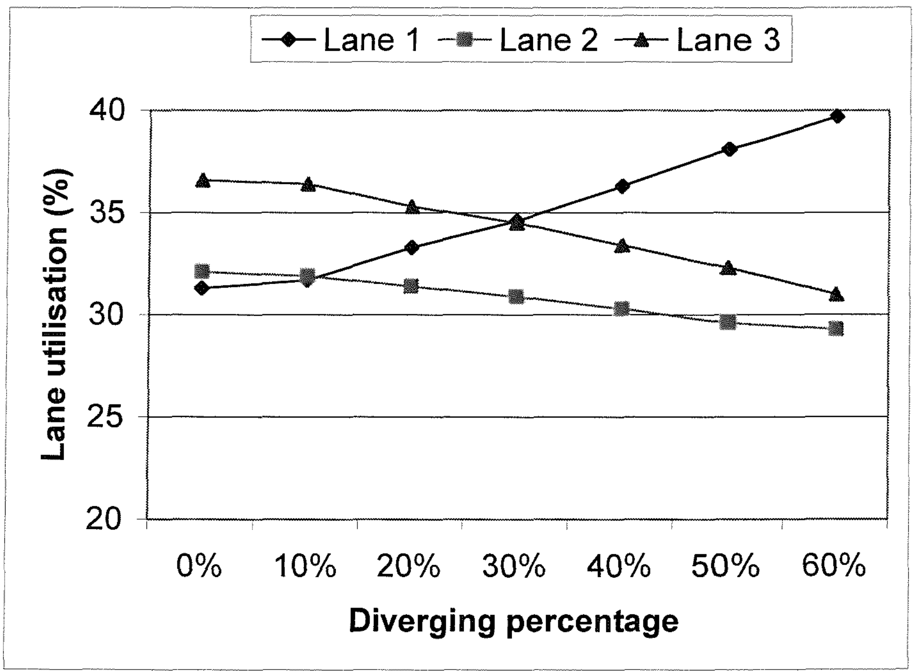


Figure 9.2: Utilisation of mainline before the Ghost Island diverge

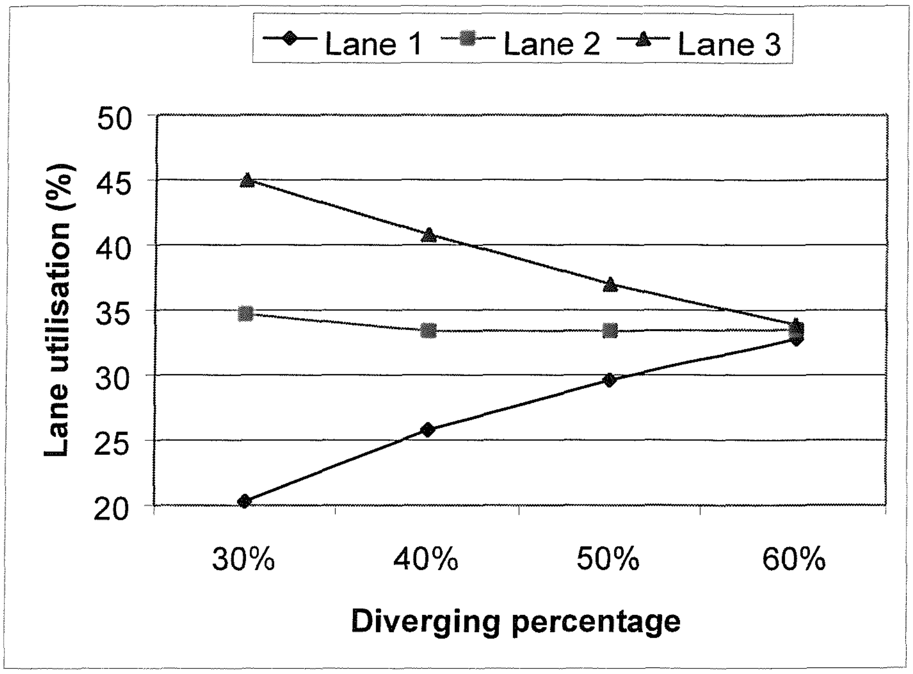


Figure 9.3: Utilisation of mainline before the Taper lane drop diverge

9.2.3 Lane utilisation of the slip lanes

Figures 9.4 and 9.5 show how the lane utilisation for the two slip lanes varied with the diverging percentage for the Taper and Taper lane drop respectively. They showed that for lower diverging percentages, the majority of exiting vehicles used slip lane 1. As the slip road approached capacity, the utilisation of slip lane 2 rose slightly but was still under utilised due to vehicles unaware of its presence within SISTM (see sections 6.3.4 and 10.2.3.2). For the Ghost Island layout, the slip lane usage was fixed by means of the origin-destination table and therefore could be altered according to the user's wishes.

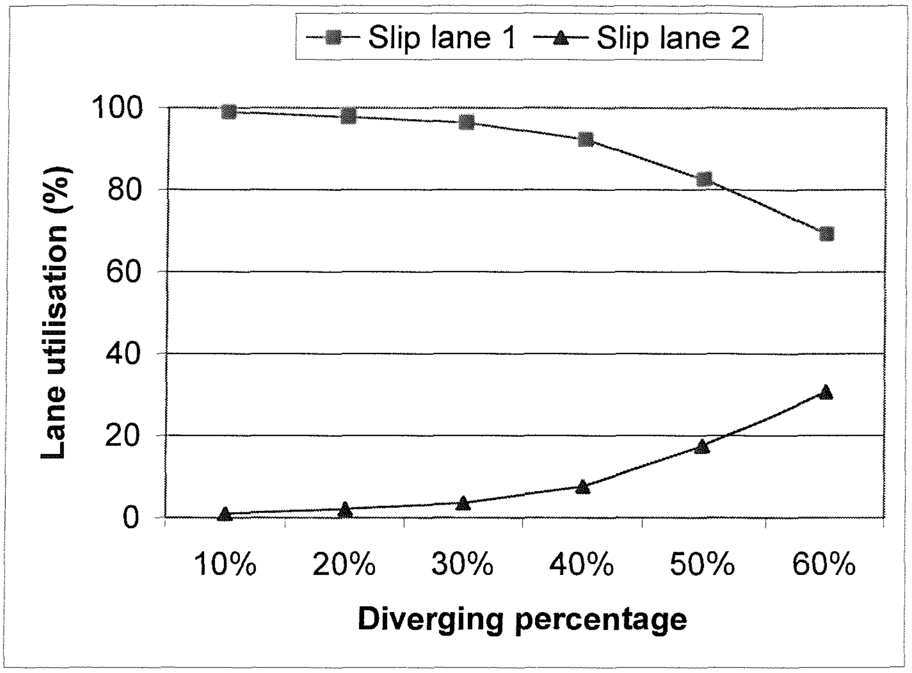


Figure 9.4: Utilisation of the slip lanes for the Taper layout

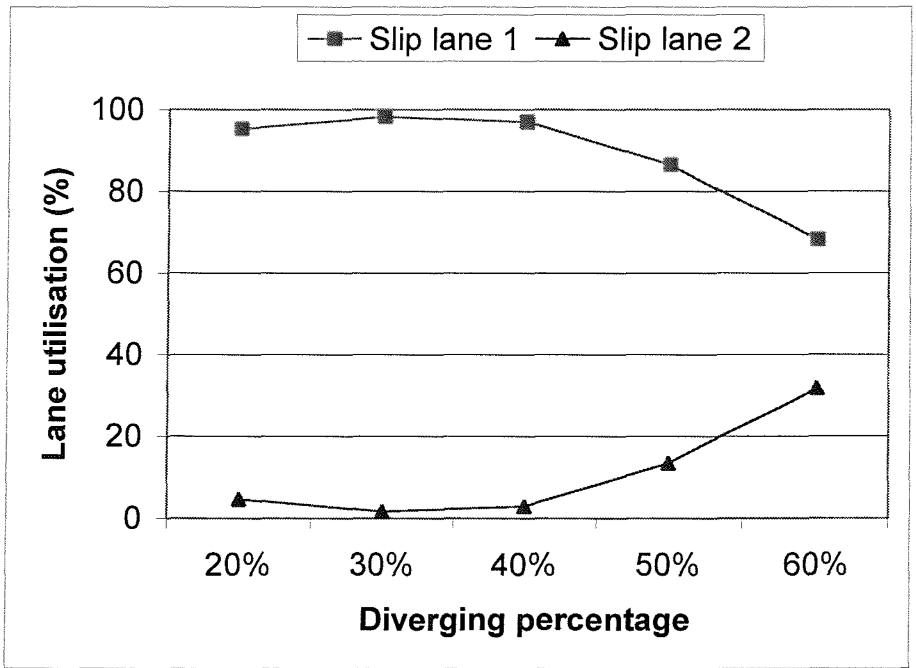


Figure 9.5: Utilisation of the slip lanes for the Taper lane drop layout

9.2.4 Lane utilisation of the mainline after the diverge

Figures 9.6, 9.7 and 9.8 show the lane utilisation for the individual mainline lanes 500m after the diverge for the Taper, Ghost Island and the Taper lane drop layouts respectively. The results for the Taper and Ghost Island layouts showed some similar trends with the utilisation of lane 1 increasing and the other two lanes decreasing with an increased diverging percentage. As the diverging flow increased, the remaining mainline traffic flow decreased enabling more vehicles to move back into lane 1. In reality, there may be a number of drivers who stay in the middle or outer lanes in order to avoid having to change lane many times in order to overtake slower or merging vehicles (known as lane hogging).

For the Taper lane drop, lane 2 was utilised more than lane 1 after the diverge, particularly for lower diverging percentages. For low diverging flows, there was a high mainline flow which was restricted to just two mainline lanes after the diverge. As the diverging flow increased, the mainline flow decreased after the diverge and the utilisation of lane 1 increased with vehicles moving back into lane 1.

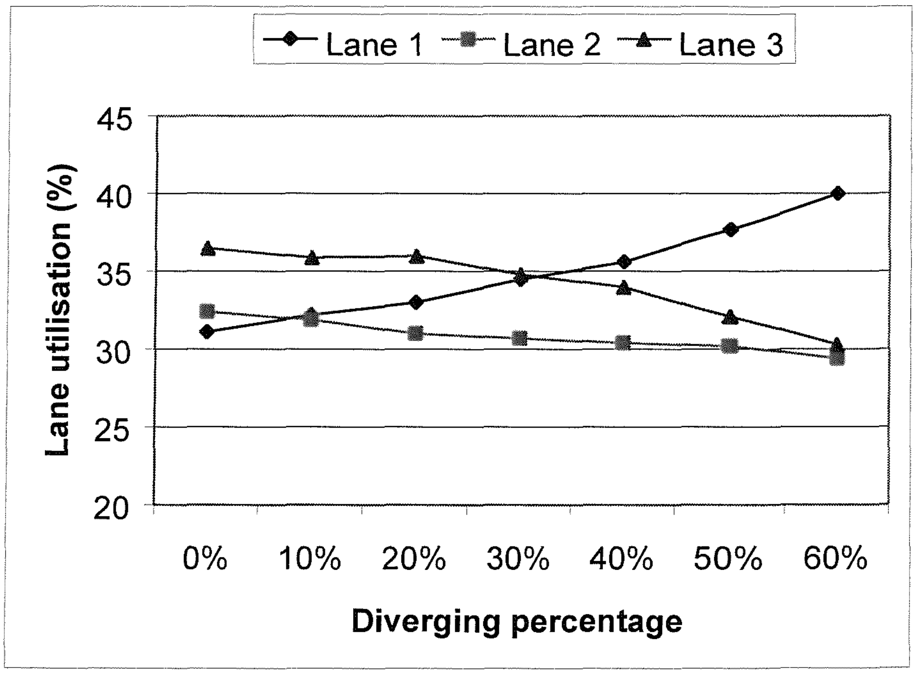


Figure 9.6: Utilisation of mainline after the Taper diverge

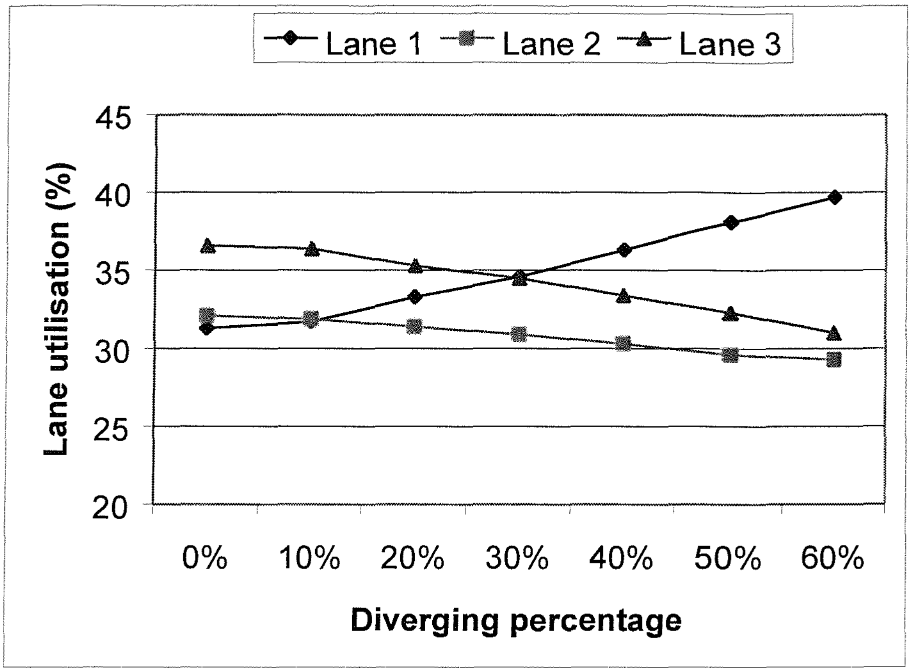


Figure 9.7: Utilisation of mainline after the Ghost Island diverge

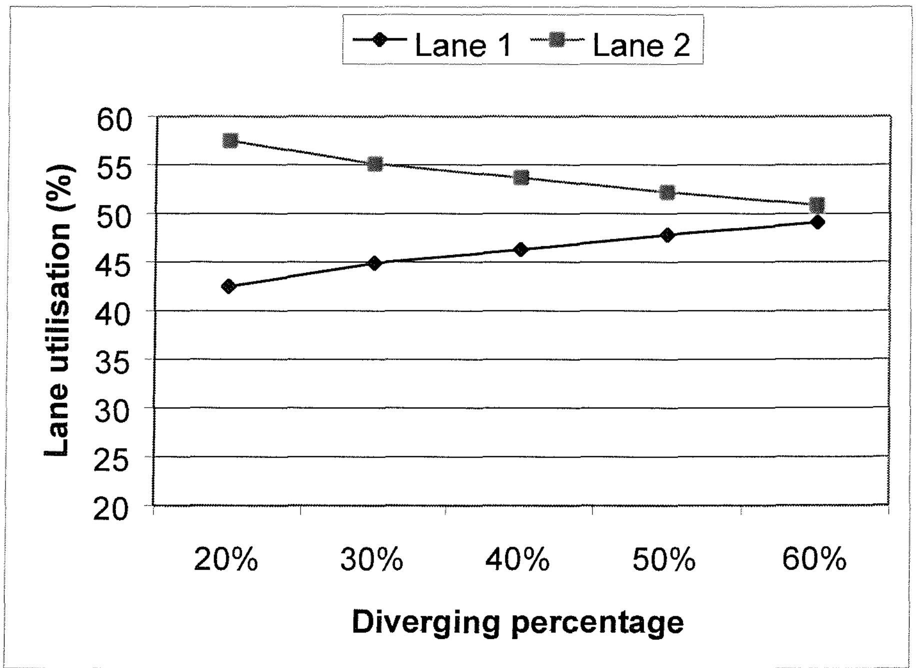


Figure 9.8: Utilisation of mainline after the Taper lane drop diverge

9.3 Lane changing results

9.3.1 Introduction

Lane changing rate is an important factor in lane utilisation and distribution of traffic on motorways. It is, therefore, an important parameter to assess as research has shown that these manoeuvres can affect the throughput, safety and reliability of the mainline (Ferrari 1989). Lane changes to the right (faster lane) normally occurs when a driver wishes to overtake a slower vehicle or to allow a merging vehicle entrance onto the mainline. It requires considerable concentration as the driver needs to look to the front, the side and behind in order to assess the speeds of the other vehicles and the existing gaps. Lane changes to the left (slower lane) normally occurs either to allow a faster vehicle to pass or to prepare to leave the mainline at the next exit. Lane changes are disadvantageous to the traffic flow and can reduce average speeds and driver comfort.

Previous research has been carried out to examine the lane changing manoeuvre in more detail, classifying them into forced or optional manoeuvres. This has resulted in the development of a simulation model looking at the manoeuvre time and the acceptable lead and lag gaps required to provide an opportunity for such a lane change to take place (Hunt and Yousif 1992). SISTM only provides the user with information regarding the number of lane changes over a specified area of the mainline.

Lane changing rate results were collected from SISTM for varying diverging percentages from the LNCHANGE output file for each layout. Lane changing rate information was collected for a 1200m area prior to the diverge and also a 600m area after the diverge.

Information about four lane changing rates were collected in particular. These were:

- Lane 1 to lane 2
- Lane 2 to lane 1
- Lane 2 to lane 3

- Lane 3 to lane 2

The results are divided into three sections; lane changing rate before the diverge, lane changing rate after the diverge and the total lane changing rate before and after the diverge.

9.3.2 Lane changing rate before the diverge

Figures 9.9, 9.10 and 9.11 show the lane changing rate for each layout type based on a 1200m area prior to the diverge. The Taper and Ghost Island layouts had similar results, with the majority of the lane changes being made to the left (lane 2 to lane 1 being the dominant lane change) enabling drivers to be correctly positioned in order to leave the mainline. The lane changing rate for all four movements increased as the diverging percentage increased which seemed a sensible result. The lane changing rate was lower for the Ghost Island layout as opposed to the Taper layout, possibly due to the exit choice provided to drivers with the two exit points. This had the effect of spreading these lane changes out over a wider area, resulting in a lower lane changing rate per km.

For the Taper lane drop layout, the lane changing rate to the left increased at a quicker rate than the lane changing rate to the right. With a diverging percentage of under 40%, lane changes to the left tended to be lower than those to the right given the fact that most of the diverging vehicles would be easily accommodated in lane 1 already and so be correctly positioned to leave the mainline. Above 40% diverging, the two lane changing rates to the left become the dominant movements, with more drivers wishing to leave the mainline needing to be in lane 1.

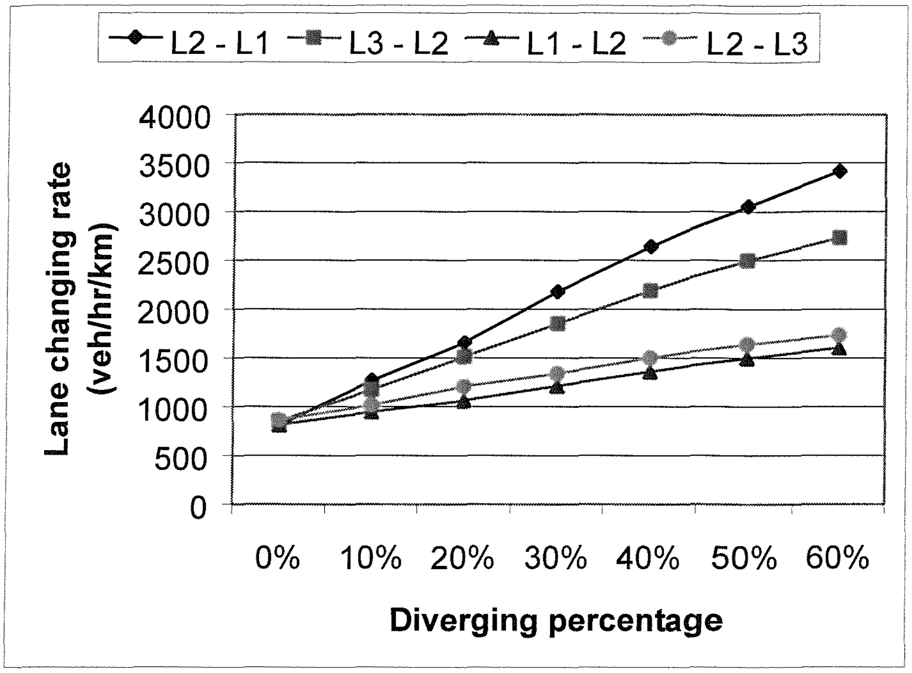


Figure 9.9: The lane changing rate before the Taper layout

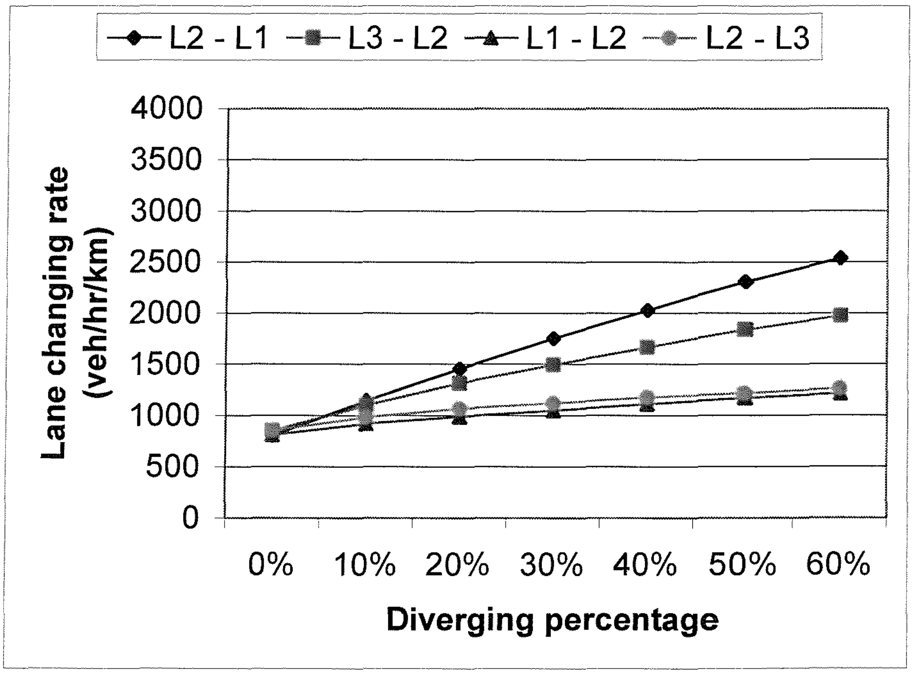


Figure 9.10: The lane changing rate before the Ghost Island layout

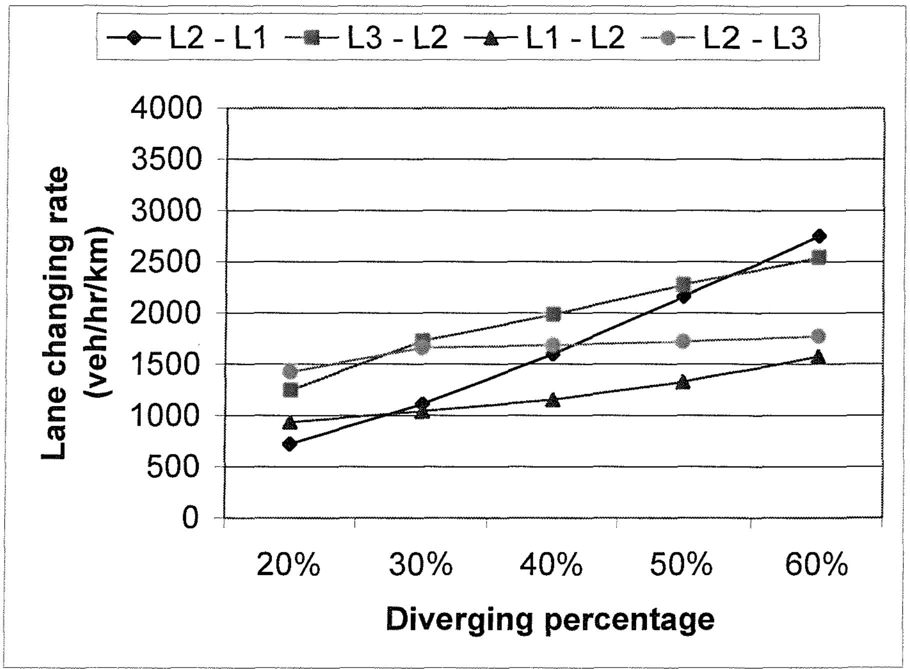


Figure 9.11: The lane changing rate before the Taper lane drop layout

9.3.3 Lane changing rate after the diverge

Figures 9.12, 9.13 and 9.14 show the lane changing rate based on a 600m area after the exit. They showed a reduced lane changing rate compared to the area before the diverge. For the Taper and Ghost Island layouts, the dominant movements were lane 1 to lane 2 and lane 2 to lane 1. As the diverging percentage increased, less traffic remained on the mainline and so the lane changing rate between lanes 2 and 3 declined. As before the diverge, the Ghost Island layout experienced a lower lane changing rate than the Taper layout.

Figure 9.14, for the Taper lane drop, shows the lane changing rate between the two mainline lanes decreasing as the diverging flow increased, leaving a smaller and smaller mainline flow. Lane 2 to lane 1 was the dominant movement with mainline vehicles moving back into the inside lane when a suitable gap was available.

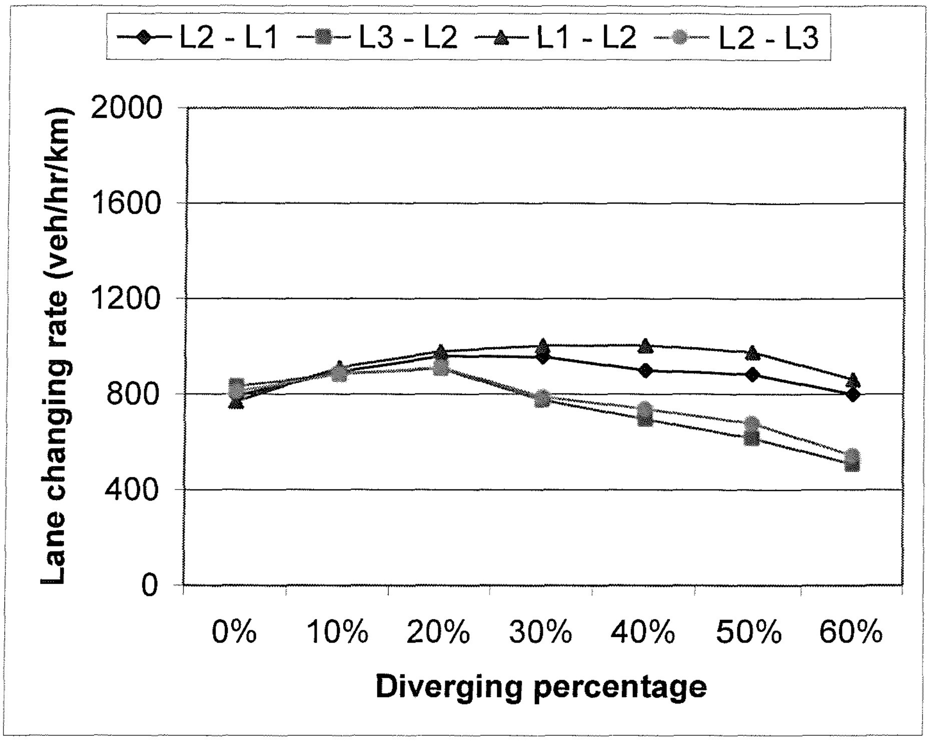


Figure 9.12: The lane changing rate after the Taper layout

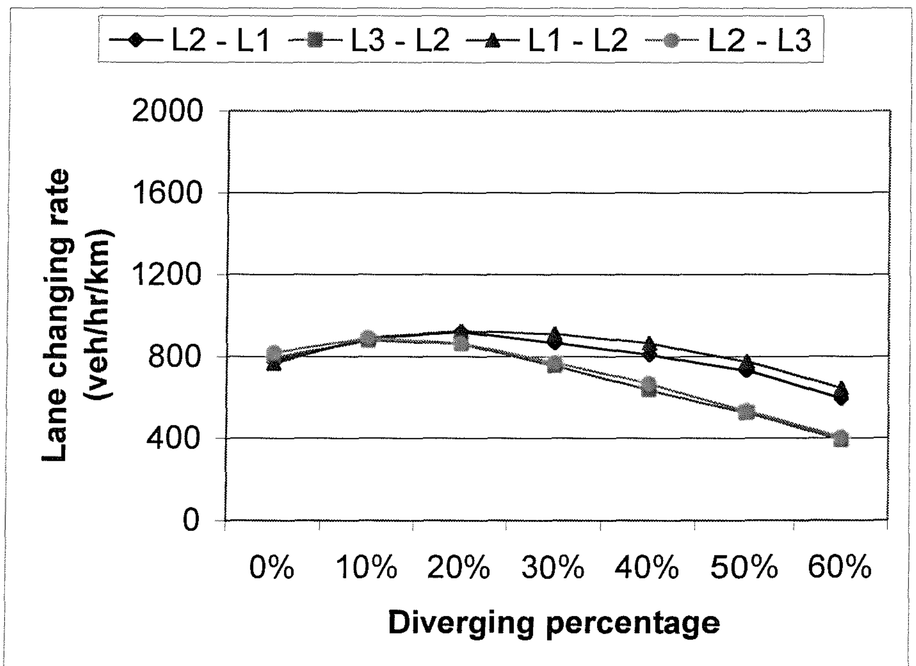


Figure 9.13: The lane changing rate after the Ghost Island layout

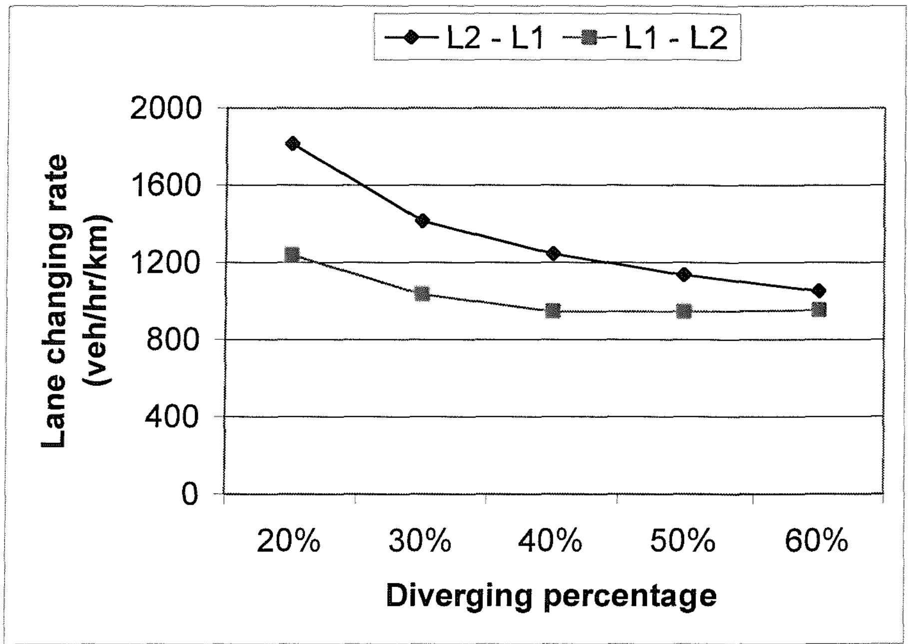


Figure 9.14: The lane changing rate after the Taper lane drop layout

9.3.4 Total lane changing rate at the diverge

Figure 9.15 shows the total lane changing rate for each layout based on a 1800m area, starting 1200m prior to the diverge and ending 600m after the diverge (600m after the second exit for the Ghost Island layout). It showed that the total lane changing rate increased with an increasing diverging percentage. The total lane changing rates for each layout were high but correspond to an area of the motorway where lane changing is numerous, particularly at high diverging percentages. The Ghost Island layout had the lowest lane changing rate between 40% and 60% diverging and a lower lane changing rate than the Taper layout, with the gap increasing as the diverging percentage increased. The Taper layout had the highest lane changing rate, particularly at high diverging percentages.

The Taper lane drop had the lowest lane changing rate particularly for diverging percentages of 20% - 40% but this was mainly due to the presence of only two mainline lanes after the diverge. In this range, the lane drop was operating effectively requiring a lower lane changing rate for exiting vehicles. However, with higher diverging flows, many more vehicles in lane 1 needed to change to lane 2 in order to remain on the mainline.

In summary, the lane changing rates for each diverge layout was affected by the amount of exit choice available to exiting drivers as well as whether there was a lane dropped at the exit.

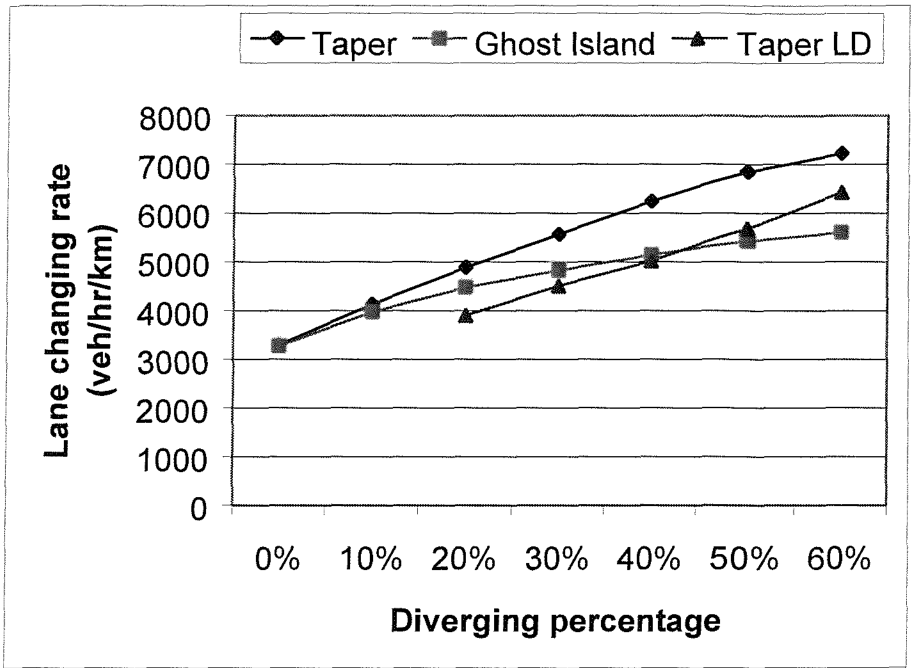


Figure 9.15: The total lane changing rate near the diverge

9.4 Journey time/speed results

9.4.1 Introduction

Journey times for exiting vehicles were collected for each of the three layouts. The journey started on the mainline approximately 1km before the exit and ended on the slip road, a journey length of 1300m. However, for the Ghost Island layout, journey times were collected for exiting vehicles using the first exit (a journey of 1300m) and those using the second exit (a journey of 1650m). Exiting traffic used the two exits equally for the Ghost Island layout. To be able to compare the results from the three layouts, the journey times were converted into average speeds. It was hoped that these results would provide some insight into the operation and efficiency of each diverge, and whether exiting traffic could leave the mainline easily and quickly. Journey times were collected from the JTIMES data files which SISTM outputs to a text file and were divided between light and heavy vehicles. Two sets of journey time information were collected. These were:

- Average journey speeds for varying diverging percentages
- Journey time distributions for 30% diverging

9.4.2 Average journey speeds for varying diverging flows

Figures 9.16 and 9.17 show the average journey speeds for varying diverging percentages for each of the three layouts for light and heavy vehicles respectively. The Ghost Island layout had the highest average journey speeds for all diverging percentages (10% to 60%). At higher diverging percentages, the average journey speeds for both the Taper and Taper lane drop layouts were similar and noticeably lower than those journey speeds for the Ghost Island layout. These two Taper layouts were struggling to cope with the number of exiting vehicles. However, the average journey speeds for the Ghost Island layout remained relatively constant, showing that this layout was coping well with the full range of diverging percentages.

The Taper lane drop had a very low average journey speed for low diverging percentages (under 30%). Many vehicles needed to change from lane 1 to lane 2 in order to remain on the mainline, causing more delay for exiting vehicles. At low diverging percentages, the layout was not operating efficiently with many vehicles moving out of lane 1 in order to continue on the mainline.

As expected, the average journey speeds for the HGVs were higher than for the light vehicles. The differences in journey speeds was about 10 kph, with the higher variations at the higher diverging percentages where more delay was to be expected with a higher lane changing rate occurring. HGVs accelerate and de-accelerate at a slower rate to light vehicles (as well as having a lower desired speed), and need more time and bigger gaps in order to change lanes.

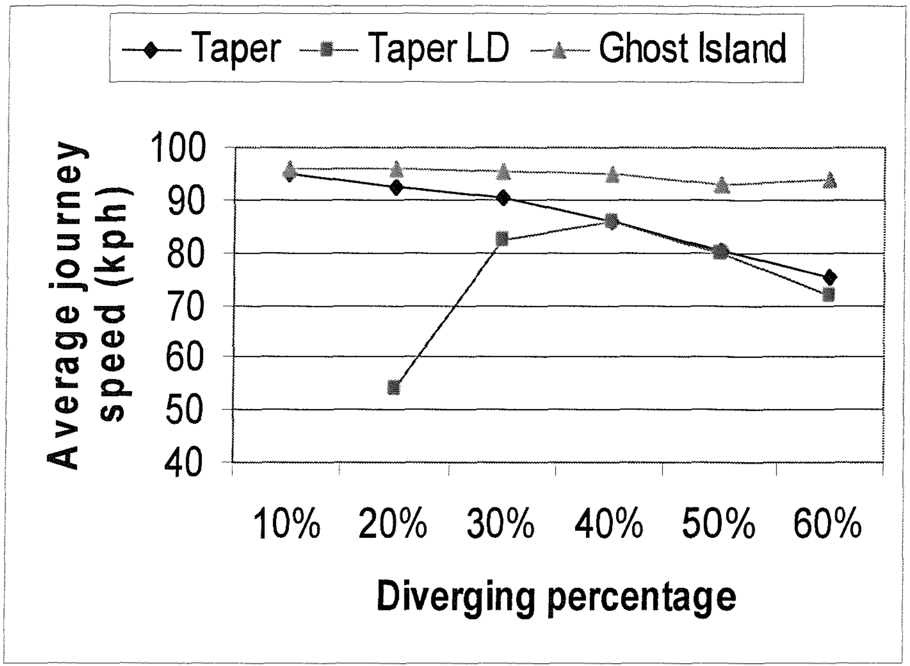


Figure 9.16: Average journey speeds for light vehicles

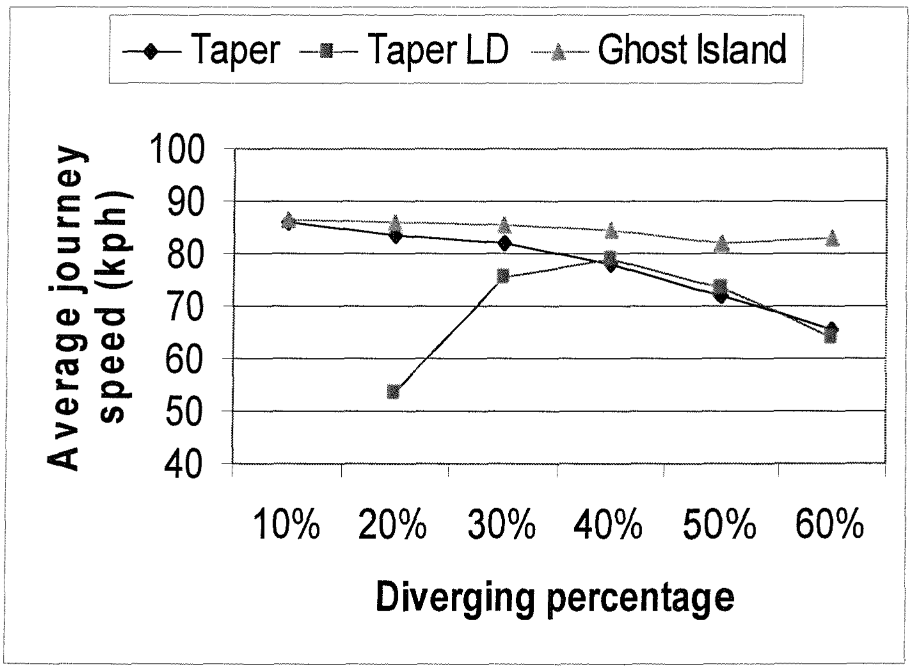


Figure 9.17: Average journey speeds for HGVs

9.4.3 Journey time distributions

As well as seeing how the average journey time varied with the diverging percentage, it was also of interest to look at the journey time distribution for each of the three layouts in order to note any major differences. The diverging percentage was fixed at

30% with the results of five runs with different random seeds used to plot the distribution for each layout. Table 9.1 below shows the sample size, the mean and standard deviation of the journey times for light and heavy vehicles for each layout respectively.

Table 9.1: Journey time distribution results

	Light			Heavy		
	Mean	Standard deviation	Sample size	Mean	Standard deviation	Sample size
Taper	51.9	4.71	969	57.0	4.22	680
Ghost Island (1st exit)	49.7	3.96	968	54.9	3.35	955
Taper lane drop	57.0	8.83	967	62.0	9.27	879
Ghost Island (2nd exit)*	61.2	4.50	963	69.4	4.25	664

- The results for the Ghost Island 2nd exit is based on a journey distance of 1650m as opposed to 1300m for the other results.

It can be seen from Table 9.1 that the Ghost Island layout had the lowest average journey time (for the first exit) and the smallest standard deviation for both light and heavy vehicles. These results are affected by the fact that only 50% of exiting vehicles use the first exit slip lane. Even so, results for the second exit were also encouraging and represented much more consistent and reliable journey times for the exit as a whole than the other layouts. An unequal use of the two exits would, however, have increased these journey times.

The Taper diverge also performed well with a slightly higher average journey time and standard deviation. However, it is thought that with higher diverging percentages (i.e. 40% - 60%), the average journey time for this layout would increase noticeably as the exit struggles to cope with all the diverging traffic.

The Taper lane drop had the worst results with the highest average journey times and a standard deviation almost double of that of the other two layouts. With a higher diverging percentage of say 40%, the journey times for the Taper lane drop would most probably have been lower.

Overall, lane and exit choice and the presence of a lane drop are important factors in the journey time results, and therefore important in how efficiently the diverge is operating.

Exiting journey time results for each of the three layouts were plotted in a frequency histogram, based on data from the five separate simulation runs. The exiting journey time results for the Ghost Island were for the first exit only. Figures 9.18 and 9.19 show the journey time distributions for the three layouts for light and heavy vehicles respectively. They show the Taper and Ghost Island layouts having a much narrower distribution with a lower mean journey time than the Taper lane drop layout.

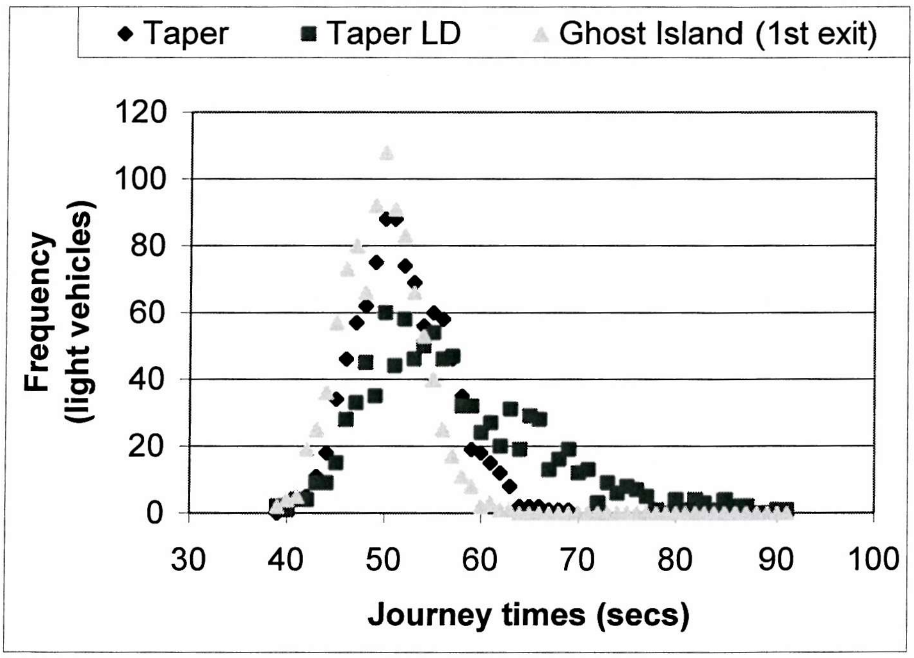


Figure 9.18: Journey time distributions for light vehicles

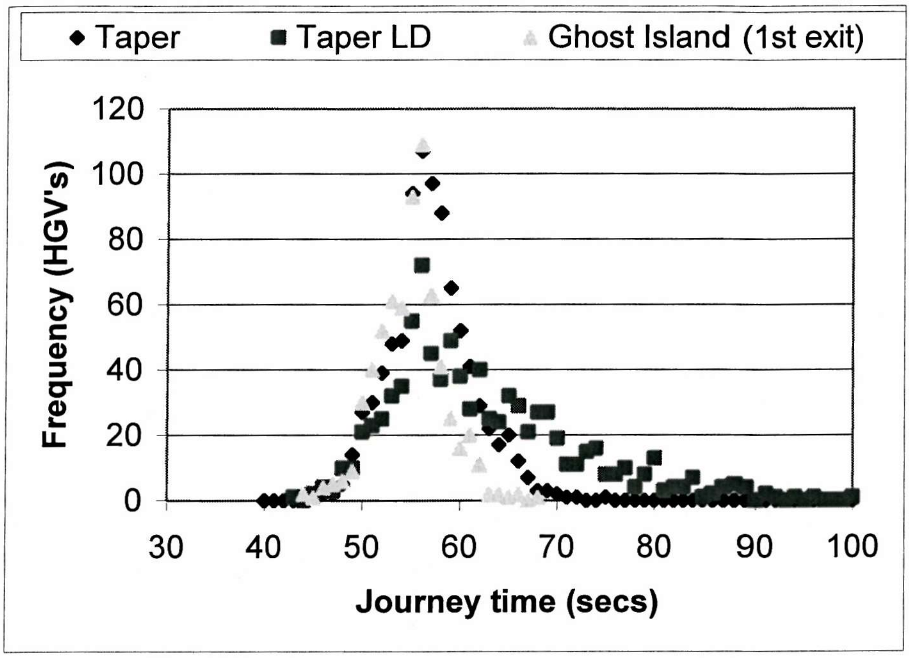


Figure 9.19: Journey time distributions for HGVs

9.5 Summary

The modelling work in this chapter has been carried out to assess the operation, potential safety and performance of various diverge layouts using a typical mainline demand flow. SISTM, a microscopic simulation computer program has been used to provide useful information regarding lane utilisation, lane changes and journey times/speeds.

The lane utilisation results showed how the traffic was distributed on the mainline for typical peak flow conditions. Before each of the three diverge layouts, lane 1 tended to be under utilised with lane 3 over utilised at low diverging percentages as vehicles used the faster lanes to reduce their journey time. With high diverging flows, lane 1 became over utilised with exiting vehicles entering this lane to leave the mainline. With the Taper lane drop, however, all the mainline lanes became reasonably equally used.

Lane changing results were collected from SISTM before and after each layout and seen as an important indicator as to the potential safety of the diverge. Results showed that the lane changing rate depended on factors such as the lane and exit choice as well as whether a lane was dropped at the exit.

Before the diverge, as the diverging percentage increased, lane changes to the left dominated with the Taper and Ghost Island layouts. This only happened for the Taper lane drop layout when the diverging percentage was over 40%, as lane 1 could easily accommodate all the exiting vehicles at low diverging percentages.

After the diverge, the lane changing rate was reduced for all layouts. The dominant movements for the Taper and Ghost Island layouts were between lane 1 and lane 2 with less vehicles remaining on the mainline with a high diverging percentage. Overall, the Ghost Island layout had the lowest lane changing rate for 40% - 60% diverging and a lower lane changing rate than the Taper layout, with the gap increasing as the diverging percentage increased. The Taper layout had the highest lane changing rate, particularly at high diverging percentages. The Taper lane drop layout had the lowest lane changing rate particularly for diverging percentages of 20% - 40%, but this was mainly due to the presence of only two mainline lanes after the diverge.

Average journey times/speeds and their distributions were collected from SISTM in order to determine how efficiently each diverge was operating. The Ghost Island layout had the highest journey speeds for light and heavy vehicles for all diverging percentages. It therefore had an almost constant journey speed for the full range of diverging percentages, showing that it performed well even at high diverging percentages. It also had the narrowest journey time distribution, with the lowest standard deviation for both light and heavy vehicles. The Taper layout performed well at low diverging percentages (under 30%), but recorded much lower journey speeds than the Ghost Island for high diverging percentages (30% - 60%). The Taper lane drop layout performed reasonably well apart from at low diverging percentages (under 30%) where journey speeds were dramatically decreased with its distribution having a high standard deviation. Exit choice and the presence of a lane drop were seen to be important factors in a particular layout's journey time/speed results.

Overall, SISTM has provided useful information concerning the potential safety and operation of each layout (lane utilisations, lane changes and journey times/speeds) and has shown how important design features relating to lane and exit choice are, as well as the presence of a lane drop at the exit.

CHAPTER 10

DISCUSSION

10.1 Introduction

This chapter includes a discussion of two themes of relevance to this PhD and its findings. The first theme concerns the limitations of the modelling work, the potential impacts of these limitations and enhancements that could be made to improve SISTM. This is based on lessons learned in this research. The second theme concerns a critical discussion of measures which could improve capacity and/or lane distribution at the diverge, using evidence from this research and literature.

10.2 Limitations of the modelling work

10.2.1 Introduction

The computer program SISTM has been used extensively for the modelling work carried out for this PhD project. The use of SISTM has been beneficial in assessing the throughput and operation of the Taper, Taper lane drop, Parallel and Ghost Island diverges by carrying out a theoretical comparison. It has many good features which have already been highlighted in Chapter 4. The main ones include that it has been extensively calibrated and validated using real data from various UK motorways, it is microscopic, it has been used on a number of different projects at TRL and TRG for the Highways Agency and it provides a wide variety of output data including speed, flow, lane changes and journey times.

The program, developed by TRL for the Highways Agency, has recently been upgraded by the company QinetiQ to make it more user-friendly, with the option of running the simulation in 3D with a full graphical display (version 6.0). Following two training days at TRL and with nearly three years of experience in using the program, the author believes he has carried out the modelling work as effectively as possible, given its capabilities. The author did experience some deficiencies in the model but the results from SISTM are still valid as modelled work was only carried out if these deficiencies were shown to have no noticeable effect on that particular scenario. Limitations to the program have been divided into four sections. The first two sections involve layout and flow modelling limitations, which can affect the accuracy of the driving behaviour within the model in some circumstances. The layout limitations include diverge designs which can not be modelled explicitly within SISTM and therefore areas where possible inaccuracies can occur. The last two sections involve factors which may be able to be modelled in the future with changes to the code and/or more research, and factors which SISTM would not be expected to model.

- Layout modelling limitations
- Flow modelling limitations
- Potential factors that could be modelled
- Factors that would be difficult to model

10.2.2 Layout modelling limitations

10.2.2.1 Lane drops

SISTM explicitly models a Taper diverge layout with a lane drop, but problems can arise at capacity flow levels with low diverging percentages when there are a noticeable number of vehicles in lane 1 wishing to continue on the mainline, but instead are forced off the main carriageway. The visual display shows these mainline vehicles still travelling at a reasonable speed and not slowing up, content to exit the mainline if no gap is available. There may be some drivers who experience this situation, but they would normally wait for a gap in the traffic in order to move out into lane 2. Changing the positions of the signs and their scores/thresholds can reduce this problem but it has limited the scope for modelling lane drops particularly at lower diverging percentages. An assessment and refinement of the scoring system at lane drop layouts within the program could help to reduce this problem noticeably.

10.2.2.2 Auxiliary lanes

SISTM does not explicitly model an auxiliary lane and therefore can not explicitly model Parallel layouts (with or without a lane drop). In order to model an auxiliary lane, a mainline lane was gained on the nearside of the main carriageway just before the diverge and then dropped at the diverge. This lane was then dedicated for exiting vehicles only who entered it at the first opportunity, leading to problems of platoons of vehicles following an HGV or a slow moving car (see Chapter 7 for more details). It would be of interest to know the exact benefits of having an auxiliary lane and in particular to know the effect of varying its length on capacity, exit blocking, uphill gradient, HGV proportion and horizontal and vertical alignment. An assessment of the driving behaviour logic could help to enable the driving behaviour on auxiliary lanes to be more realistic, allowing vehicles to join the lane and overtake at any time rather than the more unrealistic situation where vehicles just follow each other in long platoons.

10.2.2.3 Ghost island markings

SISTM can not explicitly model a Ghost Island diverge. There is an option of installing ghost island markings at the diverge but further changes to the computer code is needed to stop drivers entering the exit within the ghost island area. It would also be useful for the user to be able to enter the exit spacing and the width of the ghost island. This would require further research and computer programming. This would enable the Ghost Island layout to be modelled explicitly rather than as two closely spaced single link diverges, as in this PhD project.

10.2.2.4 Gradient

SISTM models the gradient of the mainline and the slip road as well as the length of mainline in which the gradient is present. Gradients cause vehicles to lose speed (particularly HGVs) and can cause more accidents as more overtaking of slower vehicles often takes place. SISTM can model gradient on the mainline and the slip road. Sensitivity testing, reported in Chapter 6, showed that gradient had an effect on average mainline speed for HGVs (5 kph reduction for every 1%) but no effect on light vehicles. There was, however, no noticeable reduction in throughput at the diverge. The length of gradient parameter seemed to have little impact on speed or flow. In reality, gradient does have an effect on average speeds and may have an effect on throughput. Drivers may compensate for an uphill gradient by increasing their acceleration rate so they maintain their speed. For motorways with steep long uphill gradients, an auxiliary lane would normally be installed on the approach to the exit in order to let slower moving exiting HGVs and cars leave the mainline early, causing less disruption to the mainline traffic. Gradient is an important factor in the choice of diverge to install, and further research would establish more exact relationships concerning its effect on average speed and throughput, which could then be incorporated into SISTM.

10.2.3 Flow modelling limitations

10.2.3.1 Flow breakdown and/or queuing

At very high flows, congestion and flow breakdown can be a common occurrence. It normally initially occurs in the fastest lane and is characterised by a sudden reduction in speed of at least 20 – 30 kph (Hounsell et al 1994). With high demand flows, SISTM generates as many vehicles as it can (up to a threshold) and the rest are stacked in a virtual queue at the start of the network. Even with a high mainline and diverging percentage, there are signs of the mainline slowing down but never any sign of very slow moving/queuing vehicles in the visual display of SISTM. As already explained above, vehicles will travel at a reduced but steady speed, even if that means missing their destination. SISTM uses the Gipps car following model (see section 4.6.3) which results in more generous gaps between vehicles being generated than may be expected in reality. This limitation has actually enabled better throughput results at high demand flows to be obtained using SISTM, without the unpredictability of flow breakdown affecting the results. Further research and validation is necessary to enable SISTM to replicate flow breakdown more effectively.

10.2.3.2 Utilisation of slip lane 2

In SISTM, exiting vehicles do not know about the presence of the second slip lane at the diverge and will always use slip lane 1 if available. Vehicles will only use the second slip lane if the exiting vehicle changes lane too late to move into slip lane 1, or access to slip lane 1 is blocked by another vehicle. This can result in slip lane 2 being under utilised even at reasonably high diverging flows, reducing the capacity of the slip road. Vehicles still use slip lane 2 for overtaking purposes. In practice, drivers will be aware of the presence of both slip lanes, either through familiarity with the layout or from vertical signing located before the diverge.

The Taper, Parallel and Taper lane drop layouts were all affected by this situation, unlike the Ghost Island layout which was modelled as two distinct closely spaced single link diverges. Given the fact that exiting vehicles used each exit equally (controlled by the user), the results for the Ghost Island layout would be more favourable than for the other layouts. However, in order to make the comparison fairer, the percentage of exiting vehicles using each exit was varied from 50%-50% to 90%-10% in order to get a range of throughput profiles for different usages of the two exits.

In practice, many drivers may choose to use slip lane 2 in order to overtake slower moving vehicles in slip lane 1. They also may use slip lane 2 if it leads to a separate destination (as with some Ghost Island layouts) or they wish to turn right at the junction at the end of the slip road. Further changes to the code could enable vehicles to know of the presence of both slip lanes in order that the driver has a choice of which one to use and so enable the slip road to be more equally used (particularly at high diverging flows) with the resulting driving behaviour more realistic.

10.2.4 Potential factors that could be modelled

10.2.4.1 Environmental factors

The construction or alteration of a diverge normally involves a large land take, and therefore can have a high environmental cost with the loss of green field land, poorer air quality and higher noise levels. SISTM can model noise levels, but these have not been assessed as they were considered not to be within the scope of the PhD. SISTM does allow the user to input the weather conditions and the time of day (which could have an impact on the throughput at the diverge), but these factors at present have no effect on the results. The program was originally written such that it has scope for future development by the inclusion of additional factors. With the required research/data, these factors could be modelled within SISTM, when the program has been developed further.

10.2.4.2 Geometric factors

There are a number of geometric factors which the user can enter data for but which have no effect on the results. These include factors such as lane widths, angle of slip road to the mainline, the presence or otherwise of a hard shoulder and the radii of curvature of bends in the mainline. As with the environmental factors, additional research/data could allow these geometric factors to be modelled in a future development of the program.

The latest Standard TD22/92 (Department of Transport 1992a) provides mandatory values for all of the geometric parameters, and it would be therefore difficult to validate a range of values for them with data from UK motorway diverges. SISTM, at present, can not be used as a geometric design tool unlike other traffic software packages such as OSCADY (Binning 1998). In addition to the fact that these geometric factors have no effect on the results in SISTM, TD22/92 does not allow traffic engineers to alter these geometric parameters (except the length of the auxiliary lane); only a choice between five layout types. These geometric factors may well have an effect on the throughput. For example, a wider lane 1 and the possible use of the hard shoulder as a running lane may have a positive impact on the lane distribution of the mainline and the throughput (see sections 10.3.2 and 10.3.4).

10.2.5 Factors that would be difficult to model

10.2.5.1 Exiting blocking

SISTM assumes that the diverge is free-flowing, with exiting vehicles just disappearing of the screen at the end of the slip road. With the exception of major motorway-to-motorway interchanges, this would not normally be the case. At the end of the slip road would normally be either a traffic-signalled junction, a priority junction or a roundabout. If there are delays at the end of the slip road due to either heavy flows, an accident, road-works or a badly design junction then exiting traffic can block back up the slip road and even onto the mainline, causing disruption to the main carriageway. The slip road could be modelled with a single slip lane to reduce the capacity of the slip road, but this would increase the numbers of "incorrect destinations" as well as not accurately reflecting the loss in capacity due to exit blocking. It is important that the junction at the end of the slip road is designed in the most efficient way in order to disperse queuing slip road traffic quickly. However, the installation of an auxiliary lane at diverges where exit blocking may be likely is important, as it reduces this risk considerably.

10.2.5.2 Diverging flow variability over time

Given the difficulty in predicting the mainline and diverging flow at a particular diverge, it is important that the choice of diverge layout is flexible enough to be able to cope with future higher diverging flows in years to come. The diverging flow at a particular exit may also vary at different times of the day (peak or off-peak), on different days of the week and in different seasons of the year. The Standard TD22/92 assumes that the mainline and diverging flows selected have low seasonal variation by selecting the 30th highest combined hourly flows (see section 2.4.1), catering for the majority of operating conditions but not the 'worst case' situation.

The modelling work showed that the Taper layout has a limited range of diverging flows in which it can operate efficiently (0% - 30% at capacity levels). It is the simplest and cheapest diverge layout and therefore an attractive option for an exit with low diverging flows. It is, however, important when designing such a layout that consideration is given to the ease at which it could be converted into a Parallel diverge in the future, if an increase in diverging flows required it. The modelling work showed that the Parallel layout coped well with the full range of diverging percentages (0% - 60%), and would therefore be a beneficial change. With existing Taper diverges, part of the hard shoulder could be used in order to make space for the auxiliary lane. For proposed Taper diverges, it is important that extra space is available; this could be achieved by either using part of the hard shoulder or by having extra land available to enable it to be converted into a Parallel diverge (if required) sometime in the future.

There may also be a desire to convert a Parallel layout into a Ghost Island layout particularly at motorway interchanges where there is a high diverging percentage and a long auxiliary lane, resulting in numerous lane changes between the auxiliary lane and the mainline. Again, part of the hard shoulder may be required for a short distance in order to install the ghost island markings. Converting a Taper layout to a Ghost Island layout would require use of the hard shoulder for a few hundred metres, and possibly additional land in order to install an auxiliary lane and the ghost island marking. Figure 3.10 shows recommended layouts for the Ghost Island diverge, converted from a Taper, a Parallel and a Taper lane drop layout.

The modelling work showed that the Taper lane drop is most suited for diverging percentages between 30% and 50% at capacity levels. Like the Taper layout, it also has a limited range of diverging flows where it can operate efficiently. With a diverging percentage below 30%, the diverge is not operating efficiently with large numbers of vehicles having to change into lanes 2 or 3 in order to stay on the mainline. Lane drops are only normally used when there is a sufficiently high diverging percentage to justify the dropping of a lane at the exit. It is also important to check that this will not cause problems for mainline traffic beyond the diverge by the removal of the lane. As with the Taper, it is important that any new Taper lane drop layouts have the potential of being converted into a Parallel lane drop in the future if the diverging flows required it.

10.2.5.3 Accident prediction

In the design of diverges, safety is the most important requirement and one of the main challenges to traffic engineers. Many traffic junction software products, such as OSCADY, predict accident rates based on the signal, geometric and flow data provided by the user. SISTM can not predict accidents rates but can provide lane changing data, which can give an indication of the safety and operation of the diverge. A full accident study on an extensive range of different diverge types would be required in order to develop statistical significant relationships, which could then be used to predict future accident rates. This could then be incorporated into SITSM and be another factor in the decision making process in the selection of the most suitable diverge layout.

10.2.5.4 Swooping

Swooping (vehicles moving directly from lane 2 or 3 of the mainline into the slip road in order to leave the main carriageway) is only modelled within SISTM as two lane changes to the left in quick succession. These manoeuvres are not recorded and so no details about the number of these manoeuvres or their location is available. Changes to the computer code in order to record these manoeuvres would provide useful information, particularly as swooping has been identified as hazardous behaviour at diverges and as a possible "seed point" for flow breakdown (Abou-Rahme 2001). Changes to the behavioural logic in the program would be needed in order to model the swooping manoeuvre explicitly as one continuous double (or even triple) lane change into the slip road.

10.2.5.5 Vertical signing

SISTM allows 'scoring' signs to be placed at strategic points before the diverge. As diverging vehicles pass these signs, they are given extra stimulus to change lane to the left and therefore be correctly positioned in lane 1 in order to leave the mainline. However, SISTM can not give any indication of how drivers react to vertical signing and their effectiveness in improving driving behaviour. As shown with the anti-swooping trials in Chapter 3, a well designed and clear vertical sign can help to inform drivers of the layout ahead and encourage good driving behaviour. Further research could establish the relationship between signing and driving behaviour.

10.2.5.6 Horizontal and vertical alignment

The forward visibility available to drivers due to the construction of the main carriageway is an important factor in the choice of diverge layout. If the mainline is on a noticeable right hand bend, then a Taper diverge could result in a tangent alignment which could be confusing to drivers. The installation of an auxiliary lane can help drivers align themselves correctly in such a situation. This can affect the choice of diverge layout to install, but may be difficult to model within SISTM.

10.3 Measures to improve the capacity and lane distribution

10.3.1 Introduction

Due to the increasing demand on the UK's motorway network, low cost measures for improving capacity, particularly at bottlenecks such as diverges, will be important in reducing congestion and delay. The modelling work in SISTM showed how important the utilisation of the mainline lanes before the diverge was in achieving maximum throughput. This section looks at six ways in which either the capacity could be increased and/or the lane distribution of the mainline before the diverge could be made more optimally distributed, maximising the throughput at the diverge. The first three measures all involve increasing the capacity of the mainline by physically increasing the road space available for drivers. The final three measures are control measures, aimed at improving the distribution of the mainline. The measures are:

- Use of hard shoulder as a running lane
- A short lane (or buffer)
- Wider lane(s)
- Variable speed limits
- Real-time road markings
- Automated highway

10.3.2 Use of hard shoulder as an additional running lane

Due to the rapidly increasing travel demand on motorways, low cost temporary measures are needed to increase its capacity particularly at bottlenecks often before diverges. One solution is the use of the hard shoulder in order to provide additional capacity on the mainline. This has been done in a number of ways.

1. Use of hard shoulder to provide four mainline narrower lanes
2. Use of hard shoulder at congested periods

An example of the first option is in the USA where research was carried out looking at the effectiveness of providing four narrower lanes as opposed to three normal width lanes (McCasland 1978). This measure was carried out on two sections of the US-59 Southwest freeway in Houston, Texas, with alterations made to the lane markings. Results showed that it produced benefits in terms of travel times, safety, capacity and level of service.

An example of the second option is on the M42 between junctions 3a and 7, where the Highways Agency are piloting a scheme allowing use of the hard shoulder during congested periods as part of an active traffic management project (see Figure 10.1). This has followed the success of trials in the Netherlands, where the use of the hard shoulder as an additional running lane has been in existence since 1996 (Local Transport Today 2003). When there are congested conditions, a variable message sign will read "Queue Ahead Caution". A variable speed limit also comes into effect with, in some instances, the permitted use of the hard shoulder. Normal conditions return once the congestion has dispersed. In the case of an incident, a variable message sign indicates that a particular lane has been blocked and that they should move out of that lane. The use of dedicated lanes is sometimes permitted in very congested conditions. Figure 10.1 shows an example of the new diverge layout with the hard shoulder running lane incorporated on the M42. The hard shoulder running lane will normally act as a lane drop at each diverge as it will naturally follow the curve of the slip road, forcing mainline drivers to change lane in order to continue straight ahead. The last advanced direction sign then takes the form of a lane drop warning. When the hard shoulder is open on the approach to the diverge, the variable message signs tell drivers that they should only use the hard shoulder if they wish to leave the mainline.

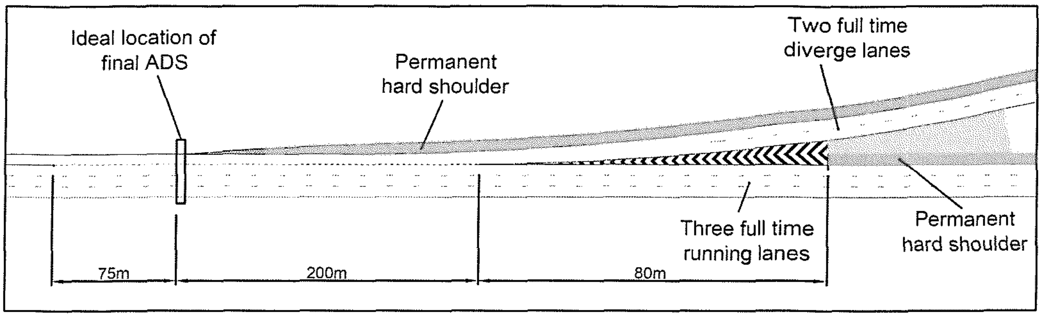


Figure 10.1: Diverge layout incorporating the hard shoulder running lane (M42)

Results from the M42 trial will show how effective this measure has been at reducing congestion, particularly before the diverge. It will help to ease congestion when a lane becomes blocked by an accident or a breakdown, as well as providing additional capacity during peak periods. However, concerns have been raised with regard to the safety aspects of losing the hard shoulder in such a situation. As long as safety is not compromised and action plans are in place if and when an incident occurs, this low cost measure could provide a short term solution to the congestion problems of diverge bottlenecks.

SISTM can not model a hard shoulder running lane as shown in Figure 10.1 on the M42. With fundamental differences in design associated with this layout, more research/data would be needed to calibrate and validate the resulting driving behaviour in SISTM. The ability to model hard shoulders explicitly within SISTM would further enhance the program and provide a useful tool to traffic engineers in assessing the benefits of such a measure in terms of throughput, average speeds and exiting journey times.

10.3.3 Introducing a short additional lane

Another possible solution is introducing a short additional lane to the nearside of lane 1 prior to the diverge (Okura et al 1996a and 1996b). The aim of the short additional lane would be to increase the density of lane 1 (D_1) in order that the lowest utilised lane (normally lane 1 in high flow situations and denoted by U_1) can be increased (see Figure 10.2).

This short additional lane is also referred to as a buffer, which is used as a local widening of the motorway just before a bottleneck such as a diverge, with the aim of reducing secondary congestion effects due to queuing traffic blocking back from the exit. Buffers can shorten queues, reduce delay and be seen as a cost-effective measure in reducing congestion before the exit (Broeren and Westland 1998).

It is hoped that both the density and utilisation of lane 1 would be higher after the short lane/buffer than before it. It is unclear how many drivers would be prepared to move into this short lane knowing that they would need to merge again into lane 1 within a short time. It would also require the possible use of the hard shoulder or extra land take, as well as new signing and road marking to inform drivers of its presence. Care would be needed in setting the geometric parameters of the buffer, with particular attention given to the control of traffic at its beginning and end. Due to these problems, it is not seen as a realistic solution to improving the capacity of the area before the diverge and therefore has not been modelled in SISTM.

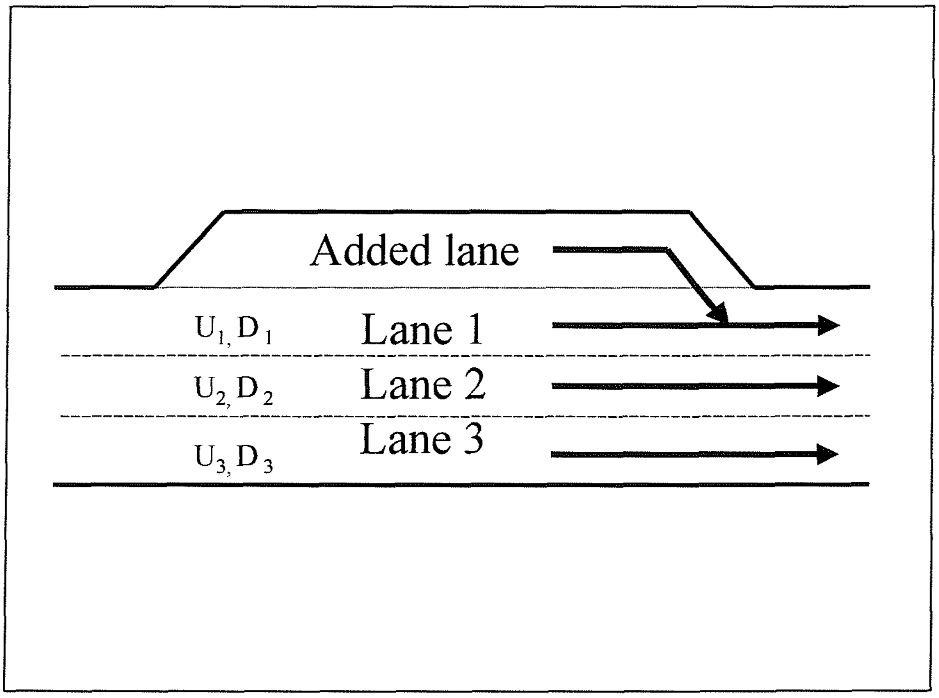


Figure 10.2: Adding a short additional lane before the diverge

10.3.4 Increasing the lane width of the inside lane

When there is a larger proportion of HGVs in the traffic composition, lane 1 can become full of slow moving vehicles particularly before the diverge. One possible solution would be to increase the lane width of lane 1 (the most under-utilised lane particularly at low diverging flows) and so "enable the HGV flow rate to match more equally with other vehicles, thus reducing unnecessary lane changes" (Okura et al 1996a and 1996b). It would also give HGVs more lateral clearance of other vehicles on the motorway.

In OSCADY (Binning 1998), it is assumed that for every 1m increase in lane width, there is a corresponding increase of 100pcu/hr in saturation flow (e.g a modest increase of about 5%). In the UK, the standard lane width on motorways is set at 3.65m (Department of Transport 1992a). Lane widths have no effect on the results in SISTM and so this change could not be modelled. Any changes in lane widths would require good signing, road markings and the possible use of part of the hard shoulder (if not additional land).

10.3.5 Variable speed limits

This control measure concerns the implementation of a reduced speed limit on a motorway section, in order to smooth the traffic flow. These reduced speed limits are only introduced when the traffic flows approach the capacity of the mainline, and are kept constant for a predefined section of motorway. In the UK, a variable speed limit scheme was introduced in 1995 on the M25 between junctions 10 and 15 (see Figure 10.3).

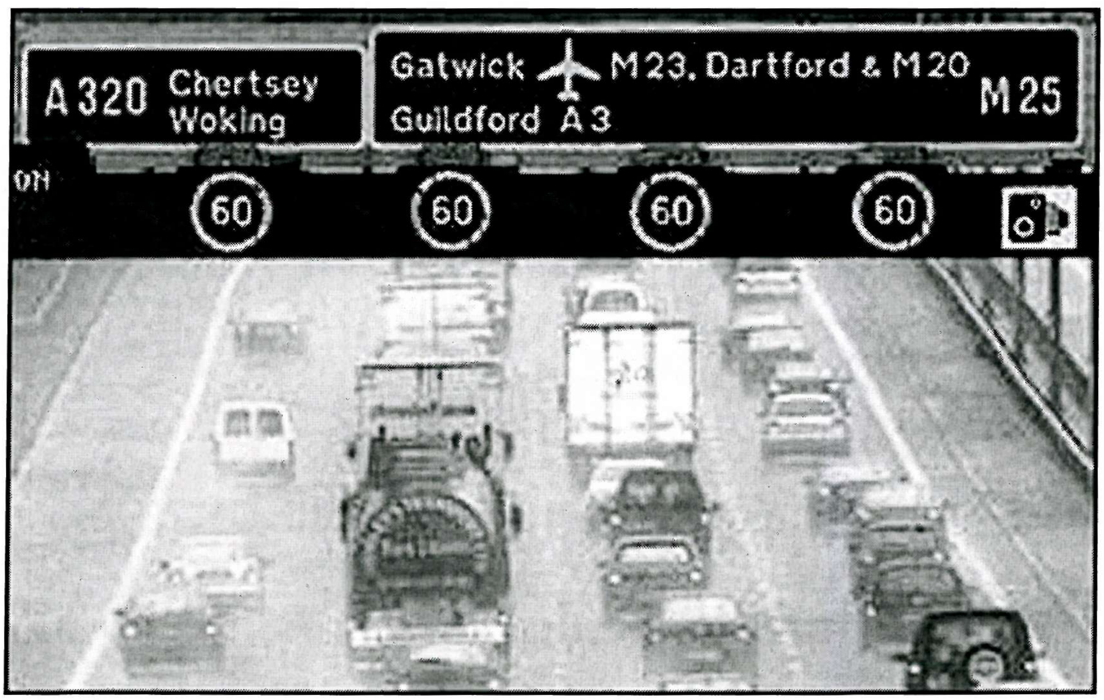


Figure 10.3: Variable speed limits on the M25

It consisted of mandatory speed limits enforced by cameras (Harbord 1995). Variable speed limits of 40mph, 50mph and 60mph were used on the M25 and displaced every 1km. The decision about which speed limit should be applied is based on detected vehicle flows. The speed limit changes from 70mph to 60mph when the flow exceeds 1650 veh/hr/lane, and from 60mph to 50mph when the flow exceeds 2050 veh/hr. Midas loop detectors record the vehicle flows and are positioned every 500m along the mainline. These variable speed limits enable the difference between the average mainline speed and the speed limit to be kept as small as possible.

SISTM has already been used to model the effect of variable speed limits on the M25 (Hardman 1996) and can use various flow measurement periods, thresholds and smoothing factors. In SISTM, data can be entered describing the detectors, the signs and means of controlling the signs from measurements made by the detectors. The maximum that can be specified are 50 detectors, 40 signs and 10 control measures.

One of the aims of variable speed limits is to reduce speed differences within and between lanes, in order that the mainline lanes are more equally utilised, making better use of all of the available road space and thus increasing the throughput. Smaller speed differences within a lane would reduce the potential for shockwaves to occur. Smaller speed differences between lanes would reduce the likelihood and need (or desire) of drivers to lane change. This may lead to a more optimal lane distribution on the mainline. A study on a 200 km stretch of the A2 motorway between Amsterdam and Utrecht (Van-den Hoogen and Smulders 1994) found that there was an improved distribution of traffic over the available road space when the limits were applied, with an increased utilisation of lane 1. The results showed a more homogenous traffic situation which was expected to lead to an increase in safety, with less lane changes and more reliable journey times.

Section 6.2 in Chapter 6 contained an investigation into the speed/flow relationship within SISTM to see if it accurately represented real data from the M27. It can be seen from Figure 6.3 that the maximum flow occurred when the average mainline speed was about 90 kph (about 56 mph). With the variable speed limits set at this value (or just below to avoid flow breakdown), the resulting throughput can be maximised if drivers keep within a small range of this speed limit.

Lower fixed speed limits together with good enforcement can also influence driving behaviour, which can affect the lane distribution. A recent study compared lane changing rates for different flow levels in four different countries (Yousif and Hunt 1995). Results showed that the lane changing rate for the USA was much lower than the other European countries examined; this was thought to be due to a lower enforced speed limit (55mph) which reduced the desire for lane changing.

From previous studies, variable speed limits have been effective in their aim of reducing speed differences within and between lanes. This measure could be applied in congested conditions on a stretch of mainline before the diverge, in order to optimise the lane distribution and so maximise the throughput. Given the large number of detectors, signs and control measures required in the set up of variable speed limits in SISTM and the complex nature of their interaction, a comparison study of their effect on the capacity of various diverge layouts was beyond the scope of this research. However, it is thought that it would be potentially beneficial in optimising lane distribution and thus maximising throughput.

10.3.6 Controlling lane changes by road markings

Controlling lane changes from under utilised lanes to their adjacent lane before the diverge may be a way of improving the usage of that lane, as well as increasing the throughput of the diverge layout. A possible solution is the use of a real-time pre-installed changeable lighting system to control the lane changes with virtual road markings (Okura et al 1996a and 1996b). Figure 10.4 shows two cases. They are :

1. $U_2 > U_3 > U_1$
2. $U_3 > U_2 > U_1$.

where U_i is the utilisation of lane i

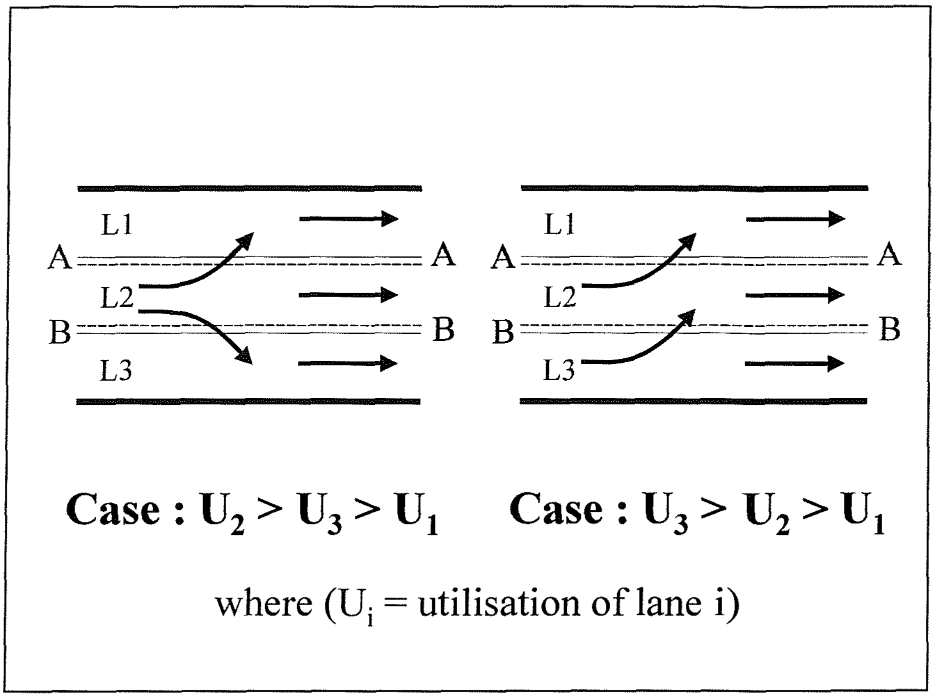


Figure 10.4: Changeable lighting system to control lane changes with road markings

Lane changes that are allowed are shown in Figure 10.4 by arcs. Extra road markings would also be needed to show drivers the specific areas in which they can and can not change lanes. When the flow reaches capacity, the lighting system may need to be switched off. It is important that the system is used with care so that it is does not lead to dangerous reactions by drivers. The success of this system would also depend on the effectiveness of the signing on driver behaviour, and whether drivers would consider a change of lane to be beneficial to their journey. Drivers want to minimise their own personal journey time and will therefore occupy the lane they think will optimise this objective. A lane change into a faster flowing lane may appear to reduce the drivers journey time, but in fact it may not and in some cases it will increase it for himself/herself and other drivers on the mainline. Drivers do not tend to think of .the community of other drivers on the mainline and how he/she can occupy a lane in order to optimise the lane utilisation and therefore the capacity of the carriageway for all drivers. Drivers would need to be convinced that the lane changes would benefit them, in order for the real time signing system to be successful.

It would be difficult to model the effect of this system in SISTM, but field trials would show the effectiveness of such a measure. It may prove to be effective in optimising the lane use before the diverge and so maximising the throughput at the junction.

10.3.7 Automated highway

Automated vehicle control has been proposed as a method to improve safety on motorways by the use of communication between vehicles, sensors and coordinated steering and speed control. One of the potential benefits is the ability to reduce the average vehicle-vehicle spacing and so increase the throughput of the carriageway. Research has been carried out to develop a model that can assign traffic to lanes in an optimal way based on trip length, and so maximising throughput (Hall 1995). This is achieved by trying to minimise the number of lane changes. This could have potential benefits in maximising the throughput of diverges by optimising lane usage.

Safety is an issue with this measure, particularly when vehicles are merging or diverging and need larger gaps in order to change lanes. Also, an important consideration is how different vehicle classes can be accommodated for in a safe environment. SISTM is unable to assign vehicles to lanes in this way other than by their desired speed. More research in the field would be needed in order to fully assess the capacity and safety benefits of this measure.

10.4 Areas of further research

Further work/research would be beneficial in the following areas:

- To update the diverging flow-region diagram in TD22/92 by producing an improved diagram incorporating more layouts including the Ghost Island layout (with or without a lane drop).
- To carry out field trials for some of the measures proposed to optimise the distribution of the mainline and so increase the throughput at the diverge such as real time road markings. Also, assessing the effectiveness of vertical signing in encouraging good driver behaviour near the exit
- To investigate the extra capacity benefits of an auxiliary lane of different lengths

- To compare the throughput results for various diverge layouts from SISTM with various other simulation packages such as PARAMICS.
- To compare SISTM's capabilities and limitations for modelling diverges with other motorway microscopic simulation models.
- To carry out an extensive accident study on a variety of diverge layouts to look for significant factors affecting the accident rate at a particular type of diverge.
- To examine the cause and effects of exit blocking and how to minimise these effects by providing various site-specific solutions.
- To carry out more research into driving behaviour near diverges such that the behavioural logic within the microscopic simulation model can be improved.

10.5 Summary

This chapter has contained a discussion of two important themes of relevance to the PhD and its findings; firstly the limitations of the modelling work and secondly a look at various measures that could improve the capacity at the diverge using evidence from the modelling work and literature.

The first section looked at the limitations of the modelling work using SISTM. SISTM has certain layout modelling limitations which limited the scope for modelling features such as lane drops, auxiliary lanes and ghost island markings. It also had some difficulty in replicating flow breakdown and queuing with high demand flows as well as under utilising slip lane 2. SISTM allows the user to enter into the program a number of environmental and geometric factors such as weather conditions, time of day, lane widths and angle of slip road to the mainline but these have no effect on the results. A future development of the program could incorporate such features if sufficient data regarding their effect on capacity and behaviour existed. There are a number of factors that SISTM can not model (and would not necessarily be expected to model), such as exit blocking, diverge flow variability over time, swooping and vertical signing. A discussion of each factor and its possible effect on the choice of layout has been carried out.

The second section looks at six ways in which either the capacity could be increased and/or the lane utilisation of the mainline lanes before the diverge could be more equally and thus optimally distributed, maximising the throughput at the diverge. The first three measures all involve increasing the capacity of the mainline by physically increasing the road space available for drivers, such as using the hard shoulder as a running lane, the introduction of a short additional lane or buffer and the increase in the width of lane 1 (or the most under-utilised lane). The final three measures were control measures aimed at improving the utilisation of the mainline lanes, such as variable speed limits, real-time road markings and having an automated highway.

Further research could be carried out in areas such as investigating the benefits of implementing some of the proposed measures to optimise the distribution of the mainline such as real time road markings. Other areas of research could look at the exact capacity benefits of auxiliary lanes, the causes, effects and solutions to exit blocking and carrying out an accident study at a variety of different diverge layouts.

CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

11.1 Introduction

The conclusions and recommendations cover the following four areas:

- Standards and the diverging flow-region diagram
- Lane choice, exit choice and throughput at the diverge
- Design implications for diverges
- Good practice for microscopic simulation modelling

The conclusions and recommendations made with regard to results from SISTM are only suited for mainlines of three lanes and an exit slip road of two lanes.

11.2 Standards and the diverging flow-region diagram

1. The standards for motorway diverges have been regularly updated over the last 40 years, in order to cater for new levels of traffic flows, vehicle performance and driver behaviour. The geometric parameters have showed a slight 'tightening' of values over time, with the tendency towards more compact designs with less generous values.

2. Safety is a major consideration in the production of geometric standards. However, little reliable evidence has been found in the literature of a link between design standards and safety for motorway diverges.

3. The diverging flow-region diagram provides engineers with a useful design tool in the preliminary selection of the most appropriate layout. However, it is important that it is seen as only a tool with engineers supplementing the diagram with their own knowledge and experience, as well as using other site-specific information in order to make the final choice.

4. The diverging flow-region diagram could be improved if it could be adapted to incorporate more layouts (including the Ghost Island layouts possibly by replacing the Parallel layouts). The accompanying updated Standard could contain more detailed advice as to the recommended length of the auxiliary lane for different circumstances, and the good use of lane drop layouts.

11.3 Lane choice, exit choice and throughput at the diverge

5. The throughput at the diverge never exceeds the capacity of the mainline before the diverge. It has been shown that the throughput will only approach this maximum capacity level if the utilisation of the mainline lanes before the diverge are optimally used (normally equally used). The utilisation of the mainline lanes before the diverge is therefore a critical factor in the resulting throughput at the diverge. At low diverging percentages, lane 1 tends to be under-utilised whereas at high diverging flows it tends to be over-utilised.

6. Lane and exit choice at a diverge are important factors in maximising throughput, by giving exiting drivers more flexibility about which lane(s) to use and where to leave the mainline. They are dependent on the type of diverge layout and, with good driving behaviour, can help to reduce the lane changing rate and average exiting journey times by enabling the exit to operate more efficiently. A well designed diverge will cause little disruption to the mainline and minimise the number of necessary lane changes. Lane and exit choice enable drivers to make better use of the

available road space by utilising the mainline lanes before the diverge in a more equal way. Good signing and road markings are also necessary to regulate the exiting drivers into a more orderly stream of traffic.

7. It is recommended that proposed methods for improving the lane distribution on the mainline before the diverge, such as real time lane markings and variable speed limits, are trialed to see whether they are effective measures in increasing the throughput at the diverge.

11.4 Design implications for diverges

11.4.1 Taper diverge

8. The Taper diverge is the simplest and cheapest diverge layout. Drivers need to leave the mainline at a particular point from lane 1 and therefore have no exit or lane choice. The modelling work showed it was best suited to diverging percentages between 0% and 30% at capacity levels. This layout is therefore only suitable for low diverging flows which do not exceed the capacity of a single slip lane (as recommended in the diverging flow-region diagram). With diverging percentages of over 30%, lane 1 can not provide sufficient capacity for the exiting vehicles resulting in it being blocked with slow moving (or even queuing) vehicles.

9. The Taper diverge had the highest lane changing rate of all the layouts, with a particularly high number of lane changes at high diverging percentages (40% - 60%). Journey speeds were reasonably high for low diverging percentages (under 30%), but these decreased more noticeably for higher diverging percentages. Its journey time distribution was similar to the Ghost Island layout but with a slightly higher average and standard deviation.

10. The Taper diverge has a limited range of diverging flows in which it can operate efficiently. It is therefore important when designing such a layout that consideration is given to the ease at which it could be converted into a Parallel diverge in the future, if an increase in diverging flows required it.

11.4.2 Taper lane drop diverge

11. The Taper lane drop is the simplest and cheapest lane drop diverge layout. It is similar to the Taper in that it also provides no lane or exit choice. The modelling work showed that this layout is best suited for diverging percentages between 30% and 50% at capacity levels. With diverging percentages of over 50%, there is not sufficient capacity for the exiting vehicles resulting in lanes 1 and 2 being blocked with slow moving (or even queuing) vehicles.

12. The Taper lane drop diverge has a limited range of diverging flows in which it can operate efficiently. With a low diverging percentage below 30%, large numbers of vehicles have to change into lanes 2 or 3 in order to stay on the mainline. This is accompanied by low journey speeds, with its journey time distribution having a high standard deviation. These vehicles can experience further delay and congestion due to the loss of one of the mainline lanes, causing a capacity reduction to the mainline. Its total lane changing rate was the lowest of all the layouts, but this was due mainly to the presence of fewer mainline lanes after the lane drop.

11.4.3 Parallel diverge

13. The Parallel layout with its auxiliary lane enables exiting drivers to leave the mainline earlier, causing less disruption to mainline traffic. It provides no lane choice as exiting vehicles still need to be in lane 1 to enter the auxiliary lane, but it does provide exit choice with the driver able to choose when to leave the mainline at any point along the length of the auxiliary lane.

14. The modelling results showed that it had high throughput results even with high diverging flows (up to 60%). It can therefore cope with diverging flows which exceed the capacity of a single slip lane (as stated in the diverging flow-region diagram).

15. The main benefits of the auxiliary lane are that it helps to reduce the likelihood of queuing vehicles blocking back from the exit and onto the mainline. The longer the lane is, the less likely that exit blocking will occur. It is also beneficial when there is a

steep uphill gradient, a high percentage of HGVs or any significant horizontal alignment of the mainline.

16. Parallel diverges can be upgraded to a Ghost Island layout, particularly at major motorway-to-motorway interchanges where there is a high diverging percentage and a long auxiliary lane resulting in numerous lane changes between the auxiliary lane and the mainline. This may require the use of part of the hard shoulder in order to have the space to install the ghost island marking.

11.4.4 Ghost Island diverge

17. The Ghost Island diverge, a new alternative layout with two exit points, has been shown to be an effective layout from the video trials, the questionnaire survey and the modelling work. It is particularly effective at motorway-to-motorway interchanges where there is a high diverging percentage and where swooping is a problem. It provides drivers with exit choice and eases pressure on lane 1 by dividing the exiting traffic into two streams. The Ghost Island lane drop also provides lane choice.

18. The video trials and questionnaire showed that the Ghost Island layout:

- Reduced swooping (79% at the M20/M26, 77% at the M6 J4a and 36% at the M27/M3)
- Reduced potentially dangerous manoeuvre (80% at the M27/M3; 76% in the questionnaire survey at M27/M3)
- Smoothed traffic flow with less congestion/delay (78% in the questionnaire survey at the M27/M3)
- Provided easier access to exit the mainline (70% in the questionnaire survey at M27/M3)
- Did not reduced driver stress (only 45% in the questionnaire survey at the M27/M3)
- Regulated the diverging flow into two orderly streams of traffic (M20/M26, M6 J4a and M27/M3)

19. The modelling work showed that this layout had high throughput values and operated efficiency with the full range of diverging flows. It was most suitable at diverges where the exiting flow exceeded the capacity of one slip lane. Unequal usage of the two exit points did reduce the throughput, but only noticeably when there was at least 80% of exiting drivers using the first exit point. Altering the exit spacing had no noticeable effect on the throughput.

20. The modelling work also showed it had a lower lane changing rate than the Taper and the lowest lane changing rate for high diverging percentages (40% - 60%). It also had an almost constant journey speed for exiting vehicles for the full range of diverging percentages, and the narrowest journey time distribution with the lowest standard deviation for both light and heavy vehicles.

21. Where space is not available to install the ghost island markings, the installation of diamond marking between lanes 1 and 2 before the diverge has been shown to be an effective measure in reducing swooping. Soft plastic bollards, installed near the nose, have also been shown to be effective in reducing dangerous last minute lane changes in this area.

22. It is recommended that the Ghost Island and Ghost Island lane drop layouts are incorporated as standard layouts into an updated diverging flow-region diagram when TD22/92 is revised and updated. This could be done by simply replacing the Parallel lane drop and double lane drop with a Ghost Island lane drop and double lane drop (layouts D and E). The Parallel layout could stay (layout B) but be replaced by a Ghost Island layout if the required space was available. The new Standard would also need to provide advice about the installation of this layout, including the vertical and gantry signing, the lane markings, the geometric dimensions (such as taper length, taper width, length of ghost island, length of nose, length of overlap along with advice about if and when to use the hard shoulder).

11.5 Good practice for microscopic simulation modelling

23. Before using a microscopic simulation, it is important to know that:

- It has the required functionality for the necessary objectives
- It has been extensively calibrated and validated with real data
- It has good proven car following and lane changing logic
- It is the most suitable program available for the required task

24. Before carrying out the modelling work, it is important to:

- Check the results from the model by carrying out a series of preliminary hypothesis tests
- Check the results with different random seeds
- If available, compare the model's results with real data
- Carry out sensitivity testing on the parameters that will be used in the modelling work

25. When carrying out the modelling work, it is important to:

- Use the program only with a sensible range of realistic values which have been calibrated and validated
- Avoid using the model in areas where it has been shown to have inaccuracies or limitations
- Watch the modelling display to check for any unusual driving behaviour, particular with regards to lane use and lane changes. This is vital as the model needs to be able to replicate driving behaviour as accurately as possible.
- Only adapt the program to enable it to simulate situations it is not explicitly suited for if the visual driving behaviour and results are checked to make sure an accurate representation of the new situation has been achieved
- Make sure that any theoretical comparisons are consistent and fair

26. It is recommended that enhancements to the SISTM model are made with regard to the following:

- Reduce the occurrence of incorrect vehicle destinations, particularly at lane drops, by re-examining and improving the lane changing logic.
- Replicate flow breakdown more accurately before the diverge by re-examining the Gipps car following model, enabling drivers to anticipate and make decisions not based purely on looking at the car in front.
- Validate and calibrate the effect of both gradient and length of gradient on various vehicle types, as well as other geometric factors such as lane widths and the angle of the slip road to the mainline.
- Enable the program to model an auxiliary lane, a hard shoulder running lane and a Ghost Island layout explicitly.
- Enable drivers to be aware of both slip lanes on a two lane slip road through the use of signing.
- Enable behaviour such as lane hogging to be modelled, not just assuming all drivers will return to the left-hand lane after overtaking another vehicle (as stated in the Highway Code).

11.6 Diverge design process flowchart

Figure 11.1 is a diverge design process flowchart containing a toolkit of measures, identified in this PhD, that could be used to improve the operation and capacity of existing diverges. The flowchart assumes that a suitable microscopic model that satisfies the various modelling requirements (outlined in section 4.5) can be found.

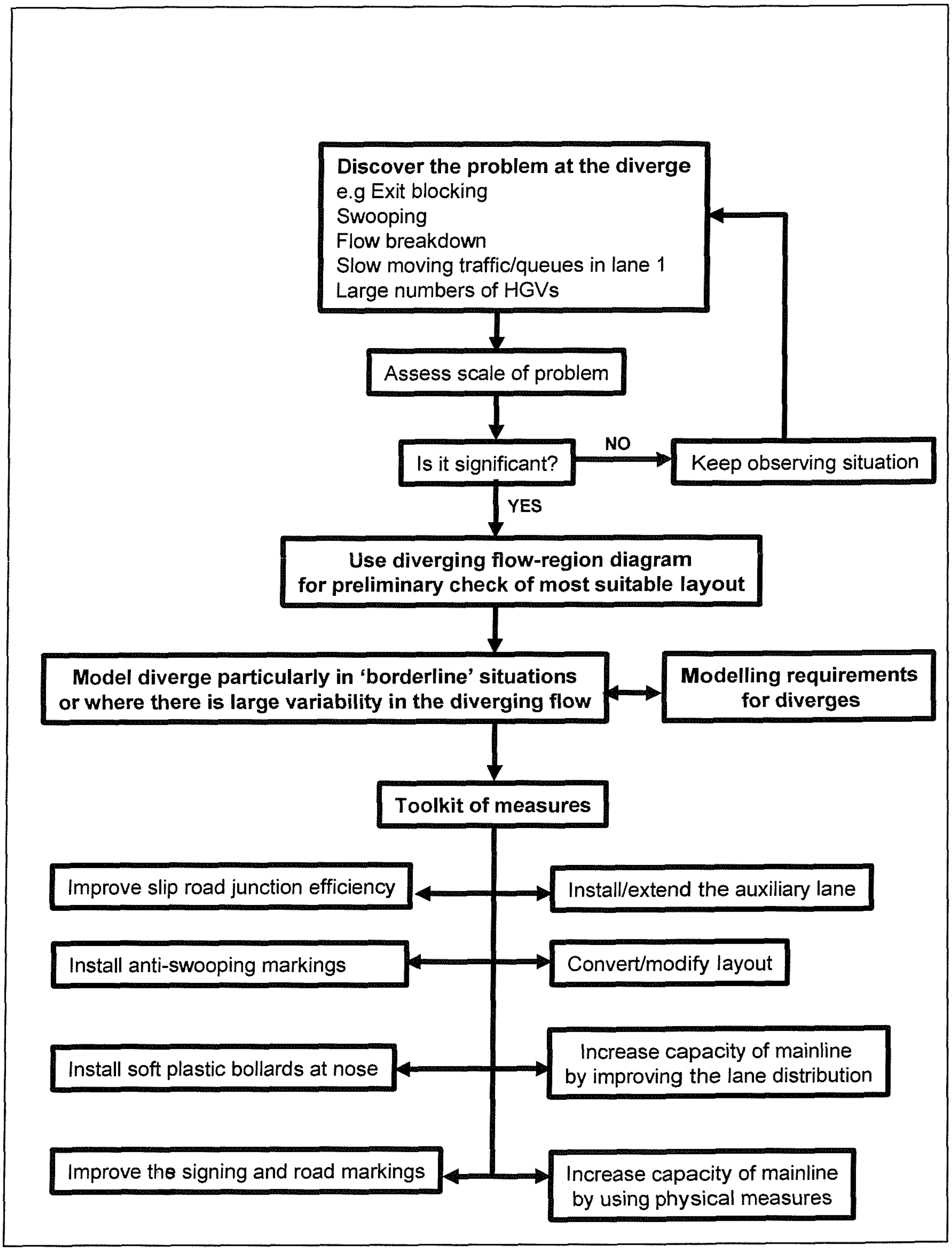


Figure 11.1: Diverge design process flowchart

Initially, the problem at the diverge needs to be identified (e.g. exit blocking, swooping, flow breakdown) and then assessed to see whether it is a significant or not. This could be achieved by either observing the diverge, using video or loop data from the diverge or collecting feedback from drivers using the diverge (through interviews or a questionnaire survey).

Before any major changes to the diverge layout are considered, the use of the diverging flow-region diagram is recommended. The diverging flow-region diagram should be used to give a preliminary assessment of the suitability of the existing layout. Microscopic modelling could also be carried out, in particular, where the downstream mainline and diverging flows are bordering several regions on the diagram or where the diverging flow is variable and/or expected to rise noticeably in the future. It could also enable the traffic engineer to assess and compare various diverge layout options in terms of their throughput, lane changes and journey times. This, however, would depend on finding a suitable microscopic model which satisfied the modelling requirements for diverges outlined in section 4.5. Given the experience of the author in using SISTM, improvements would need to be made in terms of the model's calibration and validation of the lane changing and car following behaviour near diverges before such a model could be recommended to be given for use by traffic engineers in the design and assessment of diverges.

The toolkit of measures which may be applied are as follows:

1. **Improve slip road junction efficiency (section 3.3)**

   It is important to check that the junction at the end of the slip road is operating as efficiently as possible (particularly where there is exit blocking onto the mainline) by ensuring that:

   - Both slip lanes are being used efficiently and are available for use for dominant destinations
   - There is an appropriate junction type for the given flows (e.g priority, signal-controlled or roundabout)

- The design of the junction maximises capacity (e.g. with a signal-controlled junction, the signal timings, method of control and phasing needs to be optimal).

2. **Install/extend auxiliary lane (section 10.2)**

Where space is available, part of the hard shoulder could be used to install or extend an auxiliary lane, particularly where there is regular exit blocking onto the mainline, a steep uphill gradient or a large percentage of HGVs.

3. Install anti-swooping marking (section 3.3)

Anti-swooping markings can be installed between lanes 1 and 2 before diverges which have a high amount of swooping activity. Where space is limited, diamond markings could be installed; otherwise a ghost island marking could be installed.

4. **Convert layout type (section 10.3)**

It is important to check the existing and forecasted mainline and diverging flows with the diverging flow-region diagram to see if the present layout is suitable. If not and space is available, consider converting the layout into a type which can cope with existing and forecasted mainline and diverging flows (e.g. Taper to a Parallel or Parallel to a Ghost Island). This should help to reduce flow breakdown and/or queuing before the diverge. Any major changes should follow usage of both the diverging flow-region diagram and a microscopic model (if and when a suitable one can be found).

5. Install soft plastic bollards at Nose (section 3.2)

Soft plastic bollards have been successful in reducing the problem of last minute lane changes near the Nose. These manoeuvres are potentially very dangerous and the bollards can provide a safer environment for drivers.

6. Increase the capacity of the mainline by improving the lane distribution (section 10.3)

The throughput of the mainline before the diverge may be much lower than its capacity due to unequal usage of the mainline lanes. Measures such as real-time road markings and/or variable speed limits (once verified as effective in trials) could be used to improve the lane distribution.

7. Improved signing and road markings (section 3.3)

Good clear signing and road markings can help to inform the driver of the diverge layout ahead and his/her expected behaviour. It can also help to reduce the number of potentially dangerous last minute lane changes.

8. **Increase the capacity of the mainline with physical measures (section 10.3)**

If the mainline experiences regular flow breakdown before the diverge, consider increasing the capacity of the mainline with physical measures such as installing a hard shoulder running lane before the diverge.

APPENDICES

APPENDIX A: M27/M3 QUESTIONNAIRE

The following questionnaire is being carried out as part of research towards a PhD into the design and layout of motorway junctions. It is intended for drivers who are familiar with the M27/M3 eastbound junction, near Southampton (travelling towards Portsmouth on the M27 or London on the M3). Please tick the appropriate boxes when answering the questions below.

1. Age 18 – 30 ☐ 31 – 40 ☐ 41 – 50 ☐ 51 – 60 ☐ over 60 ☐

2. Sex Male ☐ Female ☐

3. How long have you been driving for ?

Less than 1 year ☐
1 – 5 years ☐
6 – 10 years ☐
Over 10 years ☐

4. How often do you drive on motorways ?

Every week day ☐
About once a week ☐
About once every two weeks ☐
About once a month ☐
Less than once a month ☐

5. How often do you drive past the M27/M3 eastbound junction (Portsmouth/London bound)?

Every week day ☐
About once a week ☐
About once every two weeks ☐
About once a month ☐
Less than once a month ☐

6. When do you normally drive past the M27/M3 eastbound junction ?

During the AM peak period (i.e. 06:30 – 09:30) ☐
During the PM peak period (i.e. 16:00 – 19:00) ☐
During the off-peak periods (i.e any other time) ☐

7. Do you normally stay on the M27 or leave the M27 to join the M3 ?

Stay on the M27 ☐
Join the M3 ☐

8. Did you notice any changes to the M27/M3 junction layout since April 2000 ?

No ☐
Don't remember ☐
Yes (please specify) ☐

BEFORE THE CHANGES

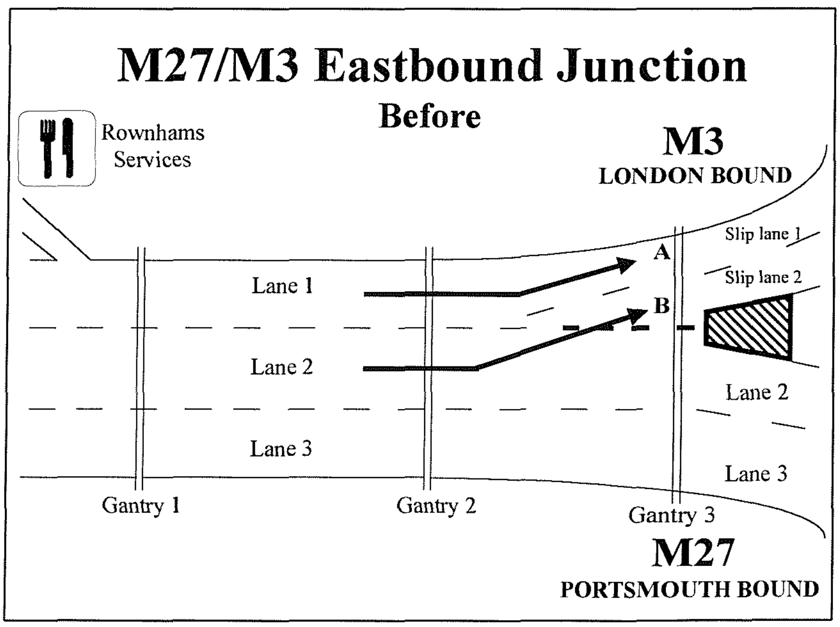
9. Did you experience any problems at the M27/M3 eastbound junction before April 2000 (before the new layout was installed ?)

No ☐
Yes ☐

If yes were they (please tick more than 1 box if appropriate)

Long, slow moving queues in lane 1 leaving the M27 for the M3 ☐
Dangerous last minute lane changes ☐
Slow moving lorries in lane 2 ☐
Other (please specify) ☐

10. When wishing to join the M3, before the new layout was installed, did you normally



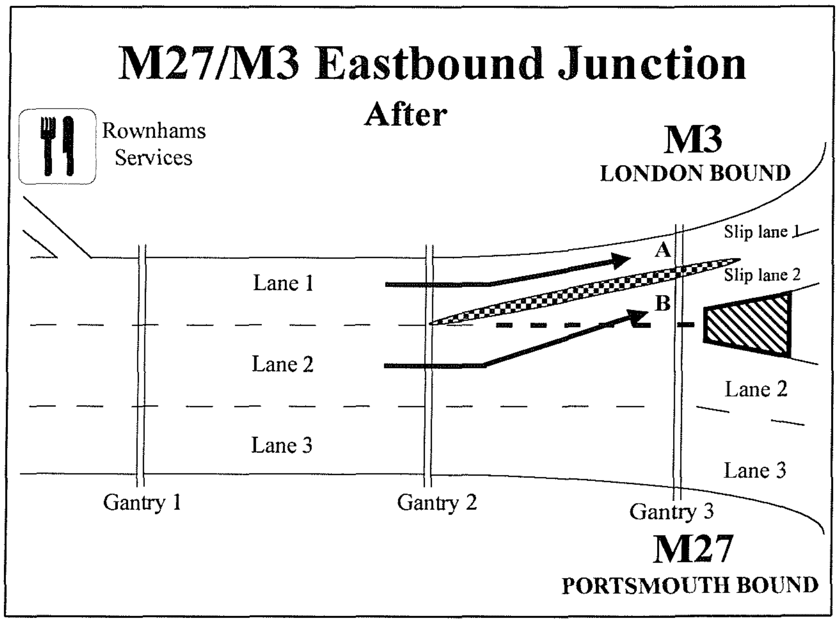
Stay in lane 1 and join slip lane 1 well before the exit (manoeuvre A) ☐
Stay in lane 2 change into slip lane 2 near the exit (manoeuvre B) ☐

AFTER THE CHANGES

11. Do you think the new layout is better than the old layout in terms of

	Yes	No	Same
Smoother traffic flow (less congestion/queues)	☐	☐	☐
Easier access to the M3	☐	☐	☐
Less last minute dangerous lane changes	☐	☐	☐
Less driver stress	☐	☐	☐
Slow moving lorries in lane 2	☐	☐	☐
Other (please specify)			

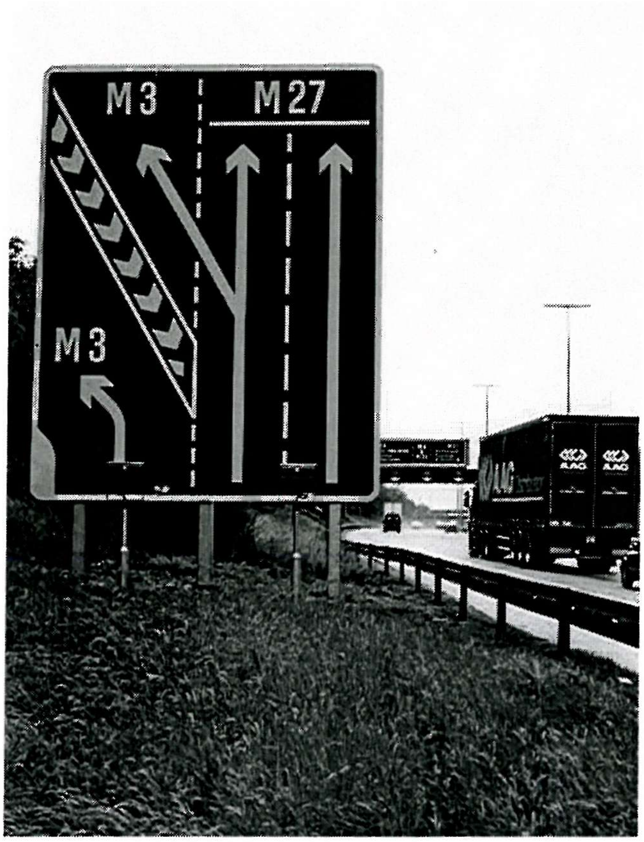
12. When wishing to join the M3, after the new layout was installed, do you normally



Stay in lane 1 and join slip lane 1 at the first exit (manoeuvre A) ☐

Stay in lane 2 and join slip lane 2 at the second exit (manoeuvre B) ☐

13. Have you noticed the new sign-post informing drivers of the new layout ?



Yes ☐

No ☐

14. Do you think the new sign-post adequately informs drivers of the new layout ?

Yes ☐

No (please specify) ☐

15. Do you have any other comments about driving on this stretch of motorway ?

THANK YOU FOR YOUR HELP

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UNIVERSITY OF SOUTHAMPTON

APPENDIX B: PRELIMINARY SISTM EXERCISE RESULTS

Table B.1: Origin-destination flow data from CONTRAM

		8 -7	8 – 5	8 - 3	8 - 1	6 - 5	6 - 3	6 - 1	4 - 3	4 - 1	2 - 1
0700 – 0730	Car	406	128	334	1757	0	164	429	167	398	170
	HGV	18	0	0	2	0	2	0	2	0	2
0730 – 0745	Car	168	95	209	685	3	125	238	137	182	198
	HGV	9	0	0	1	0	1	0	1	0	0
0745 – 0800	Car	182	140	162	525	0	83	274	85	276	168
	HGV	13	0	0	2	0	2	1	1	0	0
0800 – 0815	Car	186	127	177	515	0	160	211	122	239	148
	HGV	16	0	2	2	0	0	0	0	0	3
0815 – 0830	Car	213	116	226	630	0	149	182	71	249	135
	HGV	15	3	1	3	0	1	1	1	3	4
0830 – 0845	Car	177	87	131	409	0	179	156	91	189	167
	HGV	9	5	0	5	0	3	0	2	1	3
0845 – 0900	Car	175	105	147	509	0	110	138	163	178	150
	HGV	12	2	2	6	0	1	2	1	0	2
0900 – 0915	Car	192	86	99	416	0	104	97	120	112	144
	HGV	12	1	1	2	0	0	0	1	1	1
0915 - 0930	Car	239	99	116	451	0	73	69	112	72	36
	HGV	6	6	2	2	0	0	0	0	2	2

Table B.2: Modified origin destination flow data entered into SISTM

		8 -7	8 – 5	8 – 3	8 - 1	6 - 5	6 - 3	6 - 1	4 - 3	4 - 1	2 - 1
0700 – 0730	Car 1	203	64	167	878	0	82	214	83	199	85
	Car 2	203	64	167	879	0	82	215	84	199	85
	HGV 1	9	0	0	1	0	1	0	1	0	1
	HGV 2	9	0	0	1	0	1	0	1	0	1
0730 – 0745	Car 1	84	47	104	342	1	62	119	68	91	99
	Car 2	84	48	105	343	2	63	119	69	91	99
	HGV 1	4	0	0	0	0	0	0	0	0	0
	HGV 2	5	0	0	1	0	1	0	1	0	0
0745 – 0800	Car 1	91	70	81	262	0	41	137	42	138	84
	Car 2	91	70	81	263	0	42	137	43	138	84
	HGV 1	6	0	0	1	0	1	0	0	0	0
	HGV 2	7	0	0	1	0	1	1	1	0	0
0800 – 0815	Car 1	93	63	88	257	0	80	105	61	119	74
	Car 2	93	64	89	258	0	80	106	61	120	74
	HGV 1	8	0	1	1	0	0	0	0	0	1
	HGV 2	8	0	1	1	0	0	0	0	0	2
0815 – 0830	Car 1	106	58	113	315	0	74	91	35	124	67
	Car 2	107	58	113	315	0	75	91	36	125	68
	HGV 1	7	1	0	1	0	0	0	0	1	2
	HGV 2	8	2	1	2	0	1	1	1	2	2
0830 – 0845	Car 1	88	43	65	204	0	89	78	45	94	83
	Car 2	89	44	66	205	0	90	78	46	95	84
	HGV 1	4	2	0	2	0	1	0	1	0	1
	HGV 2	5	3	0	3	0	2	0	1	1	2
0845 – 0900	Car 1	87	52	73	254	0	55	69	81	89	75
	Car 2	88	53	74	255	0	55	69	82	89	75
	HGV 1	6	1	1	3	0	0	1	0	0	1
	HGV 2	6	1	1	3	0	1	1	1	0	1
0900 – 0915	Car 1	91	43	49	208	0	52	48	60	56	72
	Car 2	91	43	50	208	0	52	49	60	56	72
	HGV 1	6	0	0	1	0	0	0	0	0	0
	HGV 2	6	1	1	1	0	0	0	1	1	1
0915 - 0930	Car 1	114	49	58	225	0	36	34	56	36	18
	Car 2	115	50	58	226	0	37	35	56	36	18
	HGV 1	3	3	1	1	0	0	0	0	1	1
	HGV 2	3	3	1	1	0	0	0	0	1	1

Table B.3: Average speeds (kph) from the ten pseudo-detectors

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
07:15 - 07:30	106	103	105	90	90	105	106	107	106	107
07:30 - 07:45	105	105	90	91	91	106	107	105	106	108
07:45 - 08:00	105	105	91	90	91	106	107	105	105	107
08:00 - 08:15	104	105	91	90	105	106	108	105	107	105
08:15 - 08:30	103	105	90	90	105	106	107	106	107	105
08:30 - 08:45	105	90	91	91	106	107	105	106	108	104
08:45 - 09:00	105	91	90	91	106	107	105	105	107	104
09:00 - 09:15	105	91	90	105	106	108	105	107	105	104
09:15 - 09:30	105	90	90	105	106	107	106	107	105	103

Table B.4: Total flows (vehs) from the ten pseudo-detectors

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
07:15 - 07:30	212	298	1413	1411	135	282	1557	1559	305	84
07:30 - 07:45	178	365	1369	1369	160	321	1533	1541	409	197
07:45 - 08:00	194	361	1202	1212	189	360	1385	1410	360	168
08:00 - 08:15	200	370	1194	1189	183	362	1372	1374	400	151
08:15 - 08:30	229	335	1299	1298	184	324	1435	1422	413	139
08:30 - 08:45	187	337	1008	1013	139	285	1174	1235	401	171
08:45 - 09:00	186	252	1010	1012	148	182	1050	1053	286	152
09:00 - 09:15	203	202	821	823	124	233	943	971	301	145
09:15 - 09:30	244	142	816	818	137	187	865	874	297	38

Table B.5: Total flows (vehs/hr) from the ten pseudo-detectors

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
07:15 - 07:30	848	1192	5652	5644	540	1128	6228	6236	1220	336
07:30 - 07:45	712	1460	5476	5476	640	1284	6132	6164	1636	788
07:45 - 08:00	776	1444	4808	4848	756	1440	5540	5640	1440	672
08:00 - 08:15	800	1480	4776	4756	732	1448	5488	5496	1600	604
08:15 - 08:30	916	1340	5196	5192	736	1296	5740	5688	1652	556
08:30 - 08:45	748	1348	4032	4052	556	1140	4696	4940	1604	684
08:45 - 09:00	744	1008	4040	4048	592	728	4200	4212	1144	608
09:00 - 09:15	812	808	3284	3292	496	932	3772	3884	1204	580
09:15 - 09:30	976	568	3264	3272	548	748	3460	3496	1188	152

APPENDIX C: SISTM INPUT FILES

SISTM input data file (DAT file)

```
02.08.01M27/J5
NO-OUTER

VDDATA
     VDCOND
      DRY      MORNING GOOD    LIGHT
*
      VCLASS
      1L       LIGHT   CARS AND LIGHT GOODS VEHICLES
      2L       LIGHT   CARS AND LIGHT GOODS VEHICLES
      3L       LIGHT   CARS AND LIGHT GOODS VEHICLES
      4L       LIGHT   CARS AND LIGHT GOODS VEHICLES
      5H       HEAVY   HEAVY GOODS VEHICLES
      6H       HEAVY   HEAVY GOODS VEHICLES
*
      VATTR
      1        LENGTH  UNIFORM 4.31    4.31
      1        WIDTH   UNIFORM 1.52    1.52
      1        MAXDBR  UNIFORM -28.30  -28.30
      1        MAXACC1 UNIFORM 9.65    9.65
      1        MAXACC2 UNIFORM 8.25    8.25
      1        MAXACC3 UNIFORM 5.06    5.06
      1        MAXACC4 UNIFORM 3.83    3.83
      1        SPDLOSS UNIFORM 0.00    0.00
      1        SLRATE  UNIFORM 0.00    0.00
*
      2        LENGTH  UNIFORM 4.31    4.31
      2        WIDTH   UNIFORM 1.52    1.52
      2        MAXDBR  UNIFORM -28.30  -28.30
      2        MAXACC1 UNIFORM 9.65    9.65
      2        MAXACC2 UNIFORM 8.25    8.25
      2        MAXACC3 UNIFORM 5.06    5.06
      2        MAXACC4 UNIFORM 3.83    3.83
      2        SPDLOSS UNIFORM 0.00    0.00
      2        SLRATE  UNIFORM 0.00    0.00
```

*

```
3    LENGTH   UNIFORM 4.31    4.31
3    WIDTH    UNIFORM 1.52    1.52
3    MAXDBR   UNIFORM -28.30  -28.30
3    MAXACC1  UNIFORM 9.65    9.65
3    MAXACC2  UNIFORM 8.25    8.25
3    MAXACC3  UNIFORM 5.06    5.06
3    MAXACC4  UNIFORM 3.83    3.83
3    SPDLOSS  UNIFORM 0.00    0.00
3    SLRATE   UNIFORM 0.00    0.00
*
4    LENGTH   UNIFORM 4.31    4.31
4    WIDTH    UNIFORM 1.52    1.52
4    MAXDBR   UNIFORM -28.30  -28.30
4    MAXACC1  UNIFORM 9.65    9.65
4    MAXACC2  UNIFORM 8.25    8.25
4    MAXACC3  UNIFORM 5.06    5.06
4    MAXACC4  UNIFORM 3.83    3.83
4    SPDLOSS  UNIFORM 0.00    0.00
4    SLRATE   UNIFORM 0.00    0.00
*
5    LENGTH   UNIFORM 15.42   15.42
5    WIDTH    UNIFORM 2.12    2.12
5    MAXDBR   UNIFORM -19.79  -19.79
5    MAXACC1  UNIFORM 3.71    3.71
5    MAXACC2  UNIFORM 1.35    1.35
5    MAXACC3  UNIFORM 1.13    1.13
5    MAXACC4  UNIFORM 0.81    0.81
5    SPDLOSS  UNIFORM 5.00    5.00
5    SLRATE   UNIFORM -0.50   -0.50
*
6    LENGTH   UNIFORM 15.42   15.42
6    WIDTH    UNIFORM 2.12    2.12
6    MAXDBR   UNIFORM -19.79  -19.79
6    MAXACC1  UNIFORM 3.71    3.71
6    MAXACC2  UNIFORM 1.35    1.35
6    MAXACC3  UNIFORM 1.13    1.13
6    MAXACC4  UNIFORM 0.81    0.81
6    SPDLOSS  UNIFORM 5.00    5.00
6    SLRATE   UNIFORM -0.50   -0.50
```

```
*
        SUBGROUP
        1       34.89   9.32    55.79
        2       34.89   9.32    55.79
        3       34.89   9.32    55.79
        4       34.89   9.32    55.79
        5       24.35   24.35   37.38   9.57    4.35
        6       24.35   24.35   37.38   9.57    4.35
*
        VDATTR
        1234    DESPEED NORMAL  109.46  9.11
        1234    PERMAXBRTRIANGL -28.30  -30.30  -26.30
        1234    LEADBR  TRIANGL -16.50  -18.90  -13.00
        1234    LAGBR   TRIANGL -16.50  -18.90  -13.00
*
        56      DESPEED NORMAL  95.83   7.32
        56      PERMAXBRTRIANGL -19.80  -21.80  -17.80
        56      LEADBR  TRIANGL -12.00  -17.80  -6.10
        56      LAGBR   TRIANGL -12.00  -17.80  -6.10
*
        VDCORR
        1234
        AGGRO   0.50    0.50
        AWARE   0.50    0.50
        56
        AGGRO   0.50    0.50
        AWARE   0.50    0.50
*
        STRESS
        1.000   1.000   2.000   1.000   10.000
        75.00           2.00    0.40    2.00    0.40                    500
        -5.00
9999
```

```
 *
 ICNET
MDSGEOM
       ULINK
        11      21      1000    0
        0.0             3       3.65    3.65    3.65
*
        DIVERGE J5 off
        21              5410    5410
        0.0
        0.0             2       3.65    3.65
                        5.0     5210    120     5300    120
                        5.0     5300    120     5390    120
        0.0
*
        LINK
        21      13      6000
        0.0             3       3.65    3.65    3.65
*
SIGNALS
MDSSIGN
        DIVERGE
        4210            20
        DIVERGE
        4710            50
        DIVERGE
        5110            120
9999
*
DEMCTRL
        0700 0705   0710   0715   0720   0725   0730   0830
*
TIMEDEM
       0700
       RATES    DETAILED1.00
       1      1             0      1785
       2      1             0      1785
       3      1             765    0
       4      1             765    0
       5      1             0      630
       6      1             270    0
```

```
0705
RATES   DETAILED1.00
1       1               0       2082
2       1               0       2083
3       1               892     0
4       1               893     0
5       1               0       735
6       1               315     0
0710
RATES   DETAILED1.00
1       1               0       2380
2       1               0       2380
3       1               1020    0
4       1               1020    0
5       1               0       840
6       1               360     0
0715
RATES   DETAILED1.00
1       1               0       2380
2       1               0       2380
3       1               1020    0
4       1               1020    0
5       1               0       840
6       1               360     0
0720
RATES   DETAILED1.00
1       1               0       2380
2       1               0       2380
3       1               1020    0
4       1               1020    0
5       1               0       840
6       1               360     0
0725
RATES   DETAILED1.00
1       1               0       2380
2       1               0       2380
3       1               1020    0
4       1               1020    0
5       1               0       840
6       1               360     0
```

```
        0730
        RATES   DETAILED1.00
        1       1               0       2380
        2       1               0       2380
        3       1               1020    0
        4       1               1020    0
        5       1               0       840
        6       1               360     0
        0830
*
9999
```

SISTM control file (CNT file)

```
SIMCTRL
         1999
*        P1        P4        P5        P6        P8        EPOCH     P21       P22
P VALUES
         2.00      -3.00     -5.00     30        5.000     10        110       8
*        P9        P10       P11       P12       P13                 P15
         2         50        1.85      40        99                  -3.10
*        P3(1)     P3(2)     P3(3)     P3(4)     P3(5)     P3(6)     P3(7)     P3(8)
         1         1         2         2         0         0         0         0
*                  T4        T5        T8                                                T18
T VALUES
                   6         2         31                                                3
*                            F3        F4        F5                  F7
F VALUES
                             4         4         2                   100
*        Q1        Q2        Q3
Q VALUES
         60        50        4
*
GENPARMS
         LIGHT     F1(1)     UNIFORM 15        10
                   F1(2)     UNIFORM 15        10
                   F1(3)     UNIFORM 15        10
                   F1(4)     UNIFORM 15        10
                   F1(5)     UNIFORM 15        10
                   F2        UNIFORM 4         4
                   P14       UNIFORM 25        15
                   F6        UNIFORM 100       100
```

```
               P18      UNIFORM 50       0
               F8(2)    UNIFORM 50       50
               F8(3)    UNIFORM 50       50
               F8(4)    UNIFORM 50       50
               F8(5)    UNIFORM 50       50
               F8(6)    UNIFORM 50       50
               T3       UNIFORM 8        6
               T9       UNIFORM -89      -99
               T10      UNIFORM 90       80
               T16      UNIFORM -219     -239
               T17      UNIFORM 180      160
        HEAVY  F1(1)    UNIFORM 15       10
               F1(2)    UNIFORM 15       10
               F1(3)    UNIFORM 15       10
               F1(4)    UNIFORM 15       10
               F1(5)    UNIFORM 15       10
               F2       UNIFORM 4        4
               P14      UNIFORM 25       15
               F6       UNIFORM 100      100
               P18      UNIFORM 50       0
               F8(2)    UNIFORM 50       50
               F8(3)    UNIFORM 50       50
               F8(4)    UNIFORM 50       50
               F8(5)    UNIFORM 50       50
               F8(6)    UNIFORM 50       50
               T3       UNIFORM 8        6
               T9       UNIFORM -89      -99
               T10      UNIFORM 90       80
               T16      UNIFORM -219     -239
               T17      UNIFORM 180      160
*
        CORREL                  F8(2)    F8(3)    F8(4)    F8(5)    F8(6)
               LIGHT    AGGRO   0.50     0.50     0.50     0.50     0.50
*                               T3       T9       T10      T16      T17
                                -0.50    0.50     -0.50    0.50     -0.50
*                               F8(2)    F8(3)    F8(4)    F8(5)    F8(6)
                        AWARE   0.50     0.50     0.50     0.50     0.50
*                               T3       T9       T10      T16      T17
                                0.50     -0.50    0.50     -0.50    0.50
*                               F8(2)    F8(3)    F8(4)    F8(5)    F8(6)
               HEAVY    AGGRO   0.50     0.50     0.50     0.50     0.50
*                               T3       T9       T10      T16      T17
                                -0.50    0.50     -0.50    0.50     -0.50
```

```
*                                 F8(2)  F8(3)  F8(4)  F8(5)  F8(6)
                          AWARE   0.50   0.50   0.50   0.50   0.50
*                                 T3     T9     T10    T16    T17
                                  0.50   -0.50  0.50   -0.50  0.50
OUTCTRL

      NETWORK
               2.000    10
      DETECTOR
               100      4710    1      3
      DETECTOR
               100      5390    -1     -2
      DETECTOR
               100      5910    1      3
SIMEVENT
9999
```

APPENDIX D: SISTM OUTPUT FILES

SISTM output detector file (DAT file)

```
Run name   Seed   Date      Time  Chain  GAdd  AllS AllF AllO L04S L04F L04O L05S L05F L05O L06S L06F L06O L07S L07F L07O L08S L08F L08O L09S L09F L09O L10S L10F L10O L11S L11F L11O L12S L12F
L12O
M27/M3   1999 02/08/01 07:01 4710   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:01 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:01 5910   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:02 4710   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:02 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:02 5910   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:03 4710 111.7  20   1.7 0 0 0 0 0 0 0 0 0 112  9  3 108  5  1 114  6  1 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:03 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:03 5910   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:04 4710 100.0  76   9.2 0 0 0 0 0 0 0 0 0  96 23 13 102 27  8 101 26  7 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:04 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:04 5910 110.6  32   3.0 0 0 0 0 0 0 0 0 0 107 12  4 112  8  2 113 12  3 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:05 4710  99.1  80  10.3 0 0 0 0 0 0 0 0 0  94 28 18 102 21  5 102 31  8 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:05 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:05 5910  99.0  95  10.9 0 0 0 0 0 0 0 0 0  93 27 14 100 32  9 102 36  9 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:06 4710  96.9  83  10.4 0 0 0 0 0 0 0 0 0  92 26 15 101 25  8  98 32  8 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:06 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:06 5910  99.2  70  10.0 0 0 0 0 0 0 0 0 0  95 25 16  96 21  8 106 24  6 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:07 4710  95.6 105  12.7 0 0 0 0 0 0 0 0 0  86 30 17  97 36 11 102 39 10 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:07 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:07 5910  99.0  91  10.2 0 0 0 0 0 0 0 0 0  95 31 14  97 29  9 105 31  8 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:08 4710  98.0  90  11.0 0 0 0 0 0 0 0 0 0  91 26 15  99 32 10 102 32  8 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:08 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:08 5910  99.4 106  12.2 0 0 0 0 0 0 0 0 0  94 31 17 102 33  9 101 42 11 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:09 4710  95.1  83  10.9 0 0 0 0 0 0 0 0 0  86 27 16  97 28 10 102 28  7 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:09 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:09 5910 100.0  82   9.8 0 0 0 0 0 0 0 0 0  96 27 12 101 26 10 103 29  7 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:10 4710  94.2 110  12.1 0 0 0 0 0 0 0 0 0  94 34 12  93 32 12  95 44 12 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:10 5390   0.0   0   0.0 0 0 0 0 0 0 0 0 0   0  0  0   0  0  0   0  0  0 0 0 0 0 0 0 0 0 0
M27/M3   1999 02/08/01 07:10 5910  95.7  84  11.0 0 0 0 0 0 0 0 0 0  88 29 17  98 25  8 102 30  8 0 0 0 0 0 0 0 0 0
```

Key to columns:				
	Run name:	Name of run (as supplied by user)	AllS:	Average speed of all lanes (kph)
	Seed:	Initial random number seed	AllF:	Vehicle flow in all lanes (vehs)
	Date:	Date of simulation run	AllO:	Average occupancy in all lanes (%)
	Time:	1-minute period ending	LnnS:	Average speed of internal lane nn
	Chain:	Chainage of detector	LnnF:	Vehicle flow in lane nn
	Gadd:	Geographic address of detector	LnnO:	Average occupancy in lane nn

SISTM output network file (NETDAT file)

M27/M3 *** NETWORK STATISTICS SUMMARY *** 02.08.01

Time Slice	Generated Vehicle Hours	Generated Vehicle km	Assigned Vehicle Hours	Assigned Vehicle km
0700-0705	24.0	2574	15.6	1679
0705-0710	24.0	2574	24.0	2574
0710-0715	23.9	2568	24.0	2571
0715-0720	24.0	2574	24.0	2571
0720-0725	24.0	2574	24.0	2574
0725-0730	24.0	2573	24.0	2574
0730-0735	23.9	2562	23.9	2566
0735-0740	24.0	2574	24.0	2570
0740-0745	24.0	2574	24.0	2574
0745-0750	24.1	2580	24.1	2578
0750-0755	23.9	2562	24.0	2568
0755-0800	24.0	2574	24.0	2570
0800-0805	24.0	2574	24.0	2574
0805-0810	24.0	2574	24.0	2574
0810-0815	23.9	2562	23.9	2567
0815-0820	24.1	2580	24.0	2574
0820-0825	24.0	2574	24.0	2576
0825-0830	24.0	2573	24.0	2574
AFTER 0830			8.4	895
0710-0830	384.0	41154	384.0	41155

Key to columns (all data assumes no capacity restraint in the system)

Generated vehicle hours:	Hours of all vehicles generated within the 5-minute period
Assigned vehicle hours:	Kilometres travelled by all vehicles generated within the 5-minute period
Assigned vehicle hours:	Hours of all vehicles assigned to the 5-minute period, but generated in this or earlier periods
Assigned vehicle km:	Kilometres travelled by all vehicles assigned to the 5-minute period, but generated in this or earlier 5-minute period

SISTM output network file (NETDAT file) (continued)

Time Slice	Vehicle hours	Vehicle km	Average Speed (km/h)	Stopped Vehicle Minutes	Stopped Time (%)	Number of Stops	Stacked Vehicle Minutes	Noise dB(A)	Number of Incorrect Dest'ions	Number of Vehicles Generated	Number of Vehicles in MDS
0700-0705	14.7	1468	99.5	0.0	0.0	0	51.9	78.62	0	417	320
0705-0710	26.6	2587	97.4	0.0	0.0	0	76.6	80.89	0	417	347
0710-0715	26.1	2543	97.6	0.0	0.0	0	103.0	80.88	0	416	347
0715-0720	27.2	2609	95.8	0.0	0.0	0	100.1	80.86	2	417	338
0720-0725	26.4	2567	97.3	0.0	0.0	0	76.6	80.85	0	417	337
0725-0730	26.4	2550	96.7	0.0	0.0	0	134.5	80.78	0	417	342
0730-0735	26.6	2598	97.5	0.0	0.0	0	45.4	80.91	0	415	336
0735-0740	27.3	2660	97.3	0.0	0.0	0	19.0	81.00	0	417	324
0740-0745	26.2	2566	97.8	0.0	0.0	0	20.4	80.91	0	417	318
0745-0750	26.3	2580	98.2	0.0	0.0	0	28.2	80.94	0	418	322
0750-0755	25.5	2480	97.4	0.0	0.0	0	20.5	80.74	0	415	320
0755-0800	26.1	2518	96.4	0.0	0.0	0	30.7	80.76	2	417	338
0800-0805	27.4	2645	96.6	0.0	0.0	0	48.0	80.98	1	417	334
0805-0810	26.3	2542	96.6	0.0	0.0	0	39.3	80.78	1	417	336
0810-0815	27.5	2630	95.6	0.0	0.0	0	19.9	80.92	0	415	316
0815-0820	26.6	2577	96.8	0.0	0.0	0	19.4	80.85	0	418	320
0820-0825	26.6	2593	97.4	0.0	0.0	0	15.2	80.96	1	417	317
0825-0830	25.7	2484	96.5	0.0	0.0	0	28.7	80.67	1	417	327
0710-0830	424.3	41142	97.0	0.0	0.0	0	749.1	80.86	8	6667	

Key to columns

Vehicle hours:	Total time spent by all vehicles
Vehicle km:	Total distance travelled by all vehicles
Average speed:	Vehicle hours/vehicle km
Stopped veh minutes:	Total time spent by vehicles travelling at a speed less than a threshold value
Stacked veh minutes:	Total time spent by vehicles stacked in a vertical queue at the upstream end of the motorway or on an entry slip road - these vehicles enter a mainline lane based on their desired speed, and only when a large enough headway becomes available
No. of incorrect dest:	Number of vehicles taking an incorrect destination (missed exit or wrong exit)
No. of vehs in MDS:	Number of vehicles on the motorway (or in the vertical queue) at the end of the period.

SISTM output lane changes file (LCCDATA file)

M27/M3 *** LANE ÇHANGING MOVEMENTS *** 02.08.01

Time Slice	Start & end	No. left movements from lane									No. right movements from lane									All Movements		
	chainage	5	6	7	8	9	10	11	12	Total	4	5	6	7	8	9	10	11	Total	Number	Rate/VehHr	Rate/VehKm
0700 - 0705	4200 - 5400	0	0	43	81	55	0	0	0	179	0	0	0	41	34	0	0	0	75	254	138.7	1.42
0705 - 0710	4200 - 5400	0	0	119	227	171	0	0	0	517	0	0	0	138	125	0	0	0	263	780	141.0	1.53
0710 - 0715	4200 - 5400	0	1	124	217	178	0	0	0	520	0	0	0	119	128	0	0	0	247	767	144.6	1.57
0715 - 0720	4200 - 5400	0	0	124	205	197	0	0	0	526	0	0	0	117	144	0	0	0	261	787	135.7	1.53
0720 - 0725	4200 - 5400	0	0	126	223	170	0	0	0	519	0	0	0	130	123	0	0	0	253	772	145.2	1.56
0725 - 0730	4200 - 5400	0	0	120	224	200	0	0	0	544	0	0	0	127	142	0	0	0	269	813	149.1	1.64
0730 - 0735	4200 - 5400	0	1	128	245	212	0	0	0	586	0	0	0	146	145	0	0	0	291	877	161.8	1.74
0735 - 0740	4200 - 5400	0	0	136	243	226	0	0	0	605	0	0	0	123	162	0	0	0	285	890	157.5	1.70
0740 - 0745	4200 - 5400	0	2	124	236	186	0	0	0	548	0	0	0	128	125	0	0	0	253	801	149.1	1.60
0745 - 0750	4200 - 5400	0	2	116	204	189	0	0	0	511	0	0	0	123	142	0	0	0	265	776	146.9	1.56
0750 - 0755	4200 - 5400	0	0	125	232	204	0	0	0	561	0	0	0	120	147	0	0	0	267	828	155.6	1.72
0755 - 0800	4200 - 5400	0	0	128	223	208	0	0	0	559	0	0	0	126	149	0	0	0	275	834	153.5	1.71
0800 - 0805	4200 - 5400	0	2	116	235	209	0	0	0	562	0	0	0	144	160	0	0	0	304	866	151.9	1.69
0805 - 0810	4200 - 5400	0	3	125	237	194	0	0	0	559	0	0	0	133	144	0	0	0	277	836	155.3	1.70
0810 - 0815	4200 - 5400	0	1	135	239	205	0	0	0	580	0	0	0	135	156	0	0	0	291	871	144.8	1.67
0815 - 0820	4200 - 5400	0	0	122	220	210	0	0	0	552	0	0	0	131	151	0	0	0	282	834	154.8	1.70
0820 - 0825	4200 - 5400	0	0	127	226	189	0	0	0	542	0	0	0	124	143	0	0	0	267	809	142.1	1.58
0825 - 0830	4200 - 5400	0	0	127	224	188	0	0	0	539	0	0	0	134	139	0	0	0	273	812	150.0	1.68
Totals:	4200 - 5400	0	12	2165	3941	3391	0	0	0	9509	0	0	0	2239	2459	0	0	0	4698	14207	148.0	1.64

Lane numbers are internal lane numbers; lane 1 of the main carriageway is usually internal lane 7, lane 2 is internal lane 8 etc; the nearside slip road (of a 2 lane slip road) is internal lane 5; the offside slip lane is internal lane 6.

SISTM output journey time file (JTIMES file)

M27/M3
02.08.01

JOURNEY TIME STATISTICS

JOURNEY TIMES IN SECONDS FOR VEHICLES BETWEEN CHAINAGES 4000 AND 5300 METRES

ORIGIN NODE : 11 DESTINATION NODE : 22

Time of Sample	Journey Time (Vehicle Class 3) seconds	Journey Time (Vehicle Class 6) seconds
07:00:00	-	-
07:00:27	-	-
07:00:54	-	-
07:01:21	-	-
07:01:48	-	-
07:02:15	44	-
07:02:42	48	-
07:03:09	48	58
07:03:36	52	-
07:04:03	45	-
07:04:30	47	-
07:04:57	48	-
07:05:24	-	-
07:05:51	55	56
07:06:18	48	-
07:06:45	46	59
07:07:12	46	-
07:07:39	43	59
07:08:06	56	-
07:08:33	54	57
07:09:00	-	-
07:09:27	53	60
07:09:54	50	-
07:10:21	45	47
07:10:48	50	60
07:11:15	50	58
07:11:42	-	-
07:12:09	52	52
07:12:36	47	55
07:13:03	52	-
07:13:30	50	-
07:13:57	-	60
07:14:24	56	-
07:14:51	50	56
Mean Journey Times	49.4	56.7

Mean journey time over total period for vehicle class 3 = 49.4 seconds
Mean journey time over total period for vehicle class 6 = 54.6 seconds

KEY : < DENOTES THAT A VEHICLE WAS SELECTED AT THE START CHAINAGE, BUT HAS NOT BEEN FOUND AT THE END CHAINAGE. THIS IS PROBABLY BECAUSE IT DID NOT COMPLETE ITS JOURNEY BY THE END OF THE SIMULATION.

- DENOTES THAT NO VEHICLE OF THE REQUIRED CLASS AND O-D CROSSED THE START CHAINAGE IN THAT TIME INTERVAL.

GLOSSARY

ARCADY - a macroscopic computer program used for predicting capacities, queue lengths and delays at non-signalised roundabouts and mini-roundabouts (Assessment of Roundabout CApacity and DelaY).

Auxiliary lane (or Parallel lane) - an extra lane running parallel to the mainline providing the exit with extra capacity and reducing the risk of exiting vehicles blocking back onto the mainline.

Capacity - the maximum amount of traffic per unit time that can pass through the junction or section of roadway under the prevailing conditions.

Connector roads - a collective term for slip roads, link roads and loops (i.e. a link or slip road that passes through an angle of approximately 270 degrees).

CONTRAM - a macroscopic traffic assignment computer program (CONtinuous TRaffic Assignment Model).

Departure - using a design that goes beyond the 'absolute minimum' recommended in the Standard.

Diverge - area of the motorway where drivers can leave the mainline.

Diverging flow-region diagram - a diagram used by traffic engineers to select the most appropriate diverge layout for a given diverging and downstream mainline flow.

Ghost Island diverge layout - a new alternative diverge layout incorporating a wide 'tiger-tailed' painted area and two distinct exit points in order to separate exiting traffic into two orderly streams

Grade-separated junctions - junctions where the mainline traffic passes through the junction unhindered whilst turning traffic enter or leave the mainline via connector roads constructed at different levels above or below the mainline.

Interchanges - grade-separated junctions that provide free unhindered movement to all streams of traffic. Three or four levels may be required.

Lane distribution - a parameter indicating the way in which the traffic flow is 'spread' over all of the available lanes on the mainline. This can depend on traffic flow, speed and composition as well as the O-D patterns of drivers.

Lane drop - occurs when the inside mainline lane(s) feeds into the exit slip road at the diverge. This results in the number of lanes downstream of the diverge being less than the number upstream of the diverge. It is often used where there is a high diverging flow at the exit.

Lane-separation markings - carriageway markings used between lanes 1 and 2 of the mainline prior to the diverge in order to discourage swooping.

Macroscopic model - a computer simulation program used to model traffic as a whole, in terms of quantities such as volume, speed and density.

Mainline - the carriageway carrying the main flow of traffic.

Merge - area of the motorway where drivers can join the mainline.

Microscopic model - a computer simulation program used to model traffic at the level of an individual vehicle.

Midas loops - detectors installed on motorways to record parameters such as speed and flow.

Nomograph - a graphical diagram used to calculate the inside lane flow of the mainline, upstream of the merge.

Nose - paved section of carriageway before the merge taper or after the diverge taper that separates the mainline from the connector road, which is delineated by road markings (sometimes referred to as exit or entry gore areas).

OSCADY - a macroscopic computer program for calculating capacities, queues lengths, and delays for isolated, traffic signal controlled, junctions (Optimised Signal Capacity And Delay).

Parallel diverge layout - a layout where exiting drivers move into an auxiliary lane, which feeds into the exit slip road.

PICADY - a macroscopic computer program for predicting capacities, queue lengths and delays at non-signalised major/minor junctions (Priority Intersection CApacity and DelaY).

Relaxation - using a design that goes beyond the 'desired minimum' recommended in the Standard.

SISTM - a microscopic motorway simulation computer program developed by TRL for the Highways Agency (SImulation of Strategies for Traffic on Motorways).

Standards - technical specifications published by the Government providing guidelines for the design of new roads.

Swooping - a driving manoeuvre where vehicles move directly from lanes 2 or 3 of the mainline into the exit slip road, typically within 500m of the diverge point, in order to leave the mainline.

Taper - distance from the end of the Nose to the end of the slip road at the merge and from the start of the slip road to the start of the Nose at the diverge.

Taper diverge layout - a layout where exiting drivers move from lane 1 directly into the exit slip road (also referred to as a Wedge layout). This layout has no auxiliary lane.

Throughput - the sum of the vehicle flows on the slip road and the mainline after the diverge.

TRL - Transport Research Laboratory based in Crowthorne, Berkshire.

Weaving length - distance between the point of the diverge taper and the point of the merge taper.

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