Microscopic modelling of motorway diverges

G.T. Wall and N.B. Hounsell
School of Civil Engineering and the Environment
University of Southampton
Southampton
U.K.
e-mail: grahamw@soton.ac.uk

EJTIR, **5**, no. 3 (2005), pp. 139-158

Received: April 2005
Accepted: August 2005

This paper describes research looking at the design and operation of motorway diverges using the microscopic computer program SISTM. A diverge is the area of the motorway or other major road where drivers can leave the main carriageway. Low cost measures including the installation of alternative designs (such as the Ghost Island diverge) are assessed which could improve the operation, capacity and driving behaviour at the diverge. Following on from a recent study reviewing the diverging flow-region diagram (used in the UK as a tool to help traffic engineers select the most suitable diverge layout for a particular site with given downstream mainline and diverging flows), it was thought that microscopic models could offer potential benefits in confirming such a choice (particularly in border line situations) as driving behaviour aspects which affect capacity are not catered for in the diagram. SISTM has been used to evaluate existing and alternative diverge layouts in terms of their throughput as well as several other parameters. Modelled and observed data for the speed-flow relationship and the lane distribution of the mainline was compared and differences noted in order that the results could be interpreted correctly. A theoretical comparison of four layouts was carried out; Taper, Parallel, Taper lane drop and Ghost Island diverge. The link between throughput and lane distribution on the mainline before the diverge was also assessed as well as the importance of lane and exit choice. This research presents a summary of some of the key results from the modelling along with a discussion of their accuracy and application. Conclusions and recommendations are made with regard to design implications for diverges along with a list of modelling requirements (essential and desirable) for motorway diverges.

Keywords: Microscopic modelling, Throughput, Lane distribution, Motorway diverge, Lane changing, Car following and SISTM.

1. Introduction

A diverge is the area of the motorway or other major road 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. There are two basic designs; the Taper and the Parallel diverge layouts. These are recommended in the latest UK Standard TD22/92 (Department of Transport, 1992). Figure 1 shows these two basic designs.

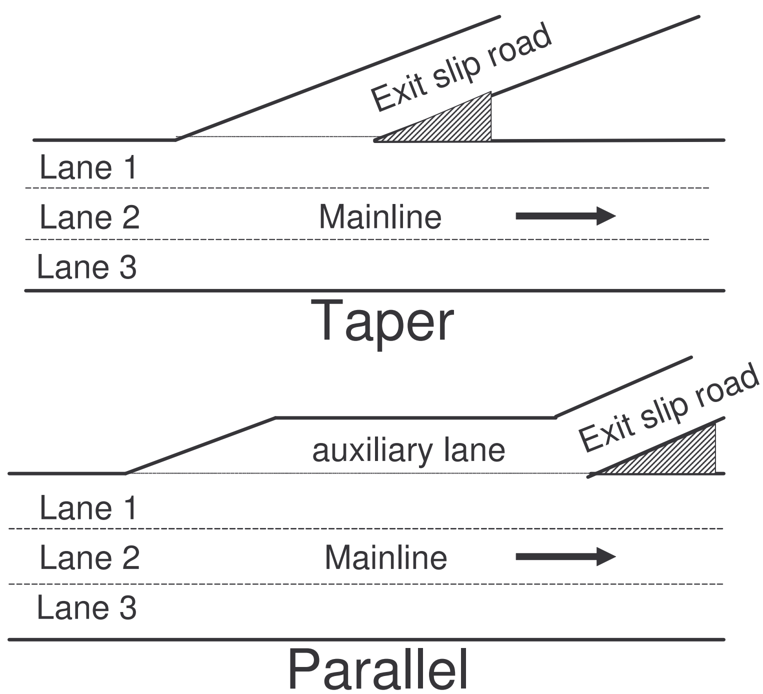

Figure 1. Two basic diverge designs (adapted from Wall and Hounsell, 2004)

With the Taper diverge, drivers wishing to leave the motorway need to stay in lane 1 prior to the exit and then move directly into the exit slip road whereas with the Parallel diverge, drivers need to stay in lane 1 and then move into the auxiliary lane that feeds into the exit slip road. An auxiliary lane provides extra capacity, reducing the risk of traffic blocking back onto the main carriageway. These layouts can also be associated with a lane drop; this occurs when the number of lanes downstream of the diverge is less than the number of lanes upstream of the diverge 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 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.

A new alternative layout which has been trialed in the UK is the 'tiger-tailed' Ghost Island diverge layout (with or without a lane drop). It has been installed at a number of motorway diverges over the last 10 years, particularly at motorway to motorway interchanges (Highways Agency, 1998; Wedlock, Peirce and Wall, 2001; Wall, 2004b). It provides drivers with two opportunities to leave the mainline, with a 'tiger-tail' ghost island marking regulating the diverging traffic into two orderly streams. It has been particularly useful in the reduction of swooping, a dangerous manoeuvre where a vehicle moves directly into the slip road from lanes 2 or 3 in order to leave the mainline. Drivers have a choice of two exit points; they either leave at the first exit point and use slip lane 1 or leave at the second exit point and use slip lane 2. Figure 2 shows a schematic representation of the Ghost Island and Ghost Island lane drop layouts respectively. Figure 3 shows the new Ghost Island layout at the M6 junction 4a, near Birmingham, which incorporates a lane drop which is then regained after the exit.

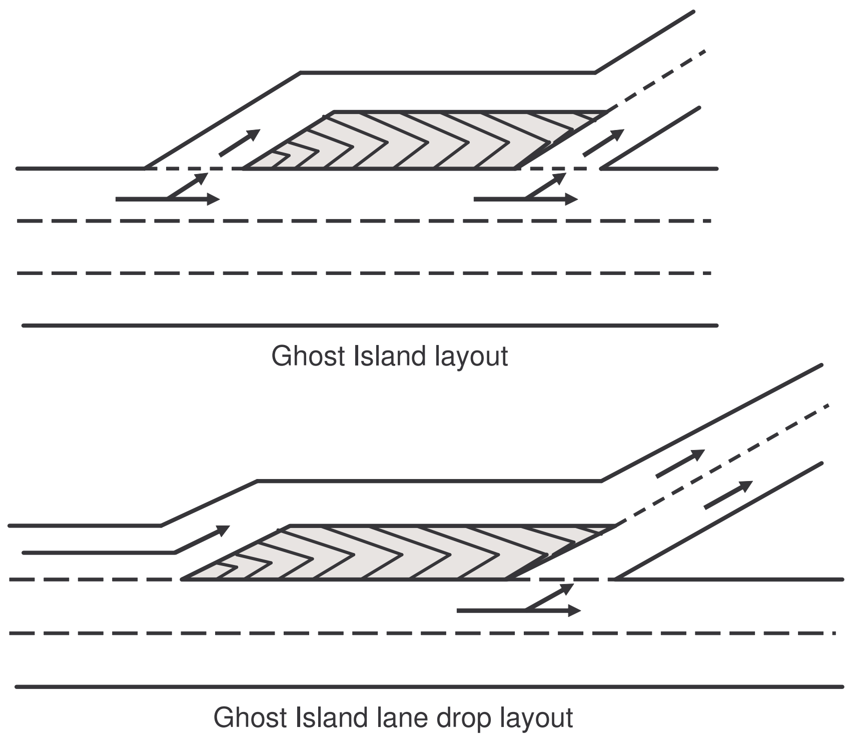

Figure 2. The Ghost Island diverge layouts (from Wall and Hounsell, 2004)

Figure 3. The Ghost Island layout at the M6 junction 4a (from Wedlock et al., 2001)

A diverging flow-region diagram is available for use in the UK to help traffic engineers select the most appropriate layout (Taper, Parallel, Taper lane drop, Parallel lane drop or Parallel double lane drop) for a given site (Department of Transport, 1992). A critical review of the use of this diagram and other related design processes was carried out and revealed that it was “a useful tool for providing a preliminary indication of which diverge layout was most suitable for a given set of downstream mainline and diverging flows” (Wall and Hounsell, 2004). However, there were problems in border line situations where the data point appeared on the border of two or more regions on the diagram or where the diverging flow was variable. It also did not take into account driver behaviour which can vary at different layouts and affect capacity. It was also recommended that the diagram was updated to include the new Ghost Island layouts shown in figure 2.

One of the conclusions of the critical review was that a suitable microscopic model could be used as an additional tool for the traffic engineer, supplementing the diverging flow-region diagram by helping to confirm the choice of layout, particular in border line situations or where the diverging flow was very variable (Wall and Hounsell, 2004). This paper, therefore, reports on the potential benefits of using a microscopic model (in this case SISTM) in assessing the capacity and operation of various diverge layouts. Microscopic models have been used extensively to model the merge and its associated driver behaviour and applications (Ran-Bin et al., 1998; Wu et al., 2003; Ozbay et al., 2004) but only more limited work has been carried out near the diverge. Section 2 discusses the validation of SISTM and how the models for each diverge layout were set up and checked to make sure they were a realistic representation. The results of the modeling work in assessing four different diverge layouts are presented and discussed in section 3. Section 4 contains the conclusions and recommendations which includes design implications for diverges and a list of essential and desirable modelling requirements for motorway diverges. The acknowledgements and references conclude the paper.

2. Validation, setting up and testing the models

2.1 Validation of SISTM

In order to assess a number of diverge layouts, the microscopic simulation computer program SISTM (SImulation of Strategies for Traffic on Motorways) (TRL Ltd, 2001) was used to carry out a theoretical comparison. It was developed by the Transport Research Laboratory (TRL Ltd) for the Highways Agency (HA), to model motorways of up to 6 lanes. It was selected for a number of reasons including the fact that it has been extensively calibrated and validated with data from a number of UK motorways, it has been used by TRL Ltd on a number of related motorway projects for the HA such as ramp metering and variable speed limits (e.g. Harbord, 1995) and could provide a wide variety of output including parameters such as flow, speed, lane changes and journey times. The program 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). Development work of the model is ongoing to further improve its lane changing and car-following logic. For an assessment of alternative models, a recent study complied a list of 57 existing microscopic models, most of which were being used as research tools (Institute of Transport Studies, University of Leeds, 2000).

Before using SISTM to model various diverge layouts to assess their throughput and operation, it was thought necessary to check how well the model replicated the speed-flow relationship and the lane distribution on the mainline. This would highlight the model's car-following and lane changing logic (crucial to its accuracy) and see if the modelled results were similar to those observed. A model was set up for Junction 5 westbound on the M27, near Southampton, in the UK. Pseudo-detectors were installed within the model at various places in order to obtain information regarding speed and flow. A mainline demand flow of 6500 veh/hr was used as this had been shown to generate a detector flow that caused congested conditions but not flow breakdown (see figure 4). 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 vehicle composition was 85% light vehicles and 15% heavy vehicles, the standard composition given in the UK Standard (Department of Transport 1992). It was assumed that there was 0% gradient on the mainline.

Firstly, the speed-flow results from SISTM were compared with observed speed-flow results from Midas loops on the M27 for all mainline lanes between Junctions 7 and 5. Figure 4 below shows the two sets of results plotted on the same graph so they can be easily compared.

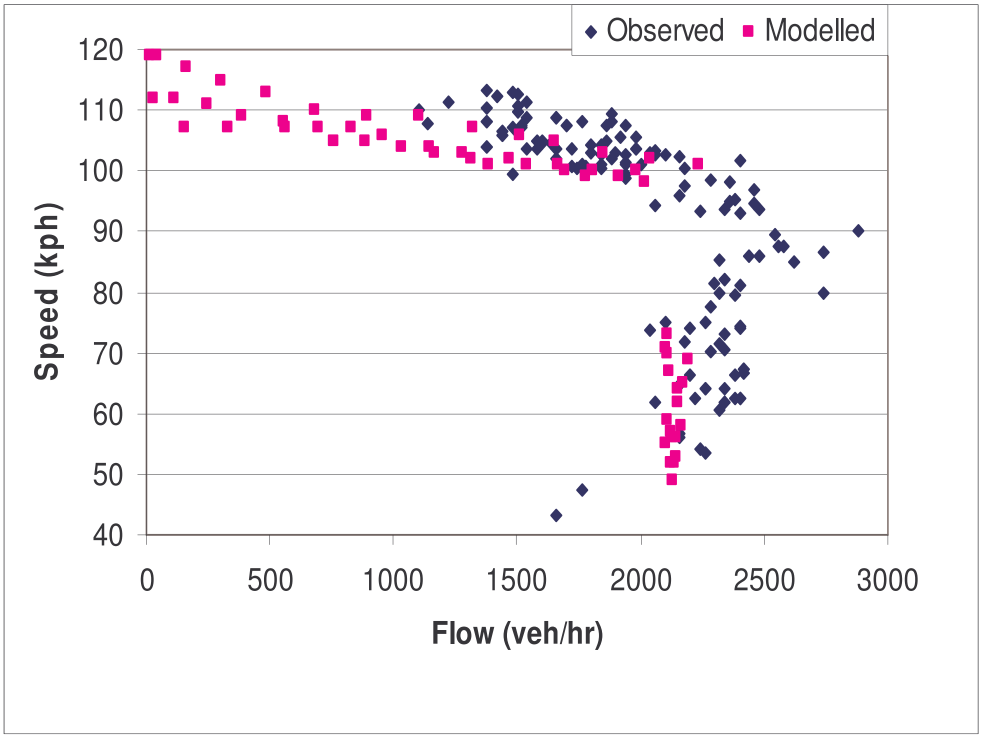

Figure 4: The observed and modelled speed-flow results on the M27

Figure 4 showed that the observed and modelled results matched reasonably well but with some differences occurring. The observed flows did not go below 1000 veh/hr as they were taken from Midas loops during the morning peak period. A small proportion of the Midas loop data was at flows in excess of 2500 veh/hr whereas data from SISTM decreased at a slightly lower flow of about 2200 veh/hr per lane. This seems very high and may be due to the inductive loops over counting the flow. The differences were though partly due to a lower Heavy Goods Vehicle (HGV) percentage on the M27 (normally less than 10%) compared to the standard in the model of 15%. In addition, SISTM uses the Gipps car following model (like other models such as AIMSUN) which is based on collision avoidance (Gipps 1981). 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). This results in more generous gaps between vehicles being generated than may be expected in reality and thus higher headways and a lower mainline capacity in the model. Also, in reality, drivers will tend to use lower headways as they are not just focussed on the vehicle ahead but can anticipate traffic conditions further downstream and therefore do not have to brake as hard as vehicles in the model.

Secondly, the lane utilisation results from SISTM were compared to observed data from the M27. SISTM uses a scores and thresholds lane changing model (TRL Ltd 2001; Wall 2004a). 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. Exiting vehicles are given extra stimulus to change lane to the left as they pass signing normally 1000m, 500m and 100m from the diverge point. The scores given are normally in ascending order. Within the model, a psuedo-detector was placed on the mainline approximately 2km. from the diverge (far enough away to make sure exiting vehicles receive no additional stimulus to change lane to the left). The demand flow was increased by 1000 vehicles per hour on each run and the results are shown in figure 5.

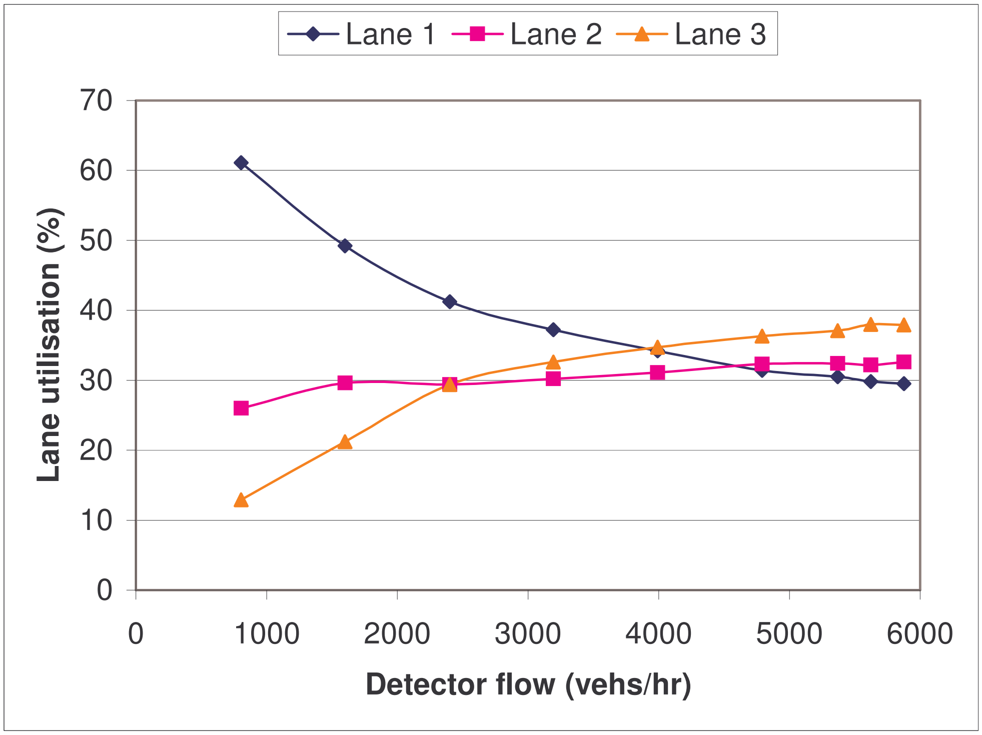

Figure 5. Lane utilisation of the mainline with increasing flow

The observed results came 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 et al 1998). The Midas loop on the mainline was situated well away from any diverge or merge. Figure 6 shows the lane utilisation of each of the mainline lanes on the M27 against vehicle flow.

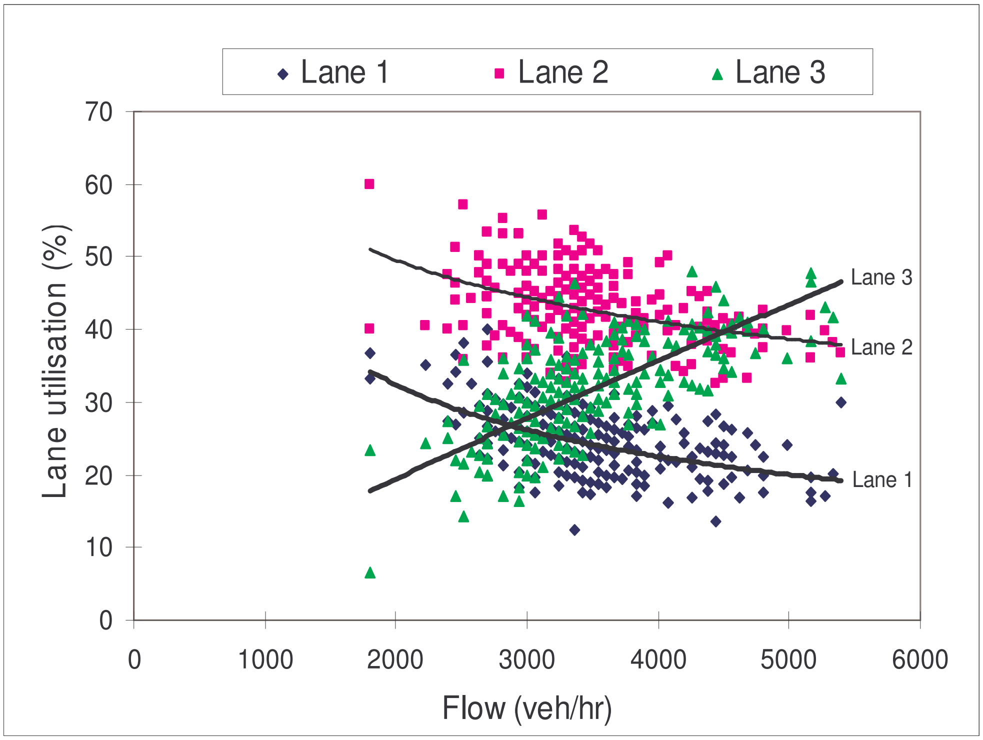

Figure 6. Lane utilisation of the mainline of the M27 (from Brackstone et al., 1998)

With low flows, the majority of drivers in SISTM used lane 1 which is the recommended behaviour in Rule 238 of the UK's "The Highway Code" (Road Safety Directorate/Driving Standards Agency, 2001). As the flow increased in the model, the utilisation of lane 1 decreased as the utilisation of lanes 2 and 3 increased. With higher mainline flows, many vehicles used lane 2 or 3 in order to overtake slower moving traffic in lane 1. In reality, drivers do not always follow this Highway Code Rule. 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). This assumption has led to an over estimation of the percentage of traffic using lane 1. For example, at 5000 vehicles/hour, SISTM assumes that lane 1 is utilised with about 30% of the mainline traffic whereas the observed value is 20%. This means that there are approximately 500 more vehicles in lane 1 in the model than would be expected. Some of these extra vehicles could be due to the presence of more HGVs within the model which are constrained to lanes 1 and 2.

These tests could not in themselves prove that the driving behaviour in SISTM was correct as only the results were being compared. They did however highlight some differences between the observed and modelled data which were noted and closely monitored in the subsequent modelling work, in order that a correct interpretation of the throughput results could be made.

2.2 Setting up and testing of the models

The modelling work carried out was a theoretical exercise and was designed to assess various diverge layouts in terms of their:

- Throughput (sum of the flow on exit and mainline after the diverge) (see section 3)
- Potential impact on safety from predicted lane changes (Wall 2004a)
- Operation (by collecting journey time data) (Wall 2004a)

Models were set up in SISTM for four diverge layouts; Taper (no lane drop), Taper with a lane drop, Parallel with no lane drop, and a Ghost Island (with no lane drop). The models represented a 3-lane main carriageway of 6km with the diverge starting at just over 5km. (modelled again on the mainline stretch on the M27 westbound between Junctions 7 and 5, near Southampton). The geometric dimensions of the various layouts were taken from the TD22/92 "Layout of Grade Separated Junctions" (Department of Transport 1992) or "A Review of Anti-Swooping Trials" (Wedlock, Peirce and Wall, 2001).

SISTM models the diverge as a Taper layout (with or without a lane drop) but other diverge layouts were modelled by adapting the input data. For the Parallel diverge, a lane gain node was added at least 200m. prior to the exit in order to represent the auxiliary lane. This extra lane (set up as a dedicated lane for exiting vehicles) was then dropped at the exit. The Ghost Island layout was represented by two closely spaced single link diverges. The origin-destination flow table was used to determine the proportion of diverging vehicles using each exit. Therefore, with the exception of the Ghost Island layout, all the other layouts were modelled with a double link.

For each set of results, five runs were carried out using a different random seed number. With any microscopic simulation computer program, more than one run with different random seeds is necessary in order to account for a range of random components of the model. A warm up period of at least 10 minutes was also used in order to fill the motorway with traffic with the corresponding data deleted from the output file.

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

1. Checking the traffic movements associated with each layout were as expected.
2. Checking that the driving behaviour (e.g. lane distribution, lane changing and lane choice) for each diverge was realistic.

The results of the tests showed that the Taper and Ghost Island models appeared realistic in terms of their associated driving behaviour. However, with the Taper lane drop at low diverging percentages (under 20%), many drivers wishing to remain on the mainline were forced to leave the main carriageway as no suitable gap in lane 1 was available for them to continue on the motorway. This led to a number of incorrect destinations. In reality, drivers are likely to either 'force' their way into relatively small gaps in the neighbouring lane, or drivers already in this lane may 'give-way' to drivers on their inside. SISTM, in common with other microscopic models, does not replicate this behaviour. Vehicles continue to travel at a reasonable speed and if no suitable gap can be found, they will continue on to an incorrect destination. To keep this error to an acceptable level (under 5%), the modelling work focussed on a diverging percentage of at least 20%. In practice, a lane drop layout would only be installed when there is a significant number of diverging vehicles.

With the Parallel layout, all exiting vehicles entered the auxiliary lane (a dedicated lane for exiting vehicles) at the start of its existence (unless unable to do so). 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. The simulation display showed at times platoons of cars following a slow moving HGV or car 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 the slower vehicle for a longer period of time with no possibility of overtaking. Given these observations regarding the Parallel layout, it was still thought beneficial to look at the throughput results (even if it the model did not fully reflect the capacity benefits of having an auxiliary lane). For the modelling work, the auxiliary lane was kept at 400 m. in order to minimise this error.

3. Throughput results from SISTM

3.1 Introduction to throughput results

The throughput is defined to be 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. The maximum throughput for each layout can be no higher than the capacity of the 3-lane mainline before the diverge. This was appropriately 6600 veh/hr in SISTM (see figure 4). Two additional constraints can be the capacity of the slip road and for lane drop layouts, the capacity of the mainline (with at least one fewer lane) after the diverge.

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, thus increasing the throughput at the diverge. This theoretical 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 can enable the lane distribution on the mainline 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. They are:

- **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.

- **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 lane distribution on the mainline may not be optimal. 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.

Various measures have been suggested as possible ways of increasing the capacity and/or lane distribution of the mainline before the diverge so that it becomes more optimum and so maximising its throughput. Three such examples are:

1. **Hard shoulder running lanes** have been seen as a short term solution to increase capacity on the mainline. A trial has been carried out allowing the hard shoulder to be used during congested periods on the M42 between junctions 3a and 7, near Birmingham, as part of an active traffic management project (Freight, 2002). This has followed successful trials in the Netherlands and Germany (Local Transport Today, 2003; Kellermann, 2000). It has also been used to allow space for more (narrower) lanes on the mainline (McCasland, 1978). 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.

2. **Variable speed limits** involve 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 junction 10 and 15 (Harbord, 1995). These variable speed limits enable the difference between the average mainline speed and the speed limit to be kept as small as possible. They also help 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 reduce the potential for shockwaves to occur with smaller speed differences between lanes reducing the likelihood (or desire) of drivers to lane change as studies in the Netherlands have shown (Van-den Hoogen and Smulders, 1994).

3. **Real-time road markings** are designed to encourage better lane distribution by controlling lane changes with a pre-installed changeable lighting system working in real-time (Okura et al., 1996a; Okura et al., 1996b). On certain stretches of the motorway, only lane changes from over utilised to under utilised lanes would be allowed. Trials would be necessary to see how effective this measure could be in improving the lane distribution and throughput of the mainline.

3.2 Throughput and lane utilisation results

For each of the four layout types modelled, a demand flow of 8000 veh/hr (way above the capacity of the 3-lane mainline) 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 was increased to 8000 veh/hr in several easy steps. 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 traffic (0% - 60% for Taper, Ghost Island and Parallel layouts; 20% - 60% for Taper lane drop layout). For this scenario, the two exits of the Ghost Island layout were set up to be equally used by exiting traffic; the Parallel layout was modelled with an auxiliary lane of 400m; the traffic composition consisted of 85% light vehicles and 15% HGVs. and the mainline had 0% gradient. The throughput results are shown in vehicles per hour in figure 7.

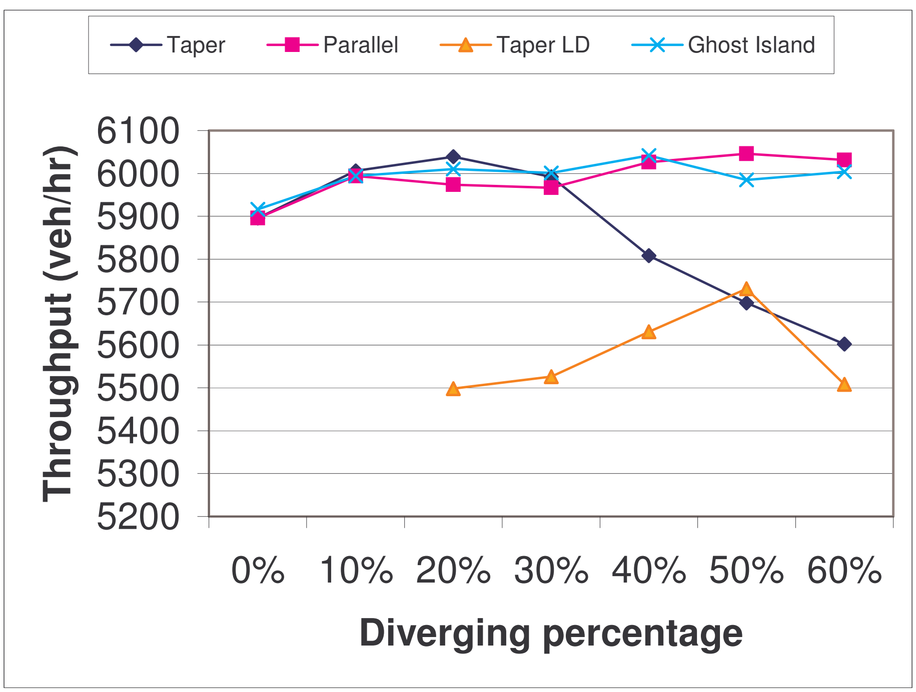

Figure 7. Throughput results for the four layouts with 15% HGV

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.

Figure 8 shows the lane utilisation for the individual mainline lanes against diverging percentage for the Taper layout. It shows that the three lanes were most equally utilised with 30% diverging percentage, which corresponds approximately to the maximum throughput value at 20%. At this point, lane 1 has reached capacity and could not cope with any more traffic resulting in vehicles having to use lane 2 and lane 3. At larger diverging percentages (over 30%), exiting vehicles on the slip road were more likely to be prevented from travelling at their desired speed. In practice the exit slip road may lead very shortly to a roundabout, traffic signalled junction or a priority junction which would result in all vehicles using it to reduce their speed.

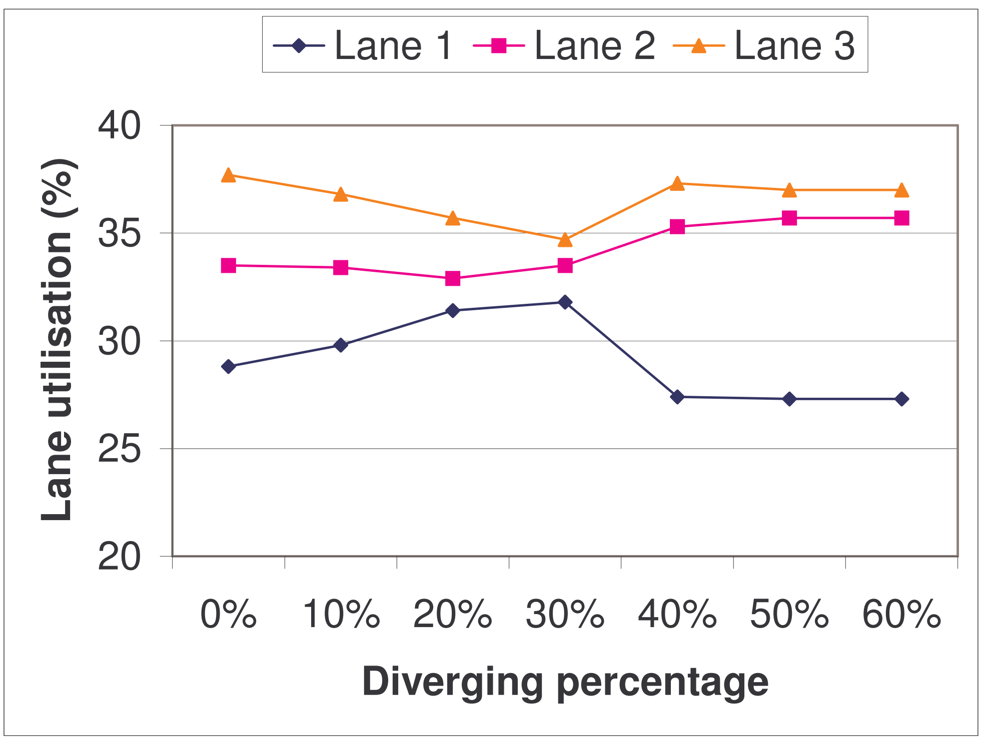

Figure 8. Lane utilisation 500m before the Taper diverge

For the Parallel layout, the throughput remained high for the full range of diverging flows, with the most equal lane distribution at 50% diverging. The results showed that the presence of an auxiliary lane provided extra capacity at the junction (even if not fully reflected in the model), enabling exiting vehicles to leave the mainline early and cause less disruption to mainline vehicles.

For the Ghost Island layout, the throughput also remained high for the full range of diverging flows. Exiting traffic were divided into two streams with only those vehicles using 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 a period of time in which to move into lane 1 prior to the second slip lane. Both slip lanes were set up to be equally utilised and coped well with the high numbers of diverging vehicles. The lane utilisation for the individual mainline lanes before the Ghost Island diverge converged to being more equally utilised as the diverging percentage increased.

For the Taper lane drop layout, the throughput increased between 20% and 50% diverging (reaching a peak at 50% when the lane distribution was most equal) and then started to decrease. As with the Taper layout, exiting vehicles needed to be in lane 1 which was 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 reducing the capacity of the mainline after the diverge.

It is worth noting that the lane changing logic in SISTM has resulted in more vehicles using lane 1 before the diverge than would be expected (up to 500 vehicles at 5000 vehicles/hour (see figures 7 and 8) although some of these could have been due to a large percentage of HGVs in the model than in the observed data. Given the maximum throughput for the Taper was at 20% diverging with a throughput of about 6000 vehicles/hour (i.e. 1200 vehicles diverging), the observed result could be as much as 10% lower (i.e. 1080 vehicles) resulting in the graph moving to the left such that the maximum throughput actually corresponds to 18% diverging. This would also apply to the other layouts and provides an error band for the diverging percentage at which the peak throughput is achieved.

Overall, the results showed that both the Parallel (even with the limitations of the model) and the Ghost Island layouts had a consistently high throughput for the full range of diverging flows (0% - 60%). Both layouts offered exiting drivers some flexibility as to when they needed to be in lane 1 and when to leave the mainline. This improved the distribution of the mainline before the diverge, contributing to a higher throughput. The Taper and Taper lane drop layouts had a more limited range of diverging flows at which they achieved a high throughput, offering drivers no lane or exit choice.

Further runs showed that the throughput results for each layout were also affected by the traffic composition. With high diverging percentages and a high HGV percentage, the demand for lane 1 (and lane 2) could exceed its capacity causing slow moving traffic before the exit. As HGVs are constrained to lanes 1 and 2 only, a more unequal lane distribution could result. In addition, throughput results for the Ghost Island layout were also affected by exit usage. Further runs showed that when the two exits were unequally used, the throughput was lower but only noticeably when the diverging percentage was above 30% and when at least 70% of exiting traffic used the first exit. An unequal usage of the two exits is likely where they lead to two different destinations or enable the driver to be positioned in the correct lane for the subsequent junction at the end of the slip road.

4. Conclusions and recommendations

4.1 Introduction

The conclusions and recommendations cover the following three areas:

- Lane choice, exit choice and throughput at the diverge
- Design implications for diverges
- Modelling requirements for motorway diverges

These 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.

4.2 Lane choice, exit choice and throughput

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 theoretical maximum capacity level if the utilisation of the mainline lanes before the diverge are optimally used (normally equally used).

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 time by enabling the exit to operate more efficiently. 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. Measures such as a hard shoulder running lane, variable speed limits and real-time road markings may also help to improve the capacity and/or the lane distribution of the mainline.

4.3 Design implications for diverges

The modelling work showed that the Taper and Taper lane drop diverge layouts had a limited range of diverging flows in which they can operate efficiently. They offered no lane or exit choice to drivers. 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.

The modelling results for the Parallel layout (an under-estimation due to the model) showed that it had high throughput results with the full range of diverging flows as it provided some degree of exit choice to drivers with the presence of the auxiliary lane. This layout 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, which can result in numerous lane changes between the auxiliary lane and the mainline. This may require, however, the use of part of the hard shoulder in order to have the space to install the Ghost Island.

The modelling work showed that the Ghost Island diverge (like the Parallel layout) had high throughput results with the full range of diverging flows (up to 60% at capacity levels). This has complemented previous research which has shown it to be an effective layout in terms of capacity, operation and driving behaviour. It offers drivers exit choice with the Ghost Island lane drop also providing lane choice. It has been recommended that the Ghost Island and Ghost Island lane drop layouts are incorporated as standard layouts into the new Standard when TD22/92 is revised and updated (Wedlock, Peirce and Wall, 2001; Wall, 2004b).

4.4 Modelling requirements for motorway diverges

The research reported in this paper has shown the great potential benefits of microscopic models as well as some of its present limitations. SISTM still compares favourably with other similar models and is regarded as one of the better motorway microscopic models. Many of the limitations highlighted apply to all microscopic models. Its status will be improved further when many of the planned enhancements, particularly to the lane changing and car following logic, are made. A list of microscopic modelling requirements for motorway diverges has been compiled based on lessons learnt carrying out this research using SISTM. The list has been divided into requirements that are essential and those that are desirable. Many of these requirements would require extensive studies at a large number of sites in order to collect sufficient data to incorporate statistically significant relationships into the model. If such a model could be developed to have the following requirements, then it could be an excellent tool for traffic engineers to use alongside the diverging flow-region diagram as well as using their own experience and knowledge in selecting a suitable diverge layout for a particular site.
Essential requirements are as follows:

- It has been extensively calibrated and validated using data from a variety of locations and so can provide the user with default parameter values. It is important that when modelling a stretch of motorway in a particular country, the model used has been calibrated and validated in that country as driver behaviour can vary due to factors such as speed limits.
- It has well researched lane changing and car following logic.
- It is able to model explicitly a Parallel and Ghost Island layout (with or without a lane drop).
- It is able to model different vehicle classes including HGVs.
- It can model gradient and length of gradient.
- It provides the user with a wide variety of output data including flow, speed, journey times and lane changes at specific points before, on or after the diverge.
- It is able to cater for up to at least 6 lanes on the mainline and 2 lanes on the slip lanes.

Desirable requirements include:

- It can explicitly model the swooping manoeuvre.
- It can model a hard shoulder running lane and variable speed limits.
- It provides the opportunity to study flow breakdown near the diverge.
- It can model the behavioural aspects of directional vertical signing.
- It contains an accident prediction model.
- It can model environment factors such as weather conditions, air quality and noise levels.
- It provides the opportunity to alter some of the geometric parameters associated with the diverge such as lane widths, angle of slip road to the mainline and radii of curvature of bends in the mainline.
- It is user-friendly program (compatible with a range of operating systems) suitable for traffic engineers to use easily when assessing or re-assessing the most suitable layout for a particular site. It should therefore provide output in a form that can be easily understood and incorporated into reports or other documents.

Acknowledgements

The authors would like to thank the Highways Agency and TRL Ltd for their permission to use SISTM for this project and figure 4 from TRL Report 491, EPSRC for the financial support to carry out this research and Dr. Beshr Sultan (University of Southampton) for his input and expert advice with regard to the microscopic modelling aspect of the research.

References

Brackstone, M., McDonald, M. and Wu., J. (1998). Lane changing on the motorway: factors effecting its occurrence, and their implications. *Proceedings of 9th International Conference on Road Transport Information and Control*. IEE, London, April, 1998, Conference Publication No. 454. pp. 160-4. IEE, London.

Department of Transport (1992). Design manual for roads and bridges, Vol 6, Section 2, Part 1, Layout of grade-separated junctions, Departmental Standard TD22/92, London.

Freight (2000). Issue 25 (12), p15, Freight Transport Association, Tunbridge Wells, Kent.

Gipps, P.G. (1981). A behavioural car-following model for computer simulation. *Transportation Research B*, 1981/04, 15B(2), pp. 105-111.

Grant, D. (2003). M42 active traffic management project. *ITS UK Smart Moving Conference*, 7-10th April 2003, National Exhibition Centre, Birmingham.

Harbord, B. (1995). The application of SISTM to dynamic control of the M25. *Proceedings of an IEE colloquium on 23rd February 1995*, Reference 95/039, ISSN 0963-3308.

Highways Agency 1998). *Towards a balanced transport system: The Highways Agency's Toolkit*. Version 1: 9/1/98.

Institute for Transport Studies, University of Leeds (2000). *Review of micro-simulation models*. Final Report for the Smartest project, University of Leeds, Leeds.

Kellerman, G. (2000). Experience of using the hard shoulder to improve traffic flows. *Traffic Engineering and Control*, Volume 2000(11) 41 (10), pp. 412-414, London.

Local Transport Today (2003). Issue 371, 24th July 2003, pp. 10-11, London.

McCasland, W.R. (1978). Use of freeway shoulders to increase capacity. *Transportation Research Record, Pavement Surface, Properties, Evaluation and Shoulders*, Volume 666, pp. 46-51, Washington DC.

Okura, I. and Somasudaraswaran, K. (1996a). Analysis of traffic distribution in two and three lane uni-directional freeway for capacity improvement. *Combined 18th ARRB Transport Research Conference and Transit New Zealand Land Transport Symposium*, Part 7, pp 423-436, 2-6 September 1996, Christchurch, New Zealand.

Okura, I. and Somasudaraswaran, K. (1996b). Lane distribution of uncongested traffic on multi-lane freeways and its application. *Third World Congress on ITS, Orlando, Intelligent transportation: realising the future*, ITS America, Washington DC.

Ozbay, K., Yasar, I. and Kachroo, P. (2004). Comprehensive Evaluation of Feedback-Based Freeway Ramp-Metering Strategy by Using Microscopic simulation, Taking Ramp Queues into Account. *Transportation Research Record*, No. 1867, Washington, DC. 2004, pp 89-96.

Ran-Bin, Leight-Shawn and Chang-Ben (1998). Microscopic Simulation Analysis for The AHS Merging Process. *The 77th annual meeting of the Transportation Research Board*, Washington, D.C. Jan. 11-15, 1998

TRL Ltd (2001). SISTM version 5.3: Introductory user guide, Unpublished Project Report PR/T/097/01, Crowthorne, Berkshire.

Van-den Hoogen, E. and Smulders, S. (1994). Control by variable speed signs: Results of the Dutch experiment. *7th International Conference on Road Traffic Monitoring and Control*, Road Traffic Monitoring and Control, pp. 145-149, IEE, London.

Wall G.T. (2004a). *The design and operation of motorway diverge areas*. Unpublished PhD Thesis 2004, University of Southampton, Southampton.

Wall, G.T. (2004b). The 'tiger-tailed' ghost island gets favourable reception. *Traffic Engineering and Control*, Volume 45, No. 9, October 2004.

Wall, G.T. and Hounsell N.B. (2004). A critical review of the standards and design processes for motorway diverges in the UK. *European Journal of Transportation Infrastructure Research*, Volume 4, No.2, December 2004.

Wedlock, M.S., Peirce, J.R. and Wall, G.T. (2001). A review of anti-swooping trials. TRL Published Report 491, *Transport Research Laboratory*, Crowthorne.

Wu, J., McDonald, M. and Chatterjee, K. (2003). Ramp Metering: How does it impact the Traffic on Motorway Intersections? *10th World Congress on Intelligent Transport Systems and Services*, Madrid, Spain, Nov., 2003.

Yousif, S.Y. and Hunt, J.G. (1995). Modelling lane utilisation on British dual-carriageway roads: effects on lane-changing. *Traffic Engineering and Control*, Volume 36, No. 12, December 1995, pp. 680-687, London.