Motorway design guide

Capacity and flow analysis
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1 Design guide information

1.1 Design guide purpose

The purpose of this design guide is to support Roads and Maritime Services (Roads and Maritime) *Smart Motorway Technical Direction*[^1] and the *Smart Motorway Guidelines*[^2].

1.2 Smart motorway document framework

This design guide is part of a suite of smart (managed) motorway documents that provide information relating to overall planning, project development, delivery and the on-going operation of smart motorways in New South Wales (NSW). This design guide is included in the group of documents highlighted in Table 1.

<table>
<thead>
<tr>
<th>Document</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical direction</td>
<td>Core overarching policy defining Roads and Maritime smart motorway implementation intentions.</td>
</tr>
<tr>
<td>Guidelines</td>
<td>A ‘scene setting’ document providing an overview of smart motorways, the elements and a guide for their application in NSW.</td>
</tr>
<tr>
<td>Design guides</td>
<td>A document set providing design requirement guidance for the provision, positioning and other traffic engineering considerations of smart motorway elements.</td>
</tr>
<tr>
<td>Specifications</td>
<td>Technical, construction, installation and quality specifications for smart motorway elements including the commissioning (transference to full operational mode) of smart motorway elements.</td>
</tr>
<tr>
<td>Operations</td>
<td>Operating policies and procedures, system and element administration and use documents</td>
</tr>
</tbody>
</table>

*Note:* The design guide group of documents also includes external primary reference documents with a Roads and Maritime supplement to define Roads and Maritime enhanced practice, complementary material or departures. This is an interim measure until a complete suite of design guides are available.

1.3 Design guide scope

This design guide provides guidance relating to traffic volume determination and capacity analysis for the NSW (smart) motorway network. It is applicable for use when assessing operation of the mainline, entry ramps, exit ramps and the arterial road interfaces.
This guide incorporates the latest traffic flow theory and research and builds on the experience of Roads and Maritime and other road agencies in (smart) motorway planning and design. This guide will:

- Highlight important traditional methods of motorway analysis
- Identify key tools that can help with capacity and flow analysis
- Provide guidance on current best practice, particularly where there are gaps or shortcomings in existing guidelines and where additional care should be taken.

This design guide is not a definitive guide on all aspects of motorway analysis and modelling, and should be used with the other reference materials listed in Section 6.2.
2 General

2.1 Introduction

A smart motorway uses various technologies to keep traffic moving for safer and more reliable journeys. This includes preventing and minimising congestion, providing traveller information and managing speed and lane use safely and efficiently, particularly during incidents.

To maximise resilience and flexibility of operations after construction for both new motorways in the network and upgraded motorways, project designs should be based on:

- Appropriate processes and information for determining design volumes
- Analysing capacity and traffic flow based on the motorway’s traffic mix, geometry and a desired concept for operation.

The use of appropriate values for capacity as well as the determination of design volumes and application of rigorous analysis processes is fundamental to understanding project needs and for maximising the likelihood of a completed project performing as desired.

The remainder of this section covers the key principles of (smart) motorway traffic design, as well as a background to both traditional and contemporary traffic flow theory.

2.2 Principles

Motorway traffic design requires the determination of sound forecast design volumes for all components of the project, including the mainline, entry ramps, exit ramps and interchanges. Appropriate analyses are also required to achieve the desired motorway and interchange operational performance.

As described in the *Operational Efficiency Audit Guidelines for Managed Freeways* [16], capacity optimisation and safety of a smart (managed) motorway are achieved primarily by managing traffic flows with coordinated ramp metering signals. This is achieved by controlling traffic demands at the entry ramps and managing traffic flows within the capacity of the mainline.

Therefore, the ultimate performance of a motorway can be related to the rigour involved in the processes for developing design volumes and carrying out the capacity analyses. Forecast traffic volumes are also important for determining whether various smart motorway control elements (eg coordinated ramp metering signals, variable speed limits, lane use management systems, etc) are warranted and should be included in a project’s scope.

The capacity and traffic flow analysis process is generally an iterative process where options are analysed in parallel with the functional design process and the need to investigate what is feasible within the physical constraints of the project. The processes may also need to be undertaken to suit initial as well as future project staging options.
In summary and as described in the *Operational Efficiency Audit Guidelines for Managed Freeways*[^16], the key principles for undertaking traffic flow analyses to ensure satisfactory motorway design and operation are:

- Understand the current and future performance of the network, particularly characteristics of critical bottlenecks and congested flows
- Determine sound design traffic flows for the peak periods using suitable methodologies
- Check the adequacy of the proposed roadway layout and operational environment to ensure that appropriate traffic management treatments are provided to suit the traffic needs
- Review the design (forecast) traffic flows to ensure they are within the mainline capacity of a (smart) motorway; ie undertake a flow/capacity analysis with adjustment factors appropriate to vehicle and mainline characteristics to provide an understanding of performance along the route.

Flow charts of the general sequences for traffic flow determination and capacity analysis processes are provided in Figure 1 and Figure 2. Further details relating to the determination of design volumes and mainline capacity analysis are in Sections 3 and 4, respectively. Guidance related to the capacity at interchange ramps (entry and exit) and ramp/arterial road intersections is in Section 5.
Figure 1: General sequence for traffic volume determination
Figure 2: General sequence for capacity analysis

Legend
- General sequence
- Sequence if applicable

Capacity Analysis of Mainline Segments and Interchanges (Sections 4 and 5)

Mainline layout and analyses (Section 4)
- Proposed geometry
  - Lane arrangements
  - Interchange spacing etc.
    (Sections 4.1 and 5.2)
- Determine operational capacity values for basic motorway segment
  - Unmanaged motorway, or
  - Managed motorway
    (Section 4.2)
- Route traffic flow/capacity analysis
  - Adjust segment capacities for physical characteristics
    (Sections 4.3 and 4.4)
- Analyse critical areas using HCM and/or microsimulation
  - Weaving areas
  - Diverge areas
    (Sections 4.5 and 4.6)
- Check performance outcomes
  - Flow/capacity ratios
  - Density
  - Levels of Service
    (Section 4.7)
- Reconsider project option layouts, if necessary
- Finalise mainline geometry and layout

Ramp layouts and analyses (Section 5)
- Proposed geometry
  - Lane arrangements
  - Ramp lengths etc.
    (Section 5.1)
- Entry ramp analyses
  - General lane arrangements
  - Number of lanes and storage
    (Section 5.3)
- Exit ramp analyses
  - General lane arrangements
  - Ramp length for storage
    (refer SIDRA INTERSECTION analysis)
    (Section 5.4)
- Check performance outcomes
  - Levels of Service
  - Degree of Saturation
  - Lane storages
    (Section 5.6)
- Reconsider project option layouts, if necessary
- Finalise ramp geometry and layout

Interchange intersection layouts and analyses (Section 5)
- Proposed traffic management
  - Form of intersection
  - Lane arrangements
  - Signal phasing etc.
    (Section 5.1)
- Ramp intersections analysis
  - Micro analysis e.g. SIDRA INTERSECTION
    (Section 5.5)
- Check performance outcomes
  - Degrees of Saturation
  - Turn lane storages
    (Section 5.8)
- Reconsider project option layouts, if necessary
- Finalise intersection layout and traffic management
2.3 **Staging of an ultimate project**

Where an ultimate layout is to be stage constructed, the analysis and design process should be carried out for each separate construction stage as well as the ultimate arrangement, to ensure that the operation will be satisfactory at all stages in the project life (refer to Section 4.8). This may require the development of interim design volumes for the initial stage layouts.

2.4 **Defining motorway objectives and performance**

2.4.1 **Objectives in project development**

When undertaking capacity analysis as part of project development, consideration needs to be given to the objectives of the project in relation to the desired motorway operation and performance after completion of the project, as well as at the design year for the project.

The project outcomes are generally directly related to the desired performance targets and these are related to project capacity and scope, particularly in the context of satisfying travel demand and forecast volumes.

Project objectives may vary significantly from project to project depending on the nature of the project, funding etc. For example, for a new motorway project, objectives may include satisfactory performance (Level of Service) with traffic forecasts at a specified future design year. For motorway upgrading projects (with or without widening), it may not be practicable to satisfy demand and objectives may be to improve throughput, reduce congestion and/or improve travel times. Further guidance on appropriate performance measures and outcomes for mainline and entry/exit ramp capacity analyses and design is provided in Sections 4.7 and 5.6.

2.4.2 **Satisfying demand and/or managing demand**

If possible, a motorway upgrading project should be designed to accommodate traffic demand (forecast traffic volumes) at the design year. It would also be necessary to manage the smart motorway with coordinated ramp signals to ensure optimum operation.

However, in busy cities where increasing the network capacity often lags behind traffic needs, or where there is insufficient funding or priority for required work, an upgrading project may not satisfy traffic demands or have difficulty accommodating demand at the date of, or soon after, completion of the project. In other situations, for example, where the motorway is fully developed within the available right-of-way and widening is not feasible as part of an upgrade, an upgrading project may not be able to accommodate traffic demand.

In these situations, there would still be significant benefits in providing an upgraded motorway with Intelligent Transport System treatments. However, it should be made clear during the project development process that the project scope is not expected to satisfy traffic demand. In these circumstances there should also be a clear operational strategy to ensure that after completing the project, demand is managed to match the capacity of the motorway.
As described in the *Operational Efficiency Audit Guidelines for Managed Freeways*\[^{16}\], the operational philosophy in these situations is to operate the coordinated ramp metering signals to manage traffic demand so that the flows on the entry ramps match the capacity of the mainline. With this form of operation the control of all entering flows is essential and ramp storages become a critical part of the ramp signal designs\[^{16}\].

Failure to manage demand will generally result in ongoing flow breakdown and congestion with adverse consequences, including reduced safety, increased travel times, and loss of throughput relative to what could be achieved with a well-managed motorway.

2.5 **Background: traditional traffic flow theory**

2.5.1 **General**

Motorway traffic flow is considered to be ‘uninterrupted flow’ where traffic is not interrupted or affected by external factors such as traffic signals or intersections. The quality of traffic flow is generally based on relationships governed by internal traffic interaction, where the three basic parameters used to describe traffic flow states are:

- Flow rate (traffic volume)
- Speed
- Density.

**Note:** Occupancy (proportion of time over which there is a vehicle present at a specified point) is proportional to density and is easier to measure and use in real-time systems.

The theoretical relationships between these parameters are often referred to as the fundamental relationships of uninterrupted traffic flow. The relationships are shown in the ‘fundamental diagrams’ presented in Figure 3.

Further description relating to the various traffic states are in the *Austroads Guide to Traffic Management (AGTM) Part 2: Traffic Theory*\[^{3}\] and the *Highway Capacity Manual 2010 (HCM)*\[^{4}\]. In summary, at point A in each diagram in Figure 3, the density and volume are low, ie there are very few vehicles on the road and there are insignificant interactions between vehicles in the traffic stream to prevent drivers from travelling at their desired speeds.

From A to B, traffic conditions can be described as ‘free flow’. As point C is approached, traffic conditions become unstable and fluctuations in both speed and density can occur. Point C is the maximum achievable volume and any further increases in density will decrease speed rapidly to such an extent that volume also decreases. Traffic is congested and operating in the ‘forced flow’ region from C to D.
The relationships shown above form the basis of traditional ‘two phase’ traffic flow theory, ie the traffic is stable and fluent, or it has broken down and becomes congested. The maximum flow is achieved when flow is stable just before flow breakdown occurs. Subsequent flow is then at a lower speed until flow recovers.

### 2.5.2 Theoretical capacity

The *HCM*[^4] has traditionally been the reference for theoretical motorway capacity values, ie maximum service flow rates. The *AGTM Part 3: Traffic Studies and Analysis*[^5] also provides information relating to capacity values.

The *HCM*[^4] defines vehicle capacity as ‘the maximum number of vehicles that can pass a given point during a specified period under prevailing roadway, traffic and control conditions. This assumes that there is no influence from downstream traffic operation, such as queues backing into the analysis point’.

The above references indicate that the traditional capacity value for ‘basic motorway segments’ on a 100 km/h motorway is 2300 pc/h/lane. Capacity would generally increase as free flow speed increases, and decrease for lower travel speeds. Historically, values in this order of magnitude have been used for lane capacity in design and strategic modelling. However, recent research and design practice (refer Sections 2.6 and 2.7) has shown that this is inappropriate because hourly flows at this level are rarely achieved in practice and when they do occur over short periods, cannot be sustained for a full hour.

Further guidance and discussion relating to operational capacity values to be used for analysis and design (for a basic motorway segment) are provided in Section 4.2.
Guidance on capacity adjustments for various road and traffic conditions are provided in Sections 4.3 and 4.4.

2.5.3 Levels of service

The HCM[^4] defines the quality of traffic flow within six Levels of Service (LOS). The LOS ranges are based on the density of traffic (pc/km/lane), which reflects the freedom for motorists to manoeuvre within the traffic stream. A summary of each LOS is provided in Table 1.

Table 2: Levels of service descriptions

<table>
<thead>
<tr>
<th>Level of Service</th>
<th>Maximum Density (pc/km/lane)</th>
<th>Description</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7</td>
<td>LOS A describes free-flow operations. Vehicles are almost completely unimpeded in their ability to manoeuvre within the traffic stream.</td>
<td><img src="https://via.placeholder.com/150" alt="Image" /></td>
</tr>
<tr>
<td>B</td>
<td>11</td>
<td>LOS B represents reasonably free flow conditions. The ability to manoeuvre within the traffic stream is only slightly restricted and the general level of physical and psychological comfort provided to drivers is still high.</td>
<td><img src="https://via.placeholder.com/150" alt="Image" /></td>
</tr>
<tr>
<td>C</td>
<td>16</td>
<td>LOS C provides for flow with speeds at or near the free flow speed. Freedom to manoeuvre within the traffic stream is noticeably restricted, and lane changes require more care and vigilance on the part of the driver.</td>
<td><img src="https://via.placeholder.com/150" alt="Image" /></td>
</tr>
<tr>
<td>D</td>
<td>22</td>
<td>LOS D is the level at which speeds begin to decline slightly with increasing flows and when density begins to increase more quickly. Freedom to manoeuvre within the traffic stream is more noticeably limited and the driver experiences reduced comfort levels.</td>
<td><img src="https://via.placeholder.com/150" alt="Image" /></td>
</tr>
<tr>
<td>Level of Service</td>
<td>Maximum Density (pc/km/lane)</td>
<td>Description</td>
<td>Image</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------</td>
<td>-------------</td>
<td>-------</td>
</tr>
<tr>
<td>E</td>
<td>28</td>
<td>LOS E describes operation at capacity. Operations at this level are volatile, because there are virtually no usable gaps in the traffic stream. Vehicles are closely spaced leaving little room to manoeuvre within the traffic stream. At capacity, the traffic stream has no ability to dissipate even the most minor disruption and any incident can be expected to produce a serious breakdown with extensive queuing.</td>
<td><img src="image1.jpg" alt="Image" /></td>
</tr>
<tr>
<td>F</td>
<td>&gt; 28</td>
<td>LOS F describes a breakdown in vehicular flow. These conditions generally exist at locations where flow breakdown occurs and within queues forming behind breakdown points. Breakdowns occur where the number of arriving vehicles is greater than the number of vehicles that can move through the area, i.e., traffic demand exceeds the motorway capacity.</td>
<td><img src="image2.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

Source: Summary based on HCM⁴ and AGTM Part 3⁵.

2.6 Background: contemporary traffic flow theory

2.6.1 General

Research over recent years has provided further insights and information relating to the operational capacity of motorways, the probability of flow breakdown, the mechanisms of flow breakdown and recovery, as well as the behaviour of shockwaves in congested conditions. Smart motorway technologies based on the application of contemporary traffic flow theory are enabling better motorway design and improved potential for enhanced operations and prevention of congestion.

2.6.2 Probability of flow breakdown

Researchers have shown that the capacity of a motorway is not so much deterministic, but rather stochastic in nature, i.e., a random probability distribution or pattern that may be analysed statistically but may not be predicted precisely. In the case of unmanaged motorways, flow breakdown probability can be related to traffic flow and this is shown in Figure 4 from research findings by Brilon, Geistefeldt and Regler⁶ based on the hourly equivalent of five minute flow data from German motorways.
Data analysis by Main Roads Western Australia\(^7\) has found similar relationships for unmanaged flow and a copy of the results is shown for comparison in Figure 5. The probability is likely to be higher than indicated if average flow values are considered over longer time periods, e.g., 15 minutes or one hour.

Flow breakdown may be triggered by various factors, including rapid increases in traffic density with high flow over a short time period, merging traffic at an entry ramp or lane drop, weaving and lane changing, as well as road characteristics causing a capacity drop such as steep grades and low radius curves.

*Figure 4: Probability of flow breakdown for unmanaged flow (three-lane German freeways)*

![Graph showing probability of flow breakdown for unmanaged flow](image)

*Note: Flow data based on hourly equivalent of five minute flow data.*

*Source: Brilon, Geistefeldt and Regler\(^6\)*

*Figure 5: Probability of flow breakdown for unmanaged flow (Mitchell Freeway southbound at Whitfords Avenue entry ramp, Perth, WA)*

![Graph showing probability of flow breakdown for Mitchell Freeway](image)

*Source: Main Roads Western Australia\(^7\).*
2.6.3 Operational capacity

Roess\(^8\) carried out research relating to the HCM\(^4\) speed-flow curves, where the investigation was based on a database consisting of 48 basic freeway sites over nine states in the USA. This research has provided significant information relating to actual operational motorway capacity flows. The chart most closely relating to a motorway free-flow speed of 100 km/h is the curve shown in Figure 6. The red line indicates the HCM\(^4\) capacity of 2300 pc/h/lane appropriate for a 60 mph (96.6 km/h) motorway. The traffic data points from the investigation plotted in blue indicate the maximum flow (capacity) attained for a relatively short period before flow breakdown was in the order of 2100 pc/h/lane, which is significantly less than the theoretical capacity. After flow breakdown, the flow dropped to as low as 1200 to 1800 pc/h/lane.

![Figure 6: Speed-flow curve data representing typical motorways at 60 mph (96.6 km/h)](image)

An objective of smart motorway traffic management with coordinated ramp metering signals is to prevent or minimise flow breakdown and keep the motorway operating to achieve optimum traffic flow and speed. This proactive management can improve reliability of traffic flow to minimise random flow breakdown. However, analysis of existing smart motorways demonstrates that the traditional capacity values will generally still not be achieved in practice.

When designing new motorway projects or when investigating the upgrading of existing motorways, operational capacity values should be used rather than theoretical values to gain a realistic understanding of how the project will perform after construction and to ensure adequate infrastructure is provided for the anticipated demands. Values to be used in strategic modelling and flow/capacity analyses are provided in Section 4, together with further guidance relating to adjustment of these values for traffic and roadway characteristics.

Further guidance relating to the application of contemporary traffic flow theory for analysis and design practice is provided in Sections 4 and 5.
2.7 Complementary material

Other complementary material relating to contemporary traffic flow theory and operational capacity values used for motorway design in other jurisdictions are provided in Table 2. The operational capacity values to be used for motorways in NSW are given in Section 4.4.2.

Table 3: Complementary material related to motorway capacity

<table>
<thead>
<tr>
<th>Subject</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational capacity values for freeway design (for basic freeway segments) are:</td>
<td></td>
</tr>
<tr>
<td>Unmanaged freeways: An unmanaged freeway may experience flows up to 1800 pc/h/lane (typically 1700 veh/h/lane), which accepts a low risk of flow breakdown.</td>
<td>VicRoads’ Managed Freeways: Freeway Ramp Signals Handbook[9] and Main Roads Western Australia’s Operational Efficiency Audit Guidelines for Managed Freeways[16].</td>
</tr>
<tr>
<td>Managed freeways: A well-designed and managed freeway can generally accommodate flows in the order of 2100 pc/h/lane (typically 2000 veh/h/lane) with a low risk of flow breakdown.</td>
<td></td>
</tr>
<tr>
<td>UK entry ramp merge design uses a maximum mainline flow of 1800 veh/h/lane.</td>
<td>UK Design Manual for Roads and Bridges[10].</td>
</tr>
<tr>
<td>Freeway capacity values for design (0 per cent heavy vehicles) are:</td>
<td></td>
</tr>
<tr>
<td>Two-lane carriageways: 4100 pc/h (2050 pc/h/lane).</td>
<td></td>
</tr>
<tr>
<td>Other values are provided for 10 per cent and 20 per cent heavy vehicles.</td>
<td></td>
</tr>
</tbody>
</table>
3 Traffic flow determination

3.1 Overview

Appropriate and realistic design traffic volume information for a (smart) motorway project is essential to ensure appropriate capacity is provided and to help in determining required roadway layouts, as well as the need for and design of, traffic management devices.

For some projects, the design flows may be based on existing traffic volumes with provision for appropriate growth and/or adjustment of demand based on existing problems and the scope of the upgrading. For other projects such as an upgraded route or particularly a new motorway link in the network, a strategic model would generally need to be used to determine forecast traffic volumes.

This section provides guidance on how to determine traffic volumes for assessing the warrants for provision of smart motorway elements, as well as for the design year of those elements selected for application, based on either existing traffic data or strategic modelling.

3.2 Warrants for providing smart motorway elements

Many of the warrants for providing appropriate geometry and various smart motorway elements are based on design traffic volumes for an appropriate forecast year determined for the project. The general warrants and relevant future design year are provided for geometric and foundations systems elements in the Smart Motorway Guidelines\(^2\), with further details provided in the relevant design guide or supplement for the smart motorway element.

The application of warrants for smart motorway elements relates to forecast volumes for a design year 10 years after opening.

3.3 Design volumes based on existing flows

3.3.1 Base data required

When a (smart) motorway project involves the upgrading of an existing route, existing vehicular flows for the mainline, entry ramps and exit ramps generally provides the base data. Data for the AM and PM peaks should be obtained for both directions of traffic flow. In some situations, the counter-peak direction may be a ‘worst case’ scenario at some interchanges, due to major employment centres or other traffic generators.

Other information to be considered to understand the needs of the existing route includes:

- Proportion of trucks in the mainline traffic stream or at specific ramps
- 24-hour data relating to the traffic profile throughout the day
- Public transport (bus) routes and the ramps utilised (entry and exit ramps), if applicable.
A safety analysis or crash investigation may also be considered as part of the project development process. This is a separate but complementary investigation and may also feed into considerations of the needs of the route and provision or layout design of devices.

3.3.2 Analyses of existing conditions

An analysis of existing flows and operation during the peak periods, including consideration of flow, speed and occupancy data, should be carried out to understand the current traffic demands as well as the problem areas at interchanges or along the motorway where recurrent congestion may be occurring (e.g., bottlenecks). When upgrading an existing motorway, the identification of problems with current operations is generally a good starting point in an investigation, before developing a scope of works. This can help to ensure that solutions target current problems as well as what may be considered necessary for the future.

Understanding existing flows (as well as forecast flows) can also be relevant when considering warrants for smart motorway elements, and can provide insights into future traffic patterns and the likely problem areas that should be considered during analysis and design.

Due to the consequences of flow breakdown, existing hourly flows through the peak period may not represent capacity flows. If flow breakdown does occur, subsequent flows can be significantly less than operational capacity, even though capacity flow may occur for a short time before flow breakdown.

Presentation of information and analyses that can be carried out to determine maximum flows and if flow breakdown is occurring, are described below.

A route and flow schematic can be effective in providing an overview of corridor performance. The example in Figure 7 is a combination of speed data (colour-coded) to show congestion as well as AM/PM peak flows and theoretical capacity to highlight potential bottlenecks.
Figure 7: Route schematic indicating flows and speeds
Analysis of the existing traffic profiles through the peak periods, particularly at critical bottlenecks where flow breakdown first occurs. This may involve the use of peak period data for an extended period, say 6–10am and 3–7pm. This is particularly important if there is significant peak spreading, i.e. the peak period is greater than one or two hours, and to determine the time of flow breakdown where demand exceeds capacity (refer to Figure 8).

Figure 8: Example of flow and speed profiles

![Flow and Speed Profiles](source: Roads and Maritime Investigation (M4, Site MS004005A 8 March 2010).)

Route analysis using a number of vehicle detector sites along a route to create a ‘heat map’. This is generally colour-coded to show areas of low speed or high occupancy (refer to Figure 9). For some investigations it may also be necessary to consider the impacts arising from intersecting sections of motorway. The presentation of data in this format can also help identify detector faults.

Figure 9: Example of heat map showing flow breakdown

![Heat Map](source: Roads and Maritime Investigation (M4, 3 March 2010).)

Development of peak period fundamental diagrams to indicate flow/occupancy and speed/flow relationships (refer to Figure 10).
Further investigation of the causes and effects of congestion can be made through on-site observations and use of CCTV.

### 3.3.3 Growth in existing traffic

The upgrading of an existing motorway would generally require estimation of forecast traffic volumes at the design year. A suitable percentage increase may be appropriate, or alternatively, highway assignment modelling (refer to Section 3.4) may be needed for major upgrades.
Traffic growth rate for an existing roadway has traditionally been based on an analysis of historic traffic surveys over a number of past years and then extrapolating the growth trend to a future year. This type of analysis may lead to inappropriate assumptions for future forecasting, particularly if growth rates have flattened out due to a suppressed demand resulting from inadequate roadway capacity and congested motorway operation (as described in Section 3.3.4 below).

### 3.3.4 Suppressed (unmet) demand

Existing hourly flows may not always reflect peak demand traffic flows. Where there is suppressed or unmet demand this can generally be identified in the following circumstances:

- Inadequate mainline capacity leading to recurrent flow breakdown and congestion
- Long delays for motorists gaining access to the motorway
- Road users avoiding the motorway and taking alternative routes.

Suppressed or unmet demand should be factored into projected design volumes for an upgraded facility where the practical network capacity constrains actual growth along a route, or in some situations, across a travel corridor as road users make significant changes to travel routes across the network. Traffic demand may increase significantly to make use of additional capacity in an upgraded motorway, as road users move to the motorway from other routes. An improved indication of traffic demand may need to be determined by using highway assignment traffic modelling (refer to Section 3.4).

### 3.4 Design volumes based on modelling

#### 3.4.1 Background

Information in this section is provided to enable a project designer to understand different types of modelling and apply appropriate modelling assessments in the context of project development. It also provides the designer with information relating to good practices, some of the shortcomings of modelling and areas where care may need to be taken in project design.

This section is not intended to be a guide relating to the modelling process or methodology, but is provided so that designers are aware of some specific matters affecting outcomes when discussing the needs and process with modellers. Reference should also be made to the *Traffic Modelling Guidelines*.¹²

Models used in transport and traffic engineering consist of a series of relationships between parameters which can simulate travel demand, mode choice, route selection, or traffic interaction and performance. The following types of models (as summarised from the *Traffic Modelling Guidelines*) are generally available and each has its specific use.

**Strategic models**: These macroanalytical models are high-level models used primarily for estimating the effects on the transport network of major infrastructure changes, various population/employment growth distribution scenarios, and evaluation of travel demand management options such as the introduction of alternative public transport, parking and pricing policies.
Demand models: These macroanalytical models are used in high-level urban transportation planning and can assist in the process of evaluating decisions on transportation policies and infrastructure programs. In the transport planning process, planners develop information about the impacts of the provision of alternative transportation facilities, such as new highways, changes in public transport or parking restrictions, etc.

Highway assignment models: These macroanalytical and mesoscopic models provide a level of detail greater than strategic or demand models. These traffic assignment models are generally used in motorway project development for the estimation of future year forecast traffic design volumes based on projected travel demands and project scenarios or options being investigated. Typical highway assignment modelling software packages are Aimsun (mesoscopic) and VISUM (macroanalytical). Further guidance for the use of these models in project development is provided in Section 3.4.2.

Overview information relating to the use of microsimulation and microanalytical models and software is provided in Sections 4.6 and 5.5, respectively.

3.4.2 Use of highway assignment models for motorway design

Highway assignment model assessments have close links to strategic model assessments and may be used for a base case situation (existing conditions), future base case (includes increasing traffic demand) as well as various project options with different scopes of work.

Peak period models are appropriate for peak period forecast design flows. Models that provide 24-hour volumes are appropriate for economic appraisal of projects.

The major assumptions in a model relate to population and employment patterns, future land use, mode choice, travel behaviour, and characteristics of the transport infrastructure. Therefore, the traffic estimates will change with any changes to the underlying assumptions.

A motorway project, either for upgrading or for a new motorway, would generally have strategic implications for traffic flow well beyond the immediate vicinity of the works. Therefore, the geographic extent covered by the model in the broader study area needs to be sufficient to include existing causes of congestion (motorway and arterial network) so that all potential issues and implications are considered. Local knowledge of the network is necessary to identify the extent of the likely impacts and potential changes to travel patterns.

The benefits of the model outputs are in determining trends and traffic volume changes resulting from possible changes to the arterial road network and land use scenarios. However, care should be taken with the modelling process and outputs, with attention given to how much emphasis and reliance is put on absolute traffic numbers for individual road sections or links.

Traffic estimates produced by the model can be useful to assess the magnitude of future traffic flows but should be correctly interpreted (as outlined in Section 3.4.5). Traffic estimates are to be checked, and in some cases adjusted, before they can be used in project design. The local road network may not be accurately represented in strategic models, so care needs to be taken with estimates relating to local roads.
Typical information that can be produced by highway assignment models for project planning and design purposes includes:

- Traffic volume plots that show estimated daily traffic volumes on the modelled road network. The volumes on each road link may be for each direction, or combined as a two-way volume. Plotted traffic volumes may be scaled down to simplify the output, so it may be necessary to factor up the figures (multiply by 100) to produce daily traffic volumes.

- Intersection turning volumes for road intersections contained in the modelled network.

- Volume difference plots that show the differences in estimated daily traffic volumes between two modelled scenarios with different road networks.

- Volume/capacity plots that show the estimated volume divided by the capacity for each link in the modelled road network.

- Select link plots that show the estimated daily traffic on a selected (nominated) network roadway (link) and the links used by traffic travelling along that link.

- Project benefits, ie the project case compared with the future base case, which are estimated from savings in vehicle operating costs, commercial time, and crashes. Benefits can be discounted over a period of time (typically 30 years for road projects) from the expected date of opening. A typical use of project benefits is for project evaluation to determine a benefit-cost ratio.

### 3.4.3 Calibration of base case (existing) model

An essential component of developing a model is providing appropriate characteristics for each link (eg number of lanes, speed limit, etc), as well as an appropriate value for lane capacity, which in the case of motorways varies according to the extent of mainline control (refer to Section 4.2).

The calibration of a strategic model applies to the existing network before improvement scenarios are introduced. Before running project scope options in the model, it should be calibrated at the existing/base case level to ensure that capacities, traffic volumes and travel patterns are realistic within the model and to provide a level of confidence that it forms a good basis for modelling future scenarios. Comparison of existing and modelled volumes to help in the calibration process should be based on a number of checks, including:

- Volumes across a screen line (eg across a river bridge to check total traffic entering an area).

- Individual volumes using the motorway.

- Individual ramp volumes.

- Arterial road traffic routes in the network, particularly arterials generally parallel to the motorway.

Where differences between existing and forecast volumes cannot be rectified by recalibration, an adjustment process for forecast volumes should be carried out. This may apply to daily and peak hour volume estimates.
### 3.4.4 Modelling options and scenarios

When modelling future scenarios and project options, it can be useful to start with running the model based on unconstrained capacity or on capacity values somewhat greater than the expected final outcome (mainline or interchanges). This can help in ensuring that actual traffic demands and forecasts are known, and that demands are not limited by scope constraints which may need to be investigated. When running an unconstrained model care needs to be taken to ensure traffic is not detouring to use the motorway unnecessarily (unrealistic route choices), as this can lead to volumes which are overestimated or excessive. After initial ‘unconstrained’ modelling, adjustments can be made for other scenarios, such as:

- Predefined limitations on project scope that may result in potential bottlenecks or capacity deficiencies (eg lower capacity at a bridge where widening is not feasible)
- Options for the motorway layout including widening, removal of bottlenecks, upgrading of interchanges, etc
- Options for implementation of smart motorway control elements (eg coordinated ramp metering signals, lane use management systems, variable speed limits, motorway shoulder use, etc).

Modelling of project layout options (ie lane arrangements) with unmanaged operation compared with managed operation (ie using coordinated ramp metering signals, etc), should utilise appropriate motorway lane capacities (refer to Section 4). Modelling of a future base case option would include provision for traffic growth but retain existing infrastructure capacity.

### 3.4.5 Traffic volume forecasts

Modelling outputs from a well-calibrated model can provide a good source of forecast traffic volume information for input into project design. Traffic forecasts can be variable, so modelling outputs should be checked to ensure outputs are realistic and where a motorway is being upgraded, comparison relative to existing peak hour travel patterns may be necessary.

Forecast flows should also be realistic relative to link capacities, with checks required on flow/capacity ratios and assigned speeds. Highway assignment models can provide flow outputs in excess of capacity or can indicate low operating speeds. This may be due to the volume/capacity curves in the model and would generally indicate that there is demand greater than capacity. The use of modelling forecasts can also be beneficial in determining traffic demand for an existing facility when suppressed demand is a concern (refer to Section 3.3.4).

Highway assignment models are generally able to provide outputs as daily volumes or peak period volumes for the modelling scenarios. Two-hour peak volume outputs are generally used for project design (converted to peak hour flows). Daily volumes are more appropriate for economic evaluation used in a business case, as benefits can be determined for the full day’s operation. Further detail is provided on how to approach peak hour conversions in Sections 3.4.5.1 and 3.4.5.2.
3.4.5.1 Peak period/peak hour conversion

Where peak two-hour or possibly three-hour volumes are provided by a highway assignment model, these values should be converted to peak hour volumes for capacity analysis and design. A factor of 50 to 55 per cent may be appropriate for converting the two-hour volume to a peak hour or a factor based on surveys of existing traffic patterns for the area appropriate to the length of the peak period used in the model.

3.4.5.2 Peak hour/24-hour conversion

Where a strategic model output provides forecast daily project volumes, these should be converted to peak hour design flows for the purposes of traffic design. A peak/24-hour ratio generally used for determining peak hour traffic flows is typically 10 per cent of the 24 hour flow. This provides an estimated maximum hourly flow, which is generally the desirable value for meeting peak hour demand.

Where lower percentage values are observed in real data (eg eight per cent of the 24-hour flow), it may not mean that the peak demand is any less or that the peak is less congested. Lower percentages generally indicate that demand continues for periods greater than a peak hour due to peak spreading, or that peak flows are less than capacity due to flow breakdown and congestion. A desirable peak/24-hour proportion of 10 per cent (minimum 9 per cent) should generally be used for design purposes to ensure designs have adequate capacity. A concern in adopting a figure lower than these values is that projects will be designed for lower peak demands than will occur in practice and that inadequate infrastructure could result.

3.5 Use of model traffic volume forecasts for design

Highway assignment modelling outputs for project options relate to general flows to/from or on the motorway and are only intended to be to a reasonable order of magnitude. As the flow on a specific ramp may not be realistic, designs may need to be flexible to allow for potential variations in flow, eg on a particular ramp or between adjacent entry ramps.

In situations where an existing motorway is being upgraded, the modelling forecasts should be checked against existing ramp flows and may need to be adjusted according to current travel patterns to establish appropriate traffic flows for design, ie not less than existing flows.

In new motorway situations, the modelling forecasts may need to be considered indicative and used for relative comparison, with suitable flexibility built into the ramp designs. Detailed analysis should apply a sensitivity test to assess design implications.

Forecast design volumes from either manual methods or modelling of project options may need to be refined through an iterative process until appropriate values are determined for analysis.
3.6 Complementary material

Further detail on Roads and Maritime modelling practice can be found in the *Traffic Modelling Guidelines*[^12]. These are available to develop consistency in traffic modelling practice and promote high quality model outputs that will lead to high quality project design.
4 Mainline capacity analysis

4.1 Overview

Capacity analysis is an assessment of existing or proposed infrastructure to determine its adequacy to accommodate existing or forecast design traffic flows. This section includes the operational capacity values to be used in analysis and design, factors affecting capacity that may need to be considered during project development, as well as guidance related to analysis and design processes and methodologies.

An initial proposed layout for a motorway project is generally adopted to address identified problems and/or project objectives. This is then adjusted and refined based on the design volumes and analyses undertaken.

4.2 Mainline operational capacity values for basic motorway segments

4.2.1 Context

The Highway Capacity Manual\(^4\) defines motorway facility capacity as ‘the capacity of the critical segment among those segments composing the defined facility. This capacity must, for analysis purposes, be compared with the demand flow rate on the critical segment’.

The ‘critical segment’ is defined as ‘the segment that will break down first, given that all traffic, roadway and control conditions do not change, including the spatial distribution of demands on each component segment’.

The operational capacity of a motorway for analysis and design is often found to be significantly less than ‘traditional’, theoretical values cited in the HCM\(^4\) due to the stochastic nature of capacity (refer to Section 2.6.2) and the various traffic and roadway conditions that create turbulence and capacity drop (refer to Section 4.3).

4.2.2 Operational capacity for modelling, analysis and design

The motorway mainline capacity values for modelling and flow/capacity design based on operations at 100 km/h and for an ‘ideal’ basic motorway segment, are shown in Table 3. The definition of a basic motorway segment is provided in Section 4.2.3.

The smart motorway capacity value should only be used where full control of the mainline is achieved by controlling all upstream entry ramps with coordinated ramp signals, including motorway-to-motorway ramps. In all other cases, the unmanaged capacity should be adopted for analysis.

Although higher values may be achieved in practice at some locations (eg where a maximum flow is achieved), this is generally of relatively short duration prior to flow breakdown. The capacity values in this section are therefore realistic upper limits for an ‘ideal’ basic motorway segment for the peak hour design. These capacity values are consistent with the economic drivers for keeping motorway traffic moving, as well as road user values of travel reliability.
The capacity values in Table 3 should be adjusted for site-specific traffic and road characteristics which will impact motorway capacity, as described in Sections 4.3 and 4.4.

### Table 4: Operational capacities for basic motorway segments

<table>
<thead>
<tr>
<th>Motorway Control</th>
<th>Capacity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart motorways</td>
<td>2100 pc/h/lane (typically 1910 veh/h/lane)*</td>
<td>Motorway has all entries controlled with coordinated ramp metering signals and well-designed infrastructure.</td>
</tr>
<tr>
<td>Unmanaged motorways</td>
<td>1800 pc/h/lane (typically 1640 veh/h/lane)*</td>
<td>All or some motorway entries are not controlled. Value accepts around 10 per cent risk of flow breakdown.</td>
</tr>
</tbody>
</table>

* Based on 10 per cent trucks, with trucks equivalent to two passenger cars (grade up to three per cent).

Further guidance relating to capacity values for entry ramp merges and exit ramp diverges is provided in Sections 5.3 and 5.4, respectively.

#### 4.2.3 Basic motorway segments

The capacity values in the *HCM*[4] and the Austroads Guide to Traffic Management Part 3[5] are based on ideal ‘basic motorway segments’ at specific free flow traffic speeds.

The capacity values provided in Section 4.2.2 are based on similar assumptions and assume the following typical characteristics for a basic motorway segment:

**Physical characteristics of the motorway**
- Multilane divided road, essentially straight with full access control
- Interchange spacing at three kilometres or greater
- Level terrain, with grades no greater than two per cent
- Minimum lane widths of 3.6 m
- Minimum left shoulder lateral clearance of 1.8 m between the edge of the travel lane and the nearest obstruction that influences traffic behaviour
- Minimum median lateral clearance of 0.6 m.

**Traffic and driver characteristics**
- Traffic stream composed entirely of passenger cars
- A driver population composed principally of regular users of the facility
- No traffic influence from opposing flows.
Basic motorway segments are rarely bottlenecks, although flow breakdown may occur due to the stochastic nature of capacity (refer Section 2.6.2). Flow breakdown generally occurs at locations where traffic or geometric factors cause a capacity drop, eg areas with merging, weaving, lane drop, upgrade or tight radius curve, etc. These factors are explored further in Section 4.3.

4.3 Factors affecting mainline capacity

For analysis of ‘real-life’ motorways, the effects of traffic and motorway characteristics are considered by a number of adjustment factors relating to vehicle mix, speed and roadway characteristics.

Section 4.3.1 provides guidance on how to adjust capacity values for the route to account for the proportion and type of heavy vehicles and considering the grade and length of grades, using passenger car equivalents. This allows direct comparison of design flows with capacity in passenger cars (pc/h/ lane).

Section 4.3.2 then provides further detail on the identification of locations along a motorway segment where there may be a ‘capacity drop’ and where adjustments to the capacity values from Section 4.2.2 (which apply to a basic motorway segment) may be required. Further detail on the capacity analysis process and guidance on appropriate adjustment values is provided in Section 4.4.

4.3.1 Passenger car equivalents for heavy vehicles

Traffic flows (veh/h) for design and analysis should generally be converted to equivalent passenger cars (pc/h) to allow for the effect of trucks and other commercial vehicles in the traffic stream. The conversion of traffic volumes to passenger car equivalents then provides units consistent with the capacity values which are expressed in pc/h.

Heavy vehicles are defined in the HCM [4] as vehicles with more than four wheels on the ground during normal operation and includes buses. An adjustment factor for heavy vehicles on motorways is that a truck is typically equivalent to two passenger cars for upgrades up to three per cent. Other adjustment factors based on the type of terrain and length of an upgrade are provided in the HCM [4] (Chapter 11).

4.3.2 Identifying capacity drop and bottleneck locations

In reviewing the design (forecast) traffic flows and capacity, there is a need to consider areas of turbulence and to identify critical bottleneck locations and design features where a lower mainline capacity value may be applicable.

Areas where a mainline capacity drop is likely to occur along a motorway and where adjustments may need to be made are:

- At uncontrolled entry ramp merge areas. Mainline capacity values equivalent to unmanaged operations would generally be applicable
- At geometric features:
  - Lane drops
  - Narrow lanes
  - Tight curves
− Steep upgrades
− Transitions in vertical geometry; for example, a long downhill section (particularly in a tunnel) where drivers do not adjust their speed (due to the lack of cues) to account for a flatter grade or start of a sag vertical curve
− Lateral clearance or other tunnel effects; for example, walls/barrier adjacent to running lanes or a change in width of the emergency stopping lane
− The combination or close arrangement of geometric features may also affect capacity; ie one feature on its own may not result in significant impact but multiple features may. For example, a change in the median from wide to constrained close to a tight horizontal curve.

- At areas with high weaving movements or significant lane changing, including closely spaced interchanges/ramps or areas before a lane gain
- Where there is the potential for overspilling of exit ramp queues into the mainline from short ramps or exits with inadequate interchange intersection capacity. If this is expected to be a common occurrence, it would result in the left lane capacity needing to be ignored in the capacity analysis for carrying mainline through traffic
- At sections within tunnels
- Where there is an absence of emergency stopping lanes/shoulders
- At sections where there is a lower default speed limit (e.g. 80 km/h in relation to narrow lanes/narrow lateral clearances), either on a permanent basis or as part of a part-time operational regime.

The emergence of new bottlenecks further downstream after project changes occur may also need to be considered on adjacent sections of the motorway, or in some cases, on intersecting motorways.

4.4 Route traffic flow/capacity analysis

4.4.1 Balancing flow and capacity

An analysis to balance flow and capacity along the mainline can ensure that capacity is provided where necessary and confirm that excessive capacity is not provided where it is not needed. Design flows also should be reviewed, ie flow/capacity ratios relative to the number of lanes available, to ensure they are within the mainline capacity of the motorway. The key principle of balanced capacity along the motorway system is designing the whole route to match the capacity of all critical bottlenecks along the route. This ensures that the mainline has adequate capacity so that flows can be managed.

A network view is also required as improvements on one section of motorway may lead to problems downstream, ie a downstream bottleneck with low capacity may become critical in the overall network. This may then require consideration of a broader route solution (or another project), compared to what might be in the current project scope. The analysis of downstream impacts to accommodate increased flows should consider the performance of exit ramps and interchanges (refer to Section 5).
Route flow/capacity analysis should be carried out to ensure balanced operation along the route, to confirm that flows are within the capacity being provided (ie, confirm appropriate flow/capacity ratios), and to identify bottleneck areas.

As stated by Main Roads Western Australia[16], ‘generally, the locations with the highest flow/capacity ratios are the areas that become the critical bottlenecks’. The worst case is generally in the direction of the peak traffic but may also apply in the counter-peak direction in some situations, particularly on circumferential routes where flows may be similar in each direction. Therefore, analyses should consider both the AM and PM peak flows in each direction.

For each mainline segment, the flow/capacity ratio should be considered to ensure that the mainline has adequate capacity, ie flow/capacity ratio ≤ 100 per cent. Examples of two analyses comparing flow and capacity for existing unmanaged operation and projected managed operation along a motorway route are in Figure 11 and Figure 12 on p31. For most route analyses consideration of road characteristics also needs to be factored in to the capacity value for each segment as outlined in Section 4.4.2. Performance outcomes to be met for analyses are provided in Section 4.7.

The design process of identifying bottlenecks and balancing the number of lanes relative to design flows along the route is intended to ensure the mainline has adequate capacity to cater for the forecast flows. This assessment can be used to check if the number of lanes is appropriate, as well as identify the proposed locations for added lanes and/or lane reductions along the motorway.

When aiming to balance the number of lanes relative to design flows, consideration should also be given to the basic number of lanes (refer to AGTM Part 6)[13] to maintain lane continuity and to minimise frequent changes in cross-section. In this context, consideration of safer and more productive flow outcomes may need to take priority over the basic number of lanes concept in some instances. Where changes to lane configuration are needed for improved traffic flow outcomes (eg for an exclusive exit lane or a lane gain), appropriate signing and pavement markings should be provided in the detailed design to manage driver expectations and ensure safe and efficient operation.
### Figure 11: Example of system flow and capacity analysis for an unmanaged motorway

**M4 Western Motorway - Existing Flows and 10% HV**

<table>
<thead>
<tr>
<th>Analysis year:</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy vehicles:</td>
<td>10%</td>
</tr>
</tbody>
</table>

| Lane capacity (Unmanaged): | 1,800 pc/h/lane |
| Flow / Capacity ratio (%): AM Peak | 134% |
| Mainline capacity (pc/h) | 5,400 |
| Capacity drop (%) | 0% |
| No. Mainline lanes | 3 |
| AM | 7,260 |
| Westbound | 1,720 |
| Silverwater Rd | 5,540 |
| Hill Rd | 6,800 |
| Homebush Bay Dr | 3,170 |
| Parramatta Rd | 820 |

**Note:** Capacity reduced at the exit 10%.

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### Figure 12: Example of system flow and capacity analysis for a smart motorway

**M4 Western Motorway - Existing Flows and 10% HV**

<table>
<thead>
<tr>
<th>Analysis year:</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy vehicles:</td>
<td>10%</td>
</tr>
</tbody>
</table>

| Lane capacity (Managed): | 2,100 pc/h/lane |
| Flow / Capacity ratio (%): AM Peak | 115% |
| Mainline capacity (pc/h) | 5,400 |
| Capacity drop (%) | 0% |
| No. Mainline lanes | 3 |
| AM | 7,260 |
| Eastbound | 1,720 |
| Silverwater Rd | 5,540 |
| Hill Rd | 6,800 |
| Homebush Bay Dr | 3,170 |
| Parramatta Rd | 820 |

**Note:** Capacity reduced at the exit 10%.

---
4.4.2 Mainline capacity adjustments

Adjustments to capacity may need to be considered in a route traffic flow/capacity and lane balancing analysis to address matters associated with capacity drop. The following general ‘rules-of-thumb’ can be used to help in design and/or assessment of relevant capacity factors, and in a number of cases are referenced from guidance provided in Main Roads Western Australia design guidelines\[16\].

In some cases further research needs to be carried out to determine more precise guidance relating to these factors. Therefore, the analyst/designer will need to exercise judgement according to the situation and may need to carry out sensitivity analyses to determine the significance of the various capacity adjustments.

4.4.2.1 Horizontal alignment

As described in the Operational Efficiency Audit Guidelines for Managed Freeways\[16\], the horizontal alignment of the main carriageway can impact capacity when minimum standard curve radii and sight distances contribute to traffic turbulence and do not allow comfortable operation at 100 km/h. For example, curves in the order of 600 m radius (which meet a design speed of 110 km/h) have been known to contribute to slowing traffic and flow breakdown in a 100 km/h speed environment, particularly when associated with an upgrade and/or minimal sight distance.

Where operational speeds may be affected by alignments that restrict a comfortable free flow speed of 100 km/h, the capacity is likely to be reduced. Typically, a capacity reduction in the order of five per cent (say 100 pc/h/lane), or up to 10 per cent if combined with other factors, could be considered.

4.4.2.2 Vertical alignment

As described in the Operational Efficiency Audit Guidelines for Managed Freeways\[16\], the vertical alignment of the main carriageway can impact capacity when a long, steep grade does not allow comfortable operation at 100 km/h. For example, long motorway grades in the order of 2.5 per cent have been known to contribute to slowing traffic and flow breakdown in a 100 km/h speed environment, particularly when associated with a high proportion of trucks, a curve, or lane changing.

Trucks are particularly impacted by long, steep grades, as the Truck/Passenger Car Equivalent (PCE) value generally increases as the length of the grade increases (grades more than two per cent), and this impacts capacity relative to the overall traffic stream\[16\].

The vertical geometry in tunnels can also be challenging for motorists, with significant impact on capacity. Tunnels usually have lower speed limits and generally have relatively steep grades where the location of the sag vertical curve and start of the upgrade are difficult to identify. Appropriate adjustment factors are also required in this operating environment. Further information on research on the impacts of sag vertical curves on driver behaviour is provided in the Smart Motorway Design Guide for Tunnel Traffic Management\[14\].
If the PCE adjustment for the analysis is based on a general equivalent factor for the route rather than at a particular isolated steep or long grade, then a capacity reduction at a particular location can be considered in the route analysis, say in the order of five per cent (say 100 pc/h/lane), for two or three per cent grades longer than 1000 m and for steeper, shorter grades, subject to the percentage of trucks in the traffic stream. A capacity reduction up to 10 per cent or more may need to be considered for steeper/longer grades or when grades are combined with other factors.

4.4.2.3 Weaving and lane changing areas

Lane changing has a significant impact on traffic flow and capacity. Weaving and lane changing areas include sections between entry and exit ramps (with or without an auxiliary lane), as well as areas upstream of a lane gain where road users are positioning themselves to enter the additional lane (refer to Section 4.4.2.5). The example shown Figure 13 results in 300 lane changes per hour prior to the lane gain and 1000 lane changes per hour in the ‘weaving’ area. Subject to the entry and exit flows involved the lane changing manoeuvres can be significantly more in some instances.

Figure 13: Example of lane changing movements

Note: 300 lane changes/h upstream of lane gain; 1000 lane changes/h between exit and entry ramps.

The spacing between entry and exit ramps should be considered as high flows generally result in capacity drop due to weaving and lane changing manoeuvres. The provision of two-lane entry or exit lanes at an interchange can also increase the number of lane changes and is likely to affect capacity. Further guidance on ramp spacing is in Section 5.2.

The HCM[4] provides guidance for calculations of capacity in weaving areas, however researchers have raised concerns that the methods tend to overestimate capacity (refer to complimentary material in Section 4.9).

The definition of weaving in the HCM[4] involves lane changes to/from an auxiliary lane between an entry ramp and the downstream exit ramp. Where there is no auxiliary lane, the HCM[4] analyses only consider turbulence in the adjacent ramp influence areas. The HCM[4] weaving analysis considers the total number of weaving vehicles but does not consider the origin-destination pattern for the ‘weaving’ vehicles.
Concerns are such that further research and refinement of procedures relating to capacity analysis in areas of high weaving and lane changing is needed, particularly when design traffic flows are close to capacity. Some research has suggested that the capacity could be reduced by a value equivalent to the number of lane changing movements expected, e.g., for the example in Figure 13, the roadway capacity of the ‘weaving’ area would be reduced by 1000 pc/h. In Germany, the capacity of a weave area is considered to be similar to an unmanaged entry ramp flow entering the mainline.

Until further research and improved procedures are available, when carrying out weaving analyses involving high lane changing or merging/diverging flows with minimal separation between ramps, consideration should be given to a conservative approach by adopting the lowest value for capacity that would result from:

- A capacity reduction in the order of 10 per cent
- A capacity value equivalent to a basic segment of an unmanaged motorway (refer to Section 4.2.2)
- A reduction equivalent to the number of lane changing movements expected.

As described in the Operational Efficiency Audit Guidelines for Managed Freeways[16], in critical areas where weaving or high lane changing manoeuvres could create excessive turbulence and capacity drop, or where inadequate distance is available for manoeuvres to occur, consideration may need to be given to providing an alternative layout, including:

- Changes to proposed entry or exit locations
- An auxiliary lane to improve overall capacity in the lane changing area and to reduce traffic density
- A separate collector-distributor road or braided ramps to accommodate weaving clear of the main carriageway.

4.4.2.4 Lane reductions

Lane reductions have an impact on capacity and should have appropriate analysis and design to minimise turbulence and capacity drop. The mainline capacity in the merge area of a lane drop between interchanges would generally be in the order of 1500 to 1600 veh/h/lane. Therefore, midblock lane drops should generally be avoided.

As described in the Operational Efficiency Audit Guidelines for Managed Freeways[16], a 'conventional' lane drop after an exit (as shown in Figure 14) may also reduce capacity by up to 10 per cent relative to the capacity of the downstream cross-section (unmanaged or managed capacity). The bunching and merging of traffic from the terminating lane is similar to an uncontrolled entry ramp merge. This may become a critical bottleneck area along the route, which could affect motorway capacity. As an example, the route analyses in Figure 11 and Figure 12 include a situation where capacity is reduced at a point on the mainline where there is a lane drop.

To avoid capacity drop and operational efficiency problems in the vicinity of lane reductions, consideration during the analysis and project development process may need to be given to:
• Providing an exclusive exit lane (as shown in Figure 15) to enable dispersed lane changing manoeuvres over a longer distance where there is greater capacity to accommodate the manoeuvres. This layout is consistent with lane balance design principles, and when needed, it can minimise turbulence at a localised point. An exclusive exit lane may need to be considered where the forecast design flows are greater than 90 per cent of the downstream capacity. Lane changing/weaving volumes and the distance relative to the upstream entry ramp should also be taken into account when an exclusive exit lane layout is being considered, as well as appropriate signing and pavement markings to clearly inform road users of the lane status situation.

• Continuing the wider cross-section and number of lanes through the interchange to a location where a conventional lane drop can be provided, ie where lower volumes would not impact capacity[16].

Figure 14: Example of conventional lane drop with sudden merging

Figure 15: Example of exclusive exit lane with dispersed lane changing

Source: Operational Efficiency Audit Guidelines for Managed Freeways[16].

4.4.2.5 Lane gains

As described in the Operational Efficiency Audit Guidelines for Managed Freeways[16], lane gains generally begin at an entry ramp with high entry flows. Lane gains should be considered where entry ramp flows are in the order of 1500 pc/h or more (unless the mainline is significantly underutilised), as high merging flows can create greater potential for turbulence. The provision of a high volume entry ramp joining a motorway as an added lane generally has the following advantages:

• Improved opportunities and greater mainline capacity for downstream weaving manoeuvres between interchanges

• Safer and more efficient operation as an added lane rather than as a merge.

Midblock lane gains may be used when creating an auxiliary lane before areas of high weaving, such as for closely spaced interchanges. Turbulence can occur in the area immediately upstream of an additional lane as drivers change lanes and position themselves to take advantage of the new lane. These areas can experience a capacity drop due to the higher than normal lane changing manoeuvres. If a capacity drop due to turbulence is likely to impact traffic flow, ie the forecast design flow is close to capacity, subject to other design considerations, it may be preferable to begin the lane gain at an entry ramp.
4.4.2.6 Narrow lane widths

As described in the *Operational Efficiency Audit Guidelines for Managed Freeways*[^16], narrow lane widths can affect the free flow speed of vehicles and hence operational capacity. This may need to be considered where a carriageway arrangement is to be modified to accommodate additional lanes without widening, such as when an existing cross-section with an emergency stopping lane is reconfigured to provide all-lane running. The *HCM*[^4] provides guidance on adjusting free flow speed for narrow lane widths and these have been used as the basis for typical adjustment factors, as provided in Table 4.

<table>
<thead>
<tr>
<th>Average Lane Width (m)</th>
<th>Reduction in Free Flow Speed (km/h)</th>
<th>Reduction in Capacity*</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 3.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>≥ 3.35 – 3.5</td>
<td>3.1</td>
<td>65 (pc/h) 3.1 (%)</td>
</tr>
<tr>
<td>≥ 3.1 – 3.35</td>
<td>10.6</td>
<td>223 (pc/h) 10.6 (%)</td>
</tr>
</tbody>
</table>

* Based on HCM free flow speed reductions (speed: 100 km/h, flow: 2100 pc/h and density: 21.0 pc/km/lane)

4.4.2.7 Reduced lateral clearance

A lateral clearance on the left side of the carriageway of less than 1.8 metres between the edge of the travel lane and the nearest obstruction can influence traffic behaviour. Longitudinal motorway obstructions would generally include concrete barriers, guard rail or a wall.

In most situations, urban motorways with low lateral clearance operate with a default speed limit lower than 100 km/h (typically 80 km/h). As motorists generally become accustomed to these obstructions, there is usually minimal impact on capacity. However, the *HCM*[^4] provides guidance on speed adjustments if the designer considers there is a need to adjust for lateral clearance.

4.4.2.8 Lower default operating speeds

For projects where the operational speed may be affected by an alignment or cross-section that restricts a comfortable free flow speed of 100 km/h (eg no motorway shoulder or designs for 80 km/h operation), the capacity relative to operation at 100 km/h is generally reduced.

Typically, a capacity drop adjustment in the order of five per cent (say 100 pc/h/lane) should be considered.
4.4.2.9 Auxiliary lanes

As described in the *Operational Efficiency Audit Guidelines for Managed Freeways*[^16], an auxiliary lane is formed on the mainline at an entry ramp as an added lane, which generally continues at least to the next interchange or possibly beyond to a second interchange.

In the mainline context, it is not a short parallel speed change or storage lane extension to an entry or exit ramp. Auxiliary lanes are additional lanes that provide extra capacity between interchange ramps or through a series of interchanges.

Auxiliary lanes may be used when entry and exit lanes are closely spaced (refer to Section 5.2.1) or to increase capacity where there are high weaving flows. In this context, auxiliary lanes generally cater for entering and exiting traffic weaving to/from the mainline lanes and traffic moving between ramps at adjacent interchanges.

As an auxiliary lane is not continuous over a significant distance, the auxiliary lane flow is generally less than the adjacent through lanes. Therefore, it should not be used to determine average lane flows across the carriageway for the purposes of mainline capacity analysis. Analysis of flow relative to capacity for the through traffic can consider the remaining lanes, with adjustment for weaving, if necessary (refer to Section 4.4.2.3).

4.5 HCM analyses

The *HCM*[^4] and the *AGTM Part 3*[^5] provide traditional methodologies for assessing project capacity and operational performance. The analyses can be applied to assess the capacity and quality of flow relating to the mainline, merge areas, diverge areas and weaving.

The *HCM*[^4] provides similar guidance to this guideline in relation to provision of capacities for ‘basic motorway segments’ and adjustments to account for different physical and traffic/driver characteristics of the motorway.

While the *HCM*[^4] methodology may still provide useful complimentary guidance, the operational capacity values and adjustment factors outlined in this design guide (in Sections 4.2 to 4.4) take precedence over the HCM. In particular, care should be taken when using *HCM*[^4] methodologies for calculating capacities on sections with high volume weaving/lane changing, as explained in Section 4.4.2.3.

Performance outcomes to be met when using the *HCM*[^4] analyses are provided in Section 4.7.

4.6 Microsimulation models

Microsimulation models can provide guidance on operational performance and the suitability of design options. These models can be set up to suit a range of projects with varying size and complexity, from single intersections to road corridors/networks or entire activity centres.
In the project analysis process, the models simulate traffic movements using car-following algorithms and driver behaviour attributes (reaction time, acceleration rate, etc.) to assess performance of the project or a part of the project including delays, weaving, saturation levels, queuing, etc. Typical microsimulation modelling software packages are VISSIM and PARAMICS.

Nanosimulation modelling is a type of microsimulation modelling to assess a finer level of performance for road users, e.g., individual vehicle, pedestrian and cyclist movements. Nanosimulation models would not normally be required for a motorway project, unless there was a need to check for this level of operational detail, e.g., at an interchange.

The traffic analysis built into microsimulation models may not always reflect on-road operational characteristics of real data, particularly in high volume weaving areas. Therefore, care is needed to ensure the car-following and driver behaviour attributes are adjusted to accurately replicate on-road operations. For weaving analyses in high volume weaving situations consideration needs to be given to calibration of the model to replicate empirical data at other similar locations, i.e., the model needs to be verifiable by observation or experience.

Further information relating to microsimulation investigations is in the Traffic Modelling Guidelines[12]. Performance outcomes to be met for microsimulation analyses are provided in Section 4.7.

4.7 Performance targets for analysis and design

4.7.1 Context

The adoption of appropriate targets for capacity analysis and design can help ensure project goals and objectives are met and that a design will function as intended after it is constructed.

The performance values in this section are based on sustainable operations and should be adopted for motorway designs.

Following analysis, proposed layouts may need to be adjusted and refined as part of an iterative process.

On projects where analyses indicate that traffic demands cannot be satisfied by the proposed final design (i.e., analysis outcomes exceed the values below), this should be made clear during the project approval process. A clear operational strategy is required for these projects to ensure that after completing the project, traffic demand and access is managed consistently to match the capacity of the motorway (refer Section 2.4.2).

4.7.2 Flow/capacity ratio

The maximum flow/capacity ratio (degree of saturation) of mainline traffic for sustainable operations is 100 per cent (desirable 95 per cent) based on the capacity values outlined in Section 4.2.

4.7.3 Level of service

The Level of Service (LOS) is calculated as part of the capacity design process to provide a measure of the quality of traffic flow that will be achieved.
The maximum LOS value that should be adopted for sustainable operations at 100 km/h is LOS D, i.e. a maximum density of 22 pc/km/lane.

LOS E, which has traditionally meant operation at capacity prior to flow breakdown (density up to 28 pc/km/lane), is inappropriate for design and sustainable traffic operations.

The HCM describes operations on a motorway at this level as ‘highly volatile because there are virtually no usable gaps within the traffic stream, leaving little room to manoeuvre within the traffic stream. Any disruption to the traffic stream, such as vehicles entering from a ramp or a vehicle changing lanes, can establish a disruption wave that propagates throughout the upstream traffic flow. At capacity, the traffic stream has no ability to dissipate even the most minor disruption, and any incident can be expected to produce a serious breakdown and substantial queuing. The physical and psychological comfort afforded to drivers is poor’.

For sustainable operations as a smart motorway based on an operational capacity of 2100 pc/h/lane operating at 100 km/h (refer to Table 3), the density is 21 pc/km/lane, which is at the high end of LOS D.

4.7.4 Headway

In performance outputs from microsimulation investigations, minimum vehicle headways in the order of 1.7 seconds (managed) and 2.0 seconds (unmanaged) should be adopted.

These values are consistent with the operational capacity requirements in Section 4.2, where the relationship of headway to traffic flow is calculated by: Headway (s/pc) = 3600 (s) / Flow (pc/h).

4.8 Ultimate layout and staging of construction

The planning phase of a project may consider ultimate motorway layout and smart motorway ITS treatments which may, or may not, be built in the initial stage of construction. If the motorway construction is staged, either in the number of mainline lanes or in the length of construction, analyses should be undertaken for the initial stages as well as the ultimate project layout. Initial stages of construction should then be consistent with the ultimate needs to minimise rework.

As traffic management needs and smart motorway ITS treatments may differ for staging options involving interim and ultimate operations, the checking of analyses and design (including warrants) may also need to be carried out.

When initial traffic demand is lower than coordinated ramp metering signals warrants, a project may need to be checked for unmanaged operations as well as for managed operations in future years as demands increase.

4.9 Complementary material

Further complementary material relating to weaving and lane changing capacity is provided in Table 5.
### Table 6: Complementary material related to weaving and lane changing capacity

<table>
<thead>
<tr>
<th>Subject</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>The need to allow for turbulence and the stochastic nature of capacity in the weaving area. This paper provides comparisons of HCM 2000 analyses with their simulation work and fit to real data, and demonstrates that the proposed model capacity estimates are consistent with field data while the HCM procedures tend to overestimate weaving section capacities significantly (exceeding 100 per cent).</td>
<td>Analytical Procedures for Estimating Capacity of Weaving, Merge and Diverge Sections[17].</td>
</tr>
<tr>
<td>The comparison of HCM 2000 with the Dutch method demonstrates significant differences in capacity depending on the weaving percentage per leg. Neither the HCM nor the Dutch approach considers different weaving flows per incoming leg.</td>
<td>Freeway Weaving Comparison of “Highway Capacity Manual” 2000 and Dutch Guidelines[18].</td>
</tr>
<tr>
<td>The studies demonstrate that the HCM 2000 procedures tend to overestimate weaving section capacities significantly (even in excess of 100 per cent in some instances).</td>
<td>Review of Evaluating Existing Capacity of Weaving Segments[19].</td>
</tr>
<tr>
<td>The present analysis models in Sweden are compared to other international models to check for reasonableness. The research notes the high capacity resulting from the HCM 2010. The reason for this is that the auxiliary lane between an entry ramp and exit ramp is included in the capacity calculation. The Swedish and German procedures do not include capacity for the auxiliary lane.</td>
<td>Analysis of the Weaknesses in the Present Freeway Capacity Models for Sweden[20].</td>
</tr>
</tbody>
</table>
5 Motorway and arterial road interface capacity analysis

5.1 Overview

The efficiency of the motorway and arterial road interface affects accessibility to the motorway as well as the ability of traffic to leave the motorway to access the arterial road network. Efficient operation can help to ensure effective use and optimisation of the overall motorway infrastructure. This section provides guidance related to interchange spacing, interchange capacity analysis, entry ramp capacity analysis, and exit ramp capacity analysis.

Initial proposed layouts for interchanges and intersections are generally adopted to address identified problems and/or project objectives. These are then adjusted and refined based on the design volumes and analyses undertaken.

5.2 Interchange spacing

Interchanges along a motorway form the principal means of vehicles gaining access to, and egress from, the motorway. The spacing, locations and layout of interchanges should be given careful planning and design to ensure motorways operate efficiently and safely within the arterial road network as a whole.

The location and spacing of motorway interchanges with arterial roads is determined by a number of factors including:

- Proximity to motorway-to-motorway interchanges
- Arterial road network requirements for motorway accessibility, traffic distribution and route interconnectivity
- Accessibility, including the capacity of the crossing roads and their strategic connections
- The physical suitability of the site, including horizontal and vertical alignment as well as the availability of land.

Entry and exit ramps create turbulence in the traffic stream as vehicles change lanes, diverge and merge. Where insufficient distance exists between ramps, turbulence is also created between the end of an entry ramp merge taper and the start of the downstream exit ramp diverge taper as vehicles weave and change lanes to position themselves for the desired movement. This weaving area distance should be considered, as outlined in Section 4.4.2.3.

5.2.1 Matters related to spacing

Interchanges should be designed to suit the ultimate form of the motorway (ie number of mainline lanes) and ultimate interchange capacity requirements (ie traffic volumes through the interchanges), as well as accommodate proposed motorway management systems and technologies (initial stage and anticipated future needs).
Interchange spacing is defined as the distance between the centrelines of successive crossroads with interchanges on the motorway. *AGTM Part 6: Intersections, Interchanges and Crossings*[^13], indicates that the minimum spacing between arterial roads at successive interchanges in an urban environment is 1.5 km to 2.0 km. However, the *Austroads Guide to Road Design (AGRD) Part 4C: Interchanges*[^15] provides a minimum spacing of:

- Two kilometres for four-lane motorways (two lanes in each direction)
- Three kilometres for six-lane motorways (three lanes in each direction)
- Four kilometres for eight-lane motorways (four lanes in each direction).

Further, the *AGRD Part 4C*[^15] indicates that the ultimate number of lanes should also be considered when the location of interchanges is initially planned.

When considering interchange spacing, rather than emphasize the distance between adjacent arterial road interchanges, the focus of a desirable minimum distance should be on the design, operational, safety and signing considerations of the ramps and the capacity and operation of the weaving areas between interchanges.

The desirable minimum distance in the urban motorway context is generally based on the total of:

- **Length of the entry ramp:**
  - Length from the arterial road to the ramp nose (including desirable vehicle storage at the ramp metering signals)
  - Length of the merge taper entering the mainline.
- **Distance required for lane changing and weaving:**
  - For single lane entries and exits (ie without excessive weaving movements), the desirable minimum distance is four seconds of travel time between the end of the entry ramp merge taper and the start of the exit ramp diverge taper (ie around 100 m for travel at 100 km/h).
- **Length of the exit ramp:**
  - Length of the diverge taper from the mainline
  - Length of the exit ramp from the ramp nose to the arterial road (includes deceleration distance and vehicle storage area at the exit ramp intersection).

The form/layout of adjacent interchanges may also have a bearing on interchange designs and spacing. For example, the motorway alignment and location or skew of the arterial road crossings can reduce the ramp spacing, as shown in Figure 16.
In restricted situations, if appropriate interchange spacing cannot be achieved for satisfactory operation of adjacent ramps, one of the following solutions may need to be considered:

- Choosing a form of interchange that increases separation (e.g., using a loop ramp rather than diamond ramps (refer to Figure 17)), subject to volume, capacity and space considerations
- Providing a single interchange with a second diverge off the initial exit ramp, and/or combining two entry ramps to enter the mainline as a single entry
- Providing separate collector-distributor roads parallel to the mainline between two interchanges, which provide one entry and one exit ramp in each direction to service two or more interchanges, as shown in Figure 18
- Braiding of ramps (grade separation), as shown in Figure 19.
The distance between interchanges may also need to consider the positioning and effectiveness of exit ramp direction signing to avoid the potential for driver confusion when advance signs for one interchange have to be placed close to, or within, a preceding interchange.

### 5.2.2 Major single entrances compared with multiple entrances

Interchange options relating to the use of a single major entry, collector-distributor road or braiding of ramps, bring together vehicles from two or more ramps so that traffic enters or leaves the motorway at a single location. This arrangement may provide flexibility in the ramp location and minimise weaving. However, a single major entrance concentrates traffic and can have the following disadvantages:

- Lane continuity may not be maintained (i.e., the number of continuous through lanes along the motorway to minimise unnecessary lane changing)
- Balancing traffic flow and capacity along the route can be more difficult (i.e., the motorway is unable to ‘unload’ the left lane of the mainline at an exit before accepting entering traffic at the downstream entry ramp)
- Greater weaving and lane changing movements generally occur downstream of a major entry or before a major exit
• It can be more difficult to provide ramp capacity for ramp metering of higher volumes (number of lanes and storage length).

5.2.3 Complementary material

Complementary material related to interchange spacing is shown in Table 6.

Table 7: Complementary material related to interchange spacing

<table>
<thead>
<tr>
<th>Subject</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning and design consideration of interchange spacing and layout.</td>
<td>AGTM Part 6: Intersections, Interchanges and Crossings [13], Sections 6.3.1 and 6.6.6.</td>
</tr>
<tr>
<td>Planning and design consideration of interchange spacing and layout.</td>
<td>AGRD Part 4C: Interchanges [15], Section 2.4.2.</td>
</tr>
</tbody>
</table>

5.3 Entry ramp capacity analysis

5.3.1 General

General guidance relating to the choice of an entry ramp layout is provided in Table 7. The ramp volumes provided in the table represent the upper limit of what can be expected from the road design configuration based on the mainline having adequate capacity to accommodate the entry traffic in the merge area and downstream section of the motorway, irrespective of whether the mainline is managed with coordinated ramp signals (refer to Sections 5.3.2 and 5.3.3 below).

Matters associated with design of the number of lanes required on the ramp for operation with ramp signals is provided in the Smart Motorway Supplement for Ramp Metering Signals [21].

Table 8: Typical entry ramp capacities

<table>
<thead>
<tr>
<th>Ramp description</th>
<th>Entering Traffic Volume (pc/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lane loop</td>
<td>Up to 900</td>
</tr>
<tr>
<td>Single lane at entry ramp nose with merge</td>
<td>Up to 1200</td>
</tr>
<tr>
<td>Single lane at entry ramp nose with an added lane on the mainline</td>
<td>Up to 1800</td>
</tr>
<tr>
<td>Two lanes at entry ramp nose including an added lane on the mainline</td>
<td>1500 to 2700</td>
</tr>
<tr>
<td>Two exclusive entry lanes with two added lanes on the mainline</td>
<td>2700 to 4000</td>
</tr>
</tbody>
</table>

Source: Adapted from AGTM Part 6 [13] and the Smart Motorway Supplement for Ramp Metering Signals [21].

5.3.2 Entry ramps on a smart motorway

When designing new projects or when upgrading existing motorways, the operational capacity value for mainline capacity analysis of entry ramp merges on smart motorways is provided (for a basic motorway segment) in Section 4.2. This capacity value may need to be adjusted for site specific conditions which will impact mainline capacity (refer to Sections 4.3 and 4.4).
Reference should also be made to the *Smart Motorway Supplement for Ramp Metering Signals*\textsuperscript{[21]} in regard to the number of lanes at the stop line and ramp storage.

**5.3.3 Entry ramps on an unmanaged motorway**

The capacity of an entry ramp merge on an unmanaged motorway is lower than the mainline sections of the motorway as it does not have coordinated ramp metering signals to minimise turbulence and regulate the flow of entering traffic.

When designing new projects or when upgrading existing motorways, the operational capacity value for mainline capacity analysis of entry ramp merges on unmanaged motorways (for a basic motorway segment) is provided in Section 4.2.

Where design volumes indicate that the mainline is over capacity, for the proposed number of mainline lanes, consideration generally should be given to either:

- Providing a two-lane entrance with an added lane downstream on the mainline, or
- Providing ramp signals along the route and analysing the merge using the capacity for a smart motorway.

Entry ramp design for an unmanaged motorway should also consider ultimate needs when smart motorway operation within a coordinated ramp signal system is implemented (refer to the *Smart Motorway Supplement for Ramp Metering Signals*\textsuperscript{[21]}).

**5.3.4 Complementary material**

Complementary material of research related to entry ramp capacity is detailed in Table 8.

*Table 9: Complementary material related to entry ramp capacity*

<table>
<thead>
<tr>
<th>Subject</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing entry ramp flows leads to lower</td>
<td>\textit{Study of Traffic at a Freeway Merge and Roles for Ramp Metering}\textsuperscript{[22]}.</td>
</tr>
<tr>
<td>mainline downstream capacity.</td>
<td></td>
</tr>
<tr>
<td>Increasing the ratio of entry ramp flow to</td>
<td>\textit{Characteristics of Breakdown Phenomenon in Merging Sections of Urban Expressways in Japan}\textsuperscript{[23]}.</td>
</tr>
<tr>
<td>outflow rates leads to higher breakdown</td>
<td></td>
</tr>
<tr>
<td>probability.</td>
<td></td>
</tr>
<tr>
<td>Entry ramp merge capacity.</td>
<td>\textit{Freeway and Interchange: Geometric Design Handbook}\textsuperscript{[24]}.</td>
</tr>
</tbody>
</table>

**5.4 Exit ramp capacity analysis**

**5.4.1 General**

The safety and operational efficiency of the mainline, as well as the motorway system as a whole, can be affected by the performance of exit ramps. Features related to exit ramps affecting capacity include:

- Number of lanes available on the motorway for exiting vehicles
- Number of lanes at the ramp nose for vehicles entering the exit ramp
- Number of lanes on the exit ramp for vehicles to manoeuvre and queue at the exit ramp intersection
- Length of the exit ramp for deceleration and queuing.

Adequate capacity in each of these areas is required to minimise turbulence on the mainline before the exit (eg due to lane changing) and to ensure exit ramp vehicles do not queue back onto the mainline from the exit ramp or cause deceleration of vehicles on the mainline before the exit. This is for both safety and efficiency purposes.

The volume of traffic leaving the motorway generally determines the number of lanes required next to the exit ramp nose. Table 9 can be used as a guide to the number of lanes required at the nose and whether an auxiliary exclusive exit (left-turn) lane(s) should be provided. As turbulence in the diverge/influence area can affect the mainline operation, traffic analysis may also be required to assess operation using the HCM\(^\text{4}\).

To enable the capacity of a two-lane exit to be developed, the additional left lane(s) for exiting traffic should include a significant length of auxiliary exclusive lane to reduce turbulence and allow for lane changing into the second exit lane. The length of the left exclusive lane(s) should be in the desirable range of 300 m to 800 m long (as indicated in AGRD Part 4C\(^\text{15}\)) plus taper, subject to the traffic volume and position of any entry ramp merge taper from the preceding interchange.

### Table 10: Typical exit ramp capacities

<table>
<thead>
<tr>
<th>Ramp description</th>
<th>Exiting Traffic Volume (pc/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lane loop</td>
<td>Up to 900</td>
</tr>
<tr>
<td>Single lane at exit ramp nose</td>
<td>Up to 1500</td>
</tr>
<tr>
<td>Two lanes at exit ramp nose (includes exclusive left lane plus diverge from the adjacent through lane for exiting traffic)</td>
<td>1500 to 2700</td>
</tr>
<tr>
<td>Two exclusive exit lanes</td>
<td>2700 to 4000</td>
</tr>
</tbody>
</table>

*Source: Adapted from AGTM Part 6\(^\text{13}\) with values based on operational experience and international design guides.*

The exit ramp length and capacity (number of lanes) may also need to consider:
- Length of right-turn and left-turn lanes for queued vehicles (refer Section 5.6.4)
- The minimum length to achieve grading requirements and deceleration to negotiate a ramp curve and/or distance to the back of queue
- The ramp length to enable vehicles to change lanes within the ramp.

#### 5.4.2 Complementary material

Complementary material related to exit ramp capacity and operation are detailed in Table 10.
5.5 Capacity analysis of interchange intersections

The capacity and operation of managing entry and exit flows at motorway/arterial road interchanges can impact a motorway’s operation. Appropriate capacity analysis of design flows and proposed intersection layouts and traffic signal phasing (if signalised), should be carried out using microanalytical software packages, such as SIDRA INTERSECTION, to ensure adequate:

- Capacity for traffic entering the motorway
- Capacity for traffic leaving the motorway
- Capacity for through movements to ensure vehicles using the motorway are not delayed excessively
- Queue lengths, particularly for exit ramps and turning lanes.

Inadequate intersection capacity at the arterial road intersection which causes excessive queuing and delays on the exit ramp can be problematic and may affect mainline operations (refer to Section 5.6.4). Traffic signals are generally preferred at urban interchanges as this form of traffic management provides more control than roundabouts or Stop/Give Way signs.

5.6 Performance targets for analysis and design

5.6.1 Context

The adoption of appropriate targets for capacity analysis and design can help to ensure that project goals and objectives are met and that interchanges will function as intended after they are constructed. Following analysis, proposed layouts may need to be adjusted and refined as part of an iterative process.

5.6.2 Level of service

The maximum LOS value for analyses involving ramp merges and diverges at the mainline is LOS D, ie a maximum density of 22 pc/h/ lane.

5.6.3 Degree of saturation

The maximum degree of saturation of the critical (maximum) movement at a signalised motorway interchange intersection is 0.95 (desirable 0.9). At a roundabout or unsignalised intersection the desirable degree of saturation is 0.80.
5.6.4 Queues and storage

The desirable design performance standard for vehicle storage of right-turn and left-turn lanes at traffic signals is to accommodate 95th percentile queues. This includes the storage length for exit ramp vehicles leaving the motorway.

5.6.5 Ramp metering storage requirements

Requirements for ramp storage relating to the operation of entry ramp metering signals are provided in the *Smart Motorway Supplement for Ramp Metering Signals*[^21].
# Glossary

<table>
<thead>
<tr>
<th>Term / sign</th>
<th>Definition</th>
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<tbody>
<tr>
<td>≥</td>
<td>Greater than or equal to.</td>
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<tr>
<td>AGRD</td>
<td>Austroads Guide to Road Design.</td>
</tr>
<tr>
<td>AGTM</td>
<td>Austroads Guide to Traffic Management.</td>
</tr>
<tr>
<td>CCTV</td>
<td>Closed-Circuit Television.</td>
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<tr>
<td>Element</td>
<td>Technology or other design feature that delivers a smart motorway function.</td>
</tr>
<tr>
<td>HCM</td>
<td>Highway Capacity Manual.</td>
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<tr>
<td>ITS</td>
<td>Intelligent Transport System.</td>
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<tr>
<td>LOS</td>
<td>Level of Service.</td>
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<tr>
<td>LUMS</td>
<td>Lane Use Management System.</td>
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<tr>
<td>NSW</td>
<td>New South Wales.</td>
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<tr>
<td>PCE</td>
<td>Passenger Car Equivalent.</td>
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<tr>
<td>pc/h/lane</td>
<td>Passenger cars per hour per lane.</td>
</tr>
<tr>
<td>pc/km/lane</td>
<td>Passenger cars per kilometre per lane.</td>
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<tr>
<td>RMS</td>
<td>Roads and Maritime Services.</td>
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<tr>
<td>Smart Motorway</td>
<td>Previously referred to as managed motorway or smart managed motorway. A motorway that utilises complementary technologies to create a fully managed road environment that maximises the performance of the existing road infrastructure.</td>
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<tr>
<td>TRB</td>
<td>Transportation Research Board.</td>
</tr>
<tr>
<td>veh/h/lane</td>
<td>Vehicles per hour per lane.</td>
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<tr>
<td>VSL</td>
<td>Variable Speed Limits.</td>
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</tbody>
</table>

**Warrant**

Criteria or threshold guiding application of a smart motorway element to a section of the NSW motorway network. If a warrant is met in a particular case, then further investigation is still required to determine if it is appropriate for the smart motorway element to be applied to a specific motorway section, considering other matters relevant to smart motorway design and operation. If a warrant is not met in a particular case, it is highly likely that the smart motorway element would not be required on that motorway section.
7 References

The resources shown in the table are directly referenced in this design guideline. Some of these sources may have limited access for non-subscribers.

<table>
<thead>
<tr>
<th>Ref #</th>
<th>Resource Name</th>
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<th>Author</th>
<th>Location</th>
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<td>[16]</td>
<td>Operational Efficiency Audit Guidelines for Managed Freeways 2013</td>
<td>Main Roads WA</td>
<td>Main Roads WA website</td>
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## Document control

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### Revision history

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