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Methodology for the Analysis of the Freeway Weaving Area Capacity

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Summary

Appropriate freeway planning, design and operations rely on suitable capacity guidance for the different network elements including basic, weaving and merging/diverging segment types. Weaving areas characterised by crossing vehicle movements that must happen over a limited length can severely reduce capacity and therefore form strong bottlenecks if not appropriately addressed. Australian and New Zealand freeway capacity guidance as included in the current Austroads guides is largely based on the US Highway Capacity Manual (HCM). It has therefore unintentionally adopted the corresponding HCM limitations. Local practitioners have commented that the HCM often over-estimates the capacity on our freeways and does not provide a suitable analysis methodology for weaving areas.

Main Roads Western Australia has therefore adopted the Maximum Sustainable Flow Rate (MSFR) concept as the preferred methodology for analysing freeway capacities, instead of the HCM methodology. The MSFR methodology is a probabilistic approach based on the likelihood of flow breakdown, e.g. 1% chance of flow breakdown in a 15-minute time interval (or around 10% in a 3-hour peak period). Methodologies for weaving, merge and diverge analyses based on MSFR had not been developed yet. This project has now developed a suitable methodology for weaving, based on traffic flow and lane changing measurements at twelve weaving areas in Western Australia and Victoria. The relation between the weaving-induced lane changing concentration (LCC) and the remaining MSFR compared to typical non-weaving sections can be described by a curve that has a logarithmic shape, i.e. the curve is plateauing at a remaining MSFR of around 70% for high LCC values.

This curve can be used to define a weaving adjustment factor (F_{Weave}) for multiplication of the typical base MSFR value to arrive at the reduced weaving MSFR. The new methodology relies on estimating lane changes (LC) that must be made within the weaving area. This is straightforward for simple weaves such as single-lane entry and exit lanes connected by an added auxiliary lane between the ramps, but it can be challenging for practitioners for complex weaving areas such as those with multi-lane entry or exit ramps.

The developed methodology was successfully tested for 5 additional weaving areas in Western Australia, Victoria and Queensland. Further testing is recommended, due to this low number of sites. It is envisaged that the developed methodology will be used by other Australian jurisdictions as well. For example, it will be input into the current Austroads 'NEG 6527 – AGTM Update – Freeway Capacity Analysis' project.

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Abbreviations

Abbreviation	Definition
AGSM	Austrroads Guide to Smart Motorways
AGTM	Austrroads Guide to Traffic Management
ANPR	Automated Number Plate Recognition
CDF	Cumulative Distribution Function
EB	Eastbound
EMLC	Extended mandatory lane changes (LC that must be made by vehicles to avoid per lane MSFR exceedance potentially caused by mandatory ones)
Extended STRIDE model	Weaving area traffic model resulting from the NCHRP 07-26 research project, also referred to as the revised NCHRP 07-26 model
FBR	Flow breakdown risk
FF	Freeway to freeway
FFS	Free flow speed, i.e. average vehicle section speed if not impeded by other vehicles
FR	Freeway to ramp
F_{Weave}	Weaving adjustment factor, i.e. factor for the multiplication of the base capacity $MSFR_{Base}$ to obtain the weaving capacity $MSFR_{Weave}$
HCM	US Highway Capacity Manual (USA)
HGV	Heavy goods vehicles (term used in the VicRoads Motorway Capacity Guide, VicRoads 2019a)
HV	Heavy vehicles (according to the Austrroads 2-bin classification system)
IB	Inbound
LC	Lane changes
LC_{Mand}	Number of mandatory LC
LC_{XMand}	Combined number of mandatory and extended mandatory LC
LCC	Lane changing concentration
LCC_{Mand}	Mandatory LCC, i.e. (based on) LC that must be made to progress from origin to destination
LCC_{XMand}	Combined mandatory and extended mandatory LCC, i.e. (based on) mandatory LC and those needed to avoid lane capacity exceedance; the acronym simplifies the earlier 'mandatory and extended mandatory LCC' expression since mandatory ones are included in the extended mandatory ones
LOS	Level of service
L_s	Short length of the weaving area extending from the end of the entry ramp solid linemarking/nose to the start of the exit ramp solid linemarking/nose (also L_{Crit})
OD	Origin-Destination
MCG	Motorway Capacity Guide (Volume1, Part 3 of the Managed Motorway Design Guide)
MLC	Mandatory lane changes (LC that must be made by vehicles to progress from origin to destination). For the analysed weaving areas, these are the measured lane changes associated with the weaving traffic streams and vehicles.
MRWA	Main Roads Western Australia
MSFR	Maximum Sustainable Flow Rate
$MSFR_{Base}$	Maximum Sustainable Flow Rate for a basic freeway/motorway section
$MSFR_{Weave}$	Maximum Sustainable Flow Rate for a weaving section
NB	Northbound
NCHRP	National Cooperative Highway Research Program (USA)
NCHRP method	New methodology for the assessment of weaving areas from NCHRP 07-26 project (also referred to as the extended STRIDE model)
OB	Outbound
PC	Passenger Cars
PCU	Passenger Car Units
q	Volume (veh/h)

Abbreviation	Definition
Revised NCHRP 07-26 Model	Also referred to as the extended STRIDE model
RF	Ramp to freeway
RMS	Roads and Maritime Services New South Wales
RMSE	Root Mean Square Error
RR	Ramp to ramp
SB	Southbound
SIW	Speed Impedance due to Weaving
STRIDE	Southeastern Transportation Research, Innovation, Development and Education Center (University of Florida), also used to describe the corresponding STRIDE UTC weaving area traffic model
SVO	Speed, volume, occupancy (data)
TIRTL	The Infra-Red Traffic Logger
TRB	Transportation Research Board
VDS	Vehicle Data Station (FDS in Victorian terminology)
Vic DTP	Department of Transport and Planning Victoria
VR	Weaving ratio (the ratio of weaving vs all traffic)
WB	Westbound

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Executive Summary

Appropriate guidance for freeway weaving area capacity is essential for freeway planning, design and operations. Weaving areas are characterised by strong crossing vehicle movements that must happen over a limited length. They can severely reduce capacity and, therefore, form strong bottlenecks if not appropriately addressed.

Current Australian and New Zealand freeway capacity guidance, as included in the Austroads *Guide to Traffic Management* (AGTM) and Austroads *Guide to Smart Motorways* (AGSM), is largely based on the US *Highway Capacity Manual* (HCM). Several deficiencies of the HCM methodologies for standard sections and, especially, weaving areas are documented in research reports and have also been reported by road design practitioners. In particular, the HCM over-estimates the capacity of basic freeway sections, especially of carriageways with many lanes, and the weaving methodology is not applicable to many real-world situations such as lane-adds and -drops. Another reported issue is a lack of sensitivity of the corresponding analysis results to changes in the weaving area length.

Australian and New Zealand jurisdictions have increasingly adopted the Maximum Sustainable Flow Rate (MSFR) concept as the preferred methodology for analysing freeway capacities, instead of the HCM methodology. The MSFR method is a probabilistic approach. It is based on the probability of a flow breakdown, e.g. 1% chance of a flow breakdown in a 15-minute time interval (or around 10% in a 3-hour peak period), and on the flow rate at maximum productivity, which is defined in Austroads guidance as the mathematical product of traffic speed and flow.

The MSFR concept is embedded in the Main Roads Western Australia (MRWA) *Smart Freeway Guidelines*, and in the Department of Transport and Planning Victoria (Vic DTP) *Managed Motorway Design Guide*. The Austroads research report *Improved Traffic Management Guidance: Freeway Capacity Analysis* has recommended the MSFR concept for adoption in future versions of the AGTM and AGSM.

Methodologies for analysing weaving area capacity based on the MSFR concept have not been developed yet. This project has focused on closing this gap.

The project initially reviewed and assessed the different methodologies for analysing weaving area capacity that are currently available. It focused on the USA, since the HCM is regularly used in Australia and New Zealand, and on some European countries whose guidelines are used as an alternative to the HCM by some jurisdictions.

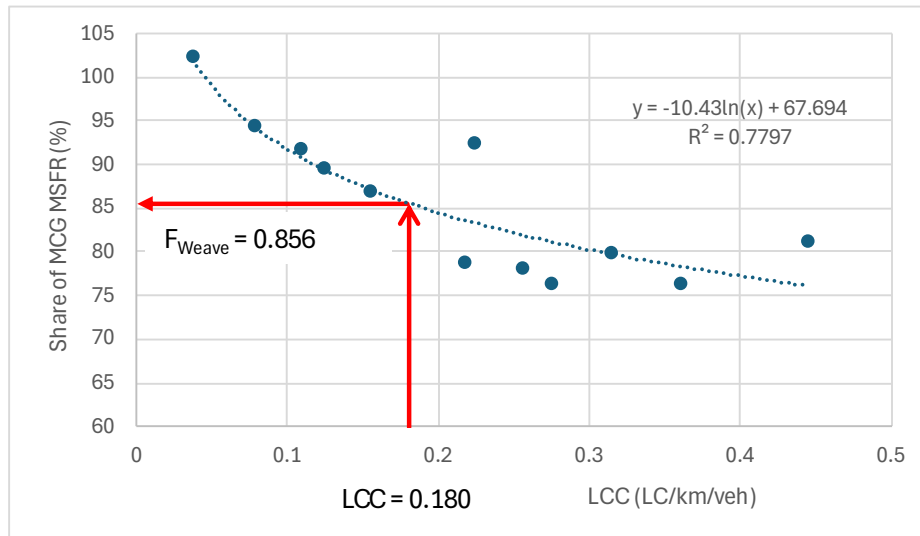
Twelve weaving areas in Western Australia and Victoria were identified to investigate the impact of weaving-induced lane changing on capacity, aiming to establish a functional relationship between these 2 parameters. The data that were sourced and validated were speed, volume and occupancy (SVO) data and lane changing data, which were measured with Automated Number Plate Recognition (ANPR) technology in Western Australia, and advanced Freeway Data Stations (FDS) in Victoria. These FDSs are capable of routinely estimating lane changing between adjacent detector sites. A functional relationship was established between the lane changing concentration (LCC) (in lane changes (LC) per vehicle per kilometre) and the capacity loss (in percent) compared to a typical freeway section not affected by weaving. This relationship is statistically significant and has a logarithmic shape, i.e. the curve is plateauing at a remaining MSFR of around 70% for high LCC values.

The overarching objective of the project was to provide suitable capacity guidance for practitioners. Based on the measurement results, a refined methodology was developed for determining weaving area capacity. This is supported by a detailed description of the process for estimating the number of LC, which is the most important input parameter for the methodology. The estimation of LC is straightforward for simple weaves, such as single-lane entry and exit lanes connected by an added auxiliary lane between the ramps, but it can be complex for multi-lane weaves, e.g. those characterised by multi-lane entry-ramps or exit-ramps, or multiple lane-adds or lane-drops such as at freeway bifurcations.

The central input parameter LCC can be determined by dividing the estimated number of essential LC per unit of time by the number of vehicles traversing the weaving area during that same period (e.g. an hour), and by the weaving area length in kilometres. The developed graph shown in Figure S.0-1 is then used to determine a weaving adjustment factor (F_{Weave}). This factor is multiplied by the typical MSFR values as included in the Main Roads Smart Freeway guidelines or other capacity guidance documents, resulting in the weaving area MSFR.

It is recommended that this procedure is only applied to weaves with an estimated LCC exceeding a value of 0.05 LC/veh/km. Otherwise, random capacity fluctuations can be stronger than the systematic, capacity-reducing impact of weaving (refer to the measured point in the upper left corner of the graph shown where the MSFR is slightly greater than the typical value).

Figure S.0-1: Weaving adjustment factor as a function of the LCC



The methodology was tested for 5 weaving areas. To maintain the needed statistical independence, these areas were not used for developing the methodology. The test areas included 2 test sites from Queensland, because most suitable ones in Western Australia and Victoria had already been used for methodology development. The testing concluded with an assessment of the pre-selected methodologies, including a new US methodology that will be part of the next HCM edition, and of the one newly developed by this project and described above. The following criteria were used to test the methodologies:

- coverage of real-world cases (scope)
- user-friendliness
- plausibility of equations
- accuracy.

The newly developed methodology performed better for all criteria except user-friendliness. The abovementioned challenge of estimating the essential LC for complex weaves could limit the take-up of the new methodology by practitioners in such cases. It is expected that automating the rule-based estimation of essential LC for certain roadway designs (e.g. MS Excel based) could mitigate this challenge. Other methods for LC estimation such as microscopic traffic simulation may also be suitable for use by practitioners. In contrast, the identified limitations in the plausibility of the newly developed US methodology are expected to be permanent because some of the assumptions made for the methodology's development appear to be unrealistic and are, therefore, expected to remain as error sources (e.g. that flow breakdown always happens at a certain, fixed vehicle density).

It was found that the methodology developed in this project is better aligned with the MSFR concept and achieves better results under local conditions, when compared to the new US methodology. It performs better regarding the plausibility of equations and accuracy. The method also allows for transparent scenario testing. For example, extending the length of a design scenario weaving area achieves a proportionate reduction of the LCC, and therefore, the remaining capacity changes.

The relatively low sample size for methodology development (12) and testing (5), as well as some SVO data availability limitations suggest that based on a greater sample size the validity of the method including the statistical significance of the curve in Figure S.0-1 could be further improved. This may also lead to a slightly changed shape of the curve. The intended method use is to reasonably estimate MSFR in weaving areas (through reduction of the base capacity); this implies that not 100% accuracy is the goal, but to avoid gross misjudgement as was often the result of the HCM methodology application. It is therefore concluded that the method can be adopted, despite potential future improvements through a greater sample size.

It is envisaged that the developed methodology will be used by other Australian jurisdictions as well. For example, it will be an input into the current Austroads 'NEG 6527 – AGTM Update – Freeway Capacity Analysis' project, for which the MSFR concept was adopted.

Adoption and further testing is recommended, due to the low number of sites used for this project, which did not allow for the coverage of all combinations of geometrical and traffic conditions. This could partially happen as part of the Austroads NEG 6527 project, e.g. based on weaving areas nominated by other jurisdictions involved in the project.

1 Introduction

1.1 Background

Appropriate guidance for analysing weaving area capacity is essential for freeway planning, design and operations. Weaving areas characterised by crossing vehicle movements that must happen over a limited length can severely reduce capacity and, therefore, form strong bottlenecks if not appropriately addressed.

Current Australian and New Zealand guidance for weaving area capacity, as included in the Austroads *Guide to Traffic Management* (AGTM, Austroads 2020a) and Austroads *Guide to Smart Motorways* (AGSM, Austroads 2016), is largely based on the 2016 outdated version of the US Highway Capacity Manual (HCM) (Transportation Research Board [TRB] 2016).

Section 5.4.3 of the AGTM acknowledges that 'the analysis of weaving sections is less developed than other freeway analysis procedures' (AGTM Part 3, Page 58). The HCM contains deficiencies in its guidance on weaving area capacity, and the AGTM and AGSM have adopted these deficiencies as well.

Since the first release of the Department of Transport and Planning Victoria's (Vic DTP's) *Motorway Capacity Guide* (MCG) (VicRoads 2019a), Australian jurisdictions have increasingly adopted the Maximum Sustainable Flow Rate (MSFR) concept as the preferred methodology for analysing freeway capacities, instead of the HCM methodology. The HCM over-estimates the capacity on Australian and New Zealand freeways, and the MSFR methodology provides a more realistic outlook. The MSFR method is a probabilistic approach based on the probability of flow breakdown i.e. 1% chance of flow breakdown in a 15-minute time interval (or around 10% in a 3-hour peak period).

The MSFR methodology was adopted by Austroads for mainline capacity analysis, and it is outlined in the Austroads (2020b) document *Improved Traffic Management Guidance Freeway Capacity Analysis*. This guidance will be further detailed by the Austroads 'NEG 6527 – AGTM Update – Freeway Capacity Analysis' project. All assessments for mainline analysis, particularly managed freeways, will be done using the MSFR method.

1.2 Research Need

Methodologies for weaving, merge and diverge analyses based on the MSFR concept have not been developed yet. Therefore, all jurisdictions currently use the HCM methodologies for these analyses, albeit with a few tweaks to address MSFR. However, the concept of MSFR is different from HCM capacities. MSFR is based on the probability of flow breakdown, whereas the HCM capacities refer to the maximum flow each lane can handle. Therefore, whilst the HCM methodologies for weaving, merge and diverge provide an indication of their impact on capacity, they cannot provide a true picture of the capacity impact in the MSFR realm. MSFR-based methodologies for weaving, merge and diverge are the missing links in Australian and New Zealand freeway modelling.

The objective of this project was to develop an analysis method for weaving area capacity based on MSFR that can be used to assess capacity constraints due to vehicle weaving on freeways in Western Australia as well as in other Australian jurisdictions. Recent advances in capacity analysis methodologies and traffic measurement technologies support this development.

1.3 Methodology

This project reviewed and assessed the different analysis methodologies for weaving area capacity that are currently available. Since the HCM is regularly used in Australia and New Zealand, the review focused on

the USA. Some European countries were also reviewed as alternatives occasionally used by jurisdictions. This review is described in Section 2.

Several weaving areas in Western Australia and Victoria were identified to investigate the impact of weaving on capacity. The selected measurement sites and data required for the analysis are described in Section 3.

The data that was sourced and validated were speed volume and occupancy (SVO) data and lane changing data, which are measured with Automated Number Plate Recognition (ANPR) technology and advanced Freeway Data Stations (FDS), capable of re-identifying individual vehicles, including the lane they were travelling in, at adjacent detector sites. The data sourcing and validation is described in Section 4.

A core element of the proposed methodology was the quantification of the capacity loss of a weaving area in comparison to a typical section not impacted by weaving. To do this, a baseline outlining typical Western Australian freeway section capacities had to be created. This is described in Section 5.

The analysis of the selected weaving areas, as described in Section 6, is the core of this study. This culminated in the development of a functional relationship between capacity loss and weaving intensity, characterised by the lane changing concentration (LCC).

The overarching objective of the study was to provide suitable capacity guidance for practitioners. Based on the previous steps, a refined methodology for determining weaving area capacity was developed, and it is provided in Section 7. This is supported in Section 8 where a detailed methodology describes the potentially complex process of estimating the essential number of lane changes (LC), which is a very important input parameter for the methodology for weaving area capacity analysis.

Finally, the methodology was tested for a limited number of weaving areas that were not used for methodology development. The testing concluded with an assessment of the 2 pre-selected methodologies, including the revised US methodology and the one newly developed for this project, against the following criteria:

- coverage of real-world cases (scope)
- user-friendliness
- accuracy.

This is summarised in Section 9.

Details of the revised HCM weaving methodology ('Extended STRIDE'), as per the corresponding National Cooperative Highway Research Program (NCHRP) report (NCHRP 2023) are included in Appendix A and Appendix B. An overview of the selected measurement sites can be found in Appendix C. Appendix D and Appendix E show details regarding the ANPR camera locations (Western Australia) and advanced FDS locations (Victoria) used for capacity analysis and weaving quantification (lane changing). Appendix F describes the geometrical and traffic conditions for the selected weaving areas and Appendix G shows the results of the ANPR analysis for LC quantification for the Western Australian weaving areas. Appendix H states the results of the capacity analysis (flow breakdown risk [FBR] curves).

2 Review and Comparison of Analysis Methodologies for Weaving Area Capacity

This project initially reviewed and assessed the different weaving area capacity analysis methodologies that are currently available. The focus was on the USA, since the HCM is regularly used in Australia and New Zealand, and on some European countries as an alternative occasionally used by jurisdictions. This section describes the review and provides a comparison between the different methodologies.

2.1 Review

The objective of the review was to identify and assess the different weaving area capacity analysis methodologies that are most used in Australia and New Zealand and in other parts of the world.

The Austroads (2020b) *Improved Traffic Management Guidance: Freeway Capacity Analysis* provided the basis for identifying the most promising methodologies. In addition, a scan of current research activities based on ongoing discussions with experts was undertaken.

The review focused on the HCM, which has traditionally been used in most countries, including in Australia and New Zealand (Section 2.1.1). Multiple attempts have recently been made to improve the original methodology included in the HCM 7th edition (TRB 2022). A recently published US NCHRP report summarises the comprehensive efforts to improve the current HCM methodology (NCHRP 2023). This report was reviewed in detail as described in Section 2.1.2. Also, a research effort that directly builds on the MCG MSFR concept was reviewed as per Section 2.1.3, because this methodology is directly linked to the capacity guidance currently used by Main Roads Western Australia (MRWA) and Vic DTP. The other relevant international methodologies were reviewed as described in Sections 2.1.4 to 2.1.6.

The review documentation is structured as follows:

- introduction
- capacity calculation
- assessment.

The assessment of the identified methodologies was based on the following criteria:

- scope (i.e. coverage of real-world scenarios)
- user-friendliness
- plausibility of procedure and equations
- criticisms.

The results of the assessment are summarised in Section 2.2.

An additional criterion focusing on the accuracy of the methodology application results will be assessed later in this report (Section 9), based on the testing for real-world scenarios. A comprehensive assessment of the methodologies requires their application to a range of practical examples on the MRWA freeway network (and/or potentially on the Vic DTP motorway network). This must comprise a comparison between the modelled and the measured weaving area capacities or MSFR values (based on the MCG methodology).

2.1.1 US Highway Capacity Manual 7th Edition (TRB 2022)

Introduction

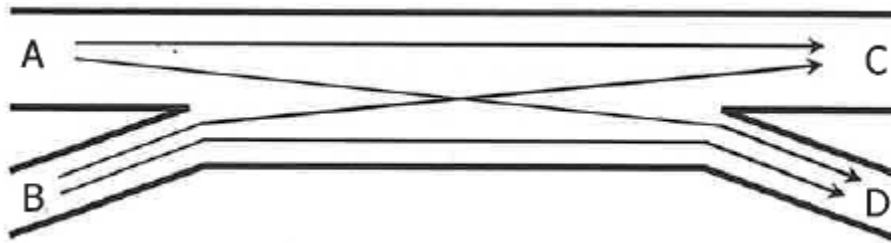
The current HCM analysis methodology for weaving area capacity was first introduced in the 5th edition (TRB 2010) and has remained generally unchanged since. The methodology is based on the NCHRP project report *Analysis of Freeway Weaving Sections* (Roess 2008).

The HCM 7th Edition defines weaving as follows (TRB 2022, Page 13-1):

Weaving is generally defined as the crossing of two or more traffic streams travelling in the same direction along a significant length of a highway without the aid of traffic control devices (except for guide signs). Thus, weaving segments are formed when merge segments are closely followed by diverge segments. 'Closely' implies that there is not sufficient distance between the merge and diverge segments for them to operate independently.

Figure 2.1 illustrates a 'classical' freeway weaving segment in its simplest form.

Figure 2-1: Formation of a Weaving Segment

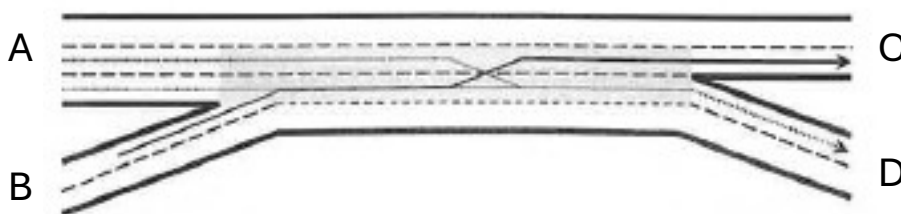


Source: Based on HCM 7th edition (TRB 2022), Exhibit 13-1.

In this example, any vehicle forming part of a weaving traffic stream (crossing movements B–C or A–D) must change lanes. Vehicle drivers that must change lanes over a short length while competing with the other crossing movement drivers may feel pressured during times of high traffic volumes, and in the worst case, this results in abrupt braking and lane changing into gaps that are too small. This can lead to flow breakdown and congestion at relatively low traffic volumes.

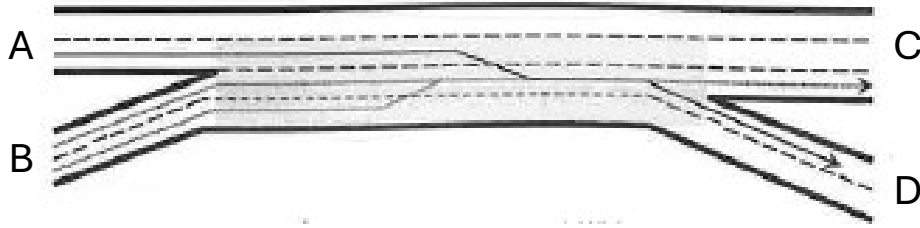
In contrast, the below figures show more complex weaving segments where only crossing movement B–C (Figure 2.2) or A–D (Figure 2.3) must change lanes. This may lead to different driver behaviour and, therefore, to a less severe weaving problem.

Figure 2-2: Four-lane major weave segment without lane balance



Source: Based on HCM 7th edition (TRB 2022), Exhibit 13-5.

Figure 2-3: Four-lane major weave segment with lane balance



Source: Based on HCM 7th edition (TRB 2022), Exhibit 13-5.

Capacity calculation

The HCM 7th edition approach to determining the capacity of a weaving area requires the application of 2 equations where the smaller of the values resulting from the application of Equation 1 (criterion: reaching a density of 43 passenger cars (PC) per mile and lane (pc/mi/ln) and Equation 2 (criterion: maximum weaving flow rates) defines the resulting capacity.

$$C_{IWL} = C_{IFL} - [438.2(1 + VR)^{1.6}] + (0.0765L_S) + (119.8N_{WL}) \quad 1$$

where

- C_{IWL} = capacity (per lane) of the weaving segment under equivalent ideal conditions (pc/h/ln)
- C_{IFL} = capacity (per lane) of a basic freeway segment with the same free flow speed (FFS) as the weaving segment under equivalent ideal conditions (pc/h/ln)
- VR = volume ratio (decimal), v_w/v
- v_w = weaving demand flow rate within the weaving segment (pc/h)
- v = total demand flow rate in the weaving segment (pc/h)
- L_S = length of the weaving segment (ft), based on the short length definition (between the end points of any barrier markings (solid white lines) that prohibit or discourage lane changing)
- N_{WL} = number of lanes from which a weaving manoeuvre may be made with one or no LC

$$C_{IW} = \begin{cases} \frac{2,400}{VR} \\ \frac{3,500}{VR} \end{cases} \text{ for } N_{WL} = 2 \text{ lanes or } N_{WL} = 3 \text{ lanes respectively} \quad 2$$

Before Equation 1 can be applied, different volume adjustments to reflect the peak hour factor and the heavy vehicle (HV) factor (f_{HV}) must be made. The corresponding equation that considers both factors can be found as Equation 13-1 in the HCM. This applies to v_w as well as to v as listed above.

A conversion from PC to vehicles per hour by application of f_{HV} is needed for the results of Equations 1 and 2 (refer to Equations 13-6 and 13-8 of the HCM). The result for Equation 1 can easily be converted to a carriageway-level value by multiplying it by the number of lanes (Equation 13-6 of the HCM).

Prior to determining capacity, the HCM first determines whether the segment is short enough to operate as a weaving segment. If the threshold distance L_{MAX} is exceeded, the segment is analysed as a sequence of

merge, basic and diverge segments. The corresponding threshold distance is calculated as follows in Equation 3 (refer to Equation 13-4 of the HCM).

$$L_{MAX} = [5,728x(1 + VR)^{1.6}] - [1,566xN_{WL}]$$

3

Assessment

Scope

The methodology is not applicable to many real-life conditions such as lane drops or lane additions or complex weaves.

User-friendliness

In contrast to many other HCM procedures, the application of this methodology as per Equations 1 to 3 is relatively simple. Also, the capacity loss compared to the base capacity (i.e. C_{IFL} minus C_{IWL}) can easily be expressed as a percentage of the original value C_{IFL} . The MSFR value for a basic freeway section, as sourced from the MCG (VicRoads 2019a, Chapter 2), can then be multiplied by this percentage value, resulting in the final weaving area MSFR value.

Plausibility of procedure and equations

Regarding Equation 1, the subtracted (first term) and added (second and third terms) volumes make intuitive sense since a greater weaving ratio (VR) reduces the capacity and a greater weaving length L_s and a greater number of lanes from which a weaving manoeuvre can be completed N_{WL} both increase the capacity. This does not also mean that the selected equation format including the multipliers/exponents is intuitive. Further details on this consideration can be found in Section 2.2.

Criticisms

The following issues with the HCM weaving methodology were identified (NCHRP 2023):

- There is an unclear relationship between the merge and diverge methodologies (i.e. discontinuities between the methods that cause inconsistent and counterintuitive results).
- Limited data were used for the development of the methodology (13 hours of manually reduced data collected at 14 sites, using a combination of video from fixed-wing aircraft [10 sites], ground- or pole-based video [2 sites] and simulation efforts [2 sites]).
- There is a relative lack of sensitivity to the segment short length (L_s).

For example, increasing the short length from 500 to 2,000 ft increases capacity by a little over 100 pc/h/ln, assuming other variables are kept constant. This trend is likely to discourage designers from improving the design of the weaving segment as apparently it would have no measurable effect on capacity and quality of service. (NCHRP 2023, Page 68)

- It is not applicable to many real-life conditions such as lane drops or lane additions, or complex weaves.

Several additional sources detail issues and concerns with the HCM weaving methods as follows:

- The HCM weaving method underestimates speeds in the 50 to 65 mph range (Xu et al. 2020).
- The HCM weaving method includes weaving length as an input, but performance measure outputs are insensitive to weaving length for practical purposes (Ahmed et al. 2019).
- The HCM weaving method underestimates capacities at high VR values (Skabardonis & Mauch 2014).
- The HCM weaving method can indicate that volumes are less than capacity but produce densities greater than the density at capacity.

- The HCM weaving analysis considers the total number of weaving vehicles but does not consider the origin–destination (OD) pattern for the weaving vehicles (Roads and Maritime Services [RMS] 2017, Page 33). It should be noted that this comment refers to the 5th edition of the HCM.

2.1.2 Update of Highway Capacity Manual: Merge, Diverge, and Weaving Methodologies (NCHRP 2023)

Introduction

NCHRP (2023) endeavoured to make suggestions to update the freeway operations methods in the HCM. It developed new methodologies for analysing the capacity and speeds at freeway merge, diverge and weaving segments based on a national dataset (120 measurement sites, including 27 weaving areas, 5 not used for methodology development due to concerns with downstream congestion). The data used were mainly sensor data (speed and flow, comprehensive for mainline and partial for ramps) which were complemented by the purchase of StreetLight data (probe data) to close the gaps in the availability of ramp data.

The project was meant to address issues with the HCM 6th edition weaving methodology that are listed in the ‘Criticisms’ of Section 2.1.1. The methodology is still the same in the HCM 7th edition.

Capacity calculation

The speed estimation methodologies presented in NCHRP (2023) are based on earlier research by the Southeastern Transportation Research, Innovation, Development and Education Center (STRIDE) (Rouphail et al. 2021 and Rouphail et al. 2023), which was discussed and amended in different stages throughout the project. ‘The intent of this approach was to provide the best fit to field observations of the segment speed and then use the same model to estimate capacity’ (NCHRP 2023, Page 68). These stages and the corresponding capacity calculation methodologies are described in the following sections.

Stage 1: STRIDE UTC

The form of the proposed speed model is as follows in Equation 4:

$$S_0 = S_b - SIW \quad 4$$

where

- S_0 = average weaving segment speed (mi/h)
- S_b = average speed of an equivalent basic segment with the same total volume, number of lanes and FFS (mi/h)
- SIW = speed impedance due to weaving (mi/h)

Speed impedance (SIW) represents a speed decline due to weaving turbulence. The parameters used for the calculation of SIW should represent the geometric characteristics and traffic demand at the weaving section.

The corresponding equation for the calculation of S_b (Equation 5) is included in Chapter 12-1 of the HCM 6th edition (TRB 2016).

5

$$S_b = FFS - \frac{(FFS - \frac{C_B}{4.5})(V - BP)^2}{(V - BP)^2}$$

where

- FFS = free flow speed (mi/h)
- C_B = capacity for the basic freeway segment (pc/h/ln)
- V = total volume (pc/h/ln)
- BP = breakpoint volume (pc/h/ln)

Equation 5 is generally accepted and is therefore not discussed here.

The SIW term based on multiple input parameters can be calculated as follows in Equation 6 (in its generic form).

6

$$SIW = \alpha \times \left(\frac{\beta x V_{RF} + V_{FR}}{N_l^3} \right)^\gamma \times \left(\frac{V}{N_l} - 500 \right) \times \left(\frac{1}{L_s} \right)^\delta$$

where

- V_{RF} = weaving volume from ramp to the freeway (pc/h)
- V_{FR} = weaving volume from freeway to the ramp (pc/h)
- N_l = number of lanes in the segment
- V = total volume (pc/h)
- L_s = short length of the weaving section (ft)
- $\alpha, \beta, \gamma, \text{ and } \delta$ = model coefficients

In this model, the weaving volumes (V_{RF} and V_{FR}) are presented as independent variables, and eliminating one of them cannot remove the entire SIW. Moreover, coefficient β in Equation 6 is included to enable the model to represent the different effects of V_{RF} and V_{FR} . The model assumes that when the volume per lane $\left(\frac{V}{N_l} \right)$ is less than 500 pc/h/ln, then the speed in the weaving section is equal to the speed in the equivalent basic freeway segment. For all sites used in the STRIDE database, when the volume is close to 500 pc/h/ln, the value of SIW approaches zero, and speed in the weaving section is equal to the equivalent basic freeway section. This value may change for different weaving sections (based on FFS, etc.). Finally, the term $\left(\frac{1}{L_s} \right)$ represents the effect of the length of the weaving section. Because the authors expect a weaving L_s section with longer L_s to have higher speed than a section with shorter L_s , L_s is included in the denominator.

With calibrated parameter values, Equation 6 presents itself as follows in Equation 7.

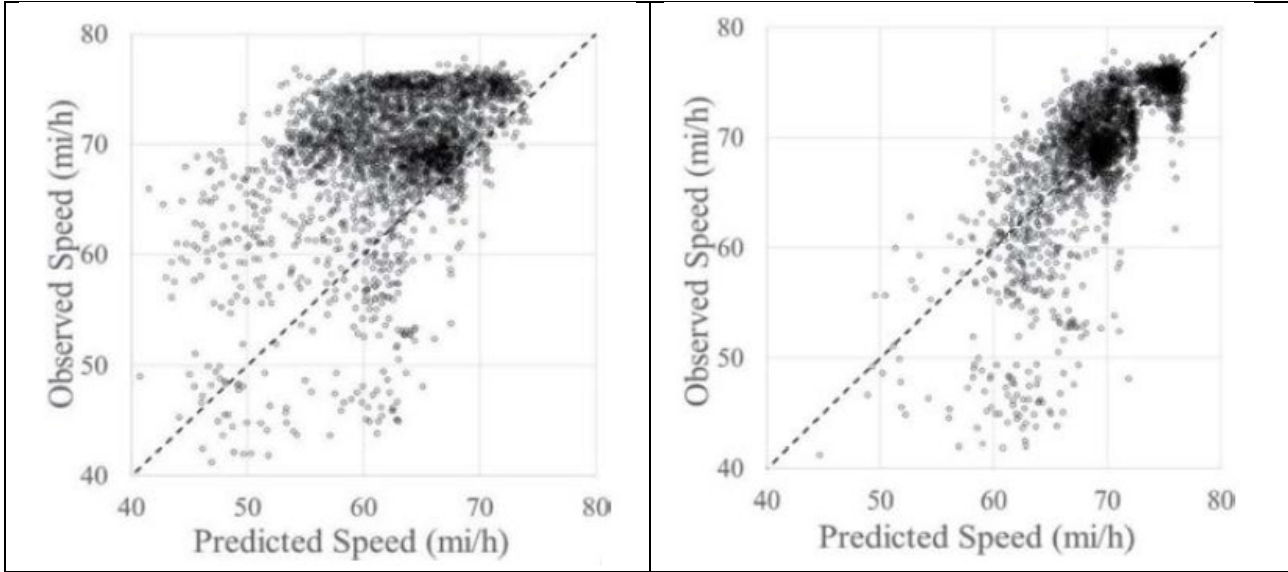
7

$$SIW = 0.025 \times \left(\frac{17.3xV_{RF} + V_{FR}}{N_l^3} \right)^{0.344} \times \left(\frac{V}{N_l} - 500 \right) \times \left(\frac{1}{L_s} \right)^{0.369}$$

The main purpose of the improvement of the original HCM speed was to achieve a better alignment between the (model) predicted speed and the observed speed. This implies that no attempt was made to achieve a

good alignment between the (model) predicted capacity and the measured capacity. Figure 2.4 clearly shows the better fit for the newly suggested method in NCHRP (2023).

Figure 2-4: Illustration of the alignment between measured and modelled speed values for HCM (left) and STRIDE UTC–suggested methodology (right)



Source: Adopted from NCHRP 2023, Figure 20.

The next calculations follow the HCM's guidance that weaving segment capacity occurs at a density of 43 pc/mi/ln.

Speed at capacity is then as follows in Equation 8¹.

$$S_0(C_W) = \frac{C_W}{43} = S_b - 0.025 \times \left(\frac{17.3xV_{RF} + V_{FR}}{N_l^3} \right)^{0.344} \times (C_W - 500) \times \left(\frac{1}{L_s} \right)^{0.369}$$

8

Equation 5 (replacing C_B by C_W) can be inserted into Equation 8, which can subsequently be solved for C_W . Alternatively, the difference between the left and the right term of the equation (i.e. left and right side of the equal sign) can be minimised by applying the Excel Solver functionality (with C_W in the Variable Cell).

Discussion of the STRIDE UTC model

All the explanations for the selected form of Equation 6 as stated in the paragraph following the equation make broad intuitive sense while the model coefficients have been selected to achieve an optimal fit between measured and modelled speeds as shown in Figure 2.4.

Some remaining issues are as follows:

- It would be more intuitive if the absence of V_{RF} or V_{FR} did not constitute a weaving problem anymore (i.e. $SIW = 0$ in this case).
- The weighting of V_{RF} and V_{FR} is very different in Equation 7 (i.e. the coefficient $\beta = 17.3$ is used here). It is unclear if this reflects reality (although this value has resulted from validation).
- The application of Equation 7 can result in a negative value for SIW when the volume is lower than 500 pc/h/ln.

¹ In Equation 6, the total volume V is for all lanes N_l whereas c_w is for one lane only.

The methodology can only be sensibly applied to a weaving problem within defined boundary conditions (e.g. V_{RF} and V_{FR} greater than 0, volume greater than 500 pc/h/ln).

The underlying assumption used for the determination of C_W – that capacity is reached at a density of 43 pc/mi/ln – may not be realistic (as the research report itself acknowledges in different locations such as in the report summary [Page 74]). It could be an option to calibrate the model to local conditions where the average breakdown density was identified at slightly higher densities (Kwinana Freeway: 46 pc/mi/ln, no numbers for Victoria).

It should be noted that the value of 43 pc/mi/ln was reviewed during a later project phase and subsequently reduced to 35 pc/mi/ln. Also, a formula for the direct calculation of the capacity for a revised version of Equation 8 was developed. Both elements are included in Stage 3: Extended STRIDE below).

Stage 2: Recalibrated STRIDE

The original STRIDE UTC speed model as per Equation 7 resulted in considerable speed differences compared to field-observed speeds for certain sites. To provide a better model fit, the research team investigated recalibrating the STRIDE model parameters while maintaining the model form with a marginal change of the parameter N_l as follows in Equation 9.

$$SIW = \alpha \times \left(\frac{\beta x V_{RF} + V_{FR}}{N_{l-GP}^\varepsilon} \right)^\gamma \times \left(\frac{V}{N_{l-GP}} - 500 \right) \times \left(\frac{1}{L_S} \right)^\delta \quad 9$$

where

$\alpha, \beta, \gamma, \delta, \varepsilon$ = model parameters

N_{l-GP} = number of **general purpose** lanes in the segment (i.e. the impact of managed lanes such as diamond lanes on the weaving speed is not considered)

According to the authors of the report, this resulted in a better fit between modelled and measured speed points at the diverging sites.

Table 2.1: Recalibration of the STRIDE model parameters for simple weave sites

Model	α	β	γ	δ	ε	RMSE (mph)
Original STRIDE model	0.025	17.302	0.344	0.369	3.000	7.15
Recalibrated NCHRP 07-26 model	0.060	0.088	0.131	0.423	2.861	2.82

RMSE = root mean square error.

Source: NCHRP 2023, Table 19

Discussion of the recalibrated STRIDE model

In addition to the discussion points for the original STRIDE UTC model as listed above, the very significant differences between the β parameters of the original versus the recalibrated model should be noted. It is intuitively difficult to understand why the importance of V_{RF} is either 17-fold that of V_{FR} (original STRIDE) or less than 1/10 of it (recalibrated STRIDE).

Stage 3: Extended STRIDE

Speed model

While the re-calibrated model greatly improved the speed predictions especially for simple weaves (that is, a single-lane entry-ramp connected to a single-lane exit-ramp by an auxiliary lane), the model does not perform as well for a few more complex sites. This resulted in the team revisiting the weaving model

formulation to consider the geometry of complex weaving segments more explicitly. Following a few iterations, this resulted in the Equation 10.

$$S_0 = S_b - \alpha x \left(\frac{(LC_{RF} + 1) x V_{RF} + (LC_{FR} + 1) V_{FR}}{N_{l-GP}^\varepsilon} \right)^\gamma x \left(\frac{V}{N_l} - 500 \right) x \left(\frac{1}{L_s} \right)^\delta \quad 10$$

where

- LC_{RF} = minimum number of LC for ramp-to-freeway (RF) weaving traffic
- LC_{FR} = minimum number of LC for freeway-to-ramp (FR) weaving traffic
- NW_{RF} = number of lanes from which a weaving manoeuvre from the entry-ramp to the freeway can be made with one or no LC (improved example included in Appendix B)
- NW_{FR} = number of lanes from which a weaving manoeuvre from the freeway to the exit-ramp can be made with one or no LC (improved example included in Appendix B)

For simple weaves, all LC and NW values are equal to one. This results in a simplification of Equation 10 as follows in Equation 11.

$$S_0 = S_b - \alpha x \left(\frac{V_{RF} + V_{FR}}{N_{l-GP}^\varepsilon} \right)^\gamma x \left(\frac{V}{N_l} - 500 \right) x \left(\frac{1}{L_s} \right)^\delta \quad 11$$

It should be noted that the SIW formulation in this equation is identical to Equation 9, except that there is no more β coefficient included, i.e. the weighting of V_{RF} and V_{FR} is identical.

The final set of model parameters for both simple and complex weaves is given in Table 2.2.

Table 2.2: Parameter and RMSE values for proposed weave model

Weave	Description	α	γ	δ	ε	RMSE (mph)
Simple	$0 > \alpha \leq 0.025$, γ and δ are positive and unbounded, $\varepsilon \geq 3$	0.025	0.156	0.311	3.0	3.22
Complex	α is positive and unbounded $\gamma \geq 0.3$, $\delta \geq 0.4$, $0 > \varepsilon \leq 3$	0.056	0.300	0.400	3.0	4.86

Source: NCHRP 2023, Table 22

As with the previous STRIDE, the equation format, including the model coefficients, have been selected to achieve an optimal fit between measured and modelled speeds as, for example, shown in Figure 2.4.

Capacity model

For the extended STRIDE described above, the assumed breakdown density as per the HCM 6th edition was revised from 43 pc/mi/ln to 35 pc/mi/ln (Equation 12).

$$\frac{C_W}{35} = S_b(C_W) - SIW \quad 12$$

Also, a series of equations for the direct calculation of capacity based on Equation 10 is provided as follows in Equation 13.

$$C_W = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad 13$$

where

$$\begin{aligned} a &= 1 \\ b &= \frac{W}{B} + \frac{1}{35B} - 2BP \\ C &= BP^2 - \frac{FFS}{B} - \frac{500W}{B} \\ B &= \frac{FFS - S_C}{(C_b - BP)^2} \\ W &= \alpha x \left(\frac{\frac{(LC_{RF} + 1)}{(NW_{RF} + 1)} x V_{RF} + \frac{(LC_{FR} + 1)}{(NW_{FR} + 1)} V_{FR}}{N_l^\epsilon} \right)^\gamma x \left(\frac{1}{L_S} \right)^\delta \end{aligned}$$

The model parameters α , β , γ , and δ can be adopted from Table 2.2.

Discussion of the extended STRIDE model

The suggested refined HCM methodology described in NCHRP (2023) aims to determine the level of service (LOS) based on density as a function of the traffic volume. The calculation of the speed as per Equations 10 or 11 is an interim step on the way towards this aim. The corresponding model coefficient definition (multipliers/exponents) was undertaken so that the predicted speeds fit optimally to the observed speeds.

In contrast to the MCG methodology for the definition of MSFR values, which is used by MRWA and Vic DTP, capacity is not at the core of the extended STRIDE methodology which focused on the density and speed parameters. However, part of the research was to develop equations for the direct calculation of the capacity (Equation 13).

The extended STRIDE equation term makes intuitive sense, especially regarding:

1. putting the added weaving traffic in relation to the number of lanes
2. having L_S in the denominator of the final multiplier
3. weighting V_{RF} and V_{FR} equally.

Appendix A includes a comparison of capacity estimation qualities for the HCM and the extended STRIDE model (referred to as 'Revised NCHRP 07-26 Model' here). It shows that the revised NCHRP model improves the HCM estimation results although there are still significant discrepancies compared to the observed capacities (on average 14% and up to 40% of the observed capacity). Part of the reason for the discrepancy could be the HCM capacity estimation methodology that may have some flaws (e.g. capacity is assumed to occur at 15% FBR, which seems too high). Testing the methodology as part of this project, based on local data and using the MCG capacity estimation methodology, provided additional insights (Section 9).

Based on a personal discussion with Dr Nagui Rouphail, who provided significant input into the methodology development, the extended STRIDE model will be adopted for the next edition of the HCM. The corresponding HCM chapter is included in Appendix B. The L_{MAX} maximum weaving length criterion as per Equation 3 was removed from the newly suggested draft Chapter 13 (refer to Appendix B). However, it is still planned to apply this criterion in Chapters 12 (basic) and Chapter 14 (merge and diverge sections), i.e. before application of the procedures for these freeway section types, it will be tested if the problem is in fact a weaving problem. In this case, the user is directed to apply the Chapter 13 procedure. Long weaving

sections will analytically lead to small weaving problems because L_s is in the denominator of the W term in Equation 13.

Assessment

A detailed assessment of the extended STRIDE model in the different categories resulted in the following observations.

Scope

- The form of the developed models generally also applies to the more complex segment configurations, including complex weaves, 2-lane merges and diverges, and closely spaced merges and diverges.
- Two-sided weaves or multiple weaves (that is, weaving segments containing overlapping weaving movements between different sets of ramps) were not studied by the project. They are, therefore, also not covered by the developed model.

User-friendliness

- Capacity can be directly calculated based on a number of parameters (refer to Equation 13). The calculation appears complex but can be easily implemented in MS Excel.
- Like with the original HCM methodology, the resulting weaving area capacity can be divided by the base capacity. The resulting factor can then be multiplied by the MCG MSFR value, which results in the weaving area MSFR value.
- According to NCHRP (2023) the recommended methods are simpler to apply than the current HCM methods, requiring just 4 calculation steps:
 1. estimate and adjust the volumes within the segment
 4. estimate the segment's average speed
 5. estimate the segment's capacity
 6. estimate the segment's density and LOS.

The recommended models require fewer inputs than the HCM models, use inputs that are more likely to be available to practitioners, and are sensitive to the inputs included in the model.

Plausibility of procedure and equations

- The general speed model form for all 3 segment types (i.e. merging, diverging and weaving) shares the same consistent approach in which the average speed of an equivalent basic freeway segment (without ramp turbulence effects) is reduced to account for impedances due to the presence of merging, diverging or weaving manoeuvres.
- The model formulation is consistent with the fundamental speed–flow–capacity relationship.
- The recommended models are sensitive to the inputs included in the model.

Criticisms

- The report documented significant site-to-site variability, suggesting capacity variability between sites. This variability is likely attributable to differences in driver behaviour, the effects of pavement conditions and other site-specific nuances not observed or measured during the project (NCHRP 2023). This statement refers to the general uncertainty in capacity predictions, i.e. it should not necessarily be interpreted as criticism.
- The underlying assumption used for the determination of C_w – that breakdown of weaving segments is expected to occur when the average density of all vehicles in the segment exceeds 35 pc/mi/ln – may not always be realistic.
- No additional literature-articulating criticism has yet been identified.

2.1.3 Vic DTP 2021 TRB Annual Meeting Contribution (Zurlinden et al. 2021)

Introduction

The methodology was presented in a preliminary (draft) form at the 2021 TRB annual meeting (Zurlinden et al. 2021). It is based on the MSFR concept that is comprehensively described in VicRoads (2019a).

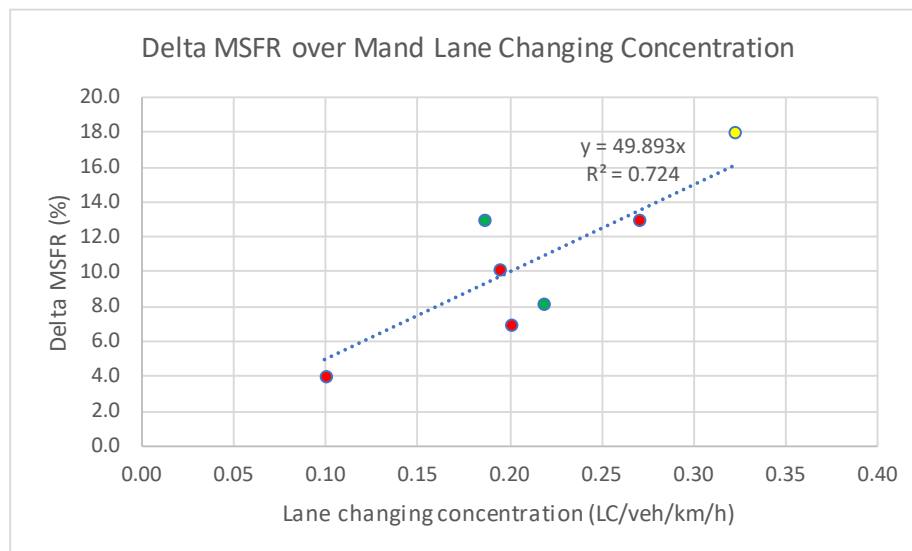
The intended output of this research was to provide a method for practitioners to reasonably estimate MSFR in weaving areas. The method would enable practitioners to determine lane changing within a defined weave length and then estimate an appropriate LCC for the weaving segment. Empirically derived MSFR adjustment factors associated with the estimated LCC rate could then be applied to the general MSFR without weaving to inform planning and design.

In terms of the methodology development, the principal idea was to put an MSFR loss measured in weaving segments in relation to the corresponding LCC that is caused by a combination of geometrical and traffic conditions such as the weaving area length and the percentage of weaving traffic in all traffic.

It is important to note that this methodology is not intended to produce the same sort of outcome as the HCM, especially not an estimate of the speed performance (or other measure) in a weave section under varying demands and weaving proportions. The approach is, in principle, to reduce complexity as much as possible in order to also reduce potential sources of errors or uncertainties.

The methodology established a functional (e.g. linear) relationship between the essential LCC across a 'critical line' in a weaving area and the MSFR loss compared to a freeway section with 'normal' lane changing intensity (i.e. a basic freeway section). Figure 2.5 illustrates the approach in principle.

Figure 2-5: Decrease in MSFR (per cent) over combined mandatory LCC and extended mandatory LCC



Source: Zurlinden et al. 2021

The LCC is defined as shown in Equation 14.

$$LCC = \frac{LC}{v * L_s}$$

where

LCC = lane changing concentration (LC/veh/km)

LC = number of mandatory and extended mandatory LC per hour (LC/h)

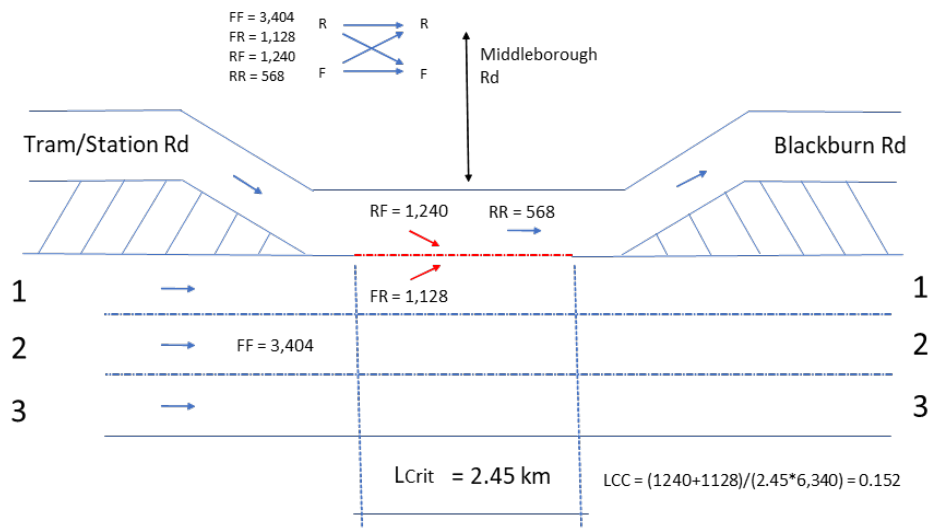
v = traffic volume (veh/h)

L_s = short length of the weaving section, i.e. length of the 'critical line' over which the mandatory LC must be made (km)

The inclusion of 'per vehicle' into Equation 14 ensures general applicability, irrespective of the traffic volume, which is linked to the capacity and to the number of carriageway lanes. Importantly, the number of LC refers to only those that **must** be made by weaving vehicles, e.g. by those that progress from A to D or from B to C in Figure 2.1 ('mandatory lane changes' = MLC), plus those that **must** be made to avoid MSFR exceedance due to the mandatory ones ('extended mandatory lane changes' = EMLC).

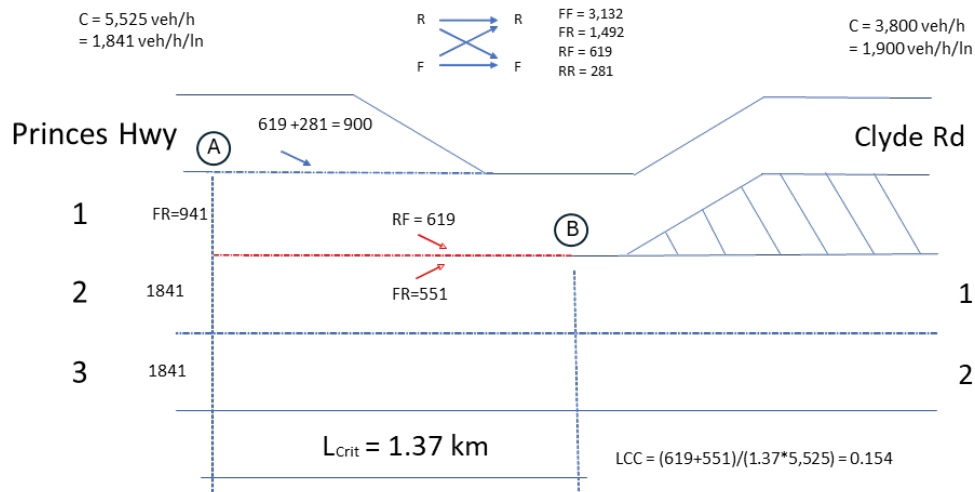
In the case of a simple weave, such as that shown Figure 2.6, the MLC cross a 'critical line' that separates the through lanes from the auxiliary lane. The length of this line can be easily defined as the distance between the end points of any barrier markings (e.g. solid white lines) that prohibit or discourage lane changing. The definition of this length is a bit more challenging in the case of a lane drop or lane add (Figure 2.7). For the illustrated lane drop, it is the length that is available for the RF movement to complete the weaving manoeuvre, i.e. the distance between the solid white line end at the Princes Highway entry ramp (Point A) and the start of the solid white line at the Clyde Road exit ramp (Point B). It is only the LC that must cross this line that are relevant to the developed approach.

Figure 2-6: 'Critical line' (red) for an auxiliary lane



Source: NTRO based on Zurlinden et al. 2021

Figure 2-7: 'Critical line'(red) for a lane drop



Source: NTRO based on Zurlinden et al. 2021

The example shown in Figure 2.7 also illustrates the estimation of MLC and EMLC: The FR movement of 1,492 veh/h cannot be entirely accommodated on the approaching Lane 1. This is because the capacity in this lane ($MSFR = C = 1,841 \text{ veh/h/ln}$) is partially consumed by the RF and ramp-to-ramp (RR) movements (900 veh/h). Hence, the remainder of the FR number of vehicles ($1,492 - 941 = 551 \text{ veh/h}$) must also cross the 'critical line'.

Capacity calculation

The LCC parameter is calculated by estimating the number of MLC and EMLC and dividing this by the total number of vehicles on the carriageway and by the length of the 'critical line' (Equation 14).

LCC is the input parameter for the diagram shown as Figure 2.5. The resulting Delta MSFR in per cent must be subtracted from 100 per cent and the base MSFR value sourced from VicRoads (2019a) must be multiplied by this percentage (Equation 15).

$$MSFR_{\text{Weave}} = MSFR_{\text{Base}} * (100 - \text{Delta MSFR})$$

15

where

$MSFR_{\text{Weave}}$ = MSFR for the weaving area (veh/h)

$MSFR_{\text{Base}}$ = MSFR for a basic freeway section (veh/h)

Delta MSFR = reduction due to weaving turbulence (%)

Table 2.3 shows an example of the base MSFR values sourced from VicRoads (2019a).

Table 2.3: MSFR values sourced from

Number of lanes	HGV percentage (%)						
	0%	5%	10%	15%	20%	25%	30%
2	4,175	3,975	3,800	3,625	3,475	3,325	3,200
3	6,050	5,775	5,525	5,250	5,050	4,850	4,625
4	7,800	7,450	7,125	6,775	6,500	6,225	5,975
5	9,275	8,875	8,475	8,050	7,750	7,425	7,100

HGV = Heavy goods vehicles.

Source: VicRoads (2019a).

Discussion

This methodology encompasses the following characteristics:

- compatibility with the MCG MSFR concept (application of just one adjustment factor)
- transparency regarding the LCC factor that reduces capacity, i.e. it is intuitive that a high LCC (many LC per vehicle that must be performed over a short length) has a capacity reducing influence.

The turbulence caused by the weaving-related MLC and EMLC is put in relation to the total number of vehicles (i.e. the 'per vehicle' component). This makes intuitive sense, since a greater traffic volume (number of lanes/capacity) can more easily absorb such disruptions. The number of measurement points used for the development of the functional relationship shown in Figure 2.5 is low (7). It could therefore be argued that, based on a greater sample size, the shape of the function might change. Differences between the measurement points and the trendline are relatively significant (up to 44% in terms of Delta MSFR and up to 4% in terms of the resulting, reduced MSFR).

It would be important to see how a greater sample size impacts the trendline.

Assessment

A detailed assessment of the methodology from the Vic DTP 2021 TRB annual meeting contribution resulted in the following conclusions regarding the different categories.

Scope

- The methodology is applicable to simple and complex weaving area configurations, including lane adds and lane drops.

User-friendliness

- The application of the methodology is very simple once the LCC has been properly defined.
- Better guidance should be developed for the definition of the
 - number of EMLC
 - L_s /critical length of the weaving sectionso that there is less ambiguity for practitioners applying the method.
- It would be more user friendly to show 'Reduced MSFR' rather than 'Delta MSFR' in Figure 2.5. This could be easily done by creating another diagram that shows the decline of the remaining MSFR depending on the LCC, starting at a value of 100%.

Plausibility of procedure and equations

- The LCC unit in Figure 2.7 appears to be incorrect; rather than LC/veh/km/h it should be LC/veh/km, based on the input parameters and their units, refer to Equation 14
- It is intuitive that a high LCC has a capacity-reducing influence (many LC that must be performed over a short length)
- It is also intuitive that a very low 'critical length' leads to a very high LCC and capacity reduction (i.e. L_s is in the denominator of the LCC calculation as is also the case with the extended STRIDE methodology described in Section 2.1.2).

Criticisms

- The number of measurement points used for the development of the functional relationship between LCC and capacity loss (Delta MSFR) is too low for a methodology mature enough to be recommended for use

by practitioners. It should be noted that, for the MCG, the number of measurement sites was only 10. This is therefore regarded as the minimum target number for a potential improvement of the methodology in the context of this study (the greater the sample size, the higher the quality).

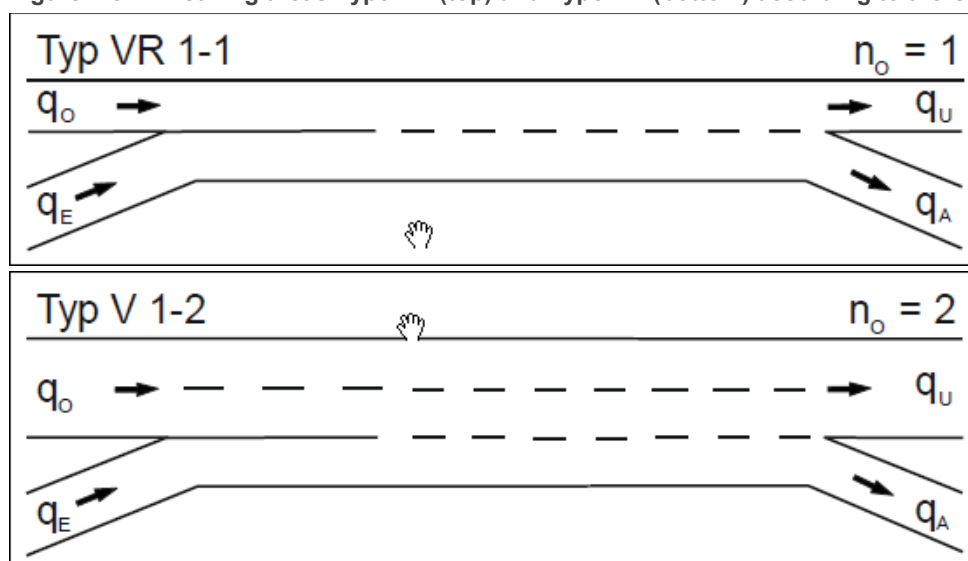
- There is some ambiguity for practitioners applying the method (number of EMLC, short length/critical length of the weaving section), i.e. current user guidance is insufficient. Additional guidance should be developed for complex weaves as shown in Figure 2.2 and Figure 2.3.

2.1.4 German HCM (FGSV 2015)

The German HCM (Handbuch fuer die Bemessung von Strassenverkehrsanlagen, FGSV 2015) was included in this analysis because it has informed the development of the MCG. It was considered more reliable in terms of realistic capacity value estimation than the HCM, and therefore, it was used in Victoria for design before the MCG was developed. Some of the German HCM principles were adopted for the development of the MCG speed-flow diagrams and FBR curves (e.g. long-term observations needed over at least one month, average speed for density classes calculated and used for the speed flow curve generation).

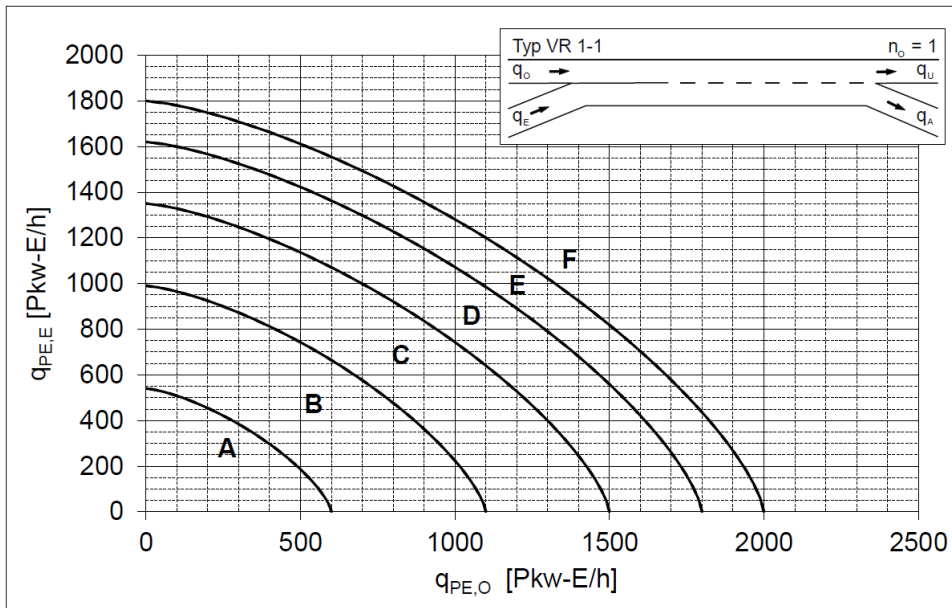
The German HCM only covers standard weaving areas as shown in Figure 2.8 and Figure 2.9. These arrangements can typically be found in the so-called ‘cloverleaf’ motorway interchanges, which are the standard solution on the German motorway network. This motorway network is generally more standardised than in other countries. Especially, in Australia, there are many different interchange forms (e.g. diamond interchanges). Also, the weaving problem is often linked to lane adds or lane drops.

Figure 2-8: Weaving areas Type 1-1 (top) and Type 1-2 (bottom) according to the German HCM



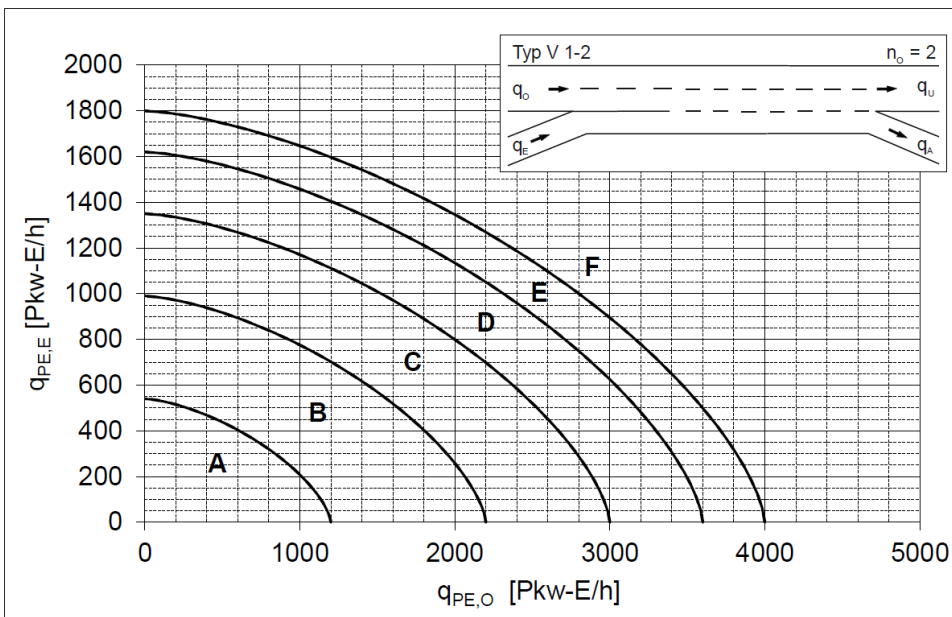
Source: FGSV (2015).

Figure 2-9: LOS of a weaving area Type VR 1-1 according to the German HCM



Source: FGSV (2015).

Figure 2-10: LOS of a weaving area Type VR 1-2 according to the German HCM



Source: FGSV (2015).

The German HCM methodology defines the expected LOS as a function of the following input parameters:

- q_o (Figure 2.8) or $q_{PE,O}$ (Figure 2.9 and Figure 2.10) where PE stands for Pkw-h or passenger car equivalents per hour. It should be noted that q_o is the sum of q_{FF} and q_{FR} .
- q_e (Figure 2.8) and $q_{PE,E}$ (Figure 2.9 and Figure 2.10) where PE stands for Pkw-h or passenger car equivalents (or passenger car units - PCU) per hour. q_e is equivalent to q_{RF} .

It appears that the value for q_{FR} is insufficiently covered by this methodology. For example, if q_{FR} (or q_A in the figures) is close to or equal to 0 then this problem is different compared to a case when q_{FR} is close to q_o , i.e. when the main carriageway upstream traffic is almost entirely made up of traffic exiting through the downstream ramp.

The following conclusions can be drawn regarding the suitability of the German HCM weaving capacity analysis for local use:

- The guideline only covers a small subset of all potential weaving area types in the context of Australian and New Zealand major conurbations and metropolitan freeways/motorways
- It appears that the methodology used for the analysis of the remaining standard cases covered is not transparent.

Especially, due to the limited **scope**, the German HCM methodology was not pursued for this study.

2.1.5 Dutch HCM (Henkens & Heikoop 2015)

The Dutch HCM (Capaciteitswaarden Infrastructuur Autosnelwegen, Henkens & Heikoop 2015) includes capacity values for discrete parameter values such as:

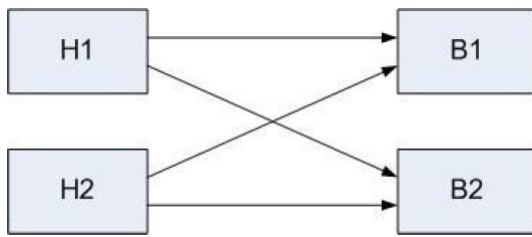
- number of lanes for the main carriageway (or collector-distributor carriageways) and ramps (Dutch: weefvak configuratie)
- weaving area length (Dutch: weefvaklengte)
- traffic stream relations H2 -> B1 and H1 -> B2 (percentages v_{RF} and v_{FR} in all weaving traffic).

These values are based on FOSIM microsimulations that were undertaken for the development of the guideline. Interpolations are permitted for small parameter value differences only. No further specification is included in the guideline as to what 'small' means in this context. With greater differences, microscopic traffic modelling must be done (using FOSIM software).

Figure 2.11 shows the capacity values for symmetrical weaving areas with a 15% HV percentage. Symmetrical means that the number and type of lanes is the same at the entry point as at the exit point.

Figure 2-11: Capacity values in vehicles per hour ('mvt') for symmetrical weaving areas with a 15% HV percentage (e.g. 'weefvak 2+1' means 2 main carriageway lanes and 1 weaving/auxiliary lane)

weefvak configuratie	weefvaklengte [m]	H2 -> B1 ⁴ [%]	H1 -> B2 ⁵ [%]	capaciteit [mvt/h]
weefvak 1+1 ⁶	200	100 %	100 %	1.750
weefvak 2+1	600	50 %	25 %	5.590
		75 %	38 %	5.100
		100 %	50 %	4.860
weefvak 1+2	700	25 %	50 %	5.330
		50 %	100 %	4.520
weefvak 3+1	700	50 %	17 %	7.570
		75 %	23 %	6.840
		100 %	33 %	6.440
weefvak 2+2	750	25 %	25 %	7.690
		50 %	50 %	6.640
		75 %	75 %	5.620
weefvak 4+1	700	50 %	13 %	9.310
		75 %	19 %	8.450
		100 %	25 %	7.980
weefvak 3+2	900	25 %	17 %	9.710
		50 %	33 %	8.290
		75 %	50 %	6.790
weefvak 4+2	900	25 %	13 %	11.710
		50 %	25 %	9.880
		75 %	38 %	8.000
weefvak 3+3	1000	25 %	25 %	10.660
		50 %	50 %	7.810
		75 %	75 %	6.250
weefvak 5+1	700	50 %	10 %	11.090
		75 %	15 %	10.150
		100 %	20 %	9.130



Source: Henkens & Heikoop (2015).

The following conclusions can be drawn regarding the suitability of the Dutch HCM weaving capacity analysis for local use:

- The developed capacity tables only cover standard lane configurations for discrete geometrical and traffic condition parameter values.
- In the case of non-standard conditions, which are most real-world cases, the discrete parameter values require interpolations which are only allowed under the condition of small deviations from standard conditions. If this condition is not met, then microscopic simulation must be undertaken.
- The intent of the guidance text envisaged to be produced as a result of this study is that no microsimulation will be needed as this is resource consuming and often prone to error (in fact, the guideline should inform traffic modelling, not vice versa).

Especially due to the limited **scope** of the developed capacity tables, the Dutch HCM methodology was not pursued for this study.

2.1.6 Others

NSW RMS Motorway Design Guide

The New South Wales Roads and Maritime Services (NSW RMS) *Motorway Design Guide: Capacity and Flow Analysis* (RMS 2017) states that the 5th edition of the HCM (TRB 2010) provides guidance for the calculation of capacity in weaving areas; however, researchers have raised concerns that the methods tend to overestimate capacity. References to multiple literature sources are provided in the design guide to underpin this statement.

The *Motorway Design Guide* notes that, 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%
- a capacity value equivalent to a basic segment of an unmanaged motorway
- a reduction equivalent to the number of lane-changing movements expected.

This relatively basic advice can be seen as the starting point for this study. The information identified is not relevant to the development of the envisaged new, improved methodology.

UK TA 79/99

The Technical Advisory Note 79/99 (TA 79/99) as part of the UK *Design Manual for Roads and Bridges (DMRB)* (UK Highways Agency 1999) was reviewed because it was used for the development of VicRoads (2019a). The note was withdrawn in 2020. No methodology for the definition of capacity based on weaving traffic was included in the TA.

Swedish HCM

The Swedish HCM (Trafikverket, 2014) contains a set of formulas similar to the HCM, one for the direct calculation of capacity values for weaving areas that include an auxiliary lane. Three different formulas reflecting the number of main carriageway lanes from 1 to 3 plus an auxiliary lane are provided, where the example for 2 carriageway lanes is provided below in Equation 16.

16

$$K_V = 4150 - 0,0065 \cdot \left(\frac{q_{AV}}{q_{PA} + 1} \right)^{0,1} \cdot (0,43 \cdot q_{AV} + 1,87 \cdot q_{PA}) \cdot \left(1 + (q_{AV}^{1,4} \cdot q_{PA})^{0,3} \right) + 3,44 \cdot (L - 250)^{0,875}$$

where

- K_V = capacity of the weaving area (veh/h)
- q_{AV} = volume of exiting traffic (veh/h), equivalent to V_{FR}
- q_{PA} = volume of entering traffic (veh/h), equivalent to V_{RF}
- L = length of the weaving segment between the barrier markings (m)

The scope of this methodology is quite limited (1 to 3 carriageway through lanes plus auxiliary lane). It should be noted that typical carriageway cross-sections under Australian and New Zealand metropolitan conditions often have more than 3 lanes (refer to Table 3.4 and Table 3.5 in Section 3). Also, there is not always an auxiliary lane associated with a weaving problem. This methodology was therefore not pursued.

2.2 Comparison and Conclusions

This section summarises the assessment of the following analysis methodologies for weaving area capacity that were reviewed as documented in Section 2.1.

- HCM 7th edition
- NCHRP Report 1038 (extended STRIDE model)
- Vic DTP 2021 TRB annual meeting contribution
- German HCM
- Dutch HCM.

Table 2.4 shows an overview of the assessment results. The scope criterion was seen as critical because comprehensive coverage of most real-life scenarios including lane adds and lane drops is essential to creating a suitable methodology. Any methodology included in the next project stages had to provide comprehensive coverage.

The scope criterion ruled out the HCM 7th edition, the German HCM and the Dutch HCM methodologies from further analyses due to their lack of comprehensive coverage.

The STRIDE UTC, recalibrated STRIDE and extended STRIDE models are different development stages towards a more comprehensive and accurate methodology. In this sense, only the latest development stage i.e. the extended STRIDE was pursued.

Whilst the extended STRIDE model, which is recommended for the next HCM edition, is ready to be tested, the Vic DTP 2021 methodology was further developed as part of this study (greater sample size and improved user guidance), before testing it based on Western Australian, Vic DTP and Queensland real-world examples. The resulting accuracies of the predicted capacities could then be used as a second crucial criterion for the required methodology selection process.

As a conclusion, only the extended STRIDE and the Vic DTP 2021 methodologies were recommended for further development/testing. All other methodologies have identified deficiencies that are too severe for these methodologies to be further pursued.

Table 2.4: Overview of the assessment of the different methodologies analysed

	HCM 7th edition	Extended STRIDE	Vic DTP 2021	German HCM	Dutch HCM
Scope	Some gaps	Comprehensive	Comprehensive	Limited (cloverleaf type weaving areas only)	Limited (discrete geometries/traffic conditions only)
User-friendliness	Direct capacity calculation	Direct capacity calculation	Easy to use (generally) Estimation of MLC and EMLC required	Easy to use	Interpolations required
Criticisms	Several (refer to Section 2.1.1)	None	Insufficient number of measurement points and lack of user guidance	N/A	N/A
Consistency of the calculation method	Equation terms not intuitive	Equation terms intuitive		N/A (graph)	N/A (microsimulation based)
Accuracy	N/A	To be added after testing	To be added after testing	N/A	N/A

3 Measurement Sites and Data Specification

Several weaving areas in Western Australia and Victoria were identified to investigate the impact of weaving on capacity. The selected measurement sites and data required for the analysis are described in this section.

3.1 Selected Measurement Sites

The project first aimed to establish a capacity baseline to represent capacity values for 'normal' freeway sections that are not impacted by weaving or excessive lane changing. For this purpose, several bottlenecks on the Western Australian freeway network were identified and the corresponding traffic data was requested and delivered. The corresponding bottlenecks are described in Section 3.1.1. This step was not needed for the Victorian motorway sections since a corresponding guideline defining base capacities for 'normal' motorway sections already exists (VicRoads 2019a).

The project's second aim was to identify enough weaving area bottlenecks where the capacity loss compared to the baseline can be measured, as well as the LCC. This is described in Section 3.1.2. This step was done for Western Australia as well as for Victoria. All sites are shown in the maps provided in Appendix C.

The National Transport Research Organisation (NTRO) requested vehicle data station (VDS) data (parameters: SVO) over an entire month (February 2025) for the following freeways in Western Australia:

- Kwinana Freeway northbound (NB)
- Kwinana Freeway southbound (SB)
- Mitchell Freeway NB
- Mitchell Freeway SB
- Graham Farmer Freeway eastbound (EB)
- Graham Farmer Freeway westbound (WB).

The MRWA Traffic and Road Network Performance team provided NTRO with data for 28 days between 5 am and 9 pm in 1-minute granularity for all detector sites along these freeways. This period covers the times that are most relevant to capacity estimation, namely the morning and evening peaks where congestion occurs. The provision of this comprehensive dataset allowed for the needed flexibility in determining and analysing all potential bottleneck locations within the high-volume sections of the freeway network.

MRWA also provided NTRO with so-called 'heat plots' showing congestion hotspots (bottlenecks) in the time space plane. Figure 3.1 shows an example of a heat plot for the Mitchell Freeway NB. Congestion hotspots are visible as red or orange horizontal lines, where these colours indicate lower than FFS speeds (red < 30 km/h, orange = 30–50 km/h).

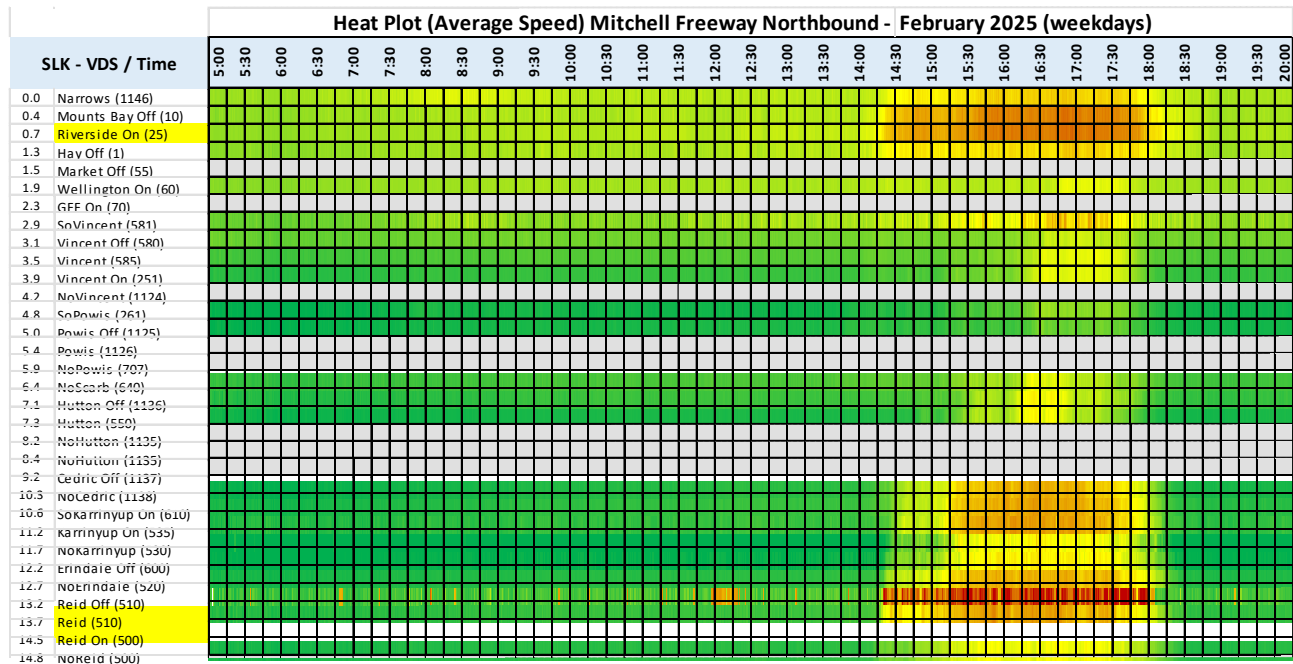
Finally, MRWA provided NTRO with OD data sourced from TomTom probe data for the identified weaving areas (refer to Section 3.1.2). The purpose of the corresponding NTRO request was to quantify the relative relation between the following traffic streams/movements:

- Freeway to freeway (FF)
- Ramp to freeway (RF)
- Freeway to ramp (FR)
- Ramp to ramp (RR).

The established methodologies for the analysis of weaving areas use these relations as input parameters. Whilst probe data does not describe the characteristics of the entire vehicle fleet (i.e. penetration rate 10–30%, rather than 100%), it is assumed that the relative relation between the quantities of the traffic streams is representative. This assumption is supported by the results of a discussion with the MRWA Project Manager involved, where TomTom data and the relation with 'ground truth' (i.e. the complete vehicle fleet)

was presented. The slides presented during this meeting showed a high correlation between TomTom data and ground truth.

Figure 3-1: Heat plot for the Mitchell Freeway NB



3.1.1 Freeway Bottlenecks for Base Capacity (Western Australia)

Western Australia

Freeway bottlenecks were identified based on the following steps:

- identification of freeway bottlenecks using heat plots (Figure 3.1)
- analysis of the lane configuration using aerial images
- site visits undertaken between 07 April 2025 and 24 April 2025.

Table 3.1 shows the identified bottlenecks.

Table 3.1: Bottlenecks on the Western Australian freeway network selected for further analysis

	Freeway	Direction	From	To	Mainline lanes	Comment
1	Mitchell Freeway	SB	Hepburn Ave	Warwick Rd	3	Managed
2			Reid Hwy	Erindale Rd	3	Managed
3	Kwinana Freeway	NB	Mortimer Road	Thomas Rd	2	Unmanaged
4			Anketell Road	Rowley Road	2	Unmanaged
5			Rowley Road	Russell Road	2	Unmanaged
6		SB	Manning Rd	Cranford Ave	3	Unmanaged
7			Russell Rd	Rowley Road	2	Unmanaged
8			Anketell Rd	Thomas Rd	2	Unmanaged
9			Thomas Rd	Mortimer Rd	2	Unmanaged

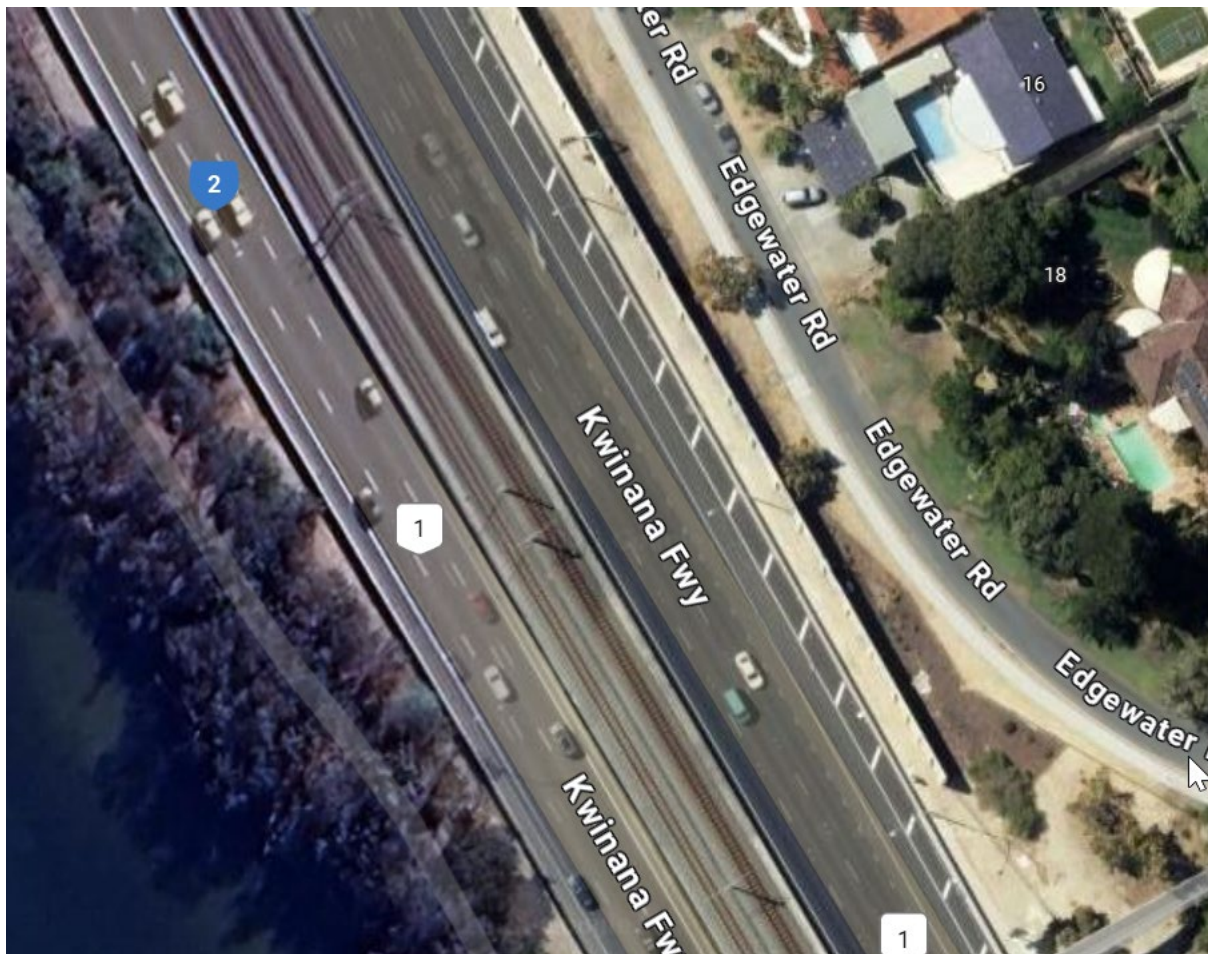
The bottleneck between Manning Road and Cranford Avenue (Figure 3.2) was originally assessed as a potential weaving area (following a discussion with MRWA Network Operations stakeholders on 10 April 2025). However, the lane reduction from 4 to 3 to the south of Manning Road is not directly associated with an exit-ramp but rather with a lane merge before the next exit-ramp. No traffic stream must cross another traffic stream on this section. The section was, therefore, considered a 'normal' freeway bottleneck.

In addition, and to increase the sample size for increased reliability of the analysis results, 3 sites from the Kwinana Freeway in the NB direction for the period before the upgrade to a Smart Freeway were also included in the analysis (refer to Table 3.2). The corresponding data was available from an earlier study undertaken (Main Roads, 2024).

Table 3.2: Additional bottlenecks on the Western Australian freeway network selected for further analysis (unmanaged, before the upgrade of the Kwinana Freeway to a Smart Freeway)

	Freeway	Direction	From	To	Mainline lanes	Comment
10	Kwinana Freeway	NB	Canning Hwy	Mill Point Rd	3	Unmanaged
11			Cranford Ave	Manning Rd	3	Unmanaged
12			Leach Hwy	Cranford Ave	3	Unmanaged

Figure 3-2: Freeway bottleneck between Manning Road and Cranford Avenue



Source: Google Maps (2025), NTRO Perth, map data, Google, California, USA.

Also, 2 additional bottlenecks were identified for the Kwinana Freeway NB between Farrington Road and Narrows Bridge after the upgrade to a Smart Freeway (Table 3.3). Capacity values are expected to be higher on smart freeways than on unmanaged sections. The analytical challenge is exacerbated by the fact that this section was considered partially managed during the Kwinana Smart Freeway Evaluation (MRWA 2024) mainly because of an unmetered ramp at the Manning Road entry.

The Mitchell Freeway, Kwinana Freeway and Graham Farmer Freeway are generally heavily saturated during peak hours, i.e. there are usually upstream and/or downstream bottlenecks with varying severity. Detector locations are generally densely spaced, i.e. around 500–1,500 m for Smart Freeway and high-volume sections (representing the majority) and greater (up to 7.5 km) for lower volume sections.

Table 3.3: Additional bottlenecks on the WA freeway network selected for further analysis (managed, after the upgrade of the Kwinana Freeway to a Smart Freeway)

	Freeway	Direction	From	To	Mainline lanes	Comment
13	Kwinana Freeway	NB	Cranford Ave	Manning Rd	3	Managed
14			Leach Hwy	Cranford Ave	3	Managed

Victoria

For the Victorian motorway network, no 'normal' bottlenecks were identified as part of this project because a baseline showing capacity values for sections unaffected by weaving and higher than normal LCC has already been developed (refer to VicRoads 2019a).

Conclusion

A minimum of 10 bottlenecks is needed to establish a robust capacity baseline (the greater the sample size, the higher the quality). This is based on the information provided in the MCG where 10 sites were needed to complete the guide, which includes capacity guidance for Victorian basic motorway sections under a variety of circumstances (VicRoads 2019a). The view at the time was that enough bottlenecks are available. The needed SVO data was provided by MRWA.

3.1.2 Freeway/Motorway Weaving Area Bottlenecks (Western Australia and Victoria)

Western Australia

Weaving areas were identified based on the following steps:

- identification of freeway bottlenecks using heat plots (Figure 3.1)
- analysis of the lane configuration using aerial images (e.g. auxiliary lanes, lane adds/lane drops indicating crossing traffic streams which correspond to weaving)
- discussion with MRWA Network Operations stakeholders on 10 April 2025
- site visits undertaken between 7 and 24 April 2025.

Table 3.4 shows the identified weaving areas.

Table 3.4: Weaving areas on the Western Australian freeway network selected for further analysis

	Freeway	Direction	From	To	Mainline lanes	Comment
1	Mitchell Freeway	NB	Reid Hwy	Warwick Rd	4	Auxiliary lane (included in the lane count)
2		SB	Powis St	Vincent Street	5	Auxiliary lane (included in the lane count)
3	Kwinana Freeway	NB	Mill Point Rd on	Mill Point Rd off	5	Lane add
4	Reid Highway	EB	Malaga Dr	Tomkin Hwy	3	Auxiliary lane

Some photos taken from the first 2 weaving areas are shown in Figure 3.3 and Figure 3.4.

Figure 3-3: Weaving area on Mitchell Freeway NB between Reid Hwy and Warwick Road (left: facing north, right: facing south, photos taken from the Guinevere Way/Walter Way pedestrian overpass)



Figure 3-4: Weaving area on Mitchell Freeway SB between Powis Street and Vincent Street (left: facing north, right: facing south, photos taken from the Britannia Road pedestrian overpass)



Whilst the first 3 identified weaving areas appear to be standard cases, the fourth one is located on a highway rather than on a freeway. There are no heat plots available for this area, and it is characterised by a lower density of detector sites. The suitability of the area for the subsequent analysis was therefore unclear.

The Mitchell Freeway and Kwinana Freeway are generally heavily saturated during peak hours, i.e. there are usually upstream and/or downstream bottlenecks with varying severity. It was therefore challenging to analyse the weaving area bottlenecks independently of the downstream bottlenecks forming in the peaks. During the development of the *Vic DTP Managed Motorway Design Guide* (VicRoads 2019a), techniques were developed that generally allow for this.

Another challenge associated with the analysis is that weaving areas with an auxiliary lane, compared to the surrounding network, provide additional capacity to absorb the weaving movements. It was therefore anticipated that less flow breakdown and congestion events than on the 'normal' bottlenecks listed in Section 3.1.1 would be observed here. This could make the generation of FBR curves difficult, where a minimum of 10 flow breakdown events (as a general rule) is needed for reliable curves.

Additional locations such as the ones between Murray Street and Riverside Drive (Mitchell SB), between Riverside Drive and Hay Street (Mitchell NB) and between South Street and Leach Highway (Kwinana NB) were also considered. Following detailed analysis and a discussion with MRWA Planning and Technical Services and Network Operations, it was decided not to pursue these options. Reasons for this decision were:

- the complexity of these sections linked to a predicted difficulty in separating the problem from other congestion causes such as spillback from further downstream
- anticipated problems with measuring lane changing on these sections with additional equipment such as cameras
- weaving but not 'mandatory' weaving in the case of the South Street to Leach Highway section.

There is a high density of VDS on the Mitchell and Kwinana freeways in the relevant sections. This means that it was possible to source the relevant data as listed in Section 3.1.1 close to the bottleneck and to select a control section downstream of the bottleneck to ensure that intervals when congestion spilled back from downstream did not corrupt the analysis.

The following additional data types were needed for the analysis:

- Origin-Destination (OD) data (ratio of FF, RF, FR and RR movements)
- LC during peak hours between the end of the entry ramp nose and the start of the exit ramp nose (based on ANPR techniques).

There was no The Infra-Red Traffic Logger (TIRTL) data available on the weaving areas listed in Table 3.4, i.e. video analytics for ANPR was needed to quantify lane changing.

Victoria

For the Victorian motorway network, no 'normal' bottlenecks were identified as part of this project because a baseline showing capacity values for sections unaffected by weaving and higher than normal LCC has already been developed (refer to VicRoads 2019a).

Weaving areas were identified based on the previous Vic DTP work (Zurlinden et al. 2021) and confirmation with the Senior Specialist Managed Motorways and Network Optimisation at Vic DTP. The weaving areas on the Victorian motorway network that were analysed for this project are shown in Table 3.5. These sites were used for the previous Vic DTP work and presented at the 2021 TRB annual meeting. Additional weaving areas were identified in a session with the Senior Specialist Managed Motorways and Network Optimisation at Vic DTP on 01 May 2025. These are shown in Table 3.6. Number 5 and number 10 were both included in the study despite their being the same freeway section. Number 5 was analysed for the lane configuration before the most recent Monash Freeway upgrade, whereas number 10 was analysed for the lane configuration after the upgrade.

It should be noted that some of these weaving areas required further assessment of their suitability for this study. For example, in the case of numbers 7 and 13, there can be queuing back from the exit ramp that causes flow breakdown and congestion events. The exit ramp detectors were used to control for this. Similarly, there could be a stronger downstream bottleneck due to the lane reduction downstream of Sydney Road in the case of number 14. Again, a suitable downstream detector site was used to control for this, as is routinely done for normal bottleneck capacity estimation.

For all sites except for the Eastern Freeway, TIRTL data was available as VDS data (parameters: SVO) and as lane changing data between a VDS just upstream of the weaving area and just downstream of it (refer to Figure 3.5). This data was used to estimate the LCC as described in Section 2.1.3. It also allowed for OD

data generation. For the Eastern Freeway sites, OD data was available from a traffic count that was also used for the previous Vic DTP work. A similar OD pattern was assumed for current conditions.

Table 3.5: Weaving areas on the VIC motorway network selected for further analysis

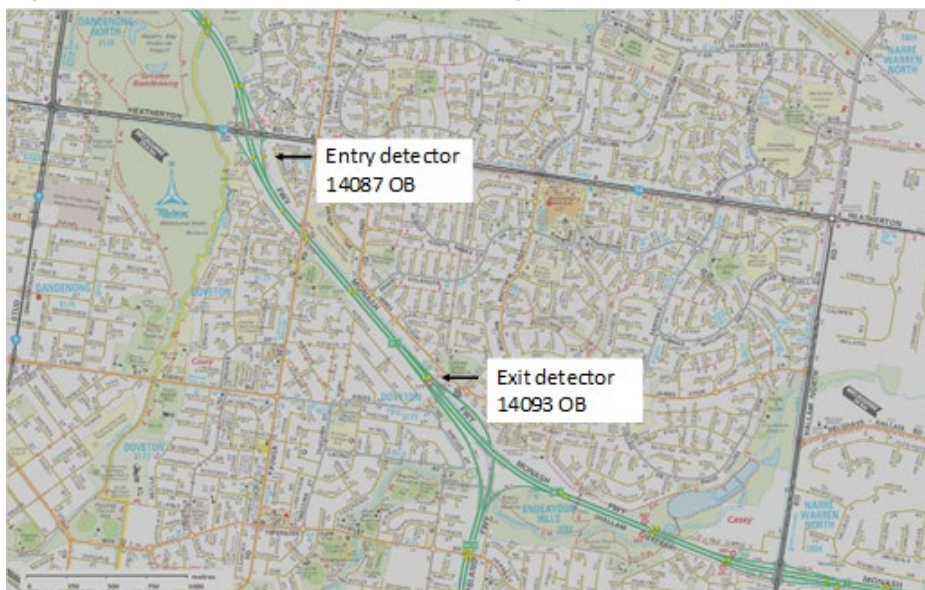
	Freeway	Direction	From	To	Mainline lanes	Comment
1	Monash Freeway	OB	Eastlink	Stud Rd	5	Lane add
2		IB	Stud Rd	Eastlink	5	Lane drop
3		OB	Heatherton Rd	South Gippsland Fwy	5	Freeway bifurcation
4		IB	South Gippsland Fwy	Heatherton Rd	5	Freeway merge
5		OB	Princes Hwy	Clyde Rd	3	Lane drop, old lane configuration
6		IB	Clyde Rd	Princes Hwy	4	Lane add, old lane configuration
7	Tullamarine Freeway	IB	English St	Calder Fwy	4	
8	Eastern Freeway	OB	Tram Rd	Blackburn Rd	4	No TIRTL
9		IB	Blackburn Rd	Tram Rd	4	No TIRTL

Note: IB = Inbound, OB = Outbound.

Table 3.6: Additional weaving areas identified

	Freeway	Direction	From	To	Mainline lanes	Comment
10	Monash Freeway	OB	Princes Hwy	Clyde Rd	4	Auxiliary lane, new lane configuration
11		IB	Clyde Rd	Princes Hwy	4	Auxiliary lane, new lane configuration
12		OB	Wellington Rd	Eastlink	5	Lane drop
13	Tullamarine Freeway	OB	M80 Ring Road	Mickleham Rd	4	Auxiliary lane
14	M80 Ring Road	WB	Hume Freeway	Sydney Rd	5	Auxiliary lane plus lane add

Figure 3-5: TIRTL detector locations (configuration in principle)



Like the analysed Western Australian freeways, the Monash Freeway is generally heavily saturated during peak hours, i.e. there are usually upstream and/or downstream bottlenecks with varying severity. Previous analyses have shown that it is possible to isolate congestion events caused by reduced capacity on the weaving section from others occurring downstream.

The VDS density on the discussed Victorian motorway sections is very similar to the Western Australian ones. This is because fundamentally the same guidelines are used for planning and design of Smart Freeways/managed motorways. This means that it was possible to undertake all the needed analysis steps as described for the Western Australian sites above.

Conclusion based on identified Western Australian and Victorian sites

The aim of the weaving area identification was to maximise the sample size. Like for the creation of a capacity baseline (Section 3.1.1), a minimum of 10 weaving areas were needed to complete the Vic DTP 2021 methodology (the greater the sample size, the higher the quality). This statement was again based on the information provided in the MCG where 10 sites were needed to complete the guide that includes capacity guidance for Victorian basic motorway sections under a variety of circumstances (VicRoads 2019a). The view at the time was that enough weaving areas were available, despite technical challenges to source the needed lane changing data on the Western Australian freeway network. Vic DTP had indicated that the needed TIRTL data including SVO and LC data could be provided according to the project time plan. Some of the listed Western Australian and potentially also Vic DTP weaving areas were later used for methodology testing of the extended STRIDE as well as of the refined Vic DTP 2021 methodology. It is important in this context that only those sites not used for methodology development were used for testing of the corresponding methodology and that there were some sites that could be used to test both alternative methodologies. A separate test plan including definition of test areas was developed as part of the testing described in Section 9. This included additional sites compared to those listed in the previous sections.

3.2 Specification of Data Types for Subsequent Analyses

SVO data over a full month in fine granularity (e.g. 1-minute resolution), sourced from multiple VDS in high density (e.g. 500 m) were required for reliable capacity definition. This was available for the sites discussed in Section 3.1 with the exception of the Reid Highway weaving area.

The following additional data types were needed for the analysis of weaving areas as discussed in Section 3.1.2:

- LC during peak hours between the end of the entry ramp nose and the start of the exit ramp nose (refer to Figure 3.5)
- OD data (ratio of FF, RF, FR and RR movements).

The following minimum requirements apply to the required lane changing data:

- number of LC per hour between Lane X (or entry ramp) at the section entry and Lane Y (or exit ramp) at the section exit
- data measured over 3 peak period hours in the relevant peak direction and over 5 working days (i.e. 15 hours per site).

The example in Figure 3.6 shows TIRTL-sourced data. The table shows the number of vehicles that have progressed from Lane X at the entry detector to Lane Y at the exit detector during a specific hour of the day. According to the CEOS TIRTL numbering system (different to the Vic DTP usual one), lanes are counted from the outer carriageway edge to the median edge (refer to Figure 3.7).

Given that the entry detector site on the M1 Monash Freeway only has 3 lanes and the exit detector site has 5 (including 2 additional ones coming from the South Gippsland Freeway = SGF in the figure), vehicles that have not changed lanes are described by the 1->3 movement (i.e. 120 vehicles for the first hour between midnight and 1 am). Vehicles associated with all other movements (i.e. 119 in total for this hour) have made LC. It can be seen from the example that many vehicles have moved from the 3 M1 lanes at the entry site to

the outer lanes at the exit site (63 with one LC, represented by the 1->2 movement, and 49 with 2 LC, represented by the 1->1 movement). Vehicle movements characterised by the @ symbol are those that were not re-identified at the exit site. These are vehicles that have most likely left the system, i.e. in this case, they have exited at the next downstream exit ramp (Heatherton Road).

The column 'Total O1' shows the total number of vehicles that were analysed. It should be noted that this is only a subset of all vehicles that have driven on the analysed motorway section during the investigated times. The column 'LC O1' shows the number of vehicles that have undertaken LC (i.e. not the total number of LC, as some vehicles have made multiple LC).

Regarding the lane changing data, TIRTL data is available for the Victorian weaving areas and additional measurements were necessary for the Western Australian ones. This could be done through video analytics, combined with ANPR.

Regarding the OD data, the ratios of the different movements (i.e. the percentages of the total cross-section volumes) during peak hours were regarded as sufficient. This can be based on TIRTL data, traffic counts or TomTom data. Video analytics/ANPR are a complementary data source. In terms of the OD data coverage duration, the same requirement as for the lane changing data applies, i.e. OD data indicating the different movements (FF, RF, FR and RR) covering the working day peak periods over one week had to be supplied.

Figure 3-6: TIRTL data produced at Victorian weaving areas and lane numbering (to be read in conjunction with Figure 3.7)

datetime	1->1	1->2	1->3	1->4	1->5	1->@	Total O1	LC O1
23/11/2019 0:00	49	63	120	7	0	0	239	119
23/11/2019 1:00	31	35	64	3	1	0	134	70
23/11/2019 2:00	27	22	63	1	0	0	113	50
23/11/2019 3:00	33	32	67	2	0	0	134	67
23/11/2019 4:00	45	45	102	2	0	2	196	92
23/11/2019 5:00	109	140	256	26	0	1	532	275
23/11/2019 6:00	160	217	477	43	5	0	902	425
23/11/2019 7:00	198	197	472	35	3	1	906	433
23/11/2019 8:00	200	326	619	31	2	2	1180	559
23/11/2019 9:00	238	366	641	31	2	0	1278	637
23/11/2019 10:00	274	373	684	45	4	1	1381	696
23/11/2019 11:00	280	395	689	39	2	4	1409	716
23/11/2019 12:00	236	414	677	40	6	1	1374	696
23/11/2019 13:00	236	374	628	26	7	1	1272	643
23/11/2019 14:00	220	353	601	32	1	4	1211	606
23/11/2019 15:00	220	337	565	31	3	0	1156	591
23/11/2019 16:00	188	312	658	31	2	1	1192	533
23/11/2019 17:00	226	368	718	35	4	3	1354	633
23/11/2019 18:00	208	317	642	34	3	2	1206	562
23/11/2019 19:00	151	227	491	29	2	2	902	409
23/11/2019 20:00	153	175	353	11	0	2	694	339
23/11/2019 21:00	134	168	337	23	4	0	666	329
23/11/2019 22:00	121	145	313	27	1	0	607	294
23/11/2019 23:00	119	127	238	13	0	1	498	259

Note: The @ symbol indicates the downstream exit ramp at Heatherton Road.

Figure 3-7: CEOS TIRTL lane numbering convention



Source: Google Maps (2025), NTRO Perth, map data, Google, California, USA.

Note: The @ symbol indicates the upstream entry ramp at South Gippsland Freeway.

4 Data Sourcing and Validation

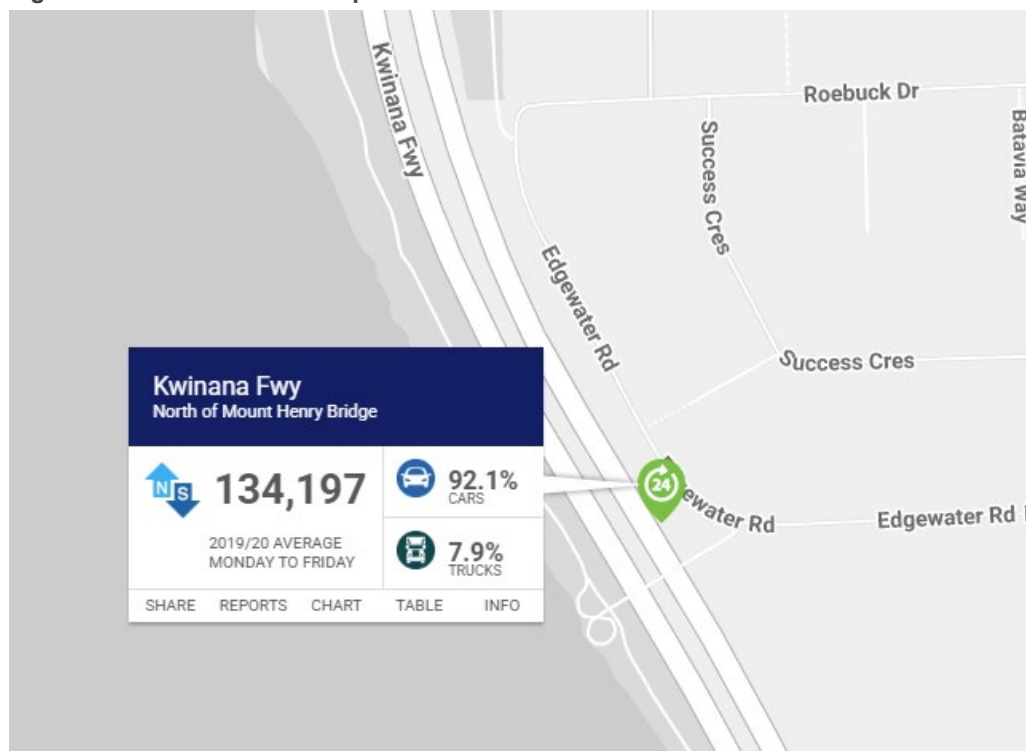
Consistent with the requirements described in Section 3, the needed traffic data was sourced and validated, with a focus SVO data and lane changing data, based on measurements with ANPR technology and advanced FDS. The data sourcing and validation is described in this section.

4.1 Description of Validated Data Sources

MRWA provided NTRO with heat plots for the Kwinana and Mitchell freeways. This allowed for the initial identification of bottlenecks (refer to Section 3.1) and for the selection of suitable data stations (VDSs) for capacity measurements, including 'backup stations' in the case of data gaps at the originally selected sites (e.g. next upstream VDS where the bottleneck impact can also be measured). It also allowed for the selection of downstream control stations. Intervals when downstream congestion was detected here (e.g. caused by incidents) were excluded from the analysis to avoid that spillback from further downstream corrupts the analysis.

As requested, SVO data over a full month (February 2025) in fine granularity (1-minute resolution), sourced from all VDSs (induction loops) along the Kwinana and Mitchell freeways were provided by MRWA. This covered all the sites discussed in Section 3.1 except for the Reid Highway weaving area. For the weaving areas where only a low number of congestion events was observed over the month (Kwinana Freeway NB: Mill Point Road to Mill Point Road; Mitchell Freeway SB: Powis Street to Vincent Street), data for 3 months was provided and analysed (February to April 2025). Later in the project, for verification of the ANPR data and confirmation of the results from the previous capacity/MSFR analysis based on February to April 2025 data, data measured between May and July 2025 was also provided. The provision of data for entire freeway corridors allowed for the needed flexibility for bottleneck identification and analysis, as well as for downstream control section consideration. The SVO data quality was generally good, except for the Mitchell Freeway NB where major gaps existed, especially between Reid Highway and Burns Beach Road. For example, for the identified 0500MIN weaving area bottleneck site, no data was measured for the inner (median) lane during the times of interest. Data on HV percentages were sourced from the MRWA Trafficmap tool. An example is shown in Figure 4.1.

Figure 4-1: MRWA Trafficmap tool



NTRO contributed gradient data in 10-m segment granularity. These were measured with network survey vehicles in the context of general road surveillance. The 10-m segment data was converted to 500-m rolling averages, and it was checked whether there were any bottlenecks with a gradient $\geq 2\%$. This is the defined threshold for gradients that reduce capacity as included in the MCG (VicRoads 2019a, Table 3-7), consistent with comparable international guidelines. Conditions on the analysed freeways were generally relatively flat.

MRWA provided NTRO with comprehensive ANPR-based lane changing data for their weaving areas, based on the requested format as shown in Figure 3.6, which was adjusted to reflect the camera-based detection technology used. An example of the format is shown in Table 4.1 below.

Table 4.1: Example of ANPR-based lane changing and OD data provided by MRWA

5 DAY AVERAGE

LANE 1

LANE 2

LANE 3

LANE 4

LANE 5

ALL LANES

MITCHELL FREEWAY LANE 1

LANE CHANGES

DAY AVERAGE (1500 - 1800)

Fwy NB to Warwick F

Fwy NB to Warwick F

LANE 5

114

2.3%

LANE 4

16

0.3%

LANE 3

117

2.4%

LANE 2

51

1.0%

LANE 1

180

3.6%

LANE 1

4592

92.9%

49.6 km/h

44.6 km/h

49.0 km/h

48.3 km/h

LANE 1

4941

100%

Reid Hwy EB to NB L

Reid Hwy WB to NB L

Mitchell Fwy L3

Mitchell Fwy L2

Mitchell Fwy L1

	6OUT	5OUT	4OUT	3OUT	2OUT	1OUT
RAW	75	12	84	38	127	3274
FACTORED	79	15	93	42	161	3947
TOTALLED	92	17	108	49	187	4604
% FLOW	1.9%	0.3%	2.2%	1.0%	3.8%	93.0%
AVE TT			01:46	01:59	01:59	02:00
AVE SPEED			47.8	42.5	42.7	42.3
						1IN

	6OUT	5OUT	4OUT	3OUT	2OUT	1OUT
RAW	282	42	288	201	2606	227
FACTORED	296	52	319	222	3295	274
TOTALLED	309	54	333	232	3447	246
% FLOW	7.2%	1.3%	7.8%	5.4%	80.2%	6.7%
AVE TT			01:47	02:03	02:10	02:04
AVE SPEED			47.4	41.3	38.9	41.0
					2IN	

	6OUT	5OUT	4OUT	3OUT	2OUT	1OUT
RAW	1321	113	1392	1736	129	23
FACTORED	1386	139	1540	1917	163	28
TOTALLED	1487	149	1653	2057	175	30
% FLOW	38.0%	3.8%	42.2%	52.5%	4.5%	0.8%
AVE TT			01:51	02:20	02:16	02:06
AVE SPEED			45.9	36.3	37.2	40.3
				3IN		

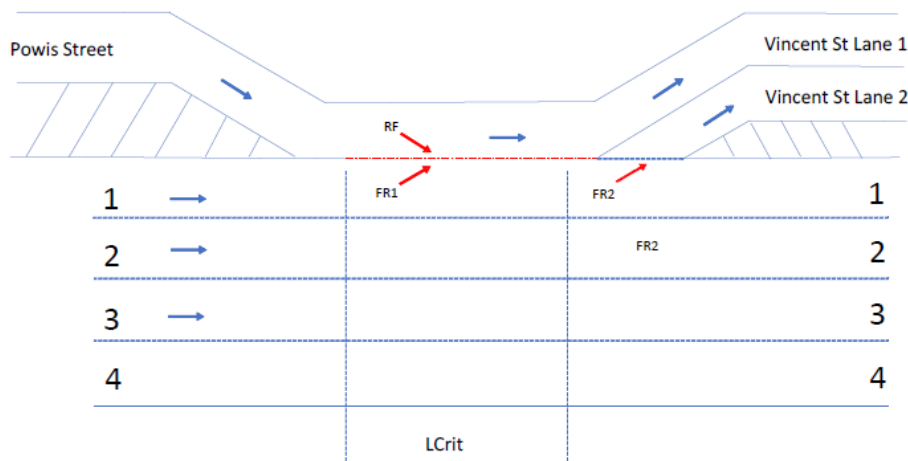
	6OUT	5OUT	4OUT	3OUT	2OUT	1OUT
RAW	380	5	425	1749	770	440
FACTORED	399	6	470	1931	974	530
TOTALLED	417	6	491	2018	1017	554
% FLOW	10.2%	0.2%	12.0%	49.4%	24.9%	13.6%
AVE TT			01:41	02:03	02:07	02:05
AVE SPEED			47.2	38.8	37.7	38.4
			4IN			

The data was provided for the 3 peak hours of 5 successive working days (25 June to 1 July 2025; 6–9 am or 3–6 pm, respectively, depending on the carriageway direction of travel, i.e. towards or away from Perth

CBD). It was also provided for all weaving areas included in Table 3.4, except for the Reid Highway one where the installation of cameras was too challenging (in the absence of suitable bridges/gantries).

In addition to the Vic DTP data, the MRWA LC data not only covers the mainline but also the entry-ramps and exit-ramps, which allows for additional insights in the case of multi-lane ramps. For example, in the case of the Mitchell SB Powis Street to Vincent Street weaving area with its 2-lane exit ramp (refer to Figure 4.2), the share of vehicles exiting via the auxiliary lane or slip lane, respectively, is relevant for the estimation of the LCC along the critical length L_{Crit} , which is illustrated as a red line in the drawing.

Figure 4-2: Illustration of the Powis Street to Vincent Street weaving area



The ANPR-based traffic volume data was cross-checked with the VDS-based volumes. In-pavement detectors such as induction loops are known to over- or undercount $\pm 5\%$ of the total traffic. Table 4.2 shows the comparison for the sites where sufficient VDS data was available. For the Reid Highway to Warwick Road weaving area, the Main Roads Traffic and Road Network Performance team advised that no data were available from the median lane for the relevant days. Simply extrapolating the volume measured on the other 3 lanes to obtain the volume on 4 lanes, e.g. by applying a factor of $4/3$, appeared to be too uncertain. This is because it is known that traffic is not equally distributed across the freeway carriageway lanes (Geistefeldt 2007). For the other sites, the 2 data types were broadly consistent, within typical inaccuracies. This allows for the conclusion that the ANPR data were sufficiently accurate for the next project steps.

Table 4.2: Comparison of ANPR and VDS counts for counting days (26/06, 27/06, 28/06, 30/06, 01/07) and relevant am/pm peak hours (6–9 am or 3–6pm)

Weaving area	ANPR count (veh/h)	VDS count (veh/h)	Difference (%)
Reid Hwy to Warwick Rd	6,070	N/A	N/A
Powis St to Vincent St	7,920	7,465	-5.7%
Mill Point Rd to Mill Point Rd	7,666	7,787	1.6%

For the identified Victorian weaving areas, suitable data stations (VDSs) for capacity measurements, ‘backup stations’ in the case of data gaps and downstream control stations were pre-selected by NTRO based on a list of available detector sites, which included coordinates provided by Vic DTP and aerial photos. The same applies to weaving area ‘entry’ and ‘exit’ TIRTL detector stations for these sites as illustrated in Figure 3.5. All stations were later discussed and confirmed with Vic DTP.

Vic DTP provided NTRO with SVO data over multiple months (July 2024 to June 2025) in fine granularity (1-minute resolution), sourced from all VDSs along the following motorways:

- Calder Freeway inbound (IB)
- M80 Metropolitan Ring Road– Altona-bound
- M80 Metropolitan Ring Road– Greensborough-bound

- Monash Freeway IB (east of Toorak Road)
- Monash Freeway outbound (OB) (east of Toorak Road)
- Tullamarine Freeway IB (west and north of Bulla Road)
- Tullamarine Freeway OB (west and north of Bulla Road)

This was complemented by the needed contextual information on HV percentages and gradient data (refer to Table 6.4).

Vic DTP also provided NTRO with comprehensive TIRTL-based lane changing data for their weaving areas, based on the format shown in Figure 3.6. The data was provided in 15-minute-interval granularity for all daytime hours (5 am to 8 pm) and for 5 consecutive working days (28 April to 2 May 2025).

An example of the format is shown in Table 4.3 below. The data is based on the tracking of vehicles from the entry TIRTL (14087), over interim TIRTLs (14089 after the entry-ramp and 14091 before the exit-ramp) to the exit TIRTL (14093). The values shown in the cells represent the number of vehicles that were tracked between the respective detector sites. It should be noted that not all vehicles detected at the entry TIRTL could be re-identified at a downstream one. The parameter 'cov' represents the percentage of vehicles that could be re-identified. The first number in the column headings is the origin (including the lane number after the dot), and the last number is the destination (also including the lane number). If there is no lane number included, then the vehicles were entering the weaving area via the entry ramp upstream of the VDS or exiting it via the exit ramp downstream of the VDS. Each origin VDS is the first VDS where the vehicle was recorded for the respective query (between the entry and exit TIRTLs) and each destination VDS is the last VDS where the vehicle was recorded. This allows to linking of the column headings to OD movements, characterised by the acronyms FR, FF, RR and RF.

Table 4.3: Example of TIRTL detector-based lane changing and OD data provided by Vic DTP (only for vehicles originating from Lane 5 of the entry TIRTL 14087 or from the entry-ramp); it should be noted that, while not shown here, the coverage before the peak period (Column 2 / Parameter cov) is always greater than 50%

1	2	3	4	5	6	7	8	9	10
datetime	cov	14087.5 → 14091 (FR)	14087.5 → 14093.3 (FF)	14087.5 → 14093.2 (FF)	14087.5 → 14093.1 (FF)	14089 → 14091 (RR)	14089 → 14093.3 (RF)	14089 → 14093.2 (RF)	14089 → 14093.1 (RF)
28/04/2025 15:00	50.3	81	100	19	8	57	43	29	11
28/04/2025 15:15	33.5	14	2	3		4	3	1	1
28/04/2025 15:30	31.3	35	45	12	6	88	81	20	16
28/04/2025 15:45	31.9	84	97	7	1	26	2	11	15
28/04/2025 16:00	16.3	9	17	4	2	6	15	5	1
28/04/2025 16:15	16.8	10	4	2		13	13	6	3
28/04/2025 16:30	13.8	11	7	1	1	94	12	4	1
28/04/2025 16:45	17.6	1	5	2	2	2	6	2	1
28/04/2025 17:00	7.6					1			
28/04/2025 17:15	10.4	30	2			17	14	5	1
28/04/2025 17:30	11.4	4				11	11	3	
28/04/2025 17:45	11.4	5	15	1	4	3	7	3	1

In addition, Vic DTP has also provided the data shown in Table 4.4, which focus on the OD relations and which are suitable for a cross-check of the OD data included in Table 4.3,. Column 3 shows the origin DS and columns 4 and 5 show the corresponding destination DS with the absolute vehicle numbers for the respective OD relations (shaded). Columns 6 to 8 show the same but based on percentages.

This allows for the calculation of the OD relation percentages. For example, the total number of vehicles that have been recorded and re-identified in the 15-minute interval from 15:00 to 15:15 is 622 (sum of the numbers included in the shaded cells). This can be divided into 482 vehicles ($240 + 242 = 482$, or 77.5%) that enter via the upstream freeway section (i.e. DS 14087), and 140 ($57 + 83 = 140$, or 22.5%) that enter via the Heatherton Road entry-ramp (i.e. DS 14089 downstream of the ramp is where these have been first recorded). Multiplying these percentages by the percentages shown in Columns 7 and 8 in the table gives the OD relation percentages. An example of the calculations and resulting OD percentages is shown in Table 4.5.

Table 4.4: OD data provided by Vic DTP

1	2	3	4	5	6	7	8
datetime	cov	origin	14091	14093	origin	14091%	14093%
28/04/2025 15:00	10.4	14087	240	242	14087	50	50
		14089	57	83	14089	41	59

Table 4.5: OD percentages based on the data included in Table 4.4

OD	Calculation	Percentage
FR	$(240+242)/622*0.50$	38.9
FF	$(240+242)/622*0.50$	38.7
RR	$(57+83)/622*0.41$	9.2
RF	$(57+83)/622*0.59$	13.3

This new data was complemented by the TIRTL data used for the Vic DTP 2021 TRB annual meeting contribution and induction loop data for the Eastern Freeway site between Tram Road and Blackburn Road that was also used for this contribution. This older data was generally sourced from the same sites. Some of these were upgraded in the meantime to accommodate a greater traffic demand.

NTRO staff have previously worked with the Victorian TIRTL and in-pavement detector data. The TIRTL data, in terms of accuracy and comprehensiveness, can be regarded as state-of-the art. The sample sizes (percentage of vehicles captured), especially prior to flow breakdown, are better than those based on probe data such as Tom Tom data. It can, therefore, be concluded that the Victorian data met the needed requirements for the next project stages.

4.2 Assessment of Data Appropriateness for Subsequent Analyses

The provided SVO data was comprehensive, i.e. it covers a great number of freeway/motorway corridors and an equally great number of bottlenecks that can be used for MSFR values and a potential capacity drop caused by weaving.

The MRWA SVO data described in Section 4.1 was suitable for capacity/MSFR value determination through the generation of FBR curves and speed-flow curves. This applies to 'normal bottlenecks' (Section 5) and, generally, to weaving areas (Section 6) on the Western Australian freeway network. The data gaps between Reid Highway and Burns Beach Road mentioned in Section 4.1 posed a challenge. The research findings needed to be carefully validated and qualified correspondingly. The Vic DTP SVO data described in Section 4.1 was suitable for the analysis of the corresponding weaving areas on the Victorian motorway network.

The TIRTL-based lane changing data provided by Vic DTP allowed for sufficient characterisation of the lane changing intensities as well as of the OD relations.

Originally 14 weaving areas were nominated and agreed by Vic DTP and NTRO (refer to Table 3.5 and Table 3.6). A preliminary analysis showed that 3 sites were not suitable for further analysis for the following reasons:

- Tullamarine Freeway IB between English Street and Calder Freeway (number 7): Sharp curve is likely to reduce the base capacity so that reduced capacity cannot be attributed to weaving alone.
- Tullamarine Freeway between M80 and Mickleham Road (number 12): Strong queueing back from the high-volume downstream Mickleham Road exit-ramp causes most flow breakdown events detected by VDS on the weaving area.
- M80 Ring Road between Hume Freeway and Sydney Road (number 13): Strong queueing back from the downstream mainline bottleneck caused by a lane reduction from 5 to 3 lanes causes most flow breakdown events detected by VDS (FDS in Victorian terminology) on the weaving area.

The ANPR-based lane changing data provided by MRWA allowed for sufficient characterisation of the lane changing intensities as well as of the OD relations. As explained in Section 4.1, this data provided additional insights into lane-specific usage of the entry and exit ramps, which impacts the LCC across the analysed critical length which has corresponding impacts on the traffic flow quality (i.e. on the MSFR/capacity loss).

Originally, 4 weaving areas were nominated and agreed by MRWA and NTRO (refer to Table 3.4). Planning of the LC quantification methodology, which led to the selection of the ANPR methodology, showed that the Reid Highway site was not suitable for further analysis for the following reason:

- Reid Highway EB between Malaga Drive and Tomkin Highway (number 4): Absence of a structure such as a bridge or a combined Lane Use Management/Variable Speed Limit (LUMS/VSL) gantry suitable for video camera installation does not allow for appropriate ANPR-based LC measurement.

For Victoria and Western Australia combined, SVO and LC data from 14 sites were available. This included 4 sites where older data used for the Vic DTP 2021 TRB annual meeting was analysed (Eastern Freeway between Tram Road and Blackburn Road, Monash Freeway between Princes Highway and Clyde Road; in each case both directions). A minimum of around 10 sites was originally assumed to be sufficient for the development or refinement of a methodology for determining weaving area capacity. The available number was therefore regarded as sufficient to generate a representative set of OD, LCC and MSFR (loss) parameters needed for the methodology development. This assumed that a wide range of the parameters such as LCC and MSFR loss were represented by the available sites and data. Later analysis confirmed that this was the case.

In addition, NTRO could provide TomTom-based OD data for Victorian as well as for Western Australian weaving areas.

A remaining challenge was the need for additional sites to test a developed methodology. These had to be independent from the sites used for developing the methodology. One option was that a subset of the sites included in Table 3.4 to Table 3.6 would be used for testing only, e.g. the Victorian Eastern Freeway ones where no TIRTL data was available (only SVO and TomTom OD data). This obviously reduced the number of sites available for methodology development. Another option was to use sites from other Australian states or even overseas (note that the intent is that the methodology developed as part of this project will become part of Austroads guidance). A corresponding request was made for Queensland Department of Transport and Main Roads (TMR) who nominated two additional weaving areas and provided the SVO data needed for testing (Section 9). More weaving areas were nominated in the context of an Austroads project led by NTRO that was recently started (Austroads NEG6527 AGTM update - Motorway capacity analysis). These can only be used for testing after completion of this project.

As a conclusion, it was expected that sufficient data would be available for the next project stages, especially those that will be described in Sections 6 to 9.

For the following reasons, some LC measurement uncertainty must be considered when interpreting the analysis results included in these sections:

- Incompleteness of the LC measurements undertaken
 - The overall confidence level for the ANPR measurements (WA) was around 90%, i.e. relatively high.
 - The TIRTL vehicle re-identification algorithm (VIC) is a prototype where matching rates during peak hours are reduced, compared to non-peak hours. These were on average 52% for all weaving areas over the 3 hour peak periods, while being greater for pre-breakdown conditions (around 90%) which are most relevant for the analysis undertaken.

Overall, given the very large vehicle size, these percentages are great enough to be a representative basis for the description of the lane changing behaviour within the weaving areas.

- The locations of the entry and exit ANPR cameras or TIRTL detectors respectively (refer to Figure 6-1 and Figure 3-5) were not exactly aligned with the weaving area lengths. This creates inaccuracies in the estimation of the LCC parameter values.

It was a possibility that external data had to be used for methodology testing. This would have resulted in additional effort for data sourcing, validation and analysis, beyond what has been calculated for this project. It turned out later that this was only needed for the final testing project phase (refer to Section 9).

5 MRWA Freeway Capacity Values (Baseline)

A core element of the proposed methodology was to quantify the capacity loss of a weaving area in comparison to a typical section not impacted by weaving. To do this, a baseline outlining the capacity of typical Western Australian freeway sections had to be created. This is described in this section.

5.1 Definitions, Methodologies and Analysis

5.1.1 Definition of Capacity

The HCM 7th edition (TRB 2022) defines ‘capacity’ of a system element as (p 4-21)

The maximum **sustainable** hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions. [emphasis added]

The key to understanding the term capacity as defined above is understanding the word ‘sustainable’. It means that it must be possible to operate a freeway at the capacity level without a flow breakdown or congestion for an extended period, such as a 3-hour peak period, which is now typical for large metropolitan cities with very high traffic demands spread over extended peak periods.

It is important to understand that a range of static and dynamic factors impact the currently prevailing capacity so that it is not always the same. Table 5.1 and Table 5.2 show the corresponding factors.

Table 5.1: Static factors impacting capacity

Cross section
Number of lanes
Lane and shoulder widths: Particularly, lane widths narrower than 3.25 m (or 3.35 m), also dependent on the length of the section with narrow lanes/shoulders
Visibility conditions: E.g. driver's field of view constrained by high noise walls
Alignment
Gradient: Particularly, > 2% and sustained for > 750 m (number indicative)
Curvature: Particularly, radius < 700 m (number indicative)
Sags and crests: Particularly, sag curves in tunnels
Traffic
Long-term average share of different vehicle types (especially HV percentage)
Location
Impacting the share of commuters that are familiar with the road (high share increases capacity)
Other physical attributes
Merge/diverge tapers, acceleration/deceleration lengths, auxiliary lanes, braiding, collector-distributor lanes etc.

Source: Adapted from VicRoads (2019a).

Table 5.2: Dynamic factors impacting capacity

Operational practice
Traffic management interventions: Dynamic traveller information including Variable Message Signs (VMS) messaging (directly affects route choice, trip length and, hence, OD patterns with the corresponding impacts on lane changing), lowering speed limits, overtaking bans, closing lanes or ramps
Ramp metering actions: Independent and coordinated actions can impact the use of available capacity, both positively and negatively (i.e. uncontrolled vehicle release at entry-ramps when queues are excessive can cause flow breakdown on the mainline and, ultimately, a loss in productivity across the entire road network)
Maintenance: Routine maintenance activities, road works and presence of work zones (e.g. slow-moving maintenance vehicles or fewer and narrow lanes)
Enforcement regime (e.g. harmonised speeds increase capacity)
Driver behaviour
Increased headways: Environmental conditions including reduced visibility caused by rain or poor surface roughness
Heavy braking, large variation in vehicle speeds or harsh lane changing manoeuvres: Can cause a perturbation causing flow breakdown
Compliance with road rules: Speed limit, overtaking, lane use and ramp metering compliance
Vehicles
Short-term (e.g. 1 min) random variations of different variables (e.g. spikes in traffic demand, changes in local OD relations, HV cluster, increased lane changing intensity) can cause a perturbation causing flow breakdown
Broken down vehicles
Objects on the road (e.g. vehicle parts)

Source: Adapted from VicRoads (2019a).

The listed dynamic factors explain why it is not possible to maintain a high traffic volume for an infinite time. There will always be random fluctuations such as a cluster of slow and HVs or 'bad driver behaviours' over such a long time.

The probabilistic understanding of capacity applied in VicRoads (2019a) and used for this project supports the comprehensive consideration of these dynamic factors.

5.1.2 Understanding Capacity in the Context of this Study

Motorway 'capacity' is often determined without full consideration of all the operational factors that cause 'random fluctuations', resulting in disruptions to the traffic flow. Such approaches still built into many HCMs around the world do not reflect the likely operational outcomes that the community will experience when new freeways or motorways are built or upgraded, particularly in a major urban environment where demand will never be fully catered for. Hence, there is a need to determine MSFR values relating to the probability of flow breakdown and maximum productivity that realistically reflect the on-road outcomes achieved. Their determination must use appropriate robust and repeatable statistical analysis methods using measured traffic data from a wide range of demand and traffic flow patterns. MSFRs that relate to probability of flow breakdown and maximum productivity reflect motorists' experience, community expectations and the realised economic benefit of the built motorway system.

5.1.3 Measurement Methodology

Data

In deriving a methodology that reflects the HCM definition (refer to Section 5.1.1), the 'capacity' values and MSFRs developed have been measured at active **bottlenecks** and were determined on the basis of **statistical analysis** of data to capture the effects of **systematic** and **random** fluctuations under a wide range of **demand patterns** (i.e. based on long-term observations).

Capacity and the other related parameters (MSFR, productivity, probability of flow breakdown) vary over time because while some factors are relatively static (refer to Table 5.1), there are also a number of dynamic

factors involved (refer to Table 5.2). For example, plotting the fundamental relationships daily clearly shows that different curve shapes occur every day. Therefore, the determination of ‘capacity’ in the context of this project was based on long-term measurements (i.e. one month) to get a reasonable representation of all the different possible traffic states (i.e. combinations of dynamic factors).

Methodology selection

This section describes the selected methodologies for estimating capacity values and MSFR values. Methodology 1 was used to determine the MSFR values and Methodology 2 (as the more traditional approach) was used for plausibility checks.

To determine the capacity of the selected bottlenecks (and in line with international best practice), the influence of congestion spilling back from downstream sections was excluded by eliminating those actual 15-minute (Methodology 1) or (rolling) 1-hour (Methodology 2) intervals where the speed at the next downstream cross-section was lower than the threshold speed between ‘free flow’ and ‘forced flow’, typically 65 km/h.

Eliminating such intervals has the following effects:

- The systematically lower capacity within ‘wide moving jams’, which is unrelated to the capacity of the bottleneck itself, does not influence the capacity measurement at the bottleneck.
- The influence of major incidents happening downstream of the bottleneck on capacity measurement in the bottleneck is largely eliminated.

Methodology 1:

This methodology was adopted from the MCG (VicRoads 2019a) and is comprehensively described in Brilon et al. (2005). Capacity is determined as the flow rate that corresponds to a certain FBR, i.e. a certain risk of a transition into congestion over a certain time. The risk and time selected for the MCG was 1% over a 15-minute period, which is roughly equivalent to 10% over a 3-hour peak period. The mathematical procedure is based on established methodologies for the analysis of lifetime data, which distinguishes between uncensored and censored data. In the context of this study, uncensored data are those where the current capacity value can be directly measured as the flow rate since the prevailing conditions at the time are causing a flow breakdown. Censored data are those intervals where only the information is available that current capacity is higher than the flow rate since no flow breakdown is being triggered, i.e. the traffic state remains to be in the ‘upper branch’ of the fundamental diagram.

Equation 17, adopted from Brilon et al. (2005), is used to calculate the cumulative distribution function (CDF) of capacity.

$$F_c(q) = 1 - \prod_{i:q_i \leq q} \frac{k_i - d_i}{k_i} \quad 17$$

where

- $F_c(q)$ = value of the cumulative capacity distribution function (CDF) at q
- k_i = number of intervals with a flow rate of $q \geq q_i$,
- d_i = number of breakdowns at a flow rate of q_i (usually 1)
- $\{B\}$ = set of breakdown intervals (Interval B)

The product in Equation 17 is calculated over all observed 15-minute intervals i with flow rates $q_i \leq q$, each of which was a ‘breakdown interval’. Flow breakdown is defined as a transition from the ‘upper branch’ of the fundamental diagram (free flow or bound flow) into the ‘lower branch’ (forced flow) where it must remain for a minimum of 15 minutes (i.e. one interval length).

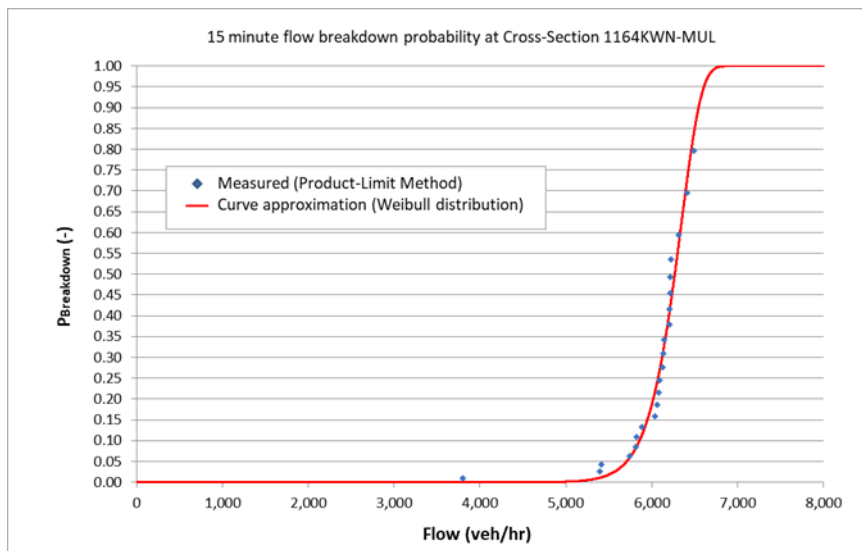
Usually, each observed ‘breakdown interval’ is used as one q_i value, so that d_i is always equal to 1. The distribution function will reach a value of 1 only if the maximum observed flow rate is a B value (i.e. a breakdown followed). Otherwise, the distribution function terminates at a value of $F_c(q) < 1$. In this case, the method does not allow complete estimation of the function $F_c(q)$. This is irrelevant as it is the lower FBR flow rates that will be adopted as MSFR values.

The advantages of this methodology compared to other established methods are as follows:

- CDF cannot be corrupted by low traffic levels. If traffic demand is too low to cause multiple flow breakdowns, the CDF is only defined up to a low value. (e.g. < 1% per 15-minute interval).
- No traffic flow model with the corresponding uncertainties around selecting the ‘right’ model and parameters is needed (if only applying Equation 17, i.e. not representing it by a Weibull curve or similar distribution function).
- Suitable MSFRs can be determined based on the tolerable breakdown risk over a certain time (e.g. lower than 10% over a 3hour peak period for critical infrastructure such as bridges/tunnels).

Figure 5.1 shows an example of an FBR curve/CDF curve that was generated based on the application of the described methodology.

Figure 5-1: Example of an FBR curve/CDF curve of capacity (Cranford Avenue to Manning Road, refer to Table 5.6)



Note: Blue dots from application of Equation 17, red curve represents Weibull curve approximation.

Methodology 1 was used to determine the MSFR values as shown in Section 5.1.4.

Methodology 2:

Capacity is determined as the maximum flow rate of the fitted carriageway speed-density and resulting speed-flow curve according to van Aerde (1995), which is the only known model that enables a realistic description of all traffic states/areas in the speed-flow diagram with a continuous curve.

The van Aerde equation is shown in Equation 18.

$$k(v) = \frac{1}{c_1 + \frac{c_2}{v_0 - v} + c_3 * v} \quad 18$$

where

k = density (veh/km)

v_0 = average vehicle speed when flow approaches zero (km/h)

c_1, c_2, c_3 = model parameters

The methodology uses (rolling) hourly average speeds, flows and densities.

Some characteristics of the methodology application are as follows:

- Average speeds are calculated for every density class (0–1 veh/km, 1–2 veh/km, etc.) based on all rolling 1-hour intervals where density fell within a certain class, resulting in a point cloud in the speed-density diagram where each point represents one speed-density pair.
- A van Aerde curve is fitted to speed-density measured values (i.e. minimisation of the sum of error squares derived from a comparison between modelled (fitted curve) and measured k (density) values).
- Flow rate (Equation 19) is determined as the mathematical product of speed and density.

$$q(k, v) = k * v$$

19

where

q = flow rate (veh/h)

k = density (veh/km)

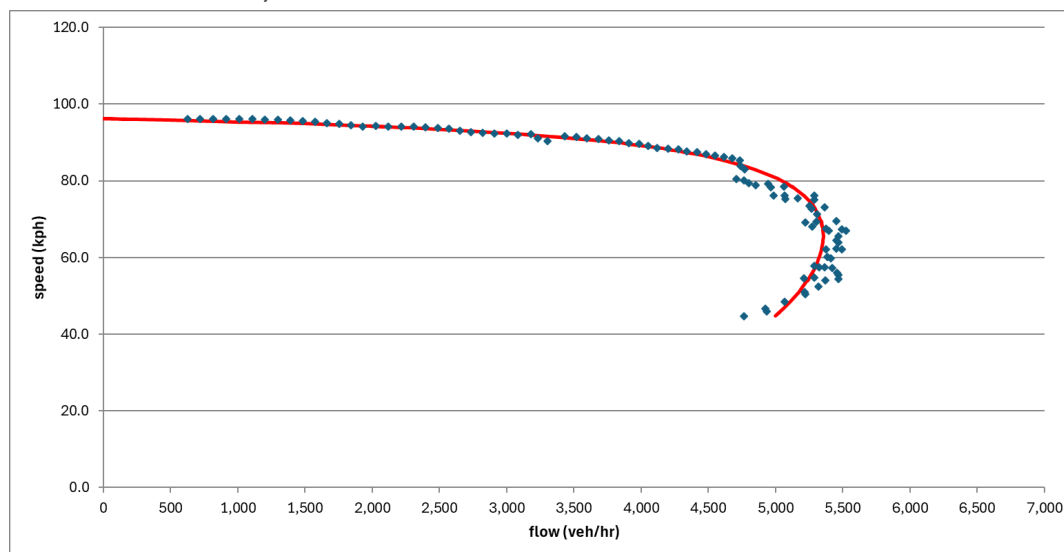
v = vehicle speed (km/h)

- Flow and, hence, capacity is determined as the highest flow rate of the van Aerde curve representation.

Figure 5.2 shows an example of speed-flow curve that was generated based on the application of the described methodology.

This capacity is then multiplied by a certain factor (traditionally 0.9) to obtain the design flow rate (which is comparable to the MSFR above and consistent with the HCM definition in Section 5.1.1). This transformation is the main disadvantage of the methodology, i.e. there is no transparent methodology to transform capacity values into suitable design values.

Figure 5-2: Example of a speed-flow curve according to van Aerde (Cranford Avenue to Manning Road, refer to Table 5.6)



Note: Blue dots represent average speed for density classes, red curve represents van Aerde curve approximation.

Methodology 2 was only used for plausibility checks. This means that it was ensured that MSFR values were in a range of between 88% and 96% of traditional capacity, as per Table 3-3 in the MCG (VicRoads 2019a).

5.1.4 Measurement Results

The bottlenecks identified and listed in Section 3.1.1 were analysed, and the corresponding MSFR values were estimated. Consistent with the MCG (VicRoads 2019a), a distinction was made between unmanaged and managed (or Smart) freeway sections, especially characterised by coordinated ramp metering and higher capacity values. Table 5.5 shows the corresponding results for unmanaged freeways, and Table 5.6 shows the results for Smart Freeways.

Two of the bottlenecks included in Table 3.1 (numbers 3 and 4) were eliminated from further analysis because during the analysis, it turned out that congestion events were overwhelmingly caused by congestion originating from further downstream (between Rowley and Russell Roads). It should be noted that the data for numbers 2 to 4 in Table 5.5 were adopted from the situation before the upgrade of the Kwinana Freeway to a Smart Freeway.

For improved comparability between measured and previously assumed values and between Smart Freeway (managed) and unmanaged conditions, the MSFR per lane values were normalised to standard conditions (HGV percentage 15% and gradient $\leq 2\%$). This was also done for the MCG measurement sites (refer to Section 3.7 in VicRoads 2019a). Table 5.3 shows the HGV normalisation factors that were applied for this normalisation:

Table 5.3: HGV percentage adjustment factors

HGV	Factor	HGV	Factor	HGV	Factor
5%	1.10	10%	1.050	15%	1.000
6%	1.090	11%	1.040	16%	0.992
7%	1.080	12%	1.030	17%	0.984
8%	1.070	13%	1.020	18%	0.976
9%	1.060	14%	1.010	19%	0.968

Source: Adapted from the MCG, based on the Dutch HCM, Henkens and Heikoop (2015).

Table 5.4 shows the gradient normalisation factors that were applied for this analysis:

Table 5.4: Gradient adjustment factors

Gradient	Factor
2%	1.00
2–3%	0.95
3–4%	0.90
4–5%	0.83

Source: Adapted from the MCG, based on the German HCM, FGSV (2015).

For the purposes of this analysis, the measured MSFR values (per lane) were then divided by these factors to arrive at values that are representative of standard conditions.

Table 5.5: MSFR values for unmanaged freeways

	Freeway	From	To	Detector	Lanes	Gradient	HGV	MSFR	MSFR per lane	MSFR per lane (normal)
1	Kwinana Freeway	Rowley Rd	Russell Rd	0098	2	$\leq 2\%$	16%	2,950	1,475	1,487
2 ⁽¹⁾		Canning Hwy	Mill Point Rd	0003	3	$\leq 2\%$	8%	4,700	1,567	1,464
3 ⁽¹⁾		Cranford Ave	Manning Rd	0150	3	$\leq 2\%$	8%	5,501	1,834	1,714

	Freeway	From	To	Detector	Lanes	Gradient	HGV	MSFR	MSFR per lane	MSFR per lane (normal)
4 ⁽¹⁾		Leach Hwy	Cranford Ave	0160	3	<= 2%	16%	4,770	1,590	1,603
5		Manning Rd	Cranford Ave	0087	3	<= 2%	8%	5,192	1,731	1,618
6		Russell Rd	Rowley Rd	0940	2	<= 2%	12.5%	2,935	1,468	1,432
7		Anketell Rd	Thomas Rd	0102	2	<= 2%	12%	3,040	1,520	1,476
8		Thomas Rd	Mortimer Rd	0104	2	<= 2%	11.5%	2,823	1,412	1,364

1. Analysis for the pre-upgrade to a Smart Freeway situation.

The MSFR values are generally comparable with the MCG reference values for unmanaged motorways. The averaged normalised per lane MSFR value as per Table 5.5 is 1,520 veh/h whereas that in the MCG is 1,515 veh/h (refer to Table 2.9 in in VicRoads 2019a).

Table 5.6: MSFR values for Smart Freeways

	Freeway	From	To	Detector	Lanes	Gradient	HGV	MSFR	MSFR per lane	MSFR per lane (normal)
1	Kwinana Freeway (NB)	Cranford Ave	Manning Rd	1164	3	<= 2	8%	5,243	1,748	1,665
2		Leach Hwy	Cranford Ave	1165	3	<= 2	8%	5,206	1,735	1,668
3	Mitchell Freeway (SB)	Hepburn Ave	Warwick Rd	1290	3	2–3%	10%	5,092	1,697	1,701
4		Reid Hwy	Erindale Rd	0520	3	<= 2	10%	5,036	1,679	1,614

As expected, the MSFR values for Smart Freeways are higher than those for unmanaged ones. The difference is around 10% higher (1,662 veh/h compared to 1,520 veh/h). This is slightly lower than assumed for the MCG (15%). This may be caused by a coordinated ramp metering system that is still maturing (refer to Section 5.2.2).

Another remarkable observation is that Smart Freeway MSFR values are much more consistent than unmanaged ones (Standard deviation unmanaged: 7.6%, Standard deviation managed: 2.2%). This allows for increased reliability in planning, design and operation with less risks, ultimately resulting in an improved customer experience with more consistent travel times.

5.1.5 Conclusion

The measured MSFR values for unmanaged freeways are consistent with those included in the MCG for unmanaged motorways. The corresponding MSFR values were, therefore, adopted for this project. MSFR values for Smart Freeways are slightly lower than those included in the MCG. For the purposes of this project, unmanaged freeway values were, therefore, increased by 10% (rather than 15%).

5.2 Maximum Sustainable Flow Rates

5.2.1 MSFR Values

The MSFR values for unmanaged freeways that are recommended for adoption by MRWA are identical with those that are already used and referenced in the MRWA Smart Freeways guidelines, which were recently updated, especially in the *Smart Freeways Supplement to Victoria's Managed Motorway Design Guide – Volume 2: Design Practice – Parts 2 and 3* (MRWA 2025a). These are based on the MSFR values for unmanaged motorways included in the MCG (VicRoads 2019a). In contrast to Vic DTP, MRWA uses the unit 'passenger car units per hour' (PCU/h) rather than 'vehicles per hour' (veh/h) in planning and design of freeway infrastructure. The corresponding tables in the MCG have, therefore, been amended as shown in Table 5.7, which is identical with Table 4.3 in MRWA (2025a).

Table 5.7: Unmanaged freeway MSFRs (PCU/h)

Number of lanes	Gradient			
	s ≤ 2%	2% < s < 3%	3% < s < 4%	4% < s < 5%
1	1,686	1,603	1,520	1,401
2	3,550	3,375	3,200	2,950
3	5,150	4,875	4,625	4,275
4	6,625	6,300	5,950	5,500
5	7,875	7,475	7,100	6,550
6	9,072	8,611	8,179	7,546
7	10,161	9,645	9,161	8,451

The MSFR values for Smart Freeways that are recommended for adoption by MRWA in the context of this study are 10% higher than those shown in Table 5.7. The corresponding values are shown in Table 5.8.

Table 5.8: Reduced Smart Freeway MSFRs (PCU/h)

Number of lanes	Gradient			
	s ≤ 2%	2% < s < 3%	3% < s < 4%	4% < s < 5%
1	1,855	1,763	1,672	1,541
2	3,905	3,713	3,520	3,245
3	5,665	5,363	5,088	4,703
4	7,288	6,930	6,545	6,050
5	8,663	8,223	7,810	7,205
6	9,979	9,472	8,997	8,301
7	11,177	10,610	10,077	9,296

Note: The intended use of this table is limited to serve as a basis for weaving area capacity analysis only.

5.2.2 Discussion

It is important to note that the values shown in Table 5.8 that are slightly lower than those currently included in Table 4.1 of MRWA (2025a) will only serve as a baseline for potentially reduced MSFR values in weaving areas in the context of this project. It is likely that the increased rollout and greater maturity of the MRWA Smart Freeway system will lead to higher MSFR values in the future that are consistent with current MRWA Smart Freeways guidelines. This could happen through a combination of the following:

1. the rollout across a greater Smart Freeway network with less problematic capacity constraints than at the downstream ends of the Kwinana/Mitchell Smart Freeway corridors
2. additional metered entry ramps upstream of the current bottlenecks
3. metering of all ramps along a Smart Freeway corridor

4. finetuning of the Alinea Hero ramp metering algorithm.

Care must be taken when interpreting the MCG MSFR values (VicRoads 2019a) and the equivalent Western Australian values shown in Table 5.7. and Table 5.8. This is because they are typical values only. Also, the MCG data basis for unmanaged motorways was relatively weak. Most conclusions, including the lane-specific MSFR decrease with increasing carriageway lane number, were based on managed motorway data only. For example, the values shown in Table 5.5 do not show this phenomenon.² In the context of this study, baseline MSFR values should, therefore, also be determined based on data sourced from a measurement site nearby (i.e. on the same freeway, with the same traffic conditions except that there is no weaving), i.e. this can be used as a complementary data source.

The comparison of typical MSFR values as per Table 5.7 and Table 5.8 to those MSFR values that were determined for weaving areas must consider the standard deviation/variance of MSFR values across the different MCG measurement sites. This means that a certain deviation is normal and not necessarily attributable to the capacity-reducing effect of weaving. The clearest impact will likely be seen for weaving areas with high weaving/LCC. This also means that for weaving areas with low weaving/LCC (compared to the total flow rate/volume), the capacity-reducing effect can be too low to exceed the abovementioned variations of MSFR values across different measurement sites. For low intensity weaving areas, this could even result in MSFR values that are higher than those shown in Table 5.7 or Table 5.8.

² It is possible that the capacity increasing influence of ramp metering is greater for a 2-lane carriageway than for multi-lane ones because it helps facilitate the merge process, which is a greater problem for smaller carriageways.

6 Analysis of Weaving Areas

The analysis of the selected weaving areas, as described in this section, was the core of this study. It culminated in the development of a functional relation between capacity loss and weaving intensity, characterised by LCC.

6.1 Detector and Camera Arrangement

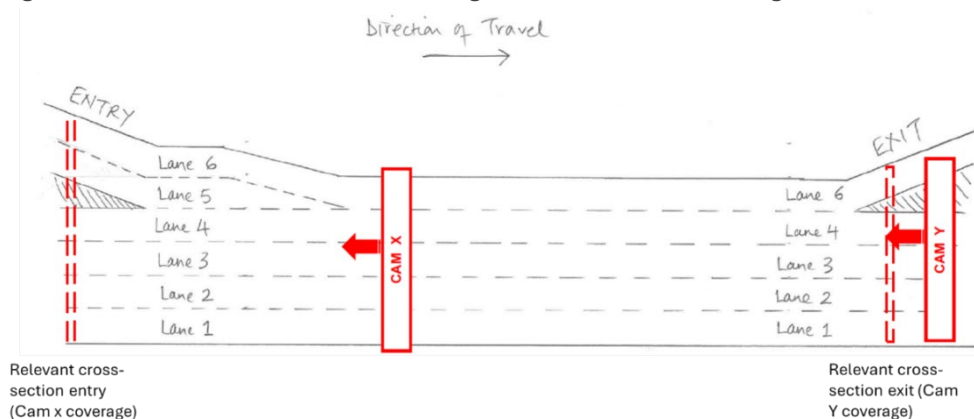
Based on the previous Vic DTP 2021 TRB annual meeting contribution (Section 2.1.3), the typical TIRTL arrangement suitable for the MSFR definition and for the measurement of OD data (FF, FR, RF and RR), as well as of the LCC is as follows:

1. The capacity VDS (FDS in Victorian terminology) used to define the site-specific MSFR value is usually the first DS after the actual (section) entry ramp merge.
7. The control VDS used to eliminate the influence of downstream congestion events from further analysis is usually the first DS after the following exit ramp diverge.
8. The entry TIRTL (or entry video camera location) used as the start point for the detection of LC is usually the VDS immediately upstream of number 1.
9. The exit TIRTL (or exit video camera location) used as the end point for the detection of LC is usually the VDS identical with number 2 (or the next downstream one).

The proposed TIRTL arrangement is consistent with the specification of data types requested for further analysis as included in Section 3.2, with the corresponding Figure 3.5, Figure 3.6 and Figure 3.7 showing an example for suitable TIRTL detector locations, measured data and the CEOS TIRTL lane numbering convention for proper data interpretation.

Detailed camera location and arrangement plans reflecting the previous TIRTL-based analysis were developed for the Western Australian weaving areas, which were based on the schematic sketch shown in Figure 6.1 (refer to Appendix D). The sketch, in principle, follows the TIRTL location principles outlined in the previous paragraph, i.e. the detection (TIRTL or video) must capture the lateral vehicle position (ideally immediately) before entering the weaving area and (ideally immediately) after leaving it. This includes the respective lane position, not only for the mainline but also for the ramps. The latter can be important for the definition of the LCC in the case of complex multi-lane entry and exit ramp configurations. A corresponding Western Australian example is shown in Figure 6.2 and a Victorian one is shown in Figure 6.3. The analytical challenge with these examples is that the FR (Figure 6.2) and RF (Figure 6.3) movements are only partially weaving vehicles that conflict with the entering or exiting traffic, respectively (i.e. only those that enter/exit via the outer lane). As illustrated in the figures, the selected value for L_s is the length separating the auxiliary lane from the outer through lane. The quantification of the different ramp lane flows is therefore important, and this can only be done with certain camera or TIRTL detector configurations.

Figure 6-1: Schematic sketch illustrating the video camera coverage for the ANPR survey



Source: MRWA.

Figure 6-2: 'Critical line' (red) for an auxiliary lane combined with a 2-lane exit ramp (including analytical challenges caused by the 2-lane ramp, expressed as question marks)

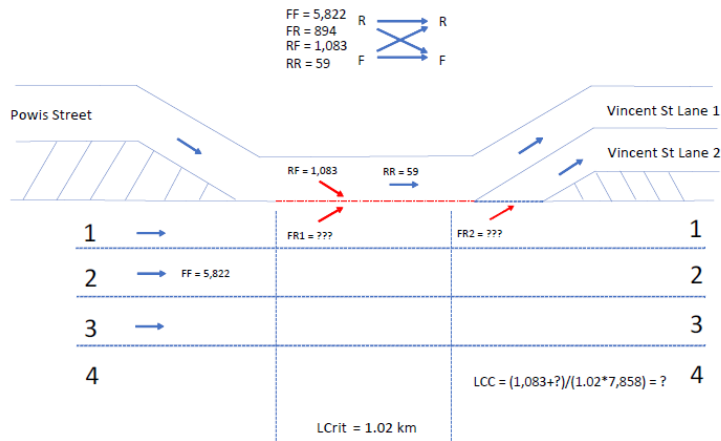
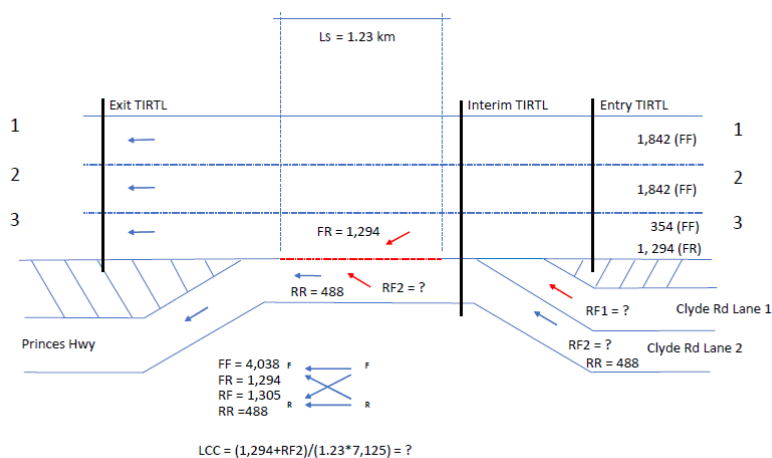


Figure 6-3: 'Critical line' (red) for an auxiliary lane combined with a 2-lane entry ramp (including analytical challenges); new entry ramp configuration



6.2 Geometrical and Traffic Conditions

Table 6.1 shows the most important geometrical and traffic conditions for the weaving areas on the Western Australian freeway network. Schematics of the sites are shown in Appendix F. All acronyms are described in the Abbreviations section at the start of this report.

The OD percentages (FR, FF, RR and RF) are based on the camera-based measurements that were undertaken and evaluated for this study. This means that the OD-relation specific volume was divided by the total volume that was measured. The LCC parameter in the table is based on MLC only. The quantification of the MLC number is usually straightforward for these sites as it is equivalent to the number of vehicles that must change lanes and, therefore, cross another traffic stream to progress from their origin to their intended destination (i.e. they can be measured or estimated based on OD percentages and site geometry). As explained earlier, in the case of multi-lane entry- and exit-ramps, this is a bit more challenging.

The table shows that the LCC for section number 3 is relatively low. This is because the exit-ramp volume (FR movement) is lower than on an average ramp. As expected, and as will later be demonstrated, the low LCC did not lead to a significant capacity loss compared to standard conditions (refer to Section 6.4).

Table 6.1: Geometrical and traffic conditions for the Western Australian weaving areas

	Freeway	From	To	Lanes	Gradient (%)	HV (%)	L _s (km)	Total flow rate ⁽¹⁾ (veh/h)	FR (%)	FF (%)	RR (%)	RF (%)	VR	LCC _{Mand} ⁽²⁾ (LC/veh/km)
1	Mitchell NB	Reid Hwy	Warwick Rd	4	<= 2	10	1.09	5,314	11.6	61.4	3.6	23.4	0.342 ⁽³⁾	0.314
2	Mitchell SB	Powis St	Vincent St	5	<= 2	10	1.02	6,560	11.3	72.9	0.8	14.9	0.228 ⁽³⁾	0.223
3	Kwinana NB	Mill Point Rd on	Mill Point Rd off	5	<= 2	8	0.375	6,670	1.4	83.0	0.0	15.6	0.014	0.037

1. Average May 2025 working day flow rates between 6 and 9 am or between 3 and 6 pm.

2. LCC is based on the MLC only.

3. Considers only the vehicles that exit via the outer exit lane (refer to Appendix F)

Table 6.2 shows the geometrical and traffic conditions for the weaving areas on the Victorian motorway network. Schematics of the sites are shown in Appendix F.

The selected sites shown in the table are generally the same as those selected for the 2021 Vic DTP contribution. New and more comprehensive data was analysed for these sites.

An additional site with significant weaving intensity was identified on the Monash Freeway OB between Wellington Road and Eastlink. The Tullamarine Freeway and M80 Ring Road sites were later removed from further analysis, due to a sub-standard narrow curve or frequent spillback from the off-ramp (refer to Table 6.2).

Also, for the Princes Highway to Clyde Road section, the entry ramp configuration was changed since the 2021 analysis, as was described above (refer to Appendix F, Figure F.8 and Figure F.9). The same applies to the counterflow direction, i.e. to the Princes Highway to Clyde Road section (refer to Appendix F, Figure F.10 and Figure F.11). To increase the sample size for the analysis, these sections were included into the table for the old and new configurations. This is clarified by adding the term old or new in Table 6.2. This appears to be justified due to the changed geometrical conditions, supported by traffic conditions that have also changed over the last years. There is clear evidence of the changed traffic conditions as can be seen from the different LCC values for each of the sites. These, in turn, are linked to the different geometries after the upgrade (refer to Appendix F).

The OD percentages (FR, FF, RR and RF) are based on the TIRTL detector-based measurements that were undertaken or evaluated for this study.

Table 6.2: Geometrical and traffic conditions for the Victorian weaving areas

	Freeway	From	To	Lanes	Gradient (%)	HV (%)	L _s (km)	Total flow rate ⁽¹⁾ (veh/h)	FR (%)	FF (%)	RR (%)	RF (%)	VR	LCC _{Mand} ⁽²⁾ (LC/veh/km)
1	Monash Freeway	Eastlink	Stud Rd	5	<= 2	8	1.06	6,563	10.6	60.8	7.9	20.7	0.106	0.100
2		Stud Rd	Eastlink	5	3.1	8	1.44	6,204	21.2	70.0	3.1	5.7	0.057	0.034
3		Heatherton Rd	South Gippsland Fwy	5	<= 2	8	1.33	7,103	36.2	40.9	12.0	10.9	0.109	0.164
4		South Gippsland Fwy	Heatherton Rd	5	<= 2	7	1.49	7,093	2.5	50.1	3.1	44.2	0.025	0.034
5		Princes Hwy	Clyde Rd	3	<= 2	10	1.37 (old)	4,244 (old)	27.0	56.7	11.2	5.1	0.051	0.037
6		Clyde Rd	Princes Hwy	3	<= 2	10	1.74 (old)	4,817 (old)	8.5	56.3	3.5	31.7	0.085	0.049
7	Tullamarine Freeway	English St	Calder Fwy	Removed from further analysis (non-standard conditions incl. narrow curve) ⁽³⁾										
8	Monash Freeway	Clyde Rd	Princes Hwy	4	<= 2	6	1.23 (new)	4,617 (new)	23.0	51.6	8.7	16.7	0.397	0.323
9		Princes Hwy	Clyde Rd	4	<= 2	6	1.26 (new)	5,931 (new)	13.2	68.2	6.9	11.7	0.249	0.198
10		Wellington Rd	Eastlink	5	<= 2	10	1.08	7,360	28.7	43.9	10.5	16.9	0.169	0.156
11	Tullamarine Freeway	M80 Ring Road	Mickleham Rd	Removed from further analysis (frequent spillback from downstream) ⁽⁴⁾										
12	M80 Ring Road	Hume Freeway	Sydney Rd	Removed from further analysis (frequent spillback from downstream) ⁽⁴⁾										

1. Average May 2025 working day flow rates between 6 and 9 am or between 3 and 6 pm, respectively (Exception: numbers 5 and 6, which use December 2019 data).

2. LCC is based on the MLC only.

3. Tight curve (around 400 m radius) may contribute to low MSFR, literature on the impact is very limited (January to March data).

4. Downstream congestion severely affecting weaving area capacity measurements.

6.3 Discussion of the LCC

Part of this project's aim to develop a new methodology for determining weaving area capacity was to establish a relationship between the capacity or MSFR loss and other parameters, such as the LCC, that can be derived from the combination of geometrical and traffic conditions that are characteristic for a weaving area.

MSFR reductions are caused by turbulences that are, in turn, caused by all LC that must happen for a motorway section to function. This includes the MLC needed for vehicles to progress from origin to destination and the EMLC needed to avoid oversaturation in a lane. The EMLC component cannot be separately measured since it is only a certain portion of the total LC made by a movement, and it is usually linked to a 'neutral' movement such as the FF movement where vehicles can usually stay in the same lane when progressing from an origin to a destination, unless forced to change lanes to avoid lane capacity exceedance.

For the methodology development, it is important that the MLC and EMLC concentration can be estimated without earlier camera- or TIRTL detector-based LC measurements, i.e. only based on the road configuration such as the number of ramp and mainline lanes and OD patterns. This is because:

1. EMLC cannot be separated from discretionary ones during measurements (as explained)
2. such comprehensive measurements are generally not possible when planning or designing a freeway element.

The approach selected for this study was, therefore, to establish a functional relationship between the estimated or modelled MLC and EMLC concentration and the MSFR loss. This appears to be the logical consequence of the challenge that the EMLC, whilst impacting the capacity loss, cannot be measured during field observations for methodology development, nor during the planning and design phase. It must be estimated by the practitioner for the subsequent methodology application.

Considering the MLC and EMLC, the corresponding LCC values are discussed in Section 6.4 and are correspondingly included in Table 6.4. Their estimation requires a sophisticated process, which is described in Section 8 where an illustrative example is shown in Figure 8.1. The application and results for each weaving area are shown in Appendix F.

6.4 Capacity/MSFR Values and LCC

Table 6.3 and Table 6.4 show the expected MSFR values for a comparable section without concentrated weaving, according to the MCG, and the actual MSFR values in comparison. The difference labelled as Delta MSFR or capacity loss is also shown.

The MSFR estimation methodology is the same that was used for the development of the MCG (VicRoads 2019a) and is described in Section 5.1.3.

Moreover, the tables show the estimated or modelled combined MLC and EMLC concentration. The corresponding estimation process is described in Section 8.

The preliminary Vic DTP study published at the 2021 TRB annual meeting resulted in the finding that there might be a linear relationship between the LCC and the MSFR loss. This was shown in Figure 2.5. The linear relationship shows a good coefficient of determination. It should be noted that this was based on the MLC only. As was argued in Section 6.3 above, it is expected that the combined MLC and EMLC is a better indicator of the induced turbulence in a certain weaving area and, therefore, also of the corresponding capacity loss. This is because EMLC must also happen for a freeway/motorway to function and will induce the turbulences in the same way as the MLC. The remainder of this study, therefore, focuses on this type of LC.

Table 6.3: Base versus actual MSFR values and MSFR loss for the Western Australian weaving areas

	Freeway	From	To	Lanes	Gradient (%)	HV (%)	MSFR baseline (veh/h)	MSFR actual (veh/h)	Delta MSFR (%)	LCCx _{Mand} ⁽¹⁾
1	Mitchell NB	Reid Hwy	Warwick Rd	4	<= 2	10	6,997	5,584	-20.2	0.314
2	Mitchell SB	Powis St	Vincent St	5	<= 2	10	7,875	7,397	-6.5	0.223
3	Kwinana NB	Mill Point Rd on	Mill Point Rd off	5	<= 2	8	8,021	8,346	3.9	0.037

1. LCC is based on the MLC and EMLC.

Table 6.4: Base versus actual MSFR values and MSFR loss for the Victorian weaving areas

	Freeway	From	To	Lanes	Gradient (%)	HV (%)	MSFR baseline (veh/h)	MSFR actual (veh/h)	Delta MSFR (%)	LCCx _{Mand} ⁽¹⁾
1	Monash Freeway	Eastlink	Stud Rd	5	<= 2	8	8,635	6,754	-21.8	0.255
2		Stud Rd	Eastlink	5	3.1	8	8,160	7,309	-10.4	0.124
3		Heatherton Rd	South Gippsland Fwy	5	<= 2	8	8,635	6,593	-23.6	0.360
4		South Gippsland Fwy	Heatherton Rd	5	<= 2	7	8,755	8,262	-5.6	0.078
5		Princes Hwy	Clyde Rd	3 (old)	<= 2	10	5,525	4,806 (old)	-13.0 (old)	0.154 (old)
6		Clyde Rd	Princes Hwy	3 (old)	<= 2	10	5,525	5,072 (old)	-8.2 (old)	0.109 (old)
7	Tullamarine Freeway	English St	Calder Fwy	Removed from further analysis (non-standard conditions including narrow curve) ⁽²⁾						
8	Monash Freeway	Princes Hwy	Clyde Rd	4 (new)	<= 2	6	7,385	5,817	-21.2	0.217
9		Clyde Rd	Princes Hwy	4 (new)	<= 2	6	7,385	5,643	-23.6	0.275
10		Wellington Rd	Eastlink	5	<= 2	10	8,475	6,879	-18.8	0.444
11	Tullamarine Freeway	M80 Ring Road	Mickleham Rd	Removed from further analysis (frequent spillback from downstream) ⁽³⁾						
12	M80 Ring Road	Hume Freeway	Sydney Rd	Removed from further analysis (frequent spillback from downstream) ⁽³⁾						

1. LCC is based on the MLC and EMLC.

2. Tight curve (around 400 m radius) may contribute to low MSFR, literature on the impact is very limited (January to March data).

3. Downstream congestion severely affecting weaving area capacity measurements.

The definition of the MSFR baseline values for the Western Australian weaving areas proved more challenging than expected for the following reasons:

- The measured MSFR values in Table 5.5 used for the definition of the baseline for unmanaged motorways as per Table 5.7 were based on 2-lane and 3-lane carriageways, i.e. no 4-lane carriageway was included here. The assumed reduction of per lane capacities with increasing carriageway lane number was not observed between 2-lane and 3-lane sites, so the corresponding extrapolation to 4 lanes involved uncertainties. To generate a more reliable baseline for Table 6.3 number 1, an additional MSFR measurement at a nearby site was undertaken (Mitchell Freeway NB, Karrinyup Road to Erindale Road, cross-section 530 MIN-MUT)³. The resulting MSFR of 6,997 veh/h for this 4-lane cross-section is a more reliable baseline (given the similarity of traffic and geometrical factors).
- For the Mill Point Road to Mill Point Road weaving area listed in Table 6.3 (number 3), the assumed baseline MSFR value was for a Western Australian Smart Freeway consistent with Table 5.8. Whilst the immediate upstream ramp is unmetred, this is a Smart Freeway with many metered upstream ramps impacting traffic flow in this location. Importantly, due to the low LCC, no MSFR reduction was observed here, so the site does not significantly impact the overall result.

As a conclusion, for the interpretation of the analysis results, the reader should bear in mind that there are some uncertainties regarding the validity especially of the analysis results for the Mitchell NB Reid Highway to Warwick Road site.

6.5 Relation Between Influencing Parameters and Capacity Loss

As part of this study, the relation between the reduced MSFR, expressed as a percentage of the base MSFR as generally included in the MCG, and different traffic and geometrical conditions was explored. The reduced MSFR is the remaining percentage after adding the (usually negative) Delta values shown in Table 6.4. The corresponding objective was to evaluate which one of these conditions or their combinations shows the strongest relation with the MSFR reduction as the equivalent of the corresponding capacity loss.

The following relations were tested:

1. volume ratio VR (unitless) vs reduced MSFR (volume ratio = weaving volume divided by total volume)
2. weaving area length L_s (in kilometres) vs reduced MSFR
3. combination of the VR and L_s vs reduced MSFR (i.e. combination of numbers 1 and 2; i.e. the ratio of VR (unitless) and L_s (in kilometres) was put in relation to the reduced MSFR)
4. LCC vs reduced MSFR (like number 3 but considering the MLC and the EMLC undertaken by vehicles; the ratio of the combined number of MLC and EMLC per vehicle traversing the segment (unitless) and L_s (in kilometres) was put in relation to the reduced MSFR).

The VR and L_s parameters used are those included in Table 6.1 and Table 6.2. The LCC parameters used have been adopted from Table 6.1 and Table 6.2 (MLC) or Table 6.3 and Table 6.4 (MLC and EMLC).

The visual impression of the scatter in the diagrams shown in Figure 6-4 to Figure 6-9 provides a first indication, whereas the Coefficient of Relation R^2 gives a second, more objective indicator. The greater this value (with a maximum of 1), the stronger the relation between the 2 parameters. It can be seen from Figure 6-4 that there is a reasonably strong dependency between VR and the remaining MSFR. It is intuitive that the turbulences and the capacity loss caused by them are linked to the amount of weaving traffic in relation to the total traffic volume. In contrast, there is no significant relation between the weaving area length and the remaining MSFR (refer to Figure 6-5). It is also intuitively clear that the length over which the weaving movements, including the corresponding LC, must be accommodated can only be a complementary

³ The same approach was selected for the Eastern Freeway weaving areas analysed for the Vic DTP 2021 TRB annual meeting contribution (Zurlinden et al. 2021). There appears to be some uncertainties with MSFR values for unmanaged motorways in the MCG (especially for multi-lane carriageways). Most MCG measurement sites were on managed motorways. It is anticipated that this issue will be addressed as part of the Austroads NEG 6527 project that is currently underway.

variable that influences the induced turbulences, i.e. it does not make sense to analytically consider the length as an influencing variable without considering the traffic component.

Figure 6-4: Relation between the VR and the MSFR/capacity loss

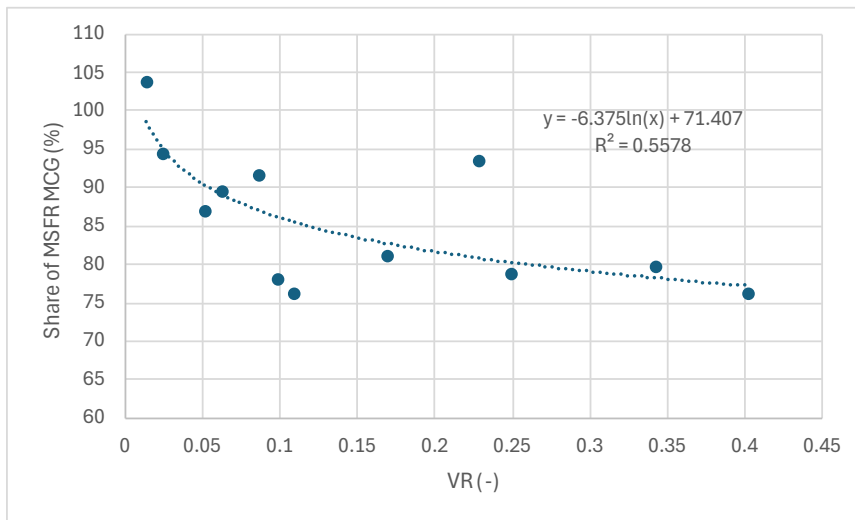
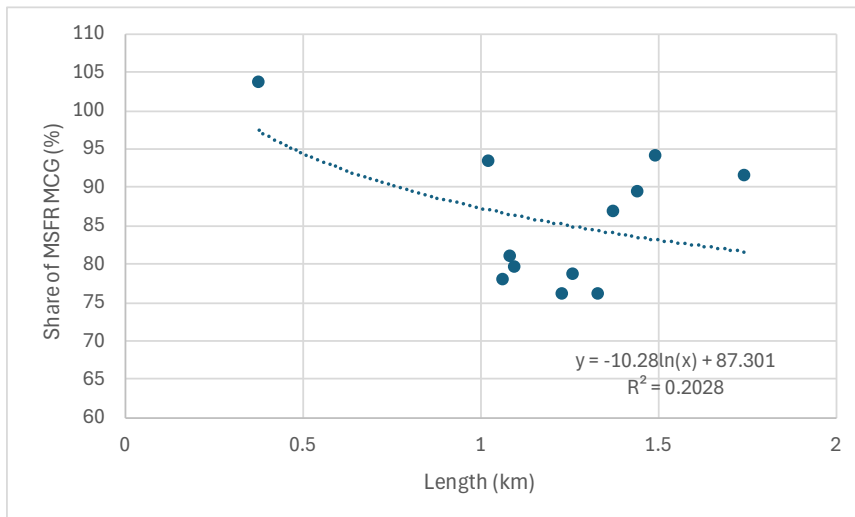


Figure 6-5: Relation between the weaving area length L_s and the MSFR/capacity loss



The combination of the 2 parameters VR and the weaving area length seemed to be a promising approach since the amount of weaving per total traffic (VR) that must be processed over a limited length (L_s) gives an indication of the weaving concentration. Figure 6-6 shows that there is a reasonable, but not very strong, dependency between the 2 parameters.

The most meaningful approach appears to be to test the relation between the MLC and/or EMLC concentration and the reduced MSFR (refer to Figure 6-7 to Figure 6-9). The Coefficient of Relation R^2 is relatively low (0.47) when only considering MLC (from Table 6.1 and Table 6.2). The interpretation of mandatory in this case was that only the minimum number of LC that a weaving vehicle must undertake to reach its destination was considered (i.e. it was assumed that all exiting vehicles line up in the outer lane when entering the weaving area and entering vehicles stay in the outer mainline lane after they have entered). This means that one LC per weaving vehicle was considered, except for the Monash Freeway site between Heatherton Road and South Gippsland Freeway (both directions) where two LC per weaving vehicle are needed (refer to Appendix F).

A different analysis interpreted mandatory as the measured LC undertaken by the weaving vehicles, i.e. also considering the LC manoeuvres over multiple lanes before the exit or after the entry (sourced from TIRTL and ANPR measurements, as included in Appendix G). Figure 6-8 shows that there is an even lower Coefficient of Relation R^2 in this case. This is likely caused by a high number of discretionary lane changes

that do not necessarily impact significantly on capacity. For example, many vehicles entering the Kwinana NB section between the Mill Point Rd entry and exit ramps undertake multiple discretionary lane changes to position themselves in the right lanes for needed manoeuvres to the north of the Narrows Bridge (refer to the highlighted point in Figure 6-8). Discretionary lane changes do not necessarily impact on weaving area capacity because they do not have to be made in the analysed weaving area, i.e. motorists do not have to force their way into smaller than their desired gaps etc.

The low Coefficient of Relation R^2 changes when considering the combination of MLC and EMLC (from Table 6.3 and Table 6.4), based on measured OD patterns and geometrical conditions (refer to Section 8 and Appendix F for the methodology and application). This reflects all LC that must be made by vehicles progressing from origin to destination and those that must be made to avoid capacity exceedance under average conditions. Whilst the overall Coefficient of Relation R^2 is relatively high in this case (0.77) and the relation is statistically significant there are some outliers that cannot be fully explained.

Figure 6-6: Relation between the combination of the VR and the weaving area length L_{crit} and the MSFR/capacity loss

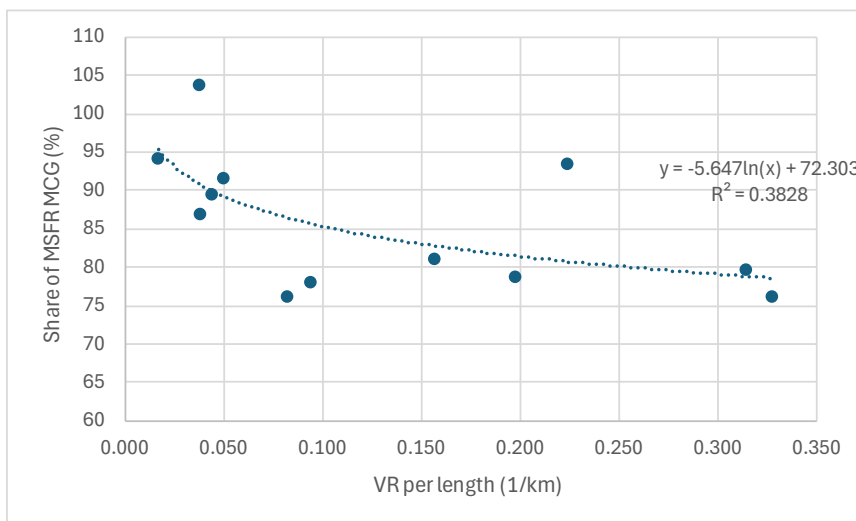
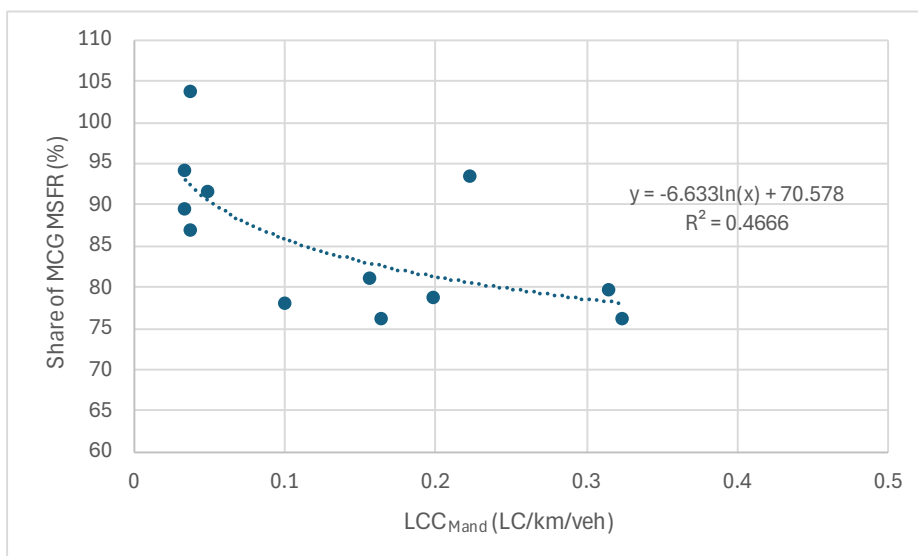


Figure 6-7: Relation between the strictly MLC concentration and MSFR/capacity loss; assumption is that all exiting vehicles line up in the lane closest to the exit, and all entering vehicles merge into the outer lane



It should be noted in this context that deviations of measured capacity values from the typical values included in the MCG or other guidelines under seemingly identical external conditions are normal. For example, even the measurement sites used for the MCG development show deviations of up to 10% from the typical values listed in the corresponding tables when considering their external conditions such as the

number of lanes, gradient and HV percentage (refer to VicRoads 2019a, Table 3-3 in combination with Tables 2-1 to 2-8 and Table 3-1).

The probability p that the model's R^2 shown in Figure 6-9 happened by random chance is only 0.000171. This is much smaller than a common significance level of $\alpha = 0.05$. The statistical significance at this level still exists when removing the Mitchell NB Reid Highway to Warwick Road site or even both WA sites discussed in Section 6.4 from the analysis.

Another observation is that at very low LCC values, the measured MSFR can be greater than 100% of the typical value. This may be due to random deviations of measured capacity values from the typical values, as explained in the above (likely). Whilst less likely, some limited MLC or EMLC may even have a capacity increasing effect (like the well-known phenomenon that at very low volumes, speed first increases from the FFS when volumes increase). In absence of full understanding of this phenomenon, a methodology based on Figure 6-9 should only be applied from a certain minimum LCC value onwards.

A further observation is that the fitted logarithmic curve seems to be plateauing, i.e. the capacity loss seems to be limited to around 25% to 30%, even for very high LCCs. This is also consistent with reasonable expectations and traditional road design practice. Often, an auxiliary lane equivalent to an additional 20% to 25% capacity is added to the cross-section to absorb heavy weaving.

Figure 6-8: Relation between the measured MLC concentration and MSFR/capacity loss; sourced from ANPR and TIRTL measurements

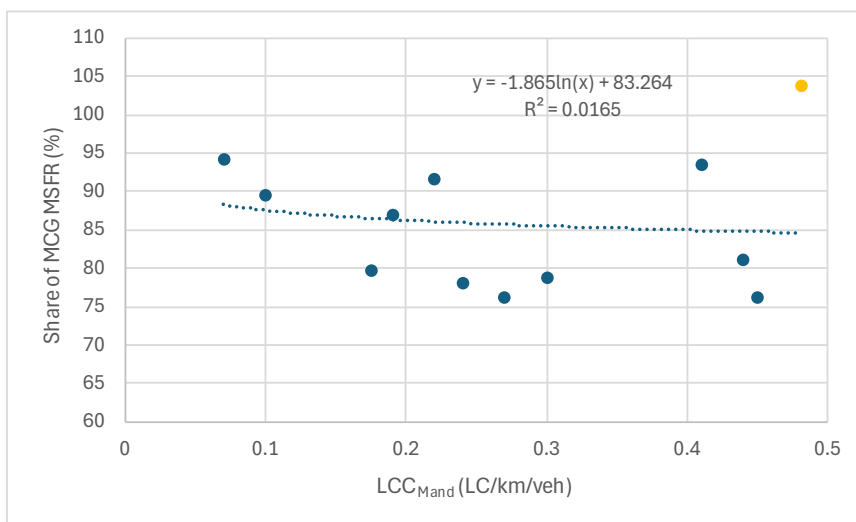
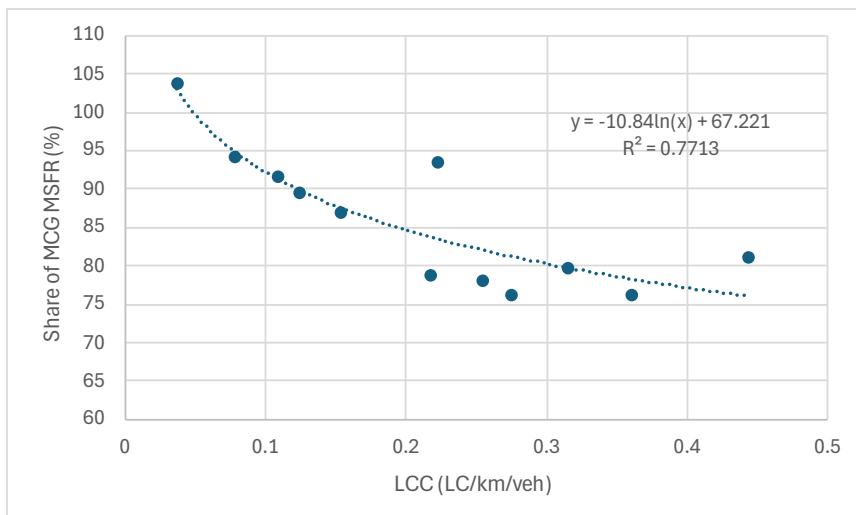


Figure 6-9: Relation between the modelled MLC and EMLC concentration and MSFR/capacity loss



7 Refined Weaving Area Capacity Determination Methodology

As a result of the review and comparison of existing and newly proposed methodologies for analysing weaving area capacity – which is described in Section 2 – it was concluded in Section 2.2 that only the extended STRIDE and the Vic DTP 2021 methodologies were recommended for further development/testing. The extended STRIDE methodology was completed as part of the NCHRP 07-26 project and is described in the corresponding report 1038 (NCHRP 2023). This method was tested under local conditions. The Vic DTP 2021 methodology was recommended for further development, especially based on a greater sample size. This section, in combination with Section 8, focuses on the completion of the Vic DTP 2021 methodology so that it is suitable for later testing.

7.1 Description of the Proposed New Methodology Including Rationale

It was shown in Section 6.5 that there is a strong relation between the combined MLC and EMLC concentrations and the MSFR loss (refer to Figure 6.8). This relation is especially stronger than between any of the other tested parameters or their combinations and the MSFR loss. This result is the starting point for the description of the proposed methodology in this section. In the future, the established functional relationship should be further strengthened through more data inputs from additional weaving areas across Australia and New Zealand, e.g. as part of an Austroads project. It should be noted in this context that any new research result and novel methodology can benefit from consolidation based on additional test site data.

The application by practitioners is described in Section 7.2. The described methodology was applied during the test phase of this project (refer to Section 9). This phase also included the testing of the only other potentially suitable methodology, namely the extended STRIDE one first described in the NSHRP 1038 report (NCHRP 2023), which according to the responsible TRB committee member, will become part of the next HCM edition (refer to Section 2.1.2).

7.1.1 Input Parameters

The application of the proposed methodology requires the following input parameters, which can be collected from the sources as included in brackets:

- geometrical conditions, including
 - number of entry-ramp, mainline and exit-ramp lanes (project plans, as-built plans, aerial photos)
 - height profile suitable to identify the steepest 500-m segment within the analysed section (project plans, as-built plans, topographical map, GIS system information, road survey information)
 - acceleration and deceleration lane lengths (project plans, as-built plans, aerial photos)
 - linemarking information suitable to identify details such as continuous and dotted lines, hatched areas (road marking plans, aerial photos)
- traffic information
 - total traffic volume and peak hour volume (VDSs, continuous traffic counting stations, traffic surveys, state road agency information including open data portals or web pages)
 - heavy vehicle percentage (VDSs, continuous traffic counting stations, traffic surveys, state road agency information including open data portals or web pages)
 - percentages of volume for the different OD relations (traffic modelling, traffic surveys, probe data such as TomTom or potentially Bluetooth data, specific VDS types such as TIRTL detectors that allow for vehicle re-identification)
- traffic management context
 - availability of managed motorway technology focusing on coordinated ramp metering (project plans, as-built plans, aerial photos or street view images).

7.1.2 Needed Graphs, Tables or Equations

The needed graphical illustrations or numerical resources are currently limited to the following items:

- general capacity guidance used in Western Australia or Victoria, namely
 - MRWA Smart Freeway guidelines (MRWA 2025a; VicRoads 2019b)
 - Vic DTP, *Managed Motorway Design Guide: Volume 1, Part 3* (VicRoads, 2019a)
 - potentially, AGTM and/or AGSM, after completion of the Austroads NEG 6527 – AGTM Update – Freeway Capacity Analysis project
- diagram shown in Figure 6.8 or corresponding look-up tables derived from this (refer to Table 7.1).

Table 7.1: Weaving adjustment factor

$LCC_{X_{Mand}}$ (LC/veh/ln)	F_{Weave}
0.050	99.7
0.075	95.3
0.100	92.2
0.125	89.8
0.150	87.8
0.175	86.1
0.200	84.7
0.225	83.4
0.250	82.2
0.275	81.2
0.300	80.3
0.325	79.4
0.350	78.6
0.375	77.9
0.400	77.2
0.425	76.5
0.450	75.9
0.475	75.3
0.500	74.7

If finer granularity is required, then Equation 20 can be used to identify the resulting F_{Weave} .

$$F_{Weave} = 67.221 - 10.84 \cdot \ln(LCC_{X_{Mand}}) \quad 20$$

where

F_{Weave} = weaving adjustment factor, i.e. factor for the multiplication of the base capacity from MRWA Smart Freeways guidelines (MRWA 2025a), MCG (VicRoads 2019a), or future versions of the Austroads AGTM/AGSM

$LCC_{X_{Mand}}$ = combined mandatory and extended mandatory LCC (LC/veh/km); to be determined based on the procedure described in Section 7.1.3 combined with Section 8

7.1.3 Methodology Description

The project has established a clear and direct relationship between the combined MLC and EMLC concentration $LCC_{X_{Mand}}$ and the MSFR loss or remaining, reduced $MSFR_{Weave}$, respectively. The $LCC_{X_{Mand}}$ is

calculated by dividing the number of MLC and EMLC $LC_{X_{Mand}}$ by the total number of vehicles traversing the weaving area and by the weaving area length (refer to Equation 21).

21

$$LCC_{X_{Mand}} = \frac{LC_{X_{Mand}}}{q * L_s}$$

where

- $LCC_{X_{Mand}}$ = combined mandatory and extended mandatory LCC (LC/veh*km)
- $LC_{X_{Mand}}$ = combined mandatory and extended mandatory LC (LC/veh*km)
- q = volume (veh/h)
- L_s = short length of the weaving area (also L_{Crit})

The estimation of the parameter $LC_{X_{Mand}}$ while considering lane balancing, i.e. avoidance of per lane MSFR exceedance, is therefore at the core of the application by practitioners. The parameter is modelled for a saturated traffic state, i.e. the overall weaving area volume q is assumed to be equivalent to the MSFR for a basic freeway/motorway section ($MSFR_{Base}$). The parameter L_s can be directly adopted from project plans, as-built plans or aerial photos.

Section 8 shows that, whilst the estimation is relatively straightforward, it can be challenging to monitor the project steps including input and output parameters and interim results without getting confused. It would therefore be desirable to develop a suitable tool such as an Excel spreadsheet to support the modelling.

The $LCC_{X_{Mand}}$ parameter is the only needed input for the diagrams or table for the estimation of F_{Weave} that must be multiplied by the base MSFR, sourced from the relevant capacity guidance documents listed in Section 7.1.2 (e.g. MRWA Smart Freeway guidelines) to obtain the resulting MSFR for a weaving section ($MSFR_{Weave}$).

The estimation of $MSFR_{Weave}$ is simply as follows from Equation 22.

22

$$MSFR_{Weave} = F_{Weave} * MSFR_{Base}$$

where

- $MSFR_{Weave}$ = MSFR for the weaving area (veh/h)
- F_{Weave} = weaving reduction factor (-)
- $MSFR_{Base}$ = base MSFR for a section without intense weaving (veh/h)

It should be noted that the application of F_{Weave} allows for a reasonable $MSFR_{Base}$ adjustment to arrive at a realistic $MSFR_{Weave}$ value. Its use is not expected to allow for a precise prediction of $MSFR_{Weave}$.

The resulting $MSFR_{Weave}$ can then be directly compared to the total predicted traffic volume, i.e. to the sum of all OD movement related volumes (FF+FR+RF+RR) to decide if there is sufficient weaving area capacity or not.

7.1.4 Output Parameters

The main output parameter of the methodology is the reduced MSFR value for a weaving area $MSFR_{Weave}$. This value will then support the mainline design procedure as described in VicRoads (2019b, Section 4.4).

This means that it replaces the $MSFR_{Base}$ values for the areas characterised by intense weaving. An $LCC_{X_{Weave}}$ threshold value of 0.05 LC/veh/km is recommended to support this decision, i.e. only higher

LCC_{XWeave} values require a separate weaving area capacity analysis as per the procedure described in Section 7.2.

The rationale for this recommendation is that below this value, random MSFR fluctuations can be stronger than the influence of the MLC and EMLC.

7.2 Guidance Text for Practical Application

The steps that must be taken for the application of the methodology are as follows:

1. Collate the relevant traffic and geometrical conditions, including
 - a. number of mainline carriageway lanes (-)
 - b. number of entry ramp and exit ramp lanes (-)
 - c. L_s of the weaving area (km)
 - d. gradient s (%)
 - e. HV percentage (%)
 - f. traffic management conditions (i.e. availability of coordinated ramp metering).
2. Identify the base case capacity value $MSFR_{Base}$ from the MRWA Smart Freeway guidelines/MCG or from the envisaged updated AGTM or AGSM version (following the completion of the Austroads NEG 6527 project).
3. Estimate the combined number of MLC and EMLC $LC_{X Mand}$ as per the methodology described in Section 8.2.1 of this report.
4. Calculate the combined MLC and EMLC concentration $LCC_{X Mand}$ from Equation 21.
5. Look up F_{Weave} as the remaining percentage of $MSFR_{Base}$ from Figure 6.8 or Table 7.1.
6. Multiply this percentage by the base case $MSFR_{Base}$ as per Equation 22.

Some more details are as follows:

- 1.a: The lowest number of lanes within the section determines the capacity/MSFR value and must therefore be selected here.
- 1.b: The number of entry and exit ramp lanes from which it is possible to enter or exit the mainline must be selected here.
- 1.c: L_s is the length across which it is legally permitted to change lanes, e.g. as illustrated by dotted or special linemarking according to Australian Standard AS 1742 *Manual of Uniform Traffic Control Devices* (Standards Australia, 2022), which refers to pavement markings that go beyond standard longitudinal and transverse lines.
- 1.d: The greatest (positive) identified gradient value s from all 500-m rolling averages within a freeway/motorway section will be used as an input to the tables included in the capacity guides as listed in Section 7.1.2. Rounded values can be used for this purpose. Only values greater than or equal to 2% are relevant.
- 1.e: The most easily applicable classification system for the HV determination is the Austroads 2-bin system that only distinguishes between light vehicles and HV. Any more sophisticated bin system (e.g. 8-bin or 12-bin) can be easily converted back to the simpler 2-bin one. If a conversion into PCU is needed (e.g. for the application of the MRWA Smart Freeway guidelines) this can be done by using Table 12-10 of the HCM (TRB 2022). The HV percentage input parameter is an average value measured over a longer period including peak and off-peak periods as well as weekdays and weekend. This is because such average values were also used for the development of the MCG (VicRoads 2019a) and the tables included therein.
- 1.f: A distinction between Smart Freeways/managed motorways and foundational/unmanaged ones must be made. In the sense of the application of the foundational MCG (VicRoads 2019a), a Smart Freeway/managed motorway is characterised by a minimum number of metered and coordinated upstream ramps as specified in VicRoads (2019b, Section 4.4.5.2).
3. The estimation of the MLC and EMLC is comprehensively described in Section 8. Since this is a sophisticated process based on multiple assumptions, there could be different interpretations leading to more than one result for LCC_{XWeave} . In this case, the average of the resulting values might be used as an input for the further procedure steps.

8 Methodology for Estimating Weaving Area Lane Changing Quantity

A refined methodology for determining weaving area capacity was developed as described in Section 7. This is supported by a detailed methodology that describes the potentially complex process of estimating the essential number of LC, which is the most important input parameter for the overarching capacity estimation methodology. The lane changing quantification method is described in this section.

8.1 General Considerations

The combined analysis of the measured weaving area LCC and local MSFR reductions compared to typical values has produced a functional relationship between these 2 parameters (refer to Section 6.5).

It was originally intended to measure the MLC only, i.e. the LC that are essential for vehicles to progress from origin to destination, and to put these in relation to the MSFR loss (refer to Figure 6.7). However, the measurement of LC made by weaving vehicles included some seemingly discretionary or extended mandatory LC as well (i.e. LC not needed to progress from origin to destination), e.g. when vehicles did not exit from the mainline lane closest to the exit-ramp or did not enter to the mainline lane closest to the entry-ramp. In contrast to the strictly MLC, this component can be discretionary or extended mandatory, needed to avoid lane-specific oversaturation in the outer lane.

The EMLC needed to avoid capacity exceedance in a lane cannot be measured, or more precisely, they cannot be identified as a subset of all measured lane changing. This is also lane changing that must be made for a freeway/motorway to function, so there is likely a relation between this type of LC and the measured MSFR loss as well. In conclusion, the establishment of a functional relationship between the MSFR loss and the measured lane changing is of little use for subsequent application by practitioners.

This issue creates a significant challenge for the desired provision of guidance for the application of the proposed methodology, i.e. ultimately for the estimation of the MSFR loss based on the induced lane changing associated with predicted traffic patterns and planned geometrical conditions.

As an alternative, it was therefore attempted to establish a functional relationship between the estimated combined MLC and EMLC concentrations and the MSFR loss measured for the investigated Western Australian and Victorian weaving areas (refer to Figure 6.8). The corresponding modelling technique could then, once appropriately described, also be applied by practitioners for the planning of upgrades or new facilities.

A relatively straightforward method (or model) to estimate the combined MLC and EMLC concentrations, i.e. the LCC that results from LC that motorists must make to progress from an origin to a destination plus those that other vehicles must make to facilitate these mandatory ones through the avoidance of local oversaturation, was developed by Hall (Hall et al. 2018). This method was refined as is described in Section 8.2.

In the context of the pursued methodology development, this method can be used for the following:

- to estimate the MLC and EMLC concentrations for the selected Western Australian and Victorian weaving areas and to develop a functional relationship with the MSFR loss, plus assess its reliability (e.g. based on a Coefficient of Correlation R) – methodology development phase
- to estimate the MLC and EMLC concentrations for weaving areas that were not used for methodology development (in Western Australia, Victoria or other states/countries), to predict the MSFR loss based on the abovementioned functional relationship and to compare it to the measured MSFR loss – methodology testing phase
- to estimate the MLC and EMLC concentrations and predict the MSFR loss for upgrades or new weaving areas – methodology application.

The inherent consistency between the development and testing/application methods is a significant advantage, e.g. assumptions that are not 100% realistic impact both methodology development and application alike.

The following Section 8.2 covers many real-world scenarios including complex cases. It should be noted that many application cases are simple weaves such as single entry and exit lanes connected by an auxiliary lane. The estimation of the combined MLC and EMLC is then straightforward. For the more complex cases, comprehensive testing is required to assess the ease of application and robustness of results.

The relatively complex lane changing quantity estimation methodology described in Section 8.2 was assessed and refined as part of the testing described in Section 9.

8.2 Estimation of LC

This section describes the methodology for the estimation of the number of MLC and EMLC and their concentration, including the needed input parameters such as graphs, tables, equations and drawings to be used, and output parameters (Section 8.2.1). It also describes the initial application (Section 8.2.2).

The below text describes the methodology that was originally used for the development of the previously presented Figure 6.8 and Table 7.1. The methodology was applied to all Western Australian and Victorian weaving areas as is described in Appendix F. It was also used for methodology testing. The text frequently references MSFR values that can be sourced from the MRWA Smart Freeway guidelines (in pc/h) or MCG (in veh/h). For simplicity, the term MCG (and veh/h) is preferentially used throughout the text.

The identified relationship between LCC and MSFR loss (refer to Figure 6-9 and Figure 8-4 respectively) is based on the absolute number of LC and simple traffic volumes, both based on the unit 'veh' rather than 'PCU'. For method application as described in the following sections, the number of estimated LC as well as the total volumes would be proportionately greater when using 'PCU'. These two effects neutralise each other. The developed methodology can therefore be applied based on PCU/h or veh/h alike. It may be challenging to understand that the estimated number of LC in PCU does not describe real movements of individual vehicles between two lanes, but rather the abstract movement of PCU.

8.2.1 Methodology

The methodology requires the following input parameters:

- OD ratios/percentages for the corresponding movements (FF, FR, RF and RR)
- weaving area layout including adjacent mainline sections and ramps (i.e. number of lanes, gradient, HV percentage)
- MSFR values on a carriageway and lane level (upstream, within, and downstream of the weaving area).

The methodology is based on the following assumptions:

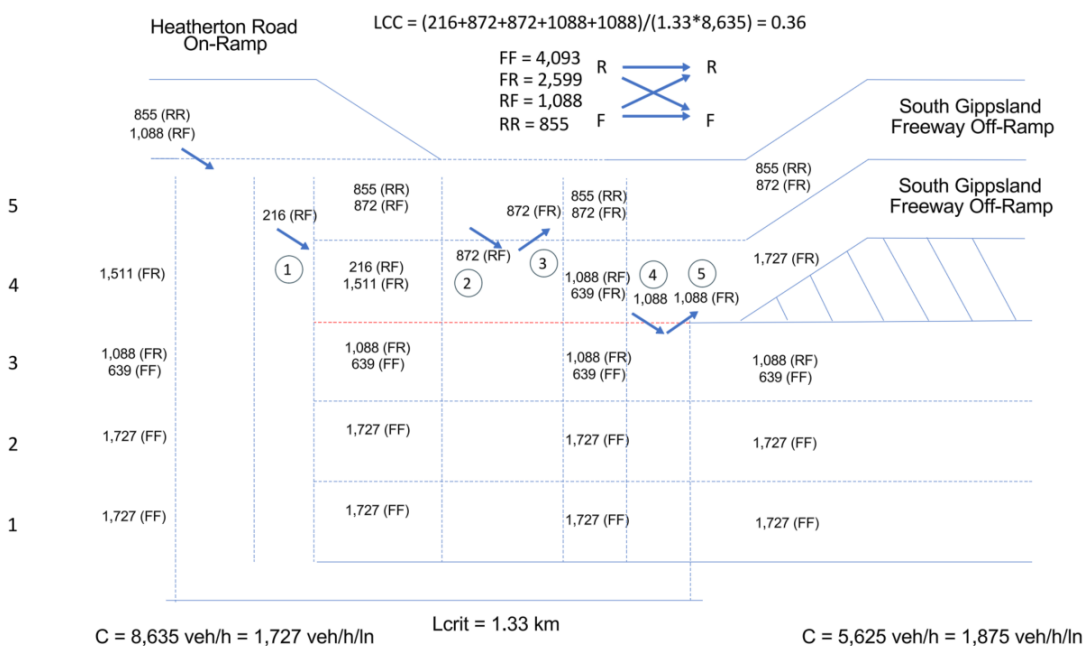
- The weaving area is saturated, i.e. the total volume is equivalent to the carriageway MSFR ('saturation volume'). It is important to note that, according to the MRWA Smart Freeway guidelines/MCG, the weaving area per lane MSFR can be different (often smaller) than that of upstream/downstream sections, e.g. because of a greater carriageway lane number (e.g. an additional auxiliary lane). This is reflected by the drawings included in Appendix F.
- The carriageway or lane MSFR must not be exceeded upstream, within or downstream of the weaving area. The default lane MSFR is the carriageway MSFR divided by the number of lanes. Local measurements may show that the real lane-specific MSFR value is different from this. The measured value will then be a more suitable input parameter for the methodology. In some cases, e.g. weaving areas with auxiliary lanes, the 'saturation volume' may be determined by upstream or downstream section constraints, i.e. the corresponding MSFR limitations must be considered. The total volume, while maintaining the OD percentages, must then be reduced until there is no more remaining MSFR exceedance.

- All lanes by default have the same per lane MSFR value, except when local measurements provide additional insights.
- Vehicles line up in the lane that is closest to their destination before entering the weaving area; if the lane MSFR is insufficient to accommodate all relevant OD movement vehicles, then they also line up in the next, adjacent lane(s).

The (iterative) process to estimate the number of MLC and EMLC is described below. The process **steps** can be interpreted with reference to Figure 8.1:

1. adoption of OD ratios (FF, FR, RF and RR percentages) from traffic counts, detector measurements, probe data or traffic modelling
10. definition of the carriageway MSFR values for the upstream, weaving area and downstream sections/segments, depending on the respective traffic (managed vs unmanaged, HV percentage) and geometrical (number of lanes, gradient) conditions
11. estimation of the per-lane mainline flow rates at the start of the section (following the division of carriageway volume by the number of lanes)
12. estimation of the entry-ramp flow rates (per lane in the case of multi-lane ramps)
13. assignment of initial (primary) MLC (based on the required OD movements)
14. assignment of (secondary) EMLC caused by lane balancing (i.e. needed to avoid per lane MSFR exceedance – there may be no EMLC for simple weaves or for relatively low RF / FR volumes)
15. check downstream mainline and exit-ramp constraints (identify potential exceedance of local downstream capacities/MSFR values – process complete if no downstream MSFR exceedance)
16. adjust the OD movement flow rates if downstream MSFR is exceeded (i.e. reduce critical flow rates to avoid downstream MSFR exceedance)
17. reiterate if needed (i.e. re-do Steps 1 to 7 if downstream MSFR is exceeded).

Figure 8-1: Calculation of LC – basic schematic and OD flows



In more detail, the process as described above and illustrated in Figure 8.1 is as follows:

Step 1: The OD percentages totalling 100% can be adopted from traffic counts, detectors (e.g. TIRTL) or probe data (e.g. TomTom) based on measurements over a representative period. They can also be adopted from traffic modelling, especially for new facilities.

Step 2: The percentages resulting from Step 1 (FF = 47.4%, FR = 30.1%, RF = 12.6%, RR = 9.9%) must be converted into flow rates through their multiplication by the weaving area carriageway MSFR value

(8,635 veh/h for the 5-lane managed motorway carriageway at 8% HV and flat conditions $\leq 2\%$) as can be seen to the left of the FF, FR, RF and RR arrow illustrations at the top of Figure 8.1.

Step 3: The estimation of the mainline volumes at the section entrance starts on the median side with the through movements that do not have to change lanes. The inner lanes are 'filled' with FF movements, and the remaining capacity of the last FF lane (Lane 3 in Figure 8.1) is 'filled up' to their capacity with FR vehicles. The remaining FR vehicles are assigned to the next lane (Lane 4), or if the capacity of this lane is insufficient, also to the following lane (Lane 5). The remaining capacity of the outer lane(s) will be filled with RF and RR movement vehicles. It should be noted that this step may already include some MLC such as those 216 RF ones indicated by Number ① in Figure 8.1. This is a special, complex case where large parts of the outer lane capacity is consumed by RF and RR movement vehicles so that not all FR movement vehicles can line up in the outer lane(s) as would be their preference (refer to Section 8.2.1, assumptions).

Step 4: Double lane entry-ramps are a special case with currently insufficient knowledge regarding the distribution of entering and exiting traffic. The balancing approach that was selected for the process so far is also applied here:

- Single lane entry-ramp: The total entering volume is equivalent to the combined RF and RR volume.
- Double lane entry-ramp: The inner entry-ramp lane is 'filled' with RF movements so that the sum of this volume and the outer mainline volume is equivalent to the per-lane MSFR of the weaving area (i.e. to the carriageway MSFR divided by the number of lanes). The remainder of the entry-ramp RF volume is assigned to the outer ramp lane, together with the RR movements. Like with the outer mainline lane, the sum of this proportion of the RF volume and the total RR volume must not exceed the per lane MSFR. An example of this process is shown in Figure 8.2. The assumed per lane capacity in the entering Lane 3 is 1,908 veh/h (adopted from the MCG). After subtraction of the FF and FR movement vehicles volumes in the outer mainline lane totalling 1,710 veh/h (369 veh/h plus 1,341 veh/h), this leaves capacity for the RF1 movement in the inner ramp lane of 198 veh/h.

Step 5: The next MLC following ① that must be made by RF movements to reach their destinations are illustrated by number ② in Figure 8.1. The corresponding EMLC that must be made by the FR movement for lane balancing are illustrated by number ③. To avoid MSFR exceedance in Lane 4, the RF LC must be matched by an equivalent number of FR LC.

Step 6: The same steps as illustrated under Step 5 above are repeated for any additional LC that the RF, FR or other movements must make to reach their destinations (number ④) or to avoid lane capacity exceedance, respectively (number ⑤).

Step 7: This step reflects the needed plausibility check that completes the described process. The total downstream/upstream mainline and exit-ramp volumes must not exceed the corresponding MSFR values as this would not align with the selected volume and capacity balancing approach. In the case of exceedance, it is necessary to reduce the total volume so that it is lower than the MSFR value for the analysed section. This step may result in an iterative process until no carriageway or ramp MSFR exceedance is left. It should be noted in this context that, according to the MRWA Smart Freeway guidelines/MCG, per lane capacities increase with lower carriageway (or ramp) lane numbers so that the downstream mainline and ramp cross-sections in Figure 8.1 have greater per lane capacities than the (not adjusted) weaving area capacities.

The following example is based on Figure 8.2: For the 3-lane downstream mainline carriageway section (MSFR = 5,725 veh/h), the following condition based on the combined FF (56.7%) and RF (18.3%) percentages shown must be met (Equation 23)

$$q_{Weaving Area Max} * (0.567 + 0.183) \leq 5,725 \text{ veh/h}$$

23

Based on this equation, the maximum permitted volume within the weaving area can be calculated as follows (Equation 24):

$$q_{Weaving\ Area\ Max} (1) = \frac{5,725}{(0,567 + 0.183)} = 7,633\ veh/h$$

If the currently assumed combined FF, FR, RF and RR volume exceeds this value, it must be reduced while maintaining the percentages in brackets in Figure 8.2, i.e. the percentages must be multiplied by 7,633 veh/h to arrive at the OD movement volumes. The same check should be done for the upstream area (with FF = 56.7% and FR = 18.2%) to ensure that the entire section sequence is in balance (Equation 25).

$$q_{Weaving\ Area\ Max} (2) = \frac{5,725}{(0,567 + 0.182)} = 7,644\ veh/h$$

For completeness, the exit-ramp and entry-ramp volumes should also be checked.

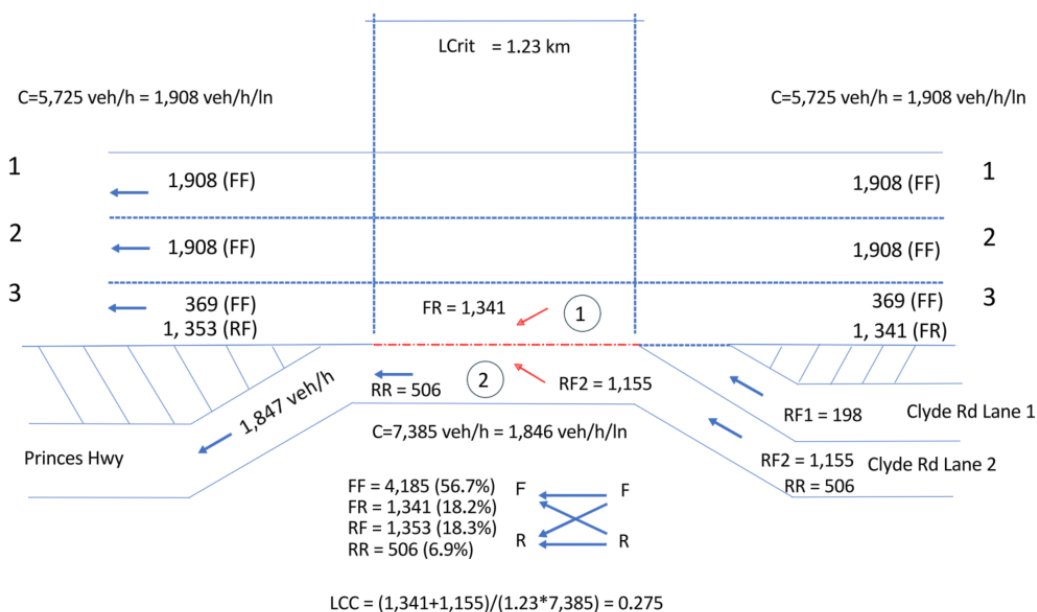
No rebalancing is needed for this example or the one shown in Figure 8.1.

Step 8: Repeat Step 1 to Step 6 if rebalancing according to Step 7 was necessary. This must be done until each combined downstream/upstream exit-ramp or mainline volume is lower than the corresponding MSFR values as sourced from the MRWA Smart Freeway guidelines/MCG or other capacity guideline. Based on experience, the number of iterations is limited to 1 or 2.

Step 9: Sum up all MLC and EMLC and calculate the LCC by dividing the resulting LC by the weaving area length L_s and by the total number of vehicles. This volume is equivalent to the assumed MSFR for the weaving area (or the reduced volume if Step 7 was needed). In the described example shown in Figure 8.1, this calculation leads to the following result (Equation 26):

$$LCC_{xMand} = \frac{216 + 872 + 872 + 1088 + 1088}{1.33 * 8,635} = 0.360$$

Figure 8-2: Example for the assignment of entry ramp flows to individual ramp lanes in the case of multi-lane ramps



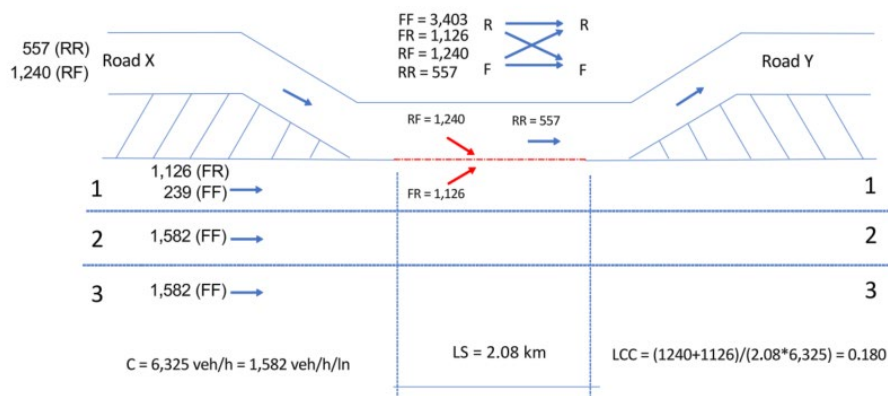
The expected output parameter is the combined MLC and EMLC concentration $LCC_{X\text{Mand}}$ for the assessed weaving area. The potential reduction of the volumes as per Steps 7 and 8 will lead to lower numbers in the nominator and denominator alike.

8.2.2 Initial Application

This section explains the initial application of the described methodology to a simple, fictitious weaving area (refer to Figure 8.3) with the following parameters:

- unmanaged motorway
- 4-lane carriageway (including auxiliary lane)
- auxiliary lane to accommodate the FR and RF movements
- single entry and exit ramp
- gradient $s \leq 2\%$
- HV percentage = 5%.

Figure 8-3: Example application of the proposed methodology



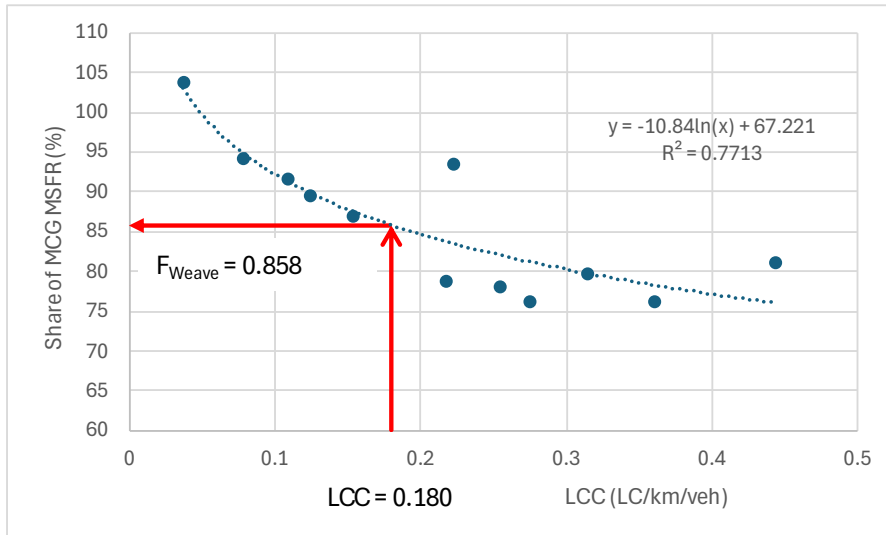
These values allow for the definition of an $MSFR_{\text{Base}}$ value of 6,325 veh/h, according to the MCG (refer to VicRoads 2019a, Table 2-9).

Additional parameters needed for the calculation of the combined MLC and EMLC concentration $LCC_{X\text{Mand}}$ are as follows:

- $L_S = 2.08$ km
- OD percentages: FF = 53.8%, FR = 17.8%, RF = 19.6%, RR = 8.8%.

Multiplication of the OD percentages by the $MSFR_{\text{Base}}$ value leads to the corresponding volumes shown to the left of the FF, FR, RF and RR arrow illustrations at the top of Figure 8.3. Application of the parameters based on the methodology described in Section 8.2.1 results in an $LCC_{X\text{Mand}}$ value of 0.180 LC/km/veh (Equation 21). This value is the input parameter for the estimation of initially F_{Weave} (Equation 20) and finally $MSFR_{\text{Weave}}$ (Equation 22). Using the $LCC_{X\text{Mand}}$ value of 0.180 as an input for Figure 8.4 (identical with Figure 6.8), an F_{Weave} of 0.858 can be read off from the diagram.

Figure 8-4: Determination of F_{Weave} based on the relation between the modelled MLC and EMLC concentration and the measured MSFR/capacity loss



This value will be used for the application of Equation 27 as follows:

$$MSFR_{Weave} = F_{Weave} * MSFR_{Base} = 0.858 * 6,325 = 5,427 \text{ veh/h}$$

27

No volume reduction due to upstream or downstream carriageway capacity exceedance is needed in this case since the corresponding volumes are lower than the capacities/MSFR values (VicRoads 2019a, Table 2-9 and VicRoads 2019b, Section 3.7.2).

It should be noted that this is a very simple example with little ambiguity regarding the assignment of OD vehicles to lanes. For more complex cases, including multi-lane ramps or lane drops or lane adds, there is more room for different interpretations. It is only comprehensive testing that will be described in Section 9 that will show the usability for practitioners and robustness against different interpretations of the user guidance provided in Section 8.2.1.

As a potential methodology extension, through multiplication of different base capacity values by F_{Weave} , also the weaving area capacities equivalent to 2%, 5% and 15% FBR can be estimated once the base capacity values for these FBR risks are known. As part of the Austroads NEG 6527 project, such discrete base capacity values will be provided. These values are a suitable basis for the generation of complete FBR curves, covering other FBR values as well. The procedure is equivalent to the one used to obtain $MSFR_{Weave}$ as the weaving area total volume at 1% FBR per 15-minute interval,

8.3 Caveat

When testing and assessing the described methodology based on a comparison of estimated and measured $MSFR_{Weave}$ values, it should be acknowledged that the application combines 2 different parameter estimations with the corresponding uncertainties as follows:

- **MSFR value:** The MCG measurement sites used for the guide development showed a relatively strong deviation of individual measurement site MSFR values from averages, which resulted in the MSFR guidance provided (4–5%). The same observation was made and discussed when updating the parameter values for international capacity guidelines⁴. This means that a certain deviation of estimated

⁴ Example: BAST project 'Update of freeway/motorway capacity values for the German HCM' (not published, discussion attended by the main author of this report).

MSFR values from typical values in the order of 5% and up to 10% is normal, even under seemingly identical external conditions.

- Estimation of MLC and EMLC as per Section 8.2.1: A range of assumptions was made as is outlined in this section. Naturally, not every assumption will be realistic under all circumstances.

These uncertainties should be considered when interpreting the test results included in Section 9. As this is a novel methodology that may require a few more iterations and improvements over time, the relative performance compared to other methodologies such as the extended STRIDE one is a suitable measure of success.

8.4 Estimation of Other Needed Input Parameters

It is expected that no additional input parameters, other than the ones described in Section 8.2.1, are needed for the application of the methodology.

9 Testing of the Proposed New Methodology

The testing was based on a comparison of the measured MSFR loss for the test weaving areas to the estimated MSFR loss, based on the extended STRIDE (Section 2.1.2) and newly developed, refined Vic DTP methodologies (Section 7.1). The initial aim was to identify new weaving areas for the testing that had not previously been used for methodology development as is described in Section 6 to Section 8. This presented a challenge, since almost all sites in Western Australia and Victoria that were identified as weaving areas characterised by strong crossing movements and significant capacity losses compared to typical sections had already been used for methodology development. A low number of weaving areas could be identified that had not been used for methodology development, especially due to difficult conditions to measure LC (i.e. no ANPR video camera installations possible, or TIRTL detectors available). Due to this low number, the project team contacted TMR in Queensland and asked for the nomination of suitable weaving areas for testing and provision of the traffic data needed (SVO). This resulted in the nomination of 2 additional weaving areas.

Testing for the Reid Highway between Malaga Drive and Tonkin Highway led to additional insights and to a potential modification of the refined Vic DTP method that could better deal with strong imbalances between crossing traffic streams. The resulting alternative approach achieves better results for cases when one crossing stream is much stronger than the other one, and it achieves very similar results for conventional cases with relatively evenly balanced crossing streams (refer to Section 9.1.1 and 9.1.2), i.e. the difference in test results compared to the original approach is around 1%.

9.1 Weaving Sites Selected for Testing

The test sites from Western Australia (Reid Highway), Victoria (Eastern Freeway) and Queensland (Bruce Highway and Pacific Motorway) described in Sections 9.1.1 and 9.1.2 were identified and assessed as suitable for full testing, i.e. testing of the newly developed and extended STRIDE methodologies. More weaving areas identified in Queensland were investigated but could not be used for testing for various reasons (e.g. Pacific Motorway between Cornwall Street and Stanley Street turned out to be an issue linked to frequent spillback from the exit-ramp).

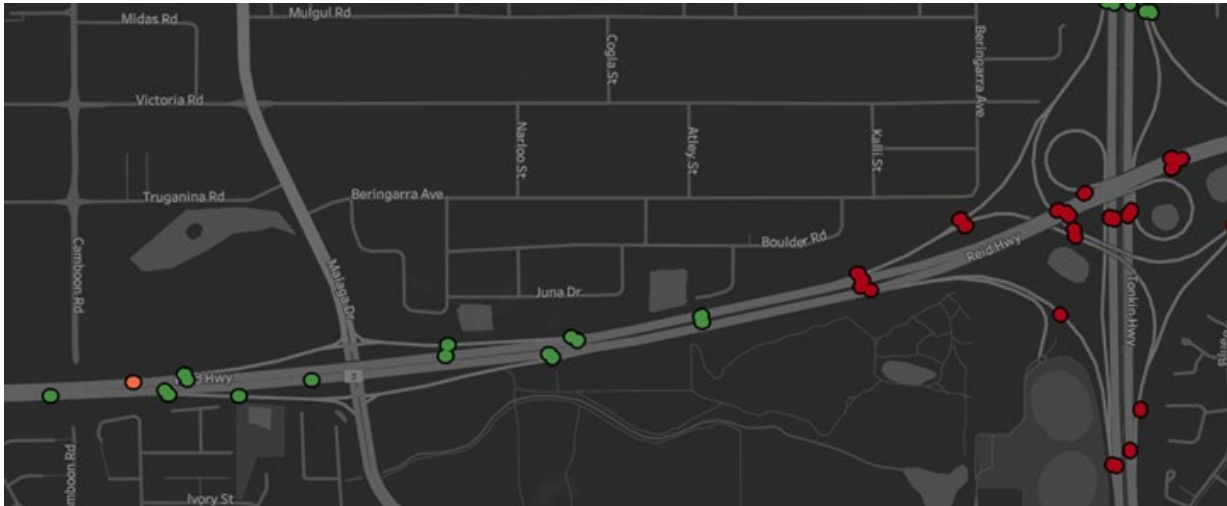
It was considered to use the same Western Australian and Victorian sites that were used for methodology development for full testing, based on different months, weeks, days or times of the day with different OD patterns. However, this idea was dismissed after careful consideration since testing of the methodology requires the reliable estimation of MSFR values, which in turn depends on well-defined FBR curves. These must be based on a minimum of 10 observed flow breakdown events. This high number cannot be observed during periods with OD patterns that are different to the most congested ones, which were already used for methodology development. As an example, for the Victorian site on the Monash Freeway between Wellington Road and Eastlink (OB), almost all FB events are observed during the evening peak, and close to none (depending on the observation period) during the morning peak characterised by different OD patterns. It is, therefore, not possible to sensibly assess the methodology based on morning data for this location. However, these sites could still be used for testing the extended STRIDE methodology. This means that they could not be used for a comparative test between the 2 methods, but they could be used for a plausibility test of the extended STRIDE methodology, i.e. an incomplete test could be undertaken.

9.1.1 Western Australia and Victoria

Perth Reid Highway – Malaga Drive to Tonkin Highway

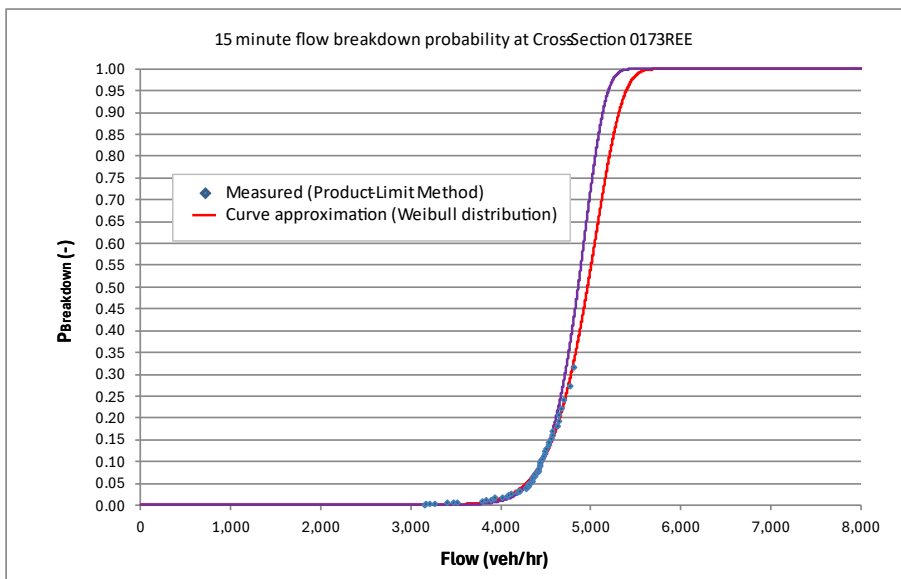
The Western Australian weaving area on Reid Highway between Malaga Drive and Tonkin Highway, which was identified early in the project for methodology development, was investigated as a candidate site to be used for testing (refer to Section 3.1.2 and Figure 9.1).

Figure 9-1: Data availability on Reid Highway between Malaga Drive and Tonkin Highway (Status: 11/02/2026)



From the resulting FBR curve after filtering out the intervals when there was downstream congestion (refer to Figure 9.2), it could be concluded that the $MSFR_{Weave}$ in this location was 3,904 veh/h for this 3-lane section, including an auxiliary lane (gradient $s \leq 2\%$, $HV = 11.5\%$), compared to a typical $MSFR_{Base}$ of 4,843 veh/h. This reduction was caused by strong FR movements towards Tonkin Highway (51.0% of all traffic), which conflicted with a relatively low RF movement (4.4%) from Malaga Drive to the downstream section of Reid Highway (OD data sourced from TomTom).

Figure 9-2: FBR curve for Reid Highway between Malaga Drive and Tonkin Highway after filtering for downstream congestion (cross-section 0173 REE-MUL and 0173 REE-ORL combined)



When applying the methodology for the estimation of LC as described in Section 8.2.1, this resulted in a high LCC of 0.852, especially due to the short section length (Figure 9.3). The LCC based on Equation 20 suggests a F_{Weave} of 0.690 and therefore an MSFR reduction of around 31%, whereas the measured reduction is only 19.5% ($MSFR_{Base} = 4,843$ veh/h vs $MSFR_{Weave} = 3,904$ veh/h). This is a relatively great discrepancy.

To improve this result and as was indicated in Section 8.2.1, the assumed outer lane-specific MSFR value of 1,615 veh/h shown in Figure 9.3 could be replaced by a measured lane-specific MSFR. Figure 9.4 shows an example for a measured localised outer lane MSFR of 1,800 veh/h. The LCC is only 0.612 in this case, and the corresponding F_{Weave} is 0.725, equivalent to an MSFR reduction of around 27-28%. For a further increased outer lane-specific MSFR of 1,900 veh/h, the LCC is 0.482 and the MSFR reduction 25%. This example shows that validation and refinement of the assumptions listed in Section 8.2.1 based on local conditions and available data can achieve better results.

Figure 9-3: Reid Highway between Malaga Drive and Tonkin Highway (volumes based on upstream 2-lane cross-section saturation flow and TomTom-based OD ratios)

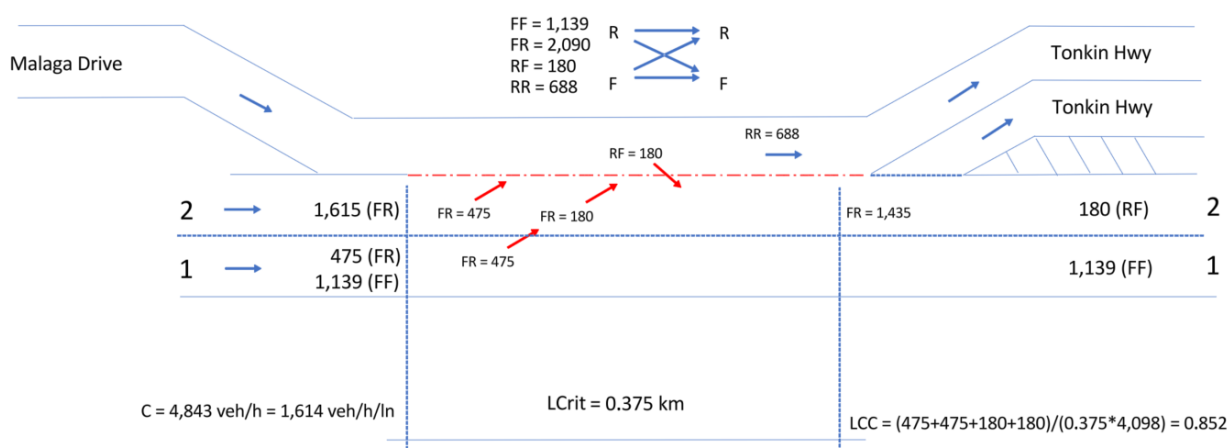
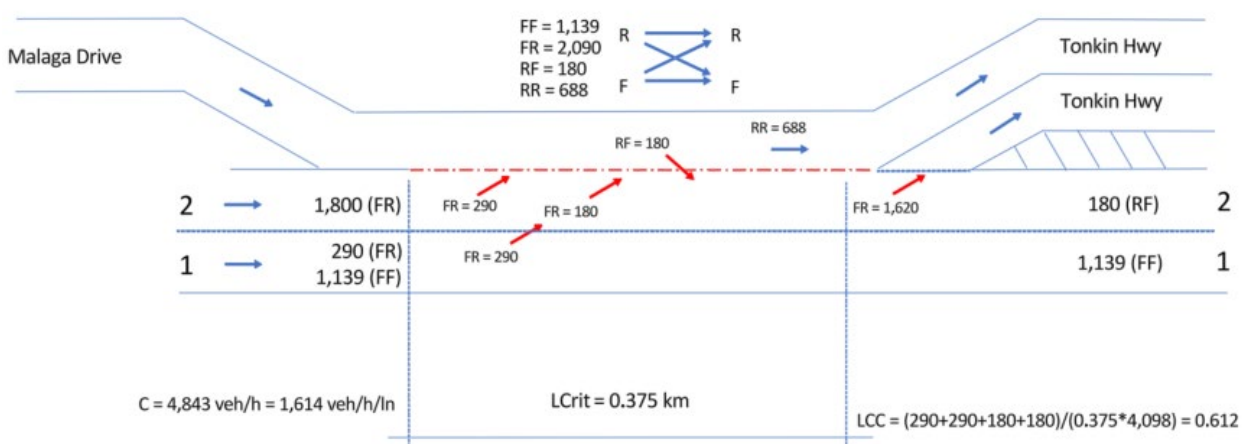


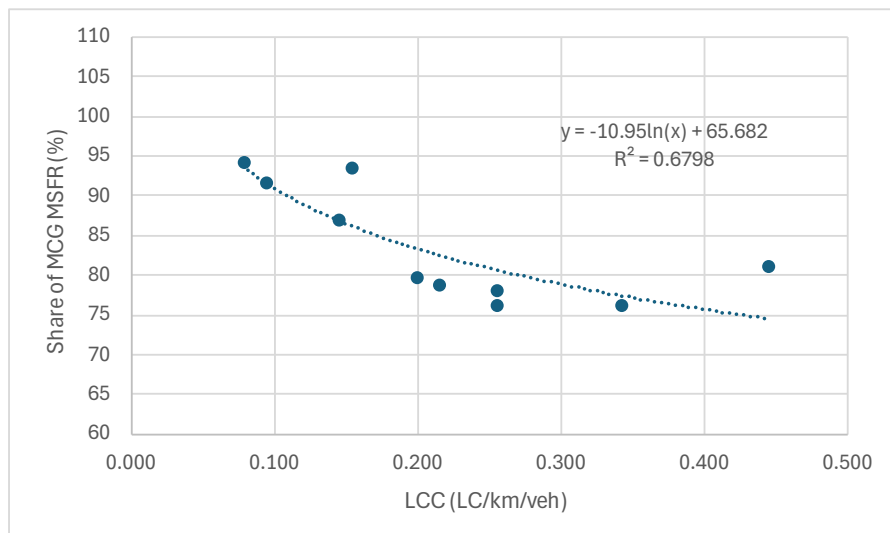
Figure 9-4: Reid Highway between Malaga Drive and Tonkin Highway with increased outer carriageway lane MSFR



This site is a rare case of extreme imbalance between one crossing vehicle stream and the other. The lower measured than modelled MSFR loss suggests that the real impact on capacity is also influenced by the ratio of the 2 crossing movement volumes, because conflicts only occur when a crossing vehicle is 'matched' by another crossing one that is moving in the opposite direction. This could lead to an alternative estimation of the LCC. Based on the volumes shown in Figure 9.3, calculating the LCC based on this 'matching requirement' principle would lead to 360 LC only (180 in each direction) and to an LCC value of 0.234, resulting in an F_{Weave} of 0.830, which is equivalent to an MSFR loss of around 17% (Figure 6.8). This result is more realistic in this special case. Consequently, this alternative approach also leads to an alternative version of Figure 6.8 where the LCC values for the weaving sites used for methodology development only included those LC that are 'matched' by a conflicting movement (Figure 9.5). This makes intuitive sense for cases with strong imbalance between crossing traffic streams where one stream could theoretically be close to zero so that almost no crossing conflict exists. Applying the alternative LCC value of 0.234 to Figure 9.4 results in an F_{Weave} of 0.816. This aligns very closely with the measured MSFR loss of 19.5%.

As a conclusion, it is recommended that practitioners always consider the local context, including the results of site-specific traffic volume or capacity/MSFR measurements, if such information is available. This can be useful to refine the generic assumptions made for the recommended methodology (refer to Section 8.2.1). The alternative approach and diagram (refer to Figure 9.5) can be used in cases of strong imbalance between crossing movements (e.g. from an FR/RF volume ratio 70%/30% upwards, or vice versa). Only more comprehensive testing and application to several cases with pronounced imbalance of traffic stream volumes can show if this is a better approach for such cases.

Figure 9-5: Alternative relation between the modelled MLC and EMLC concentration and the MSFR/capacity loss; for cases with strong imbalance between FR and RF volumes



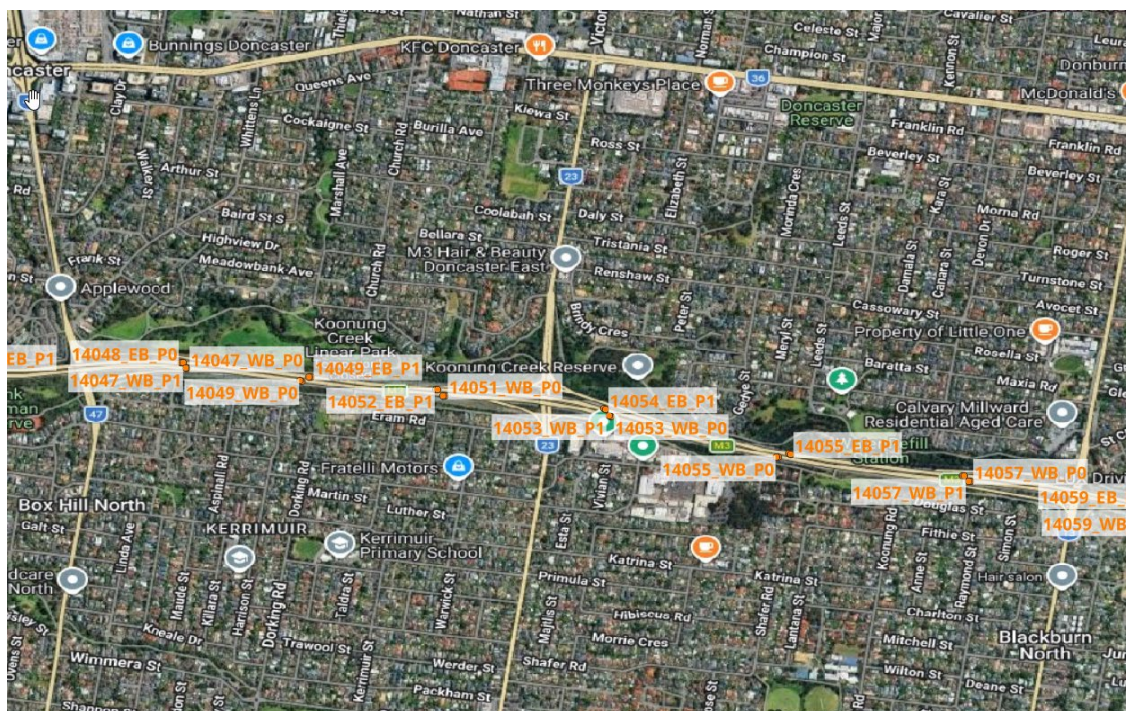
Note: Only LC that are 'matched' by conflicting crossing ones in the opposite directions are included in the LCC; the results from the 2 sites shown in Figure F.3 and Figure F.5 are not included, due to the absence of conflicting, crossing movements.

Melbourne Eastern Freeway – Tram Road/Station Street and Blackburn Road

This site is a double-weaving area which is characterised by a 3-lane cross-section plus an auxiliary lane between Tram Road/Station Street and Blackburn Road with the additional Middleborough Road located between the other interchanges. This configuration applies to both directions so that there is a weaving area on this section in the EB as well as in the WB direction of travel. The section is around 2 km long and is currently undergoing major road works in the context of the North -East-Link major project. Therefore, and consistent with data quality analysis undertaken in collaboration with Vic DTP, data from November 2018 was sourced for this analysis. The site is located on the unmanaged Eastern Freeway (i.e. no coordinated ramp metering is available here).

The detector density was good (refer to Figure 9.6), and data granularity was the same as for the Victorian weaving areas analysed for this study. However, there are relatively old induction loops rather than TIRTL detectors deployed on this section, generally leading to less accurate traffic data. Moreover, it should be noted that there are uncertainties around the baseline MSFR values provided in the MCG for unmanaged motorways (VicRoads 2019a) because all MCG measurement sites were located on managed motorways. These values are currently being revisited in the context of the Austroads NEG 6527 project. The baseline MSFR values needed to calculate the MSFR losses due to weaving were therefore adopted from nearby sites on the Eastern Freeway (14033 EB and 14021 WB).

Figure 9-6: Melbourne Eastern Freeway test sites including detector locations



The OD percentages were sourced from TomTom Traffic Stats over a full month (November 2018) but only working days during peak hours were analysed. These percentages were multiplied by the base case MSFR value for the 4-lane section while considering the upstream and downstream capacity constraints. These constraints were an important consideration in this case, due to the reduced lane number upstream and downstream, and the great combined FF/FR or FF/RF percentages, leading to high traffic volumes on the upstream or downstream 3-lane cross-sections, respectively. This means that the baseline MSFR values for the adjacent 3-lane sections influenced the saturation flow rates of the weaving sites which were reduced so that the entire section sequence is in balance (refer to Section 8.2.1 and Equations 23 to 25 for the procedure, and to Figure F.13 and Figure F.14 for the geometrical and traffic conditions). The parameters and the results of the testing can be seen from Table 9.1.

The measured MSFR remainder is 91.9% and 92.7% (Table 9.2), respectively. The $LCC_{X_{Mand}}$ values are moderate (0.180 LC/veh/km EB, 0.191 LC/veh/km WB), which according to Equation 20 resulted in Vic DTP F_{Weave} values of 85.8% and 85.2%, respectively. The Extended STRIDE F_{Weave} values, i.e. the estimated weave capacities divided by the basic section capacities, are 83.5% and 83.6%, respectively. The Vic DTP F_{Weave} values are, therefore, still reasonably well-aligned with the measured MSFR remainders, in contrast to the Extended STRIDE F_{Weave} values, which appear to be already too low.

Table 9.1: Geometrical and traffic conditions for the Victorian testing weaving areas

	Freeway	From	To	Lanes	Gradient (%)	HV (%)	L _s (km)	Total flow rate ⁽¹⁾ (veh/h)	FR (%)	FF (%)	RR (%)	RF (%)	VR	LCC _{Mand} ⁽²⁾ (LC/veh/km)
1	Eastern Freeway	Tram Rd	Blackburn Rd	4	<= 2	5	2.08	6,579	17.8	53.7	8.9	19.6	0.374	0.180
2		Blackburn Rd	Tram Rd	4	<= 2	5	1.98	5,930	19.6	55.5	6.7	18.2	0.378	0.191

1. Average November 2018 working day flow rates between 6 and 9 am or between 3 and 6 pm, respectively.

2. LCC is based on the MLC only.

Table 9.2: Base versus actual MSFR values and MSFR loss for the Victorian testing weaving areas

	Freeway	From	To	MSFR baseline (veh/h)	MSFR actual (veh/h)	MSFR remainder (%)	LCC _{XMand} ⁽¹⁾ (LC/veh/km)	Vic DTP F _{Weave} (%)	Delta Vic DTP ⁽²⁾ (%)	Extended STRIDE F _{Weave} ⁽³⁾ (%)	Delta Extended STRIDE ⁽²⁾ (%)
1	Eastern Freeway	Tram Rd	Blackburn Rd	7,029 ⁽⁴⁾	6,457	91.9	0.180	85.8	-6.1	83.5	-8.4
2		Blackburn Rd	Tram Rd	7,200 ⁽⁵⁾	6,676	92.7	0.191	85.2	-7.5	83.6	-9.1

1. LCC is based on the MLC and EMLC.

2. Percentage difference between MSFR remainder and Vic DTP F_{Weave} or Extended STRIDE F_{Weave}, respectively.

3. Calculated as the ratio of C_w (Equation 13) and C_B which is the equivalent basic freeway segment capacity (TRB 2022, Exhibit 12-4).

4. Based on data sourced from nearby 14033 EB site. Note that this is a 3-lane section in a curve where the MSFR was extrapolated to 4 lanes. This means that there are some uncertainties regarding this comparison.

5. Based on data sourced from nearby 14021 WB site. Note that this is not a bottleneck with frequent flow breakdown. Understanding of the capacity in this location is limited to the fact that it is at least 7,200 veh/h (regular observation of this flow rate and no pronounced lower branch of the fundamental diagram for this site).

It should be noted that there are uncertainties around the baseline MSFR values for this location since for the EB direction, the only bottleneck, is a 3-lane curve with a radius of around 400 m (14033 EB). For the WB direction, the reference site (14021 WB) is no pronounced bottleneck, so the capacity had to be estimated based on the frequently observed maximum flow rate of 7,200 veh/h that did not cause flow breakdown. The test results for the Eastern Freeway are, therefore, indicative.

Perth and Melbourne weaving sites used for methodology development

An additional test undertaken was the application of the NCHRP (2023) methodology to the weaving sites that were used for the development of the proposed methodology (Section 7.1). For these sites, no comparison with the newly developed methodology (aka refined Vic DTP) was possible.

Table 9.3: MSFR loss for the Western Australian and Victorian weaving areas and extended STRIDE method results

	Freeway	From	To	$LCC_{X_{Mand}}^{(1)}$ (LC/veh/km)	MSFR baseline (veh/h)	MSFR actual (veh/h)	MSFR remainder (%)	Extended STRIDE $F_{Weave}^{(2)}$ (%)	Delta Extended STRIDE ⁽³⁾ (%)
1	Mitchell Freeway	Reid Hwy	Warwick Rd	0.314	6,997	5,584	79.8	79.3	-0.5
2		Powis St	Vincent St	0.223	8,007	7,397	92.4	81.0	-11.4
3	Kwinana Freeway	Mill Point Rd on	Mill Point Rd off	0.037	8,156	8,346	102.3	82.2	-20.1
4	Monash Freeway	Eastlink	Stud Rd	0.255	8,635	6,754	78.2	80.7	+2.5
5		Stud Rd	Eastlink	0.124	8,160	7,309	89.6	82.4	-7.2
6		Heatherton Rd	South Gippsland Fwy	0.360	8,635	6,593	76.4	79.4	+3.0
7		South Gippsland Fwy	Heatherton Rd	0.078	8,755	8,262	94.4	81.3	-13.1
8		Princes Hwy	Clyde Rd	0.154	5,525	4,806 (old)	87.0	79.2	-7.8
9		Clyde Rd	Princes Hwy	0.109	5,525	5,072 (old)	91.8	82.8	-9.0
10		Princes Hwy	Clyde Rd	0.217	7,385	5,817	78.8	82.7	+3.9
11	Monash Freeway	Clyde Rd	Princes Hwy	0.275	7,385	5,643	76.4	79.5	+3.1
12		Wellington Rd	Eastlink	0.444	8,475	6,879	81.2	81.1	-0.1

1. LCC is based on the MLC and EMLC (listed here to assess the plausibility of the results only).
2. Calculated as the ratio of C_w (Equation 13) and C_B which is the equivalent basic freeway segment capacity (TRB 2022, Exhibit 12-4).
3. Percentage difference between MSFR remainder and Extended STRIDE F_{Weave} .

The Extended STRIDE F_{Weave} values were generally poorly aligned with the measured MSFR remainders. It is conspicuous that the extended STRIDE results are all around the 80% margin (between 79% and 84%). The actual measurement results show a much wider spread (between 76% and 102% – note that the latter can be caused by random deviations from typical MSFR values when the LCC is low). All equations and calculations that the Extended STRIDE F_{Weave} value calculation was based on were carefully checked. It is, therefore, suspected that this phenomenon is inherent in the methodology, which assumes that reaching the capacity is associated with a fixed density of 35 veh/mi/ln (Equation 12). The traffic data analysed for this study showed that flow breakdown happens at a wide range of densities, rather than at a fixed value. This observation aligns with a stochastic rather than deterministic interpretation of traffic flow which is underlying the MSFR concept.

As a conclusion, this means that an unrealistic assumption has at least contributed to the significant differences between measured and estimated MSFR losses due to weaving. In addition, it appears that a lack of consideration of the EMLC has also led to the different results. EMLC are not included in the V_{RF} and V_{FR} parameters in the corresponding capacity calculation equations (Equation 13).

9.1.2 Queensland

General remarks

The detector density for the Queensland sites was good (refer to Figure 9.8), and data granularity was comparable to the Western Australian and Victorian weaving areas analysed for this study (1-minute interval lane-level SVO data over a full month). These data were provided by TMR specifically for this study (Bruce Highway site) or for the Austroads NEG 6527 project (Pacific Motorway site). There were many gaps in the data provided as visualised by the grey detectors in Figure 9.8, indicating faulty detectors. This applied to individual lane detectors and to entire carriageway level detector sites. However, this deficiency was compensated by selecting sites with a complete set of functioning lane detectors.

It was possible to create a solid baseline of MSFR values for Queensland for unmanaged motorways because several unmanaged bottleneck sites on 'basic' (or standard) sections were nominated by TMR for the Austroads NEG 6527 project. These could be standardised and averaged while following the methodology described in VicRoads (2019a, Chapter 3). This methodology takes the HV percentages and gradients of the measurement sites into account to generate typical values for a range of HV and s values (refer to Table 2.3 for an example) so that base MSFR values can be estimated for other sites including the test sites analysed here. The corresponding factors extracted from the MCG are shown in Figure 9.7. For example, for an HV percentage of 5%, the measured MSFR value must be divided by 1.10 to obtain a comparable value for standard conditions ($s \leq 2\%$, $HV = 15\%$). For the generation of baseline values for a test site characterised by steeper gradients or different HV percentages, the standard value must be multiplied by the factors shown in Figure 9.7. This results in the MSFR value for a weaving area if it were unaffected by the weaving.

Figure 9-7: Gradient and HV percentage adjustment factors for non-standard conditions ($s \leq 2\%$, $HV = 15\%$)

Gradient	'capacity' multiplication factor ²⁾	HGV Percentage	'capacity' multiplication factor ¹⁾
2%	1.00	0%	1.15
3%	0.95	5%	1.10
4%	0.90	10%	1.05
5%	0.83	15%	1.00
		20%	0.96
		25%	0.92
		30%	0.88

Source: VicRoads 2019a

The baseline unmanaged motorway MSFR values were derived from measurements across Queensland (6 sites). TMR had nominated 22 bottlenecks across their motorway network for the Austroads NEG 6527 project. It turned out that the typical, standardised Queensland MSFR values are slightly higher than those in the MCG, by a bit more than 1% (Table 9.4).

Table 9.4: Calculation of a Queensland baseline MSFR value for unmanaged motorways

Site	Number of lanes	Carriageway MSFR (veh/h)	Lane MSFR (veh/h)	HV percentage (%)	Gradient (%)	Normalised (veh/h)
1	3	4,928	1,643	8	2	1,535
2	4	6,178	1,545	8	2	1,443
3	3	4,832	1,611	8	2	1,505
4	2	3,263	1,632	4	2	1,525
5	2	3,482	1,741	4	2	1,568
Average						1,541

The baseline MSFR values for managed motorways were adopted from the MCG, which is a robust guideline for managed motorways including coordinated ramp metering. This is because the selected measurement sites used for the MCG development were exclusively located on managed motorways.

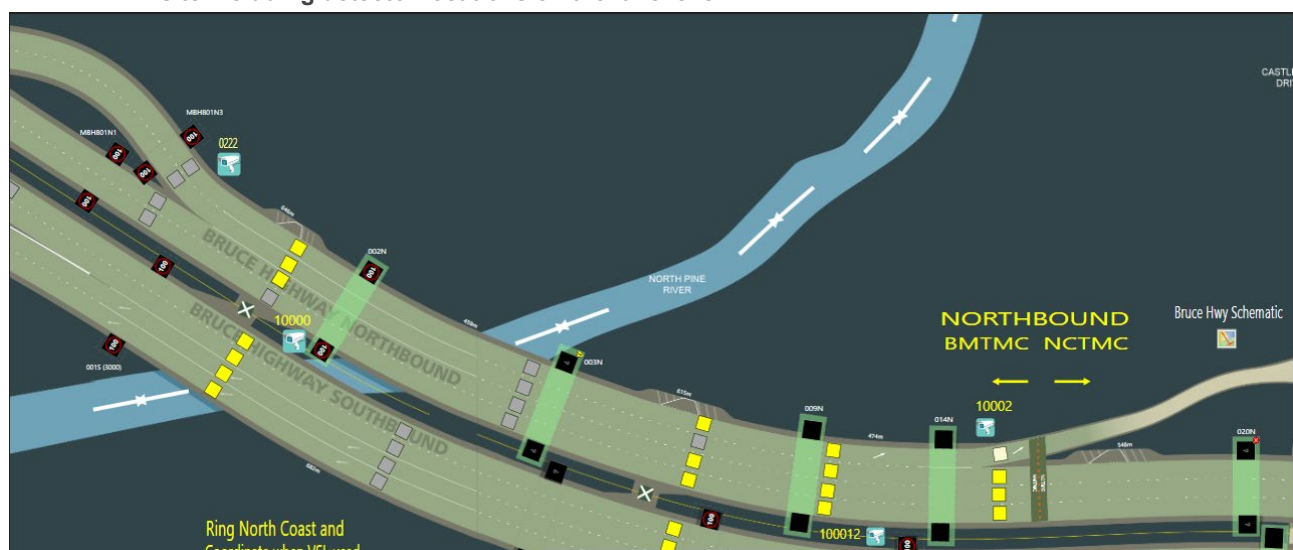
QLD Bruce Highway – Gateway Motorway/Gympie Arterial Road to Dohles Rocks Road

This site is a complex weaving area that is characterised by the merging of two 2-lane motorway carriageways into a 4-lane carriageway and a lane drop at the end of the section. Weaving happens over a relatively long distance of almost 2 km (Figure 9.8 and Figure 9.9).

The OD percentages were sourced with TomTom Traffic Stats over a full month (March 2025) but only working days during peak hours were analysed. These percentages were multiplied by the base case MSFR value for the 4-lane section while considering the downstream capacity constraint. It should be noted in this context that there is a high combined RF and FF movement percentage. The downstream MSFR divided by this combined percentage resulted in the weaving area MSFR (refer to Equation 24).

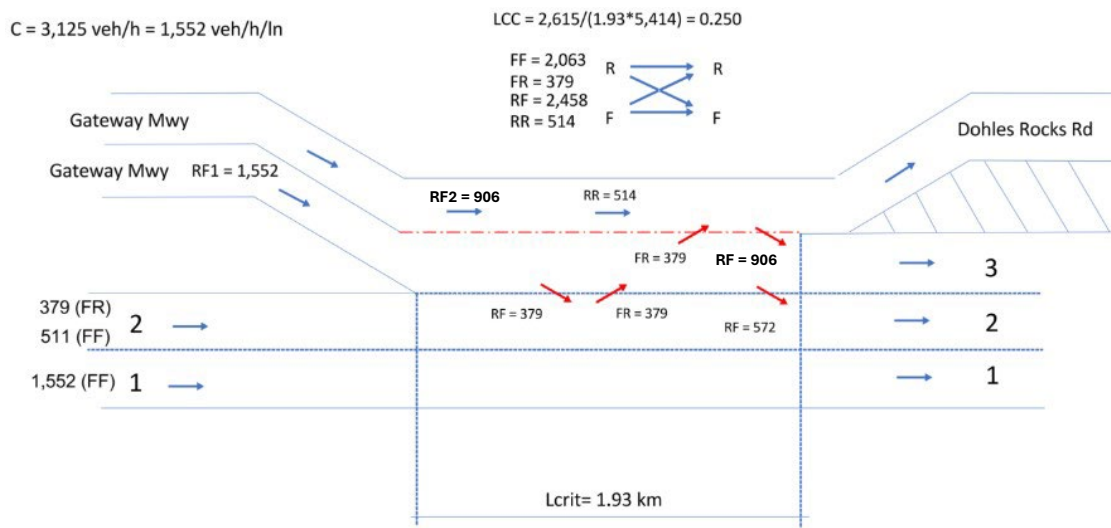
The $LCC_{X_{Mand}}$ is relatively high for this site (0.250 LC/veh/km).

Figure 9-8: Queensland Bruce Highway – Gateway Motorway/Gympie Arterial Road to Dohles Rocks Road test site including detector locations on the lane level



Source: TMR.

Figure 9-9: Bruce Highway NB from Gateway Motorway/Gympie Arterial Road to Dohles Rocks Road



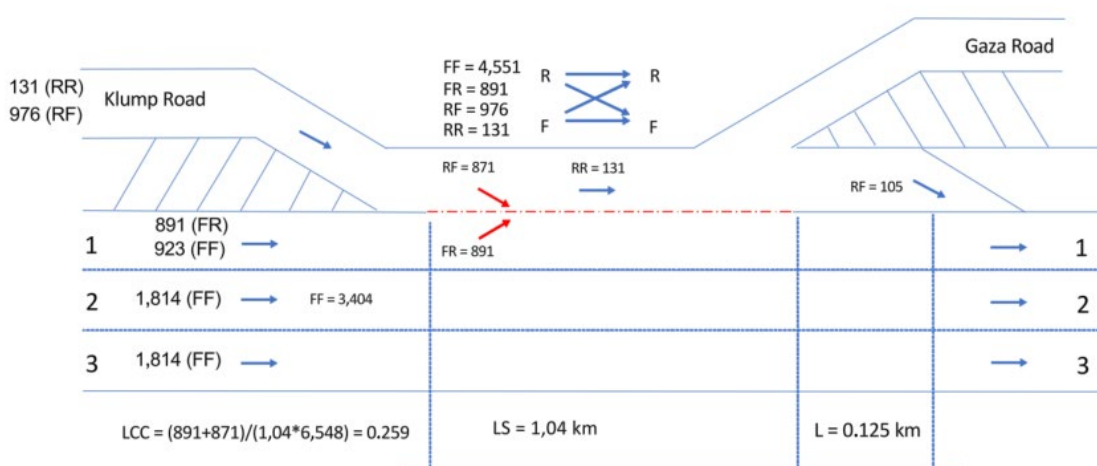
QLD Pacific Motorway – Klumpp Road to Gaza Road

This site is a simple weaving area of short length (around 1 km) that is characterised by an approaching 3-lane motorway carriageway section, a wider 4-lane weaving section that includes an auxiliary lane and a departing 3-lane motorway carriageway section. The lane reduction happens around 125 m downstream of the Gaza Road exit ramp, which slightly facilitates the weaving process as the RF vehicles can merge into the motorway mainline over an extended length.

The OD percentages were sourced with TomTom Traffic Stats over a full month (March 2025) but only working days during peak hours were analysed. These percentages were multiplied by the base case MSFR value for the 4-lane section, which resulted in the volumes for the OD streams as shown in Figure 9.10.

The baseline MSFR value was taken from the MCG (VicRoads 2019a) for managed motorways because of the existence of ramp metering on the Klumpp Road entry ramp and on 4 additional metered ramps upstream. The $LCC_{X\text{Mand}}$ is relatively high for this site (0.259 LC/veh/km).

Figure 9-10: Pacific Motorway NB between Klumpp Road and Gaza Road



Test results for selected methodologies

Table 9.5 summarises the geometrical and traffic conditions for the selected Queensland sites.

Table 9.5: Geometrical and traffic conditions for the Queensland weaving areas

	Freeway	From	To	Lanes	Gradient (%)	HV (%)	L _s (km)	Total flow rate ⁽¹⁾ (veh/h)	FR (%)	FF (%)	RR (%)	RF (%)	VR	LCC _{Mand} ⁽²⁾ (LC/veh/km)
1	Bruce Highway	Gympie Arterial Road	Dohles Rocks Road	4	<= 2	14	1.93	4,169	7.0	38.1	9.5	45.4	0.237 ⁽³⁾	0.123 ⁽³⁾
2	Pacific Motorway	Klumpp Road	Gaza Road	4	<= 2	8	1.04	5,317	13.6	69.5	2.0	14.9	0.285	0.274

1. Average March 2025 working day flow rates between 3 and 6 pm.

2. LCC is based on the MLC only

3. Considers the RF movement share that enters the mainline via the outer lane.

Table 9.6 shows the test results for the selected Queensland sites.

For the refined Vic DTP methodology described in Section 9.1.1 combined with Section 8, the results show good alignment between the measured MSFR values and the estimated ones for the Queensland sites, which were both in the higher LCC_{XMand} range.

For the extended STRIDE methodology, the results show reasonable alignment between the measured MSFR values and the estimated ones for the Queensland sites. The estimated MSFR values were based on the calculation of the Extended STRIDE F_{Weave} factors by dividing the HCM weaving capacity according to Equation 13 by the HCM capacity for the base case as included in Table 12-4 of the HCM (Transportation Research Board [TRB] 2022).

Importantly, these sites were independent of those used for methodology development. They were also characterised by a solid baseline for the estimation of the capacity reduction compared to typical non-weaving sections. The test results are, therefore, regarded as reliable.

Table 9.6: MSFR loss for the Queensland weaving areas and comparison of methodology application results (refined Vic DTP and extended STRIDE)

	Freeway	From	To	$LCC_{X_{Mand}}^{(1)}$ (LC/veh/km)	MSFR baseline (veh/h)	MSFR actual (veh/h)	MSFR remainder (%)	Vic DTP F_{Weave} (%)	Delta Vic DTP ⁽²⁾ (%)	Extended STRIDE $F_{Weave}^{(3)}$ (%)	Delta Extended STRIDE ⁽²⁾ (%)
1	Bruce Highway	Gympie Arterial Road	Dohles Rocks Road	0.250	6,226 ⁽⁴⁾	5,351	85.9	82.2	-3.7	80.5	-5.4
2	Pacific Motorway	Klumpp Road	Gaza Road	0.259	7,255 ⁽⁵⁾	5,744	79.2	81.9	+2.7	82.5	+3.3

1. LCC is based on the MLC and EMLC.
2. Percentage difference between MSFR remainder and Vic DTP F_{Weave} or Extended STRIDE F_{Weave} , respectively.
3. Calculated as the ratio of C_w (Equation 13) and C_B which is the equivalent basic freeway segment capacity (TRB 2022, Exhibit 12-4).
4. Based on measurement at 6 unmanaged motorway sites across Queensland.
5. MCG value for managed motorways.

9.2 Comparative Assessment of the Methodology Performance

The following paragraphs describe the results of a qualitative comparison between the newly proposed, refined Vic DTP and the extended STRIDE methodologies.

It must be acknowledged that only limited testing was possible during this study, due to a lack of independent weaving areas in Western Australia and Victoria that were not previously used for methodology development. This independence was necessary to ensure a 'fair' comparison between the 2 assessed methodologies. The below conclusions are, therefore, preliminary, i.e. a greater range of test sites and more testing is desirable.

While the number of test sites was limited, the results provide confidence in the validity of the methodology when compared with alternative approaches, especially the newly proposed HCM methodology ('extended STRIDE'). The intended method use is to reasonably estimate MSFR in weaving areas (through reduction of the base capacity). This means that not 100% accuracy is the goal, but to avoid gross misjudgement as was often the result of the HCM methodology application.

9.2.1 Results

Table 9.7 shows an overview of the assessed criteria and awarded marks. Based on the knowledge available today and acquired during this project, the refined Vic DTP methodology is better suited for the MSFR estimation for weaving areas than the extended STRIDE one. Details on the awarded scores can be found in the following sections.

Table 9.7: Assessment of the 2 tested methodologies against the criteria listed in Section 2.1

Criteria	Refined Vic DTP	Extended STRIDE	Comment
Scope (30%)	+	+	
User friendliness (20%)	0	+	Vic DTP: Increased lane changing estimation effort for complex weaves
Plausibility of equations (10%)	+	-	Extended STRIDE: Constant density assumption at flow breakdown appears unrealistic
Accuracy (40%)	+	-	
Total	+	0	

Legend:

+ = positive scoring

0 = neutral scoring

- = negative scoring

Percentages included in brackets in the first column represent the weighting of the criteria

9.2.2 Scope

Both methods are universally applicable to the currently known real-world weaving cases in Western Australia, Victoria and Queensland, including:

- simple and complex weaves
- 2-lane merges and diverges
- auxiliary lanes
- lane drops and lane adds

- closely spaced entry and exit ramps.

9.2.3 User-friendliness

The extended STRIDE methodology is easy to apply by practitioners once the formulas have been entered into an Excel spreadsheet or similar. Therefore, a '+' mark was awarded for this methodology.

The refined Vic DTP methodology, as described in this report, is relatively easy to apply to simple weaves. More effort is needed when applying it to complex weaves. This is because the estimation of MLC and EMLC can be complex for weaves with multi-lane entry and/or exit ramps. Some assumptions must be made for the estimation of LC in these cases (refer to Section 8.2.1). The increased effort and assumptions coincide with uncertainties regarding this correct estimation of the $LCC_{X\text{Mand}}$ parameter. This can be mitigated through increased local information such as lane-specific MSFR measurements or lane use information, including for the mainline and multi-lane ramps. Moreover, the applicability to complex weaves can be enhanced by automation, such as through the creation of special Excel spreadsheets, like the ones created for mainline section volume-to-capacity analysis as included in Section 6.3.4 (Figure 6-5 and Figure 6-10) of the Main Roads Smart Freeways Operational Efficiency Audit Guidelines (Main Roads 2025b).

The newly proposed 'Refined Vic DTP' methodology allows for increased flexibility regarding sensitivity testing for different assumptions such as different lane use levels. A range of potential results can be defined ('envelope'). The methodology is transparent so that the practitioner can understand the correlation between changed assumptions and results.

Considering the conflicting arguments as described in the previous paragraphs, a neutral '0' mark was awarded for the user-friendliness criterion for the refined Vic DTP methodology (refer to Table 9.7).

9.2.4 Plausibility of Equations

This criterion is linked to the 'Accuracy' one below, because it may explain some implausible extended STRIDE methodology application results, especially the narrow extended STRIDE F_{Weave} spread (refer to Table 9.3).

It appears that the central extended STRIDE capacity estimation assumption that flow breakdown/transition into congestion happens at a constant density of 35 pc/mi/ln is unrealistic (refer to Equation 12). This assumption was made to be able to convert the estimation of the weaving area speed at capacity into a capacity estimate.

Equation 14, which is used for the calculation of the LCC, and which is central to the newly proposed methodology, is plausible and intuitive. Changes to the number of LC, the weaving length or the traffic volume representing the ability to absorb turbulences induced by weaving have a proportional impact on the LCC. This simplicity is regarded as an advantage compared to the more complex extended STRIDE method.

9.2.5 Accuracy

The newly proposed methodology shows greater accuracy of the results than the extended STRIDE one. Applying the extended STRIDE methodology to the weaving sites used for the development of the new methodology did not produce realistic results (refer to Section 9.1.1). It is, therefore, concluded that this methodology is generally unsuitable to estimate weaving area capacities based on the MSFR concept under local conditions. The results of the refined Vic DTP methodology are better for the Eastern Freeway test sites (while acknowledging some uncertainties regarding the baseline MSFR) and also better for the Queensland sites where a solid baseline was available.

As a concluding comment, testing of the methodology for an additional weaving area in New Zealand (State Highway 1 NB between Green Lane and Market Road) as part of the Austroads NEG 6527 project that is

currently underway has shown an accuracy comparable to the Queensland test results. Approval to use this result for this study is still pending.

10 Final Remarks

This project has developed a new methodology ('refined Vic DTP') for analysing weaving area capacity while an additional HCM methodology ('extended STRIDE') that was developed as part of the US NCHRP was also identified and assessed.

The refined Vic DTP methodology is better aligned with the MSFR concept than the additional HCM one. It provides a direct linkage between the LCC and the weaving area MSFR loss, without 'detouring' via the estimation of an average speed decline, which is the basis of the extended STRIDE methodology (NCHRP 2023). This increases the robustness of the MSFR estimation and, therefore, the accuracy of the results. The application of the new methodology by practitioners can be difficult for complex weaves, e.g. those with multi-lane entry or exit ramps, or multiple mainline lane drops/lane adds, e.g. at a freeway bifurcation. This means that there could be some ambiguity in the application of the new methodology as assumptions are needed for the estimation of lane-specific volumes that impact the number of estimated LC that must be undertaken.

It is recommended that the newly developed methodology be adopted. It is also recommended that further testing of the methodology be undertaken. This will lead to a more comprehensive assessment of the methodology's accuracy and, potentially, to improved user guidance for the lane changing quantity estimation, resulting in improved LCC estimation by practitioners. Testing opportunities were limited during this project, due to a lack of weaving areas in the contributing states (Western Australia and Victoria) that were not used for methodology development and that were, therefore, statistically independent.

The recommended next steps are as follows:

- Use of the new methodology for the Austroads NEG 6527 project. This could potentially lead to a slight change and further increase of the statistical validity of the 'MSFR loss versus LCC curve' (refer to Figure 6-9 and Figure 8-4 respectively), based on weaving areas in other Australian or New Zealand jurisdictions. The NEG 6527 Project Control Group has requested the review of this project report to enable them to decide on the adoption of the new method for their project.
- Provision of formal guidance for methodology use by practitioners (e.g. as part of Main Roads WA or Austroads guidelines such as the Smart Freeway Guidelines or AGTM/AGSM). This can be based on Section 7 and Section 8 of this report.
- Optional: Excel tool for easier estimation of the required LC in weaving areas.

It is envisaged that the methodology will be used for the completion of the Austroads NEG 6527 project, which is based on the MSFR concept (AGTM update – motorway capacity analysis), i.e. for the provision of improved freeway capacity guidance for Austroads members.

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Appendix A Capacity Test Results for Simple and Complex Weaves (NCHRP 2023)

Table A.1: Capacity results for simple weave sites

Site	Observed					HCM	Original NCHRP 07-26 Model				Revised NCHRP 07-26 Model			
	an	PB Average Volume (pc/h/ln)	VR*	FFS (mph)	Capacity (pc/h/ln)	Capacity (pc/h/ln)	Capacity (pc/h/ln)	v/c Ratio	Space Mean Speed (mph)	Density (pc/mi/ln)	Capacity (pc/h/ln)	v/c Ratio	Space Mean Speed (mph)	Density (pc/mi/ln)
Simple Ramp Weave_1	58.9	2,249	0.24	73.3	2,408	2,033	2,055	1.09	53.6	42.0	2,018	1.11	51.98	43.26
Simple Ramp Weave_2	67.3	1,887	0.43	73.3	1,624	1,402	2,047	0.92	62.1	30.4	2,005	0.94	59.85	31.52
Simple Ramp Weave_7	50.2	1,809	0.27	59.3	1,845	1,764	1,878	0.96	54.4	33.2	1,833	0.99	52.72	34.28
Simple Ramp Weave_8	54.2	1,940	0.29	60.3	2,143	1,992	1,866	1.04	52.2	37.1	1,826	1.06	50.45	38.43
Simple Ramp Weave_9	54.9	1,492	0.06	62.3	1,533	2,130	1,884	0.79	57.7	25.9	1,862	0.80	57.64	25.89
Simple Ramp Weave_10	70.4	1,238	0.30	81.4	1,417	1,979	1,991	0.62	74.4	16.6	1,989	0.62	75.37	16.42
Simple Ramp Weave_12	50.9	1,505	0.46	58.4	1,654	1,312	1,849	0.81	54.6	27.6	1,805	0.83	54.15	27.78
Simple Ramp Weave_14	51.9	2,000	0.22	56.6	1,991	1,987	1,784	1.12	48.4	41.3	1,750	1.14	46.81	42.69
Simple Ramp Weave_15	49.8	1,603	0.31	57.9	1,658	1,927	1,866	0.86	54.8	29.2	1,823	0.88	53.99	29.67
Average	56.5	1,747	0.29	64.7	1,808	1,836	1,913	0.91	56.9	31.5	1,879	0.93	55.88	32.22

Source: NCHRP (2023).

Table A.2: Capacity results for complex weave sites

Site	Observed					HCM	Original NCHRP 07-26 Model				Proposed NCHRP 07-26 Model			
	PB Avg. Speed (mph)	PB Average Volume (pc/h/ln)	VR*	FFS (mph)	Capacity (pc/h/ln)	Capacity (pc/h/ln)	Capacity (pc/h/ln)	v/c Ratio	Space Mean Speed (mph)	Density (pc/mi/ln)	Capacity (pc/h/ln)	v/c Ratio	Space Mean Speed (mph)	Density (pc/mi/ln)
Complex Weave_5	50.8	1,712	0.12	55.7	1,807	2,222	1,785	0.96	51.3	33.4	1,850	0.93	55.24	30.99
Complex Weave_6	56.5	1,786	0.14	65.6	1,902	2,135	1,940	0.92	58.2	30.7	1,800	0.99	51.68	34.56
Complex Weave_7	60.1	2,345	0.20	67.7	2,524	2,249	1,952	1.20	45.5	51.6	1,782	1.32	35.60	65.87
Complex Weave_8	51.5	1,632	0.13	64.8	1,935	2,270	1,981	0.82	61.5	26.6	1,857	0.88	58.63	27.85
Average	54.8	1,869	0.15	63.4	2,042	2,219	1,915	0.98	54.1	35.6	1,822	1.03	50.29	39.82

Source: NCHRP (2023).

Appendix B HCM Chapter 13 Proposed for Future HCM Editions (NCHRP 2023)

CHAPTER 13
FREEWAY WEAVING SEGMENTS

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1. INTRODUCTION

OVERVIEW

Weaving is generally defined as the crossing of two or more traffic streams traveling in the same direction along a significant length of highway without the aid of traffic control devices (except for guide signs). Thus, weaving segments are formed when merge segments are closely followed by diverge segments. "Closely" implies that there is not sufficient distance between the merge and diverge segments for them to operate independently.

Three geometric characteristics affect a weaving segment's operating characteristics: length, width, and configuration. All have an impact on the critical lane-changing activity, which is the unique operating feature of a weaving segment. This chapter provides a methodology for analyzing the operation of weaving segments on the basis of these characteristics as well as a segment's free-flow speed (FFS) and the demand flow rates for each movement within a weaving segment (e.g., ramp to freeway or ramp to ramp).

This chapter's methodology estimates the average speed of all vehicles in the weaving segment using a model developed from field observations (1). This model reduces the speed in the weaving segment, relative to an equivalent basic segment, as a function of the ramp-to-freeway, freeway-to-ramp, and overall segment flows; the number of lanes; and the length marked for weaving maneuvers. Capacity is then determined in accordance with the fundamental equation of traffic flow, as a function of the segment speed at capacity (defined as occurring at a density of 35 pc/mi/ln). Finally, segment speed is converted to density and used to determine the segment's level of service (LOS).

This chapter describes how the methodology can be applied to planning, operations, and design applications. The methodology can further be used to estimate the effects of weather and incidents on weaving segment computations, and it includes an extension to apply concepts to weaving segments on managed lanes. Example problems are included in Chapter 27, Freeway Weaving: Supplemental.

CHAPTER ORGANIZATION

Chapter 13 presents methodologies for analyzing weaving segment operations in uninterrupted-flow conditions. The chapter presents a methodology for evaluating isolated freeway weaving segments, as well as several extensions to the core method, including analysis of weaving maneuvers on managed lanes.

Section 2 of this chapter presents the following aspects of weaving segments: length and width of a weaving segment, configurations of weaving segments, definition of key terms used in the methodology, and discussion of special cases.

Section 3 presents the core method for evaluating automobile operations on weaving segments. This method generates the following performance measures:

VOLUME 2: UNINTERRUPTED FLOW
10. Freeway Facility Core Methodology
11. Freeway Reliability Analysis
12. Basic Freeway and Multilane Highway Segments
13. Freeway Weaving Segments
14. Freeway Merge and Diverge Segments
15. Two-Lane Highways

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Revised text, figures or paragraphs denoted with green margin notes and red text

- Weaving segment capacity;
- Average speed of **all vehicles**;
- Average density in the weaving segment; and
- **LOS** of the weaving segment.

Section 4 extends the core method presented in Section 3 to incorporate considerations for multiple weaving segments, collector–distributor (C-D) roads, and weaving on multilane highways. This section also discusses operational impacts of weaving maneuvers on managed lane facilities.

Section 5 presents guidance on using the results of a freeway weaving segment analysis, including example results from the methods, information on the sensitivity of results to various inputs, and a discussion of service volume tables for weaving segments.

RELATED HCM CONTENT

Other *Highway Capacity Manual* (HCM) content related to this chapter includes the following:

- Chapter 3, *Modal Characteristics*, discusses general characteristics of the motorized vehicle mode on freeway facilities.
- Chapter 4, *Traffic Operations and Capacity Concepts*, provides background speed–flow–density concepts of freeway segments that form the basis of weaving concepts presented in this chapter’s Section 2.
- Chapter 10, *Freeway Facility Core Methodology*, provides a method for evaluating weaving segments within an extended freeway facility and their interaction with basic, merge, and diverge segments.
- Chapter 11, *Freeway Reliability Analysis*, provides a method for evaluating freeway facilities with weaving segments in a reliability context. The chapter also provides default speed and capacity adjustment factors that can be applied in this chapter’s methodology.
- Chapter 12, *Basic Freeway and Multilane Highway Segments*, must be used to evaluate the weaving in segments that exceed the maximum weaving length. For such segments, Chapter 14, *Freeway Merge and Diverge Segments*, is also used to perform ramp capacity checks.
- Chapter 27, *Freeway Weaving: Supplemental*, presents example problems and additional methodological details for weaving segments.
- Chapter 38, *Network Analysis*, evaluates the effects of queue spillback between freeway and arterial facilities.
- Case Study 4, *New York State Route 7*, in the *HCM Applications Guide* in Volume 4, demonstrates how **HCM weaving** methods can be applied to the evaluation of an actual freeway facility.
- Section H, *Freeway Analyses*, in the *Planning and Preliminary Engineering Applications Guide to the HCM*, found in Volume 4, describes how to incorporate this chapter’s methods and performance measures into a planning effort.

2. CONCEPTS

OVERVIEW

Exhibit 13-1 illustrates a freeway weaving segment with four principal entry and exit points: A, left entering flow; B, right entering flow; C, left exiting flow; and D, right exiting flow. In many cases, one entry and one exit roadway are ramps, which may be on the right or left side of the freeway mainline. Some weaving segments, however, involve major merge or diverge points at which neither roadway can clearly be labeled a ramp.

On entry and exit roadways, or *legs*, vehicles traveling from Leg A to Leg D must cross the path of vehicles traveling from Leg B to Leg C. Therefore, Flows A–D and B–C are referred to as *weaving movements*. Flows A–C and B–D are not required to cross the path of any other flow and are referred to as *nonweaving movements*.

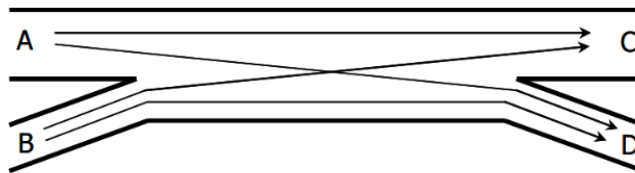


Exhibit 13-1
Formation of a Weaving Segment

Weaving segments require intense lane-changing maneuvers because drivers must access lanes appropriate to their desired exit leg. Therefore, traffic in a weaving segment is subject to lane-changing turbulence in excess of that normally present on basic freeway segments. The added turbulence presents operational problems and design requirements that are addressed by this chapter's methodology.

Three geometric characteristics affect a weaving segment's operating characteristics:

- Length,
- Width, and
- Configuration.

Length is the distance between the merge and diverge that form the weaving segment. *Width* refers to the number of lanes within the weaving segment. *Configuration* is defined by the way entry and exit lanes are aligned. All have an impact on the critical lane-changing activity, which is the unique operating feature of a weaving segment.

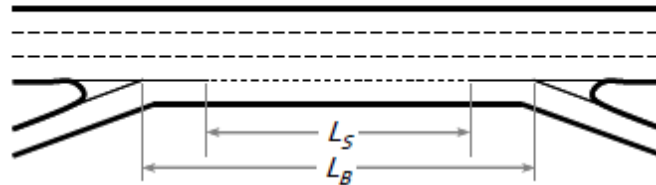
Traffic in a weaving segment experiences more lane-changing turbulence than is normally present on basic freeway segments.

A weaving segment's geometry affects its operating characteristics.

Exhibit 13-2
Measuring the Length of a Weaving Segment

LENGTH OF A WEAVING SEGMENT

The two measures of weaving segment length that are relevant to this chapter's methodology are illustrated in Exhibit 13-2.



The lengths illustrated are defined as follows:

L_S = short length, the distance in feet between the end points of any barrier markings (solid white lines) that prohibit or discourage lane changing.

L_B = base length, the distance in feet between points in the respective gore areas where the left edge of the ramp-traveled way and the right edge of the freeway-traveled way meet.

The weaving segment length used in the methodology is defined by the distance between barrier markings. Where no markings exist, the length is defined by the distance between where the left edge of the ramp-traveled way and the right edge of the freeway-traveled way meet.

This methodology involves several equations that include the length of the weaving segment. In all cases, these equations use the short length L_S . This is not to suggest that lane changing in a weaving segment is restricted to the short length. Some lane changing takes place over solid white lines and even painted gore areas. Nevertheless, research has shown that the short length is a better predictor of operating characteristics within the weaving segment than the base length.

For weaving segments in which no solid white lines are used, the two lengths illustrated in Exhibit 13-2 are the same, that is, $L_S = L_B$. In dealing with future designs in which the details of markings are unknown, a default value should be based on the general marking policy of the operating agency. At the time this methodology was developed, where solid white lines were provided, L_S was equal to $0.80 \times L_B$ on average for the available data.

The estimated speeds and densities, however, apply over the base length L_B . Some evidence also indicates that these speeds and densities may apply to the 500 ft of freeway upstream of the merge point and downstream of the diverge point because of pre-segregation of movements in each case.

Under constant demand conditions, making a weaving segment longer increases its capacity and improves its operation.

The weaving segment length strongly influences lane-changing intensity. For any given demand situation, longer segments allow weaving motorists more time and space to execute their lane changes. This reduces the density of lane changing and, therefore, turbulence. Lengthening a weaving segment generally increases its capacity and improves its operation (assuming a constant demand). The one exception to this statement is if capacity is controlled by the weave configuration itself, causing the segment to break down at the ramp entry point.

1 WIDTH OF A WEAVING SEGMENT

2 The width of a weaving segment is measured as the number of continuous
3 lanes within the segment, that is, the number of continuous lanes (including
4 auxiliary lanes) between the entry and exit gore areas. Acceleration or
5 deceleration lanes that extend partially into the weaving segment are not
6 included in this count.

7 Additional lanes provide more space for both weaving and nonweaving
8 vehicles, but they encourage optional lane-changing activity. Thus, while they
9 reduce overall densities, additional lanes can increase lane-changing activity and
10 intensity. However, in most cases, the number of lanes in the weaving segment is
11 controlled by the number of lanes on the entry and exit legs and the intended
12 configuration.

13 CONFIGURATION OF A WEAVING SEGMENT

14 Configuration of a weaving segment refers to the way that entry and exit
15 lanes are linked. The configuration determines how many lane changes a
16 weaving driver must make to complete the weaving maneuver successfully. The
17 following sections use a great deal of terminology to describe configurations; this
18 terminology should be clearly understood.

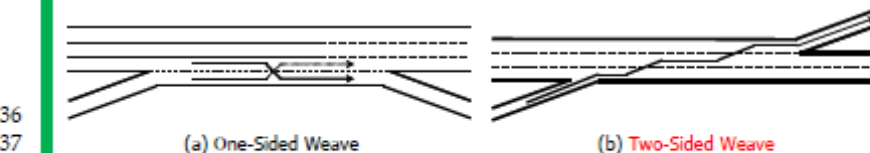
19 One-Sided and Two-Sided Weaving Segments

20 Most weaving segments are one-sided. In general, this means that the ramps
21 defining the entry to and exit from the weaving segment are on the same side of
22 the freeway—either both on the right (most common) or both on the left. The
23 methodology of this chapter was developed for one-sided weaving segments;
24 however, guidelines are given for applying the methodology to two-sided
25 weaving segments.

26 One- and two-sided weaving segments are defined as follows:

- 27 • A one-sided weaving segment is one in which no weaving maneuvers
28 require more than two lane changes to be completed successfully and in
29 which the on-ramp and off-ramp are located on the same side of the
30 freeway.
- 31 • A two-sided weaving segment is one in which at least one weaving
32 maneuver requires three or more lane changes to be completed
33 successfully or in which a single-lane on-ramp is closely followed by a
34 single-lane off-ramp on the opposite side of the freeway.

35 Exhibit 13-3 compares one- and two-sided weaving segments.



The number of continuous lanes between gore areas within a weaving segment defines its width.

One-sided weaving segments require no more than two lane changes to complete a weaving maneuver.

Two-sided weaving segments require three or more lane changes to complete a weaving maneuver or have a single-lane on-ramp closely followed by a single-lane off-ramp on the opposite side of the freeway.

Exhibit 13-3
One- and Two-Sided Weaving
Segments Illustrated

Exhibit 13-3(a) shows a typical one-sided weaving segment formed by a one-lane, right-side on-ramp followed closely by a one-lane, right-side off-ramp. The two are connected by a continuous freeway auxiliary lane. Every weaving vehicle must make one lane change as illustrated, and the lane-changing turbulence caused is clearly focused on the right side of the freeway.

Exhibit 13-3(b) is the most common form of a two-sided weave. A one-lane, right-side on-ramp is closely followed by a one-lane, left-side off-ramp (or vice versa). Although the ramp-to-ramp weaving movement requires only two lane changes, this movement is still classified as a two-sided weave because the geometry of the segment features on-ramp and off-ramps on opposite sides of the freeway.

Simple and Complex Weaving Segments

Exhibit 13-4 illustrates the difference between a **simple** weaving segment and a **complex** weaving segment. Exhibit 13-4(a) shows a typical ramp-weaving segment, which is defined as follows:

- A **simple** weave is formed by a one-lane on-ramp closely followed by a one-lane off-ramp, connected by a continuous freeway auxiliary lane.
- The unique feature of the **simple** configuration is that all weaving drivers must execute a lane change across the lane line separating the freeway auxiliary lane from the right lane of the freeway mainline.

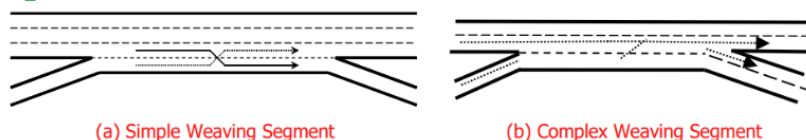


Exhibit 13-4
Simple and Complex Weaving
Segments Illustrated

One-sided configurations without a continuous auxiliary lane connecting an on-ramp to a closely following off-ramp are treated as isolated ramp junctions (Chapter 14) and not as weaving segments.

The case of a one-lane on-ramp closely followed by a one-lane off-ramp (on the same side of the freeway), but not connected by a continuous freeway auxiliary lane, is not considered to be a weaving configuration. Such cases are treated as isolated merge and diverge segments and are analyzed with the methodology described in Chapter 14. The distance between the on-ramp and the off-ramp is not a factor in this determination.

Exhibit 13-4(b) shows a typical **complex** weaving segment, which is formed when three or more entry or exit legs have multiple lanes. A major weaving segment is distinguished from a major merge or diverge segment in the sense that the latter segments do not feature an auxiliary lane movement between an on-ramp and a downstream off-ramp. A major weave can arise because of a system interchange and connection with another freeway or because of an interchange with an arterial street with multiple lanes on the on-ramp, the off-ramp, or both.

Numerical Measures of Configuration

Four numerical measures of a one-sided weaving segment characterize its configuration:

LC_{RF} = minimum number of lane changes that a ramp-to-freeway weaving vehicle must make to complete the ramp-to-freeway movement successfully.

LC_{FR} = minimum number of lane changes that a freeway-to-ramp weaving vehicle must make to complete the freeway-to-ramp movement successfully.

NW_{RF} = number of on-ramp lanes from which a weaving maneuver to the freeway may be completed with one lane change or no lane changes.

NW_{FR} = number of freeway lanes from which a weaving maneuver to the off-ramp may be completed with one lane change or no lane changes.

Two-sided weaving segments are described by LC_{RR} , the minimum number of lane changes that a ramp-to-ramp weaving vehicle must make to complete the ramp-to-ramp movement successfully. The parameter NW_{RR} is also used to describe two-sided weaving segments and is the number of freeway lanes from which a weaving maneuver to the off-ramp may be completed with one lane change or no lane changes.

Exhibit 13-5 illustrates how these parameters are determined for one-sided weaving segments. It is assumed that every weaving vehicle enters the segment in the lane closest to its desired exit leg and leaves the segment in the lane closest to its entry leg. Shading indicates lanes from which a weaving maneuver can be made with zero or one lane changes.

"Minimum number of lane changes" assumes vehicles position themselves when entering and exiting to make the least number of lane changes possible.

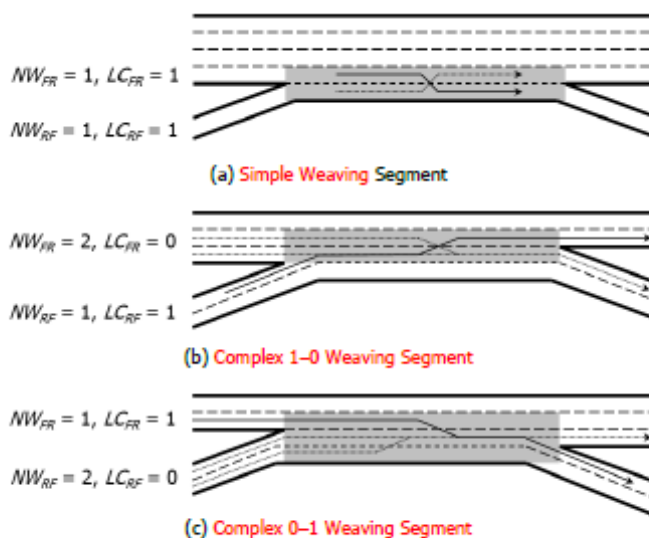


Exhibit 13-5
One-Sided Configuration
Parameters Illustrated

Lane balance within a weaving segment provides operational flexibility.

Paragraph describing N_{w_i} deleted, as this variable is no longer used.

Exhibit 13-5(a) is a five-lane **simple weave**. If a driver enters the segment on in the rightmost freeway lane and wishes to exit on the off-ramp, the driver must make a single lane change to enter the auxiliary lane and leave via the off-ramp. Thus, for this case, $LC_{FR} = 1$. Furthermore, the only lane from which this maneuver can be made with one or no lane changes is the rightmost freeway lane; thus, $NW_{FR} = 1$. A weaving driver entering the freeway via the on-ramp has no choice but to enter on the freeway auxiliary lane. To depart the segment on the freeway, that driver must make a single lane change from the auxiliary lane to the rightmost freeway lane. Thus, $LC_{RF} = 1$ and $NW_{RF} = 1$ as well. These parameter values are the same for all simple weaves.

Exhibit 13-5(b) and Exhibit 13-5(c) are both **complex** weaving configurations consisting of four lanes. They differ only in the configuration of their entry and exit gore areas. One has lane balance, while the other does not. Lane balance exists when the number of lanes leaving a diverge segment is one more than the number of lanes entering it.

Exhibit 13-5(b) is not typical. It is used here only to demonstrate the concept of lane balance in a **complex** weaving segment. Five lanes approach the entry to the segment and four lanes leave it, with the left-hand on-ramp lane and the rightmost freeway lane having an inside merge. Four lanes approach the exit from the segment and four lanes leave it, with the rightmost freeway lane forced to exit. Because of this configuration, vehicles approaching the exit gore must already be in an appropriate lane for their intended exit leg.

In Exhibit 13-5(b), the ramp-to-freeway movement requires at least one lane change ($LC_{RF} = 1$). A vehicle entering the segment on the leftmost on-ramp lane can merge into the rightmost freeway lane and make a single lane change to exit the segment on the freeway mainline; thus $NW_{RF} = 1$. The freeway-to-ramp weaving movement can be made without any lane changes ($LC_{FR} = 0$). A vehicle can enter on the rightmost freeway lane and leave on the leftmost off-ramp lane without executing a lane change. A vehicle can also enter on the center freeway lane and exit by making a single lane change; thus $NW_{FR} = 2$.

The exit junction in Exhibit 13-5(c) has lane balance: four lanes approach the exit from the segment and five lanes leave it. This is a desirable feature that provides some operational flexibility. One lane—in this case, the second lane from the right—splits at the exit. A vehicle approaching in this lane can take either exit leg without making a lane change. This is a useful configuration in cases in which the split of exiting traffic varies over a typical day. The capacity provided by the splitting lane can be used as needed by vehicles destined for either exit leg.

In Exhibit 13-5(c), on-ramp vehicles may enter on either on-ramp lane and complete a weaving maneuver with either one or no lane changes ($LC_{RF} = 0$ and $NW_{RF} = 2$). Vehicles entering the segment on the freeway may enter on the rightmost freeway lane and weave with a single lane change ($LC_{FR} = 1$ and $NW_{FR} = 1$).

The values of LC_{RF} and LC_{FR} can be used to describe the type of complex weaving segment. In Exhibit 13-5(c), $LC_{RF} = 0$ and $LC_{FR} = 1$, and the segment is described as a “Complex 0–1” weaving segment. Other “0–1” configurations are possible; for example, a two-lane on-ramp with an inside merge and a one-lane off-ramp. However, the values of LC_{RF} , LC_{FR} , NW_{RF} , and NW_{FR} will be the same for all “0–1” configurations. As a result, the relative effects of entering and exiting traffic demand on the segment’s speed and capacity will be the same across the various “0–1” configurations. The same holds true for other complex configurations; for example, all “0–2” configurations will share the same four parameter values and have the same relative effects of entering and exiting traffic.

Configuration of Two-Sided Weaving Segments

In a two-sided weaving segment, neither the ramp-to-freeway nor the freeway-to-ramp movements weave. While the through freeway movement in a two-sided weaving segment might be functionally thought of as weaving, it is the dominant movement in the segment and does not behave as a weaving movement. Thus, in two-sided weaving segments, only the ramp-to-ramp movement is considered to be a weaving flow.

The same general principles used to determine weaving parameters for one-sided weaving segments also apply to two-side weaving segments. With one-lane on- and off-ramps, LC_{RR} equals the number of lanes in the segment minus one and both NW_{RR} and N_{WL} take either the value of 1 (for a 2-lane mainline) or 0 (for a mainline with 3 or more lanes). Exhibit 13-6 illustrates these parameters for two-sided weaving segments, with shading indicating a lane where a weaving maneuver can be made with zero or one lane changes.

Only the ramp-to-ramp movement is considered to be a weaving flow in a two-sided weaving segment.

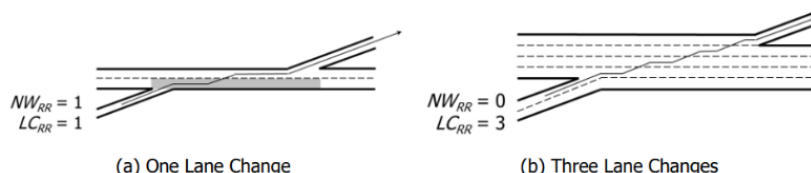


Exhibit 13-6
Two-Sided Configuration
Parameters Illustrated

In Exhibit 13-6(a), a vehicle entering from the on-ramp needs to make one lane change within the weaving segment to access the left-hand off-ramp. Thus, $LC_{RR} = 1$ and $NW_{RR} = 1$. In Exhibit 13-6(b), the minimum number of lane changes to complete the weaving maneuver is three, assuming the vehicle enters the freeway using the leftmost on-ramp lane. In this case, $LC_{RR} = 3$ and $NW_{RR} = 0$.

LOS CRITERIA

The LOS in a weaving segment, as in all freeway analysis, is related to the density in the segment. Exhibit 13-7 provides LOS criteria for weaving segments on freeways, C-D roads, and multilane highways. This methodology was developed from observations of freeway weaving segments, but may be applied to weaving segments on C-D roads, multilane highways, and uninterrupted segments of multilane surface facilities, although its use in such cases is approximate.

Exhibit 13-7
LOS for Weaving Segments

LOS	Density (pc/mi/ln)
A	0–11
B	>11–18
C	>18–25
D	>25–30
E	>30–35
F	>35, or demand exceeds capacity

Deleted mention of separate density thresholds for multilane highways and freeways.

1 The boundary between stable and unstable flow—the boundary between
2 LOS E and F—occurs when the demand flow rate exceeds the capacity of the
3 weaving segment, when density exceeds 35 pc/mi/ln. The thresholds for LOS A/B
4 and B/C are set the same as for basic freeway segments, because weaving
5 segment operations in this range are typically the same as, or slightly worse than,
6 basic segment operations. Thresholds between other levels of service were set to
7 provide a relatively even progression of densities.
8

3. CORE METHODOLOGY

The methodology presented in this chapter was developed in part by National Cooperative Highway Research Program (NCHRP) Project 07-26, *Update of Highway Capacity Manual: Merge, Diverge, and Weaving Methodologies* (1) and a concurrent study (2). Elements of this methodology have also been adapted from earlier studies and earlier editions of this manual (3–11).

SCOPE OF THE METHODOLOGY

Spatial and Temporal Limits

The methodology of this chapter is based on analysis of the peak 15-min interval within the analysis hour. The analysis hour is most often the peak hour, but the method can be applied to any hour of the day. As in most capacity analysis methodologies, demand flow rates are expressed as hourly equivalent flow rates in vehicles per hour, and not as 15-min volume counts.

The output of the analysis describes operations in all lanes within the defined weaving segment. The influence area of a weaving segment includes the base length of the segment L_p , plus 500 ft upstream and downstream. Research on the operations of weaving segments has found that the weave turbulence and associated speed reductions extend beyond the physical (gore-to-gore) boundaries of the weaving segments. This effect is accounted for in the expanded influence area, extending 500 ft on either side of the gore-to-gore distance.

Performance Measures

The procedures described in this chapter result in estimates of the average speed of all vehicles in the weaving segment S , the average density D within the weaving segment, and the segment's overall capacity. Average density is used as the service measure for the determination of LOS.

Strengths of the Methodology

The procedures in this chapter were developed from extensive research supported by a significant quantity of field data (1, 2). The methodology recognizes that freeway segment operations depend not only on weaving segment configuration but also the level of turbulence caused by weaving traffic.

Specific strengths of the HCM procedure include

- Providing capacity estimates that are consistent with traffic flow fundamentals related to volume, speed, and density;
- Recognizing the linkage between all freeway segment types explicitly in the procedure;
- Eliminating the use of multiple intermediate models, including lane change rates by movement; the method directly estimates overall weaving segment speed, thus improving the procedure's accuracy and utility;
- Producing a single deterministic estimate of LOS, which is important for some purposes, such as development impact reviews;

- Simplifying the method calibration and validation through the use of single speed and capacity estimates; and
- Evaluating the performance of managed lane (ML) access segments, as well as cross-weaving effects on general purpose lanes due to nearby managed lane access points.

Limitations of the Methodology

The methodology of this chapter does not specifically address the following subjects (without modifications by the analyst):

- Ramp metering on entrance ramps forming part of the weaving segment;
- Segment speed and other performance measure estimation during oversaturated conditions, downstream congestion, or upstream demand starvation; however, these are addressed in Chapter 10, Freeway Facility Core Methodology;
- Effects of intelligent transportation system technologies on weaving segment operations;
- Multiple weaving segments, which must be divided into appropriate merge, diverge, and simple weaving segments for analysis; and
- Weaving segments on urban streets and arterials, since urban street weaving is strongly affected by the proximity and timing of signals along the road. At the present time, there are no generally accepted methodologies for analyzing weaving movements on urban streets, including one-way frontage roads.

The methodology has been calibrated primarily for one-sided simple ramp weaves, although its application to major weave operations has yielded improved speed estimates compared to previous HCM methodologies. In addition, although the methodology can be applied with caution to two-sided weaves, this configuration is uncommon and was not fully calibrated with field observations.

Alternative Tool Consideration

Weaving segments can be analyzed by using a variety of stochastic and deterministic simulation tools that address freeways. These tools can be useful in analyzing the extent of congestion when there are failures within the simulated facility range and when interaction with other freeway segments and other facilities is present.

REQUIRED DATA AND SOURCES

To implement this analysis methodology, demand volumes for each weaving and nonweaving flow must be provided or estimated, or hourly flows must be combined with a peak hour factor (PHF), which allows their conversion to flow rates.

A complete geometric description of the weaving segment, including the number and alignment of lanes, lengths, and pavement markings, is also required.

Bullet on speed enforcement deleted.

Multiple weaving segments must be divided into merge, diverge, and simple weaving segments for analysis.

Data can be collected specifically for this purpose. Where detectors exist on entry and exit legs, they may be used to gather volume or flow rate data, and possibly to estimate weaving and nonweaving demand volumes. Aerial photos can be used to assist in defining the segment geometry.

Exhibit 13-8 lists the information necessary to apply the freeway weaving methodology and suggests potential sources for obtaining these data. It also suggests default values for use when segment-specific information is not available. The user is cautioned that every use of a default value instead of a field-measured, segment-specific value may make the analysis results more approximate and less related to the specific conditions that describe the highway. HCM defaults should only be used when (a) field data cannot be collected and (b) locally derived defaults do not exist.

Required Data and Units	Potential Data Source(s)	Suggested Default Value
<i>Geometric Data</i>		
Number of lanes in the segment	Road inventory, aerial photo	Must be provided
One-sided versus two-sided weave	Road inventory, aerial photo	Must be provided
Short length of weaving segment	Road inventory, aerial photo	Must be provided
<i>Minimum number of lane changes, ramp to freeway (one-sided weave)</i>	Road inventory, aerial photo	Must be provided
<i>Minimum number of lane changes, freeway to ramp (one-sided weave)</i>	Road inventory, aerial photo	Must be provided
<i>Minimum number of lane changes, ramp to ramp (two-sided weave)</i>	Road inventory, aerial photo	Must be provided
<i>Number of weaving lanes (on-ramp and freeway)</i>	Road inventory, aerial photo	Must be provided
Terrain type (level, rolling, specific grade)	Design plans, analyst judgment	Must be provided
<i>Free-flow speed (mi/h)</i>	Direct speed measurements, estimate from design speed or speed limit	Speed limit + 5 mi/h
Equivalent capacity of basic freeway segment	Estimated from free-flow speed and Chapter 12	Must be provided
<i>Demand Data</i>		
Hourly demand volume, freeway to freeway (veh/h)	Field data, modeling	Must be provided ^a
Hourly demand volume, freeway to ramp (veh/h)	Field data, modeling	Must be provided ^a
Hourly demand volume, ramp to freeway (veh/h)	Field data, modeling	Must be provided ^a
Hourly demand volume, ramp to ramp (veh/h)	Field data, modeling	Must be provided ^a
Analysis period length (min)	Set by analyst	15 min (0.25 h)
<i>Peak hour factor^b (decimal)</i>	Field data	0.94 urban and rural
<i>Speed and capacity adjustment factors for driver population^c</i>	Field data	1.0
<i>Speed and capacity adjustment factors for weather, incidents^d</i>	Field data	1.0
<i>Heavy vehicle percentage (%)</i>	Field data	5% urban, 12% rural ^e

Notes: **Bold italic** indicates high sensitivity (>20% change) of service measure to the choice of default value.
Bold indicates moderate sensitivity (10%–20% change) of service measure to the choice of default value.
^a Can be estimated using the simple weaving volume estimation method (Equation 13-2 to Equation 13-6).
^b Moderate to high sensitivity of service measures for very low PHF values. See the discussion in the text.
^c PHF is not required when peak 15-min demand volumes are provided.
^d See Chapter 26 in Volume 4 for default adjustment factors for driver population.
^e See Chapter 11 for default capacity and speed adjustment factors for weather and incidents.
^f See Chapter 26 in Volume 4 for state-specific default heavy vehicle percentages.

Exhibit 13-8
Required Input Data, Potential Data Sources, and Default Values for Freeway Weaving Analysis

The exhibit distinguishes between urban and rural conditions for certain defaults. The classification of a facility into urban and rural is made on the basis of the Federal Highway Administration smoothed or adjusted urbanized boundary definition (12), which in turn is derived from Census data.

Care should be taken in using default values. The service measure results are sensitive to **some input data** listed in Exhibit 13-7. For example, the numbers of lane changes from freeway to ramp, ramp to freeway, and ramp to ramp, as well as the number of weaving lanes, all change the service measure result by more than 20% when these inputs are varied over their normal range. In addition, the **short length of the weaving segment** results in a 10%–20% change in service measure when it is varied over its normal range. **Low PHF values (<0.80) result in a greater than 20% change**, compared with the results obtained for the default value for PHF; more typical PHFs vary the service measure results by less than 10%. **The peak hour factor, heavy vehicle factor, and free-flow speed can each change the service measure by greater than 20%.** Other inputs change the service measure result by less than 10% when they are varied over their normal range.

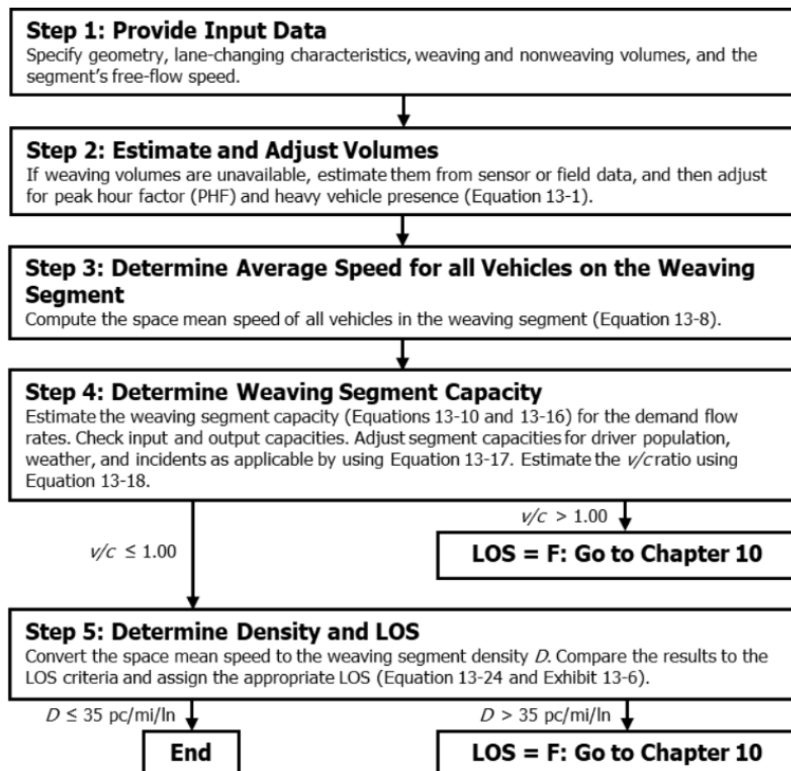
OVERVIEW OF THE METHODOLOGY

Models Used by the Methodology

Exhibit 13-9 is a flowchart illustrating the steps that define the methodology for analyzing freeway weaving segments.

Exhibit 13-9
Weaving Methodology
Flowchart

LOS F exists in a weaving segment when demand exceeds capacity or density exceeds 35 pc/mi/ln.



The methodology uses several types of predictive algorithms, all of which are based on a mix of theoretical and regression models, but in essence boil down to two models. These models are:

- A model to predict the average speed of vehicles in a weaving segment under stable operating conditions, that is, not operating at LOS F, including adjustments to account for the impacts of weather and incidents. Along with volume, speed is converted to density for LOS estimation.
- A model to predict the capacity of a weaving segment, including adjustments to account for the effects of weather and incidents.

Parameters Describing a Weaving Segment

Several parameters describing weaving segments have already been introduced and defined. Exhibit 13-10 illustrates additional variables that must be specified as inputs and defines those that will be used within or as outputs of the methodology. Some of them apply only to one-sided weaving segments. Exhibit 13-11 lists the variables that are different in applications to two-sided weaving segments.

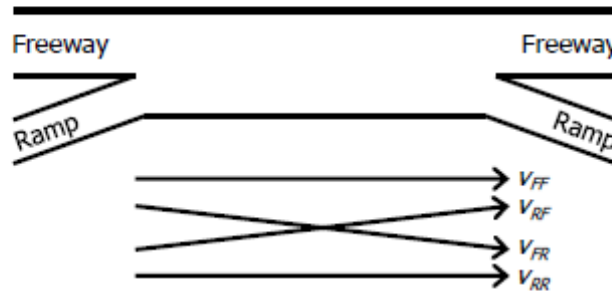


Exhibit 13-10
Weaving Variables for
One-Sided Weaving Segments

v_{FF} = freeway-to-freeway demand flow rate in the weaving segment in passenger cars per hour (pc/h);

v_{RF} = ramp-to-freeway demand flow rate in the weaving segment (pc/h);

v_{FR} = freeway-to-ramp demand flow rate in the weaving segment (pc/h);

v_{RR} = ramp-to-ramp demand flow rate in the weaving segment (pc/h);

v_F = entering freeway demand flow rate in the weaving segment = $v_{FF} + v_{FR}$;

v_N = on-ramp demand flow rate in the weaving segment = $v_{RF} + v_{RR}$;

v_X = off-ramp demand flow rate in the weaving segment = $v_{FR} + v_{RR}$;

v = total demand flow rate in the weaving segment (pc/h) = $v_F + v_N$;

VR = volume ratio (decimal) = $(v_{RF} + v_{FR}) / v$;

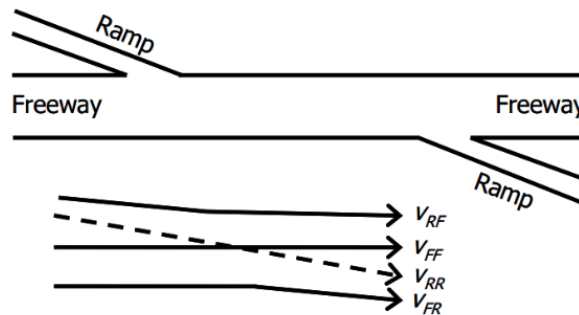
N = number of general-purpose lanes within the weaving segment (ln);

NW_{RF} = number of ramp lanes from which a weaving maneuver to the freeway may be completed with one lane change or no lane changes (ln);

Variables no longer used by
the methodology deleted.

Exhibit 13-11
Weaving Variables for
Two-Sided Weaving Segments

*The through freeway
movement is not considered to
be weaving in a two-sided
weaving segment.*



- 1 NW_{FR} = number of freeway lanes from which a weaving maneuver to the ramp
- 2 may be completed with one lane change or no lane changes (ln);
- 3 S_o = overall mean speed of all vehicles within the weaving segment (mi/h);
- 4 FFS = free-flow speed of the weaving segment (mi/h);
- 5 D = average density of all vehicles within the weaving segment in
- 6 passenger cars per mile per lane (pc/mi/ln);
- 7 L_S = length of the weaving segment (ft), based on the short length definition
- 8 of Exhibit 13-2;
- 9 LC_{RF} = minimum number of lane changes (lc) that must be made by a single
- 10 weaving vehicle moving from the on-ramp to the freeway (see Exhibit
- 11 13-5); and
- 12 LC_{FR} = minimum number of lane changes that must be made by a single
- 13 weaving vehicle moving from the freeway to the off-ramp (lc).

All variables are defined as in Exhibit 13-10, except for the following
variables relating to flow designations and lane-changing:

- 17 v_W = total weaving demand flow rate within the weaving segment (pc/h),
- 18 $v_W = v_{RR}$;
- 19 v_{NW} = total nonweaving demand flow rate within the weaving segment
- 20 (pc/h), $v_{NW} = v_{FR} + v_{RF} + v_{FF}$;
- 21 LC_{RR} = minimum number of lane changes that must be made by one ramp-to-
- 22 ramp vehicle to complete a weaving maneuver (lc);
- 23 NW_{RR} = number of freeway lanes from which a weaving maneuver to the off-
- 24 ramp may be completed with one lane change or no lane changes (ln);
- 25 and
- 26 VR = volume ratio (decimal) = v_{RR} / v .

The principal difference between one-sided and two-sided weaving
segments is the relative positioning of the movements within the segment. In a
two-sided weaving segment, the ramp-to-freeway and freeway-to-ramp vehicles
do not weave. In a one-sided segment, they execute the weaving movements. In
a two-sided weaving segment, the ramp-to-ramp vehicles must cross the path of
freeway-to-freeway vehicles. Both could be taken to be weaving movements. In

reality, the through freeway movement is not weaving in that vehicles do not need to change lanes and generally do not shift lane position in response to a desired exit leg.

Thus, in two-sided weaving segments, only the ramp-to-ramp flow is considered to be weaving. The lane-changing parameters reflect this change in the way weaving flows are viewed. Thus, the minimum rate of lane changing that weaving vehicles must maintain to complete all desired weaving maneuvers successfully is also related only to the ramp-to-ramp movement.

The definitions for flow all refer to *demand flow rate*. This means that for existing cases, the demand should be based on *arrival flows*. For future cases, forecasting techniques will generally produce a *demand volume* or *demand flow rate*. All of the methodology's algorithms use demand expressed as flow rates in the peak 15 min of the design (or analysis) hour, in equivalent passenger car units.

The methodology uses demand flow rates for the peak 15 min in passenger cars per hour.

COMPUTATIONAL STEPS

Each of the **procedural** steps noted in Exhibit 13-9 is discussed in detail in the sections that follow.

Step 1: Provide Input Data

The methodology for weaving segments is structured for operational analysis usage, that is, given a known or specified geometric design and traffic demand characteristics, the methodology is used to estimate the expected LOS.

Design and preliminary engineering are generally conducted in terms of comparative analyses of various design proposals. This is a good approach, given that the range of widths, lengths, and configurations in any given case is constrained by a number of factors. Length is constrained by the location of the crossing arteries that determine the location of interchanges and ramps. Width is constrained by the number of lanes on entry and exit legs and usually involves no more than two choices. Configuration is also the result of the number of lanes on entry and exit legs as well as the number of lanes within the segment. Changing the configuration usually involves adding a lane to one of the entry or exit legs, or both, to create different linkages.

For analysis, the geometry of the weaving segment must be fully defined. This includes the number of lanes, lane widths, shoulder clearances, the details of entry and exit gore area designs (including markings), the existence and extent of barrier lines, and the length of the segment. A sketch of the weaving segment should be drawn with all appropriate dimensions shown.

Step 2: Estimate and Adjust Volumes

Converting Demand Volumes to Ideal Equivalents

All equations in this chapter use flow rates under equivalent ideal conditions as input variables. Thus, demand volumes and flow rates under prevailing conditions must be converted to their ideal equivalents by using Equation 13-1:

$$v_i = \frac{V_i}{PHF \times f_{HV}}$$

Equation 13-1

1 where
 2 v_i = flow rate i under ideal conditions (pc/h),
 3 V_i = hourly volume for flow i under prevailing conditions in vehicles per
 4 hour (veh/h),
 5 PHF = peak hour factor (decimal), and
 6 f_{HV} = adjustment factor for heavy vehicle presence (decimal).

7 The subscript for the type of flow i can take on the following values:

8 FF = freeway to freeway, FR = freeway to ramp,
 9 RF = ramp to freeway, RR = ramp to ramp,
 10 W = weaving, and NW = nonweaving.

11 The heavy vehicle adjustment factor f_{HV} is taken from Chapter 12, Basic
 12 Freeway and Multilane Highway Segments. If flow rates for a 15-min period
 13 have been provided as inputs, the PHF is taken to be 1.00 and the 15-min count is
 14 used directly after conversion to an hourly flow rate.

15 In the event all weaving and nonweaving movements are observed in the
 16 field, Equation 13-1 is applied to all four weaving and nonweaving movements
 17 before proceeding to Step 3. Otherwise, a simple weaving volume estimation
 18 method can be applied as explained next.

19 *Simple Weaving Volume Estimation Method*

20 The simple method assumes that the off-ramp attracts a similar proportion of
 21 traffic flows P from both the mainline and the on-ramp. It also assumes the
 22 availability of flow rates for both the on- and off-ramps, information which may
 23 be available from ramp sensors. The proportion P is calculated from Equation
 24 13-2 as follows:

Equation 13-2 25
$$P = \frac{v_x}{v_F + v_N}$$

26 where all other variables are as defined in Exhibit 13-10. Once P is determined,
 27 the individual weaving movements can be estimated as follows:

Equation 13-3 28
$$v_{RF} = v_N(1 - P)$$

Equation 13-4 29
$$v_{RR} = v_N P$$

Equation 13-5 30
$$v_{FR} = v_x - v_{RR}$$

Equation 13-6 31
$$v_{FF} = v_F - v_{FR}$$

32 where all variables are as defined previously.

33 *Weaving Diagram Construction*

Old Step 3 (Determine
 Configuration Characteristics)
 and Step 4 (Determine
 Maximum Weaving Segment
 Length) deleted.

34 Once demand flow rates have been established, it may be convenient to
 35 construct a weaving diagram similar to those illustrated in Exhibit 13-10 (for one-
 36 sided weaving segments) and Exhibit 13-11 (for two-sided weaving segments).

Step 3: Determine Average Speed for all Vehicles on the Weaving Segment

Weaving segment capacity estimation is intimately tied to speed estimation to satisfy the fundamental equation of traffic flow. Conceptually, the overall speed in a weaving segment can be expressed in the following manner:

$$S_o = S_b - SIW$$

Equation 13-7

where

S_o = overall mean speed for all vehicles in the weaving segment (mi/h);

S_b = mean speed for all vehicles in an equivalent basic segment with the same number of lanes N , same demand volume v , and same free-flow speed FFS (mi/h); and

SIW = speed impedance term due to weaving and segment configuration (mi/h).

One-sided Weaving Segments

Equation 13-8 gives the general form of the speed model for S_o for one-sided weaving segments (1).

$$S_o = \min \left[S_b, S_b - \alpha \left(\frac{LC_{RF} + 1}{NW_{RF} + 1} v_{RF} + \frac{LC_{FR} + 1}{NW_{FR} + 1} v_{FR} \right)^{\gamma} \left(\frac{1}{L_s} \right)^{\delta} \left(\frac{v}{N} - 500 \right) \right]$$

Equation 13-8

where α , γ , δ , and ε are regression coefficients from Exhibit 13-12 and all other variables are as previously defined.

Segment Type	α	γ	δ	ε
Simple	0.025	0.156	0.311	3
Two-sided	0.025	0.156	0.311	3
Complex	0.056	0.300	0.400	3

Exhibit 13-12
Speed Model Coefficients

The speed impedance term (SIW) of Equation 13-8 (everything to the right of S_b) behaves properly. It includes a weighted function of the weaving flows v_{RF} and v_{FR} , increases as the overall volume v increases, decreases with an increase in the number of lanes N , and increases as the short length of weave L_s decreases. In addition, when the segment flow rate drops below 500 pc/h/ln, the segment speed approaches that of a corresponding basic segment. At flow rates below 500 pc/h/ln, the speed impedance term is negative; in these cases, the mean speed for the weaving segment is constrained to be no greater than the mean speed of an equivalent basic segment.

For convenience, because it is also used in Step 4 to determine capacity, a weaving intensity factor W can be defined from the first two portions of the speed impedance term, as shown in Equation 13-9.

$$W = \alpha \left(\frac{LC_{RF} + 1}{NW_{RF} + 1} v_{RF} + \frac{LC_{FR} + 1}{NW_{FR} + 1} v_{FR} \right)^{\gamma} \left(\frac{1}{L_s} \right)^{\delta}$$

Equation 13-9

	1	Substituting W into Equation 13-8 produces Equation 13-10:
Equation 13-10	2	$S_o = \min \left[S_b, S_b - W \left(\frac{v}{N} - 500 \right) \right]$
	3	It can be seen from Equation 13-9 that the relative weights of the ramp-to-
	4	freeway and freeway-to-ramp weaving flows in determining segment speed are
	5	dependent on the weaving segment configuration. This characteristic allows
	6	Equation 13-9 to be simplified for use with common weaving configurations.
	7	For example, as described in Section 2, a simple weaving segment always has
	8	the value of 1 for LC_{RF} , LC_{FR} , NW_{RF} , and NW_{FR} . Substituting these values into
	9	Equation 13-9, along with the coefficients for a simple weave from Exhibit 13-12,
	10	reduces the equation into the following form for a simple weave:
Equation 13-11	11	$W = 0.025 \left(\frac{v_{RF} + v_{FR}}{N^3} \right)^{0.156} \left(\frac{1}{L_s} \right)^{0.311}$
	12	Thus, in a simple weave, the ramp-to-freeway and freeway-to-ramp flow
	13	equally influence weaving segment speed (and, as will be shown in Step 4,
	14	capacity).
	15	As another example, consider a "Complex 1-0" weave (e.g., a single lane on-
	16	ramp and a two-lane off-ramp). Here, $LC_{RF} = 1$, $LC_{FR} = 0$, $NW_{RF} = 1$, and $NW_{FR} = 2$.
	17	Substituting these values into Equation 13-9, along with the coefficients for a
	18	complex weave from Exhibit 13-12, reduces the equation into the following form:
Equation 13-12	19	$W = 0.056 \left(\frac{v_{RF} + \frac{1}{3}v_{FR}}{N^3} \right)^{0.3} \left(\frac{1}{L_s} \right)^{0.4}$
	20	Thus, in a "Complex 1-0" weave, the freeway-to-ramp flow has one-third the
	21	influence on the weaving segment speed as does the ramp-to-freeway flow. This
	22	is logical, given that freeway-to-ramp traffic does not have to change lanes and
	23	thus creates less turbulence than does the ramp-to-freeway traffic, which must
	24	change lanes.
	25	<i>Two-sided Weaving Segments</i>
	26	The general form of the speed model for two-sided weaves is given by
	27	Equation 13-13.
Equation 13-13	28	$S_o = \min \left[S_b, S_b - \alpha \left(\frac{LC_{RR} + 1}{NW_{RR} + 1} \frac{v_{RR}}{N^\epsilon} \right)^\gamma \left(\frac{1}{L_s} \right)^\delta \left(\frac{v}{N} - 500 \right) \right]$
	29	Similar to one-sided weaves, a simplified form of the weaving intensity
	30	factor W can be developed for two-sided weaves and then used with Equation
	31	13-10. For example, consider a two-sided weave with one-lane on- and off-ramps
	32	and a three-lane cross-section. Here, $LC_{RR} = 2$ and $NW_{RR} = 0$ and the weaving
	33	intensity factor reduces to:
Equation 13-14	34	$W = 0.025 \left(\frac{3v_{RR}}{N^3} \right)^{0.156} \left(\frac{1}{L_s} \right)^{0.311}$

Compared to a simple weave, the weaving volume in a two-sided weave has three times the influence on the weaving segment speed. This makes sense, given that the weaving volume creates turbulence across all the freeway lanes.

Check for Undersaturated Conditions

The speed estimated in Step 3 assumes that the segment operates at or below capacity; this check is performed next in Step 4.

Step 4: Determine Weaving Segment Capacity

Breakdown of a weaving segment is expected to occur when the average density of all vehicles in the segment exceeds 35 pc/mi/ln. This value represents an average condition based on observed breakdown densities (1), with some sites showing breakdown at higher or lower density values. This condition is partially a function of the segment short length, with longer short lengths resulting in an increase in segment capacity. Note that the criteria listed in Chapter 12, Basic Freeway and Multilane Highway Segments, state that basic segment breakdowns occur at a density of 45 pc/mi/ln, which is unchanged in this methodology. Given the additional turbulence in a weaving segment, breakdown is expected to occur at lower densities than for a basic segment.

Base Weaving Segment Capacity

Given that weaving capacity is based on reaching a density of 35 pc/mi/ln, Equation 13-7 can be rewritten as Equation 13-15, which evaluates the overall speed at the weaving segment capacity:

$$\frac{C_W}{35} = S_b(C_W) - SIW$$

where

C_W = weaving segment capacity (pc/h/ln);

$S_b(C_W)$ = basic segment speed evaluated at the weaving segment capacity (mi/h); and

SIW = speed impedance term due to weaving and segment configuration (mi/h).

Equation 13-15 is a quadratic equation in C_W since the basic segment speed uses the squared value of the flow rate in its calculation. Thus it can be solved analytically to estimate capacity. Substituting the speed impedance term of Equation 13-8 into Equation 13-15 and solving for C_W yields Equation 13-16 to estimate weaving segment capacity:

$$C_W = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

with

$$a = 1$$

$$b = \frac{W}{B} + \frac{1}{35B} - 2BP$$

A weaving segment's capacity is controlled by the average vehicle density exceeding 35 pc/mi/ln.

The capacity check based on weaving demand flows has been removed from the methodology.

Equation 13-15

Equation 13-16

Equation 13-17

Equation 13-18

$$\text{Equation 13-19} \quad c = BP^2 - \frac{FFS}{B} - \frac{500W}{B}$$

$$\text{Equation 13-20} \quad B = \frac{FFS - S_c}{(C_b - BP)^2}$$

where

C_w = weaving segment capacity (pc/h/ln);

a, b, c = intermediate calculation parameters;

W = weaving segment intensity, from Equation 13-14;

B = basic segment term;

BP = basic segment breakpoint, from Exhibit 12-6 (pc/h/ln);

FFS = free-flow speed of the weaving segment (mi/h);

S_c = speed at capacity of an equivalent basic segment = $C_b / 45$ (mi/h); and

C_b = equivalent per-lane basic segment capacity, from Exhibit 12-6 (pc/h/ln).

Adjustment to Capacity for Adverse Weather, Incidents, or Driver Population

The capacity of the weaving segment may be adjusted to account for the impacts of adverse weather, driver population, occurrence of traffic incidents, or a combination of these factors. The methodology for making such adjustments is the same as that for other types of freeway segments. Default adjustment factors are found in Section 5 of Chapter 11, Freeway Reliability Analysis. The adjustments for weather and incidents are most commonly applied in the context of a reliability analysis. For convenience, a brief summary is provided here.

The segment's per-lane capacity is adjusted as shown in Equation 13-21:

$$\text{Equation 13-21} \quad C_{wa} = C_w \times CAF$$

where

C_{wa} = adjusted weaving segment capacity (pc/h/ln),

C_w = weaving segment capacity (pc/h/ln), and

CAF = capacity adjustment factor from Chapter 11 (unitless).

The CAF can have several components, including weather, incident, work zone, driver population, and calibration adjustments. CAF defaults for weather and incident effects are found in Chapter 11, along with additional discussion on how to apply them. If desired, capacity can be further adjusted to account for unfamiliar drivers in the traffic stream. While the default CAF for this effect is set to 1.0, Chapter 26 provides guidance for estimating the CAF on the basis of the composition of the driver population.

Chapter 12 provides additional guidance on capacity definitions, and Chapter 26 provides guidance on estimating freeway segment capacity, including weaving segment capacity, from field data.

Volume-to-Capacity Ratio

With the final capacity determined, the volume-to-capacity ratio (v/c ratio) for the weaving segment may be computed from Equation 13-22. The total volume v in this case represents the sum of weaving and nonweaving flows.

$$v/c = \frac{v/N}{C_{Wa}}$$

where all variables are as previously defined.

Equation 13-22

Level of Service F

If v/c is greater than 1.00, demand exceeds capacity, and the segment is expected to fail, that is, have a LOS of F. If this occurs, the analysis is terminated, and LOS F is assigned. At LOS F, queues are expected to form within the segment, possibly extending upstream beyond the weaving segment itself. Queuing on the **on-ramp** that **is** part of the weaving segment would also be expected. **The methodologies of Chapters 10 and 11, on freeway facilities, can be used to analyze the impacts of the existence of LOS F on upstream and downstream freeway segments during the analysis period and over time. Chapter 38, Network Analysis, can be used to evaluate the effects of on-ramp queue spillback into the ramp terminal.**

LOS F occurs when demand exceeds capacity. The methodologies in Chapter 10 can be used to evaluate oversaturated weaving segments.

Checking Input and Output Capacities

In most cases, the controlling capacity factor in a weaving segment is the weaving activity itself. The computational procedure for capacity of the weaving segment *guarantees* that the result will be less than the capacity of a basic freeway segment with the same number of lanes.

Last sentence in the paragraph deleted.

In rare cases, there may be insufficient capacity to accommodate the demand flows on one or more of the entry and exit roadways. Input and output roadways must be classified as either basic freeway lanes or ramps. The capacity of basic freeway lanes is checked by using the procedures of Chapter 12, Basic Freeway and Multilane Highway Segments. Ramp capacities should be checked by using the methodology of Chapter 14, Freeway Merge and Diverge Segments.

If either an entry roadway or an exit roadway has insufficient capacity, the weaving segment will not function properly, and queuing resulting from the capacity deficiency will result. LOS F is assigned, and further analysis must use the methodology of **Chapter 38**.

Step 5: Determine Density and LOS

The average speed of all vehicles, computed in Step 3, must be converted to density by using Equation 13-23.

$$D = \frac{(v/N)}{S_o}$$

where D is density in passenger cars per mile per lane and all other variables are as previously defined. The density value obtained can then be used with Exhibit 13-7 to assign a LOS letter to the weaving segment. **LOS can be determined for weaving segments on freeways, multilane highways, and C-D roads.**

Old Step 6 (Determine Lane-Changing Rates) and Step 7 (Determine Average Speeds of Weaving and Nonweaving Vehicles in Weaving Segment) deleted.

Equation 13-23

LOS can be determined for weaving segments on freeways, multilane highways, and C-D roads.

4. EXTENSIONS TO THE METHODOLOGY

MULTIPLE WEAVING SEGMENTS

When a series of closely spaced merge and diverge areas creates overlapping weaving movements (between different merge-diverge pairs) that share the same segment of a roadway, a multiple weaving segment is created. In earlier editions of the HCM, a specific application of the weaving methodology for two-segment multiple weaving segments was included. While it was a logical extension of the methodology, it did not address cases in which three or more sets of weaving movements overlapped, nor was it well supported by field data.

Multiple weaving segments should be segregated into separate merge, diverge, and simple weaving segments, with each segment appropriately analyzed by using this chapter's methodology or that of Chapter 14, Freeway Merge and Diverge Segments. Chapter 12, Basic Freeway and Multilane Highway Segments, contains information relative to the process of identifying appropriate segments for analysis.

C-D ROADS

A common design practice often results in weaving movements that occur on C-D roads that are part of a freeway interchange. The methodology of this chapter may be approximately applied to such segments. The FFS used must be appropriate to the C-D road. It would have to be measured on an existing or similar C-D road, since the predictive methodology of FFS given in Chapter 12 does not apply to such roads. Whether the LOS criteria of Exhibit 13-7 are appropriate is less clear. Many C-D roads operate at lower speeds and higher densities than do basic segments, and the criteria of Exhibit 13-7 may produce an inappropriately negative view of operations on a C-D road.

If the measured FFS of a C-D road is high (greater than or equal to 50 mi/h), reasonably accurate analysis results can be expected. At lower FFS values, results would be more approximate.

MULTILANE HIGHWAYS

Weaving segments may occur on multilane highways. As long as such segments are a sufficient distance away from signalized intersections—so that platoon movements are not an issue—the methodology of this chapter may be approximately applied.

ML ACCESS SEGMENTS

Where managed lanes have defined intermittent access segments, two types of weaving movements may be created. Exhibit 13-13 illustrates the two types of situations.

The methodology applies approximately to C-D roads, but its use may produce an overly negative view of operations.

Multilane highway weaving segments may be analyzed with this methodology, except in the vicinity of signalized intersections.

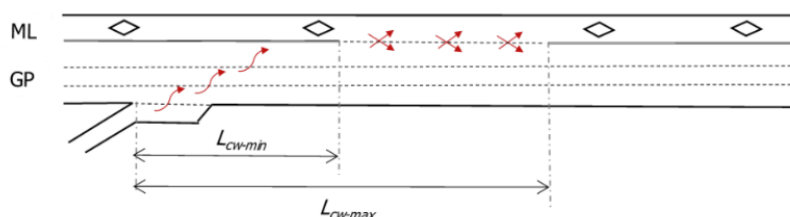


Exhibit 13-13
Weaving Movements
Associated with Managed
Lane Access and Egress

Note: ML = managed lane and GP = general purpose.

Exhibit 13-13 illustrates a managed lane with three general purpose freeway lanes. Where an on-ramp is near the ML access segment, on-ramp vehicles destined for the managed lane must cross all of the general purpose freeway lanes in the distance L_{cw-min} . The cross-weave demand can cause a reduction in the capacity of the general purpose lanes, which must be considered. While not shown, the same effect exists when an off-ramp is near the ML access segment, with the distance L_{cw-min} measured from the end of the access segment to the off-ramp junction point.

The second type of weaving occurs within the ML access segment, as vehicles entering and exiting from the managed lane cross each other within the distance $L_{cw-max} - L_{cw-min}$. L_{cw-min} is defined as the distance between the on-ramp gore area and the beginning of the ML access segment, while L_{cw-max} is the distance from the gore to the end of the ML access segment.

Cross-Weaving Between Ramps and the ML Access Segment

The impact of cross-weaving movements on general purpose lane capacity is handled by using a CAF, as shown in Equation 13-24. The approach was developed as part of NCHRP Project 03-96 (13).

$$CAF = 1 - CRF$$

$$CRF = -0.0897 + 0.0252 \ln(CW) - 0.00001453L_{cw-min} + 0.002967N_{GP}$$

Equation 13-24

where

CRF = capacity reduction factor (decimal),

CAF = capacity adjustment factor (decimal),

CW = cross-weave demand flow rate (pc/h),

L_{cw-min} = cross-weave length (ft), and

N_{GP} = number of general purpose lanes (ln).

The capacity of the general purpose lanes is then computed as

$$c_{GPA} = c_{GP} \times CAF$$

Equation 13-25

where

c_{GPA} = adjusted capacity of the general purpose lanes (veh/h) and

c_{GP} = unadjusted capacity of the general purpose lanes, estimated by using basic freeway procedures in Chapter 12 (veh/h).

Weaving Within the ML Access Segment

Weaving within the ML access segment is treated by using the procedures of this chapter. The access segment is treated as a left-side ramp-weave segment with a length of $L_{cw-max} - L_{cw-min}$.

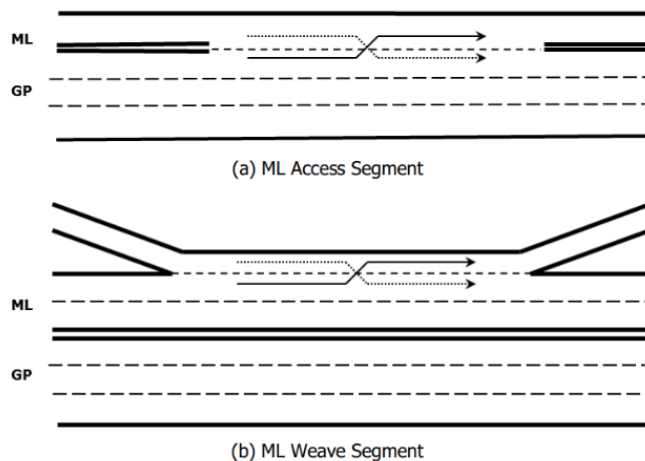
The interaction and weave turbulence effect is assumed to apply to the entire ML access segment, including all general purpose lanes. Consequently, the methodology is identical to the evaluation of a weaving segment on the left side of a freeway. When an ML access segment is evaluated as part of an extended freeway facility with managed lanes with the procedures in Chapter 10, the ML access segment represents the one exception where the general purpose and managed lanes are not treated as two separate lane groups. Instead, the calculated performance measures are applied across all lanes. In applying the weaving method, the basic segment capacity from Chapter 12, Basic Freeway and Multilane Highway Segments, should be used across all lanes when the weave capacity computations are performed (Equation 13-7).

Care should be taken when an overall managed lane facility is evaluated and the separation between the managed and general purpose lanes requires considering the adjacent friction effect, as described in Chapter 12. In those cases, the freeway facility methodology in Chapter 10 offers additional adjustments to the ML access segment for consistency with upstream or downstream ML basic segments.

ML WEAVE SEGMENTS

The procedure described in this chapter may also be used to analyze an ML weave segment. An ML weave segment is limited to managed lane facilities with nontraversable separation from the general purpose lanes. The ML weave segment type is created when an on-ramp onto the managed lane is followed by an off-ramp from the managed lane and the two are connected by an auxiliary lane. The distinction between a ML weave and a ML access segment is illustrated in Exhibit 13-14.

Exhibit 13-14
Distinguishing ML Access and Weave Segments



Note: ML = managed lane and GP = general purpose.

1 The procedure for analyzing an ML weave segment generally follows the
2 methodology for a standard weaving segment. The only modification is the use
3 of the managed lane's basic segment capacity from Chapter 12 in the weave
4 capacity computations (Equation 13-7).

5 Care should be taken when an overall managed lane facility is evaluated,
6 and the separation between the managed and general purpose lanes requires
7 considering the adjacent friction effect, as described in Chapter 12. In those cases,
8 the freeway facility methodology in Chapter 10 offers additional adjustments to
9 the ML weave segment for consistency with upstream or downstream ML basic
10 segments.

11

Appendix C Location of Western Australian and Victorian Freeway/Motorway Sections Used for the Analysis

Figure C.1: Western Australian basic freeway and weaving sections ('W' indicates a weaving area)

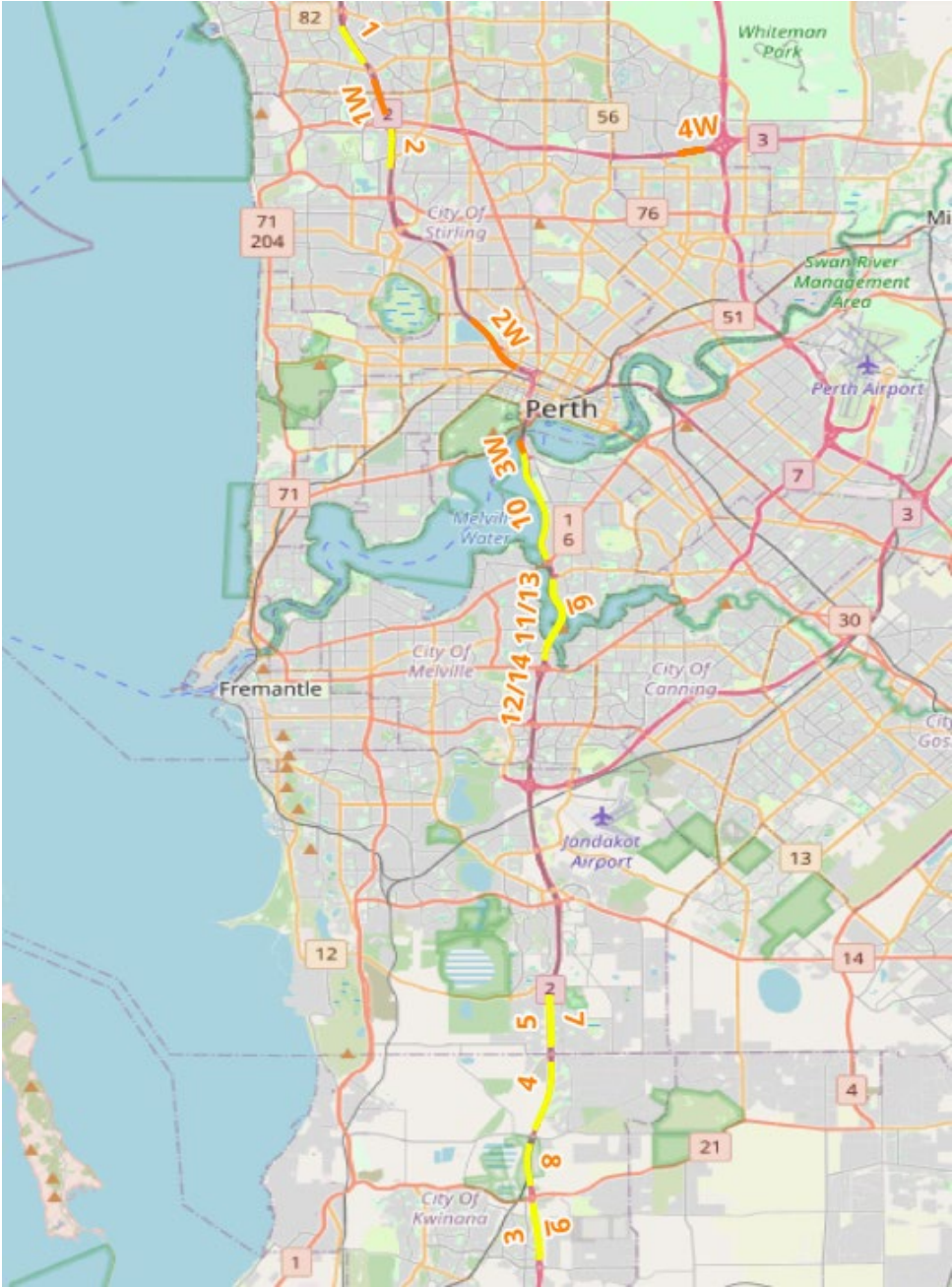
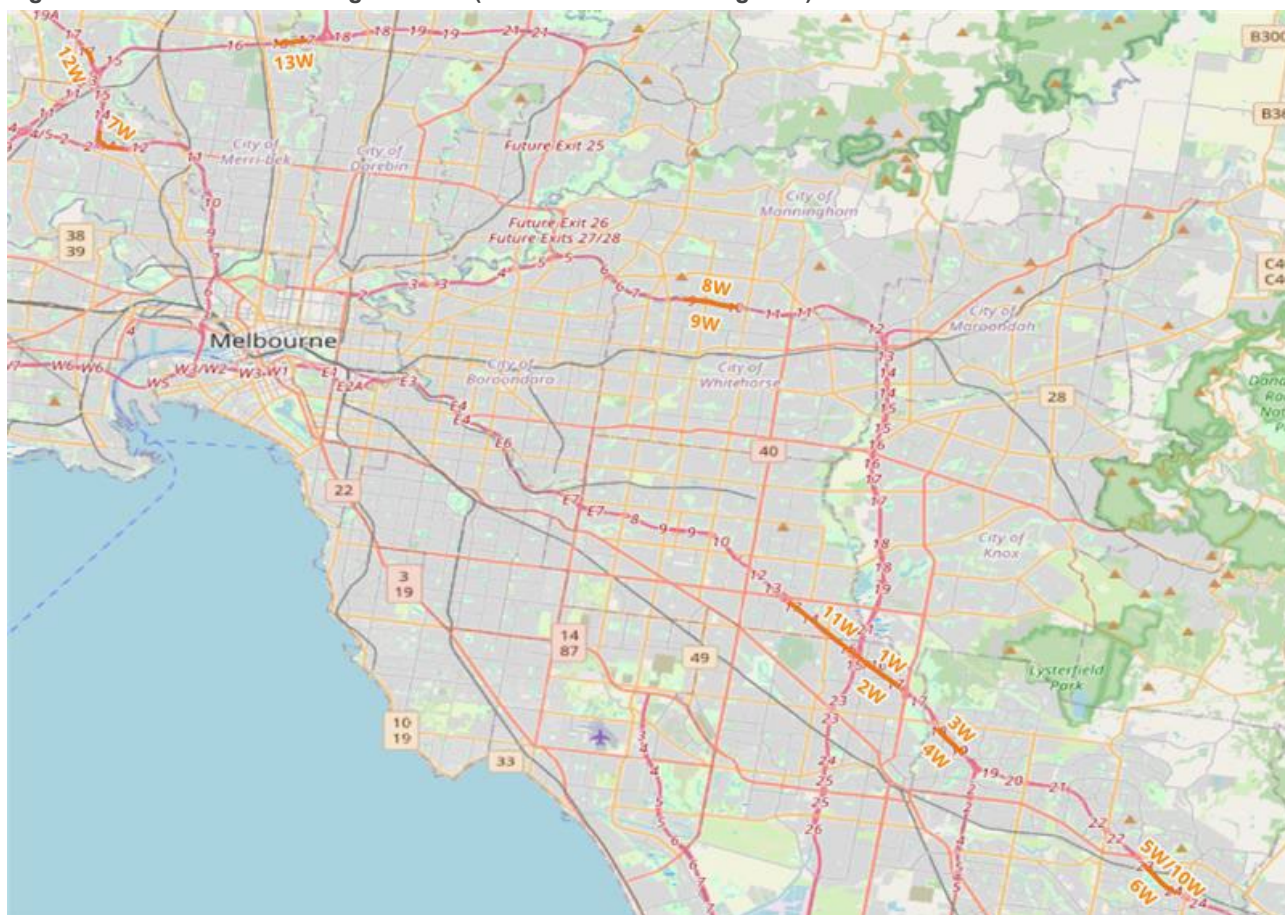


Figure C.2: Victorian weaving sections ('W' indicates a weaving area)



Appendix D Camera Locations for the Western Australian Weaving Areas

Figure D.1: Camera locations for the Western Australian Reid Highway to Warwick Road weaving areas





Figure D.2: Camera locations for the Western Australian Powis Street to Vincent Street weaving areas

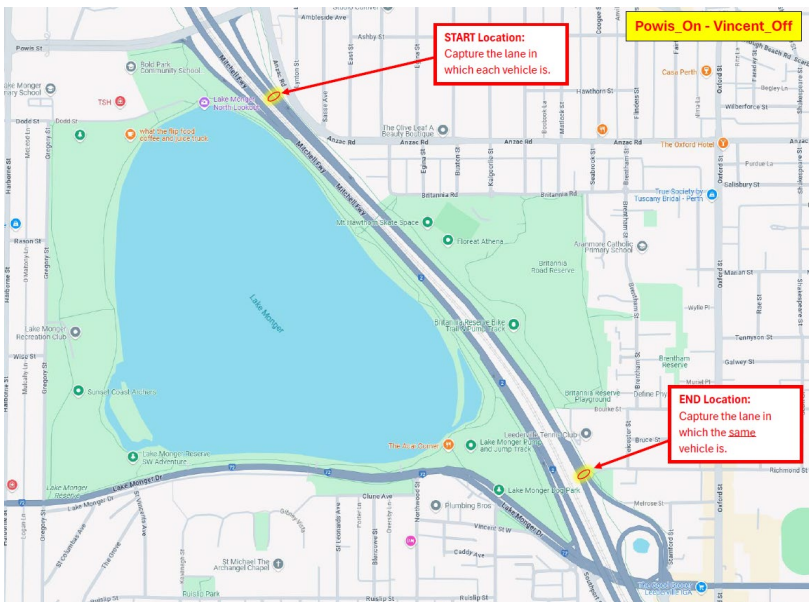
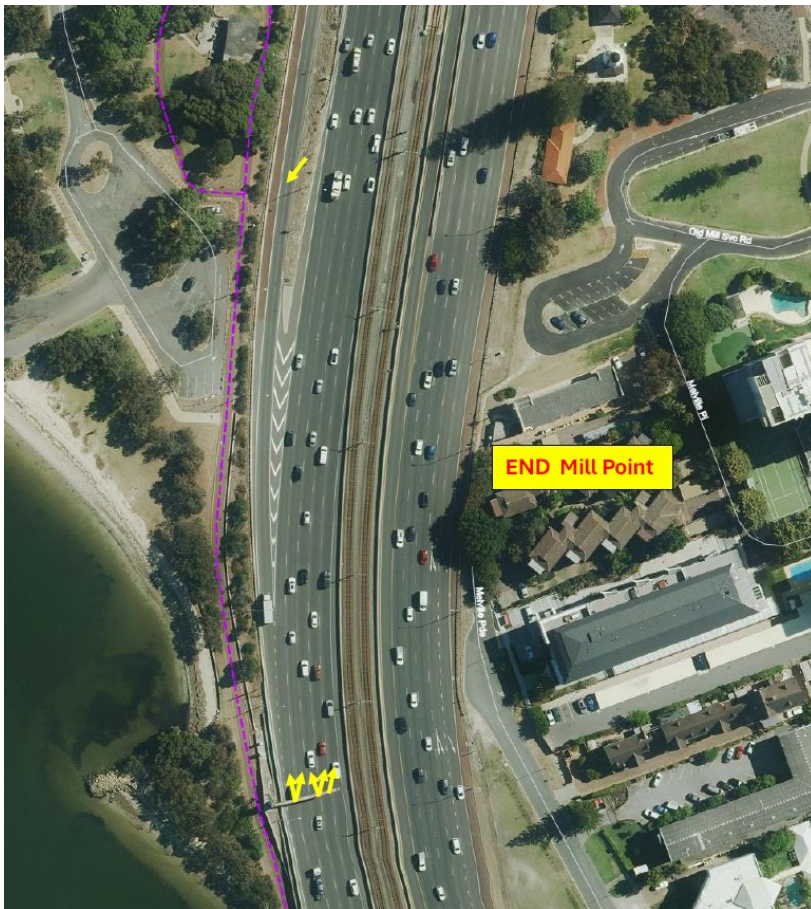




Figure D.3: Camera locations for the Western Australian Mill Point Road to Mill Point Road weaving areas





Appendix E Weaving Areas and Detectors

Table E.1: Victorian detector sites used for MSFR and LCC definition

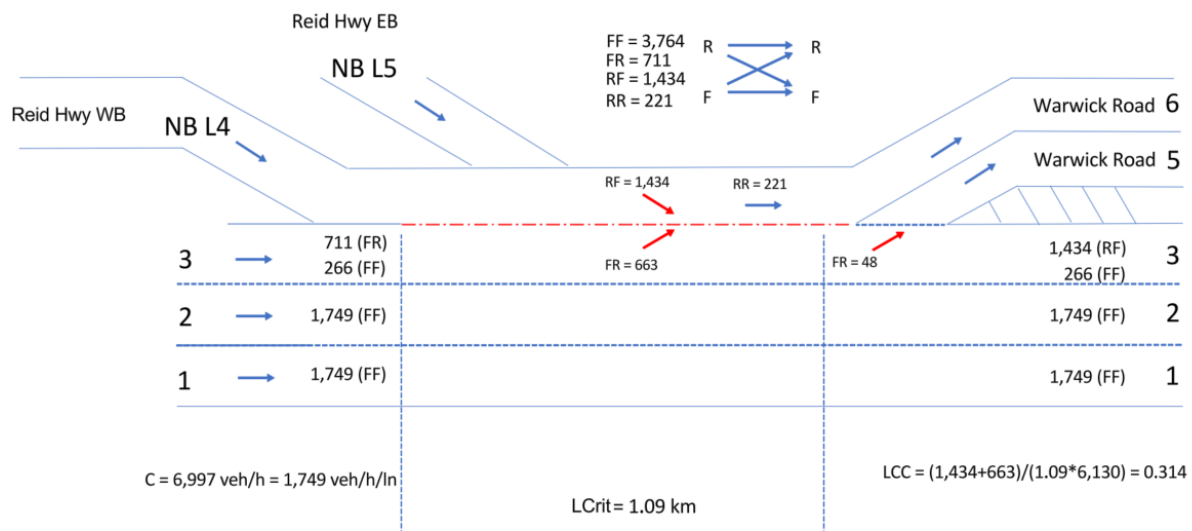
	Freeway	Direction	From	To	Entry TIRTL	Exit TIRTL	Capacity VDS (bottleneck)	Capacity VDS (downstream control section – CS)	Comment
1	Monash Freeway	OB	Eastlink	Stud Rd	14069OB	14077OB	14073OB (or 14071OB)	14077OB	
2		IB	Stud Rd	Eastlink	14076IB (or 14078IB)	14068IB	14074IB	14068IB	Entry TIRTL must be before the merge
3		OB	Heatherton Rd	South Gippsland Fwy	14087OB	14093OB	14089OB	14093OB	Entry TIRTL must be before the merge
4		IB	South Gippsland Fwy	Heatherton Rd	14092IB	14086IB	14090IB	14086IB	
5		OB	Princes Hwy	Clyde Rd	14130OB	14140OB	14134OB	14140OB	Entry TIRTL must be before the merge
6		IB	Clyde Rd	Princes Hwy	14139IB (or 14141IB)	14129IB	14137IB	14129IB	Entry TIRTL must be before the merge
7	Tullamarine Freeway	IB	English St	Calder Fwy	14366IB	14361IB	14364IB	14361IB	CS should ideally include the Calder exit-ramp as well
8	Eastern Freeway	OB	Tram Rd	Blackburn Rd	NA	NA			
9		IB	Blackburn Rd	Tram Rd	NA	NA			
10	Monash Freeway	OB	Princes Hwy	Clyde Rd	NA	NA	NA		Refer to no 5
11		OB	Wellington Rd	Eastlink	14784OB	14793OB	14785OB	14793OB (or 14795OB)	CS should be after the exit ramp diverge
12	Tullamarine Freeway	OB	M80 Ring Road	Mickleham Rd	14394OB	14611OB	14396OB	14611OB	14398OB could help with quantifying the weaving, see TIRTL photo
13	M80 Ring Road	WB	Hume Freeway	Sydney Rd	14867AB	14861AB	14865AB	14861AB	see TIRTL photo

OB = Outbound, IB = Inbound, WB = Westbound, AB = Altona-bound.

Appendix F Geometrical and Traffic Conditions for Weaving Areas

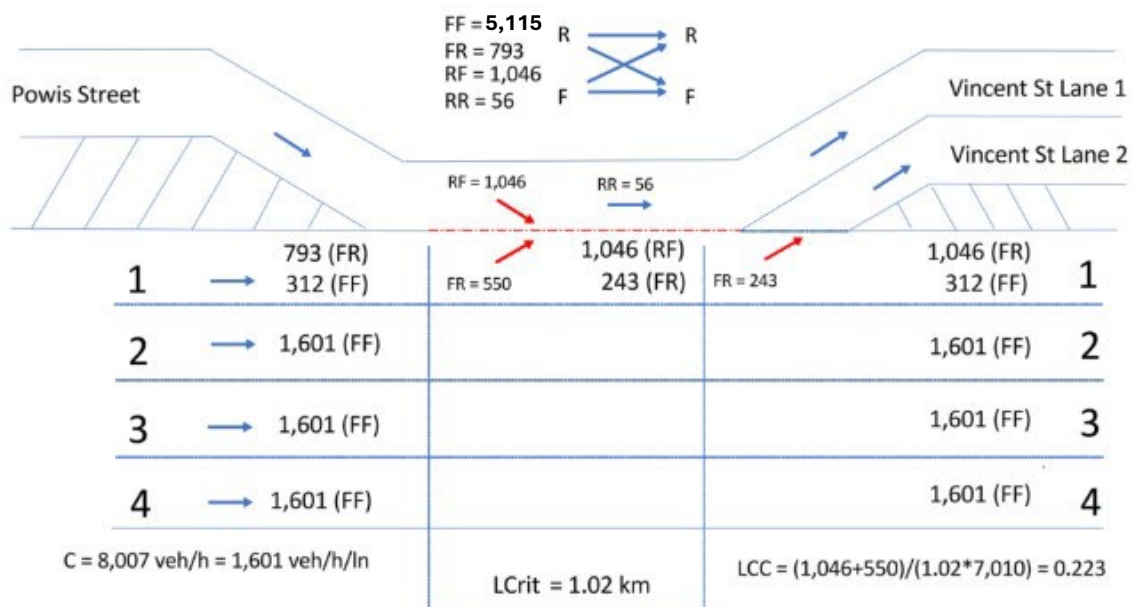
The OD movement volumes (FF, FR, RF and RR) included in the below figures are based on saturated conditions, i.e. the total volume is equivalent to the carriageway MSFR values, usually for the weaving area but sometimes also for the downstream or upstream section so that none of the MSFR values are exceeded. The OD percentages per movement have been derived from the traffic measurements undertaken for this study. This also applies to the lane split for 2-lane entry and exit ramps.

Figure F.1: Mitchell Freeway NB between Reid Highway and Warwick Road (FR split from ANPR measurement)



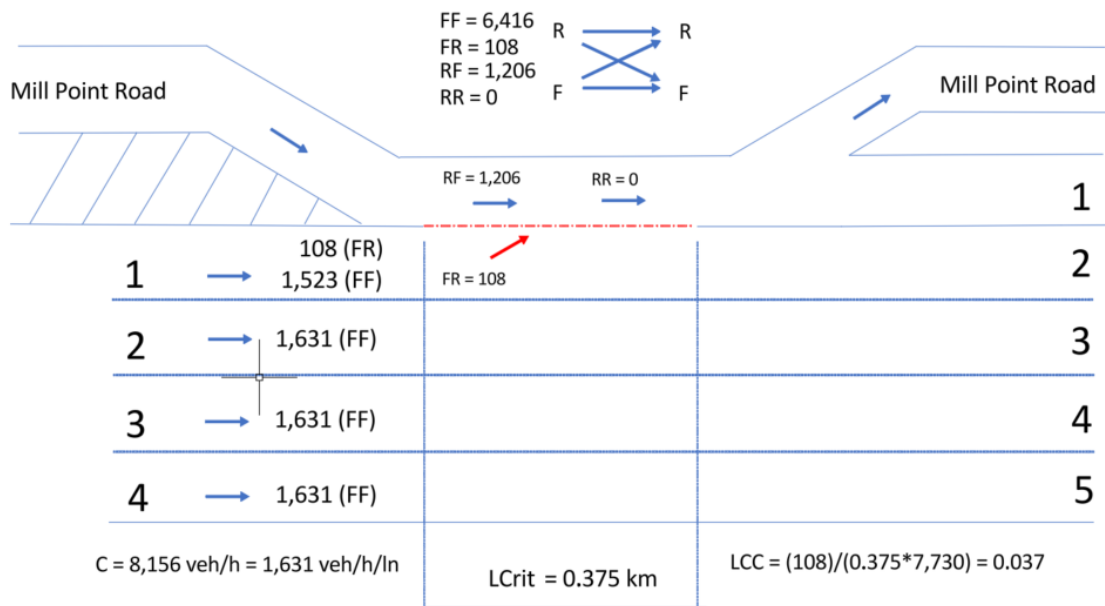
Note: Total weaving area volume adjusted to avoid downstream mainline carriageway capacity exceedance (no impact on the LCC result).

Figure F.2: Mitchell Freeway SB between Powis Street and Vincent Street (FR split from ANPR measurement)



Note: Total weaving area volume adjusted to avoid downstream mainline carriageway capacity exceedance (no impact on the LCC result).

Figure F.3: Kwinana Freeway NB between Mill Point Road and Mill Point Road Street



Note: Total weaving area volume adjusted to avoid upstream mainline carriageway capacity exceedance (no impact on the LCC result).

Figure F.4: Monash Freeway OB between Eastlink and Stud Road

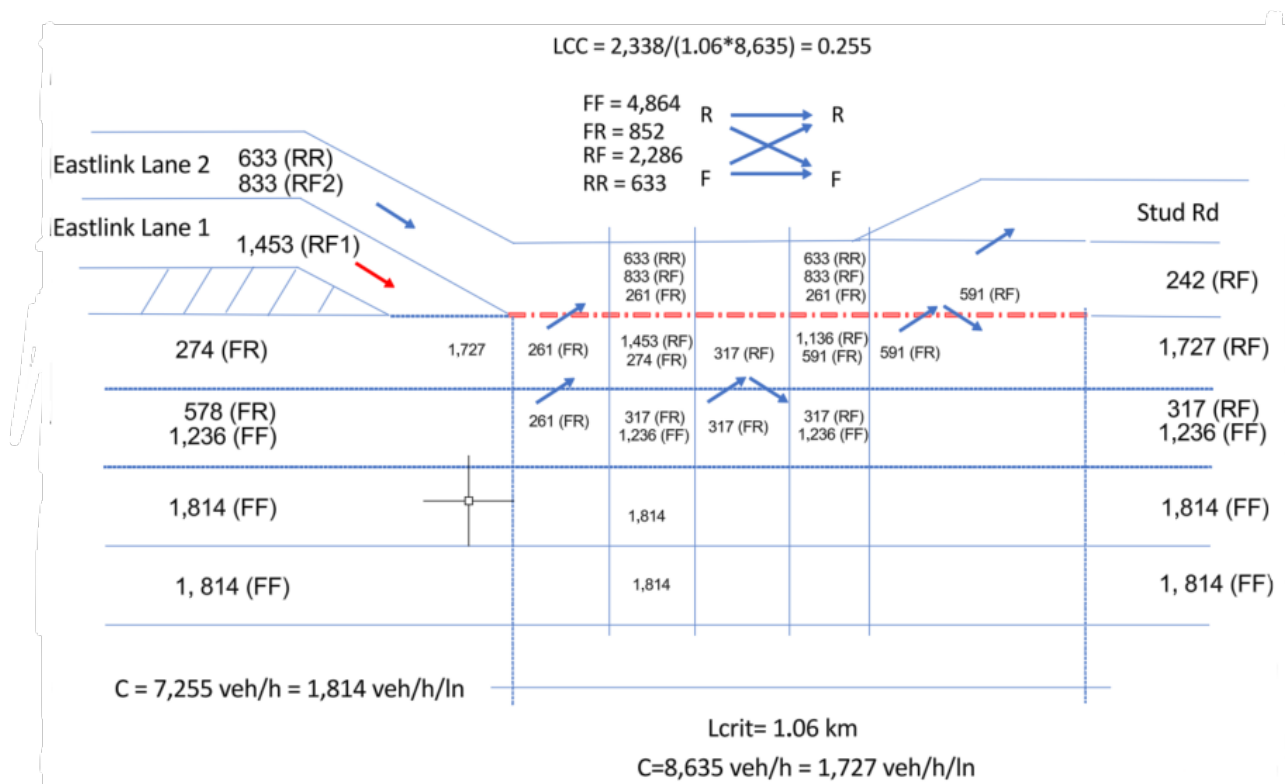


Figure F.5: Monash Freeway IB between Stud Road and Eastlink

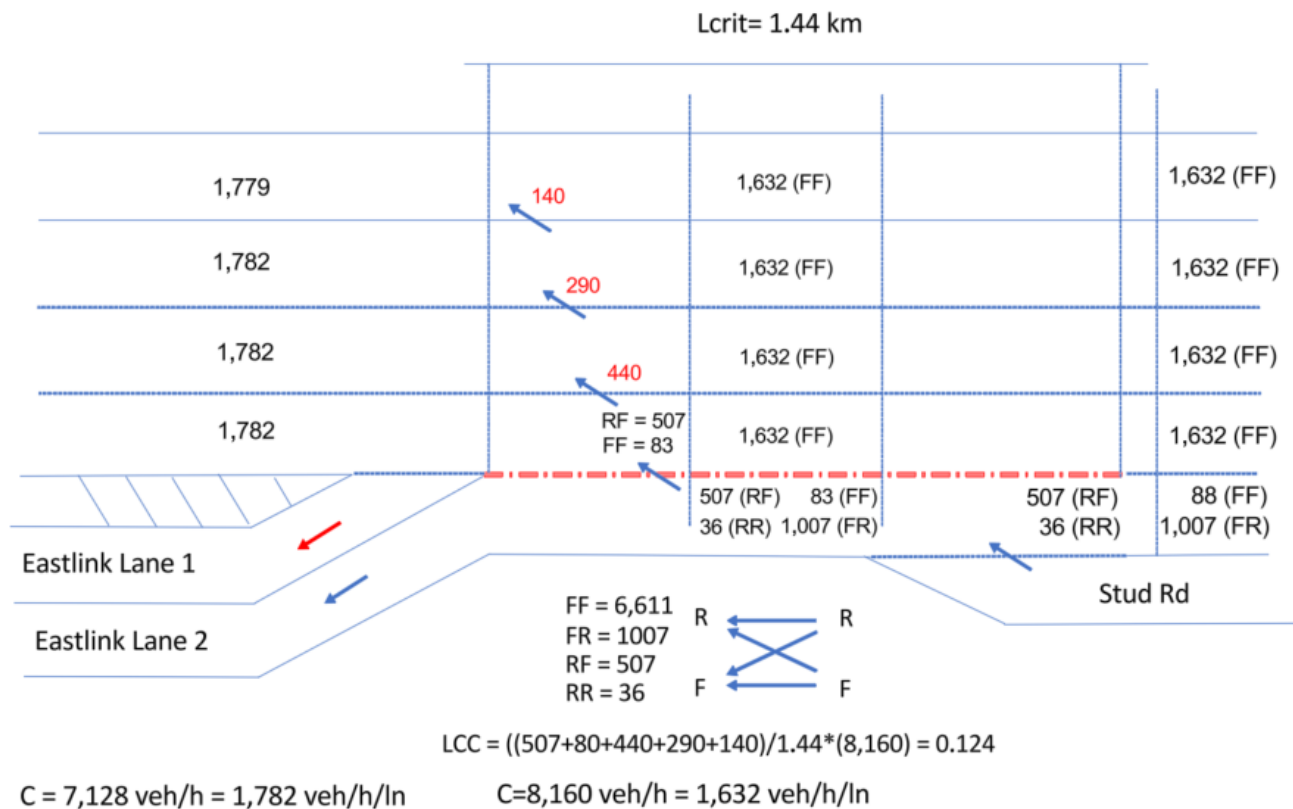


Figure F.6: Monash Freeway OB between Heatherton Road and South Gippsland Freeway

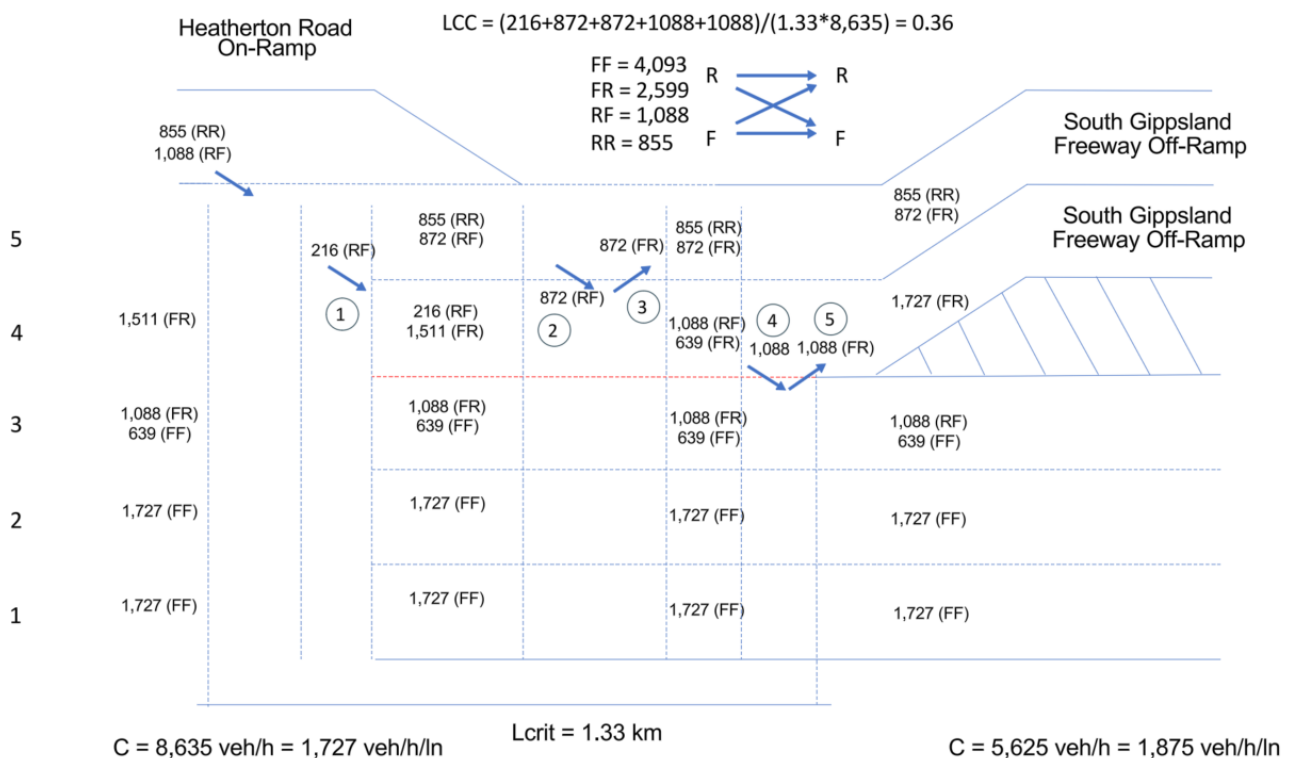


Figure F.7: Monash Freeway IB between South Gippsland Freeway and Heatherton Road

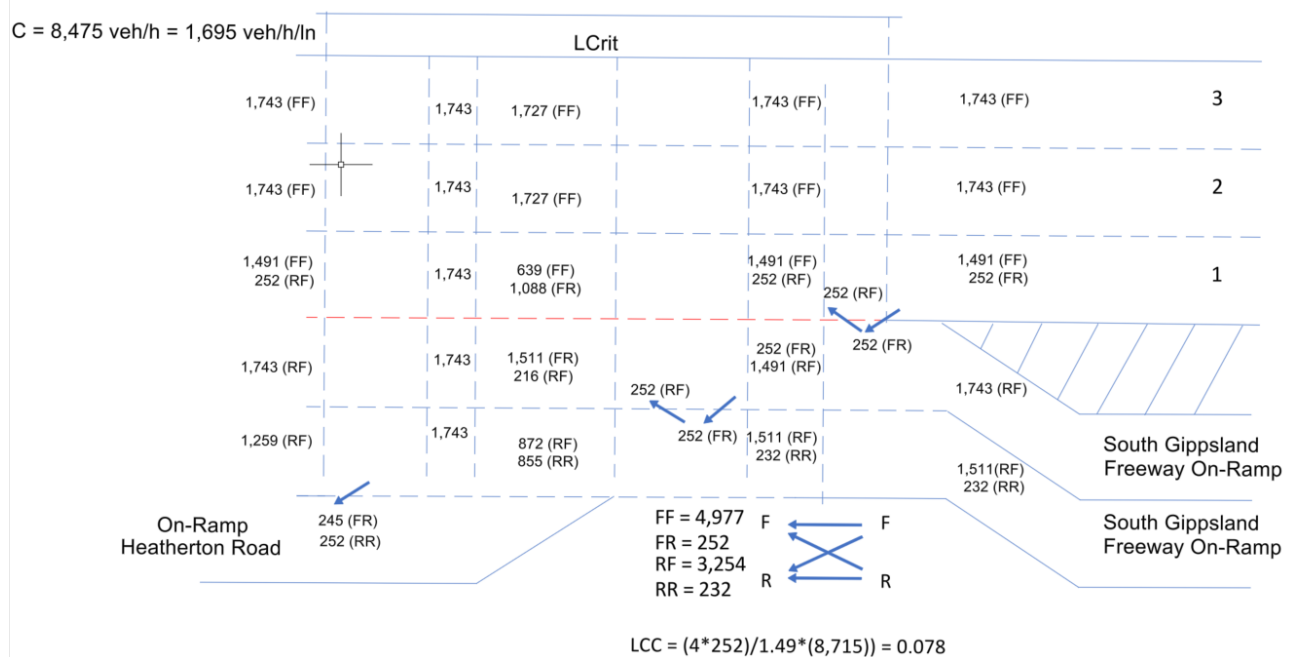


Figure F.8: Princes Freeway East OB between Princes Highway and Clyde Road (new configuration)

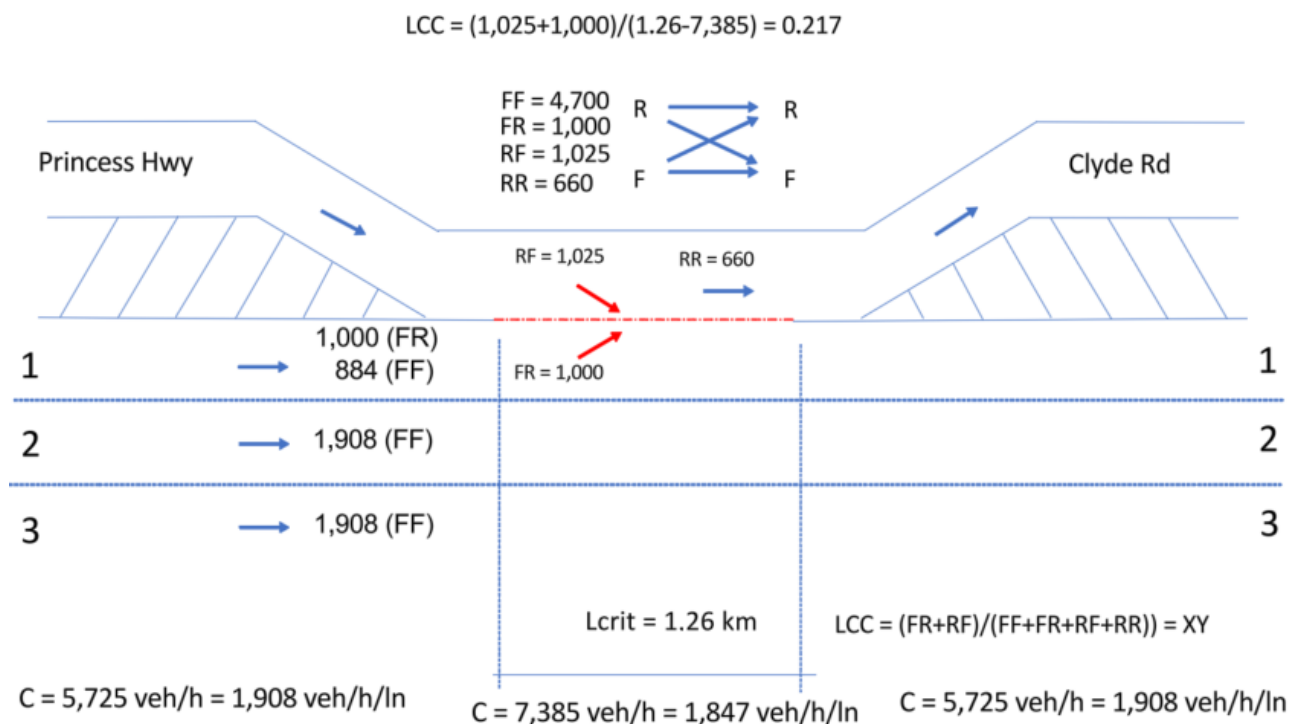
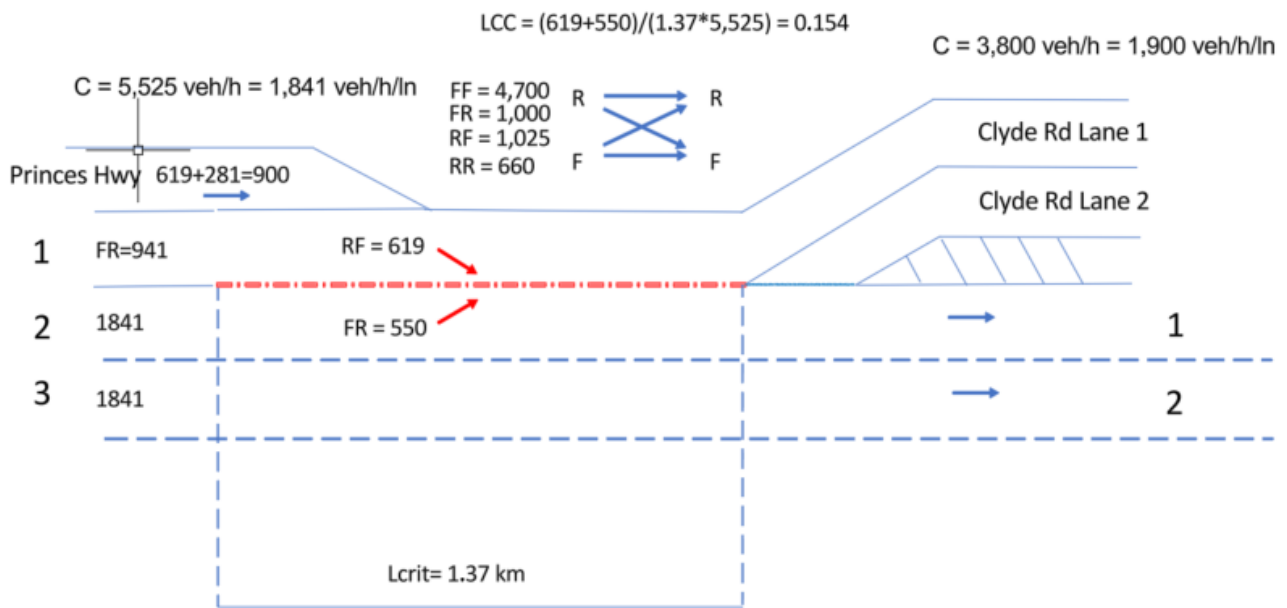


Figure F.9: Princes Freeway East OB between Princes Highway and Clyde Road (old configuration including corresponding traffic volumes as included in Zurlinden et al. 2021)



Note: The exit-ramp configuration was corrected compared to the original 2021 TRB Contribution drawings (based on Vic DTP feedback and Google Maps verification)

Figure F.10: Princes Freeway East IB between Clyde Road and Princes Highway (new configuration)

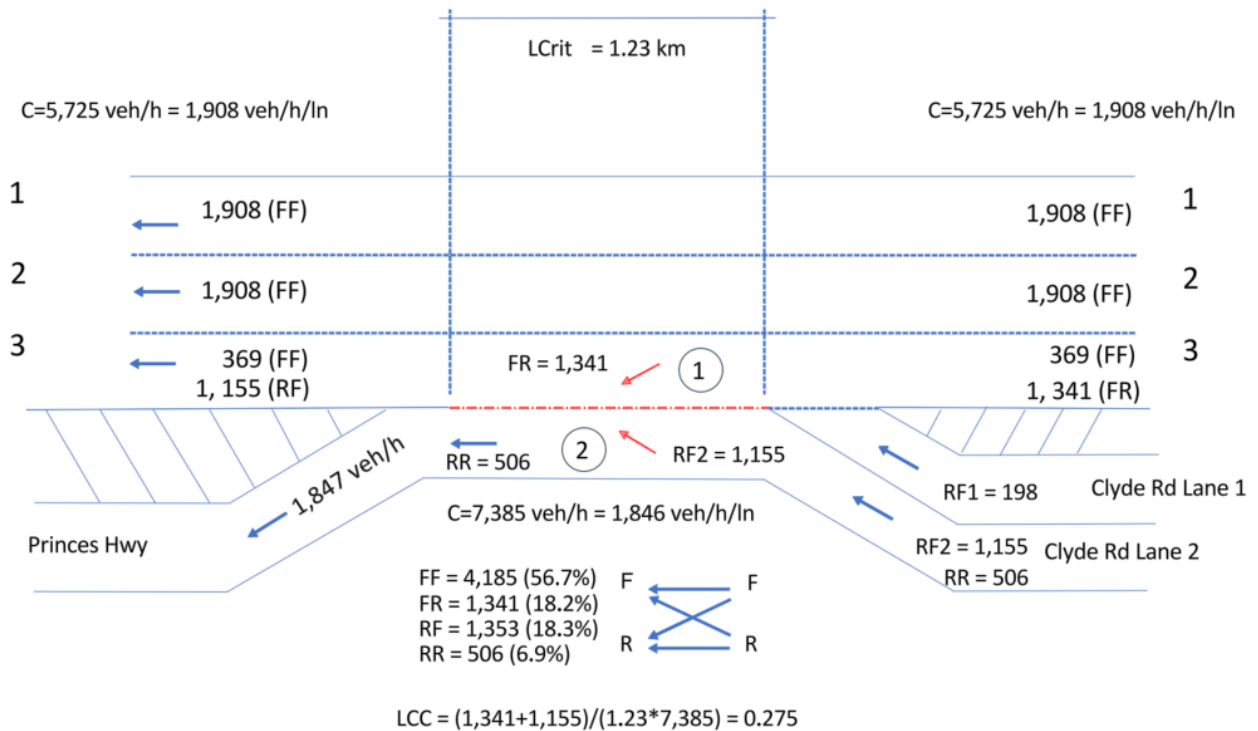


Figure F.11: Princes Freeway East IB between Clyde Road and Princes Highway (old configuration including corresponding traffic volumes as included in Zurlinden et al. 2021)

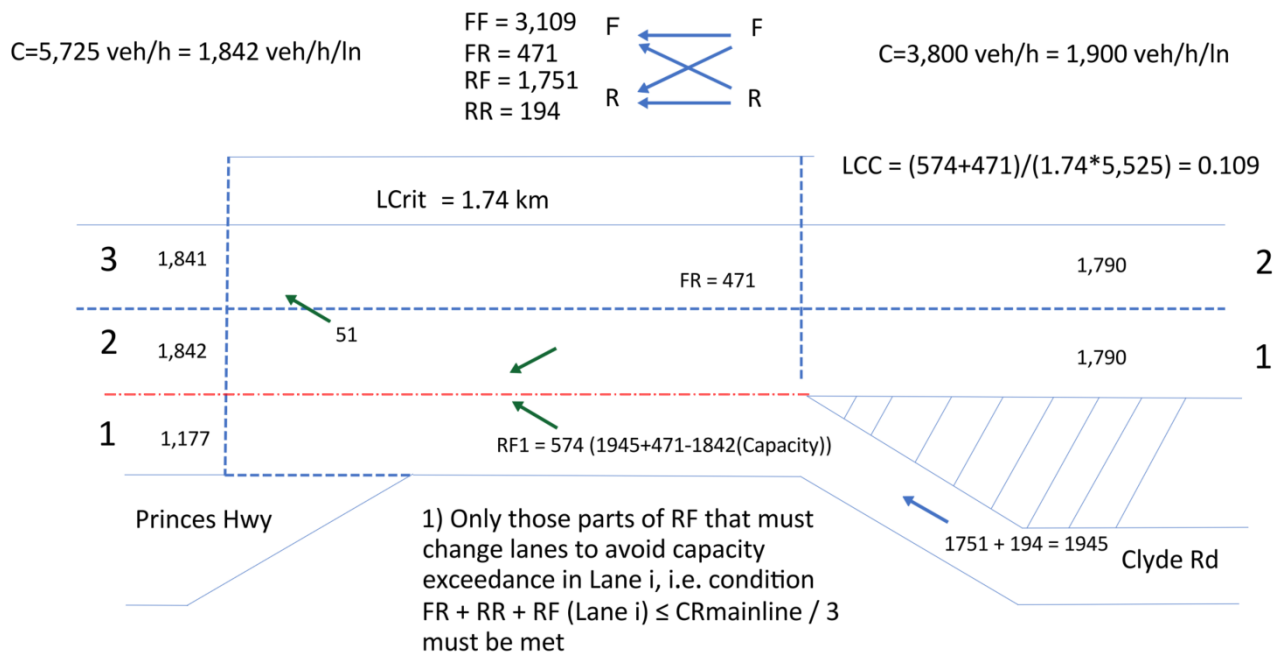


Figure F.12: Monash Freeway OB between Wellington Road and Eastlink

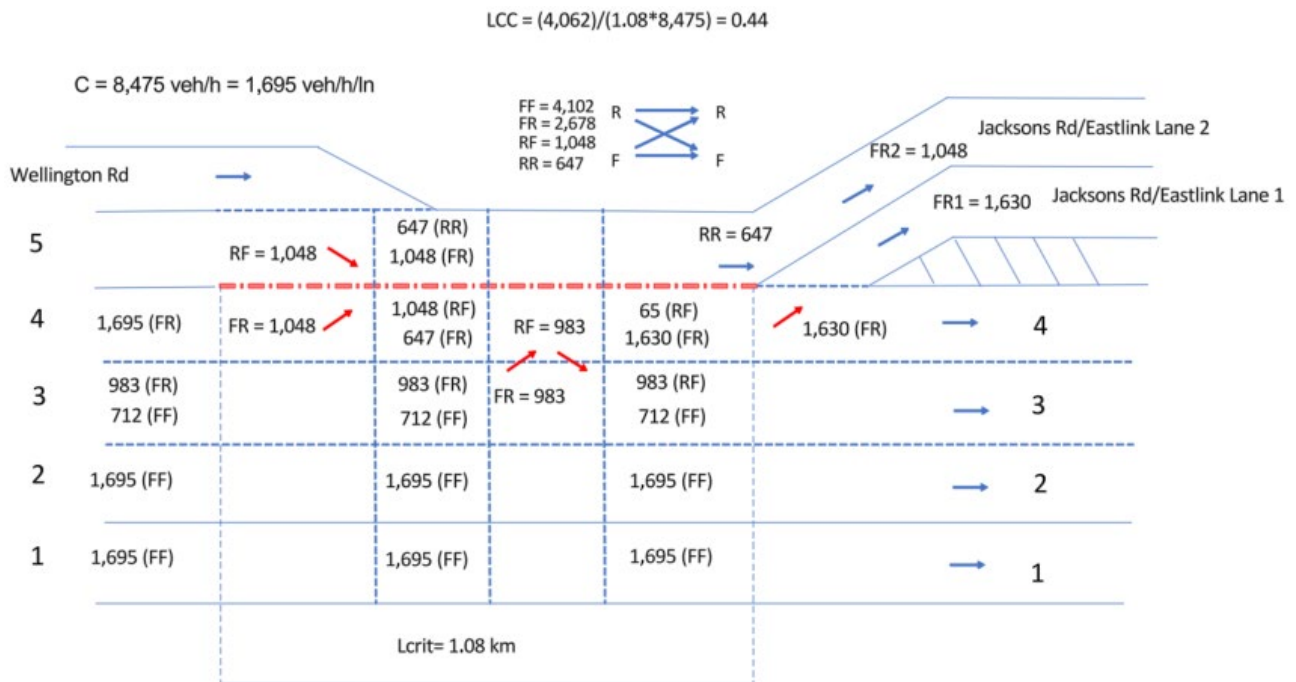


Figure F.13: Eastern Freeway OB between Tram Road/Station Street and Blackburn Road/Surrey Road (old configuration)

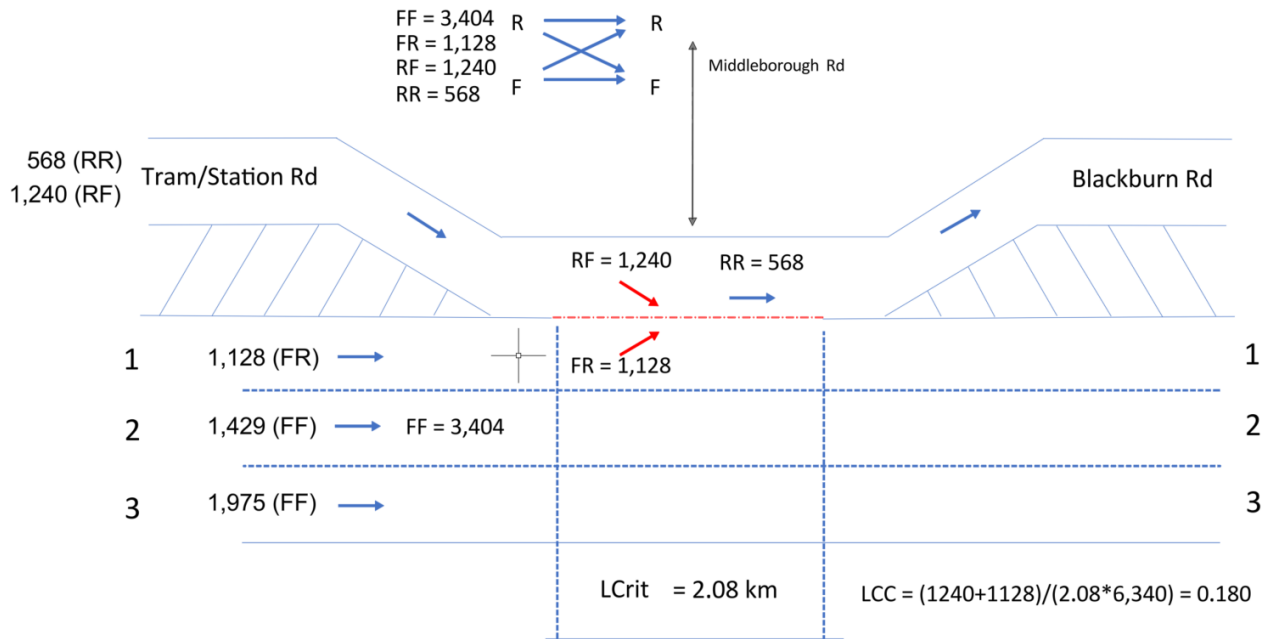
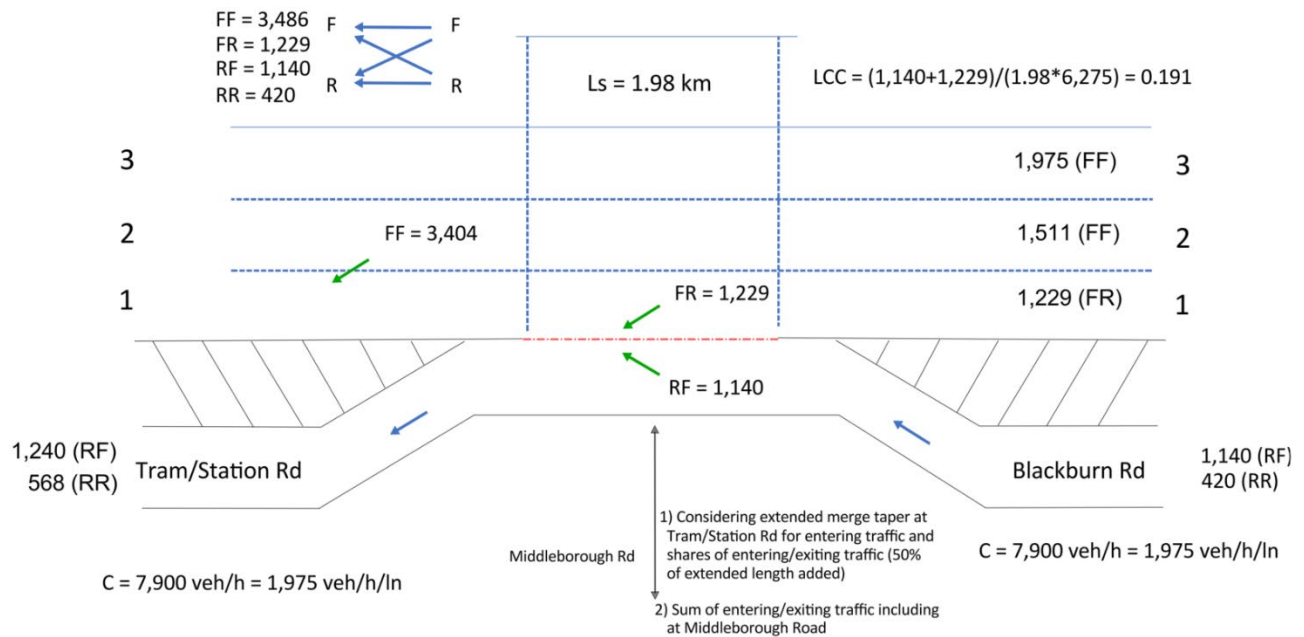


Figure F.14: Eastern Freeway IB between Blackburn Road/Surrey Road and Tram Road/Station Street (old configuration)



Appendix G ANPR Measurement results for the WA Weaving Areas

Figure G.1: ANPR LC measurement results for Mitchell Freeway NB between Reid Highway and Warwick Road

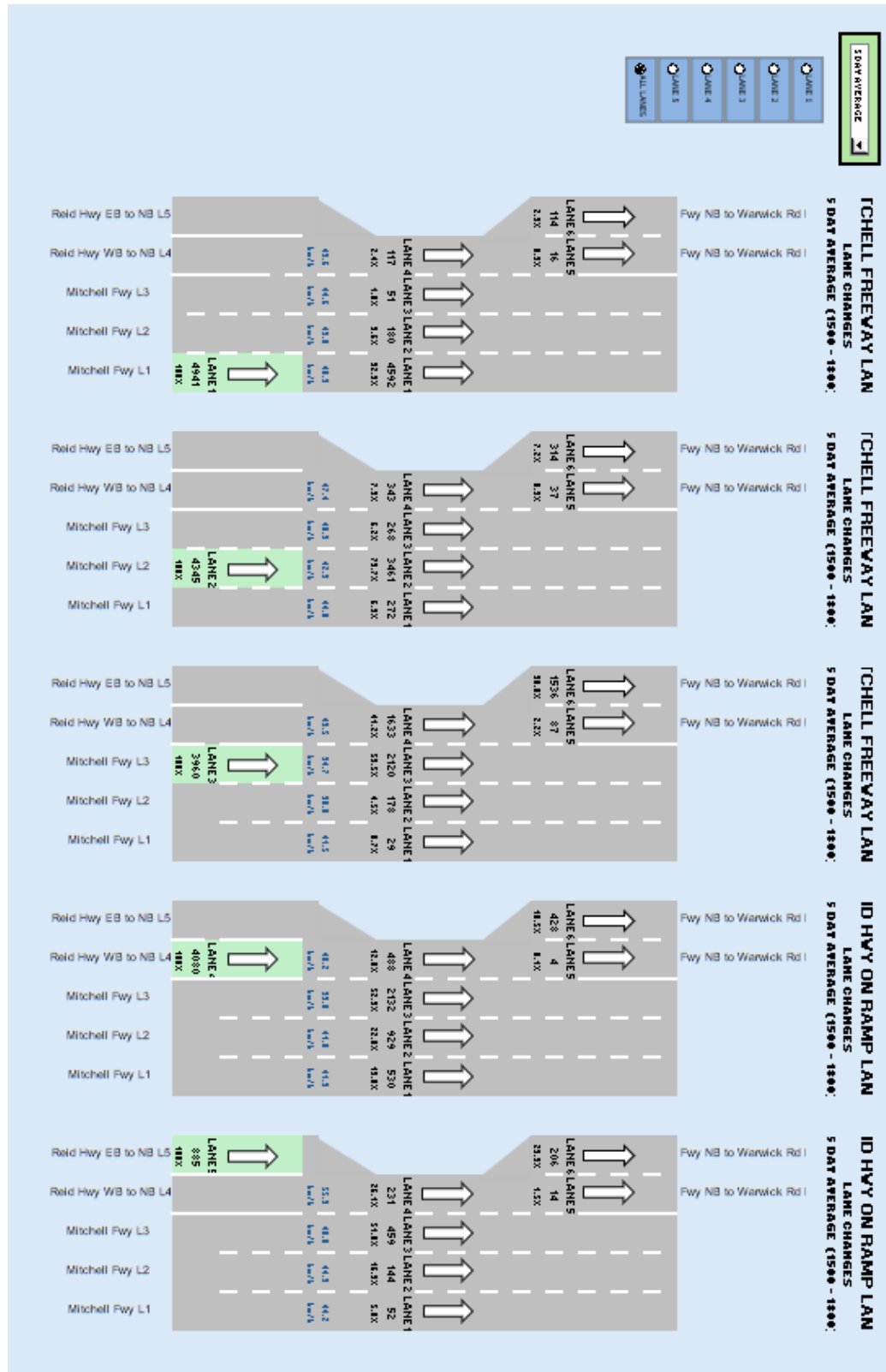
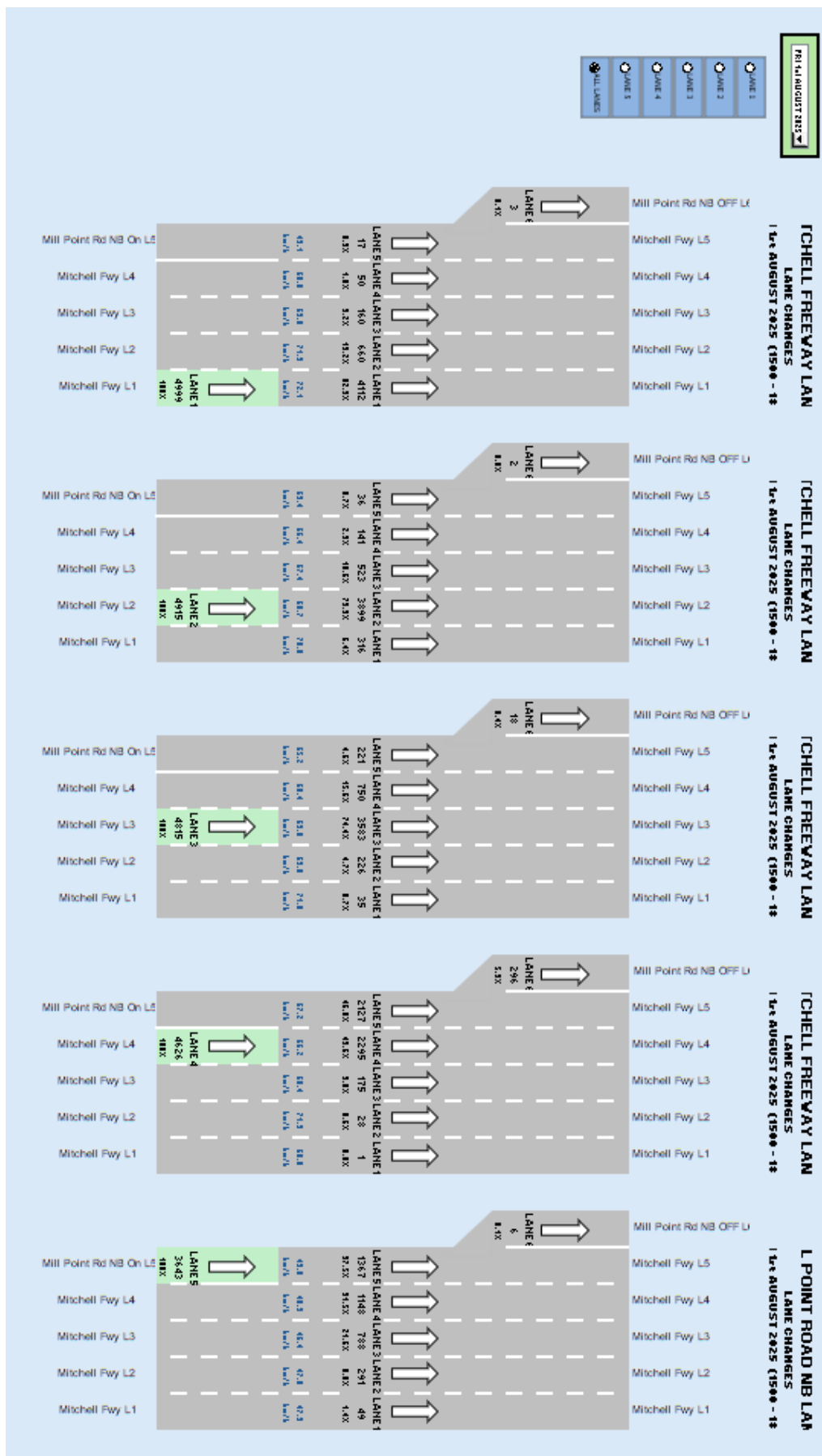


Figure G.3: ANPR LC measurement results for Kwinana Freeway NB between Mill Point Road entry ramp and Mill Point Road exit ramp (note that mainline lanes were incorrectly labelled)



Appendix H FBR Curves for Weaving Areas

The curve fit was optimised for an FBR of up to 15% per 15-minute interval since this is the area of most interest for freeway facility planning and design.

Figure H.1: Flow Breakdown Risk Curve for Reid to Warwick

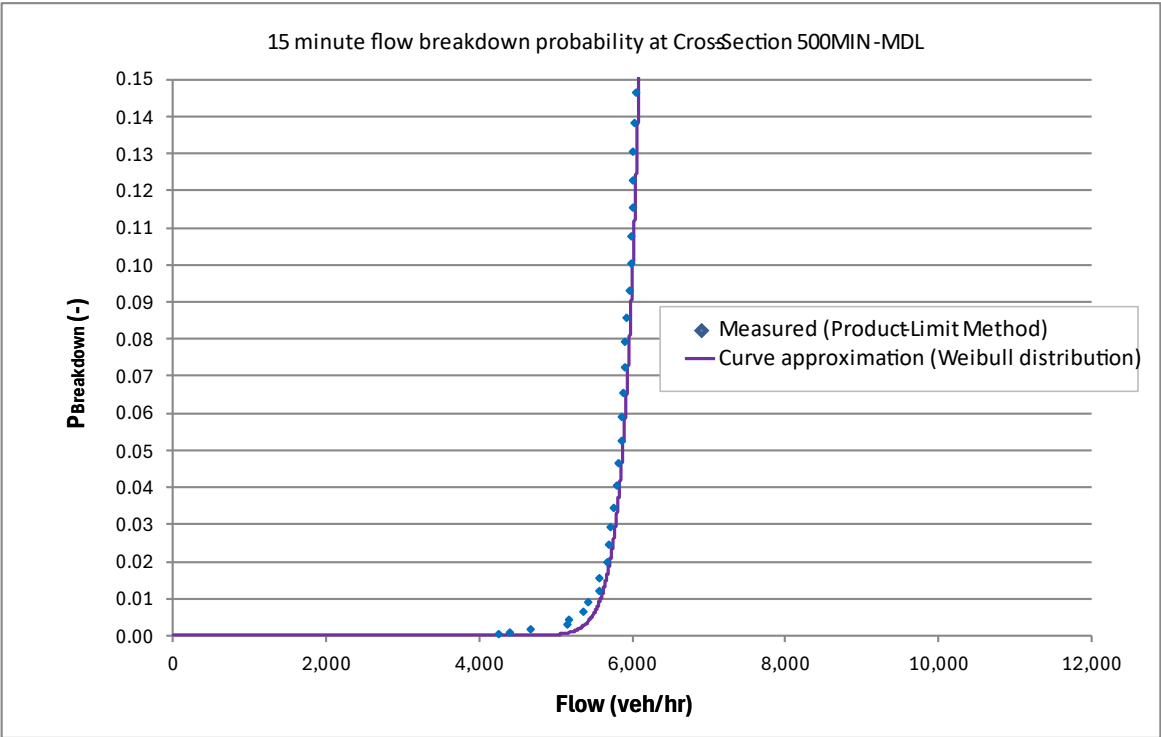


Figure H.2: Flow Breakdown Risk Curve for Powis to Vincent

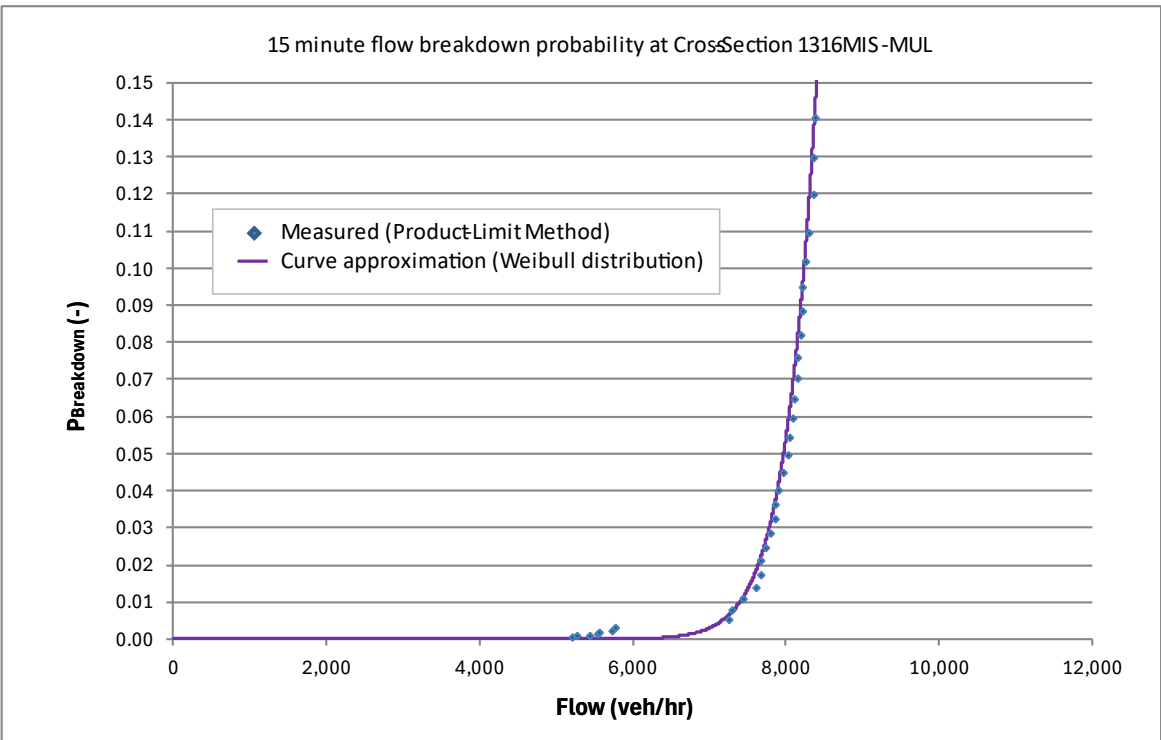


Figure H.3: Flow Breakdown Risk Curve for Mill to Mill

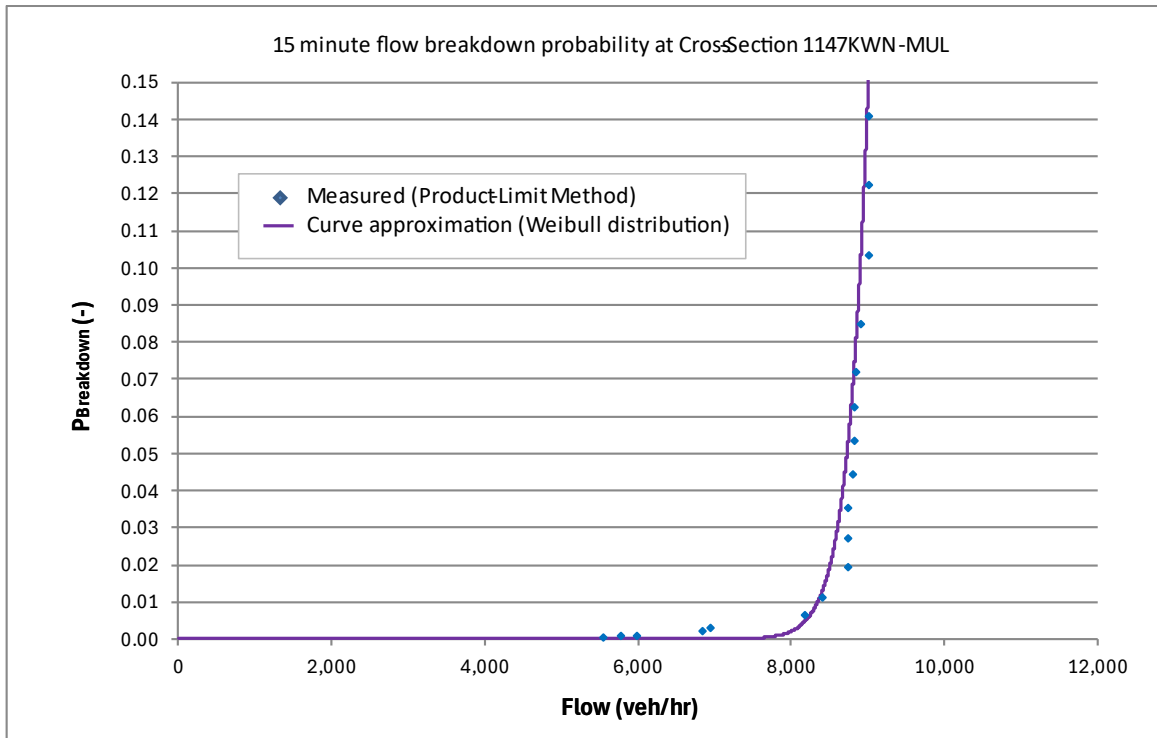


Figure H.4: FBR curve for Eastlink to Stud

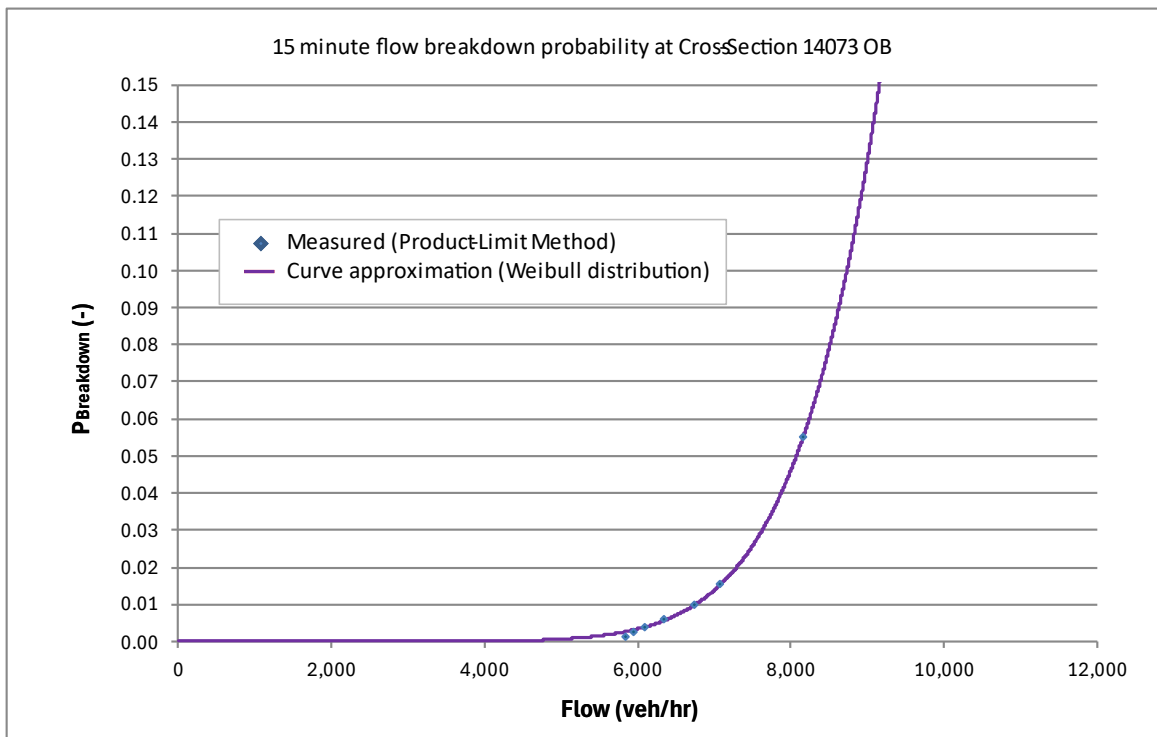


Figure H.5: FBR curve for Stud to Eastlink

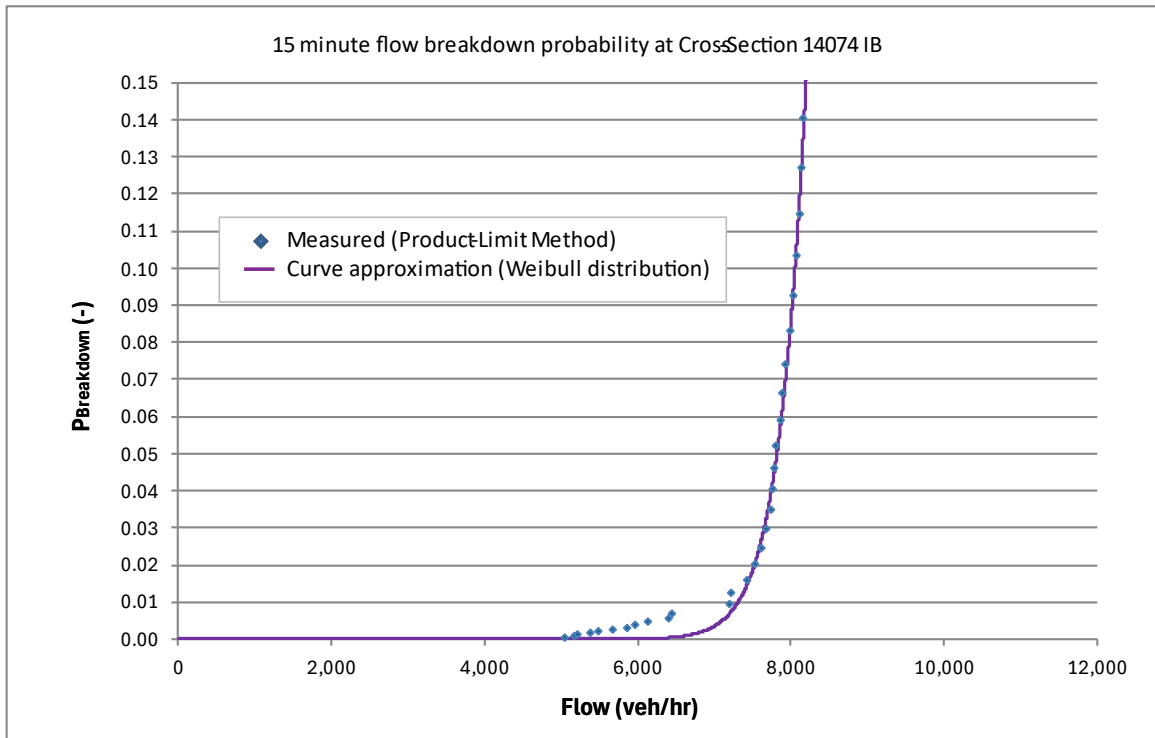


Figure H.6: FBR Curve for Heatherton to South Gippsland Freeway

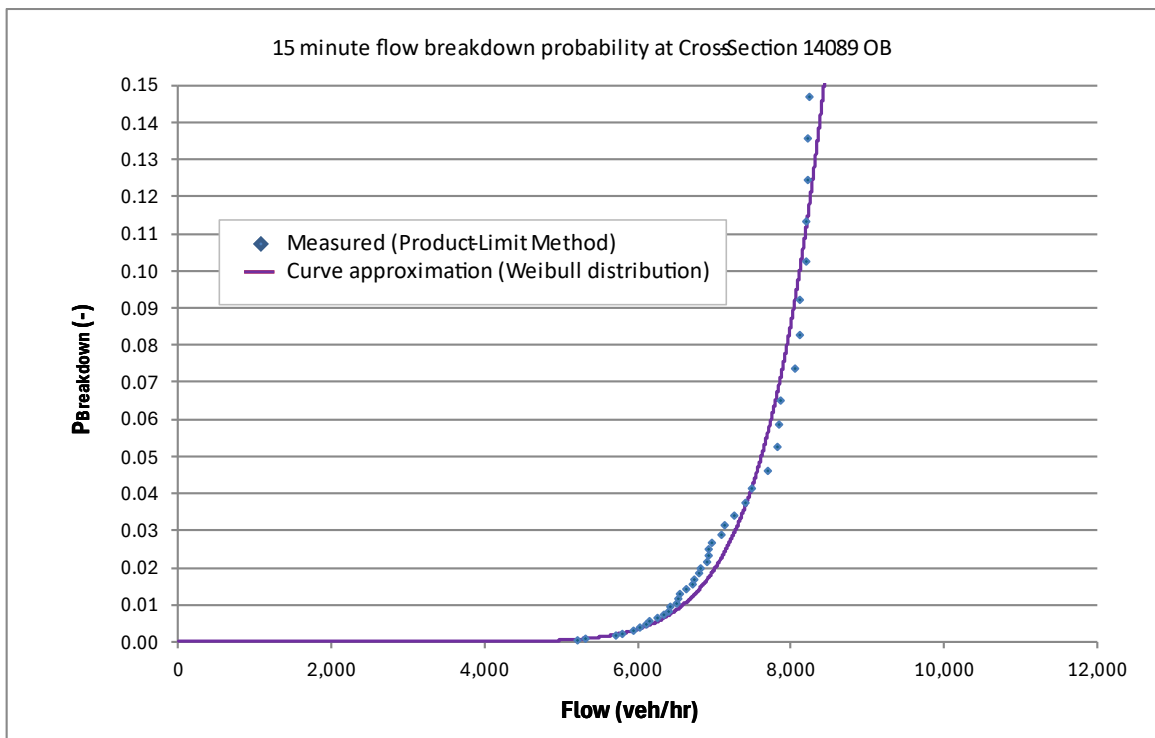


Figure H.7: FBR curve for South Gippsland Freeway to Heatherton Road

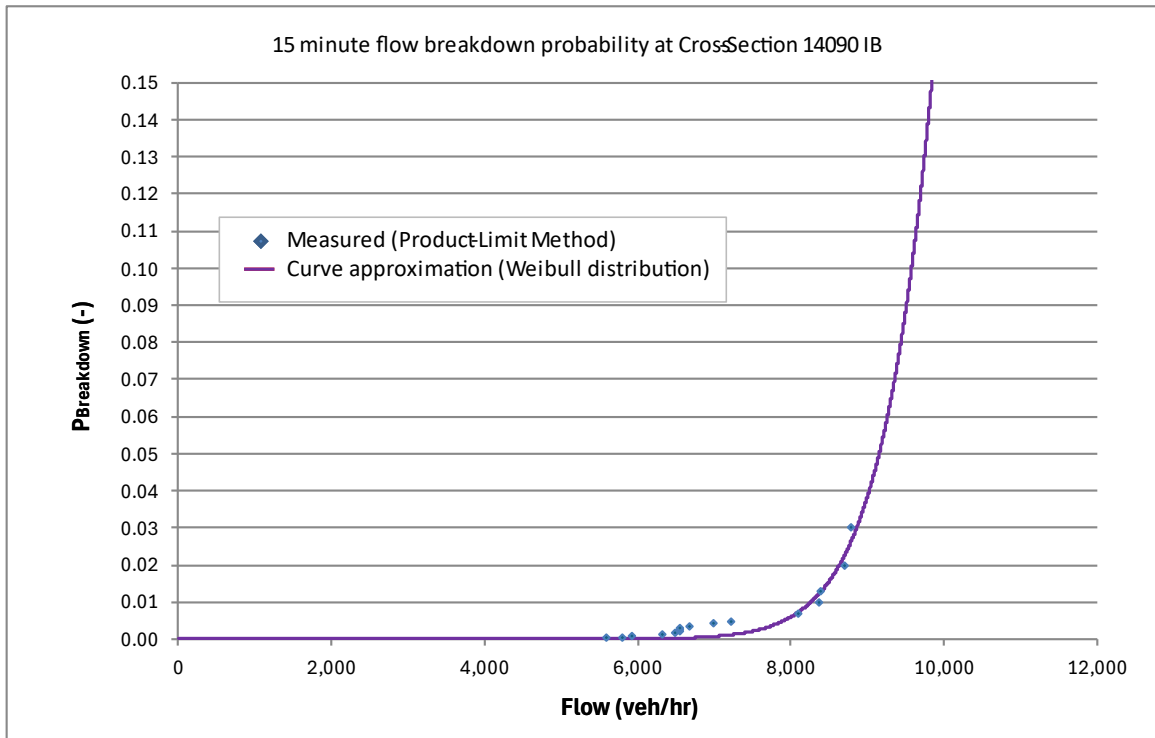


Figure H.8: FBR curve for Princes Highway to Clyde Road (new configuration)

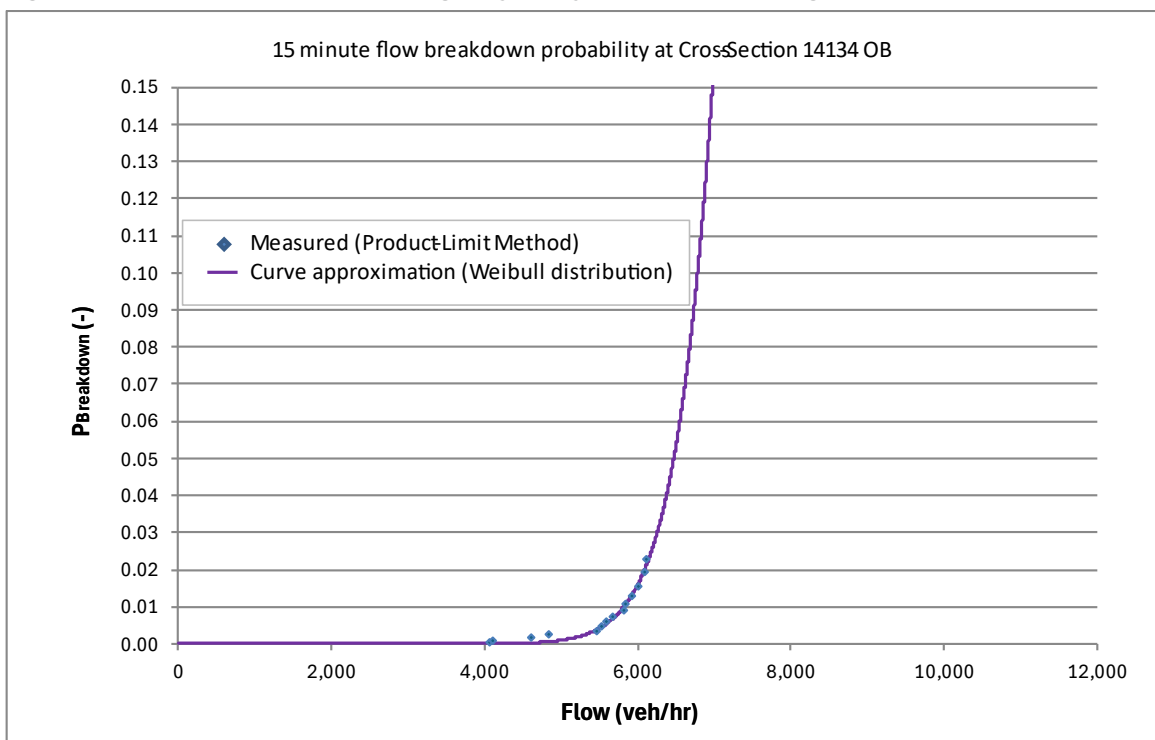


Figure H.9: FBR curve for Clyde Road to Princes Highway (new configuration)

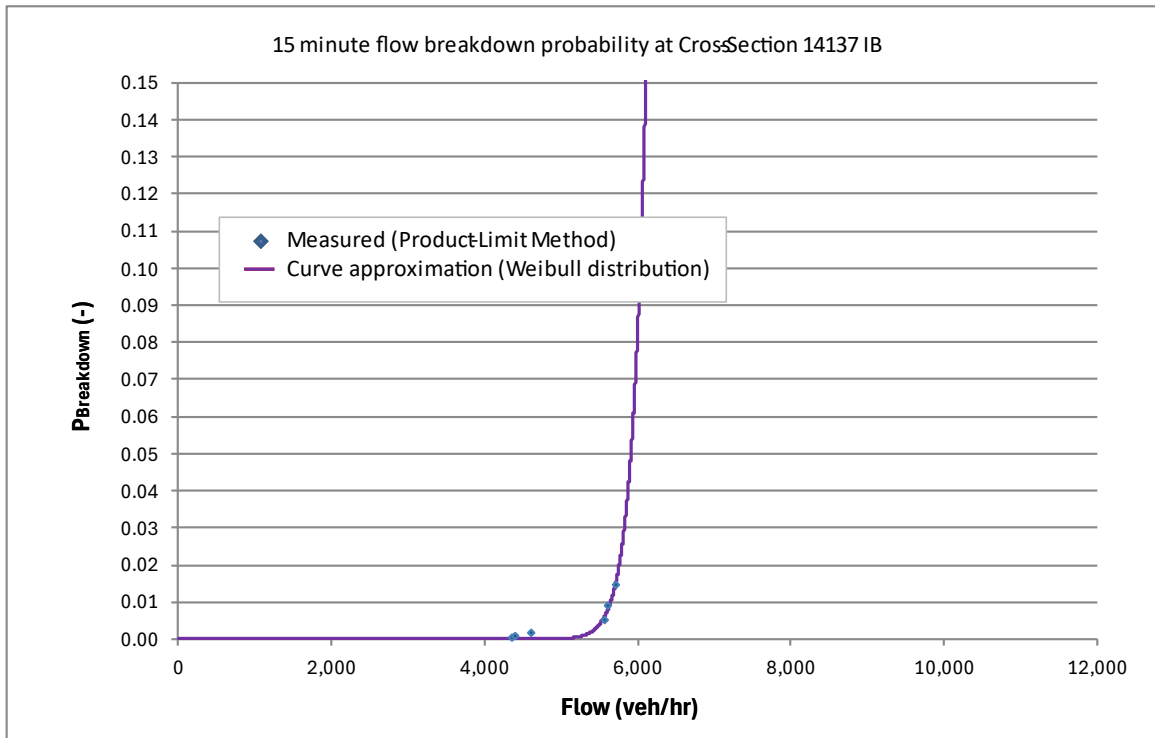
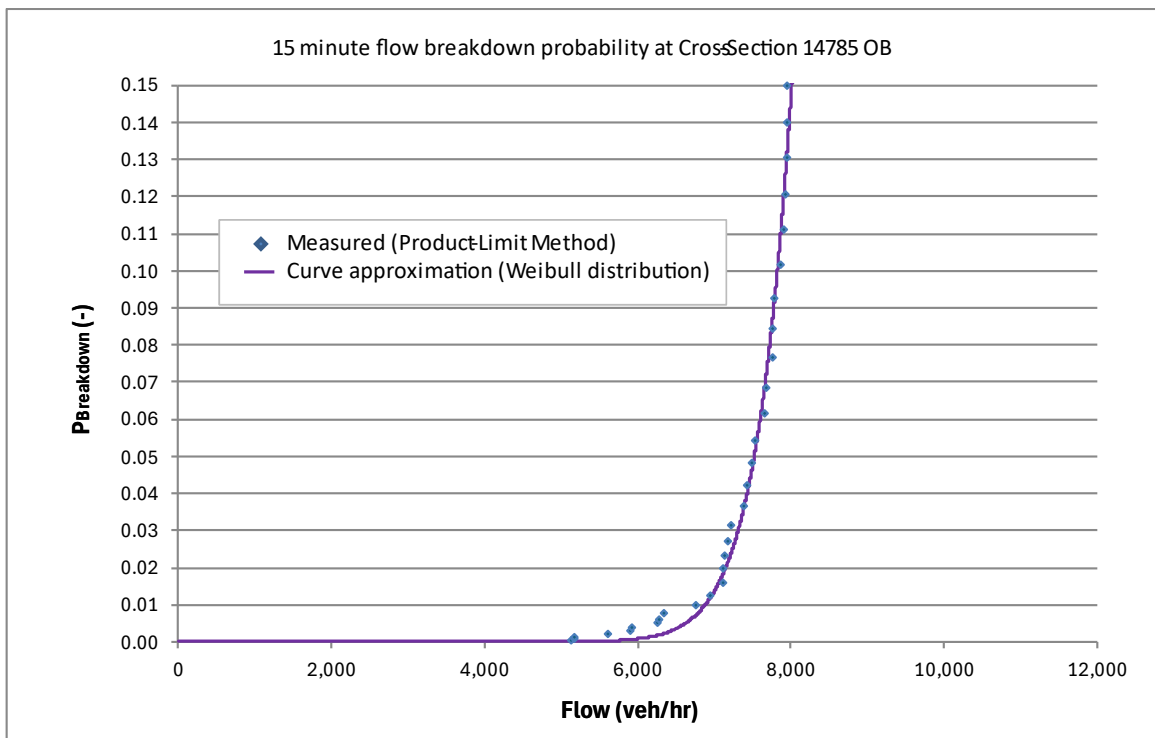


Figure H.10: FBR curve for Wellington Road to Eastlink





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