

Managed Motorway Design Guide

Volume 2: Design Practice

Part 2: Managed Motorway – Network Optimisation Tools



Managed Motorway Design Guide

Volume 2: Design Practice

Part 2: Managed Motorway – Network Optimisation Tools



Volume 1 - Managed Motorways - Role, Traffic Theory and Science

- Part 1 - Introduction to Managing Urban Motorways
- Part 2 - Traffic Theory Relating to Urban Motorways
- Part 3 - Motorway Capacity Guide
- Part 4 - Road Safety on Urban Motorways
- Part 5 - Linking Investment and Benefits Approach



Volume 2 - Managed Motorways Design Practice

- Part 1 - Managed Motorway - Design Principles and Warrants
- **Part 2 - Managed Motorway - Network Optimisation Tools**
- Part 3 - Motorway Planning and Design
- Part 4 - LUMS, VSL, Traveler Information (Update Under Development)

Volume 2: Design Practice

Part 2: Managed Motorway – Network Optimisation Tools

Published by:

VicRoads
60 Denmark Street
Kew VIC 3101

Authors:

John Gaffney (VicRoads)
Maurice Burley (Consultant)
Matthew Hall (VicRoads)

The significant contributions and reviews by Richard Fanning, Jessica Franklin and Dr. Hendrik Zurlinden, in VicRoads are also acknowledged.

VicRoads acknowledges the partnership and contributions of:

- TRANSMAX as the owner and developer of the VicRoads Motorway Management system (STREAMS).
- Prof. Markos Papageorgiou and Prof. Ioannis Papamichail from the Technical University of Crete in the development of the HERO-LIVE coordinated ramp metering system used to manage Melbourne's motorways.

Keywords:

Managed Freeways, Managed Motorways, Traffic Management, Incident Management, Ramp Metering, Coordinated Ramp Metering, Capacity, Highway Capacity, Design Volumes, Ramp Design, Mainline Design, Freeway Operation, Ramp Metering Operation, Ramp Metering Control, HERO-LIVE, Ramp Metering Algorithms, Congestion Management, Freeway Bottlenecks, Traffic Theory, Optimisation, Freeway Safety, Motorway Safety.

Amendment Record

Ed/Rev No	Page(s)	Issue Date	Amendment Description
Ed 1	All	June 2019	First Edition
Ed 1, Rev 1	3	October 2019	Minor editorial changes

© VicRoads October 2019

Electronic copies of the Guide and Standard Drawings are available on the VicRoads Website:
<https://www.vicroads.vic.gov.au/business-and-industry/technical-publications/traffic-engineering>

Enquiries or comments relating to the Guide may be directed to:

VicRoads
60 Denmark Street
Kew VIC 3101

<http://www.vicroads.vic.gov.au/Home/AboutVicRoads/ContactUs/FeedbackAndEnquiries.htm>

Table of Contents

List of Figures	9
List of Tables	10
1 Network Optimisation Control Tools	11
1.1 Overview	11
1.2 Past Experience in Melbourne	11
1.3 Overview of Managed Motorway Tools	12
2 Ramp Metering as a Network Optimisation Tool	15
2.1 Principles of Motorway Traffic Flow	15
2.2 Ramp Metering – An Overview	15
2.3 Principal Aims of Motorway Ramp Metering	16
2.4 Context and Effectiveness	19
2.5 Ramp Metering as a Management Tool	20
3 Ramp Metering Control	21
3.1 Independent Control	21
3.2 Dynamic Coordinated (Route-Based) Control	22
3.3 Managing Ramp Demands	24
3.4 Control Strategies and Algorithms	25
3.5 Why Occupancy is Used to Manage Motorway Flow	26
3.6 Managing Heavy Congestion and Incidents	26
3.7 Management of Entry Flows to Assist in Flow Recovery	28
3.8 Closing Entry Ramps and/or the Motorway.	28
3.9 Traffic Diversion by Providing Traveller Information	28
3.10 When Ramp Metering has Limited Effectiveness	28
4 The Operation of Ramp Meters	31
4.1 Legal Basis for Ramp Meters	31
4.2 Control Algorithms Used by VicRoads	31
4.3 Ramp Meter Operational Modes	35
4.4 Switching on /off Signs and Signals	37
4.5 Operating Sequence and Cycle Times (not used for design)	41
5 Ramp Signals Integration with other Managed Motorway Operations	45
5.1 Ramp Signals Response to a Lane Closure	45
5.2 Ramp Signals Response to Changing Speed Limits	45
5.3 Ramp Signals Response to a Freeway Closure	45
5.4 Emergency Vehicle Access when Ramp Signals are Operating	46
6 Benefits of Ramp Metering	47
6.1 Qualitative Benefits	47

6.2	Quantitative Benefits for the Motorway – Monash Freeway Example	47
7	Exit Ramp Management System	51
7.1	Managing traffic leaving the motorway	51
8	Interface at Surface Road Interchanges	53
8.1	Interchanges	53
8.2	Entry Ramps	53
8.3	Exit Ramps	54
9	Ramp Metering Myths and Misunderstandings	55
9.1	Introduction	55
Appendix A		59
	Ramp Metering - Information Bulletin	59
Appendix B		63
	A Short History of Ramp Metering	63
	Ramp Metering in Melbourne	64
Appendix C		68
	Paper presented at the Fifth Australian Computer Conference, Brisbane, May 1972.	68
Works Cited		73

List of Figures

Figure 2-1: Motorway Ramp Metering	16
Figure 2-2: Driver’s perception of localised ramp metering operation	17
Figure 2-3: City-wide System’s understanding of ramp metering operational needs	18
Figure 2-4: Example of Fundamental Diagrams at a Bottleneck Managed with Ramp Metering.....	19
Figure 2-5: Example of Unmanaged and Managed Motorway Flows.....	20
Figure 3-1: Metering Traffic Flow at a Bottleneck	21
Figure 3-2: Metering Traffic with Coordinated Control.....	23
Figure 3-3: Fundamental Diagram Indicating the Importance of Metering Rate.....	25
Figure 3-4: Fundamental Diagram Indicating Critical Occupancy for Ramp Metering	26
Figure 3-5: Incident Clearance without an Incident Management System	27
Figure 3-6: Incident Clearance with an Incident Management System	28
Figure 3-7: Motorway Congestion at a Terminating Motorway	29
Figure 3-8: Congestion at Terminating Motorway showing other unrelated flow breakdown that would benefit from motorway management	30
Figure 3-9: Motorway Congestion from an Exit Ramp.....	30
Figure 4-1: HERO-LIVE Coordinated Ramp Control Structure.....	33
Figure 4-2: Start-up Control Sequence – Typical Ramp Meter.....	38
Figure 4-3: Ramp Meters Start-Up Control Sequence – Motorway to Motorway Ramp Meter	39
Figure 4-4: Close-down Control Sequence - Typical Ramp Meter	40
Figure 4-5: Close-down Control Sequence – Motorway to Motorway Ramp Meter	41
Figure 6-1: Monash Freeway Summary of Increases in Volumes and Speed	48
Figure 6-2: Monash Freeway Crash History: Before and After Upgrade.....	49
Figure 6-3: Crash Rates on Melbourne’s Urban Motorway Network.....	49
Figure B-1: Freeway Speed - Eastern Freeway Outbound, East of Bulleen Rd.....	65
Figure B-2: Travel Time - Eastern Freeway Outbound, Bulleen Rd to Doncaster Rd.....	65
Figure B-3: Fixed Time Ramp Meters - Typical Speed Surface Contour Plot in the AM Peak	66
Figure B-4: Motorway Ramp Meters - Typical Speed Surface Contour Plot in the AM Peak.....	67
Figure B-5: ‘Before and after’ Austroads National Performance Indicators.....	67

List of Tables

Table 1.1: The Managed Motorways Toolkit	12
Table 4.1: Equivalent Hourly Ramp Flows relative to Cycle Time and Lanes at the Stop Line for operations	43
Table 9.1: Common Misunderstandings and Clarifications	58

1 Network Optimisation Control Tools

1.1 Overview

This Guide covers the control tools associated with Network Optimisation Control which at the time of release primarily covers City Wide Coordinated Ramp Metering (CWCRM) (refer Sections 2 - 5), and the recently developed Exit Ramp Management System (refer Section 7). With these tools the current Managed Motorway “network optimisation” tool kit now enables partial integration with the VicRoads arterial road traffic signal system (SCATS) at both the entry and exit of the motorway. The primary function of Network Optimisation control tools are to ensure the motorway asset is optimised at all times and under all conditions and, put simply, involves getting the traffic on, through and off the motorway smoothly and efficiently.

As discussed in Volume 1, Part 2: Section 4.3, work is well advanced on developing the full integration of Dynamic Variable Speed Limits (DVSL) with CWCRM which will inform future editions of this Guide. As discussed in detail in Volume 1, Part 2 Variable Speed Limits (VSL) or DVSL, while offering support as an “intervention control” tool discussed below, will offer limited benefit as an independent (operating on its own) tool for optimising and sustaining motorway flow. This is particularly the case in Australia where default speed limits on urban motorways are typically 100km/h supported by high levels of enforcement with low tolerance for non-compliance, and to a large degree effective speed homogenisation is already achieved. This compares to many overseas jurisdictions where speed limits may be set higher (e.g. 120km/h) and speed enforcement is limited with more broader tolerance ranges for non-compliance. As a result there is increased benefit from some level of speed homogenisation through speed limit control as traffic volumes rise above certain thresholds.

1.2 Past Experience in Melbourne

In 2002 VicRoads commenced the installation of ramp metering at motorway interchanges to reduce motorway traffic congestion and to improve merging. The entry ramp metering operated in an isolated manner with fixed time cycles to manage the rate at which vehicles could join the motorway.

In 2008 the trial of dynamic coordinated ramp metering resulted in increased motorway performance and improved control to minimise flow breakdown. This was based on the effective management of inflows over a length of motorway to match the capacity of the mainline at each merge as well as at other critical bottlenecks.

With the hindsight of today’s knowledge and experience (i.e. 2019), these relatively simplistic beginnings were based on empirical evidence and have provided a solid foundation that has since lead to further advances in the design of motorways themselves to be productive by limiting unnecessary turbulence, as well as leading to major advances in the way motorway control systems are designed and operate. This has been made possible by a combination of hands-on operational experience and the detailed data analysis using statistical techniques as described in the comprehensive overview of contemporary traffic science in Volume 1, Part 2 and the Motorway Capacity Guide contained in Volume 1, Part 3.

Significant and essential advances in data quality and availability have also led to statistical analysis techniques that can indicate the development of precursor bottleneck conditions that need to be managed before instability and flow breakdown occur (refer Volume 1, Part 3). From experience with ramp metering in Melbourne, some ramp metering myths and misunderstandings are included in Section 9. A short history of ramp metering in the USA as well as its use in Melbourne is in Appendix B. Also general information relating to ‘Freeway Ramp Signals’ is provided in an information bulletin in Appendix A.

1.3 Overview of Managed Motorway Tools

The Managed Motorways toolkit discussed in Volume 2, Part 1 includes various technologies and control strategies for delivering different levels of active management. Further details on these tools are provided in (VicRoads, 2017) which provides an overview of the toolkit in its entirety, providing high-level functional and technical requirements for each tool, in line with the Systems Engineering methodology.

The individual tools available for use in the active management of motorways are listed in Table 1.1, including tools that are currently in operation, as well as tools that are in development or planned for development. Each Managed Motorway tool is part of a total control system (e.g. integrated tool chain) and for function can be divided into two primary categories being “Control Tools” and “Foundation Tools”.

Control Tools		Foundation Tools	
Network Optimisation Control	Intervention Control	Information	Intelligence
City Wide Coordinated ramp Metering (CWVRM) system	Lane use management system (LUMS) including variable speed limits (VSL)	Variable message signs (VMS)	Traffic detectors (primarily speed, volume and occupancy – SVO – data)
Dynamic variable speed limits (DVSL) ¹	Entry ramp management system	External information publication for third party use	CCTV
Arterial road interface system	Wide area network dispersion (WAND) ²		Automatic incident detection (AID) ¹
Arterial road management system ²	Motorway dynamic re-configuration (including entry and exit ramp mgt systems) ²		Congestion alarms ²
Exit ramp management system			Real-time graphical user interface (GUI)
End-of-motorway management system ²			Weather and environmental monitoring system

¹ Tools currently in development to be integrated with CWCRM - ² Tools planned for development

Table 1.1: The Managed Motorways Toolkit

As illustrated in Table 1.1, “**Control Tools**” can be separated into two categories depending on their primary function in relation to the levels of active management (i.e. Network Optimisation or Intervention) as follows:

- **Network Optimisation** – These control tools for route and network optimisation and these include City Wide Coordinated Ramp Metering (CWCRM), dynamic variable speed limits (DVSL), Arterial Road Interface and Exit Ramp Management systems.
- **Intervention** – These control tools responsible for intervening to control traffic speed and lane/carrageway use following an incident, congestion or other event. For example, integrated speed and lane use management systems (LUMS) and entry ramp management systems that support motorway closures.

Likewise, “**Foundation Tools**” are split into two categories as follows:

- **Information** – These tools provide real-time information to road users via on-road variable message signs (VMS) as well as through publication of data to third parties for wider dissemination via mobile phone and in-vehicle systems. Provision of information on travel times and motorway conditions on both the arterial and motorway network can assist in managing demand across the network, particularly during incidents and congestion.
- **Intelligence** – These tools provide the real-time data that is critical to identifying and monitoring network performance issues and providing the inputs to dynamic algorithms that fine-tune towards a defined objective target.

“Control Tools” generally require various functions of “Foundation Tools” for their effective operation and use many of the same field devices and detector data. In this context tools are described as being “tool chains”. For example, the City Wide – Coordinated Ramp Metering (CWCRM) system and the entry ramp closure management system both utilise traffic signals and ramp signs to control traffic leading on to and within the entry ramp using combinations of common and specialist algorithms. These are driven by the same detector data to control the traffic and provide advice to motorists. Hence the Managed Motorway toolkit consists of a variety of “tool-chains” that assist managing traffic entering the motorway, traffic on the motorway and traffic exiting the motorway. Therefore, when designing a Managed Motorway, it is important that there is understanding that the higher order optimisation tools naturally assume that the foundation tools and intervention tools have been provided according to the warrants contained in Volume 2, Part 1 and design guidance contained in Volume 2, Parts 3 and 4.

2 Ramp Metering as a Network Optimisation Tool

2.1 Principles of Motorway Traffic Flow

This chapter focusses on the background and principles that relate to managing motorway traffic flow and in particular the principles associated with the operation of motorway infrastructure as an optimised network using City Wide Coordinated Ramp Metering (CWCRM). CWCRM is the primary tool for avoiding or recovering from flow breakdown on a motorway route or network of interconnected motorways, as it has been designed to manage the traffic density on all segments in the network at sub-1-minute level to target the delivery of maximum sustainable flow values discussed in Volume 1, Part 3.

The principles recognise the economic benefits of soundly based infrastructure design, including adoption of mainline lane arrangements to maximise throughput by minimising turbulence and operation that optimises productivity. The importance of ensuring availability of accurate, reliable, fine grained and timely data with the appropriate metrics to avoid flow breakdown is a key factor in understanding and controlling motorway infrastructure, as well as for effective design of the surface road interfaces at interchanges.

In Victoria the economy is approximately 78% service-based. A service-based economy relies heavily on transport for couriers, construction, business, trades, medical services in the home, deliveries of goods and food to retail stores, shopping, education, home services and tourism etc. In a service-based economy, many vehicles only need one person in the vehicle as it is considered to be inefficient to have two people to deliver many services or commodities. The service-based economy has transformed the way roads are used and over time has resulted overtime in significant increased peak spreading (beyond the traditional 2 hours assumed) and heavy off-peak travel particularly on urban motorways. The heavy travel demands are no longer just for, or about, commuting which represents only about 20% of total trips across the day. A large service-based economy also brings with it the problem that traffic patterns and demands vary widely from minute to minute across the entire day, hence the optimisation problem is very complex *and* must operate at the sub one-minute level to be effective. CWCRM has the ability to understand the complexity in real-time at the network level to greatly improve the productivity of the motorway infrastructure.

2.2 Ramp Metering – An Overview

Motorway ramp metering as shown in Figure 2-1 are traffic lights installed on an entry ramp to meter traffic into the motorway in a measured and regulated manner in order to manage the motorway traffic flow and prevent congestion. Flow breakdown and congestion on a motorway result in reduction in safety and throughput, increase in travel time, therefore they represent under-utilisation and lost productivity of a high value facility.

The importance of CWCRM is to optimise motorway safety and productivity. This is reinforced by the significant role the motorways fulfil, including for many local trips, as these critical arterials road may be at, or over, capacity during the peaks (or not be able to satisfy demand) and may have had relatively little additional capacity added over the years.



Figure 2-1: Motorway Ramp Metering

While the ramp metering system provides the primary traffic control tool for managing the mainline, the principles for analysing and designing the mainline are important for minimising the potential for flow breakdown and optimising productivity in relation to the objectives in Managed Motorway concepts of operation. Guidance relating to mainline analysis and design is provided in Volume 2, Part 3.

An actively managed CWCRM system based on contemporary traffic flow theory and understanding can deliver stable and reliable travel by optimising throughput and travel speed along all segments of the motorway, including ramp merges and weaving areas, as well as preventing, or delaying, the onset of traffic flow breakdown and congestion.

Local Ramp Metering controls the entry of traffic at a ramp based on local motorway bottleneck conditions and ramp data. This is isolated operation that is independent of what is happening at other entry ramps or any knowledge (i.e. input of data) of the traffic demands arriving from upstream which will also impact the local bottleneck in the next time period (i.e. 1 or 2 minute period). This may result in an oversupply of traffic at the bottleneck being locally controlled.

City Wide Coordinated Ramp Metering (CWCRM) uses a dynamic algorithm that makes a combined decision based on data from many motorway segments and the required number of entry ramps. This operation is able to regulate the entry of traffic from a number of ramps to optimise the overall motorway operation by balancing flows between ramps and regulating the supply of traffic towards the critical bottleneck area. VicRoads use of the HERO-LIVE suite of algorithms provides coordinated dynamic management of Melbourne's motorways (refer Section 4.2). This provides proven positive results towards achieving the objectives of managed motorways.

2.3 Principal Aims of Motorway Ramp Metering

The principal aims of using coordinated ramp metering on motorway entry ramps are to optimise motorway:

- Throughput,
- Travel Speed, and
- Travel Time Reliability.

Optimised throughput and travel speed are achieved (within reason) by minimising the possibility of flow breakdown on the motorway, both at ramp merges and locations further downstream, and the consequential development of congestion. Travel time reliability is provided by reducing performance variability from day to day.

The following three sections outline some of the principal actions achieved through the application coordinated ramp metering.

2.3.1 Localised Operation

Managing headways makes it easier to merge and disperse platoons (bunching) of vehicles entering from a ramp to achieve an evenly distributed flow of traffic into the merge area (refer Eleferiadou L. et al, (1995). The management of headways to assist the merging of entering traffic is the localised perspective that motorists and stationary observers generally experience (refer Figure 2-2).

Managing sustainable flow in ramp merge areas requires controlling the flow rate of entering vehicles when the motorway is near capacity. Mainline flow is managed within limits beyond which the traffic flow would typically transition to an unstable or congested condition. Localised operation of ramp metering can only be used effectively within certain limits or contexts or at certain times. It is no longer considered to be an effective solution for motorways in large urban cities as the motorway traffic arriving from further upstream can often exceed the capacity of the merge area such that the local ramp may need to operate in a very restrictive manner, assuming that there is sufficient demand at the ramp to be controlled. If the ramp demand cannot be managed in the manner required, it is inevitable that break down of flow on the motorway will occur. City-Wide Operation is required to ensure that appropriate flows all treating motorists equitable are delivered to all motorway sections such that manageable volumes of traffic arrives at bottleneck areas.

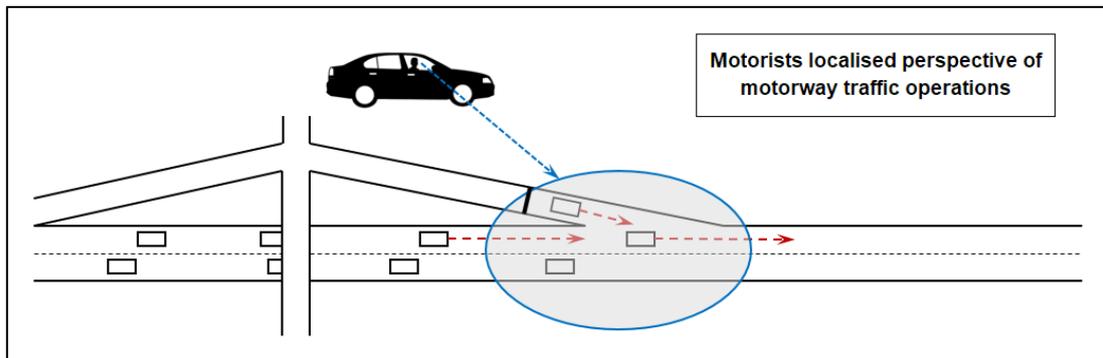


Figure 2-2: Driver’s perception of localised ramp metering operation

2.3.2 City Wide (Coordinated) Operation

City Wide (Coordinated) Operation requires management of all critical bottlenecks (whether fixed or dynamic) along the whole motorway. This requires taking a system or ‘helicopter’ view as shown in Figure 2-3 to identify all areas where traffic conditions need to be managed. This includes system level understanding of the need for management of all merges, weaving and lane changing areas, steep grades, incidents, etc., by controlling traffic using a number of coordinated ramps within the system.

Demand management of access to the motorway uses the coordinated ramps to ensure that entering traffic is controlled, managed, and at times momentarily restricted, to ensure the motorway operates within the capacity of the motorway system. This occurs by managing ‘space’ in ‘time’ to balance and match all entering traffic flows across the system and considers those already within the system and how they impact on instantaneous (real-time measured) capacity of all bottleneck locations. There is no value delivering 150 vehicles per minute to one segment if the adjoining downstream segment(s)

can only process 120 vehicles per minute as this will result in significant losses in productivity and safety outcomes due to the induced over-saturation and subsequent flow breakdown.

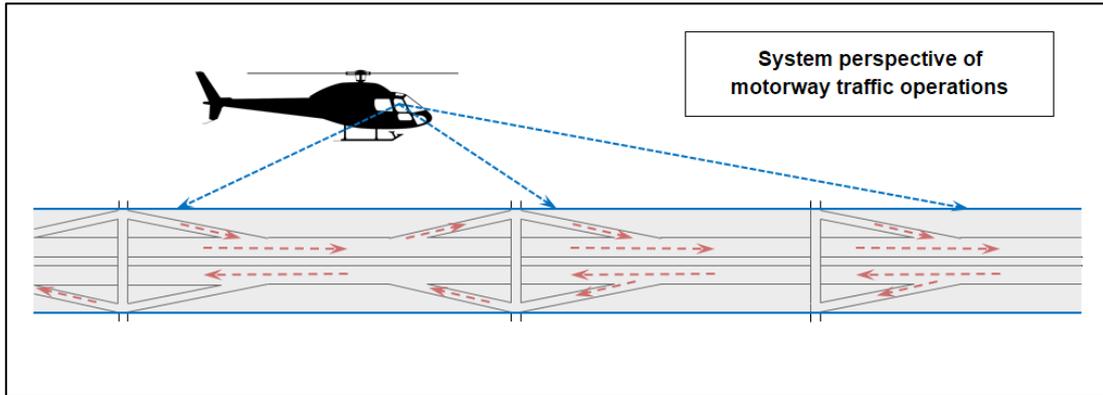


Figure 2-3: City-wide System’s understanding of ramp metering operational needs

2.3.3 Improve Safety

Safety improvement is achieved in both the localised and system context by:

- Assisting merging locally;
- Managing lane changing turbulence, particularly in the vicinity of ramps and weaving areas;
- Reducing the potential for incidents caused by braking in response to congested stop-start traffic conditions and differential speeds between lanes; and
- Allowing enough empty road space to allow for the instantaneous lane changing requirements (i.e. micro OD patterns) which vary from minute to minute across the day. Lane changing under certain conditions is regularly a precursor to flow breakdown and the trigger for crash sequences (refer Volume 1, Part 4).

Note:

The ability to control density locally at a ramp merge is relatively straightforward in control and has been adopted in many traffic control systems over many years. An outcome of metering a ramp merge effectively can be an increase in efficiency and outflow from a ramp merge bottleneck. As a result more traffic is able to enter the motorway system and proceed downstream. These higher flows can activate bottlenecks at locations further downstream on the motorway mainline, bottlenecks that may previously have remained unseen in the shadow of upstream flow breakdown prior to metering.

The ability to control distant bottlenecks is generally a more complex problem to solve than managing a local merge bottleneck. This is in part due to the time taken for traffic to travel downstream to the affected area and also the nature of the oscillations that are inherent in traffic flow and the changing conditions imposed by control actions. When a bottleneck is further away from a controlled entry ramp, there is greater delay for regulated traffic flow to arrive downstream and have the desired impact on flow stability and traffic state outcomes (i.e. the traffic state at the bottleneck is changing before traffic from the regulated ramp can arrive).

Relatively simple control approaches cannot manage such distant bottlenecks. Control systems with sufficient sophistication and complexity are required, not only to effectively respond to distant flow stability problems but also to coordinate multiple ramps to provide coordinated demand and queue management over significant lengths of urban motorway corridors.

2.4 Context and Effectiveness

Within the context of a ‘managed motorway’, which may incorporate a range of traffic management tools, controlling the entering traffic with a coordinated motorway ramp metering system is the most effective tool in managing traffic to prevent flow breakdown and optimising throughput and travel time on the mainline and motorway network as a whole.

A technically effective algorithm with proven on-road performance that is robustly tuned based on contemporary theory and analysis is essential to maximise the motorway’s productivity. Figure 2-4 shows an example of a high-volume entry ramp merge where mainline flow is managed to prevent flow breakdown and optimise motorway throughput and speed.

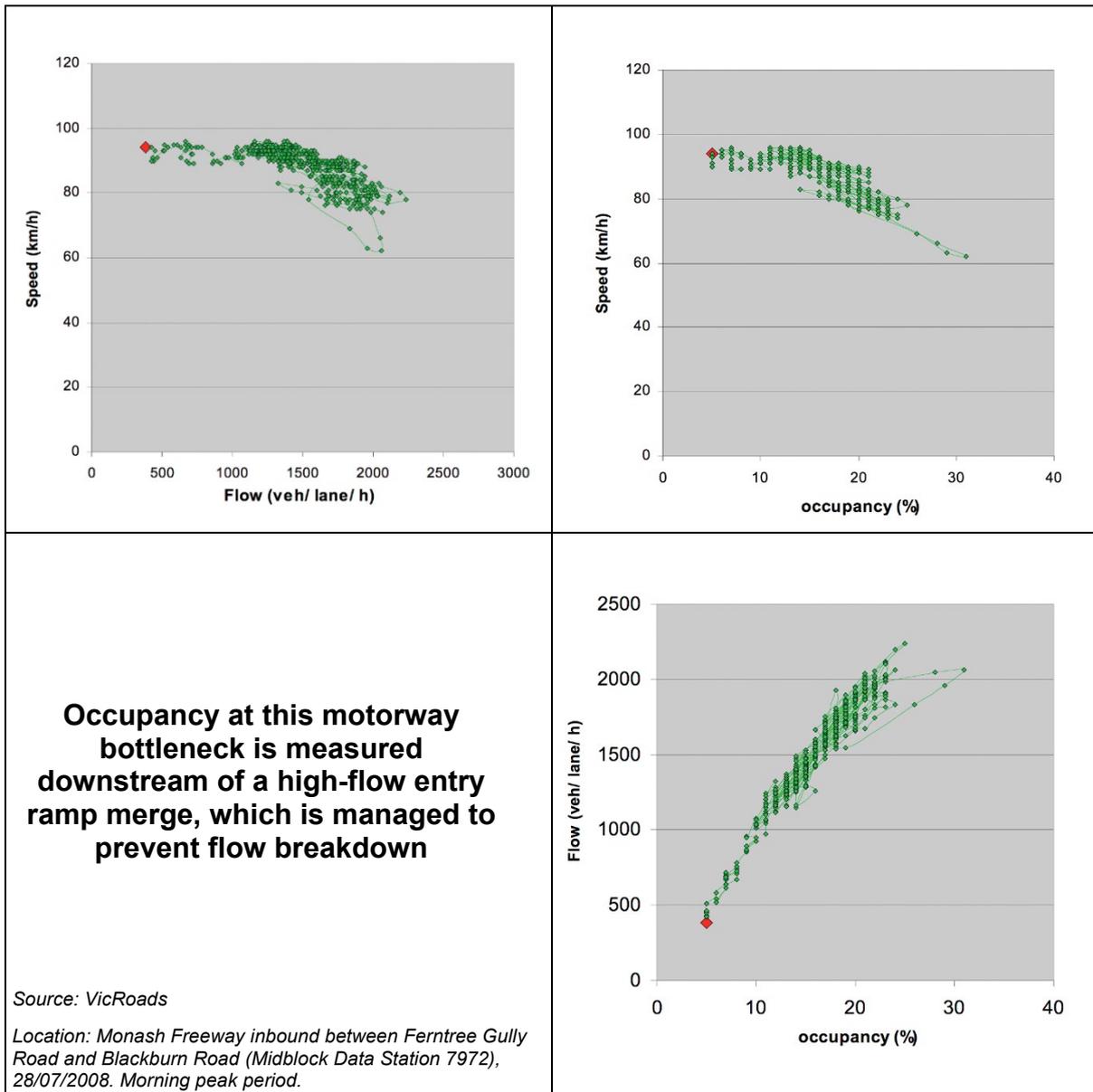


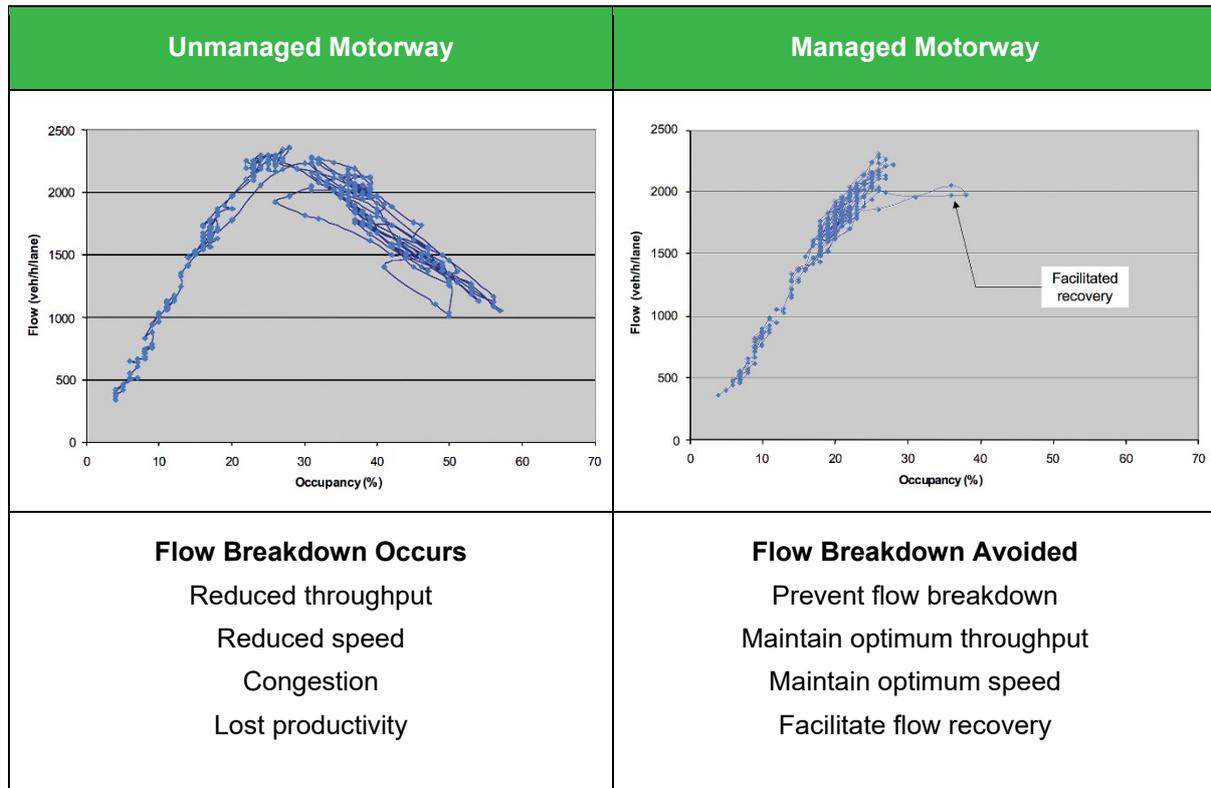
Figure 2-4: Example of Fundamental Diagrams at a Bottleneck Managed with Ramp Metering

2.5 Ramp Metering as a Management Tool

Metering of motorway entry ramps provides an effective traffic management tool for managing the motorway network in a number of ways including:

- Controlling and coordinating all entry ramps along each route to manage the mainline motorway at a number of critical bottleneck locations. This will ensure that the best overall motorway service is delivered under a wide range of conditions and contribute to reducing the variability of travel time from day to day, thus enhancing improved reliability;
- Managing the motorway flow (occupancy) in a way that would prevent or delay motorway flow breakdown at an isolated bottleneck;
- Controlling entry ramp traffic to facilitate faster restoration of free-flowing conditions after congestion caused by a crash or other unplanned incident;
- Managing the headway of entering ramp traffic onto the mainline. This can assist in merging and improve safety even when the ramp traffic does not need to be restricted to optimise mainline capacity;
- Discouraging short trips on the motorway during periods of high demand or congestion particularly where alternative arterial road routes are available, which are often shorter and potentially faster when the ramp delays increase above certain thresholds.

Figure 2-5 shows charts of motorway flows for unmanaged and managed situations. In the Managed Motorway example, controlling the vehicle access has prevented flow breakdown and maintained free flowing conditions.



Source: VicRoads

Figure 2-5: Example of Unmanaged and Managed Motorway Flows

3 Ramp Metering Control

Ramp metering signals for a Managed Motorway would generally be part of a route treatment that operates as a system under dynamic, coordinated control. While some of the information in this section may represent early superseded practice and not be directly applicable to current VicRoads practice for motorways with heavy demand, it is included to provide principles and background related to the VicRoads journey towards current understandings and best practice.

When ramp meters are coordinated in a system, the ability to manage the mainline occupancy by matching entry ramp inflows to the capacity of critical bottlenecks along the motorway is significantly improved. System control with appropriate ramp designs also has the advantage of distributing entry ramp queues and waiting times across a number of ramps to provide equity of access.

3.1 Independent Control

Independent ramp meter control within the system context may be appropriate where entering traffic causes flow breakdown in the mainline flow at an isolated bottleneck that generally has no impact on, or from, other interchanges along the route.

The function of an independent ramp meter is to manage the entering rate of traffic to overcome the impact of uncontrolled platoons of traffic coming from the ramp's upstream intersection signals. An independent meter may also be used to control the total entering volume to maintain stable conditions when the motorway is nearing capacity.

Averaged over an hour (although the system would calculate a 20 second metering rate based on occupancy), the hourly design volume calculation considering the ramp and mainline flows relative to the maximum sustainable flow rate (to minimise the likelihood of downstream flow breakdown) is shown in Figure 3-1 and is generally based on:

- Bottleneck capacity flow (q_{cap})
- Upstream flow (q_{us})
- Entry ramp arrival (demand) flow (q_{ra}), and
- Maximum metered ramp flow (q_r).

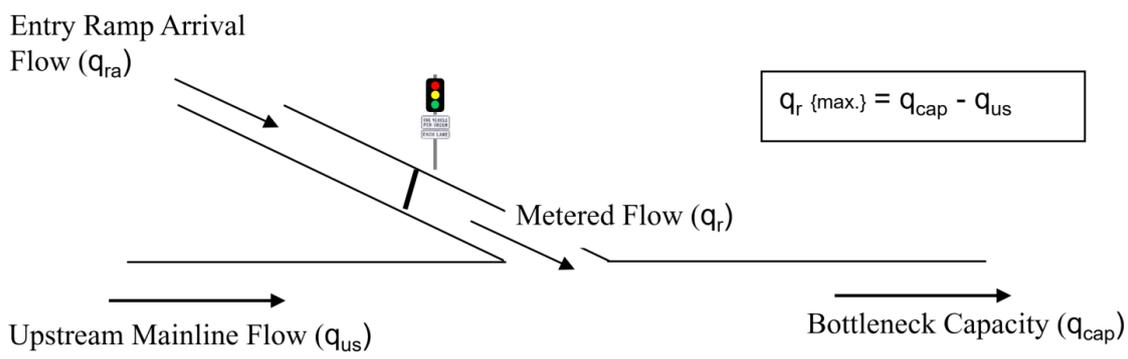


Figure 3-1: Metering Traffic Flow at a Bottleneck

Independent (or isolated) ramp metering installations may be effective in providing reductions in merging problems and improvement of motorway traffic flow where there is a high merging flow, but has limited functionality and ability to balance operation along a route when compared with coordinated control. For example:

- If the bottleneck capacity is less than the upstream flow there is no ability to control demand on the mainline
- Subject to the applied queue management strategy, this may result in earlier initiation of ramp queue override actions and potential for premature flow breakdown at the merge
- It provides reduced equity relative to upstream ramps, i.e. the ramp at the active bottleneck takes 'all the load' while the upstream ramps, while contributing to bottleneck activation, are either not controlled or do not share delays equitably
- Is unlikely to be able to maintain optimum motorway throughput if there is congestion related to other bottlenecks along the route, and
- Is not appropriate for heavily trafficked motorways where a number of entry demands need to be managed or where flow breakdown may occur at a number of locations.

3.2 Dynamic Coordinated (Route-Based) Control

Best practice coordinated control allows for ramp meters to operate in an isolated manner or to engage, when needed, upstream ramps in a master/slave relationship.

When ramp meters are coordinated in a system it improves the ability to manage the mainline motorway flow by matching traffic inflows from a group of ramps to deliver the appropriate capacity flow to a critical bottleneck along the route. It also has the capability of balancing the queues and wait times between ramps.

With dynamic coordinated control the motorway ramps are grouped to operate together and provide the necessary control when traffic conditions require coordination. Typically, coordination results in a balance between long and short trips where studies on some routes have shown that about 50% of traffic entering at a particular ramp will travel more than six interchanges¹.

Within a heavily used motorway, bottlenecks could occur at many locations including each entry ramp merge and other locations, e.g. areas with weaving and high levels of lane changing. The critical bottleneck is generally where flow breakdown occurs first. Other locations also need to be managed within the coordinated system but would be less dominant bottlenecks.

The management and control of traffic along a length of motorway requires metering at all points where traffic enters the motorway. Management of all entering traffic maximises the ability to control and manage downstream traffic conditions. This may include:

- Entry ramps with merging traffic
- Entry ramps leading to an added lane
- Collector-distributor roads entering the mainline
- Motorway-to-motorway (system interchange) entry ramps or metering of upstream ramps on the intersecting motorway, as appropriate (refer Volume 2, Part 3: Section 7), and
- The start of the motorway in some instances².

¹ Internal VicRoads reports relating to travel on Monash Freeway and Western Ring Road.

² Although not discussed in this guide consideration may need to be given to the phase times of traffic signals at the start of a motorway to ensure optimal dispersion of traffic and to match the required capacity of downstream motorway segments.

The general principle of managing entry ramp flows within a coordinated system is to match the capacity of a downstream critical bottleneck on the motorway, as shown in Figure 3-2. A critical bottleneck location may be static during operations or may change as traffic conditions change through the peak period. The system manages occupancy at critical locations and also takes into account the traffic leaving the motorway at exit ramps.

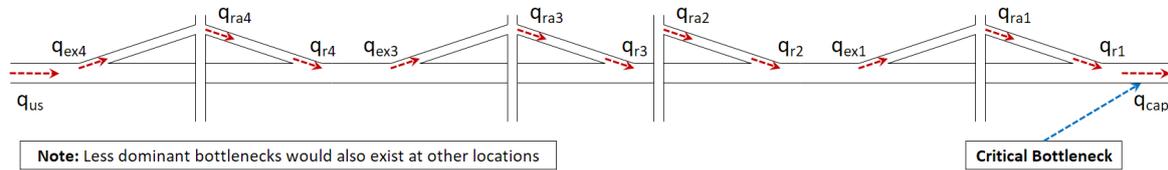


Figure 3-2: Metering Traffic with Coordinated Control

In this example:

$$\sum q_{rn \{max\}} = q_{cap} - q_{us} + \sum q_{ex} \quad \text{where } q_{cap} \text{ is the bottleneck capacity.}$$

The control system would control the total flow allowed to enter the motorway, $\sum q_{rn \{max\}}$, from the individual ramps to manage q_{r1} , q_{r2} , q_{r3} and q_{r4} according to needs at the critical bottleneck which may be at either a ramp merge or any other critical segment along the motorway, e.g. segment with lower capacity, weaving area, etc. The coordinated control is also used to balance ramp queues and delays as well as avoid flow breakdown at each localised entry ramp merge, i.e. each of the individual metered entry ramp flows would need to be managed so that the motorway capacity at each local ramp merge is not exceeded.

The ramp metering signals immediately upstream of the critical bottleneck generally becomes the ‘master’ and controls a coordinated group of ramps. Other upstream ramps are activated to become ‘slaves’ in the coordinated group to provide assistance in managing the overall entry flows.

In addition to localised improvements, coordinated ramp metering has the following benefits:

- Reduces mainline demand at a bottleneck when independent control cannot manage flow;
- Provides equity by balancing of queues and delays between a number of ramps, i.e. ‘shares the load’;
- Reduces the likelihood of ramp queue overflow on short ramps by sharing the demand management with ramps that have more storage.

A dynamic ramp metering system adapts to changing traffic flows on the motorway and ramps and can manage traffic at the local level and in a coordinated system along a motorway corridor. A dynamic system generally includes the following capabilities:

- Switch-on occurs automatically when the motorway flow at a local merge or bottleneck is approaching unstable conditions.
- Automated response to motorway conditions by continually adjusting ramp inflows, i.e. cycle times, along the route to optimise motorway occupancy as well as balancing queues and managing traffic delay on the ramps. A range of parameters in the control system algorithm can be adjusted in real time to refine the operation.
- Enhanced capability to prevent flow breakdown occurring at bottlenecks due to uncontrolled demand. It also provides more effective identification of, and response to, flow breakdown caused by an unplanned incident and can then manage inflows to the motorway to facilitate faster recovery as outlined in Section 3.6.

A fixed time signal cycle or operation with time of day settings in a dynamic system would only occur if there was a fault (fall-back operation) or with operator override. This form of operation can provide

some benefit, e.g. managing headways for ramp traffic entering the mainline flow, but has limited effectiveness in preventing flow breakdown and optimising motorway throughput.

Note:

Early ramp metering practice was based on selecting fixed cycle times (generally from a range of pre-set cycle time plans and metering rates) in response to increasing congestion. While this managed the headways of entering ramp traffic and delivered some benefits, it was unable to prevent flow breakdown where demand exceeded capacity.

Forms of dynamic ramp metering practice attempted to time the arrival of entering vehicles to coincide with gaps in the left lane of the motorway. It is now known that an important determinant of mainline traffic flow stability is the total flow across all lanes and the corresponding density of traffic in the motorway. The contemporary approach considers traffic flow in all lanes across the carriageway considering at many downstream segments, not just the localised merge location. Application of a technically effective control algorithm using this contemporary approach has the ability to deliver optimum flow as well as balancing entry ramp flows along motorway corridors.

The assessment of applying the contemporary approach to ramp metering considers the outflow of the motorway system (i.e. trips completed measured at the exit points) rather than focusing solely on the inflows alone. Ramp metering is good at increasing merge segment capacity, however, delivering too much traffic into a motorway operating near capacity or already broken down (congested) is not considered an effective or efficient network operating paradigm.

3.3 Managing Ramp Demands

While all ramp metering operates to control the rate of traffic entry into the motorway, there are situations when the control may satisfy demand and situations when the ramp demand cannot be satisfied.

3.3.1 Satisfying Ramp Demands

Ramp demands are satisfied when the entry ramp flows can be metered into the motorway flow within the motorway's capacity and with acceptable limits of delay. This form of control 'drip feeds' entry ramp flows into the mainline in a way that, on average, clears entering traffic from the signalised ramp intersection before the next platoon of traffic arrives. Residual queuing, with acceptable delays, may occur on the ramp but without extending back into the ramp intersection.

Satisfying ramp demand is the most desirable form of operation and would usually be achieved when the motorway flow warrants initial activation of the metering signals. As the motorway flow or ramp flow increases into the peak period the level of operation may progress to more restrictive forms of metering.

When designing a new ramp metering installation, satisfying ramp design hourly demands is desirable to ensure a successful project. In practice, the permitted entry flow at each ramp will be subject to the variation in demand within the peak period, the motorway conditions at the time, as well as operating strategies relating to queuing and queue balancing (dependent on the available physical ramp storage) as part of the coordinated system.

3.3.2 Not Satisfying Ramp Demands

Ramp demands cannot be satisfied when the arrival flow on the ramp within a period is greater than the permitted metering rate based on the motorway conditions, i.e. on average throughout the analysis period (generally the peak hour), the entry ramp demand flow cannot be metered into the motorway flow within the motorway's operating capacity.

During periods of high motorway flow combined with high entry ramp demands, limiting the entry flow may be the only form of operation that sustains free-flow conditions on the motorway. This metering

operation will result in residual queuing on the ramp with high delays and may also involve queues extending beyond the length of the ramp back onto the surface road.

Where long queues at ramp metering sites are anticipated during design, consideration should be given to measures that provide for increased storage. While managed queue overflow onto the surface road may be an option at some sites (refer Volume 2, Part 3: Sections 6 and 8) this should generally be avoided. In practice, with an effective coordinated ramp metering algorithm and operational strategies, ramp demands over a group of ramps can generally be balanced to optimise operations.

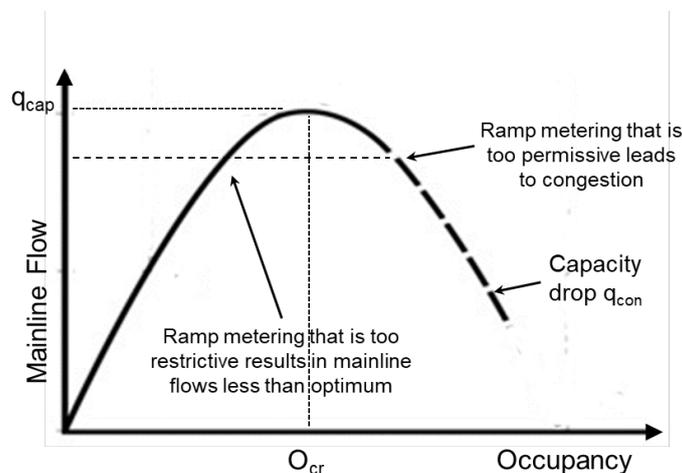
3.4 Control Strategies and Algorithms

3.4.1 Effective Algorithms

The choice of appropriate control strategies and technically effective control algorithms for coordinated ramp metering is important if the maximum productivity of a motorway is to be realised. This needs to be complemented with sound analysis, an understanding of motorway flow characteristics and geometry and appropriately designed entry ramps to provide adequate discharge capacity and storage.

Figure 3-3 illustrates the implications of a ramp metering rate that is either too high or too low. In the typical Flow / Occupancy fundamental diagram, the capacity flow, q_{cap} , occurs at a critical occupancy value, o_{cr} . When flow breakdown occurs, the mainline flow drops to the area of q_{con} (congestion).

If the ramp flow through metering signals is too restrictive, the optimum motorway flow will not be achieved. If ramp metering is too permissive, mainline congestion will occur and throughput drop to the values of q_{con} . Either form of operation would impact potential ramp metering benefits as well as disadvantage traffic with either longer than necessary ramp queues or with mainline congestion.



Source: Concept based on *Euramp Metering* (Euramp Project No. 507645, 2007)

Figure 3-3: Fundamental Diagram Indicating the Importance of Metering Rate

To achieve the full benefits of ramp metering, a technically effective and sufficiently sophisticated ramp metering algorithm is required. This needs to be capable of establishing and maintaining traffic flows near critical occupancy, i.e. achieving an optimum flow which is just below, but near the q_{cap} value (refer Figure 3-4). This is crucial to avoid the inherently unstable conditions throughout the system (not just at merges) and to target the provision of optimised productivity – achieving near capacity flows with little if any speed reductions for sustained periods.

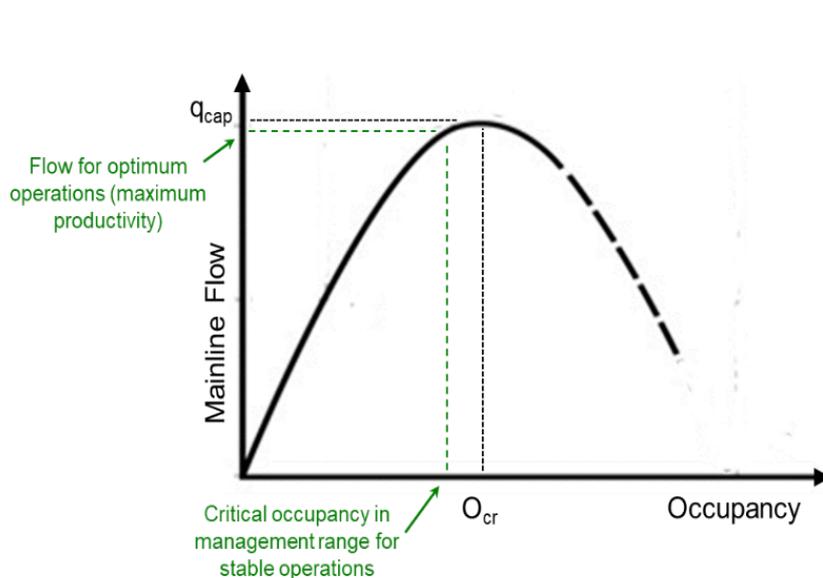


Figure 3-4: Fundamental Diagram Indicating Critical Occupancy for Ramp Metering

3.5 Why Occupancy is Used to Manage Motorway Flow

The Euramp Handbook of Ramp Metering (2007) developed by the European Ramp Metering Project has highlighted the uncertainty of mainline ‘capacity’ and summarised the conclusions from a number of relevant papers being:

- (Austroads Research Report ARR 341 - Fundamental Relationships for Freeway Traffic Flows - Monash Freeway, 1999);
- (Probabilistic Nature of Breakdown at Freeway Merge Junctions, 1995);
- (Defining Highway Capacity as a Function of the Breakdown Probability, 2001);
- (Increasing the Capacity of an Isolated Merge by Metering its On-ramp, 2005).

These demonstrate that traffic breakdown in merge areas may occur at different flow capacity values q_{cap} on different days, even under similar environmental conditions, e.g. weather, lighting. These capacity differences become even more pronounced in adverse weather conditions (refer to (Keen, Schoffield, & Hay, 1986)).

In contrast, the critical occupancy o_{cr} at which capacity flow occurs, was found to be fairly stable (Cassidy & Rudjanakanoknad, 2005) even under adverse weather conditions (Keen, Schoffield, & Hay, 1986); Papageorgiou et al., (2007). Also, within the flow/density and speed/flow planes of the fundamental diagram, it can also be seen that the same flow value can be measured at different occupancy and speed values. In general, average occupancy (as a proxy for density) is more reflective of traffic flow state and generally increases with increasing flow and reducing speed. For these reasons, the occupancy measurement is the most appropriate parameter for optimising throughput rather than speed or flow rate.

3.6 Managing Heavy Congestion and Incidents

Flow breakdown can be minimised on a Managed Motorway with a well-designed coordinated ramp metering system. However, when motorway congestion does occur, the management of the route requires an automated and integrated operational strategy that will minimise the worsening of congestion and also assist in flow recovery.

Situations that could lead to motorway congestion include:

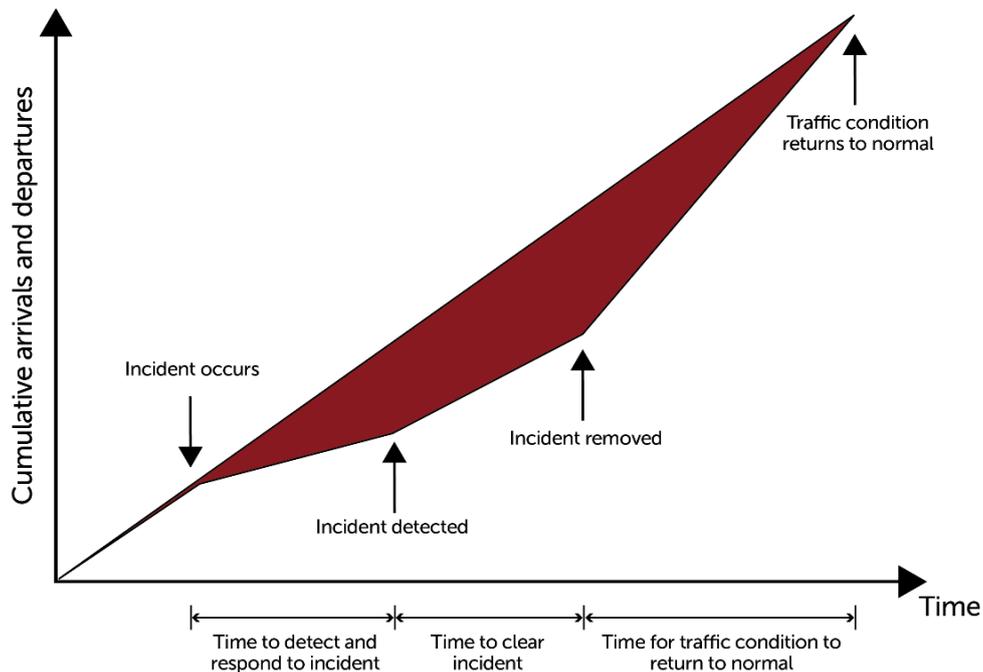
- Insufficient control of entering flows including unmetered entry ramps, for example:

- Unmetered motorway-to-motorway ramps (or where insufficient control is present on the intersecting motorway upstream of the interchange)
- Ramps with free-flow priority access lanes (an application no longer supported by VicRoads)
- The commencement of a Managed Motorway is not controlled such as locations where the motorway is the continuation of an unmanaged section of urban motorway / rural freeway or an arterial road directly feeding the start of a motorway.
- Access control strategies or policy lead to excessive ramp flows into the mainline, e.g. a strategy that allows long ramp queues to be released into the mainline when there is no ability for the mainline to accept higher flows.
- An incident on the motorway.

Figure 3-5 demonstrates incident delay with cumulative vehicle arrivals and departures plotted against time. The shaded area between the arrivals and departures represents the vehicle delay due to an incident. Before the incident, the vehicle arrival rate equals the rate of the departures. After the incident traffic is delayed and the departure rate decreases.

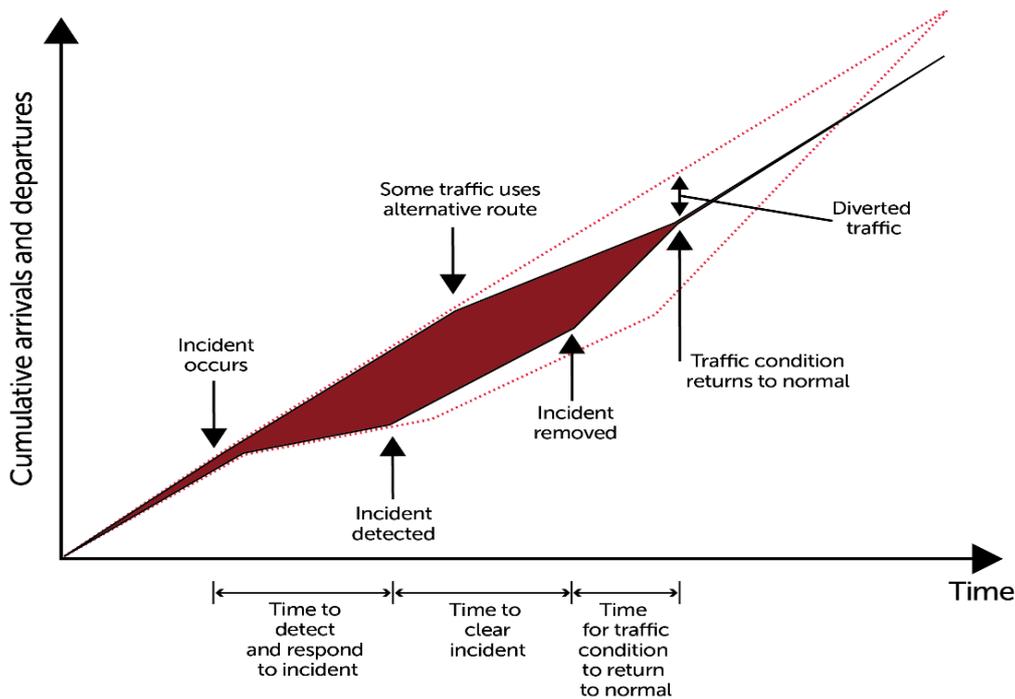
The early identification and effective management of an incident as well as actions to reduce motorway demand can assist in minimising the impact on traffic flow. Figure 3-6 indicates how an effective incident management system reduces the overall impact of an incident as well as the time for the motorway flow to return to normal. This is due to:

- Faster incident detection and response that leads to earlier incident removal
- Diverting traffic away from the incident.



Source: Based on Austroads AP-R298/07 - Improving Traffic Incident Management: Evaluation Framework

Figure 3-5: Incident Clearance without an Incident Management System



Source: Based on Austroads AP-R298/07 - Improving Traffic Incident Management: Evaluation Framework

Figure 3-6: Incident Clearance with an Incident Management System

An integrated approach is required to manage incidents and the corresponding heavy congestion. This focuses on the following complementary actions:

3.7 Management of Entry Flows to Assist in Flow Recovery

Motorway ramp metering can limit entry ramp flows upstream of the incident (refer Volume 1, Part 2: Section 3.4). This reduces the motorway flow at the incident site and also assists in diverting traffic, particularly if traveller information relating to travel time and incidents is provided. An automated response detects the onset of congestion due to oversupply of traffic or due to capacity limitations at the incident site.

3.8 Closing Entry Ramps and/or the Motorway.

In some situations managing the incident may include closing entry ramps or the motorway upstream of an incident.

3.9 Traffic Diversion by Providing Traveller Information

Some motorists will use an alternative route if travel advice is available. This can be provided by:

- Real time driver information signs on the surface road prior to the motorway entrance (refer Volume 2, Part 3: Sections 6,7 and 8 and Part 4).
- Mainline VMS to encourage motorists to leave the motorway before reaching the congested section.
- Traffic condition reports from radio stations, particularly during peak periods.

3.10 When Ramp Metering has Limited Effectiveness

In some situations, ramp meters can have limited effectiveness in preventing congestion due to conditions which limit capacity or traffic flow. The following sections discuss such situations.

3.10.1 Planned or Unplanned Events

- During road works if the capacity of the mainline is significantly restricted
- During incidents where sudden congestion occurs.

In these situations congestion management using coordinated ramp meters and traveller information can provide benefits for the duration of the event and can assist in flow recovery after the incident is cleared (refer Volume 2, Part 3: Sections 6, 7 and 8 and Part 4).

3.10.2 Inadequate Traffic Management

When some entries to a motorway are uncontrolled, situations can arise where the unmanaged flows dominate the motorway flow and limit the ability of ramp meters to prevent flow breakdown. In this situation, excessive restriction of entry flows would result in inequitable access to the motorway and excessive ramp delays on metered entries.

3.10.3 Inadequate Infrastructure

Where a motorway terminates at a surface road intersection with limited capacity. If traffic cannot be accommodated at the end of the motorway, queues and congestion develop on the motorway mainline as shown in Figure 3-7. Upstream ramp metering cannot increase the motorway throughput at this point as the intersection at the end of the motorway controls and limits the capacity. Although upstream metering would be able to reduce the extent of queuing, this could result in excessive entry ramp delays, unnecessary restriction of trips to upstream exits and underutilisation of the upstream sections of motorway.

However, in this situation the provision of upstream coordinated ramp meters would still make a contribution to improving the overall motorway safety and throughput by providing other benefits such as:

- Headway management at upstream ramps to improve local merging.
- Preventing flow breakdown on upstream sections of the motorway at ramp merges and other critical bottlenecks – refer Figure 3-8.
- Balancing entry ramp queues and delays in the coordinated system.

Where queues from the end of the motorway extend beyond an upstream exit, coordinated ramp metering signals could also assist in managing upstream entry flows to keep the exit clear.

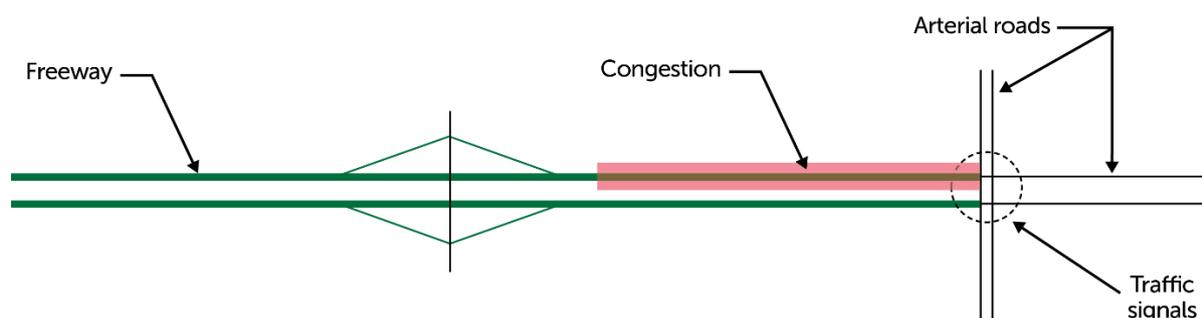


Figure 3-7: Motorway Congestion at a Terminating Motorway

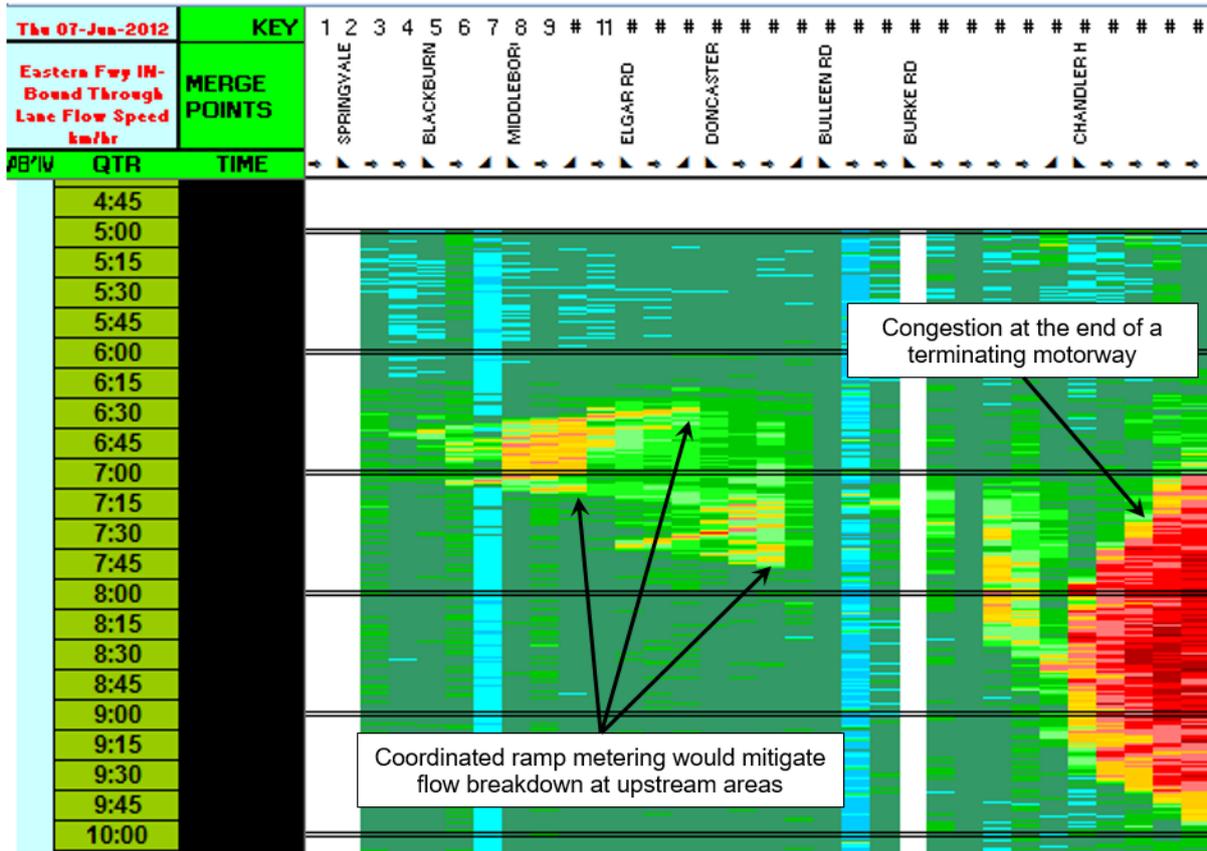


Figure 3-8: Congestion at Terminating Motorway showing other unrelated flow breakdown that would benefit from motorway management

Where an exit ramp or exit ramp intersection has inadequate capacity and queues extend back onto the motorway and block a motorway lane as shown in Figure 3-9. The management of exit ramp overflow queues is discussed in Volume 2, Part 3: Section 8.

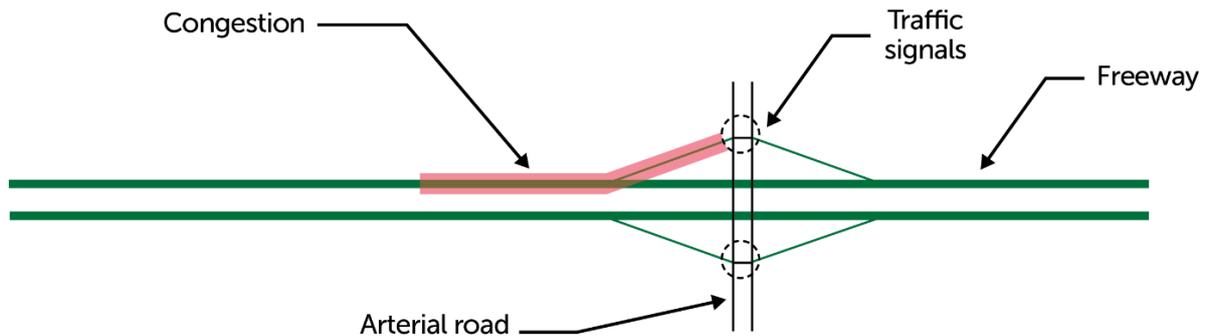


Figure 3-9: Motorway Congestion from an Exit Ramp

Theoretically, ramp metering by (grouped) destination could alleviate the above problems but would require lane designation on the entry ramps, separate meters / metering by destination etc.

4 The Operation of Ramp Meters

A general level of information is provided in this chapter relating to the operation of ramp meters including Motorway to Motorway ramp meters.

4.1 Legal Basis for Ramp Meters

Ramp Meters are traffic lights as defined in Road Safety Road Rules 2009. Rule No. 56 defines a driver's responsibilities when approaching, or at, a red or yellow traffic light. Other rules define responsibilities relating to the stop line and other regulatory signs and pavement markings associated with ramp meters.

A traffic signal is a Major Traffic Control Device (MTCI) as defined in Road Safety (Traffic Management) Regulations 2009. VicRoads must give approval to erect, establish, display, maintain or remove ramp meters.

The approval process for freeway ramp signals requires the provision of detailed Traffic Signal Plans, in an equivalent format used for signalised intersections, showing the traffic signals, ramp geometry and associated traffic control and warning devices (some of which are also MTCI's requiring itemised approval). Such plans are required to demonstrate that the design requirements in Volume 2, Part 3 have been appropriately considered and incorporated and to enable VicRoads operations to undertake required operational configuration and tuning actions.

4.2 Control Algorithms Used by VicRoads

The HERO- LIVE ramp metering control algorithms used by VicRoads on motorways in Victoria is based on the HERO / ALINEA suite of ramp metering control algorithms (refer to Section 4.2.1). The original ALINEA control philosophy which provides local control at an individual motorway entry ramp was developed by Markos Papageorgiou, et al (1991), (1997).

HERO-LIVE is an advanced suite of integrated control engineering tools which are robust in real-world (LIVE) operations where traffic conditions can be very complex to understand, where chaotic micro-conditions arise, some of which may not be seen in common aggregated freeway data. While some algorithms can perform well within offline traffic models, taking account of real-world problems is more complicated. Real-world operations need to consider and cope with the effects of rapid changes in traffic patterns (e.g. micro origin-destination patterns and demands), vehicle mix, impacts of geometric features, understanding the effects of incidents. There is also the need to handle real-time data errors, noisy data and data drop outs etc. which requires advanced levels of real-time statistical processing and evaluation for every 20 second time step.

HERO-LIVE incorporates a suite of ALINEA modules that was developed for coordination of ramp meters at a number of coordinated ramps along a length of motorway. In cooperation with Markos Papageorgiou and Associates, VicRoads has been involved in ongoing development of the algorithms with a significant number of enhancements to the algorithms and new modules, since the initial on-road trial in 2008. These enhancements specifically seek to solve unique problems encountered on complex urban motorways and have made significant advancements from a reactive coordinated ramp metering system towards a City Wide Coordinated Ramp Metering (CWCRM) system that optimises motorway networks within the urban road network (e.g. a network comprising motorways and arterial roads).

The HERO-LIVE suite, which is fully deployed in the field, has proven performance improvements based on utilisation of the following features:

- Dynamic start up and shut down algorithms that ensure the system only operates when required;

- Consistency with contemporary traffic theory for optimising motorway flow;
- The contemporary control logic is based on feedback from downstream conditions in real-time to dynamically adjust signal cycle times;
- Use of occupancy from the downstream motorway bottleneck locations as the optimising measure;
- Transparent in operation with fully configurable parameters;
- Integrated operation of local ramp control within a coordinated system based on sound operating rationale;
- Incorporation of modules for adjustments to entry flow rates based on consideration of ramp queues, and arterial road queues in some cases, as well as ramp delays;
- Potential to manage flow at motorway to motorway interchanges by linking upstream ramps on separate motorways;
- Ability to manage bottlenecks many kilometres (3 to 4 km) downstream from the nearest ramp; and
- Potential for management of multiple bottlenecks to adaptively determine and target the critical bottleneck.

The adoption of an efficient control algorithm suite is of paramount importance for a successful ramp metering system. **Designing and installing the necessary entry ramp layouts and field equipment is necessary and important, but these components are not sufficient in themselves for successful operations – effective control algorithms appropriately integrated are required.** As discussed in Volume 1, Part 5 the management of any road system requires intentional intervention, particularly when the system is operating close to capacity. It should no longer be acceptable to road agencies to wait until the system has broken down (failed) before interventions occur. As discussed in Volume 1, Parts 2 and 3: there are clearly definable metrics for which to design and operate motorway networks with a low chance of failure, and thus various components of the control system need to activate as certain target metrics are approached to limit flows within parts of the network to their optimal level to reduce the risk of failure. As discussed in Volume 1, Part 2 it is possible to achieve productivity (volume x speed) outcomes in the order of 50% higher if motorway networks are optimised in real-time.

4.2.1 HERO-LIVE Coordinated Ramp Metering Operation

The HERO-LIVE suite of algorithms is a comprehensive and complete concept (and corresponding implementation software) that applies coordinated ramp metering to motorway networks of arbitrary size, topology and characteristics. A central software installation at the coordinating road authority suffices for the coordinated ramp metering control of all equipped motorways network-wide facilitated through entry / connector ramp signals that are directly controlled by the system and operated by ramp metering optimisation specialists.

All specific data related to the network, the controllable entry-ramps and the real-time traffic conditions are communicated to the central software and made accessible via the STREAMS graphical user interface (GUI). Extensions of the motorway network under control or addition of new controlled ramps may be easily accommodated using the GUI. After its configuration, HERO-LIVE operates automatically without the need for operator interventions, except for specialist analysis, fine-tuning, checking for detector faults etc. Operator intervention is also possible for incident and emergency situations.

HERO-LIVE is fully traffic-responsive (with configurable update period that may be selected as short as 20 seconds) and adapts automatically to the prevailing traffic conditions aiming at maximising stable motorway throughput; while, at the same time, monitoring the current situation at the on-ramps and limiting any incurred vehicle queues or waiting times. HERO-LIVE uses real-time measurements from multiple locations on the motorway network and from the on-ramps and dynamically adjusts the

ramp meter cycle times. Particular attention is paid to latent motorway bottlenecks, which are the typical triggers of flow break down and traffic congestion, and appropriate ramp metering actions are initiated, whenever necessary, to target the prevention of traffic breakdown and delivery of sustained near capacity flows based on the integrated robust feedback control methods.

The HERO-LIVE algorithms have been conceived based on the latest insights of contemporary traffic flow theory for optimising motorway flow; moreover, they apply a variety of powerful and proven automatic control methods that guarantee stable, robust and efficient operation on the basis of feedback principles. This distinguishes HERO-LIVE from any approaches based on heuristic constructions or lack the fundamental feedback control principles. In addition to the theoretically sound background, HERO-LIVE decisions are transparent in operation, which enables operators to be fully aware at any time about the reasons behind the employed control actions.

Motorway bottlenecks may be due to the merge of an entry ramp, but may also be a result of other geometric or traffic factors, such as merging at a lane drop, a steep upgrade, a tight-radius curve, a bridge, a tunnel, reduced lane widths or areas with high weaving or lane changing movements, e.g. just upstream of a lane gain or high-flow exit ramp.

Traffic occupancy at mainline bottlenecks (detection locations in this control context) is the principal real-time measurement used to manage traffic flow on the motorway so as to optimise throughput and prevent flow breakdown and resulting congested traffic conditions. As average lane occupancy on the mainline approaches a value that may be unstable, ramp entry flows are controlled appropriately to regulate the mainline occupancy to an optimised value. Such actions are enabled simultaneously at multiple locations of the extended motorway network if needed. The availability of accurate and reliable traffic data for specific metrics from vehicle detectors meeting VicRoads performance requirements is essential.

4.2.2 HERO-LIVE Modules

The HERO-LIVE suite of algorithms manages the ramp traffic flow entering the motorway by monitoring and controlling the motorway flow at each ramp merge as well as other critical bottlenecks. Ramp discharge flow calculations are based on various modules providing outputs for isolated and coordinated operation as shown in Figure 4-1. It is noted that in order to protect Intellectual Property (IP) the descriptions on the following pages are limited to what has already been published in the public domain.

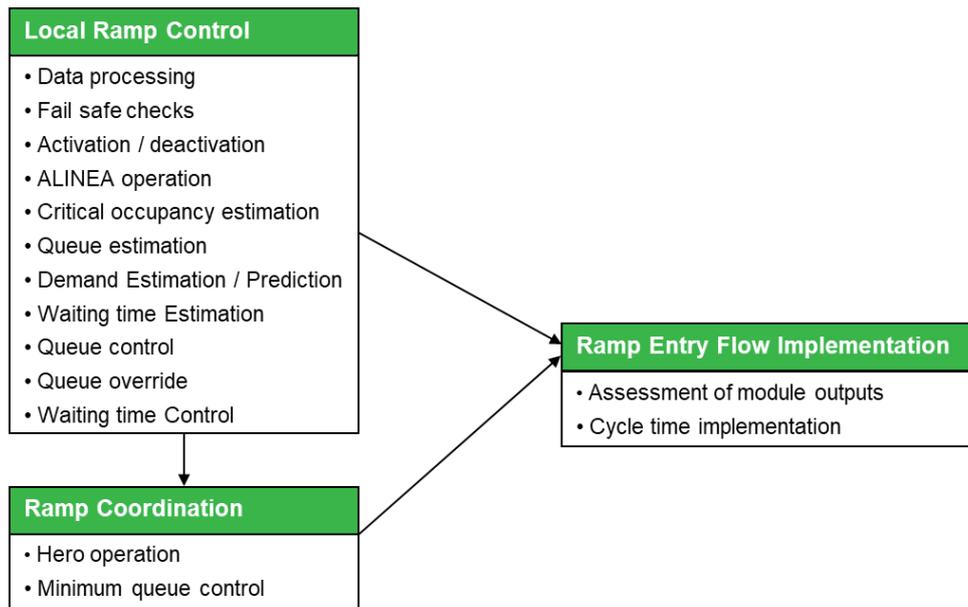


Figure 4-1: HERO-LIVE Coordinated Ramp Control Structure

The algorithms uses flow, speed and occupancy data in various modules summarised below.

Activation / Deactivation

This module switches the motorway ramp meters on according to pre-set traffic flow, occupancy and speed thresholds at the mainline bottleneck locations downstream of the ramp. The ramp meters are switched off according to pre-set occupancy and speed thresholds. Activation and deactivation is independently controlled at each ramp within a coordinated system. The thresholds are set with the intention of turning on the signal control before the onset of flow breakdown and turning the metering signals off when traffic flow conditions indicate that flow breakdown is unlikely.

ALINEA Core Module

A form of this module calculates the necessary ramp flow at each entry ramp for local maximisation of mainstream throughput according to the ALINEA feedback control algorithm, appropriately extended to enable the handling of multiple local bottlenecks simultaneously. The calculation uses the average mainstream occupancy measurement downstream of the merge (and at multiple downstream bottlenecks) relative to targeted critical occupancy values, at which the bottleneck throughput is maximised. The targeted critical occupancy at a mainline bottleneck is either set by the user or it is dynamically calculated by the critical occupancy estimation module.

Critical Occupancy Estimation Module

This module calculates the critical occupancy at motorway bottlenecks. Where and when this module is activated, the estimated value is used in the ALINEA core module as the targeted critical occupancy value. The adjustment of the critical occupancy value considers the flow / occupancy relationship that optimises capacity and prevents flow breakdown, as well as the path of flow recovery if flow breakdown has occurred.

Queue Estimation Module

For each controlled entry ramp, this module uses the flow measurements of the ramp entrance and ramp exit detectors, as well as the average occupancy of the detectors in the middle of the ramp to calculate an estimate of the current queue length on the ramp.

Demand Estimation / Prediction Module

This module estimates the arriving ramp demand and makes a short-term prediction based on past values of flow measurements on the ramp.

Waiting Time Estimation Module

This module estimates the waiting time (ramp delay) caused due to ramp meters operation based on past values of the ramp demand and the recent signal control operation. Options for approximate or exact estimation are provided.

Queue Control Module

For each controlled ramp, this module uses the estimate of the queue length of the ramp (calculated by the queue estimation module) and the ramp demand in order to calculate a desired ramp exit flow to minimise the risk of queue overspill. This flow value needs to be determined so that traffic can still be absorbed into the mainline, so as to minimise the potential for causing flow breakdown on the mainline.

Queue Override Module

This module enables the ramp entrance/surface road interface to be managed. In the event that the ramp queue will exceed the available ramp storage, a pre-specified ramp exit flow is activated to increase the metering rate. This ramp exit flow value needs to be determined so as to avoid an excessive inflow of traffic to the mainline that may trigger flow breakdown. While optimising the

motorway throughput has benefits to the road network as a whole, consideration may also need to be given to the implications of ramp queues extending onto the surface road.

Waiting Time Control Module

This module uses the waiting time estimate provided by the Waiting Time Estimation module to calculate the desired ramp flow in order to achieve a waiting time on the ramp that is less than a pre-specified maximum waiting time value.

HERO Coordinated Ramp Operation

The HERO module coordinates local ramp metering actions in order to enable efficient mainline control despite limited ramp storage spaces, while balancing ramp queues and providing equity between ramps in a coordinated system.

HERO is activated when a ramp operating under local control experiences queues that meet pre-set thresholds, based on the available ramp storage. In this event, the ramp becomes a 'master' and engages, step-by-step, upstream ramps as 'slaves.' The algorithm then balances queues between the ramps. Such clusters of coordinated ramps are created wherever and whenever necessary and may be handled simultaneously at multiple motorway locations, as required.

While the system is operating in a coordinated manner under HERO, control using ALINEA and related algorithms at each individual ramp continues according to local needs.

Minimum Queue Control Module

When coordinated ramp metering is in operation, i.e. HERO has been activated, this module uses the estimate of the ramp queue length and the ramp demand to calculate a desired metered flow rate so that the minimum queue calculated by HERO is implemented. This calculation aims to make best use of available storage on coordinated ramps and to balance queues between the ramps.

Final Ramp Flow Specification Module

This module calculates the final ramp exit flow to be applied to a ramp at the next control period. In the case of local ramp metering, the final ramp flow decision is based on exit flow values calculated by ALINEA as well as consideration of the various flow values to address ramp queue and waiting time on the ramp. In the case of coordinated ramp metering, the final ramp flow is based on ALINEA as well as individual ramp queues and the balancing of queues between ramps. The final flow rate may also be adjusted to be within pre-specified minimum and maximum flow rates.

Implementation Module

The implementation module calculates the cycle time (sum of green, yellow and red) that corresponds to the final ramp flow, considering the number of lanes at the stop line. The implemented cycle time is changed for each control period within pre-specified increments for cycle time increases and decreases.

4.3 Ramp Meter Operational Modes

4.3.1 Ramp Meters - Off (Default)

When ramp meters are not operating (default situation), the ramp, including the auxiliary storage lanes, are managed with VSL signs set to default speed limits, i.e. the VSL signs will be always on and displaying the speed limit appropriate to the operating state at that time. On motorway to Motorway ramp meters the display for warning VMS on the ramp (RC2-C) will be blank unless required for other relevant traffic situations, e.g. during an incident and the display on the mainline warning VMS for exiting motorists (RC3-C) will be blank unless required for some other relevant traffic situation.

4.3.2 Times of Operation

Ramp metering operating at an isolated ramp or within a coordinated system may be activated in a number of ways.

Dynamic Activation and Deactivation

The dynamic switch-on and switch-off of ramp meters is based on the prevailing motorway traffic conditions. A dynamic system provides traffic responsive operation that activates the ramp meter signals at any time when warranted by the motorway traffic flow conditions that could lead to the onset of flow breakdown. The activation and deactivation thresholds are set uniquely for each ramp / bottleneck during the manual fine tuning of the system.

The switch-on criteria are based on a combination of speed, occupancy and/or volume. Different criteria are used for starting up and switching off the ramp meter signals. The switching on criteria are usually set at a predetermined threshold (determined from analysis of historical conditions) to be sure that the signals start up to keep the motorway flow stable and well before the motorway flow collapses. The criteria need to be comprehensive to avoid the signals switching on at an inappropriate time, e.g. high occupancy and low speeds may occur at night due to a slow moving maintenance vehicle which may even sometimes stop on a detector. Usually, stronger criteria are used for switching off the signals to ensure the signals will not start up again soon after the deactivation.

Time of Day Activation

Although no longer broadly used by VicRoads for a primary control tool, time-of-day activation may be used according to critical periods, generally morning and evening weekday peak periods. Scheduled start-up and close-down times are chosen following an analysis of motorway and entry ramp flows during the peak periods and their respective shoulder periods. Typical times of operation would be 6:00am to 10:00am for the AM peak period and between 3:00pm and 7:00pm for the PM peak period. Other times may also be scheduled to cover known occasions outside weekday peak periods where data shows that the motorway service is at risk, e.g. Saturday shopping periods or special events.

Time of day parameters may also limit the times within which dynamic activation and deactivation may occur. Under this operation the metering signals may or may not switch on, depending on whether the criteria are met. This form of control for activation is advisable during the initial operation of a new coordinated system and when testing criteria for full dynamic activation.

During Incidents and Events

During periods of light traffic flow on the motorway (when the metering signals would normally be off), there may be advantages in using the signals to manage the headway of entering traffic or to manage the traffic flow. This may be necessary at times of a lane closure or traffic flow breakdown due to planned or unplanned incidents, e.g. roadworks, crashes etc., to assist in traffic management and/or to facilitate flow recovery (refer Volume 1, Part 2).

Manual Operation

At any time when considered warranted, VicRoads is able to manually switch on the ramp metering signals, override the dynamic operation or switch the metering signals off.

Manual operation of other traffic management devices, e.g. speed limit and lane control signs, RC2-C VMS and RC3-C VMS, including modification of displayed messages is also subject to VicRoads manual control, if warranted. Manual operation within the constraints of the system overrides default and dynamic operation.

4.3.3 Faults and Device Failures

During a communications failure (power still available), operation of the ramp metering would occur using pre-determined fixed time signal cycles which are suitable to the day of the week and time of day. In this situation VicRoads is to initiate close monitoring of the system as well as surveillance with

CCTV cameras. These signal timings are reviewed periodically to ensure their appropriateness relative to changing traffic conditions over time.

With failure of advance devices at two or more locations upstream of the ramp meters, e.g. warning signs (RC2-C), speed limit signs or VMS (RC3-C), the ramp metering signals will not switch on, or if already on, the ramp metering signals will switch off.

4.4 Switching on /off Signs and Signals

4.4.1 Start-up Sequence

The sequence for switching on typical ramp meters and associated ramp control and warning signs is shown in Figure 4-2. Details for start-up for motorway to motorway ramps is shown in Figure 4-3. Prior to start up the signals and RC1 and RC2 signs have no display.

1. Switch Sign RC1 and Sign RC2 to 'RAMP SIGNALS ON' and activate the signals to 'flashing yellow' for 10 seconds. Activate the reduced speed limit (if applicable).
2. Switch on the alternating messages on Sign RC2, if provided, and switch traffic signals to 'solid yellow' for 4 seconds.
3. Switch traffic signals to 'solid red' for 6 seconds.
4. Commence the metering cycle with the initial green and continue the metering.

For locations where combined overhead variable speed limit and lane control (VSL/LC) signs are provided on motorway to motorway metered ramps, the sequence in Figure 4-3 shows the default arrangements for lane status, i.e. displaying a speed value indicates the lane is open to traffic. Operational scenarios may exist where lanes are closed and speeds reduced due to an incident or other on-road event. Under such circumstances, ramp metering may still be permitted to start-up, however, the control system will manage a combined response to show closed lanes and other speed values based on appropriately arbitrated symbol / speed value priority. (The same principle also applies to VSL/LC signs during the close-down sequence for motorway to motorway ramp shown in Figure 4-5.)

	Device Operation and Time	RC1 Sign	RC2 Sign	Signals
1.	<p>Prior to 'Start Up'</p> <p>Signals: Off Signs: Off</p>			 ONE VEHICLE PER GREEN EACH LANE
2.	<p>'Start up' Period (10 seconds)</p> <p>Signals: Flashing yellow Signs: 'Ramp Signals On'</p>			 ONE VEHICLE PER GREEN EACH LANE Flashing Yellow
3.	<p>'Start up' Period (next 4 seconds)</p> <p>Signals: Solid Yellow Signs: 'Ramp Signals On' / 'Prepare to Stop' alternating</p>		 Alternating Messages	 ONE VEHICLE PER GREEN EACH LANE Solid Yellow
4.	<p>'Start up' Period (next 6 seconds)</p> <p>Signals: Solid Red Signs: 'Ramp Signals On' / 'Prepare to Stop' alternating</p>		 Alternating Messages	 ONE VEHICLE PER GREEN EACH LANE Solid Red
5.	<p>Signals Commence Metering</p> <p>Signals: Green-Yellow-Red Signs: 'Ramp Signals On' / 'Prepare to Stop' alternating</p>		 Alternating Messages	 ONE VEHICLE PER GREEN EACH LANE Green-Yellow-Red

Figure 4-2: Start-up Control Sequence – Typical Ramp Meter

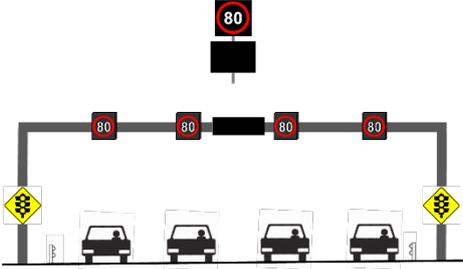
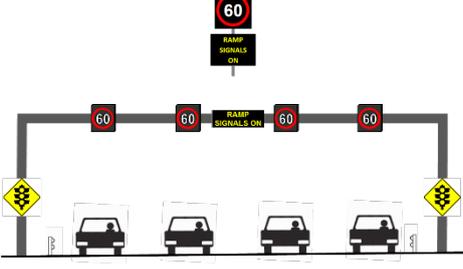
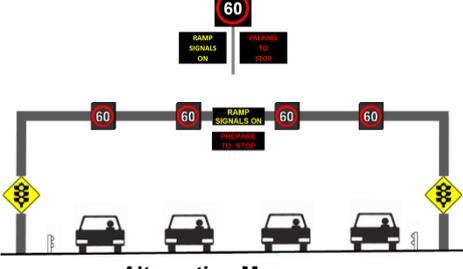
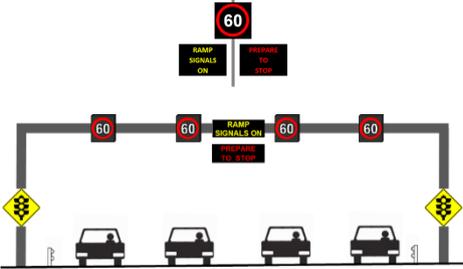
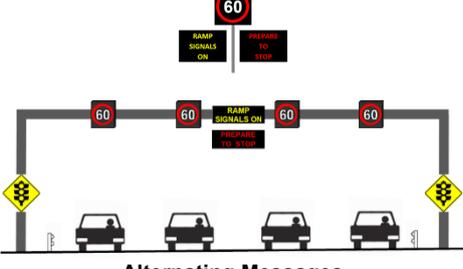
	Device Operation and Time	RC1, Mainline RC3-C	RC2, RC2-C and VSL / Overhead Lane Control (LC)	Signals
1.	<p>Prior to 'Start Up'</p> <p>Signals: Off Signs: Off VSL/LC: Default value for all lanes Mainline VMS: Default</p>		 <p>Note: The number of lanes and layout of devices varies for each ramp.</p>	
2.	<p>'Start up' Period (10 seconds)</p> <p>Signals: Flashing yellow Signs: 'Ramp Signals On' VSL/LC: Reduced on all lanes Mainline VMS: 'Ramp Signals On'</p>		 <p>Note: The number of lanes and layout of devices varies for each ramp.</p>	 <p>Flashing Yellow</p>
3.	<p>'Start up' Period (next 4 seconds)</p> <p>Signals: Solid Yellow Signs: 'Ramp Signals On' / 'Prepare to Stop' alternating VSL/LC: Reduced on all lanes Mainline VMS: 'Ramp Signals On'</p>		 <p>Alternating Messages</p>	 <p>Solid Yellow</p>
4.	<p>'Start up' Period (next 6 seconds)</p> <p>Signals: Solid Red Signs: Refer Step 3. VSL/LC: Refer Step 3. Mainline VMS: Refer Step 3.</p>		 <p>Alternating Messages</p>	 <p>Solid Red</p>
5.	<p>Signals Commence Metering</p> <p>Signals: Green-Yellow-Red Signs: Refer Step 3. VSL/LC: Refer Step 3. Mainline VMS: Refer Step 3.</p>		 <p>Alternating Messages</p>	 <p>Green-Yellow-Red</p>

Figure 4-3: Ramp Meters Start-Up Control Sequence – Motorway to Motorway Ramp Meter

4.4.2 Close-down Sequence

The sequence for switching off the signals is shown in Figure 4-4 and described below. Details for switching off motorway to motorway ramp signals is shown in Figure 4-5.

1. Activate traffic signals to 'flashing yellow' and switch Sign RC2, if provided, to 'Ramp Signals ON' only (no alternating message) for 10 seconds.
2. Switch off Sign RC1, Sign RC2, the 'flashing yellow' of the signals and return the speed limit to default or other override value (if applicable).

	Device Operation and Time	RC1	RC2	Signals
1.	<p>Signals Metering (Prior to 'Close Down')</p> <p>Signals: Green-Yellow-Red Signs: 'Ramp Signals On' / 'Prepare to Stop' alternating</p>		 <p>Alternating Messages</p>	 <p>Green-Yellow-Red</p>
2.	<p>'Close Down' Commences (10 seconds)</p> <p>Signals: Flashing yellow Signs: 'Ramp Signals On'</p>			 <p>Flashing Yellow</p>
3.	<p>Switch off Signals (Close Down complete)</p> <p>Signals: Off Signs: Off</p>			 <p>Signals off</p>

Figure 4-4: Close-down Control Sequence - Typical Ramp Meter

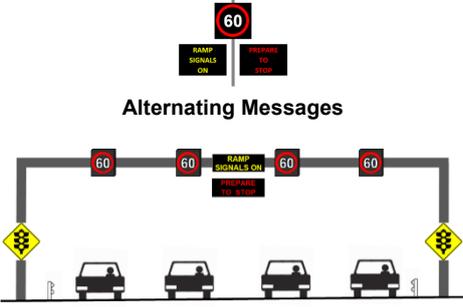
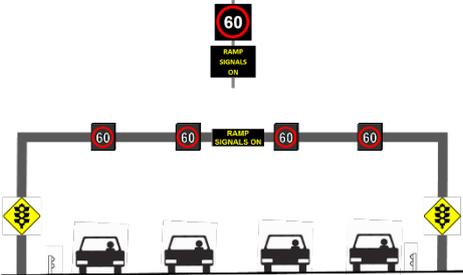
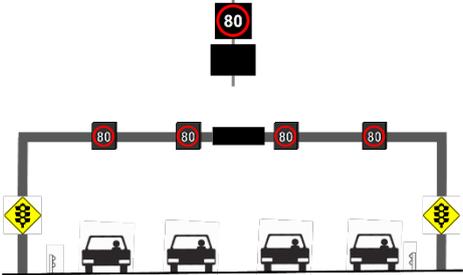
	Device Operation and Time	RC1, Mainline RC3-C	RC2, RC2-C and VSL / Overhead Lane Control (LUMS)	Signals
1.	<p>Signals Metering (Prior to 'Close Down')</p> <p>Signals: Green-Yellow-Red</p> <p>Signs: 'Ramp Signals On' / 'Prepare to Stop' alternating</p> <p>VSL/LC: Reduced on all lanes</p> <p>Mainline VMS: 'Ramp Signals On'</p>	 	 <p>Alternating Messages</p>	 <p>ONE VEHICLE PER GREEN EACH LANE</p> <p>Green-Yellow-Red</p>
2.	<p>'Close Down' Commences (10 seconds)</p> <p>Signals: Flashing yellow</p> <p>Signs: 'Ramp Signals On'</p> <p>VSL/LC: Reduced on all lanes</p> <p>Mainline VMS: 'Ramp Signals On'.</p>	 	 <p>Note: The number of lanes and layout of devices varies for each ramp.</p>	 <p>ONE VEHICLE PER GREEN EACH LANE</p> <p>Flashing Yellow</p>
3.	<p>Switch off Signals (Close Down complete)</p> <p>Signals: Off</p> <p>Signs: Off</p> <p>VSL/LC: Default on all lanes</p> <p>Mainline VMS: Default</p>	 	 <p>Note: The number of lanes and layout of devices varies for each ramp.</p>	 <p>ONE VEHICLE PER GREEN EACH LANE</p> <p>Signals off</p>

Figure 4-5: Close-down Control Sequence – Motorway to Motorway Ramp Meter

4.5 Operating Sequence and Cycle Times (not used for design)

4.5.1 Signal Timings

Ramp metering operation, which is considered differently to ramp metering design, has a variable cycle time generally in the range 4.0 to 20 seconds according to the determined metering rate. The sequence times based on one vehicle per green per lane are:

- Red Variable – generally within the range 2.0 to 18 seconds
- Green 1.3 seconds
- Yellow 0.7 seconds.

Ramp metering design uses a average cycle time as the basis for design (e.g. an average cycle time of 7.5 seconds). In operations cycle times will be variable changing as often as every 2- seconds around an average to accommodate fluctuations in demand within the network in real time.

Designers shall not nominate a lower cycle time than specified in Volume 2, Part 3: Section 6.2, in an

attempt to discharge higher flow rates into the motorway for the purposes of reducing storage provision. Such an approach reduces the necessary flexibility in operation and ramps are to be designed on the bases of ramp flows that can be achieved over a one hour period (e.g. utilising an average cycle times of 7.5 seconds – refer Volume 2, Part 3: Section 6.2 for further details).

During ramp metering operations, when there are no vehicles waiting at the stop line, the signals are to be held on red. This prevents the signals cycling when there are no waiting vehicles and helps to avoid driver confusion in relation to timing their arrival and deciding whether to stop or not.

The operation of more than 1 vehicle per green per lane (e.g. 2 or 3 vehicles per green per lane) has not been permanently implemented in Australia, although it has been used internationally (refer Volume 2, Part 3: Section 6.2). Generally, it is desirable to release a single vehicle per green per lane, even if shorter cycle times need to be adopted.

Note:

Providing separate alternating green signals for each lane to separate the departure of vehicles from the stop line is not endorsed for use at this stage. Although this practice has been used in some instances overseas, evidence is lacking on whether the operations are advantageous to performance outcomes. Observations of current operation with the simultaneous release of vehicles from the stop line indicates that motorists are able to adjust their position relative to other vehicles leaving the stop line and that separation and merging when entering the mainline is also satisfactory. Applying alternating release to metering locations with three or more lanes can limit minimum cycle times and potentially confuse motorists about when to proceed as cycle times vary dynamically.

The entry ramp flows that result from a range of cycle times with varying lane arrangements at the stop line are shown in Table 4.1. In practice, within a dynamic system the cycle time is based on the ability of the freeway to accommodate entering traffic. The signals apply to all lanes at the stop line.

Pre-set time of day signal cycle settings are used as a ‘fall back’ mode when a dynamic system experiences a fault and fail safe mode is activated.

4.5.2 Minimum Cycle Time (Operations)

The general minimum cycle time that provides a high entry ramp flow is 5 seconds for a ramp leading to a motorway merge. A general minimum cycle time of 4 seconds could be considered when ramp traffic enters the motorway via an added lane(s) – shaded yellow in Table 4.1. The minimum cycle time would generally be observed to operate under light mainline conditions, e.g. during the fringe of the peak periods or where the upstream mainline motorway flow is interrupted due to an unplanned incident. However, low cycle time values are not appropriate in design as an average value over the design hour (refer Volume 2, Part 3: Section 6.2).

Cycle times lower than the minimum indicated are not generally recommended as this could approach a situation where the discharge of vehicles is almost continuous and the metering is relatively ineffective in managing headway. However, lower cycle times during operations under certain conditions may be appropriate subject to trial and assessment of driver behaviour.

4.5.3 Maximum Cycle Time (Operations)

The general maximum cycle time that provides a low entry ramp flow is 16 seconds and would be implemented when freeway mainline flow is close to or above critical values of occupancy. Higher cycle times, shaded pink in Table 4.1, may be implemented subject to adopted operational management strategies and driver acceptance, such as in situations of very heavy motorway congestion, during an incident or when the motorway is recovering from an incident (refer Volume 1, Part 2).

Cycle Time (sec)	Cycles per hour (No.)	Equivalent Ramp Flow per hour (veh/h)			
		No. of lanes at Stop Line			
		1	2	3	4
4.0	900.0	900	1,800	2,700	3,600
4.5	800.0	800	1,600	2,400	3,200
5.0	720.0	720	1,440	2,160	2,880
5.5	654.5	655	1,309	1,964	2,618
6.0	600.0	600	1,200	1,800	2,400
6.5	553.8	554	1,108	1,662	2,215
7.0	514.3	514	1,029	1,543	2,057
7.5	480.0	480	960	1,440	1,920
8.0	450.0	450	900	1,350	1,800
8.5	423.5	424	847	1,271	1,694
9.0	400.0	400	800	1,200	1,600
9.5	378.9	379	758	1,137	1,516
10.0	360.0	360	720	1,080	1,440
10.5	342.9	343	686	1,029	1,371
11.0	327.3	327	655	982	1,309
11.5	313.0	313	626	939	1,252
12.0	300.0	300	600	900	1,200
12.5	288.0	288	576	864	1,152
13.0	276.9	277	554	831	1,108
13.5	266.7	267	533	800	1,067
14.0	257.1	257	514	771	1,029
14.5	248.3	248	497	745	993
15.0	240.0	240	480	720	960
15.5	232.3	232	465	697	929
16.0	225.0	225	450	675	900
16.5	218.2	218	436	655	873
17.0	211.8	212	424	635	847
17.5	205.7	206	411	617	823
18.0	200.0	200	400	600	800
18.5	194.6	195	389	584	778
19.0	189.5	189	379	568	758
19.5	184.6	185	369	554	738
20.0	180.0	180	360	540	720

Table 4.1: Equivalent Hourly Ramp Flows relative to Cycle Time and Lanes at the Stop Line for operations

5 Ramp Signals Integration with other Managed Motorway Operations

5.1 Ramp Signals Response to a Lane Closure

When an incident results in a lane closure, this induces a significant bottleneck that would generally have a major adverse impact on traffic flow. Lane closures of this nature are random and variable in relation to nominated (pre-set) bottlenecks within the setup of the freeway ramp signals. A lane closure activated by the lane use management system (LUMS) or at other locations not controlled by LUMS, restricts the number of lanes for the traffic flow.

When a lane closure occurs, the motorway management system can provide the number of lanes available at a relevant bottleneck location and / or utilise flow weighted data inputs to control algorithms. The lane closure situation is addressed within the control algorithm to determine the critical bottleneck from a number of potential downstream bottlenecks. The multiple bottleneck capability within the algorithm will automatically evaluate the critical flow conditions and regulate the ramp flow accordingly.

5.2 Ramp Signals Response to Changing Speed Limits

Freeway ramp signals switch on and off automatically within thresholds based on freeway flow, travel speed and occupancy. When the freeway speed limit is reduced by a variable speed limit system (VSLS), the ramp signals could activate unnecessarily under fixed value activating parameters.

In a managed motorway, a variable speed limit lower than the default speed may be activated in concert with LUMS or for other reasons, e.g. high winds on a bridge. The lower travel speed of traffic may affect pre-set values for activation and deactivation of the freeway ramp signals. To ensure that ramp metering is not falsely triggered by a reduced speed limit alone, the freeway management system can provide the current speed limit value for calculations associated with the ramp signals and also use complementary real-time measures to determine the need to start-up.

5.3 Ramp Signals Response to a Freeway Closure

When an event requires a ramp closure, either of the ramp or the downstream section of freeway, the following operation will occur:

- The Real Time Information Signs (RC3) will display the appropriate freeway closed message as outlined in the Managed Freeways Handbook for Lane Use Management, Variable Speed Limits and Traveller Information (VicRoads, 2013), and
- The RC1 sign will display a FREEWAY CLOSED message alternating with a symbolic No Right Turn / No Left Turn / No Entry sign or Special message as appropriate, and
- The freeway ramp signals will switch off by initiating the usual close-down sequence. Switching off the signals enables vehicles already on the ramp to clear so that an emergency vehicle can enter, if necessary. Switching the signals off also avoids vehicles being trapped on the ramp. Further entry of vehicles is restricted by the RC1 and RC3 signs.

The ramp closure operation may be activated manually or automatically as part of an incident response. Reopening of the ramp may also be initiated manually or automatically when there is no longer a need for the closure. When the freeway ramp is reopened to traffic the system would return to default ramp operation, i.e. subject to traffic needs at the time, the ramp signals start-up operation may or may not occur.

5.4 Emergency Vehicle Access when Ramp Signals are Operating

The queues at ramp signals may present problems for emergency vehicle access during an incident where the ramp is not closed as part of the incident response. Where an emergency vehicle requires access at a particular ramp, the emergency service will need to contact the Traffic Management Centre (TMC).

To provide uninterrupted access for the emergency vehicle the TMC operator will manually turn off the ramp signals to clear the ramp queue. After entry of the emergency vehicle the operator would then re-enable the ramp signals to continue the metering.

6 Benefits of Ramp Metering

6.1 Qualitative Benefits

There are a number of qualitative benefits that result from ramp metering. These include:

- Reduced overall trip delay for users of the road network.
- A more reliable service to motorway users.
- Reduced number of mainline traffic incidents and the consequential impacts of crashes.
- Increased motorway throughput at critical times and locations.
- Enhanced overall road network travel times. The gain in better operation of the motorway more than offsets the additional time taken for traffic to enter the motorway. The efficient and higher capacity motorway operation also improves the road network performance as a whole.
- Equitable use of the road network including distribution of traffic consistent with infrastructure capacity and discouraging the use of the motorway system for short trips during periods of high flow.
- Improved road safety due to safer management of merging traffic and more stable motorway travel, i.e. reduction in stop-start traffic conditions.
- Reduced fuel consumption and emissions as a result of efficient travel conditions.

6.2 Quantitative Benefits for the Motorway – Monash Freeway Example

The VicRoads Before and After Study of the Monash Freeway Managed Motorways (Managed Motorway Framework, 2017) showed reduced congestion and improved safety over the 5-year periods measured before and after the upgrade project over a freeway length of 25.5km spanning 14 interchanges.

6.2.1 Traffic Throughput and Travel Speed

There are significant quantitative benefits that result from preventing flow breakdown with coordinated ramp metering operations. Based on the Monash-CityLink-West Gate (M1) Upgrade project, the operational capacity performance benefits documented in the VicRoads Managed Motorways Framework (2017) included an increase in carriageway flows greater than 56% for the length widened from 3 lanes to 4 lanes as shown in Figure 6-1. Widening may have accounted for an increase in the order of say 33% (potentially less due to lower lane capacities for 4-lane motorways), i.e. over 23% increased capacity attributed to the HERO-LIVE coordinated ramp metering. The increases in flow and speed also resulted in increased productivity.

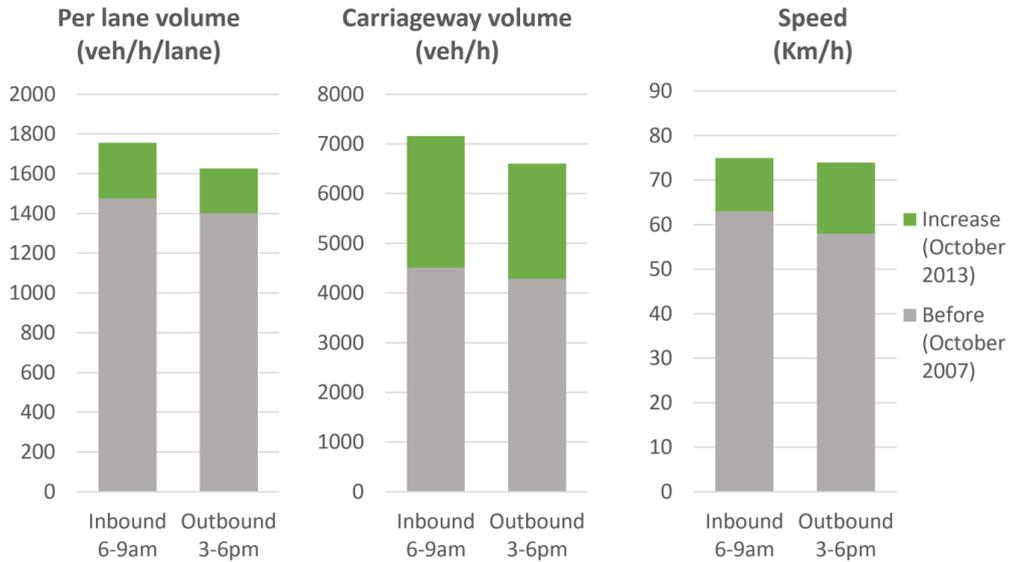


Figure 6-1: Monash Freeway Summary of Increases in Volumes and Speed

6.2.2 Safer Operation

There are significant quantitative safety benefits that result from improved operation with coordinated ramp metering signals. The VicRoads study showed that crash numbers, crash rates and severity all reduced despite the busiest sections having more than 60,000 additional vehicles per day in the ‘after’ period. Other studies have previously shown the adverse safety effects of congested motorways, (e.g. (Golob T, Recker W, Alvarez V, 2003)) and hence imply that maintaining smoother traffic is likely to improve safety.

The VicRoads study showed the following safety benefits:

- Reductions in casualty crash numbers (fatal, serious and other injury) as well as the crash rate as shown in Figure 6-2. This is discussed in detail in Volume 1, Part 4.
- A reduction in crash rates as shown in Figure 6-3, even though crash rates on other unmanaged Melbourne motorways generally increased. This was achieved even with significantly higher average speeds (+20km/h).

More recent studies of motorway crashes are contained in Volume 1, Part 4 where the relationship between “Traffic State” and crashes has been explored which reveals further potential for ramp meter and DVSL operations to activate earlier to avoid crashes.

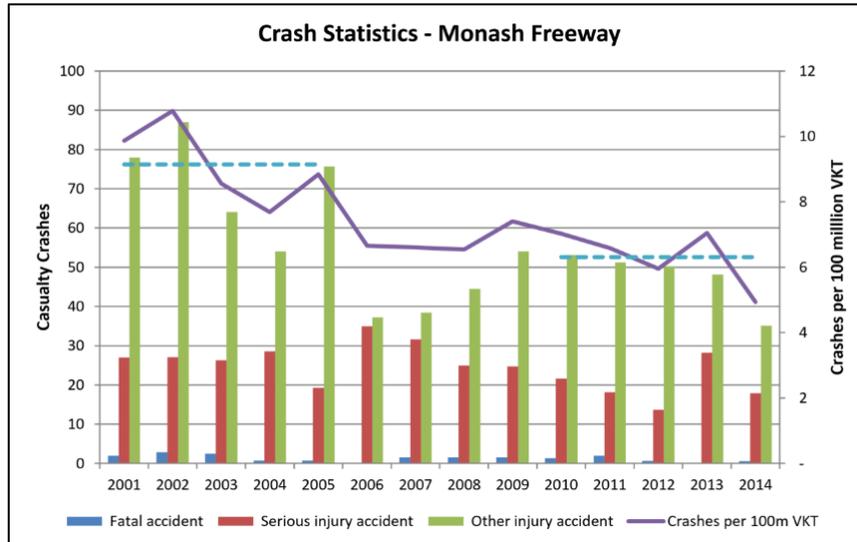


Figure 6-2: Monash Freeway Crash History: Before and After Upgrade

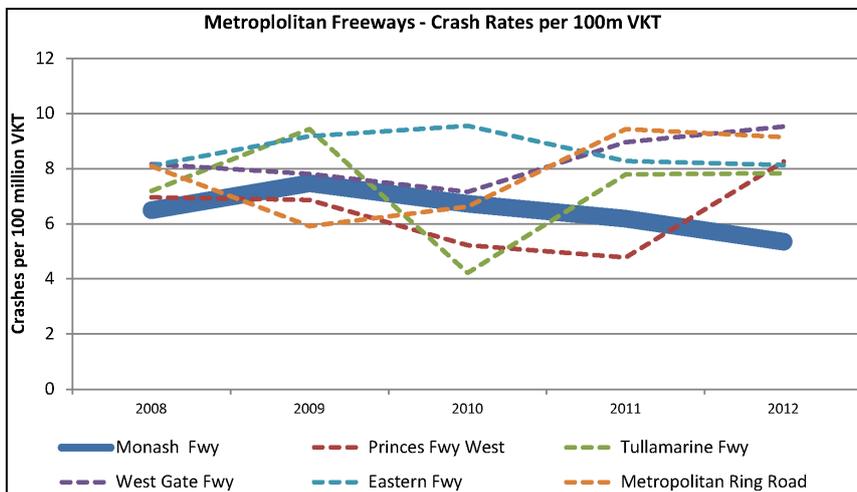


Figure 6-3: Crash Rates on Melbourne’s Urban Motorway Network

6.2.3 Quantitative Benefits for the Arterial Road Network

The benefits of managed motorways with coordinated ramp metering to achieve higher sustainable motorway flows has also been demonstrated in the context of the adjacent and broader arterial road network. These studies include:

- The business case modelling undertaken for the Monash-CityLink-West Gate (M1) Upgrade project to justify the project benefits demonstrated that with a 10% increase in efficiency on the motorway, and a 30% increase in efficiency was shown on the broader arterial road network when the motorway is operated at a higher productivity (flow x speed).
- Study by Haj-Salem & Papageorgiou (Hadj-Salem & Papageorgiou, 1995) where field trial results are reported when applying a ramp metering strategy to an urban corridor network (Corridor Périphérique in Paris) including a motorway, a parallel arterial, and connecting radial streets. The impact of ramp metering on corridor traffic is studied by comparative evaluation of several performance indices in the cases with and without control. The main finding is that application of an efficient ramp metering strategy considerably improves traffic conditions not only on the motorway but also on the parallel arterial and on the whole network within the broader corridor. This improvement is found to be even more accentuated in presence of nonrecurrent congestion caused by traffic incidents.

Direct comparative metrics are not currently available to do a quantitative analysis of the overall performance of the Melbourne arterial road network. However, qualitative assessment clearly shows that in the reverse case, when the flows on the Monash Freeway are impacted by non-recurrent congestion, e.g. incidents, the operation on the surrounding arterial road operations is significantly and detrimentally impacted.

High network demands are best managed by operating motorways at their greatest efficiency. This reinforces the need for sound organisational operational strategies as the network needs to be managed as a single network in an organised and coherent way rather than parochial way. Network Wide Strategic Models are a good tool to assess the economic performance of managing the network as it can be shown when the motorway network coughs (degrades) large parts of the entire city are affected with gridlock (refer Volume 1, Part 1 which shows the M1 Motorway services more than 50,000 trips each hour along its entire length for 12 hours a day with up to 60,000 trips per hour in the peaks).

7 Exit Ramp Management System

7.1 Managing traffic leaving the motorway

Growing demands on urban motorways have led to increasing pressures on the capacity of motorway exit ramps and arterial road interchanges. If queues from exit ramps extend back onto the motorway, this reduces the capacity of the motorway and increases the risk of crashes. Effective management is required to avoid long exit queues and to respond to queues that do occur. VicRoads has developed and deployed an Exit Ramp Management System (ERMS) to facilitate this function and the development of this system provides the potential to also fulfil the function of the End-of-Motorway Management System (EMMS) listed in Table 1.1. The ERMS can pass the status of queues and the various movement demands across to the arterial road signalling system (SCATS), upon which actions can be taken to increase priority when temporal traffic conditions indicate a potential or active operational and safety problem with the motorway.

High exit ramp flows may be a reoccurring issue during peak periods or as a result of a major incident or severe congestion on the mainline or sometimes occurs on the arterial road downstream of the exit ramp. Real time operations require the continual monitoring of exit ramp queue status (including the separate movement demands i.e. left right and through movements) and tools that to the extent possible can provide addition ramp discharge priority at the arterial road interchange to facilitate the various movement demands, and to create the path for the traffic to be dispersed into the arterial road network. This may activate a sequence of coordinated arterial signal strategies and plans to make an exit path for the temporary demand to be moved through and away from the affected interchange. Where the arterial road is experiencing a major blockage it may be necessary to advise motorists via the motorway VMS to leave the motorway at an earlier or later off ramp to reduce the safety issue associated with the blockage. In extreme situations it may be necessary to close the exit ramp with the LUMS system.

7.1.1 Estimation of exit queue length

The first step in managing exit queues is the measurement or estimation of the exit queue length, and as an extension the calculation of the proportion of ramp capacity used and the extent to which a queue may extend onto the motorway. The estimation of exit queue length uses an algorithm informed by the vehicle detection placed at multiple locations on the exit ramp and the motorway. An estimate of actual queue length and movement demands (e.g. left, right and through) is determined from these inputs, not only whether slow moving traffic is present at any particular detection location. Where an exit ramp feeds a motorway connector entry ramp with ramp metering, the estimation of queue length on the ramp is undertaken within the processes to manage that ramp metering control (refer to Section 4.2).

7.1.2 Adjustments to traffic signal operations for arterial exit ramps

When long queues are detected by the exit queue length estimation process, the motorway management system may request the arterial traffic signal system to adjust traffic signal timings at and near the interchange. The nature of the adjustments made to traffic signal timings depends on the configuration for each site. If a queue on the exit to an arterial road extends onto or near the upstream motorway mainline, it may be appropriate for the road operator to reduce the speed limits and/or provide VMS warning messages upstream as part of the management to the disruption or hazard.

7.1.3 Adjustments to speed limits on motorway connector ramps

Where the ramp is a motorway connector ramp with ramp metering controlling entry to the downstream motorway, the standard design for these ramps includes variable speed limit

functionality. Variable speed limit signs on the ramp are an integral part of the ramp metering solution. A 60km/h limit is automatically displayed on variable speed limit signs on the ramps when ramp metering is active for the area where the queue is estimated to occur and a short way in advance of that queue. The 60km/h variable speed limit applied in the queueing area on motorway connector ramps during regular metering operations does not automatically cause a speed reduction on the upstream motorway. This differs from the speed buffering approach generally applied for LUMS provided along mainline carriageways.

Additional warning signs and messages are provided for motorway connector ramps as part of the standard design to help manage this situation. If a queue on a motorway connector ramp extends onto or near to the upstream motorway, it may be appropriate for the road operator to reduce speed limits and/or provide VMS warning messages upstream as part of the disruption and hazard management function.

8 Interface at Surface Road Interchanges

8.1 Interchanges

The surface road interchanges and the road network connecting with the motorway need to be appropriately designed, integrated and managed for an effective motorway / surface road interface. The VicRoads Motorway Operational Objectives (2004) indicate that:

“The economic imperative is that, when necessary, the motorway network is to be given priority over the arterial road network and, where this would result in a negative impact on the arterial network, this should be managed accordingly to provide a net overall gain to the system’s users”.

Generally, if the motorway is able to carry more traffic in the peak periods or across the day, it follows that the operation of surface roads will also be more efficient, compared to a situation where motorways are left unmanaged (refer Section 6.2.3).

The implications at surface road interchanges relate to the capacity, management and operation of interchanges as well as the entry ramps and exit ramps for managing queues. This reinforces the importance of achieving adequate capacity and desirable standards in design, particularly for the entry ramp discharge capacities and storage. Interfacing of the motorway management system with the surface road traffic signal system (SCATS) is also available. Further information and guidance relating to interchanges is provided in Volume 2, Part 3: Sections 8 and 9.

It is also desirable to provide information for motorists on the surface road relating to estimated motorway travel time or incidents before they enter the motorway. This is achieved with strategically located signs to assist motorists with their route choice decisions. Further guidance on traveller information is provided in Volume 2, Part 4.

There may be situations where a redistribution of demand should be sought as a managed outcome. In these situations, the availability of alternate routes and the adequacy of the road network to accommodate route diversions need to be considered. The diversion of traffic is most effective where there is a well-connected road network and/or a significant proportion of entering traffic is undertaking short trips.

8.2 Entry Ramps

Prior to the introduction of coordinated ramp metering by VicRoads across Melbourne, motorways would regularly breakdown and operate in the lower LOS F categories i.e. F1, F2 F3 and F4 (refer Volume 1, Part 2: Section 3.5) often with very slow operating speed in the range 25- 40km/h excessively long delays and unreliable travel times. Under these conditions the traffic would regularly back up the entry ramps and block the arterial road system, often for a considerable distance. With the introduction of coordinated ramp metering, considerably higher levels of demand can be managed entering the motorway and travelling along the motorway each hour. This delivers more traffic to the exit ramps and necessitates that exit ramps be designed for the increased exit flows as part managed motorway upgrades. When entry ramps are designed in accordance with Volume 2, Part 3 HERO-LIVE can generally manage ramp demand to be contained within the total ramp storage provided across the motorway network.

The intention of CWCRM, is to create a series of small local delays at numerous entry ramps and only when necessary to do so, i.e. the ramps act as temporary ‘retarding basins’ to ensure the motorway traffic flow is optimal and to deliver traffic smoothly to the motorway. Where excess demand is permitted to regularly ‘flood’ the motorway, flow breakdown causes vehicles to ‘store’ on the mainline which can then to quickly back up the ramps onto the arterial road. While ramp meters may be perceived (by the observer or layperson) as a significant cause of delay, for most motorway trips, the

improved motorway flow will result in lower overall network delay. Unfortunately, many current day observers have either forgotten, or were never aware of, the prior situation when the congestion on motorways and surface roads was far greater when the network was left unmanaged. Entry ramps also experienced lower hourly flows with the motorway carrying considerably less trips each hour and over the day compared with post-managed conditions. A useful reference is contained in Appendix B – A Short History of Ramp Metering.

At some locations excess demand may need to be constrained at certain times to achieve the overall benefits and coordinated management of queues. An interface with the surface road traffic signal system (SCATS) also enables integrated control strategies to be implemented. A concern about 'overflow' effects on a connecting surface road reinforces the need for good entry ramp design, and this also needs to be considered alongside the overall traffic management objectives and road network benefits.

In Melbourne it has been possible to service higher ramp and mainline demands by operating motorways more efficiently, and in so doing, service much higher network-wide demands. This reinforces the need for sound organisational operational strategies and control system settings that avoid the release of higher than system-calculated flows when there are long ramp queues (sometimes termed 'flushing' of the ramp).

If flows higher than those calculated by the control system are released when there is inadequate ability for such flows to be accommodated on the mainline, motorway operation and safety is highly likely to be severely impacted creating flow breakdown either at the subject ramp or elsewhere in the system. If flow breakdown does occur, this will also impact the ability to service demands at other entry ramps and may also impact the performance of the surface road network as a whole. The damage to flow stability can happen very quickly, so the system as a whole may not always be able to compensate fast enough through restricting other entry ramp flows.

Using the ramp metering approach outlined in this Guide can never guarantee congestion will be eliminated. The occurrence of incidents and unexpected events are beyond the ability of optimisation control tools to predict or prevent. However, even when congested conditions may occur, be it from recurrent or non-recurrent conditions, it has been assessed that travel times and throughput are superior to unmanaged conditions. Quicker recovery from congestion is also experienced.

Further information relating to the design of entry ramps including discharge capacity, storage and geometric layouts is provided in Volume 2, Part 3: Sections 6 and 7.

8.3 Exit Ramps

Likewise traffic flow on the motorway mainline is affected when traffic queues on an exit ramp extend back to block the left lane of the motorway or cause traffic to slow down prior to exiting. In these situations; the available motorway capacity is reduced through the reduced utilisation and potential blocking of the left lane. Lane changing to avoid the left lane queue also occurs which increases turbulence and causes further potential for flow breakdown across the whole mainline carriageway. A significant safety problem can also emerge for both exiting and continuing traffic.

The management of mainline flows through ramp metering will generally produce an increase in throughput which will result in increased exit flows. Therefore, increases in capacity at interchanges needs to be analysed and considered. Section 7 of this Guide provides an overview of the Exit Ramp Management System. Further information relating to the design and management of exit ramps is provided in Volume 2, Part 3: Section 9.

9 Ramp Metering Myths and Misunderstandings

9.1 Introduction

Ramp metering principles have changed significantly since the first ramp metering was conceived many years ago. Over the last 10 years there has been substantial growth in VicRoads knowledge and understanding of traffic behaviour, motorway and ramp metering design, and sound operational strategies.

The current VicRoads holistic approach to Managed Motorway technology represents a highly developed science that has resulted in proven on-road, evidence-based motorway performance. This has resulted in improved Managed Motorway outcomes for VicRoads as a road manager and for a broad spectrum of road users. State-of-the-art understanding of Managed Motorway design and operations are aspects of traffic management not generally taught in academic institutions, and relatively few practitioners are engaged in advanced aspects of application and practice. Therefore, there can be varying opinions (and misunderstandings) between what may be science fiction (or fear), and science fact in relation to advanced coordinated ramp metering. Road users can also be unclear about the operational significance of ramp metering as their perceptions are generally the result of individual observation which can mask the perspective across broader network and all-road users'.

Table 9.1 provides a range of responses to some common misconceptions or questions about ramp metering which address some commonly expressed views and also clarify current best practice thinking.

Comment / Question		Quick Answer	Response
Ramp Metering Operation			
1.	Metering is just about the ramp merge.	False	<ul style="list-style-type: none"> Managing the ramp merge is necessary and may get more traffic into the motorway, but this also results in more traffic arriving at downstream mainline bottlenecks. Coordinated control uses feedback that also manages demand arriving at distant downstream bottlenecks. While breaking up vehicle platoons (bunching) on a ramp reduces turbulence and makes it easier to merge, coordinated (system) ramp metering also benefits the overall motorway performance.
2.	Ramp metering reduces ramp flows and causes increased delays.	False	<ul style="list-style-type: none"> A small delay shared across multiple ramps results in more reliable motorway journeys, higher flows and shorter travel times for more motorists. When motorways are allowed to breakdown, less traffic gets through and delays for all motorists increase significantly. Excessive ramp queues are usually a result of the motorway being allowed to breakdown or by restrictive metering endeavouring to recover the flow.

3.	The motorway is flowing freely so metering does not need to be on.	False	<ul style="list-style-type: none"> • A well-managed motorway may look relatively 'empty' as the traffic is kept moving. At optimum productivity the spacing of vehicles is in the order of 40 to 50 metres. • A productive motorway (with high speed and high traffic flow) is typically 80-90% empty space (gaps between vehicles). • When a motorway starts to become unstable it is usually too late to intervene. Metering needs to be on early to maintain flow stability. • Events that lead to flow breakdown can occur very quickly (less than a minute) and at relatively moderate flows (LOS C) (refer Appendix A). • Travel time from a ramp to a distant problem can often be several minutes so timely action is needed.
4.	Do drivers need to stop if there are no problems on the motorway?	Yes	<ul style="list-style-type: none"> • Ramp metering signals are traffic control devices so motorists must stop on red and then wait for a green light.
5.	Ramp metering aims to align vehicle release with gaps in the left lane traffic.	False	<ul style="list-style-type: none"> • While this was an objective of early ramp metering, it is now known that the whole carriageway needs to be managed to minimise turbulence and flow breakdown. Focusing on the left lane alone near the motorway merge is likely to overload the motorway at downstream bottlenecks
6.	Should ramp metering signals alternate for each lane as used overseas?	No	<ul style="list-style-type: none"> • There is nothing to be gained by alternating lane operation. Releasing vehicles together provides greater discharge capacity (if the motorway can accommodate more traffic) and more operational flexibility. • Some overseas jurisdictions need to release vehicles in each lane separately as their design standards provide minimal space for merging. Australian ramp metering design standards (merging and acceleration) provide for safe operation with vehicles leaving together or merging when ramp signal are off.
7.	Why is there congestion if ramp metering signals are operating?		<ul style="list-style-type: none"> • In the real world it is not always possible to prevent flow breakdown due to strong fluctuating demands and capacity (i.e. their stochastic nature), but if it is to occur, this can be delayed and their frequency reduced to minimise impact. • A well-designed and operated system (with Managed Motorway specialists and performance analysis and system refinement) will minimise the flow breakdown potential and improve safety. Insufficient control may result from inadequate design or operations.
8.	Should a full ramp queue be flushed to avoid overflow onto the surface road?	No	<ul style="list-style-type: none"> • VicRoads needs to balance needs and priorities according to safe and efficient principles. • Sudden ramp flushing generally worsens system safety, throughput and delays. • Just a few too many ramp vehicles can cause flow breakdown which would impact thousands of mainline travellers for the rest of the peak period. • Dumping traffic into the mainline could potentially have worse safety outcomes than queuing on the surface road due to the potential for higher differential speeds between vehicles. • In a safe and regulated manner, the system aims to: <ul style="list-style-type: none"> ○ Manage queues within the ramp length. ○ Discharge traffic without exceeding mainline capacity. ○ Compensate at other ramps by balancing queues and waiting times. • Meeting ramp design storage standards minimises the potential for queue overflows. Shorter trips may be discouraged from using the motorway where alternatives exist.

Ramp Metering Design			
9.	If a ramp enters as an added lane it does not need to be metered?	False	<ul style="list-style-type: none"> Coordinated ramp metering is about managing bottlenecks along the motorway, not just near a ramp. Added lane arrangements are typically provided because there is a high demand at the ramp. These ramps can contribute significantly to downstream bottlenecks being activated and require control. Effective control requires all ramps to be controlled. Even one uncontrolled ramp can cause flow breakdown.
10.	Can ramp metering resolve capacity deficiencies in design, e.g. inadequate number of mainline lanes?	No	<ul style="list-style-type: none"> Coordinated ramp metering has the potential to increase operational capacity by about 15% relative to an unmanaged motorway – but is not a panacea for fixing all motorway problems. Ramp metering cannot replace the need for an additional lane if this is necessary to meet traffic demand.
11.	As vehicles are already within the motorway system, do motorway-to-motorway ramps need metering?	Yes	<ul style="list-style-type: none"> Ideally, all vehicles entering a managed route must be controlled to manage the mainline operation. Motorway-to-motorway ramps are generally high volume ramps which can easily cause flow breakdown on the downstream motorway. Even if the motorway enters with an added lane traffic may still impact other downstream traffic operations. See Item no. 9 above.
12.	Does a separate lane for priority users on an entry ramp need to be metered?	Yes	<ul style="list-style-type: none"> All vehicles entering a Managed Motorway must be controlled for the benefit of all road users, including priority vehicles. Experience with uncontrolled priority access shows that the clustering of just a handful of vehicles, such as trucks, can contribute to flow breakdown and resulting congestion. On metered priority lanes, ramp queues and delays for priority vehicles are designed to be less than other general traffic.
13.	Ramps entering collector-distributor (CD) roads do not need ramp metering.	May be true	<ul style="list-style-type: none"> Some CD roads need to have their ramps metered if metering would alleviate capacity or weaving turbulence. Management of multiple, separated carriageways needs analysis and consideration during design. During design, a decision will be required about whether to meter the ramps entering the CD and/or meter the CD connection back to the mainline. A range of inputs and constraints need to be assessed to arrive at an appropriate design and control arrangement.
14.	If ramps are controlled entering a CD road there is no need to control the CD road entering the mainline.	May be true	<ul style="list-style-type: none"> Ideally, all entries to the mainline generally need to be controlled to minimise bunching of vehicles and to ensure the mainline can be managed effectively downstream. During design, a decision will be required about whether to meter the ramps entering the CD and/or meter the CD connection back to the mainline. A range of inputs and constraints need to be assessed to arrive at an appropriate design and control arrangement.
15.	Does combining ramps to provide a single high flow entry make control easier?	Possibly not	<ul style="list-style-type: none"> Combining flows into a single high flow ramp with one meter may create problems for: <ul style="list-style-type: none"> Designing ramp discharge capacity and storage. Controlling strong bottlenecks. Separate metering allows individual queue management and may enable improved queue balance and priority. Sometimes this is the only option available due to site constraints.

The Future			
16.	Will ramp metering be needed in the future with automated vehicles (AV) and/or connected vehicles (CV)?	Yes	<ul style="list-style-type: none"> • Future vehicles with the ability to manage headway and communicate with each other (and infrastructure) may improve some aspects of motorway operation. Such benefits may only occur when the majority of vehicles are connected to real-time traffic network control systems. • However, in the short to medium term they will not understand the 'big network picture' (e.g. a bottleneck located some kilometres downstream) relating to system traffic demand, nor be able to resolve complex traffic issues. • While AVs and CVs may improve safety, real-time traffic system operation at a local and network level will be essential (with further enhancement) to manage overall outcomes.
Implementing Managed Motorways			
17.	Just adding some ITS devices to an existing motorway and some control system updates will achieve the desired outcomes.	No	<ul style="list-style-type: none"> • The holistic Managed Motorway approach requires new thinking to be applied to how a motorway is configured, how ITS is integrated and how it is operated. • The physical design of motorways is a critical determinant of bottleneck locations and needs to be based on understanding contemporary traffic flow theory combined with aspects of control engineering through appropriate devices to enable complex real-time control and optimisation. • The approach requires integration of different ITS systems and devices on a common platform to enable the tool-chains to feed consistent and reliable inputs and delivers unique, intelligent and context driven arbitrated solution to the motorway network on a regular basis. • Organisational commitment is required to ensure that operational tuning strategies are targeted at preventing flow breakdown for sustained periods and avoiding actions that risk destabilising motorway flows.
18.	Does the VicRoads system provide full functionality “out of the box”?	Probably not	<ul style="list-style-type: none"> • While a lot of functionality has been incorporated into the control system used by VicRoads, aspects have been developed and configured for the specific regulatory and operational context that applies within the State of Victoria. • There will be many common aspects across jurisdictions, however, there may also be specific conditions that either don't apply or may not be catered for within the approach developed to date. • Application of the control tools used by VicRoads requires deep understanding of the local context and operational complexity that exists with each unique motorway network. • Highly skilled operators will always be required with in-depth knowledge of how the motorway network “behaves” and are informed by robust analysis of real-time and statistical historic performance outputs. Oversight and tuning of the system will always be required in-line with consistent commitment to achieving optimised outcomes that deliver sustained flows and safe operations. • While considerable effort may be required to change an operational control paradigm, the potential benefits to the performance of motorways networks and the broader road network are significant.

Table 9.1: Common Misunderstandings and Clarifications

Appendix A

Ramp Metering - Information Bulletin

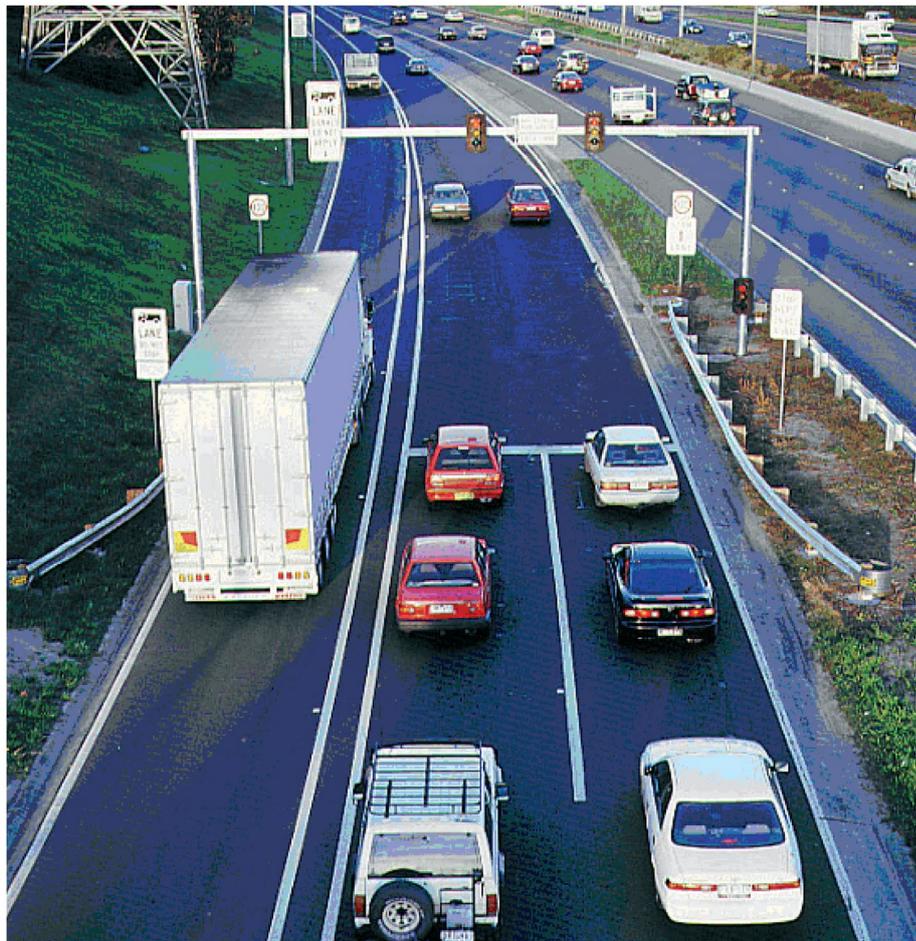
This Appendix provides an example of a Managed Motorway Ramp Metering Signals Information Bulletin.



Freeway Ramp Signals

An intelligent system to maximise freeway performance

INFORMATION BULLETIN



Introduction

Traffic congestion is common on Melbourne's freeways during peak times and often occurs around freeway entrances where a surge of traffic enters the freeway. This can cause the traffic on the freeway to slow down and sometimes results in stop-start conditions, which means the freeway operates well below its maximum capacity.

Congestion and stop-start conditions on freeways delay traffic, cause frustration for motorists, extend journey times and increase the risk of crashes. Journey times are often three to four times higher during the peak period compared to the off-peak period.

In 2002, VicRoads introduced a new system to make the freeway travel easier, safer and more reliable. This system has been successfully implemented at more than 10 sites on Melbourne's freeway network. This system uses traffic lights to allow traffic entering the freeway to join safely and easily with the freeway traffic. The current system has been operated in an isolated manner at each site and has improved the freeway performance. However, ongoing monitoring has indicated that the freeway is still operating below its maximum capacity.

To meet current and future needs of the road network, VicRoads is implementing an improved and coordinated control system. The new Freeway Ramp Signals are designed to improve the quality of service to all traffic entering the freeway. A state-of-the-art technology from Europe is incorporated into the new system.

What are Freeway Ramp Signals?

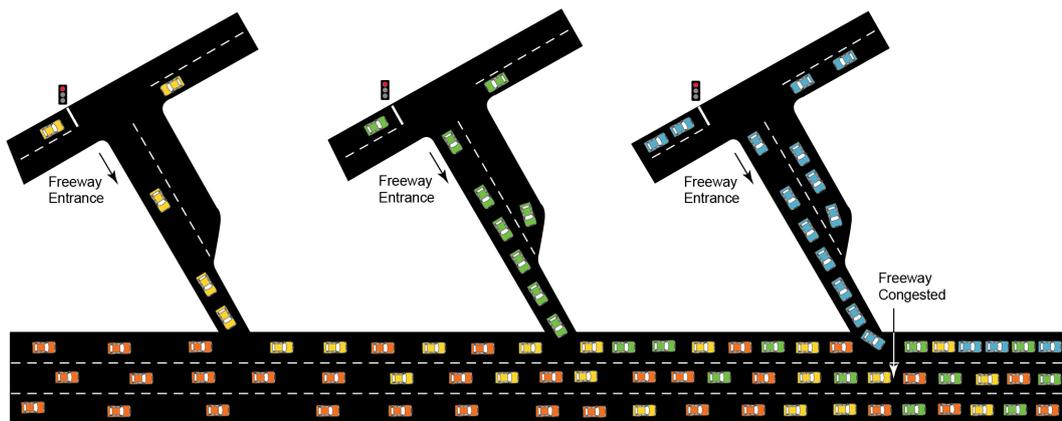
The new system will be dynamic and responsive to traffic creating the ability to manage traffic along a freeway corridor rather than at individual locations. This enables a number of consecutive ramps to be regulated to balance traffic along the route so that the freeway operates to provide optimum performance. The coordinated system will manage and control entering traffic to minimise stop-start conditions which are brought about by a high volume of traffic or incidents. The system would also enable faster recovery from a freeway incident.

As part of the Monash-Citylink-Westgate Upgrade Project, Freeway Ramp Signals will be initially installed between Narre Warren and Werribee. The system will manage access to the freeway to enable:

- easier merge;
- safer flow;
- smoother flow (less variation in speed);
- minimal delays;
- reliable travel time (travel certainty); and
- higher efficiency (up to 10 percent increase in traffic throughput).

Figure 1 Before the implementation

- ★ Congested - stop/start condition
- ★ Long delays
- ★ Variable travel time
- ★ Low efficiency - (poor flow)



Every vehicle entering the freeway contributes to the freeway congestion

What do I see on the road?

Electronic message signs at the freeway entrance let you know if the Freeway Ramp Signals are operating.

Freeway Ramp Signals are located part way along the freeway entrance. They have the same meaning as other traffic signals. However, the traffic cycle will be much shorter than normal - typically the waiting time at a red light varies between 5 and 15 seconds in response to freeway conditions. When traffic flow along the freeway route is high, you may need to wait longer before entering the freeway.

A stop line is painted on the road next to the traffic lights to show you where to stop.



Freeway ramp signals

Signs on the traffic light poles will let you know that only one vehicle in each lane may enter the freeway on a green signal.

At some locations, a special purpose lane is provided for trucks or vehicles with more than one person. This will allow these vehicles to access the freeway without delay by the signals.

When the freeway is heavily congested, e.g. due to an incident, message signs are switched on to warn motorists on the main roads that long delays can be expected on the freeway and entry ramp. This enables motorists to choose alternative routes.

How do the Freeway Ramp Signals work?

Freeway Ramp Signals will generally operate during peak hours and any time of the day when freeway conditions are heavy.

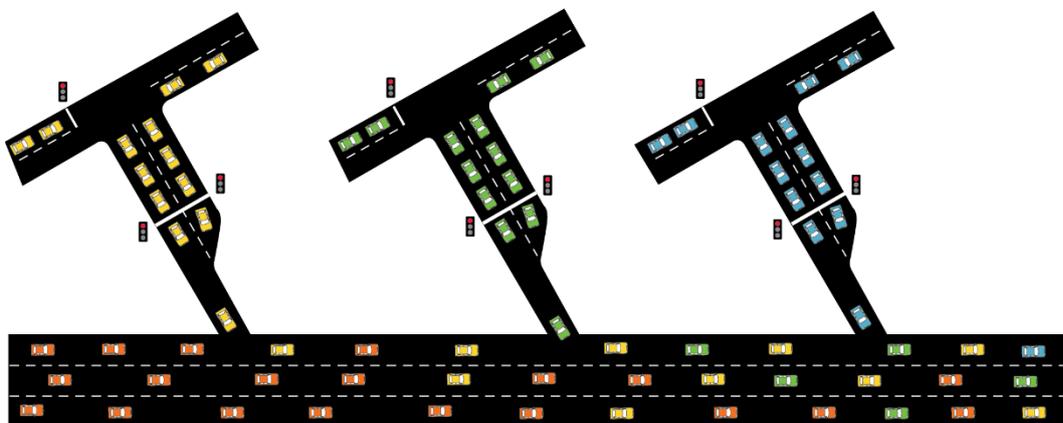
The Freeway Ramp Signals relieve congestion in a similar way to traffic signals on main roads by regulating traffic demand in an orderly manner.

They will start working when roadway sensors indicate that traffic on the freeway are heavy. At times it may seem Freeway Ramp Signals are in operation when the freeway is uncongested. This may be due to congestion at other locations along the freeway. Freeway Ramp Signals will continue to operate until the overall freeway traffic flow improves.

Freeway Ramp Signals also aim to improve traffic flow by balancing the queues on adjacent ramps to create fairness for all drivers.

Figure 2 After the implementation

- ★ Smoother and safer flow
- ★ Easier merge
- ★ Minimal delays
- ★ Reliable travel time
- ★ Higher efficiency



Freeway free-flow conditions maintained



What do I do when:

the lights are switched off?

Merge with the freeway traffic as you would normally do.

the lights are flashing yellow?

This occurs when the system is starting up or shutting down. You should merge with the freeway traffic as you would normally do.

the lights are red?

Stop at the stop line and wait for a green light.

the lights are green?

If you are the first vehicle in the queue, you can drive past the traffic lights and merge with the other vehicle leaving the signals. You can then merge with the freeway traffic as you would normally do.

Other vehicles in the queue must wait their turn, as only one vehicle per lane is allowed to join the freeway traffic on a green light.

What are the benefits?

Freeway Ramp Signals are expected to deliver the following benefits:

- easier and safer merging from freeway entrances;
- reduced congestion and improved traffic flow on the freeway;
- smoother travel and more reliable journey times;
- improved safety for motorists joining the freeway traffic and for those already travelling on the freeway;
- reduced vehicle emissions; and
- improved priority for trucks and vehicles with more than one person at some locations.

For further information:

Contact Monash-CityLink-West Gate upgrade project team:

Monash-CityLink-West Gate upgrade

PO Box 1644 Melbourne VIC 3001

Tel: 1300 881 137

Email: info@mcwupgrade.com.au

Website: www.mcwupgrade.com.au

Appendix B

A Short History of Ramp Metering

US Experience

The US Federal Highway Administration Ramp Management and Control Handbook (Federal Highway Administration, 2006) indicates that the first ramp metering was installed in 1963 on Chicago's Eisenhower Expressway. Ramp metering was developed as a technique to manage traffic demand following the launch of the Interstate Highway Program to address freeway flow problems associated with congestion and safety.

The initial application of entry ramp metering used a police officer stationed on the entrance ramp to stop traffic and release vehicles one at a time at a rate determined from a pilot detection program. This use of metering followed successful tests of the effectiveness of metering traffic entering New York tunnels and ramp closure studies in Detroit (Piotrowicz & Robinson, June 1995).

The Minnesota Department of Transportation (Mn/DOT) has used ramp meters since 1969. In 2000 the Minnesota Legislature required Mn/DOT to study the effectiveness of ramp meters in the Twin Cities Region (Minnesota Department of Transportation, 2001) by conducting a shutdown study. The evaluation report by Cambridge Systematics Inc. (2001) indicated the following annual benefits of ramp metering:

- **Traffic Volumes and Throughput:** After the meters were turned off, there was an average 9% traffic volume reduction on freeways and no significant traffic volume change on parallel arterials included in the study. Also, during peak traffic conditions, freeway mainline throughput declined by an average of 14 percent in the "without meters" condition.
- **Travel Time:** Without meters, the decline in travel speeds on freeway facilities more than offsets the elimination of ramp delays. This results in annual systemwide savings of 25,121 hours of travel time with meters.
- **Travel Time Reliability:** Without ramp metering, freeway travel time is almost twice as unpredictable as with ramp metering. The ramp metering system produces an annual reduction of 2.6 million hours of unexpected delay.
- **Safety:** In the absence of metering and after accounting for seasonal variations, peak period crashes on previously metered freeways and ramps increased by 26 percent. Ramp metering results in annual savings of 1,041 crashes or approximately four crashes per day.
- **Emissions:** Ramp metering results in a net annual savings of 1,160 tons of emissions. This is most likely due to the avoidance of stop-start conditions.
- **Fuel Consumption:** Ramp metering results in an annual increase of 5.5 million gallons of fuel consumed. This was the only criteria category which was worsened by ramp metering. This is most likely due to more traffic being processed (see previous point).
- **Benefit/Cost Analysis:** Ramp metering results in annual savings of approximately \$40 million to the Twin Cities travelling public. The benefits of ramp metering outweigh the costs by a significant margin and result in a net benefit of \$32 to \$37 million per year. The benefit/cost ratio indicates that benefits are approximately five times greater than the cost of the entire congestion management system and over 15 times greater than the cost of the ramp metering system alone.

There are now thousands of ramp meters operating in the USA. This is seen as a measure of the benefits of ramp metering installations. The following quote from the Federal Highway Administration brochure, (Federal Highway Administration, 2006) demonstrates the value of ramp metering systems:

“Every evaluation of the system has shown reduced accidents, reduced delay and increased volumes when metering was installed. No other traffic management strategy has shown the consistently high level of benefits in such a wide range of deployments from all parts of the country”.

Pete Briglia, Puget Sound Regional Council, Seattle, Washington and Chair of the TRB Freeway Operations Committee.

Ramp Metering in Melbourne

First Ramp Metering Initiative in 1971

The first ramp metering in Australia was provided in Melbourne on the South Eastern Freeway (now the M1 - Monash Freeway / Southern Link) at the Gibdon Street entry ramp. The ramp metering was initiated in 1971 by Mr Kerras Burke of the Highways Division of the Melbourne and Metropolitan Board of Works (MMBW). The rate of vehicle entry to the freeway was based on data from detectors on the freeway. The traffic was regulated by varying the phase times at traffic signals at the entry ramp from the Gibdon St / Barkly Av intersection. A paper presented by Kerras Burke at the Fifth Australian Computer Conference in Brisbane in May 1972, is included below.

The metering had limited success due to the high freeway flows. The limited spare capacity resulted in low ramp phase time for allowing additional vehicles to enter from the ramp. The release of short platoons from the controlling signals at the top of the ramp (rather than signals close to the nose with one vehicle per green) was also less than desirable. The metering was eventually deactivated due to driver complaints about short phase times, lack of publicity to inform motorists, non-compliance and lack of enforcement.

In the early 1970s other investigations promoted the value of ramp metering. A report, ‘Some Aspects of Freeway Design and Operation’ by Robin Underwood, Assistant Chief Road Design Engineer, Country Roads Board (1971), resulted from a Churchill Fellowship Study Tour of the United States, Canada, Great Britain and Europe. The report indicated that ‘a fundamental part of most surveillance and control projects is ramp control.’

2002 Ramp Metering Trial

Despite the initial application of ramp metering in 1971, there was no further ramp metering in Melbourne until 2002. In view of Melbourne’s freeway traffic problems at that time, Gary Veith (VicRoads) initiated a study relating to best practice in freeway management.

A September 2000 report, “Managing Traffic Flow on Urban Freeways”, prepared by Andrew O’Brien and Associates (now O’Brien Traffic) led to an initial trial of metering at the Thompsons Road eastbound entry ramp on the Eastern Freeway where extensive queues on the freeway resulted from flow breakdown caused by merging traffic. Bill Saggars (VicRoads) managed the project as part of VicRoads ‘Easy Merge – Safer Flow’ ramp metering trial.

The initial stage of the trial modified the right turn phase times to regulate the flow into the ramp from the Thompsons Road / eastbound entry ramp intersection. The second stage of the trial included the installation of traffic signals on the ramp, to meter the entering traffic into the freeway flow. The ramp meter design provided two lanes at the stop line with one vehicle per green per lane released each cycle. SCATS controllers were used to provide fixed time cycles for the evening peak period of 9 seconds at initial switch on and 6 seconds for periods when the ramp queue became significant.

A ‘Before and After’ study indicated the success of the project in preventing traffic flow breakdown to provide more consistent traffic flow and reduce travel times on the freeway. The results indicated:

- Up to 70 per cent increase in speed on the Eastern Freeway at Bulleen Road as a result of avoiding flow breakdown as shown in Figure B-1.
- Over the section of the Eastern Freeway between Bulleen Road and Doncaster Road, free flow speeds improved and up to 60 per cent reduction in travel times, as shown in Figure B-2.

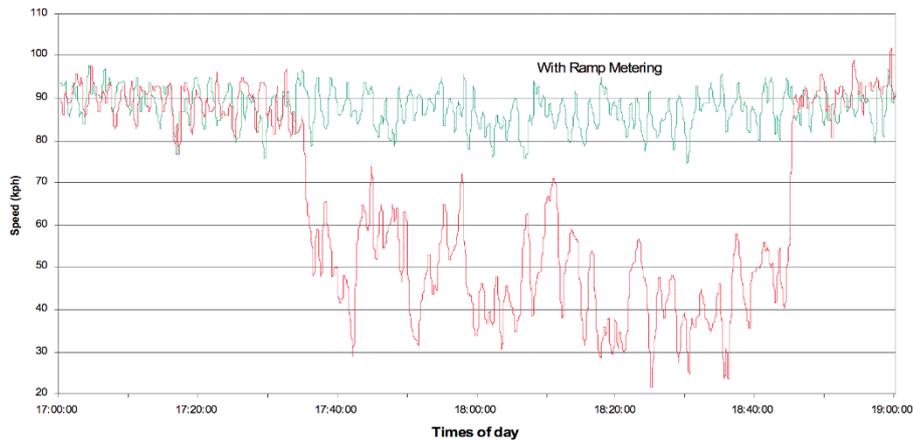


Figure B-1: Freeway Speed - Eastern Freeway Outbound, East of Bulleen Rd

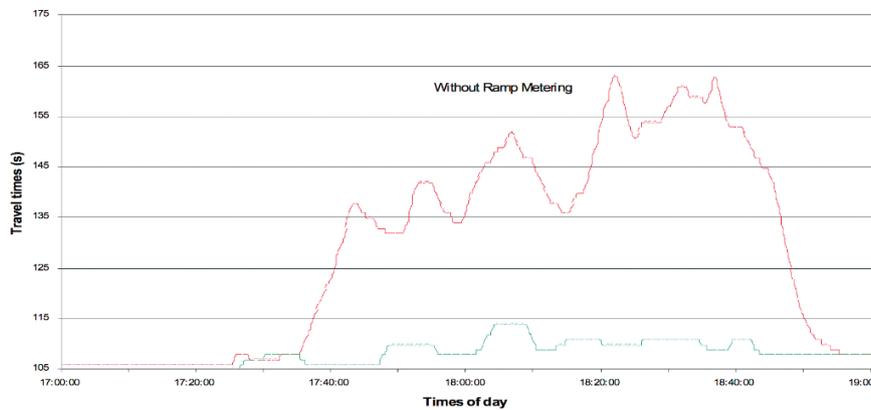


Figure B-2: Travel Time - Eastern Freeway Outbound, Bulleen Rd to Doncaster Rd

After the initial trial, ramp metering signals were then installed at 11 entry ramps on Monash Freeway, West Gate Freeway and Calder Freeway between 2002 and 2005 using SCATS intersection controllers with fixed time operation. However, benefits reduced over time due to increasing traffic demands along the freeway and the limited value of isolated fixed time operation. This experience confirmed that to control performance at the critical bottlenecks, high volume freeways need to be managed in a dynamic coordinated manner to control all inflow.

Importantly, these initial installations confirmed that:

- Implementation and broader use of this intelligent transport system technology is a cost effective means (typically BCR in excess of 10) of providing a more reliable, safer and less stressful service to road users
- Other more costly infrastructure improvements can be avoided or delayed through increased utilisation (productivity) of the existing high value infrastructure, and
- Melbourne’s motorists demonstrated that they were able to adapt to the ‘radical’ traffic control with a high level of compliance, and also supported the initiative.

Developments Leading to Current Practice

In 2004 John Gaffney undertook a 2 month technical tour to the USA, UK and Europe as part of the Kerry Burke Memorial Scholarship. During the trip significant information was obtained relating to contemporary traffic flow theory, freeway flow management and freeway ramp metering.

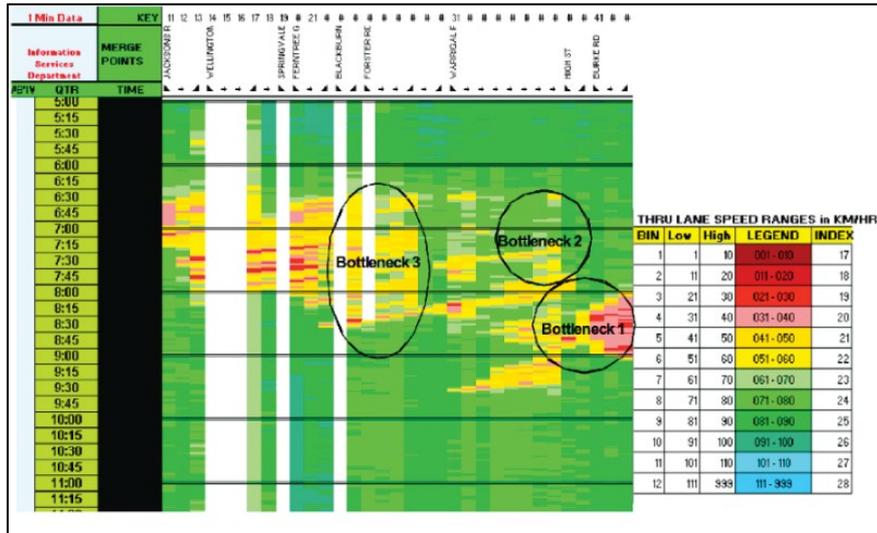


Figure B-4: Motorway Ramp Meters - Typical Speed Surface Contour Plot in the AM Peak

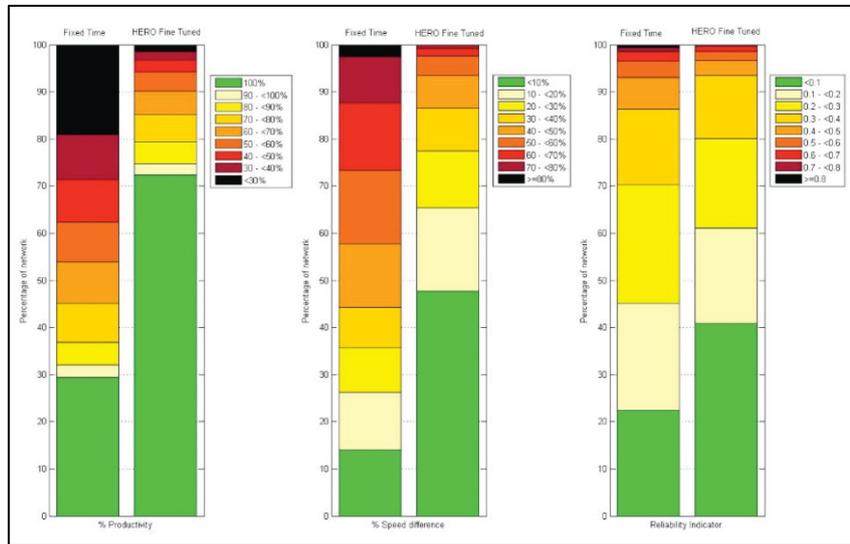


Figure B-5: ‘Before and after’ Austroads National Performance Indicators

Monash-CityLink-West Gate Upgrade (M1) Project (2007 – 2010)

As part of the Monash-CityLink-Westgate freeway upgrade project, ramp meters were installed along 75 km of Melbourne’s freeway network at 64 ramps on the Princes Freeway West, Western Ring Road, West Gate Freeway, CityLink, Monash Freeway and South Gippsland Freeway.

The ramp meter sites include one, two, three and four lane ramp meters, as appropriate, to manage the entering traffic, as well as five sites with free flow priority access lanes for trucks and high occupancy vehicles. The system uses the HERO-LIVE suite of algorithms with further enhancements since the initial pilot.

The results from a before / after study of the effectiveness of the project is provided in the VicRoads Managed Motorway Framework. It is worth noting that there were many complementary road design elements and technology enhancements to support managed motorways and thus it cannot be considered to be a simple ITS bolt-on.

Appendix C

Paper presented at the Fifth Australian Computer Conference,
Brisbane, May 1972.

Control of an Access Ramp to a Melbourne Freeway by Mini Computer

Kerras Burke

Melbourne and Metropolitan Board of Works,
Melbourne.

ABSTRACT: The demand for freeways in most cities lags behind the supply as it takes time for the community to recognise the growth in the use of the motor car and to institute those procedures necessary for the planning, financing, construction and operation of a full hierarchy of road systems.

Those links in a freeway system which are commissioned first are most attractive to motorists, and this can result in overloading of the freeways by commuter motorists in morning and evening peak hours.

Traffic on the Gibdon Street Ramp onto the South Eastern Freeway in Melbourne is regulated by traffic signals whose phases are controlled by a mini computer in accordance with traffic conditions on the freeway itself.

The equipment installed and operating principles described are applicable to a wide range of traffic engineering control situations.

KEYWORDS AND COMPUTING REVIEWS CATEGORIES: Freeway Ramp Control.
3.2, 3.8.

HISTORY

Following the construction of the first section of the four lane South Eastern Freeway for a distance of two miles between Punt Road, Melbourne and Barkly Avenue, Richmond, traffic volumes built up from 26,000 vehicles per day in 1962 to 34,000 vehicles per day in 1969, and morning peak volumes increased from 2,600 to 4,000 vehicles per hour over that period.

The dispersment of vehicles at each end of the freeway was found to be the most important factor in the operation of the freeway itself.

When the freeway was to be extended a further two and a half miles eastwards in 1969, additional traffic was expected but, because of the restricted capacity at the City end, some restriction was considered necessary at one of the ramps at Richmond, where the old freeway terminal was to be converted to a ramp connection in the new scheme.

The new freeway extension was opened in May 1970. Traffic signals were installed at the entrance to the Gibdon Street Ramp, Richmond, and brought under the control of a traffic responsive system early in 1971.

FREEWAY DEMAND

Freeways in a city are designed and located with regard to a number of factors. These include the location with respect to existing streets, the geometric (design speed) standard, the capacity of the freeway itself, and the details and loading characteristics of arterials and ramps which feed it, and into which it discharges.

The load in the morning and evening peak hour of the South Eastern Freeway is 10% of the 24 hour volume. The direction in which this occurs, and the details of peak hour traffic is most significant in conditions of travel on this freeway, as indeed on

all freeways which are built in multiples of lanes — four, six or eight — these presenting a restricted choice of different capacities.

The commuter driver travelling to work by car travels a route which is based on habit, cost, convenience and time.

Just when the trip is made depends on the hours of the working day, and results in a concentrated demand for road space in Melbourne between 7-9 a.m. and 4-6 p.m.

When many cars endeavour to use the roads at the same time there is a reduction in the space between cars and more skill and attention is required by the driver, and delays and accidents are more likely to occur.

These conditions have been graded by the U.S. Highway Capacity manual into six levels of service varying from free fast flowing condition 'A' down to congestion and stoppage 'F.'

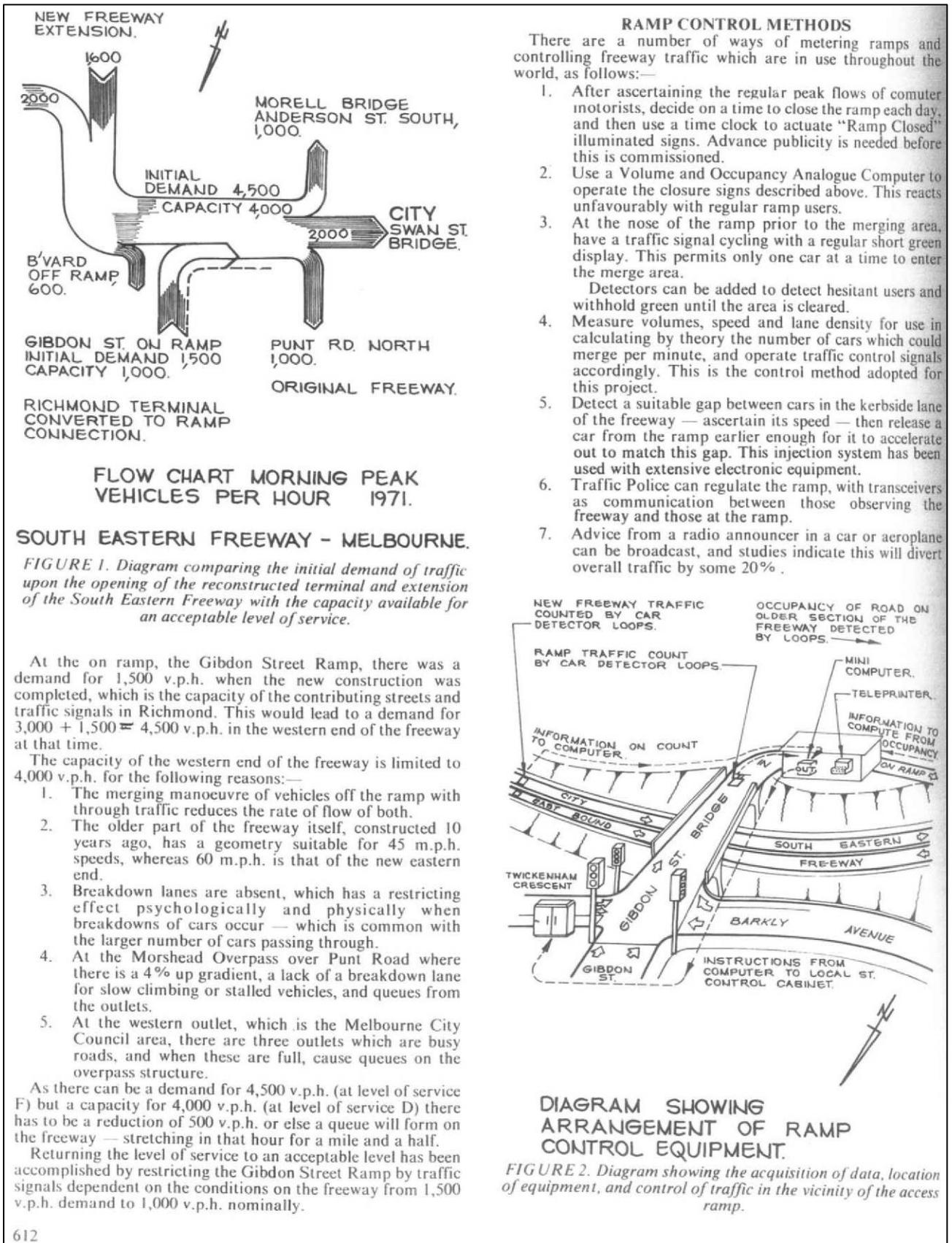
New road space can be acquired by construction of freeways which have no frontage access to properties, and no surface cross roads, and can carry a large number of cars with a lower demand on the abilities of the driver.

TRAFFIC FLOW

The flow of traffic in the normal morning peak hour is shown as a diagram in Figure 1.

Two conditions are considered. First the demand, which is number of cars which would like to use the facility and then the capacity, which is the number of cars per h. or which can be accepted and flow through the system without having to queue.

The number of cars entering from the east from Toorak Road and the freeway extension road is limited by the contributing streets and traffic signals. This amounts to 3,600 v.p.h. At the first off ramp, the Boulevard Off Ramp, 600 v.p.h. are observed to exit, and 3,000 v.p.h. remain bound for the City.



ON STREET CONTROLLER

The traffic signal control for the ramp was placed at the nearest intersection where it was felt that motorists who were unable to proceed onto the ramp and freeway could have the option of taking a surface street if they did not wish to wait. (Figure 2.).



FIGURE 3. Traffic signal display at the intersection of the local streets and the Gibdon Street On Ramp to the South Eastern Freeway.

The vertical arrow lanterns indicate access to the freeway, and the horizontal arrow lanterns indicate a right turn for local street traffic.

The intersection appears superficially as a four leg intersection with East-West, West-East movements of the local area. The approach to this for ramp traffic is from three directions — a direct movement from the North, a left hand turn from the East, and a right hand turn from the West.

These are controlled by arrays of traffic signals displaying arrows to each direction of approach (Figure 3). The motorist can obey the arrow signals which let him proceed along the local street, or can wait for the arrow alongside to direct him onto the ramp leading to the freeway.

The local street controller is housed in a steel cabinet nearby. It is a fully vehicle actuated controller supplied by the Eagle Signal Co. of Australia, Type CT 250, which has a transistorised logic and timing control. (Figure 4.).

When not "on line" to the computer, the controller functions with vehicle actuating using detector loops on the local streets and giving fixed arrow times to the ramp.

When "on line" to the computer control however, each phase is called by the computer.

There are three main phases (A1, B1 and C) for entry to the freeway from the three contributing streets. When it becomes necessary to reduce the amount of time available to enter the freeway, these phases are forced off to sub-phases which display red, but still permit local street movements with a display of green arrows.

MINI COMPUTER

The computer installed is a PDP8L model, with a store of 4096 x 12 bit words, manufactured by the Digital Equipment Corporation, and installed by the Eagle Signal Company. (Figure 5.).

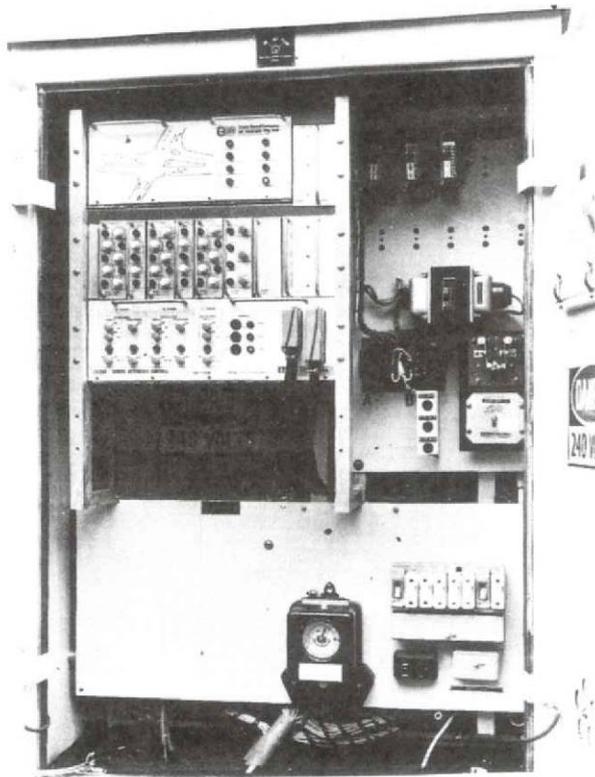


FIGURE 4. Traffic signal control cabinet, with communication with the computer indicated on the top left corner, and the vehicle control equipment in the centre left.

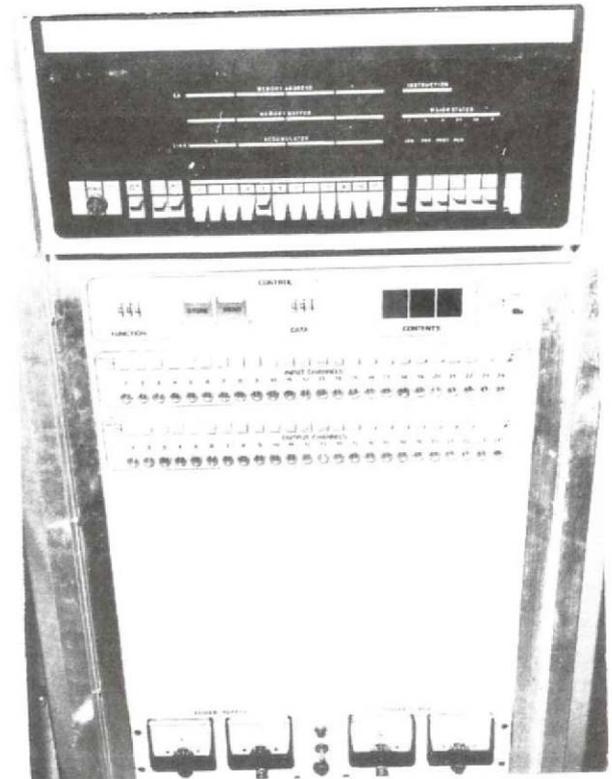


FIGURE 5. Computer control console housing the computer on the top, the signal and detector input and output (at centre) and power supply at the bottom. The input and output channels have indicator lights and test switches.

It is housed in a small brick building beside the access ramp itself. The roof and floor are of concrete, with a timber false floor and a standard fireproof door to deter vandalism. This location enables the operator to step outside and view the freeway and ramp merging area, and to see the traffic queues and signal discipline at the controlled intersection. (Figure 6.).

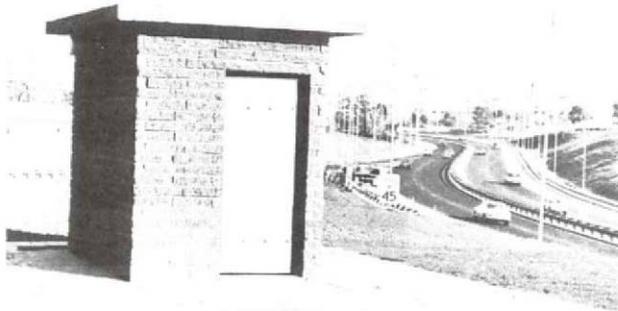


FIGURE 6. The cabin housing the computer, communication console and teletype is located between the ramp and freeway so that traffic conditions can be observed.

It is also halfway between upstream and downstream traffic detectors and close to the local street controller, thus minimising the lengths of cabling.

The interface equipment is housed in a cabinet, together with lamp displays and testing switches, and the computer itself.

A teletype model ASR 33 is used for loading and modifying programmes and for obtaining a log of operations.

DETECTORS

There is an extensive surveillance system provided by detectors over 4,000' of freeway and at the controlled intersection and ramp. (Figure 7.).

On the freeway itself the detector stations are located 2,600' upstream of the ramp nose, and at two intermediate locations; at the nose, and 1,400' downstream of the nose.

These give advance information of freeway conditions, and information after merging of ramp and freeway streams has occurred.

The detectors consist of 8' x 4' loops of wire set into the road pavement, connected to oscillator circuits, which detect the passage or presence of the mass of metal of a car.

The right hand lane and the left hand lane have a separate detector at each station. The shoulder, or emergency stopping lane, has also a loop connected to the left hand lane detector. This supplies data for vehicles which may be forced to use the shoulder.

The detectors on the ramp itself give information of conditions on it, and whether a queue is forming.

The cabling from the computer interface passes through a protective circuit, and, for expediency, was put in 1½" galvanised water pipe fastened to the back of the freeway protective guardrail. However high summer temperatures and occasional collisions has caused fractures of junction boxes and the pipes are being put underground.

The power supply is 32 volts A.C. to the individual detector boxes. These are located on pillars for ease in servicing and adjustments.

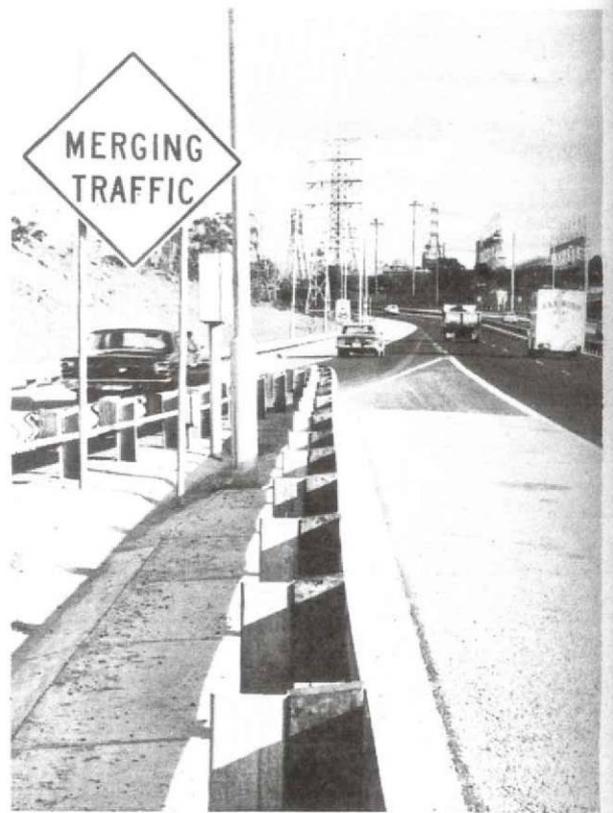


FIGURE 7. At the nose of the ramp where it joins the freeway there are wire loops set in the pavement and connected to detectors in a box which can be seen behind the traffic sign.

TRAFFIC FLOW THEORY

Observations of speed and flow of vehicles show that for a given flow there can be two speeds — and on this freeway, 4,000 v.p.h. a flow at 45 m.p.h. at level of service D or 15 m.p.h. at level of service E.

It is preferable to keep to the first level, analogous to a lamina flow in hydraulics, as it gives a shorter travel time.

When this condition breaks down, the congested slow condition results, and the first condition cannot be resumed until the flow (or demand) is reduced.

Each vehicle takes a certain time to pass over a detector. Then there is a gap, or headway between it and the next car that passes.

The lane density is a measure of the conditions on the freeway and is the percentage of time during which the detectors are activated by cars.

When the flow rate is at the higher speed level, the number of cars which can enter by a ramp depends on the gaps between cars on the freeway.

Reports by Bremer, Buhr, Drew and Messer in Highways Research Board Record No. 279 and by Drew, Buhr and Whitson (No. 244) utilise the gaps expected and use an Erlang distribution to allow for platoon effects. These occur because of differences in driver-car behaviour, and as this freeway has traffic signals at the entrance.

The expressions derived by these authors are from the number of critical merging gaps to be found and the chance of a ramp vehicle getting one.

Works Cited

- Akcelik, R., Roper, M., & Besley, M. (1999). *Austrroads Research Report ARR 341 - Fundamental Relationships for Freeway Traffic Flows - Monash Freeway*. Vermont South, Australia.: ARRB Transport Research Ltd.,.
- Cassidy, M. J., & Rudjanakanoknad, J. (2005). *Increasing the Capacity of an Isolated Merge by Metering its On-ramp*. *Transportation Research Part B*, 39, 896-913.
- Elefteriadou, L., Roess, R. P., & McShane, W. R. (1995). *Probabilistic Nature of Breakdown at Freeway Merge Junctions*. *Transportation Research Record* 1484, 80-89.
- Euramp Project No. 507645. (2007). *Handbook of Ramp Metering, European Ramp Metering Project*. European Community.
- Federal Highway Administration. (2006). *Ramp Management and Control brochure*. Washington, DC.: US Department of Transportation.
- Golob T, Recker W, Alvarez V. (2003). Freeway Safety as a Function of Traffic Flow. *Accident Analysis and Prevention* (p. 13). ELEVIER.
- Hadj-Salem, H., & Papageorgiou, M. (1995). *Ramp metering impact on urban corridor traffic: Field results*. : *Transportation Research Part A: Policy and Practice* Volume 29, Issue 4, July 1995, Pages 303-319.
- Keen, K. G., Schoffield, M. J., & Hay, G. C. (1986). *Ramp Metering Access Control on M6 Motorway*. London, UK.: Proc. 2nd IEE International Conference on Road Traffic Control.
- Lorenz, M., & Elefteriadou, L. (2001). *Defining Highway Capacity as a Function of the Breakdown Probability*. Washington DC: *Transportation Research Record* No1776, 43–51.
- Minnesota Department of Transportation. (2001). *Twin Cities Ramp Meter Evaluation Final Report*. Minnesota Department of Transportation.: Cambridge Systematics Inc.
- Papageorgiou, M., Kosmatopoulous, E., & Papamichail, L. (2007). *ALINEA Maximises Motorway Throughput- An Answer to Flawed Criticism*. *Traffic Engineering and Control*, 272-276.
- Papageorgiou, M., Hadj-Salem, H., & Middelham, F. (1991). *ALINEA: A Local Feedback Control Law for Onramp Metering*. *Transportation Research Record No 1320* (pp. 58-64). TRB.
- Papageorgiou, M., Hadj-Salem, M., & Middelham, F. (1997). *ALINEA Local Ramp Metering Summary of Field Results*. *Transportation Research Record No 1603* (pp. 90-98). Transportation Research Board.
- Piotrowicz, G., & Robinson, J. (June 1995). *Ramp Metering Status in North America (FHWA), U.S. Department of Transportation*. Retrieved from Publication DOT-T-95-17.: http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS_PR/3725.pdf
- Underwood, R. (1971). *Some Aspects of Freeway Design and Operation*. Melbourne: VicRoads library 388.122 UND 71.
- VicRoads. (2013). *Managed Freeways Handbook for Lane Use Management, Variable Speed Limits and Traveller Information*. Melbourne: VicRoads.
- VicRoads. (2017). *Managed Motorway Framework*. (J. Gaffney, P. Lam, A. Somers, D. Johnston, & K. Boddington, Eds.) Melbourne: VicRoads.