

Safety on Heavily Trafficked Urban Motorways in Relation to Traffic State

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Key Findings

- Casualty crashes on urban motorways have increased by 59 per cent over 10 years;
- Casualty crash rates are lower on managed motorways than on unmanaged motorways;
- Statistically significant association exists between traffic state and number of crashes;
- Higher than expected crashes occur if flow breakdown has occurred or is relatively certain;
- Safety is improved by minimising time of operation in unstable and congested states.

Abstract

Motorways represent seven per cent of the urban arterial road network in Melbourne yet carry 40 per cent of the urban arterial road travel in terms of vehicle kilometres travelled and this percentage is growing. The number of casualty crashes on metropolitan Melbourne motorways has increased over the decade at a faster rate than on other urban roads in metropolitan Melbourne. Police crash reports more often attribute crash cause to traffic conditions and vehicle interactions rather than infrastructure. As urban motorways are generally built to the highest standards, a new way of looking at motorway safety is needed. This led to the formulation of a hypothesis that the dynamics of the traffic flow are a significant contributor to casualty crashes on urban motorways. To test this hypothesis, in-depth analysis was undertaken on metropolitan Melbourne motorways. Crash data was linked to traffic data including vehicle occupancy (a proxy measure for density), vehicle speed and flow. Occupancy was used to categorise the 'traffic states' ranging from free flow to flow breakdown (congestion). Applying a Chi Square Goodness of Fit Test to the linked showed a statistically significant association between traffic state and crashes, with a higher than expected crashes in the traffic states where flow breakdown is relatively certain or has occurred. The results of this analysis can be used to improve safety on urban motorways through the development of Intelligent Transport System strategies to keep the motorway operating at conditions that minimise flow breakdown risk.

Keywords

Crashes, Urban Motorway Safety, Traffic State, Congestion, Managed Motorways, Freeways

Glossary

Bottleneck. A typically fixed location where the capacity is lower than the upstream capacity.

Casualty Crash. A crash where one or more persons are killed or injured. For a crash to be reportable, it needs to have occurred on a road or road-related area open to the public, involved at least one moving vehicle and resulted in one or more persons killed or injured in the crash (VicRoads, 2013).

Congestion. Traffic state where traffic volumes are medium to high and the flow is unstable or broken down with varying speeds and flows. Congestion can occur at occupancies around 18%, however this value is dependent on the site and on the type of detector system used.

Density. Number of vehicles per unit length of lane or roadway at a given instant in time (vehicles per kilometre).

Detector. Device to detect vehicles passing a certain point on the road. Detectors can measure the speed, flow and occupancy on the motorway. There are different vehicle detection technologies including inductive loops, magnetic sensors and infrared detectors.

Downstream. In the direction of the movement of traffic.

Fatal Crash. A crash where one or more persons are killed or die within 30 days of a crash.

Flow (Rate). The number of vehicles passing a given point on a lane, carriageway or road per unit of time, typically expressed in vehicles per second or an equivalent number of vehicles per hour.

Flow Breakdown. Abrupt transition from a ‘free flow’ to a ‘congested’ state that lasts for a defined period of time (for this paper the defined period is at least 15 minutes). In this state free flowing traffic experiences significant and sudden reduction in speed, with a sustained loss of throughput and may result in queuing and stop-start conditions.

Flow Breakdown Risk (FBR). The risk of flow breakdown.

Free Flow. The condition where traffic volumes are relatively low, flow is stable and there is very low risk of flow breakdown.

Lane Filtering. Situation when a motorcycle or scooter travels at a low speed through stopped or slow-moving traffic. Lane filtering is legal in Victoria.

Lane Splitting. Situation when a motorcycle or scooter travels at a high speed between moving traffic. Lane splitting is illegal in Victoria.

Level of Service (LOS). Qualitative measure that characterises operational conditions within a traffic stream, usually based on density on motorways. The six levels of service are from A to F with LOS A representing the best operating conditions and LOS F the worst.

Managed Motorway. Motorway managed with CITY-WIDE COORDINATED RAMP METERING (CWRM) signals controlling demand in the system. May also include management with other tools. The presence of a ramp meter does not necessarily mean that the motorway is a managed motorway. A managed motorway has a coordinated ramp metering system controlling access to the motorway at every on-ramp and is suitable to prevent flow breakdown and provide sufficient gaps for vehicles. Refer to the VicRoads Managed Motorways Framework for more details (Gaffney, Lam, Somers, Johnston & Boddington, 2017).

Mainline. The main through carriageway as distinct from ramps and collector-distributor roads. This is the carriageway carrying the main flow of traffic and generally passes straight through at an interchange.

Motorway. A divided roadway with no access for traffic between

interchanges and with grade separation at all road junctions. It includes urban freeways and tollways.

Occupancy. The proportion of time a length of roadway or traffic lane is covered by vehicles, usually expressed as a percentage. Occupancy is used as a surrogate for density in control systems as it is easier to measure. Occupancy values are related to the detector configuration therefore operational values may vary according to the detector type, size and spacing. Occupancy measures may be normalised to represent a fixed detector footprint to enable comparable results from different technologies and layouts.

Other Injury Crash (Minor Injury Crash). A crash where one or more persons are injured but not admitted to hospital. Excludes crashes in which persons are killed or seriously injured.

Productivity. Mathematical product of flow rate and speed.

Ramp Meter. Traffic signals installed on a motorway entry ramp to regulate traffic onto the motorway to manage traffic flow and prevent congestion and flow breakdown.

Serious Casualty Crash. A crash in which one or more persons are killed or injured. This includes fatal crashes and serious injury crashes but excludes other (minor) injury crashes.

Serious Injury Crash. A crash where one or more persons are injured and admitted to hospital. Excludes crashes where a person is killed or died within 30 days of the crash.

Shock Wave. A moving location within the traffic stream where an abrupt change of traffic conditions occurs, generally with free flow upstream and congested flow immediately downstream of the moving shock wave. It represents a discontinuity in flow-density conditions.

Speed. The distance travelled by a vehicle per unit of time, typically expressed in metres per second or kilometres per hour.

Traffic State. A description of the traffic conditions on the motorway expressed as a function of the speed, flow rate (volume) and / or density (measured by occupancy).

Upstream. In the direction opposite to the movement of traffic.

Introduction

Motorways have traditionally been perceived as safe as they are generally built to the highest safety standards, have restricted access and have a low crash risk in terms of casualty crashes per vehicle kilometres travelled. Casualty crash numbers, however, have been increasing on the motorway network at a faster rate than on other urban roads in metropolitan Melbourne. Similarly, serious casualty crashes (that is, fatal and serious injury crashes) have been increasing on metropolitan Melbourne motorways despite a decrease on other urban roads. Often this increase is masked due to a progressively reducing crash rate resulting from rapid growth in travel on motorways outstripping travel growth on other roads.

The metropolitan Melbourne motorway network represents only seven per cent of the total urban arterial road network in terms of lane kilometres, yet it carries 40 per cent of the urban arterial road travel, measured in terms of vehicle kilometres travelled. The reliance on the motorway network

is increasing, with an estimated future likely share of 50 per cent, based on trend extrapolation (VicRoads, 2018). The growing number of vehicles per unit of road space and the addition of more traffic lanes on the urban motorways result in more interactions between vehicles and an increased complexity of the driving task for motorists, particularly during peak periods where disturbances in traffic flow can result in motorists having reduced or no reaction time, requiring emergency braking or lane changing to avoid a collision.

Current road safety programs focus on infrastructure improvements to reduce fatalities and serious injuries, particularly on high speed rural roads. Infrastructure deficiencies are rarely mentioned in the Police crash reports as being causes of urban motorway crashes, rather mention is made about traffic conditions such as ‘heavy traffic’ and vehicle-to-vehicle interactions such as ‘did not see other vehicle’. Given the already high standard of infrastructure

on urban motorways, the potential to reduce fatalities and serious injuries through further infrastructure upgrades has been largely exhausted. Provision of new tools and technology solutions to manage traffic conditions may be more beneficial to reduce the casualty crash numbers on motorways than just traditional approaches to improving hard road infrastructure (civil).

New technology capable of measuring the number of lane changes per kilometre per hour has been deployed by VicRoads on some metropolitan Melbourne motorways. Analysis of this data at trial sites has highlighted the increasing complexity of traffic flow dynamics and the corresponding multiple interactions that occur between vehicles, including abrupt braking and lane changing manoeuvres. The required driver response can be challenging, cannot always be realised and at times can exceed the capabilities of the driver, contributing to the increasing number of casualty crashes. These observations are supported by international research. For example, Golob, Recker & Alvarez (2004) identified the adverse safety effects of congested motorways and stated that the casualty crash rate can rise as much as 5-6-fold under flow breakdown (congested) conditions. Kononov, Bailey & Allery (2008) concluded that the number of crashes increases only moderately with increase in traffic on uncongested segments of motorway, but once a critical traffic density is reached then the number of crashes rises at a much faster rate as traffic increases.

These observations have led to the formulation of the hypothesis that the dynamics of the traffic flow, which cause congestion and require complex driver responses, are a significant contributor to casualty crashes on urban motorways. To test this hypothesis, an in-depth investigation was undertaken on metropolitan Melbourne motorway crashes. The investigation looked at crash causation and at the occurrence of casualty crashes in relation to the traffic state. This paper outlines the investigation undertaken, the

conclusions resulting from this investigation and makes recommendations for the next steps. The purpose of this research is to provide an evidence-base for a robust problem statement that could lead to the development of suitable counter-measures that stop, or even reverse, the increasing casualty crash trend on metropolitan motorways.

Previous Research into the Dynamics of Traffic Flow and Crashes

Evidence is growing about the relationship between motorway crashes and traffic conditions. Ceder & Livneh (1982) and Martin (2002) observed that single-vehicle crashes decrease as flow increases whilst multi-vehicle crashes increase as flow increases, and that there were variations between day, night, weekday and weekend. Kononov et al. (2008) identified a linkage between the number of lanes on a motorway to the number of conflict points and noted that crash rates increase as the number of carriageway lanes increases.

Overseas and interstate examples indicate that there is likely to be an optimal occupancy range where relatively high flow rates coincide with a low breakdown probability and a low crash rate. Garber & Subramanyan (2001) observed that crashes increase with increasing density, reaching a maximum before the optimal density at which flow is at capacity. Golob et al. (2004) showed a correlation between crash rate and the inherent traffic states as traffic conditions move from free flow to congested conditions (that is, safety decreases as congestion increases). They found that in light free flow conditions the estimated total crashes per million vehicle miles of travel was 1.28. In conditions where the flow approached capacity, the rate was 0.55. Once flow was congested, the rate rose to 2.97 in variable-speed congested flow conditions and to 5.99 in heavily congested flow conditions (refer to Figure 1).

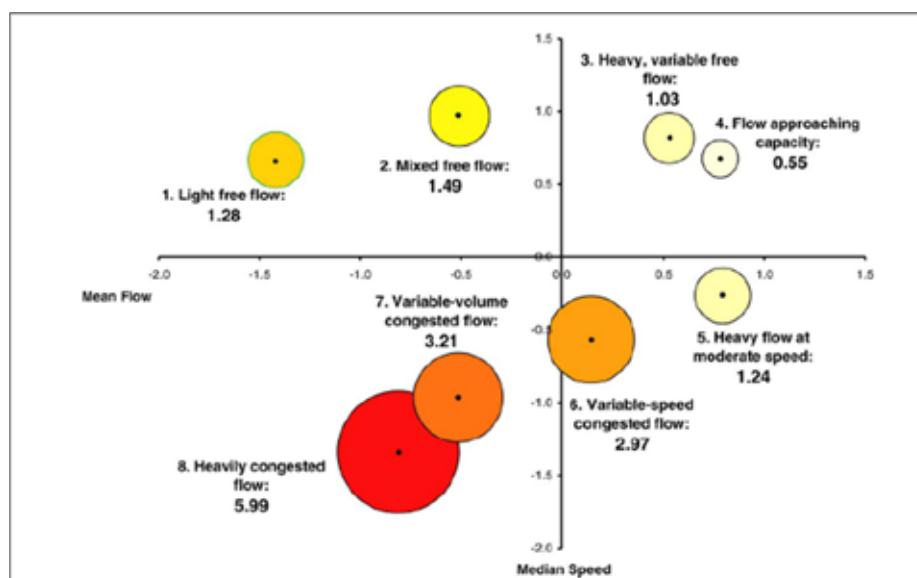


Figure 1. Estimated total crashes per million miles of travel for the eight traffic flow regimes during AM peak hours, plotted in standardised speed-flow space (Golob et al., 2004)

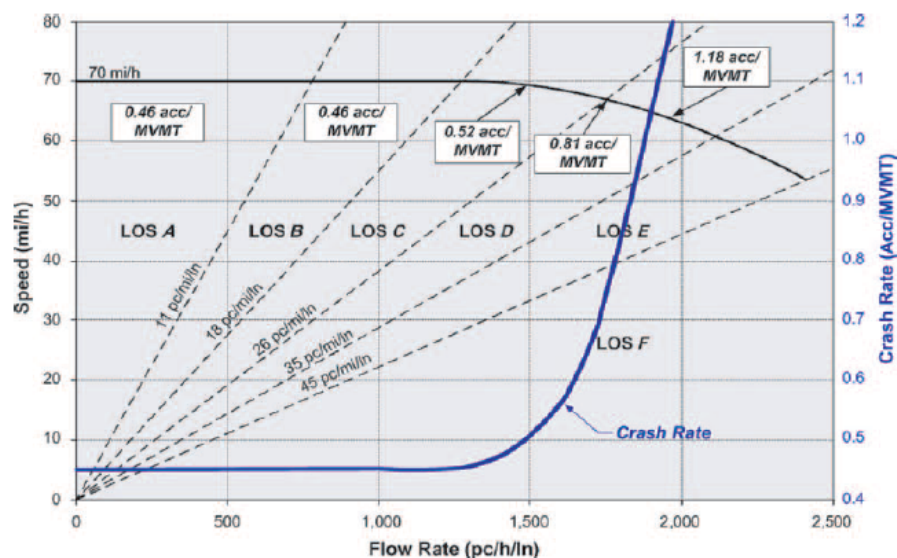


Figure 2. Crash rates relationship to speed, volume, density and Level of Service (LOS) (Kononov et al., 2012)

Kononov et al. (2008) mentioned that once some critical traffic density is reached, the number of crashes begins to increase at a much faster rate as traffic increases and Kononov, Reeves, Durso & Allery (2012) found that there was a critical threshold of speed and density beyond which the crash rate rapidly increases (refer to Figure 2). Zheng (2012) found that traffic conditions had a significant impact on the crash occurrence likelihood, with the likelihood in congested traffic flow being six times of that in free flow conditions and the likelihood in transitioning traffic flow being 1.6 times of that in free flow conditions.

Methodology

Analysis of metropolitan Melbourne motorway casualty crashes was undertaken using Police-reported casualty crashes sourced from the VicRoads Road Crash Information System. A comparison of the long-term trend in casualty crashes on urban motorways with casualty crashes on other urban roads was undertaken using data for the 2007 to 2016 10-year period. A similar comparison was undertaken for serious casualty (that is, fatal plus serious injury) crashes however, due to issues with consistency in the determination of serious injuries between 2006 and 2009, it was not possible to do a 10-year trend analysis so a seven-year period (2010 to 2016) was used instead.

A high-level analysis of metropolitan Melbourne motorway casualty crashes, focused on crash types, vehicle characteristics and time and location of the crashes, was undertaken for the period 2012 to 2016. A comparison of crash rates on selected managed and unmanaged motorways was also undertaken for the same period.

A limitation of this analysis was that recent data could not be used due to an apparent discontinuity in casualty crash data. Between 2016 and 2017, there was a state-wide decrease of 14 per cent in Police-reported casualty crashes. In previous years, the annual change in casualty crashes averaged 0.7 per

cent. As a result, the analysis in this report did not include 2017 data.

Detailed crash analysis was undertaken on casualty crashes on the Monash Freeway (a managed motorway) and the Eastern Freeway (an unmanaged motorway) that occurred on the main carriageways between 2013 and 2016. The detailed analysis involved reviewing the images and descriptions provided by the Police for each of the crashes to gain an understanding of the circumstances and causal factors of the crash, to confirm the carriageway (inbound or outbound) on which the crash occurred and to determine the lane in which the crash occurred. Spatial analysis techniques were then used to identify the closest downstream detector for each crash location and speed, volume and occupancy data was extracted for each of the crash locations on the inbound carriageway from the STREAMS application using an interface built in MS Excel. Due to the labour-intensive task of extracting the traffic condition data for each crash, the traffic state analysis focused on casualty crashes for four years of data (between 2013 and 2016) on the inbound carriageways but will be extended in the future to include the outbound carriageways and to include a fifth year.

The average downstream speed, volume and occupancy data in the five-minute period before the crash was then linked to the crash data and the crashes were grouped into five traffic states based on the occupancy. Occupancy is the most important parameter for current coordinated ramp metering on managed motorways in metropolitan Melbourne. The linking of crash occurrence with occupancy could potentially provide a basis for multi-objective traffic control that aims to maximise safety as well as improving efficiency (Haj-Salem, Farhi, Lebacque & Bhouri, 2016).

The following occupancy ranges, based on flow breakdown probability, were used in this analysis to categorise the traffic state. The VicRoads Motorway Design Volume Guide (Zurlinden, Gaffney & Hall, 2017) provides a detailed

description of the flow breakdown probability calculation methodology:

- **Free flow** ($\leq 4.9\%$ occupancy) – low traffic volumes, stable flow and very low flow breakdown risk;
- **Transition** (5% to 9.9% occupancy) – low to high traffic volumes, instabilities and breakdown risk starting to occur due to more interactions between vehicles, including abrupt braking manoeuvres and sudden lane changes at high speeds;
- **A significant level of flow breakdown risk**, i.e. flow breakdown risk (FBR) smaller or equal to around 1% per 15-minute interval or 10% per 3-hour peak period (10% to 14.9% occupancy), declining speeds and decreasing freedom to manoeuvre;
- **Flow breakdown relatively certain**, i.e. flow breakdown risk (FBR) between around 10% and 100% per 3-hour peak period (15% to 19.9% occupancy), lower speeds and limited freedom to manoeuvre;
- **Flow breakdown** ($\geq 20\%$ occupancy).

To determine the statistical significance of the relationship between crashes and traffic state, expected crashes were calculated based on exposure values. Exposure values were obtained from a randomly selected sample of detectors and various dates. These exposure values combine the percentage of time that the motorway was operated in the specified occupancy range and the typical traffic flow rate that was processed during that time. As it was not possible to use all of the detector data from the equivalent period as the crash data, a random number generator was used to select an unbiased sample of detectors and days over the analysis period in order to determine what percentage of time the motorway operated in each occupancy range. Weekends and public holiday weekdays were excluded. The average volume (flow rate) of the occupancy range relative to capacity was calculated (that is, the typical flow). These two values were multiplied and normalised so that the sum over all occupancy ranges was 100 per cent to determine the exposure. A Chi Square Goodness of Fit Test was then used to determine whether there was a significant difference in

the observed and expected number of crashes. The expected number of crashes was determined by distributing the total number of crashes on each motorway by the percentage of daily traffic processed in each traffic state (that is, the exposure). Each motorway was treated separately.

Results and Discussion

Analysis of crash data over the past decade (2007 to 2016) has shown that there has been an increase of 59% in the number of casualty crashes on Melbourne's urban motorways. In comparison, casualty crashes on other urban roads have only increased by 1.4% over this period (refer to Table 1). Whilst overall serious casualty crash numbers have decreased on metropolitan Melbourne roads between 2010 and 2016, there has been an increase of 22 per cent in the number of serious casualty crashes on metropolitan Melbourne motorways in this period (refer to Table 2).

Over the past 10 years, traffic (as measured by vehicle kilometres travelled) on the urban motorway network has increased by nearly 50 per cent (VicRoads, 2018). Whilst the measured crash rate on urban motorways is relatively low compared to other urban arterial roads, the high utilisation of motorways means that the total number of casualty crashes occurring on motorways is becoming a significant problem and is rising against the urban trend.

The increasing volumes on urban motorways result in complex traffic situations, including multiple interactions between vehicles. The exposure to risk is growing and that can contribute to higher crash numbers as well as growing congestion. Motorways are operating with peak spread and in heavy conditions over extended periods of the day. Increasing evidence exists that the continual changes required by drivers resulting from the dynamics of traffic flow contributes to the increasing number of crashes.

The overall weekday casualty crash occurrence broadly follows the distribution of traffic over the day, with the highest number of crashes occurring where the traffic volume was highest (refer to Figures 3 and 4). Figure 3 shows the distribution of the weekday casualty crashes by

Table 1. Metropolitan Melbourne casualty crash trends – motorways (main carriageway) versus other urban roads (arterial and local), 2007 to 2016 (Source: VicRoads Road Crash Information System)

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Urban Motorways	441	501	541	523	587	601	581	611	682	699
Other urban roads	9263	9622	9229	9120	9254	9268	9302	9596	9650	9394

Table 2. Metropolitan Melbourne serious casualty crash trends – motorways (main carriageway) versus other urban roads (arterial and local), 2010 to 2016 (Source: VicRoads Road Crash Information System)

	2010	2011	2012	2013	2014	2015	2016
Urban Motorways	164	196	167	190	186	193	200
Other urban roads	2949	2949	2881	2977	2864	2699	2645

crash severity and time of day. For comparison, Figure 4 shows the typical distribution of traffic on the M1 corridor over a typical weekday. It should be noted that the M1 corridor consists of three motorways, namely the Princes Freeway, West Gate Freeway and the Monash Freeway and is a good representation of traffic flow distribution over the day on the entire metropolitan Melbourne motorway network.

Managed Versus Unmanaged Motorways

A comparison of crash rates for a number of metropolitan Melbourne motorways is shown in Figure 5. The Monash Freeway and the Princes Freeway East (shaded green) are managed motorways with an effective coordinated ramp metering system. Casualty crashes are lower on these motorways than on the motorways that are substantially unmanaged. Although some of the other motorways have

some coordinated ramp signals, these are less effective both in terms of safety and productivity as the routes are only partially managed (that is, not all of the entrances are controlled) and there may also be different management influences (including by other road operators) that are outside of VicRoads control.

A before and after study was carried out by VicRoads on the Monash Freeway following its upgrade to a 'Managed Motorway' controlled with coordinated ramp metering signals (Gaffney et al., 2017). The initial upgrade included partial management of the mainline with some significant ramps not controlled, resulting in some flow breakdown at bottlenecks. VicRoads has now improved overall control and management of the route (that is, all ramps are now controlled, the algorithm was refined and improved operational strategies were developed) to address learnings from the initial 'Managed Motorway' project.

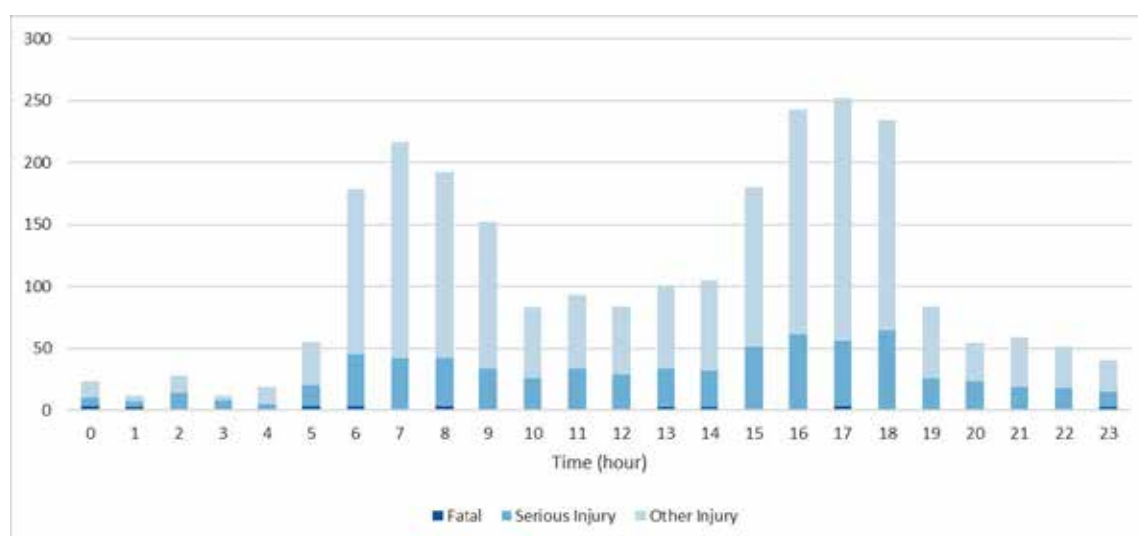


Figure 3. Weekday casualty crashes on metropolitan Melbourne motorways (main carriageway, 2-directional) by crash severity and time of day, 2012 to 2016

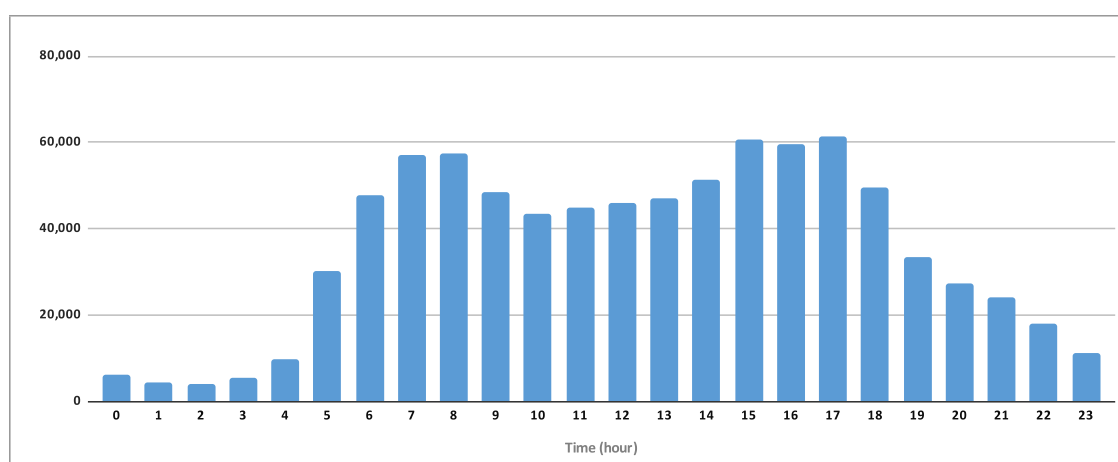


Figure 4. Vehicle trips along the M1 corridor, hourly entering volumes, Wednesday 10th February 2016 (daily count: 852,200 vehicles)

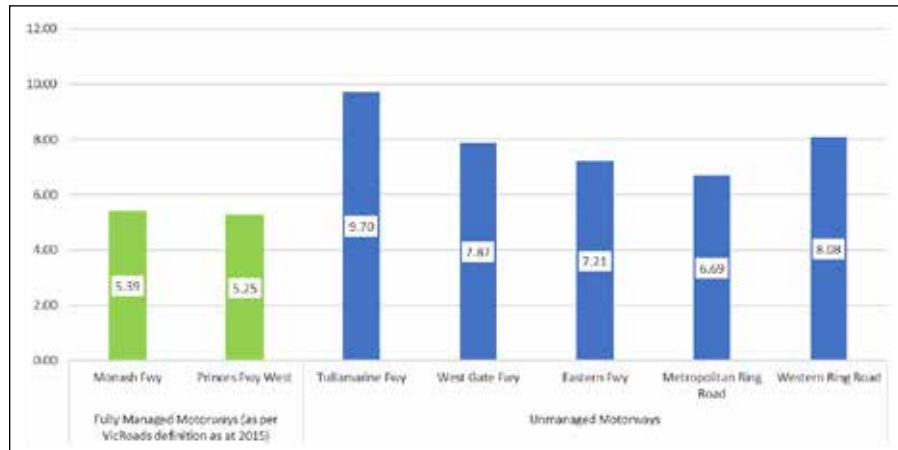


Figure 5. Comparison of casualty crash rates (per 100 million VKT) for selected metropolitan Melbourne motorways, 2012 to 2016

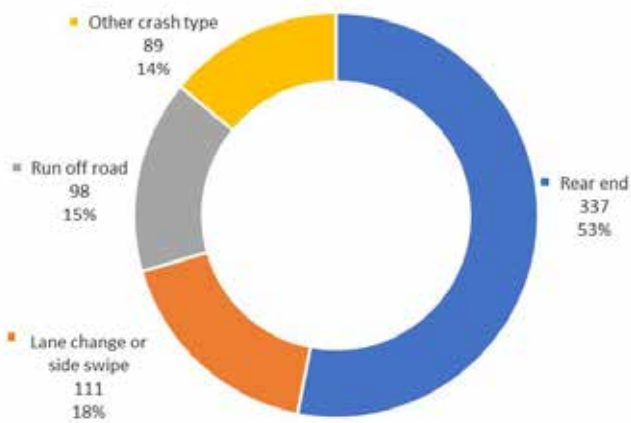


Figure 6. Predominant crash types on metropolitan Melbourne motorways (main carriageway, 2-direcational), 2012 to 2016 annual average

Over the 25.5 km length of the freeway, from Toorak Road to South Gippsland Highway and including 14 interchanges, both congestion decreased and safety improved in the five-year period after the upgrade compared to the five-year period before the upgrade despite only partial management of the motorway and despite an increase in lane flows above pre-project conditions. The improved safety outcomes included reduced crash numbers, reduced crash rates and reduced crash severity and were considered to be mainly due to the managed motorway operations with coordinated ramp metering signals which maintained smoother traffic flow, minimising flow breakdown and congestion and reducing speed variations. The latter was achieved through real-time management of mainline occupancy (as a proxy for density) to keep it at an optimal level and avoid triggering congestion (stop-start conditions) which leads to shock wave formation with stationary and slower moving vehicle clusters.

Crash Types

The majority (79%) of casualty crashes on metropolitan Melbourne motorways involve vehicles colliding with other vehicles and not vehicles colliding with fixed objects (infrastructure) which only accounts for 13 per cent of the casualty crashes. The remaining eight per cent include

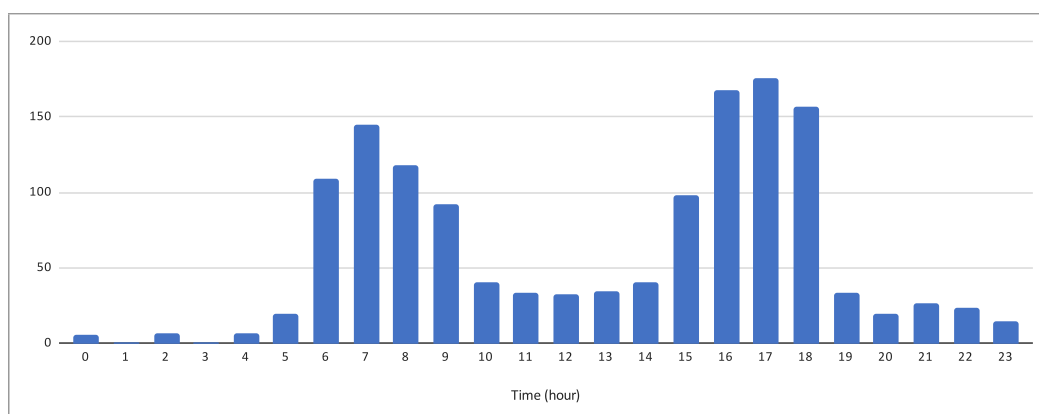


Figure 7. Weekday rear end casualty crashes on metropolitan Melbourne motorways (main carriageway, 2-direcational) by time of day, 2012 to 2016

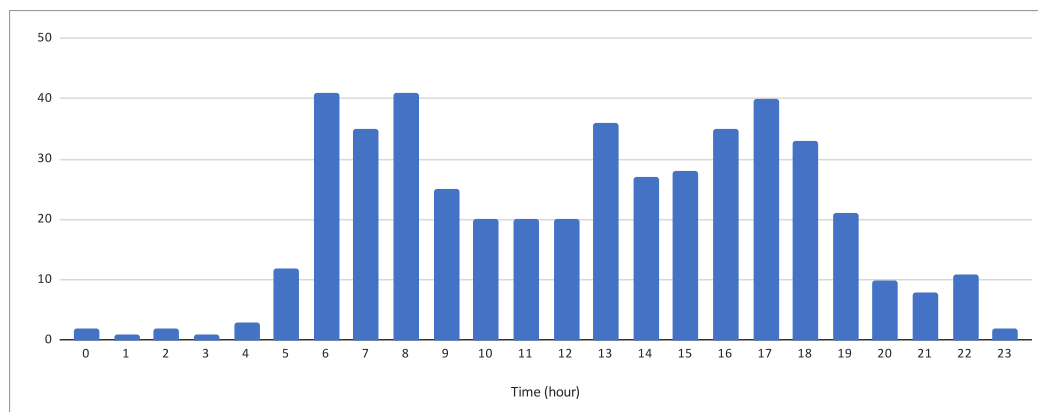


Figure 8. Weekday lane change or side swipe casualty crashes on metropolitan Melbourne motorways (main carriageway, 2-directional) by time of day, 2012 to 2016

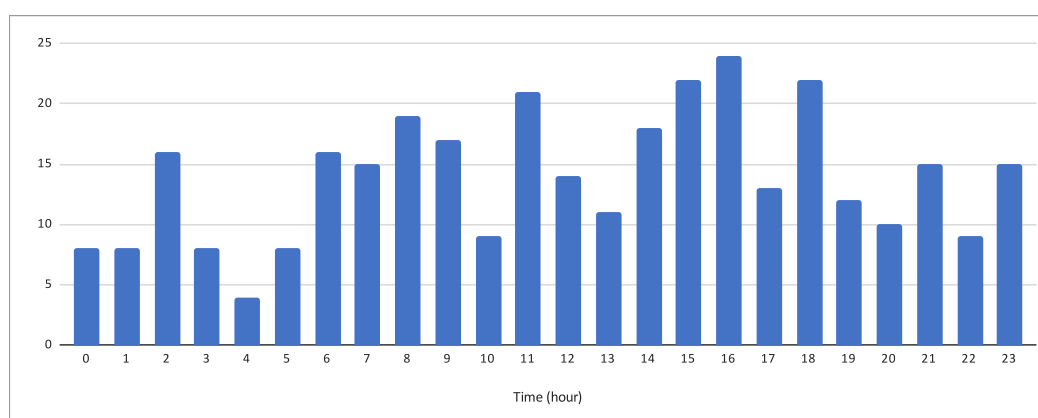


Figure 9. Weekday run off road casualty crashes on metropolitan Melbourne motorways (main carriageway, 2-directional) by time of day, 2012 to 2016

vehicles overturning or losing control (for example a motorcyclist falling off their bike), and collisions with non-fixed objects; animals or pedestrians. The predominant crash types are rear end crashes (53%), lane change or side swipe crashes (18%) and run off road crashes (15%). Collectively these three crash types represent 86 per cent of all casualty crashes on metropolitan Melbourne motorways (refer to Figure 6).

Rear end crashes

The distribution of the metropolitan Melbourne motorway crashes varies by crash type and by time of day. Rear end crashes increase with higher traffic volumes (refer to Figure 7). This may be due to a higher exposure to risk resulting from higher volumes and / or greater levels of congestion. Factors mentioned in the Police reports for rear end crashes include failing to stop due to congestion and/or heavy traffic. The number of rear end crashes in the PM peak period is higher and this may be due to commuters being more fatigued or less focussed on the driving task (Kononov et al., 2012). The introduction of Advanced Driver Assistance Systems, such as Automated Emergency Braking (AEB), could be accelerated to tackle rear end crashes and improve motorway safety.

Lane change and side swipe crashes

Lane-change and side-swipe crashes also increase with higher traffic volumes (refer to Figure 8). This may be due to a higher exposure risk resulting from higher volumes and/or congestion, or where motorists may be avoiding a rear-end crash. There may also be difficulties for motorists finding a gap in heavy traffic for lane changing manoeuvres. Factors mentioned in the Police reports for lane change and side swipe crashes include failing to see the vehicle, blind spots and heavy traffic. Heavy vehicles and motorcycles are involved in many of the lane change and side swipe crashes. The introduction of Advanced Driver Assistance Systems, such as Blind Spot Warning, could be accelerated to tackle lane change and side swipe crashes and improve motorway safety.

Run off road crashes

Run off road crashes generally occur throughout the whole day (refer to Figure 9). Although it is often thought that these crashes occur in light traffic conditions, for example at night due to fatigue and/or alcohol or drug impaired driving, the data indicates that they are also occurring at other times such as in peak hours and in the peak shoulders.

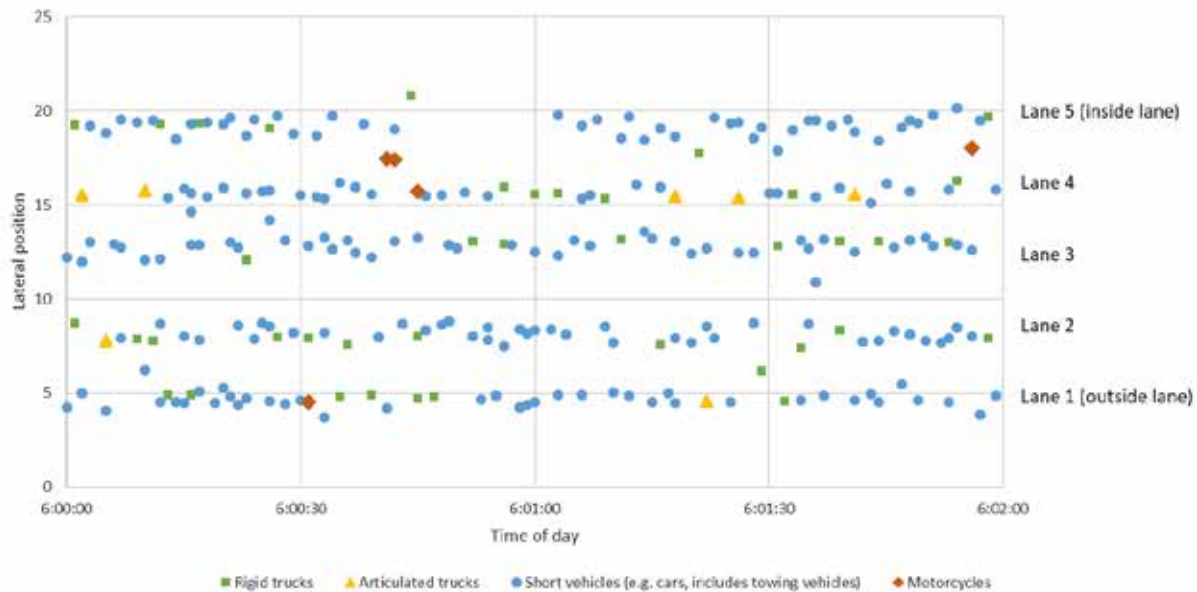


Figure 10. Lateral position (in metres) of different vehicle types on the Monash Freeway between Stud Road and Eastlink (inbound carriageway) between 6:00am and 6:02am on 4 March 2019 as measured by infrared data loggers

Factors mentioned in the Police reports for the run off road crashes include losing control whilst trying to avoid a rear end or lane change collision, losing control when merging, changing lanes or overtaking, losing control when negotiating a curve or bend (especially on a wet road), excessive speed, medical conditions and fatigue.

Vehicle Types

Heavy vehicles, utilities and motorcycles are overrepresented when comparing their involvement in casualty crashes to their share in vehicle kilometres travelled (VKT) on metropolitan Melbourne motorways. Collectively these vehicle types were involved in 43 per cent of all casualty crashes on metropolitan Melbourne motorways.

- Heavy vehicles were involved in 17 per cent of the casualty crashes but only have a 10 to 12 per cent share in all VKT on motorways. Due to their physical characteristics and weight, heavy vehicles are at particular risk of being involved in more severe crashes and were involved in 30 per cent of the fatal metropolitan motorway crashes. Heavy vehicles have issues with blind spots and were involved in 49 per cent of the weekday lane change or side swipe crashes.
- Utilities were involved in 19 per cent of the casualty crashes but have an estimated 10 to 14 per cent share in all VKT on motorways. They were involved in 25 per cent of the fatal crashes and in 25 per cent of the weekday rear end crashes.
- Motorcycles were involved in 11 per cent of the casualty crashes but have a one to two per cent share in all VKT on motorways. Due to their vulnerability, they too are at a higher risk of being involved in more severe crashes and were involved in 23 per cent of the fatal crashes. Motorcycles were involved in 20 per cent of the weekday loss of control (including run off road)

crashes and in 18 per cent of the weekday lane change or side swipe crashes.

Recently installed infrared data loggers on the Monash Freeway which can measure speed, volume, occupancy and lateral position of vehicles in real time have shown that some motorcycles are lane splitting in a high-speed environment. Figure 10 shows the lateral position of vehicles on a five-lane section of the Monash Freeway, with the measurement taken from the outside of the carriageway. Motorcycles are symbolised with a brown diamond and can be seen travelling between Lane 4 and Lane 5 (that is, the lanes closest to the median). The output from the data loggers has also shown that some motorcycles travel at extremely high speeds, particularly at night time. For example, over the one-month period, from 20 February 2017 to 20 March 2017, around 180 motorcycles travelled at speeds between 130 km/h and 205 km/h on the inbound and outbound carriageways of the Monash Freeway near Stanley Street. This can pose a significant safety risk not only to the motorcyclists themselves as the motorway is not designed for travel at such speeds, but it also poses a significant threat to slower surrounding vehicles. The current speed enforcement regime is not effective in these cases and a speed enforcement regime using point-to-point cameras integrated with real-time traffic and flow management such as Dynamic Variable Speed Limits would be more effective.

Crashes and Traffic State: Monash Freeway and Eastern Freeway

The results of the analysis of the linked crash and occupancy data on the Monash and Eastern Freeways is shown in Tables 3 and 4 and in Figures 11 and 12. The tables show the number of observed and expected casualty crashes that fall within each of the five categories, where the expected casualty crashes are based on the exposure. The figures

Table 3. Monash Freeway inbound casualty crashes by occupancy class based on ‘Traffic States’, observed versus expected (based on traffic exposure), 2013 to 2016

	Free flow (0.0 to 4.9% bin)	Transition (5.0 to 9.9% bin)	FBR significant (10.0 to 14.9% bin)	FBR relatively certain (15.0 to 19.9% bin)	Flow breakdown (20% plus bin)	Total
Casualty crashes (observed)	13	32	34	20	44	143
Daily traffic processed (%)	13.7	28.6	29.1	9.6	19.0	100
Casualty crashes (expected)	20	41	42	14	27	143
Observed versus expected	-7	-9	-8	+6	+17	-

Table 4. Eastern Freeway inbound casualty crashes by occupancy class based on ‘Traffic States’, observed versus expected (based on traffic exposure), 2013 to 2016

	Free flow (0.0 to 4.9% bin)	Transition (5.0 to 9.9% bin)	FBR significant (10.0 to 14.9% bin)	FBR relatively certain (15.0 to 19.9% bin)	Flow breakdown (20% plus bin)	Total
Casualty crashes (observed)	8	21	16	10	20	75
Daily traffic processed (%)	16.0	37.8	23.9	9.3	13.0	100
Casualty crashes (expected)	12	28	18	7	10	75
Observed versus expected	-4	-7	-2	+3	+10	-

show the percentage of crashes by crash severity that fall within each of the five categories and a comparison with exposure and average travel speed on the Monash Freeway and Eastern Freeway respectively. From these tables and figures, it can be seen that on both the Monash Freeway and Eastern Freeway the crash numbers are lower than the exposure level for all occupancy bins where the breakdown risk is still relatively low (that is, $\leq 1\%$ per 15-minute interval) and where it hasn't broken down yet (that is, the first three traffic states). In the higher occupancy ranges (15% and above) however, the crash numbers are exceeding the exposure level. These are the conditions where motorists find it harder to drive as they compete for steadily decreasing spare road space and/or where unexpected traffic conditions arise. In the traffic state corresponding to flow breakdown (occupancy of 20% and above) crash numbers are much higher relative to exposure.

Applying the Chi-Square Goodness of Fit Test to the data in Table 3 and Table 4 has shown that there was a statistically significant difference for both freeways between the observed and expected number of crashes, where the expected number of crashes is based on exposure values. For the Monash Freeway, Chi-Square ($df = 4, n = 143$) = 18.66, $p = .001$. For the Eastern Freeway, Chi-Square ($df = 4, n = 75$) = 15.65, $p = .004$. This indicated that there was a statistically significant association between traffic state and the number of crashes.

As quoted by (Kononov, Lyon & Allery, 2011, p. 11), “Accidents on an urban freeway are a by-product of traffic flow. It is reasonable, therefore, to expect that the observation of changes in the flow parameters may give clues about the probability of accident occurrence and changes in accident frequency.” By keeping the motorway operating within certain occupancy levels, it may be possible to reduce the number of crashes and improve safety. Both preliminary analysis and overseas examples indicate that there is likely to be an optimal occupancy range where relatively high flow rates coincide with a low breakdown probability and a low crash rate. A key is determining the optimal occupancy level for the conditions that improves safety as well as efficiency and further analysis is needed to specify this optimal operational state.

Crash types and the traffic state

The analysis has also shown that the highest proportion of rear end crashes occur in the traffic state corresponding to flow breakdown (occupancy of 20% and above) for both motorways whilst the highest proportion of lane change or side swipe crashes occurred in the traffic state where there was a significant risk of flow breakdown (occupancy between 10 and 14.9%) on the Monash Freeway and in the transition traffic state (occupancy between 5 and 9.9%) on the Eastern Freeway. The majority of run off road crashes occurred in the free flow and transition traffic states (occupancy less than or equal to 9.9%). Refer to Figures 13 and 14.

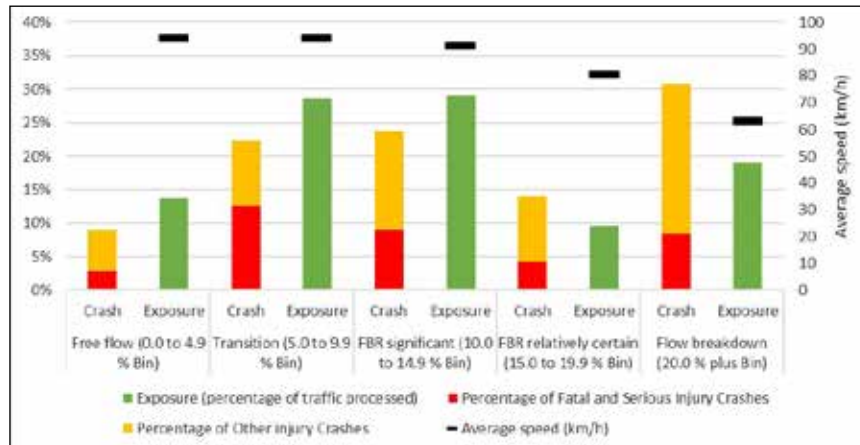


Figure 11. Weekday fatal and serious injury and other injury crashes by occupancy class based on 'Traffic States' with respect to traffic exposure and average speed on the Monash Freeway inbound carriageway, 2013 to 2016

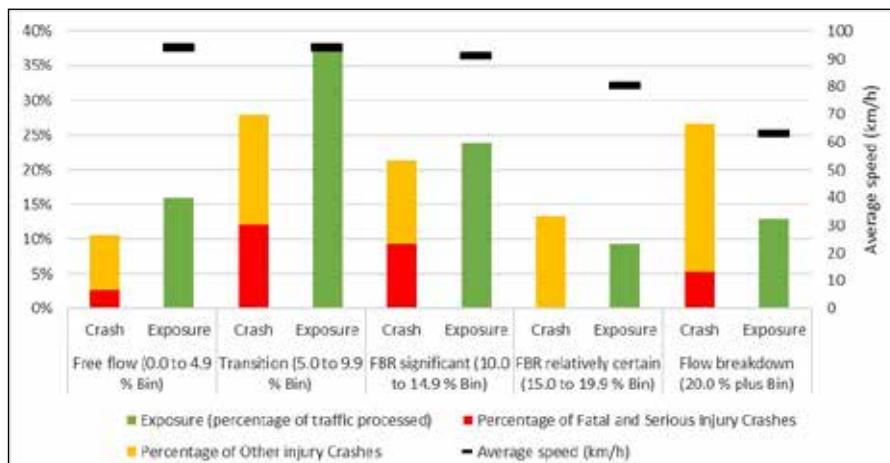


Figure 12. Weekday fatal and serious injury and other injury crashes by occupancy class based on 'Traffic States' with respect to traffic exposure and average speed on the Eastern Freeway inbound carriageway, 2013 to 2016

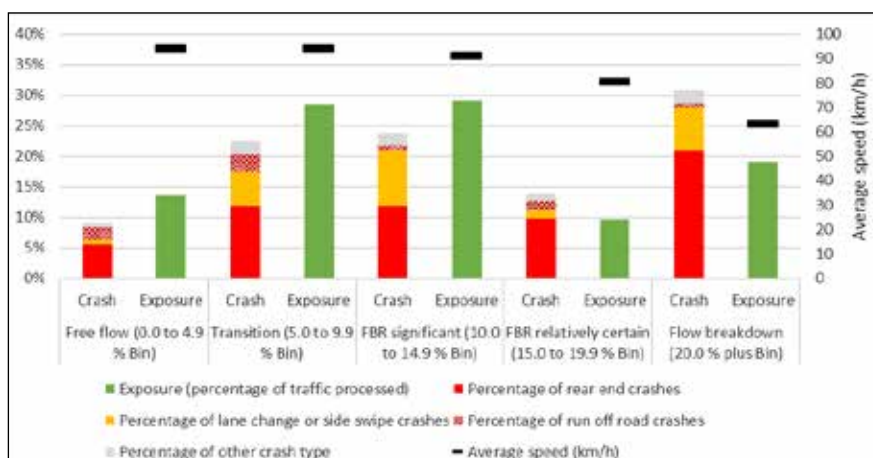


Figure 13. Weekday casualty crashes by crash type and occupancy class based on 'Traffic States' with respect to traffic exposure and average speed on the Monash Freeway inbound carriageway, 2013 to 2016

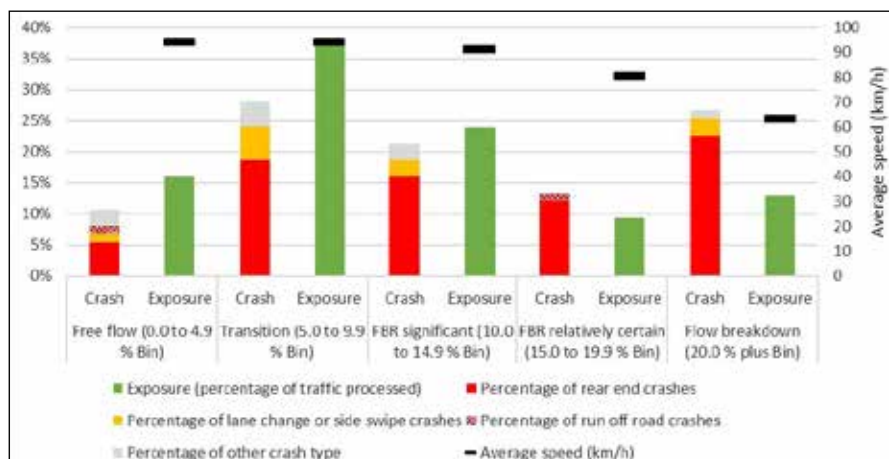


Figure 14. Weekday casualty crashes by crash type and occupancy class based on 'Traffic States' with respect to traffic exposure and average speed on the Eastern Freeway inbound carriageway, 2013 to 2016

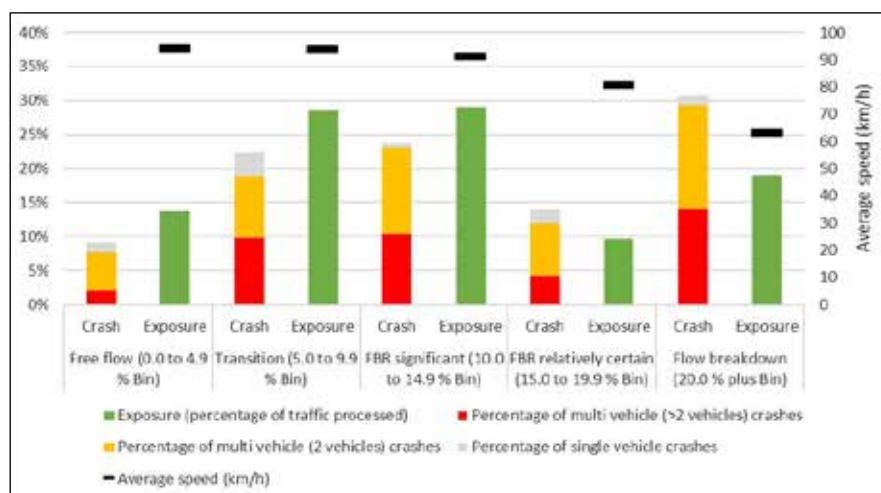


Figure 15. Weekday casualty crashes by number of vehicles and occupancy class based on 'Traffic States' with respect to traffic exposure and average speed on the Monash Freeway inbound carriageway, 2013 to 2016

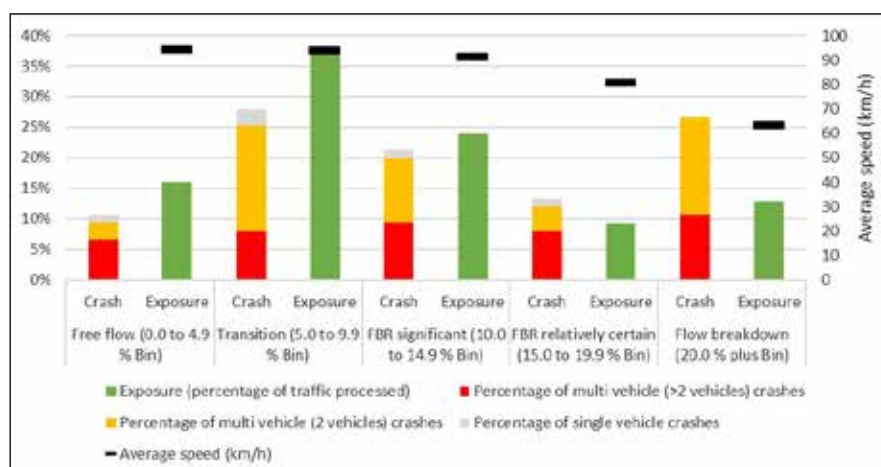


Figure 16. Weekday casualty crashes by number of vehicles and occupancy class based on 'Traffic States' with respect to traffic exposure and average speed on the Eastern Freeway inbound carriageway, 2013 to 2016

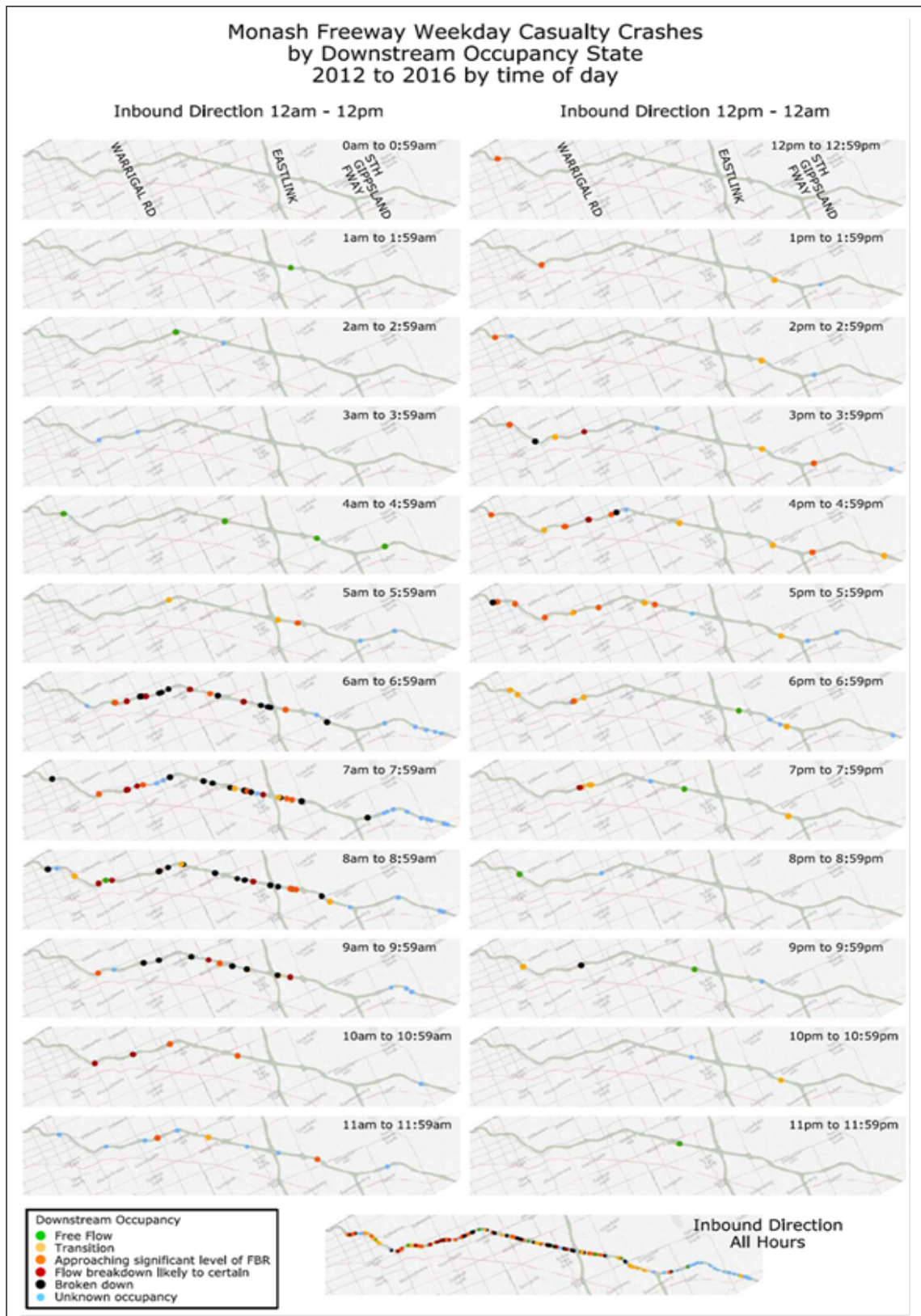


Figure 17. Inbound weekday crashes on the Monash Freeway classified into 'Traffic States' based on closest downstream detector and with respect to hour of day, 2012 to 2016

Number of vehicles and the traffic state

Another result from the analysis of the linked crash and occupancy data was that 95% of the crashes in the highest occupancy bin on the Monash Freeway and all of the crashes in the highest occupancy bin on the Eastern Freeway were multi-vehicle crashes (refer to Figures 15 and 16). Findings such as this broadly align with (Hauer & Kononov, 2018) where multi-vehicle crashes appear to be associated with increasing vehicle concentration.

Spatial and temporal aspects of motorway crashes

To examine the spatial and temporal aspects of motorway crashes, inbound weekday casualty crashes on the Monash Freeway were plotted on a map for each hour of the day and categorised into the five traffic states, plus unknown (refer to Figure 17). Very few crashes occur in free flow conditions (shown as green dots). The highest number of crashes occur in heavier traffic conditions such as where flow breakdown is relatively certain (shown as brown dots) and where flow has broken down (shown as black dots) and these conditions generally align with the peak periods.

Conclusions

Although urban motorways have traditionally been perceived as safe due to low crash rates and high standard of infrastructure, the number of casualty crashes on urban motorways has been increasing at a much higher rate than on other urban arterial roads in metropolitan Melbourne. With increasing traffic, there is a growing risk that the motorways will operate in a critical traffic state most of the day-time hours resulting in more crashes unless something is done to address this.

Both overseas research and output from new technologies deployed by VicRoads on some metropolitan Melbourne motorways provide growing evidence that there is a relationship between motorway crashes and traffic conditions. The detailed analysis undertaken on the Monash Freeway and the Eastern Freeway indicates that there is an association between traffic state and the number of crashes, with higher than expected crashes in the traffic states where flow breakdown is relatively certain (15% to 19.9% occupancy) or has occurred ($\geq 20\%$ occupancy). This supports the hypothesis that the dynamics of the traffic flow, which cause congestion and require complex driver responses, are a significant contributor to casualty crashes on urban motorways. The analysis has also shown that the casualty crash rate on managed motorways is lower than that on unmanaged motorways.

Improved urban motorway safety can be achieved through the development of Intelligent Transport Systems (ITS) strategies that keep the motorway operating at conditions that minimise flow breakdown. This could be achieved by implementing a multi-criteria motorway management operational strategy that maximises both safety and efficiency with the current cooperative ramp metering, including integrated Lane Use Management System (LUMS) and Variable Speed Limit (VSL) signs, to keep the managed

motorway operating at an occupancy that ensures low crash risk as well as high flow rates and high productivity. Safety could be further improved with the provision of additional motorway management infrastructure such as real-time localised congestion warnings, delivered via variable message signs (as done in Europe) or in-vehicle displays, in line with appropriate road design standards.

Enforcement measures such as point-to-point speed cameras integrated with real-time traffic control (for example, Dynamic Variable Speed Limits) could be implemented to tackle excessive speeding and acceleration of the introduction of Advanced Driver Assistance Systems would help to target the predominant urban motorway crash types. In particular, Automated Emergency Braking (AEB) would help tackle rear-end crashes and Blind Spot Warning would help tackle lane change and side swipe crashes.

This research provides the evidence-base for the relationship between urban motorway crashes and the traffic state. Further analyses need to be undertaken, including the determination of the optimal occupancy level that keeps the motorway operating in conditions that prevent flow breakdown, and that maximises both safety and efficiency.

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