Hi Rodger,

I am writing on behalf of Airport Motorway Limited (AML), the operator of the Eastern Distributor motorway in regards to the development application for the proposed digital advertising signage at the railway overpass above the Eastern Distributor, Woolloomooloo. It has been brought to my attention by George Bardas, from Motorway Partnerships and Planning team of TfNSW, that AML's objection and concerns regarding the DA were not submitted to the Department of Planning, Industry and Environment within the required consultation timeframes.

As TfNSW is the Landowner of the Eastern Distributor, it is customary that all submissions made by AML in response to all development applications are transmitted through TfNSW. AML do not have visibility of if and when responses are submitted to DPIE (or any other consenting authority) and rely on TfNSW meeting all submission deadlines.

For this particular DA, due to TfNSW's own internal processes and technical issues transmitting the attachments via email, AML only received the information from TfNSW on 22 December 2020. AML then went into the Christmas shutdown period from 23 December 2020 and resumed general business on 11 January 2021. AML provided comments in response to the DA to TfNSW on 14 January 2021 as per the attached email and were of the understanding that these comments were then subsequently provided to DPIE for consideration.

It was only last Friday 30 July that it became apparent to AML upon reviewing the Planning website that our concerns were not provided to DPIE as per my email to George Bardas attached.

AML are very concerned about the potential impact to road safety and increased risk of driver distraction in the immediate vicinity of the proposed digital advertising signage and would appreciate DPIE considering these concerns in its assessment of the DA.

Below are the key issues which were also provided in the attached email to TfNSW for your consideration:

1. The location of the proposed advertising sign is upstream of the tunnel entrance. The placement of unnecessary signs on the approach to tunnels or within tunnels is not supported by tunnel guidelines. The attached AustRoads research report "Measures to Reduce Crashes Adjacent to and within Tunnels" makes the following recommendation concerning signs;

   "As information overload is a safety performance factor for some drivers approaching tunnel portals, signage and the placement of signage should be reviewed so as to simplify the driving task, thereby reducing crash risk for affected drivers."

   If the proposed advertising sign is approved a driver approaching the tunnel will encounter the following signs;
   - Advance VMS used to advise of tunnel conditions and incidents
   - Proposed advertising sign
   - Tunnel portal VMS and VSLS used to reinforce advise to motorists of tunnel conditions

2. Sydney Trains must confirm if there will be impact to the readability of the ED VMS upstream of the advertising sign. It will likely that the brightness of the advertising sign will be greater than the VMS which will be an issue for motorists as the advertising sign will detract from the messaging displayed on the VMS as well as distract drivers who are planning to use either the Cathedral St exit ramp.

3. The sign is to be located in an area where an exit lane commences i.e. the southbound Cathedral Street exit ramp. In this location, motorists are required to make a decision concerning their destination and potential lane changes if they decide to exit. Any form of distraction should be minimised. In Queensland the State guidelines for the placement of advertising in this type of location is prohibited.

4. The proposed sign would be situated between two southbound VMS – VMS2S and VMS3S.

   - VMS2S is the VMS located just prior to the Cathedral St exit ramp (shown on Figure 2.4 Appendix D Woolloomooloo Digital Signage Safety Assessment).
   - VMS3S is the VMS located at the SB tunnel portal.

   Due to the Cathedral St exit being the last point motorists can exit the motorway before entering the main tunnel, VMS2S is critical in providing the ED Control Room the ability to divert traffic before entering the SB tunnel portal in the event of an incident requiring a tunnel closure. VMS2S is also triggered as part of our over height vehicle plan as a last effort to divert an over dimensional vehicle reaching the main tunnel and potentially damaging critical infrastructure, figures 2.5, 2.6 and 2.7 of the Signage Safety Assessment show the proposed signage sharing the field of view of motorists with VMS2S which could provide a visual distraction causing important messages to be missed by the approaching motorist.

   Both VMS2S and VMS3S are for the most part used in unison as part of our traffic plans, for example in the event of a tunnel fire VMS2S would be used to attempt to divert traffic away from the tunnel entry portal and onto Cathedral Off Ramp and VMS3S would be advising motorists that the tunnel was closed and not to enter, having additional signage between the two VMS's would provide a distraction to motorists at critical decision points.

5. The collision type and severity table on page 12, Table 2.1, of Appendix D Woolloomooloo Digital Signage Safety Assessment refers to crash history data between 1 January 2015 and 31 December 2019 as provided by TfNSW. The data indicates that the collisions are predominately rear end collisions suggesting the location experiences congestion and stop start driving conditions. In areas where there is congestion, additional distractions should be avoided.

6. It is our view that the performance of the motorway must consider more than only crash history data in the immediate vicinity of the proposed sign and must consider other incident types which can contribute to near misses and could potentially lead to an accident with the introduction of an additional distraction such as the proposed sign. The crash data should not be viewed in isolation and must also consider other incidents as those listed below since the VMS are used to provide advance warning and instruction to motorists of these incidents. Other incident types or events include:
   - Vehicle breakdowns, out of fuel and flat tyre events
   - Debris on the road
   - Chemical spill on the road
   - Unauthorised access by pedestrians and cyclists (prohibited user) on the motorway

   Furthermore, the physical extent of the motorway for which the data is based should extend from the exit of the Landbridge structure where the digital sign would enter the field of vision to downstream into the tunnel (to approximately the extent that William St is on the surface relative to the tunnel). This is because *VMS2S and VMS3S are used as advanced warning to motorists in the event that there is an incident within the SB tunnel they are approaching. These incidents may cause congestion tailing or provide road hazards just within the tunnel portal that motorists must be made aware of. By including these additional data points from the short extent within the tunnel which these VMSs would be used, the incident numbers are significantly higher. Please refer to the attached pdf "ED Accident & Incident Data-SB-Woolloolm-2017-2020 which provides four years of data and the locations of the accidents/incidents/events on a map within the vicinity of the proposed signage.*

7. The information on page 20 of Appendix D Woolloomooloo Digital Signage Safety Assessment concerning a Court Case about the location of a VMS and advertising sign is relevant to this situation as the ED, whilst at times congested, is a high speed motorway and the VMS is used to manage incidents in a downstream tunnel. The Court Case concerns a VMS and advertising sign at an intersection on the arterial network. There are different risks to consider.

We would appreciate DPIE's consideration of the above mentioned road safety concerns in its determination of the DA.

Should you have any questions or wish to further discuss, please don't hesitate to contact me on 0426 582 822.

Regards,

Rez Ramzan
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Transurban

Incident Types

Accident	Breakdown	Chemical Spill	Congestion	Debris	Flat Tyre	Out of Fuel	Overheight Vehicle	Pedestrian	Prohibited User	Total
48	84	2	283	35	10	9	19	19	22	**531**

Weekday and Hour Detected

	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Total
0	1	1	1	1				4
1							1	1
2	1				1		3	5
3					1			1
4		1		1				2
5			2	2	1			5
6	7	8	12	22	11	2		62
7	4	5	5	5	11	1		31
8	2	4	3	5	5	3	2	24
9	7	7	5	13	6	1	1	40
10		3	2	13	10	10		38
11	2	4	6	5	8	5	3	33
12	4	2	7	7	11	7	6	44
13	4	2	2	2	7	11	2	30
14	5	10	10	7	7	1	2	42
15	9	15	5	10	7	3	9	58
16	3	5	1	8	2	1	10	30
17	4	5	4	8	4	2	3	30
18		7	4	3	5	2		21
19	1	3	1	2	3			10
20		1	1	2	2	1		7
21	1			1	2		1	5
22			1	1	1	2	1	6
23		1					1	2
Total	55	84	72	118	105	52	45	531

Peak and Direction

	NB	SB	Total
Off Peak	5	69	74
Peak	21	462	483
Total	26	531	557

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Austroads

Research Report
AP-R557-18

Measures to Reduce Crashes Adjacent to and within Tunnels

Measures to Reduce Crashes Adjacent to and within Tunnels

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Abstract

This report identifies factors that contribute to the occurrence and severity of crashes adjacent to and within tunnels and suggests remedial treatments that will reduce the incidence and severity of these crashes.

A preliminary examination of recorded road crashes immediately adjacent to and within a selected sample of Australian tunnels found that, while tunnels are relatively safe when compared with other parts of the road network, crashes in or near them are a significant source of road trauma and cause substantial delays to road users across the road network.

As road tunnels form an important part of the road network, there is a need to ensure motorists can travel in a 'Safe System' consistent with the *National Road Safety Strategy 2011–2020*. Such a system acknowledges that road users will inevitably make mistakes, and that when they do, they should not be penalised with death or serious injury.

The outcomes of the research will help to reduce the risk and severity of crashes adjacent to and within new and existing road tunnels.

Keywords

Tunnels, portals, safety, lighting, driver distraction, driver behaviour, crashes, crash risks, safety measures, perceptual countermeasures

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About Austroads

Austroads is the peak organisation of Australasian road transport and traffic agencies.

Austroads' purpose is to support our member organisations to deliver an improved Australasian road transport network. To succeed in this task, we undertake leading-edge road and transport research which underpins our input to policy development and published guidance on the design, construction and management of the road network and its associated infrastructure.

Austroads provides a collective approach that delivers value for money, encourages shared knowledge and drives consistency for road users.

Austroads is governed by a Board consisting of senior executive representatives from each of its eleven member organisations:

- Roads and Maritime Services New South Wales
- Roads Corporation Victoria
- Queensland Department of Transport and Main Roads
- Main Roads Western Australia
- Department of Planning, Transport and Infrastructure South Australia
- Department of State Growth Tasmania
- Department of Infrastructure, Planning and Logistics Northern Territory
- Transport Canberra and City Services Directorate, Australian Capital Territory
- Australian Government Department of Infrastructure and Regional Development
- Australian Local Government Association
- New Zealand Transport Agency.

Acknowledgements

The authors acknowledge the contribution provided by the Project Advisory Group whose members are listed in Section 1.3.

Summary

Road tunnels are major pieces of infrastructure across the Australian and New Zealand road network. A preliminary examination of recorded road crashes immediately adjacent to, and within, a selected sample of Australian tunnels found that, although they are relatively safe when compared with other parts of the road network, there are a significant number of crashes both adjacent to and within them and that the most common crash types were rear-end, side-swipe and lane changing types of collisions. While these crash types are generally of a low severity, they result in extremely high crash severity outcomes, particularly when they involve multiple vehicles, trucks or when a fire results from a crash.

A further consequence of crashes associated with tunnels is that they cause major traffic flow disruptions that result in long travel time delays, while also increasing crash risk across the surrounding road network as effected traffic seek alternative travel routes to avoid delays.

The objectives of this study were to identify:

- factors that contribute to the occurrence and severity of crashes adjacent to and within tunnels
- remedial treatments that will reduce the incidence and severity of these crashes.

The main findings of the study were as follows:

- Driver behaviour is a major factor in the occurrence of crashes on the approaches to and within tunnels. Such behaviours included driver lane discipline and lane changing (refer to Section 2.3 and Section 4.4.2 for further information).
- Most crashes involve vehicles travelling in the same direction (i.e. rear-end, side-swipe and lane changing); this is as a result of variations in driver speeds, unsafe vehicle headways (i.e. vehicles travelling too close to each other or inadequate travel time gaps between vehicles), poor lane discipline, unsafe passing and high speeds for the conditions.
- Changes in driving conditions pose the greatest crash risks as drivers approach a tunnel from about 100 metres, travel through the tunnel portal along a distance of approximately 100 metres and then drive through a transitional zone of up to a further 300 metres.
- Variations in light levels when entering tunnels and the ‘quality’ of lighting within tunnels are crash risk factors.
- Trucks travelling through tunnels increase crash risk, while also increasing the risk of high-severity crash outcomes.
- The absence of a shoulder (or emergency lanes), or narrow shoulders and narrow lanes increases crash risk.
- Merge and diverge areas in tunnels increase crash risk as there is an increase in vehicle manoeuvring.

To address the factors that increase crash risk and cash severity the following conclusions and recommendations are provided for consideration:

- As information overload is a safety performance factor for some drivers approaching tunnel portals, the type and placement of signage should be reviewed so as to simplify the driving task, thereby reducing crash risk for affected drivers.
- Lighting levels upon entry to tunnels, and through the transition zone, should be reviewed and regulated so as to minimise variations in lighting that may occur over a short distance that are experienced by drivers and motorcyclists.
- The use of variable message signing (VMS) as a means of informing and advising users of incidents and driving requirements should be promoted, particularly in long tunnels.

- Review of truck access to tunnels, with the following potential measures implemented; discouraging truck access, restriction of truck access to select lanes, curfews for truck access or banning of truck access. The application of any of these options will be dependent on the tunnel location, its function as part of the road network and the viability of alternative route travel options and their crash risks.
- When trucks are permitted to travel through tunnels restrict the lanes they are permitted to travel in.
- Speed cameras should be considered for installation in all road tunnels.
- While overtaking in some circumstances in tunnels may be required, this manoeuvre should be discouraged through the use of VMS or static signing, while similarly advising tunnel users to maintain a safe distance between themselves and the vehicle ahead.
- If possible provide shoulders or breakdown bays. If these lanes are not able to be accommodated, ensure that safety management systems are provided to reduce crash risks associated with their absence.
- The application of low-cost perceptual countermeasures treatments (PCT) should be investigated as a means of affecting safe driver speed behaviour, improving lane discipline and safe driver headways. In order to determine the potential benefits, while also detecting possible adverse unintended consequences of such treatments, it is recommended that the PCT be trialled and evaluated within a driver simulator.
- The *Austroads Guide to Road Tunnels (GRT)* should be reviewed to ensure that it reflects best practice in the construction of new tunnels and in the retrofitting of older tunnels.

Contents

Tables

Figures

1. Introduction

1.1 Background

Road tunnels are major pieces of infrastructure across the Australian and New Zealand road network. The number of tunnels is expected to increase in the coming years. A preliminary examination of recorded road crashes immediately adjacent to, and within, a selected sample of Australian tunnels found that, although they are relatively safe when compared with other parts of the road network, there are a significant number of crashes both adjacent to and within them.

The analysis also revealed that the types of crashes occurring in tunnels are generally rear-end, side-swipe and lane-changing types of crashes. It was also noted that, while these crash types tend to be of a relatively low severity, they can, on occasions, result in extremely high crash severity outcomes, particularly when they involve multiple vehicles, trucks or when a fire results from a crash.

A further consequence of crashes associated with tunnels is that they create major disruptions to traffic flows that result is substantial travel time delays, while also increasing crash risk across the surrounding road work as affected drivers seek alternative routes to avoid delays.

There is also a need to provide road users with safe travel within the context of a *Safe System*, the key focus of Australia's and New Zealand's road safety strategies. Such a system acknowledges that road users will inevitably make mistakes, and that when they do make mistakes, they should not be penalised with death or serious injury.

1.2 Project Objectives

The objectives of this Austroads-funded research project were to identify:

- factors that contribute to the occurrence and severity of crashes adjacent to and within tunnels
- remedial measures that will reduce the incidence and severity of these crashes.

The outcomes of the research will assist road agencies to reduce the risk and severity of crashes adjacent to and within new and existing road tunnels.

1.3 Methodology

The project methodology involved the following key tasks:

- The undertaking of a literature review to
  - identify factors that may have contributed to the occurrence of, or severity of, crashes within tunnels or in their vicinity
  - identify safety measures implemented at or within tunnels which were designed to address crash contributing factors
  - identify national and international guidance documents related to the provision of safety measures for road users approaching, traveling through and departing road tunnels.

- Analysis and reporting of available crash data using a sample of tunnels in Australia and New Zealand to identify key characteristics associated with tunnel crashes. Data for crashes adjacent to and within tunnels in New Zealand and Australian was disaggregated by variables reflecting
  - time-of-day
  - site characteristics (e.g. speed limit)
  - crash characteristics (e.g. type of crash, object struck)
  - environmental conditions (e.g. light conditions, weather conditions)
  - road user characteristics (e.g. vehicle type, number of vehicles involved).
- Site investigation of a representative sample of two tunnels with relatively 'old' design standards and two tunnels with relatively 'new' design standards, all located in major Australian capital cities. The purpose of the site investigations was to enable the collection and analysis of real-world data in order to better understand factors contributing to safety risks and potential crashes located within, and adjacent to, tunnels.

  The investigation involved
  - a 'drive through' examination at normal traffic speeds using a digital video camera to record physical road and tunnel elements during peak and off-peak periods
  - consultation with tunnel operators to draw upon their experiences in relation to road tunnel safety.

  It should be noted that, in the interest of maintaining a collaborative approach between stakeholders, the locations of the tunnels are not provided in this report.
- Identification of an in-tunnel perception countermeasure treatment (PCT) that may influence safer driver behaviour when driving through tunnels. The intention is that the PCT will influence lower driver speed behaviour, reduce variability in driver speeds, improve lane discipline (i.e. more uniform lateral placement within lanes), and more uniform vehicle headways (both in time and distance). Typically PCTs within tunnels are wall markings and/or road pavement markings which seek to influence driver speed and travel behaviour through their visual peripheral impact on drivers as they travel through a tunnel.

  It should be noted that the project scope originally proposed the trial and evaluation of a PCT within a selected urban tunnel. However, because of concerns associated with unintended consequences – for example drivers who may be effected by the peripheral flicker associated with PCT, which may trigger an epileptic or similar episode – the Austroads Road Tunnels Task Force (RTTF) determined that such a treatment should be trialled in a driver simulator and evaluated prior to implementation.
- Consultation with the RTTF and key stakeholders to identify low-cost treatment options that may be installed that will reduce crash risk, and to identify a PCT that may be the subject of trialling with a driver simulator. It should also be noted that the RTTF and its key stakeholders also assumed the role of the Project Advisory Group (PAG) and, as such, provided direction and advice during the course of the project.

  The PAG comprised the following personnel:

Geoff McKernan	Australasian Tunnel Operators Group (ATOG), Project Manager
Richard Yeo	Austroads Assets Program Manager
Michael Tziotis	Australian Road Research Board
Mohamed Nooru-Mohamed	Queensland Department of Transport and Main Roads
Lisa Hauth/Georgia Stylianos	Road Corporation Victoria (VicRoads)
Nigel Casey	Roads and Maritime Services NSW
John Venables	Main Roads Western Australia
Kingsley Noble	Dept. of Planning, Transport and Infrastructure South Australia
Nigel Lloyd	NZ Transport Agency
Bob Allen and Greg Pipikios	Australasian Tunnel Operators Group (ATOG)

Tony Peglas	Australasian Tunnelling Society (ATS)
George Mavroyeni	World Road Association (PIARC)
Greg Buckley	Australasian Fire and Emergency Service Authorities Council (AFESAC)

- The preparation of a study design for the trialling of a PCT within a driver simulator.
- Examination of the parts of the Austroads *Guide to Road Tunnels* to identify potential crash risk practices contained in the guide that may be revised to provide safer tunnel practice outcomes.

2. Literature Review

To ensure the safe and efficient operation of tunnels, which are a critical component of road networks across Australia and New Zealand, their design, construction and commissioning are required to comply with strict codes and guidelines.

Guidance is provided in the *Guide to Road Tunnels* series, which comprises of the following three parts:

- *Part 1: Introduction to Road Tunnels* (Austroads 2010a)
- *Part 2: Planning, Design and Commissioning* (Austroads 2015)
- *Part 3: Operation and Maintenance* (Austroads 2010b).

These guides provide information on various components of a road tunnel including, but not limited to:

- implementation processes
- planning and regulatory requirements
- traffic, structural and geometric considerations
- geotechnical and environmental considerations
- drainage and flood protection
- functional safety operations
- construction methods and potential issues
- design requirements
- geometric, pavement, drainage, ventilation and lighting design
- fire safety
- operations and maintenance requirements
- human factors
- training.

The use of the guides is expected to be in accordance with Australian and New Zealand standards to produce safe tunnel motorways along the road network (Austroads 2015).

2.1 Crashes

The literature review conducted as part of this project identified international literature on safety in and around tunnels. Lemke (2000), Kircher and Ahlstrom (2012), Yeung and Wong (2014) and Elvik et al. (2009) reported lower crash rates within tunnels. However, crash and injury severity was higher in tunnels compared to exposed roadways (Ma, Shao and Zhang 2009a).

Caliendo and De Guglielmo (2012) analysed severe crash rates per million vehicle-kilometres (veh-km) travelled and found higher average severe crash rates in two-thirds (136/195) of tunnels assessed. Similarly, Amundsen and Ranes (2000) concluded that the severity of crashes within the tunnel environment was greater than on open roads. Conversely, Lemke (2000), in an evaluation of 68 German tunnels, found evidence of reduced severity in tunnel crashes.

The literature also indicated that same-direction crashes, mainly rear-end and side-swipe crashes, were the most common crash type in the tunnel environment. Lemke (2000) determined that same-direction crashes in unidirectional tunnels contributed to 69% of all crashes, with run-off-road and other crash types contributing 17% and 13% respectively. In an analysis of Chinese tunnels, Ma, Shao and Zhang (2009b) found that 58% of all crashes within tunnels were rear-end crashes.

PIARC (2016a) describes tunnels as sections of road that are in a confined space that have lateral and vertical restrictions. The PIARC report also summarises the pronounced differences and factors associated with tunnels and with crashes that occur in tunnels compared to crashes on the open road. These differences are summarised as follows:

- Tunnels are enclosed, confined structures, within which some drivers may experience anxiety and unique behaviours during a collision.
- Generally there are very few, if any, intersections or interchanges, and therefore no interacting traffic emanating from these interacting roads.
- Pedestrians, cyclists and very slow moving vehicles (e.g. mopeds and agricultural tractors) are generally not permitted in tunnels.
- The location of fixed ‘obstacles’ such as portals, signage, and the presence of tunnel ceilings and walls may influence driving behaviour.
- Protective measures generally present on the open road (e.g. safety barriers and energy absorption systems) are not provided in all tunnels.
- Emergency lanes are not provided in many motorway tunnels, unlike open road motorways.
- When driving through tunnels, drivers are required to perceive, analyse and understand a driving environment which is unlike driving on open roads.
- Decision making in tunnels occurs in a shorter timeframe from what drivers are accustomed to on open roads.
- Environmental conditions within tunnels are controlled (i.e. absence of weather conditions such as rain, snow, fog, etc.); however, this may suddenly change at tunnel portals.
- While tunnels are generally lit at all times drivers may experience sudden lighting changes at tunnel portals.
- Long monotonous tunnels may hinder driver awareness.
- Tunnel conditions might cause driver misjudgement of curves and vertical alignments as well as safe driving distances from other vehicles and obstacles.

An Austrian study cited in PIARC (2016a), which investigated 502 collisions that occurred in motorway tunnels during the period 1999–2009, determined that the overwhelming majority had occurred because of driver error (40% unidirectional and 43% bidirectional) or driver inattention (35% unidirectional and 38% bidirectional).

In terms of tunnel size, two- and three-lane tunnel freeways with hard shoulders provided the greatest crash rate per million veh-km travelled within the German tunnel system (Lemke 2000). It was also suggested that longer tunnels are associated with higher crash rates.

Ma, Shao and Li (2009a) analysed the factors affecting crash severity in expressway tunnels. They found that the major contributing factor to the severity of crashes was the ratio of daily traffic volumes and the annual average daily traffic (AADT), and the proportion of trucks. Weather conditions, alignment, grade and crash location all contributed equally to the severity of the crash while the time at which a crash occurred has negligible impact on the severity of the crash.

Similarly, Oh and Kang (2010) showed that increases in crash involvement in tunnels correlated with increasing traffic volumes. This was also true for a decrease in traffic volumes where a decrease in flow corresponded to a decrease in crashes.

PIARC (2016a) also reported that the most influencing crash factors were tunnel length, traffic volume, horizontal road alignment, lane width, tunnel cross-section, 'quality' of lighting, composition of traffic, vehicle speeds and 'last but not least driving habits and the technical standard of vehicles' traveling through the tunnels.

Nussbaumer (2007) conducted a comparative analysis of safety in tunnels in Austria. Crashes in tunnels between 1999 and 2003 were compared to those on exposed sections of road. It was found that, while the probability of a crash occurring was lower for tunnels than motorways and expressways, the probability of death resulting from a crash was twice as high for tunnels as motorways; specifically, the proportion of fatal crashes was 8.2% for tunnels and 3.3% for motorways. The study also highlighted the effect of tunnel length on crashes, indicating higher crash rates for tunnels with lengths less than 1 kilometre. Furthermore, the relative crash rate was marginally higher for uni-directional tunnels than bi-directional tunnels (0.09 crashes per million veh-km travelled (vkt) and 0.08 crashes per million vkt respectively). Further analysis showed that the highest crash rates were observed at the tunnel entrance and exit points rather than within the tunnel. The more prevalent crash type at the entrance and within the tunnel was rear-end crashes (60%) followed by single vehicle crashes and single vehicle crashes (involving speed) in areas before or after the tunnel and the tunnel's portal.

The number of fatal and serious injury accidents in tunnels and corresponding motorways was compared by Caliendo and De Guglielmo (2012). Their analysis found that the severe crash rates inside tunnels were greater than on almost all the Italian motorways analysed.

The Netherlands Institute for Road Safety Research (SWOV 2006), reported that the factors that increased crash rates in tunnels compared to roads not within tunnels included:

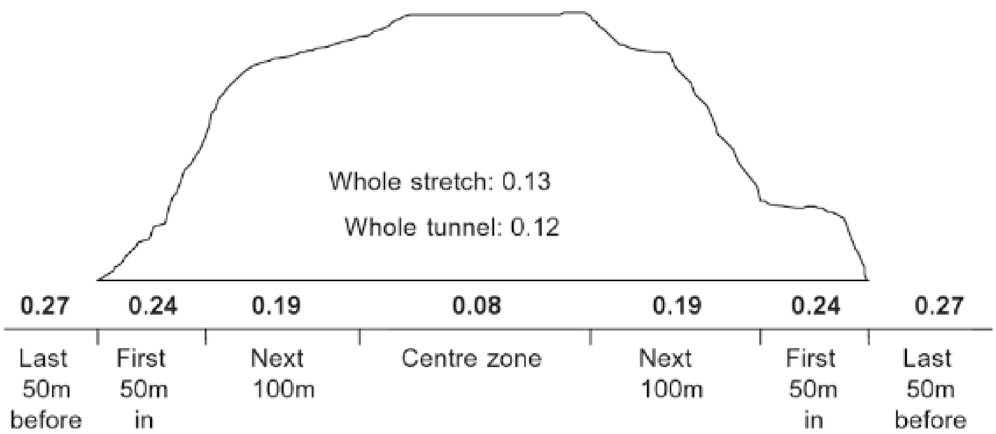
- the closeness of the tunnels walls, given the absence of emergency lanes
- slopes and resulting speed differentials
- road alignment and resulting sight distance inadequacies.

It was suggested that safety in tunnels could be improved with:

- the addition of emergency lanes
- the provision of less steep slopes (or separate lanes for heavy traffic)
- increasing the radius in horizontal curves.

Elvik et al. (2009) reported that the injury crash rate was highest at the tunnel entrance and exit zones. Amundsen and Engebretsen (2008) reported that injury crashes per million vehicle-km were much higher at the tunnel entrance and exits compared to other tunnel zones (see Figure 2.1). The segments of road on either side of the tunnel experienced the highest rate.

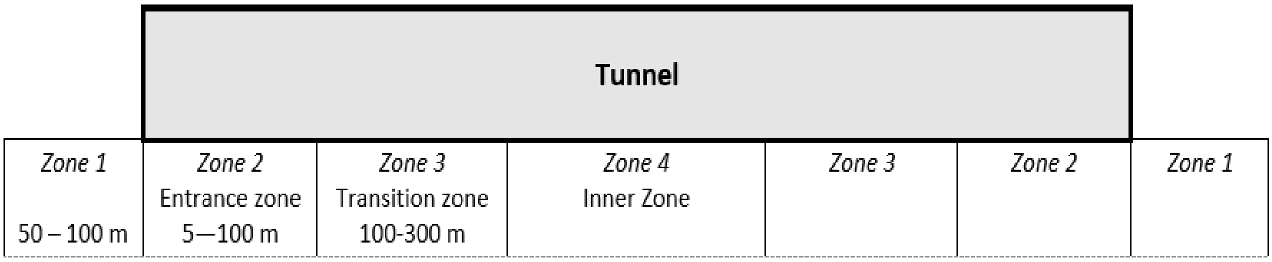
Figure 2.1: Number of injury crashes per million vkt for different zones in tunnels



Source: Amundsen & Engebretsen (2008).

Amundsen and Ranes (2000) studied crashes in road tunnels in Norway and found similar results to previous studies. Sections (or zones) were developed to determine the crash locations. The definition of zones is shown in Figure 2.2.

Figure 2.2: Tunnel zones – Amundsen and Ranes (cited in Bassan 2016)



Source: Bassan (2016).

Using five years of data, Amundsen and Ranes (2000) found a total of 499 injury crashes within the tunnels analysed and that 45% of all crashes occurred within the tunnel entrance (Zone 1 in Figure 2.3).

Figure 2.3: Crash Distribution in tunnel zone determined by Amundsen and Ranes (2000)

	Zone 1	Zone 2	Zone 3	Zone 4
Total	26%	19%	19%	36%

	Zone 2	Zone 3	Zone 4
Within tunnel	25%	26%	49%

Source: Amundsen and Ranes (2000).

Ma, Shao and Zhang (2009b) determined that the highest crash rate occurred 100 to 400 metres from the tunnel entrance (or Zone 3 in their study). However, multi-vehicle collisions occurred most frequently inside the tunnel (Zones 3 and 4), not in the transition zone (Zones 1 and 2).

Dai and Guo (2011) found that crashes occurred primarily in the morning (8 am to 12 pm) and that there were more accidents at the tunnel entrances and exits than within the tunnel. The suggested that this was due primarily to sharp transitions in lighting.

Bassan (2016) cited research that indicated that drivers approaching tunnels at high speeds had an increased crash risk. This was because drivers normally decelerate as they approach the entrance to the tunnel in order to adapt to ‘dim light’ conditions; upon entering the tunnel, the driver decelerates further to a speed lower than on the open road. These large speed variations over a relatively short distance result in an increase in crash risk.

Caliendo, De Guglielmo and Guida (2013) developed a model to estimate the number of crashes within a tunnel based on numerous variables. These variables included tunnel length, AADT per lane, the percentage of trucks, number of lanes and the presence of a sidewalk. All variables, except sidewalk presence, were significant in the crash prediction model. Caliendo suggested that the model could be utilised to estimate the reduction in traffic crash in existing tunnels or in tunnels which had been improved as well as for comparing alternative tunnel designs.

Meng and Qu (2012) estimated the frequency of rear-end crashes in urban tunnels using the negative binomial model to establish a relationship between rear-end crashes and exposure to traffic conflicts.

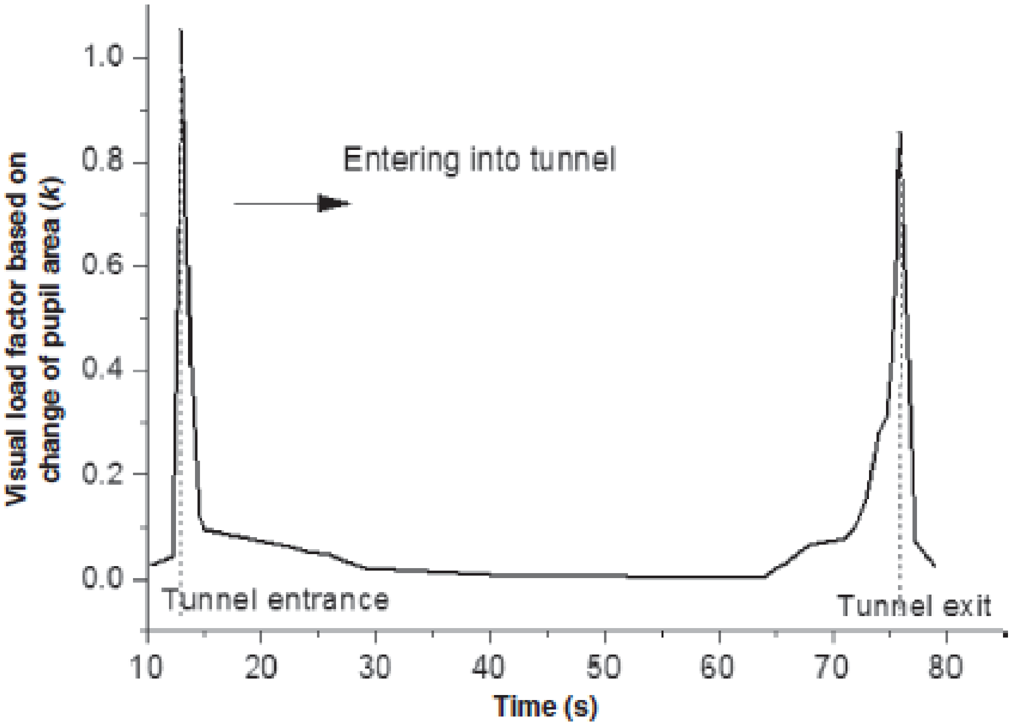
While international literature on safety in and around tunnels was identified, there was little or no literature on road safety in tunnels in Australia and New Zealand. In order to identify the extent and nature of crashes in an Australian and New Zealand context, detailed crash analyses were conducted, with the findings outlined in Section 3.

2.2 Lighting

Lighting at the tunnel transition zones was identified as one of the leading factors in the high crash rates for this section of roadway. Du et al. (2014) examined the illumination in tunnels and the effect it had on safety. They used eye-tracking technology to assess changes in the area of the pupil of the eye upon entering and exiting to determine the visual load on the driver. It was found that the visual load at the tunnel entrance was higher than at the exit. They suggested that, as a result of the severe transitions in pupil illuminance at entrances, urgent improvements were required.

The visual load factor based on the change in pupil area over time is shown in Figure 2.4. It is evident that the eye requires a large adjustment when entering and exiting a tunnel.

Figure 2.4: Visual load factor based on change in pupil area along the road tunnel



Source: Du et al. (2014).

Kircher and Lundkvist (2011) used simulation to determine changes in attention based on illumination within the tunnel environment. Illumination was varied on three levels and the tunnel wall colour and driver attention was varied on two levels each. The results indicated that brighter walls were more important for safety and comfort than a high illumination level; however, this was only the case if the illumination was sufficiently bright. Driving and gaze behaviour were heavily influenced by driver state, with distracted drivers performing poorly and displaying unsafe behaviour. Additionally, bright walls received a slightly lower demand rating than dark walls, suggesting that the use of brighter walls results in an increase in safety. An example of a lighter coloured wall is shown in Figure 2.5.

Figure 2.5: Lighter colour walls in the interior of Calle 30 Tunnel, Spain

Source: PIARC (n.d.).

These findings prompted further research on the impact of tunnel design using a simulator. Kircher and Ahlstrom (2012) assessed the impact of tunnel design on drivers using a simulator, with wall colour, illumination and task load assessed. They found that tunnel design and illumination had a minor effect on driver behaviour. However, attentiveness of the driver to the task at hand was the most crucial factor. Additionally, light-coloured tunnel walls were more important than strong illunination at keeping the full attention of the driver facing forward. This supports Kircher's previous work with Lundkvist (2011).

Mennozzi et al. (2014) found an increased crash risk when the sun position was directly above the entrance of the tunnel. Glare from direct sunlight or reflections highlighted the need for tunnel orientation, infrastructure and glare precaution assessment during the planning stage of a project. Furthermore, lighting must be carefully designed to avoid the 'black holes' at entrances and 'white holes' at exits from tunnels because this increased the risk for drivers (Lu et al. 2015). Figure 2.6 and Figure 2.7 show examples of variations in lighting on the approach to, and into, a tunnel.

Figure 2.6: Example of lighting changes from A55 Pemaenbach Tunnel portal, Wales

Source: Sabre Roads (n.d.).

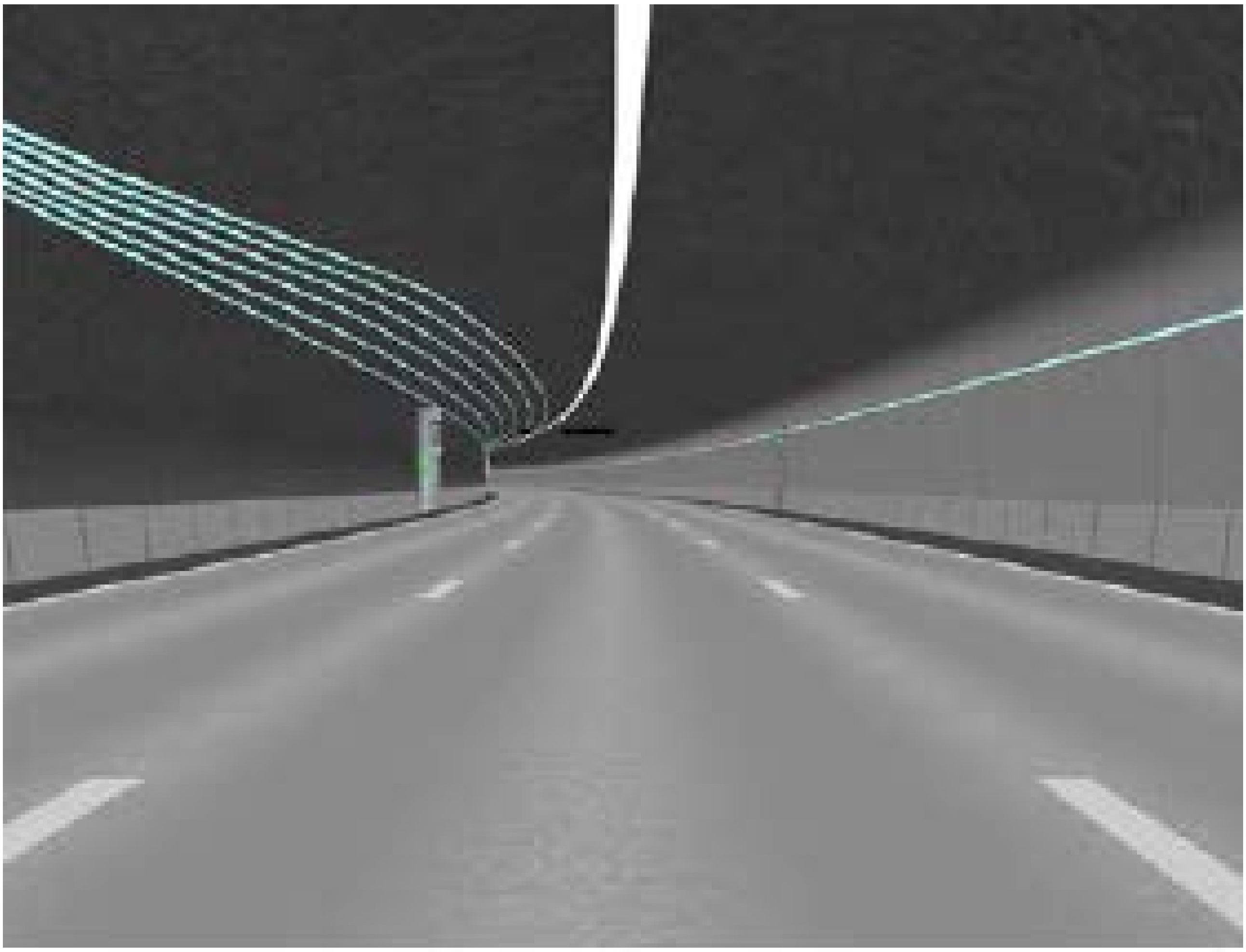
Patten and Mardh (2013) looked at various types of lighting and the effect on driver distraction and attentiveness in a long length of tunnel (18 km). 58% of subjects preferred the decoration design in terms of strings of lights along the ceiling, with 29% preferring no decoration and 13% with neither preference. It was found that the negative safety implications of the elaborate interior lighting features is minimal in terms of distraction and irritation whereas the safety benefits in this particularly long road tunnel, in terms of subjective feelings of visual stimulation is encouraging. Thus it was recommended that having stimulating lighting features be included within a long tunnel section. It is of note that this recommendation is based on reported preference of lighting decoration rather than any identified safety benefits. An example of string lighting along a tunnel ceiling is shown in Figure 2.8.

PIARC (2016b) reported that considerable crashes occurred 50 m prior to tunnel entry and 50 m past the tunnel entrance. It was also indicated that a general rule applied in a number of countries was that gradual levels of lighting change be provided within the first section of the tunnel (i.e. transitional zone), using as an example dimmers. It was further indicated that motorists should not be given information within the transition zone as driver’s experience a higher level of workload in this area which effects information processing.

Figure 2.7: Tunnel entrance at A3 Hindhead Tunnel portal, England

Source: ITS International (2015).

Figure 2.8: String lighting design along ceiling by Patten and Mardh (2013)



Source: Patten and Mardh (2013).

A report published by PIARC (2016b) also describes the setting of different lighting within a tunnel. It indicated that, depending on the tunnel lighting design, it may be possible to set different levels of lighting along any section of the tunnel. More lighting levels are the norm near the entry portal, while within the tunnel that were generally lowered to two lighting levels. Such levels are chosen automatically in response to external sunlight, during day- and night-time periods and, on occasions, on the basis of traffic conditions. It was noted in the report that lighting levels may be manually operated to increase in intensity in response to a crash or incident, the purpose being to increase the attention of drivers approaching the crash or incident, while also increasing the visibility of emergency exits and other safety elements near the occurrence.

It was also suggested in the PIARC report that increasing lighting levels would be highly effective in two scenarios: within the interior of a long tunnel when 'normal' levels are maintained, and within tunnels entrances during periods of darkness when the 'normal' light level is low and a significant effect may be achieved by increasing the level of lighting.

The hazards associated with the flicker in discrete lighting systems were researched by Kostakis (2015). He found that flickering lights may cause epileptic seizures or, with long-term exposure, headaches and impaired driving performance. It was suggested that all hazards are, in a sense, ambiguous; however, they can be minimised if kept within a critical flicker frequency (CFF) of 2–15 Hz. Utilising a continuous row of lights mitigates the effect of any flickering and improves the driving experience for the motorist. Ultimately, lighting designs should comply with current standards; however, but there are risks associated with flickering even with the 'safe' (CFF) zone (Kostakis 2015).

2.3 Driver Behaviour

Calvi, De Blasiis and Guattari (2012) conducted an empirical study to determine driver behaviour within a tunnel. They found that drivers moved laterally from the right tunnel wall[1] and that travel speed decreased slightly. An example of the proximity of a wall to travel lanes in a tunnel is shown in Figure 2.9. Calvi, De Blasiis and Guattari (2012) also found that there was a reduction in the amount of trajectory corrections as the level of driver attentiveness increased.

As an extension on previous work, Calvi and D'Amico (2013) used a simulator to assess the driving behaviour inside tunnels. They found significant differences in longitudinal speeds, acceleration and lateral position when comparing the tunnel scenario and the control simulator scenario. This finding was consistent with the previous work. The study showed that drivers behave differently in a tunnel environment, driving slightly slower and with a higher level of concentration.

Figure 2.9: Proximity of lane to wall from the interior of Port Miami Tunnel (State Road 887), USA

Source: Tunnel Business Magazine (2014).

A driving simulator was also utilised by Shimojo, Takagi and Onuma (1995) to assess driver performance and workload when subjected to lengths on tunnels. The study revealed that signage indicating the remaining tunnel length as well as the use of intelligent transport systems (ITS) increased safety within the tunnel.

1 It should be noted, as the study was conducted in a tunnel where the road users travel on the right – compared to Australia and New Zealand where the reverse is true – then if drivers in Australia and New Zealand behaved in a similar manner they would move laterally from the left tunnel wall.

The World Road Association (PIARC 2008a) developed a guide which outlines human factors and road tunnel safety regarding users. This guide is extensive and includes, but is not limited to:

- general aspects of human factors
  - information processing
  - perception of signs and signals
- behaviour in tunnels in normal situations
  - entering tunnels
  - driving within a tunnel
  - exiting tunnel
- behaviour in critical situations
  - congestion
  - breakdowns
  - injuries/vehicle damage
  - fires
- additional measures to improve safety in normal conditions
  - education and information
  - direction signage
  - approach and exits
  - portal, cross section and interior design
  - traffic guidance
- additional measures to improve safety in critical conditions
  - education and information
  - signage and signals for incidents
  - emergency stations
  - radio re broadcasting and loud speakers to alert users
  - escape routes
- future developments of ITS and safety.

As studies and crash data have shown that crash rates within the entry/transition zones of a tunnel are much greater that along the centre zone, it is considered important that ‘entering’ drivers not be overloaded with information that they need to process as part of their decision-making when driving. Drivers should be able to read and assimilate clearly the signals (signs, directional/lane markings, and lighting) across these zones.

PIARC (2016b) reported that, apart from different lighting conditions in most tunnels, tunnel walls and varying lateral dimensions may create a perception of different driving conditions which can create some fear in drivers. As a result some drivers may have a tendency to drive away from tunnel walls, particularly when entering the tunnel; this in turn creates the risk of a crash with vehicles driving in adjacent lanes. The report also presented the results of field trials which where drivers deviated 300–400 mm to the centre of the tunnel. To assist to overcome this crash risk it was recommended that shoulders wide enough to act as emergency lanes be provided.

A better understanding of human behaviour in tunnels allows designers and engineers to produce tunnels within a Safe System framework, which should eventually result in a reduction in the number of fatal and serious injury crashes within tunnels. An intelligence transport system (ITS) that provides guidance to drivers travelling through a tunnel is shown in Figure 2.10.

Figure 2.10: Intelligent transport systems with guidance from the interior: Marina Coastal Expressway Tunnel, Singapore

Source: Value Add Singapore (2013).

The PIARC (2016b) report also drew the following conclusions related to driver behaviour in tunnels:

- The driving task is complex: it requires constant perception and the processing of information.
- A substantial proportion of drivers suffer from discomfort or anxiety when driving through tunnels.
- Generally sight distances are reduced in tunnels and therefore special attention should be taken with the placement of and characteristics of signs and signals.
- Experimental and naturalistic studies have found that people required 5 to 15 minutes to determine whether to do anything at all during a tunnel evacuation.

The report also outlines the application of real-time communication systems and provides examples of when to activate such a system. The following examples are provided that are specific to crashes within a tunnel:

- For minor crashes or breakdowns the specific objectives when activating real-time communication systems are to
  - prevent the situation from worsening because that could lead to a serious crash or a fire
  - encourage those road users involved to follow instructions from the operating staff
  - encourage road users not involved to avoid dangerous situations.

- For serious crashes or breakdowns the specific objectives when activating real-time communication systems are to, in addition to the above, inform other road users that inappropriate behaviour may delay emergency teams because this could result in an increase in the severity of the crash.

Yeung and Wong (2014) analysed differences in headways between traffic on a highway and in a tunnel environment. They found that car-following behaviour in the road tunnel environment was more conservative with longer headways and a greater safety margins. This is a good outcome as rear-end crashes have been shown to be the most prominent crash type in tunnels (Ma, Shao and Li 2009). Overall, in terms of headways, tunnels perform better than highways. However, this comes at a detriment to capacity, due to the increases in safety margins imposed by the driver.

Rudin-Brown et al. (2013) conducted a simulation study assessing driver distraction in unusual environments, more specifically the effects of text messaging in tunnels. They found that, collectively, driver distraction in tunnels was associated with similar driving as freeway driving; however, the potential consequences were significantly more serious.

2.4 Risk Assessment

Current practices for risk assessment in road tunnels has been outlined in numerous papers, with the World Road Association (PIARC) providing guidance on the process (PIARC 2013). Clark and Kohl (2011) published a more concise risk assessment paper which also outlined a risk assessment process for road tunnels. They suggested, however, that quantitative risk analysis should only be considered to be accurate to an order of magnitude and risk evaluation by relative comparison might improve the robustness of conclusions.

PIARC (2008b) outlined a risk analysis for road tunnels. Two main approaches were presented: a case approach and a system approach. The findings highlight clearly that the possibilities for the harmonisation of methods of risk analyses for road tunnels were limited because national characteristics, regulations and laws differed; one unique method could not address all the relevant issues in an adequate way. However, in the future it might be possible to develop universally applicable guidelines for risk assessment for road tunnels.

An assessment of the risks associated with tunnels, both during the design stage and after construction, is required to accurately assess safety. Current practice for risk evaluation of road tunnels is outlined in PIARC (2013). Safety within the tunnel is the ultimate goal and hence evaluation of the qualitative approaches of societal risk is the main focus. The transport of dangerous goods and the legal implications of risk analysis also needs to be considered during a risk assessment.

Tamura and Mine (2009) developed a practical road disaster management procedure for various natural disasters using risk management techniques. The outputs included risk curves, risk register tables and risk treatment plans which were readily applicable to road disaster management plans for tunnels.

2.5 Safety Management

Tools for tunnel safety management were outlined in PIARC (2009). The report outlines the basic tools needed for management and decision support for tunnel safety issues. The report defines the general demands on tunnel safety documentation, referring to each of the three different stages of a tunnel project: design-construction, commissioning, operation. The report also outlines the collection and analysis of incidents that occur in tunnels, defines the significance of incidents to be recorded and presents the basic data collection requirements. The level of safety within a tunnel is using a safety investigation. It is also determined if the tunnel is currently within a legal framework or against an accepted level of risk. An example of a tunnel that aims to provide safety management as motorists use the tunnel through the application of signing, directional pavement markings, Variable Message Signing (VMS) and lane management control signals is shown in Figure 2.11.

Figure 2.11: Tyne Tunnel portal – northbound: refurbished to ensure safety standards are met

Source: Tyne Tunnel TT2 UK image (2013).

Higgins (2001) discussed incident management within tunnel infrastructure. It was explained that, once inside the tunnel, there was little opportunity for alternate routing. Therefore the ability of a vehicle monitoring system to accurately and expediently detect traffic variations was essential if traffic management and safety in tunnels was to be effectively managed. Upon analysis, it was evident that the performance of volume-occupancy incident management models, while satisfactory at high vehicle flow rates, was less than satisfactorily at very low volumes. The importance of early detection on incidents within the tunnel was stressed, with a hazard warning response undertaken immediately.

This led to research by Balz et al. (2012) who developed another real time security management system (RETISS) which provides real time information within the tunnel to the staff in the tunnel control centre. Based on the information provided by RETISS, the best preventative/reactive measures could be taken.

In terms of tools for tunnel safety management, PIARC (2009) included road safety tunnel documentation, guidance on data collection and analysis of incidents occurring within the tunnel and a comprehensive insight into a safety inspection of a road tunnel. The report adopted a holistic approach, with the need to adopt various safety measures to effectively manage a tunnel roadway emphasised.

Carrea et al. (2002) introduced a 'safe tunnel' concept, with the main objective being to reduce the overall number of crashes inside road tunnels through the use of preventive safety measures. The basic idea is to increase the knowledge of the vehicle status in order to prevent access into the tunnel to those vehicles with detected or imminent on-board anomalies and to introduce measures to achieve the tele control (from a control centre) of the speed and the distance between vehicles.

Brignolo, Annoni and Sala (2004) describes tunnel communication architecture as a means of the management of safety within tunnels. The goal was to reduce crashes in tunnels using preventative measures, including a wireless network as the communication link (ITS). This is widely used in tunnels today; an example is shown in Figure 2.12.

Figure 2.12: Interior of A86 West Tunnel, France showing ITS system in use

Source: Road Traffic Technology (2017).

2.6 Further Treatments to Increase Safety

PIARC (2012) provides guidance on how to: establish a safety framework, investigate and evaluate the current situation, and define and develop a safety improvement program when assessing the safety of tunnels.

In order to improve the automatic detection of incidents within a tunnel system, Bossu (2014) reviewed the performance of an Automated Incident Detection (AID) system. This tool, when set up correctly, reduces the time taken to attend to an incident, which is crucial to the protection of tunnel users. The paper outlines the AID set up in order to achieve the best possible performance.

Guidance on the implementation of an ITS was provided by Dodds et al. (2005). An insight into the principles and practices for the Mersey tunnels, located in Liverpool, United Kingdom, was provided. Operational and safety objectives were also explored with references to best practice. An example is shown in Figure 2.13.

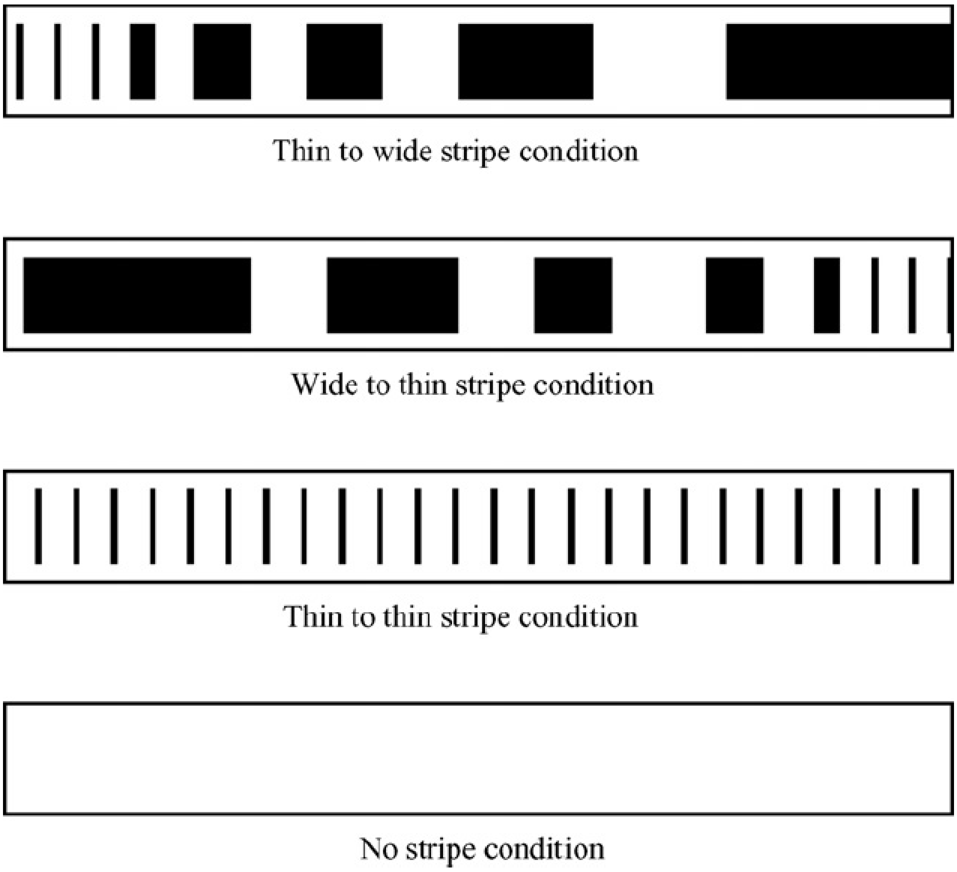
Figure 2.13: Mersey tunnel entrance with ITS implementation

Source: Merseytravel (2015).

Improving traffic safety in road tunnels using in vehicle information systems was assessed by Vashitz, Shinar and Blum (2008). They found that using in-vehicle displays improved speed control but reduced lane stability slightly. However, this was not a large change and did not compromise the driving task. Highly informative displays reduced anxiety and boredom, which is common during tunnel driving. It was concluded that an in-vehicle display that presents relevant information to the driver can be valuable in improving driving safety, as long as it does not create superfluous distraction.

Manser and Hancock (2007) assessed whether the tunnel wall characteristics affected speed perception, choice and control. Vertical lines were placed in a tunnel simulation in which the distance between the lines and the thickness increased, decreased or remained constant. It was found that, as the gap decreased, the speed also decreased their speed; as the gaps increased, the speed also increased. Figure 2.14 provides examples of visual patterns.

Figure 2.14: A depiction of the four visual pattern conditions assessed



Source: Manser and Hancock (2007).

Lu et al. (2015) recommended that geometric conditions be improved and the setting up of a tunnel entrance/exit on a horizontal or vertical curve be avoided because this would result in a reduction in crashes at transition zones. They also recommended that monitors be installed to manage travel speeds and also advanced driver assistance systems (ADAS) to make drivers more aware of potential hazards and to maintain safer headways.

Elvik et al. (2009) reported that lighting, increasing carriageway width, increasing radius of horizontal curves and duplicating the tunnels resulted in a reduction in the number of crashes as shown in Table 2.1. Tunnels appeared to be slightly safer than motorways in both urban and rural situations. However, there was a reduction in safety in tunnels when the longitudinal gradient was greater than 5%, and in sub-sea tunnel applications, compared to ‘normal’ underground tunnels (Elvik et al. 2009).

Table 2.1: Effects on crashes of different measures in tunnels (Elvik et al. 2009)

Percentage change in the number of accidents			
Accident severity	**Types of accidents affected**	**Best estimate**	**95% confidence interval**
Road in tunnel vs. road above-ground			
Injury accidents	All accidents: motorways	–2	(–15; +12)
Injury accidents	All accidents: rural	–4	(–17; +11)
Injury accidents	All accidents: urban	–61	(–77; –35)
Lighting in tunnels			
Injury accidents	All accidents in tunnels	–35	(–51; –14)
Increasing the width of the tunnel from less than 6 metres to more than 6 metres			
Injury accidents	All accidents in tunnels	–40	(–49; –30)
Tunnels with a gradient of more than about 5% compared to flat			
Injury accidents	All accidents in tunnels	+13	(–4; +32)
Doubling the radius of horizontal curves			
Injury accidents	All accidents in tunnels	–35	(–45; –24)
Dual tubes compared to single tube tunnels			
Injury accidents	All accidents in tunnels	–5	(–15; +6)
Sub-sea tunnels compared to tunnels on land			
Injury accidents	All accidents in tunnels	+16	(–15; +38)

Source: Elvik et al. (2009).

Contingency measures for unforeseen circumstances have also been developed. Sosa, Thompson and Barbero (2014) introduced a concept of an inflatable plug to seal off both ends of an underground tunnel in the event of a flood. The results suggested that this concept was plausible, with full-scale prototypes able to withhold test pressures, maintain axial stability and only allow manageable levels of water leakage.

3. Crash Analyses

In order to identify the key characteristics associated with tunnel crashes in Australia and New Zealand, an analysis of a representative sample of tunnel crash data was undertaken. Data for crashes adjacent to and within tunnels in New Zealand and Australian was disaggregated by variables reflecting:

- yearly trends
- time-of-day, and by weekday and weekend
- site characteristics (e.g. speed limit)
- crash characteristics (e.g. type of crash, object struck)
- environmental conditions (e.g. light conditions, weather conditions)
- road user characteristics (e.g. vehicle type, number of vehicles involved).

The analysis involved the evaluation of crash data from 13 tunnels across Australia and New Zealand. Crash data from 2000 to 2016 was provided in different formats and varying levels of completeness. Due to differences in the completeness of the data provided, the analysis was conducted in two stages: an individual specific level, and an aggregate level.

The level of information presented in each of the evaluations depended on the amount of information in the data provided. In some cases, crash severity, time of crash and other location and crash details were not available.

The severity of crashes was considered in the following manner:

- a fatal crash, where at least one person was killed
- a serious injury crash, where at least one person was seriously injured (i.e. taken to hospital)
- a minor or ‘other’ injury crash, where at least one person sustained a minor injured (i.e. not required to be taken to hospital).

The injury severity only applies to the highest injury severity resulting from a crash; there could be multiple persons injured. It should also be noted that the data may not be accurate as in some cases a person may have sustained a minor injury but was taken to hospital as a precautionary measure. This would have resulted in the injury being described as a serious injury crash. In other instances some minor injury crashes may not have been recorded as the person may have sustained a very minor injury (e.g. small cut or bruise) that was not recorded at the time.

It should be noted that the information provided does not take into account traffic volume and traffic mix (i.e. proportion of trucks or motorcyclists traveling through the tunnel); the information is presented in a descriptive manner only.

An analysis of crashes within and adjacent to a representative sample of tunnels for which crash data was available was conducted to provide an indication of the scale and nature of tunnel crashes in Australia and New Zealand. Most of the observed crashes were ‘no injury’ or ‘low injury’ crashes, with only one fatal injury crash observed as outlined in Table 3.1.

Comparisons of the safety performance between tunnels and their crash records should also be treated with major caution, as the attributes and age of the tunnels are unknown and may vary greatly: traffic volume and traffic compositions are unknown, while the recording of non-injury crashes by the tunnel operators may vary markedly and is very dependent on their recording protocols.

Table 3.1: Overall crashes within and adjacent to tunnels

Tunnel	Period	Tunnel crashes				
		Total crashes	Fatal (%)	Serious injury (%)	Minor injury (%)	Non-injury crashes (%)
1	Jan 2010 to Dec 2015 (6 years)	206	0 (0%)	10 (5%)	14 (7%)	182 (88%)
2	Jan 2008 to Mar 2011 (4 years 3 months)	128	0 (0%)	2 (2%)	9 (7%)	117 (91%)
3	Oct 2011 to Dec 2015 (4 years 3 months)	26	0 (0%)	0 (0%)	1 (4%)	25 (96%)
4	Jan 2010 to Dec 2015 (6 years)	19	0 (0%)	6(1) (32%)		13 (68%)
5	Oct 2007 to Dec 2015 (8 years 3 months)	75	0 (0%)	0 (0%)	1 (1%)	74 (99%)
6	Jan 2010 to Dec 2015 (6 years)	86	Crash severity data unavailable			
7	Jan 2012 to Dec 2012 (1 year)	97	0 (0%)	7 (7%)	4 (4%)	86 (89%)
8	Jan 2014 to May 2016 (3 years)	91	0 (0%)	0 (0%)	0 (0%)	91 (100%)
9	Mar 2000 to Nov 2015 (15 years 9 months)	26	0 (0%)	1 (4%)	8 (31%)	17 (65%)
10	Sept 2000 to June 2014 (13 years 11 months)	36	0 (0%)	1 (3%)	9 (25%)	26 (72%)
11	April 2000 to Sept 2015 (15 years 6 months)	136	1 (1%)	2 (1%)	34 (25%)	99 (73%)
12	Aug 2000 to Oct 2015 (15 years 3 months)	12	0 (0%)	0 (0%)	2 (17%)	10 (83%)
13	Mar 2000 to Dec 2015 (15 years 9 months)	223	0 (0%)	3 (1%)	35 (16%)	185 (83%)

1 *Severity level unavailable.*

3.1 Individual Site Analysis

3.1.1 Tunnel 1

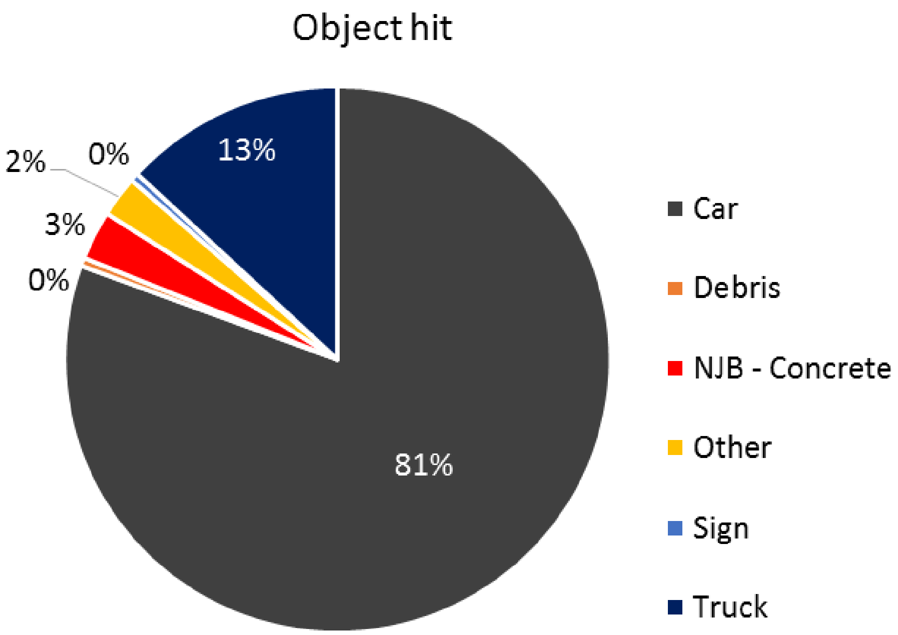
There were 206 crashes at Tunnel 1 during the six-year period between January 2010 and December 2015. Of these, 182 (88%) were non-injury crashes, 14 (7%) were minor injury crashes and 10 (5%) were serious injury crashes. Of the total, 141 (68%) crashes were rear-end crashes while 28 (14%) were lane side-swipe crashes as outlined in Table 3.2.

Table 3.2: Types of crashes – Tunnel 1

Types of crashes	Serious-injury	Minor injury	Non-injury	Total crashes
Vehicles from same direction, rear-end	4	8	129	141 (68%)
Vehicles from same direction, lane change side-swipe	1	1	26	28 (14%)
Vehicles from same direction, lane change right (not overtaking)	0	0	4	4 (2%)
Vehicles from same direction, lane change left	0	2	16	18 (9%)
Overtaking, out-of-control	3	1	3	7 (3%)
On path, struck object on carriageway	0	0	1	1 (0.5%)
Off path on straight, left off carriageway into object/parked vehicle	1	0	0	1 (0.5%)
Off path on straight, out-of-control on carriageway	1	1	1	3 (1.5%)
Passenger and miscellaneous, unknown	0	1	2	3 (1.5%)
Total crashes	10 (5%)	14 (7%)	182 (88%)	206 (100%)

An analysis of objects struck by vehicles in the different crashes found that 166 (81%) involved cars, 27 (13%) crashes involved trucks, 6 (3%) involved concrete New Jersey (NJ) barriers and seven (3%) involved 'other', signs or debris, as shown in Figure 3.1.

Figure 3.1: Tunnel 1 – Objects hit in crashes



As shown in Table 3.3, 15 crashes (11%) involving cars resulted in an injury compared to nine (13%) crashes involving a truck. When comparing severity levels, five (7%) crashes involving a truck resulted in at least one person being seriously injured compared to five (4%) crashes involving a car that resulted in a serious injury. This indicates that truck crashes were twice as likely to result in a serious injury crash compared to a crash involving a car. The data also revealed that half (50%) of the serious injury crashes involved a truck, while nine (40%) of the 24 injury crashes also involved a truck. As the proportion of trucks driving through tunnels is also markedly lower than for other vehicle types, truck travel through tunnels is shown to be a major crash risk and crash severity factor.

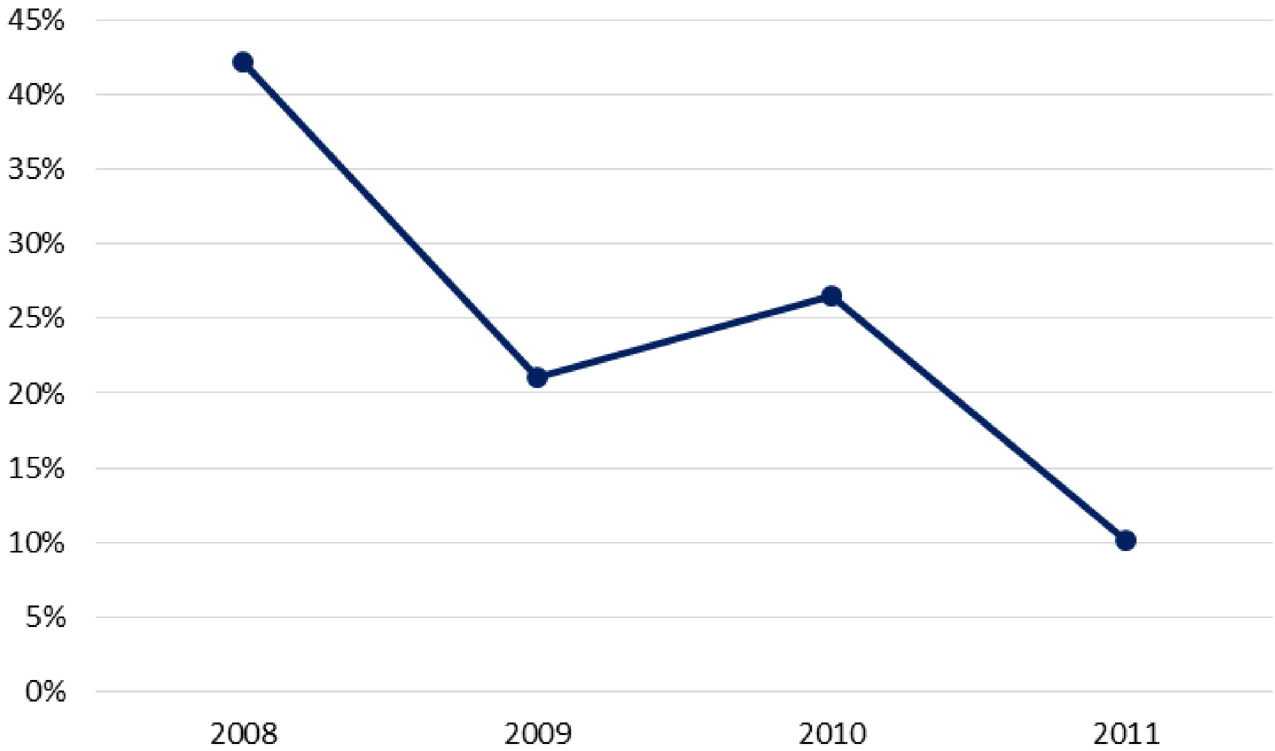
Table 3.3: Crash severity by vehicle type – Tunnel 1

	Serious injury	Minor injury	Non-injury	Total
Truck involved	5 (7%)	4 (6%)	60 (87%)	69 (100%)
Other Vehicles only involved	5 (4%)	10 (7%)	122 (89%)	137 (100%)
Total	10	14	182	206

3.1.2 Tunnel 2

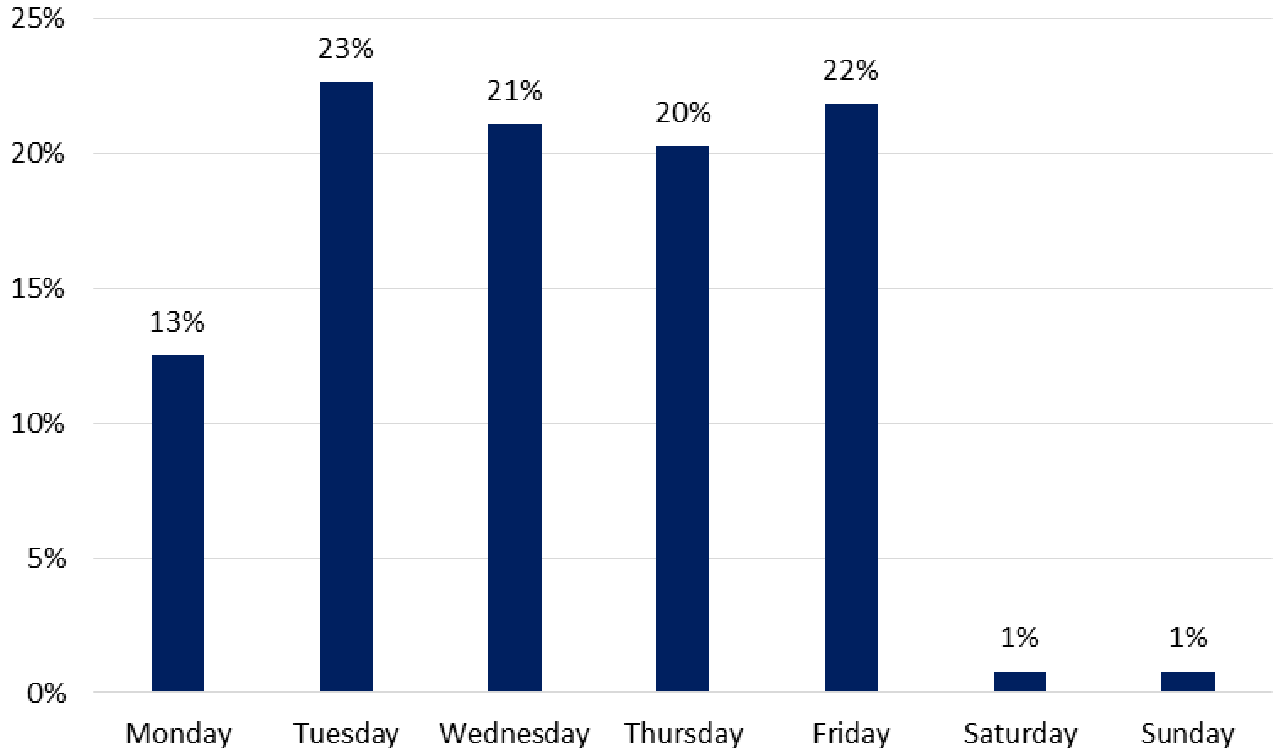
Table 3.1 shows that there were 128 crashes in Tunnel 2 during the four years and three months period between January 2008 and March 2011. Of these, 117 (91%) were non-injury crashes, two (2%) were serious injury crashes and nine (7%) were minor injury crashes. There was an overall reduction in crashes from 54 (42%) in 2008 to 13 (10%) in 2011, the most recent available data for this tunnel, as outlined in Figure 3.2. Variations in crash occurrences may, to a degree, therefore been reflective of changes in the number of vehicles driving through the tunnel each year.

Figure 3.2: Crashes by year – Tunnel 2



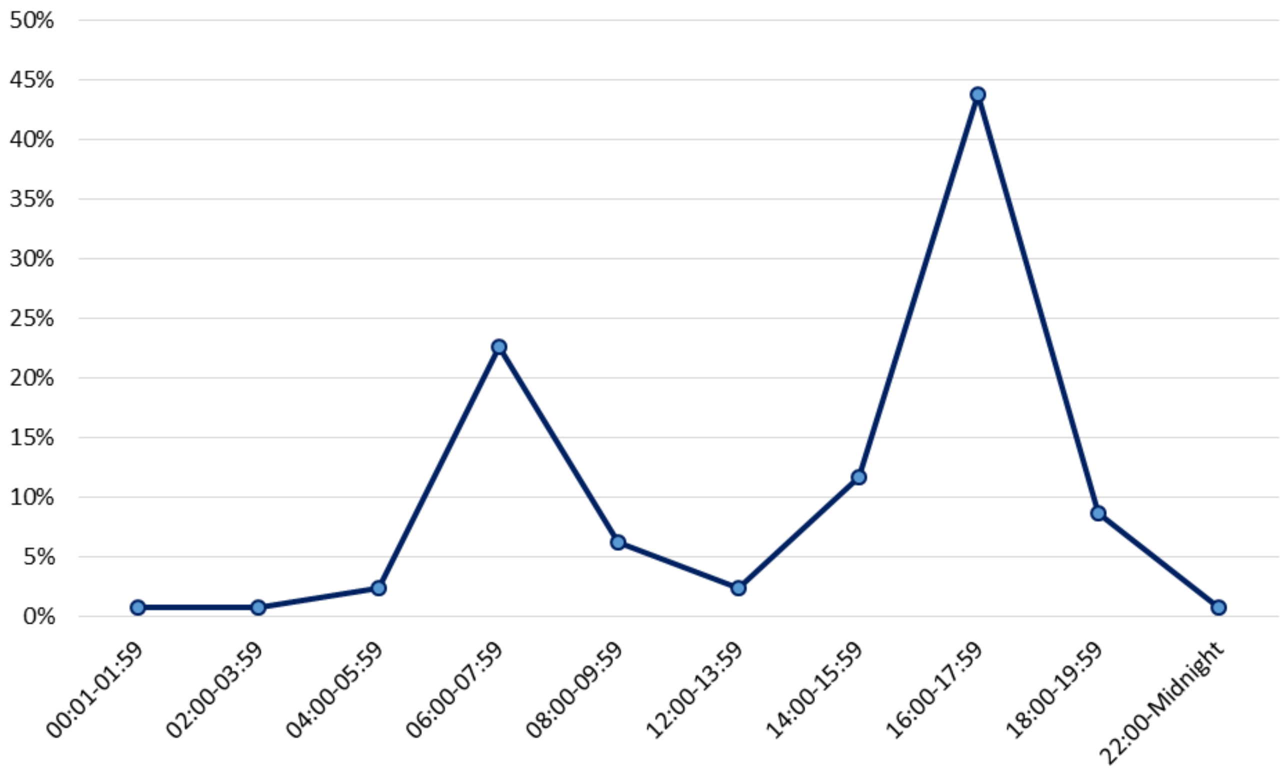
A markedly lower proportion of crashes occurred on the weekend (1% for each day) compared to weekdays (13% to 23% for each day) as shown in Figure 3.3. Overall, 126 (98%) of the crashes occurred on weekdays and two (2%) on weekends. It should be noted that the analysis did not take into account changes in traffic volume over this period.

Figure 3.3: Crashes by day of week – Tunnel 2



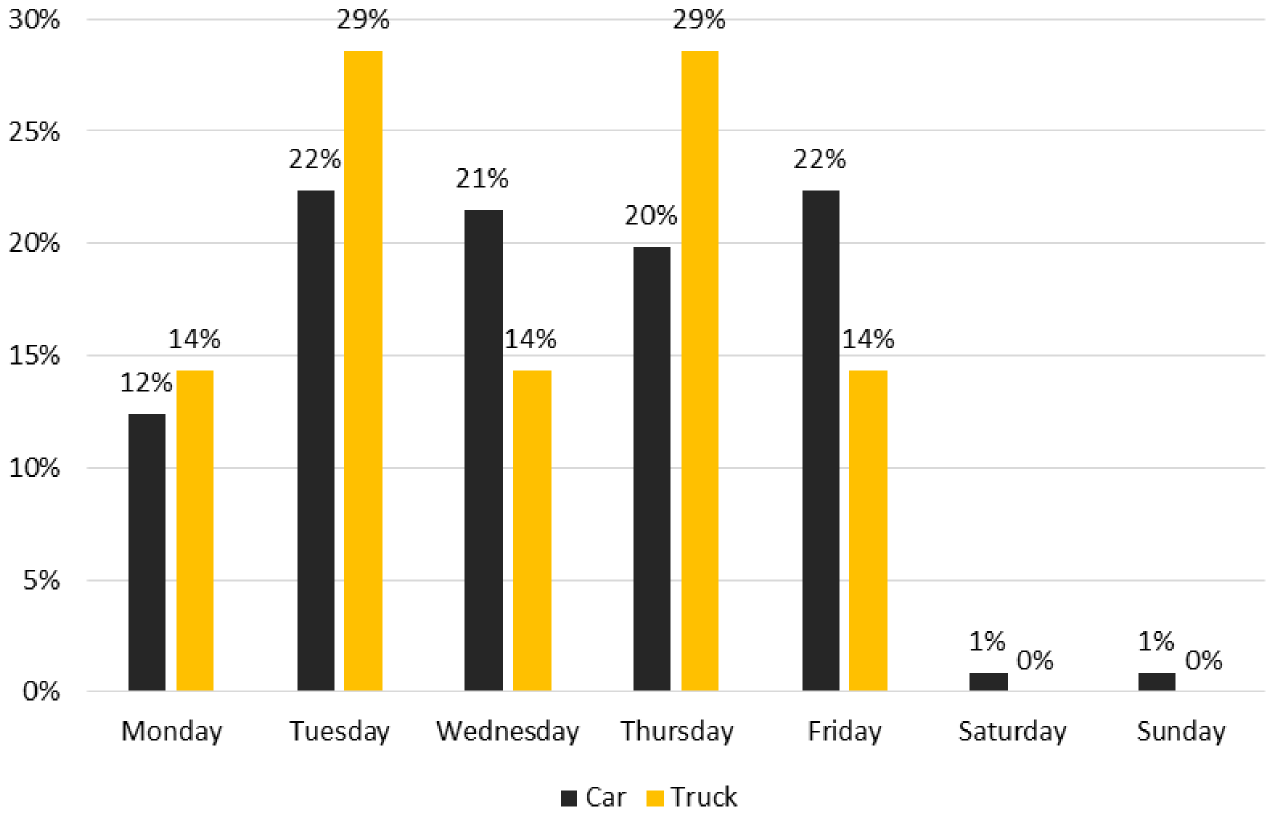
Taking into account the time-of-day, 56 (44%) of the crashes occurred during the late afternoon peak period and 29 (23%) during the morning peak as illustrated in Figure 3.4.

Figure 3.4: Crashes by time of day – Tunnel 2



A total of 111 (87%) of the crashes were multiple-vehicle crashes while 16 (13%) were single-vehicle crashes. Analysis of vehicle type involved showed that crashes involving trucks mainly occurred during weekdays, mostly on Tuesdays and Thursdays, while those involving cars were distributed across weekdays as indicated in Figure 3.5.

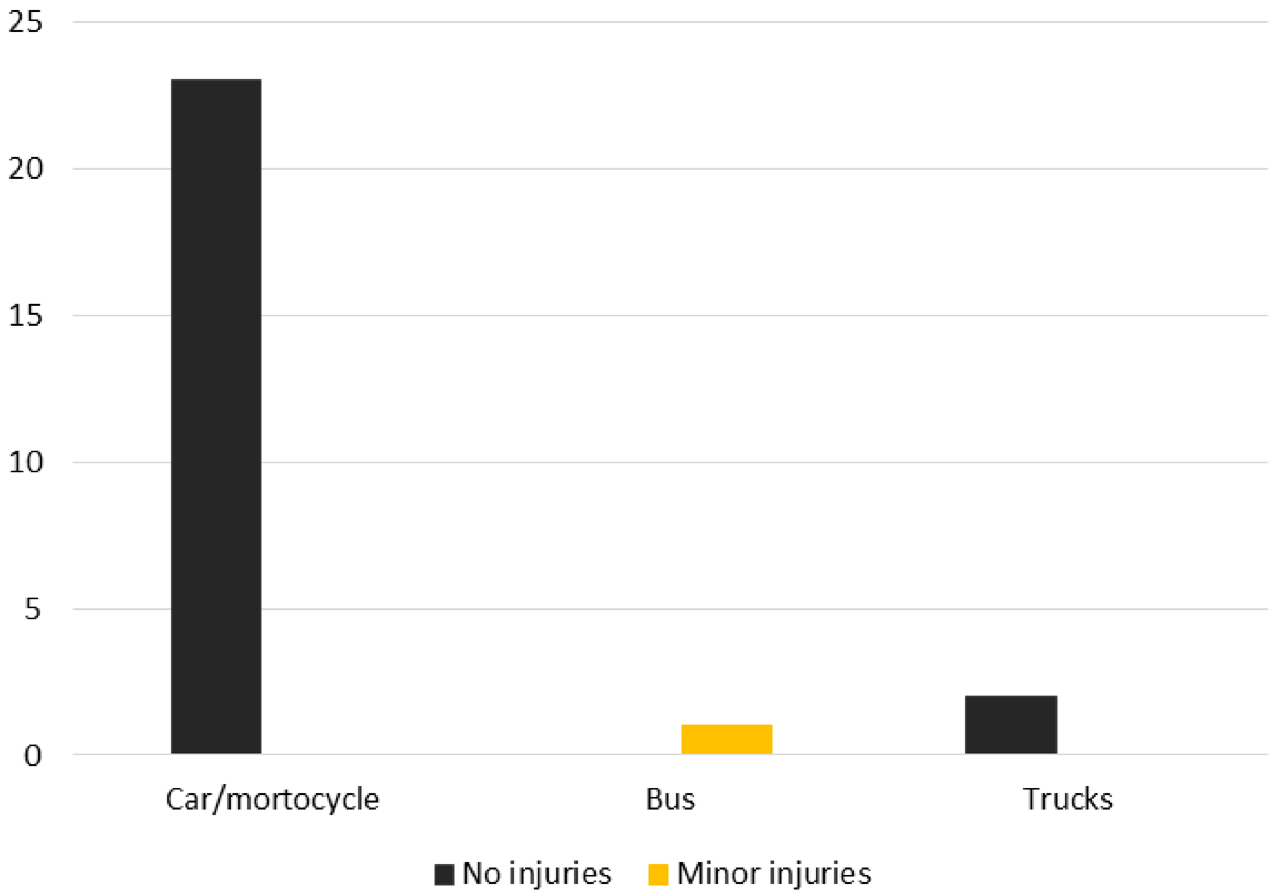
Figure 3.5: Crashes by day of week and vehicle type – Tunnel 2



3.1.3 Tunnel 3

There were 26 crashes in Tunnel 3 during the four years and three months period between October 2011 and December 2015. All of the crashes were multiple-vehicle crashes, with 23 (88%) involving cars or motorcycles, one (4%) involving a bus and two (8%) involving trucks. Twenty-five (96%) of the crashes were non-injury crashes, as shown in Figure 3.6.

Figure 3.6: Crash severity by vehicle type – Tunnel 3

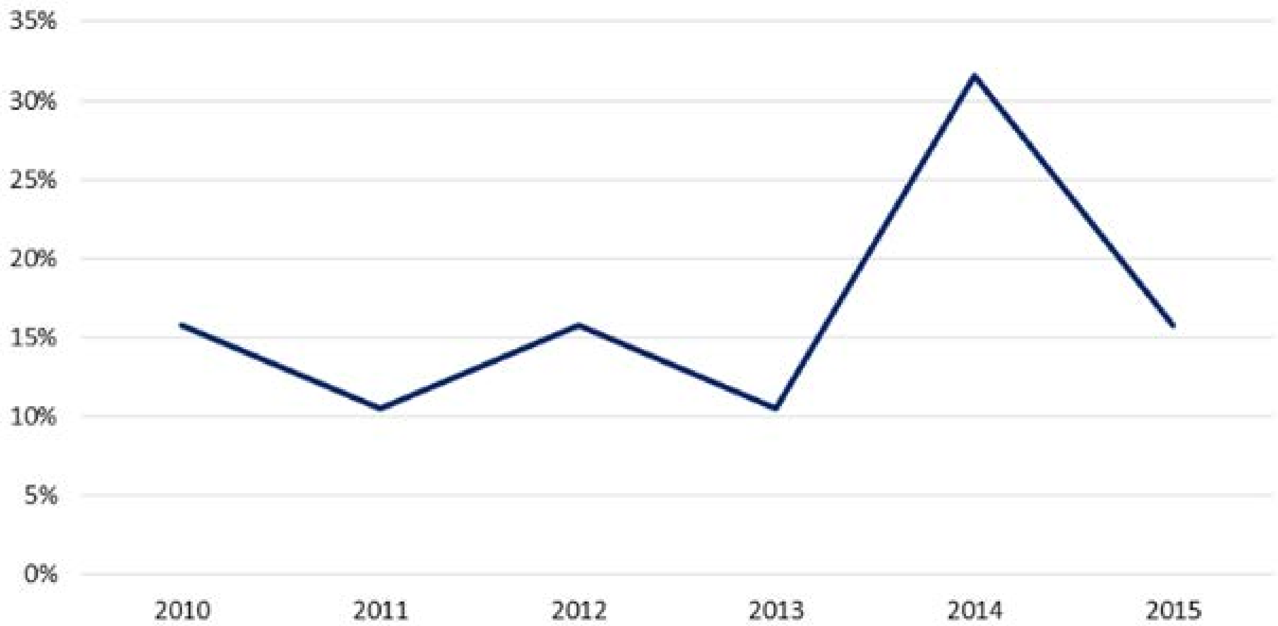


An analysis of objects hit by vehicles indicated that 25 (96%) of the objects hit were cars while one (4%) was a truck. Twenty-three (88%) of the crashes occurred on dry pavements while three (12%) on wet pavements.

3.1.4 Tunnel 4

There were 19 crashes at Tunnel 4 during the six year period between January 2010 and December 2015. The analysis found that, with the exception of 2014, when six (32%) crashes occurred, there were about three (16%) crashed in each year (Figure 3.7). It should be noted that the analysis did not take into account changes in traffic volume over this period. Variations in crash occurrences may to a degree been reflective of changes in the volume of traffic driving through the tunnel each year. Six (32%) of the crashes also resulted in at least one person being injured.

Figure 3.7: Crashes by year – Tunnel 4



Analysis according to time-of-day (Figure 3.8) revealed that seven (37%) of the 19 crashes occurred between 6 am and 8 am. Ten (53%) of the crashes occurred between 6 am to 10 am. Eleven (58%) crashes occurred adjacent to the tunnel while 7 (37%) occurred within the tunnel as shown in Figure 3.9.

Figure 3.8: Crashes by time of day – Tunnel 4

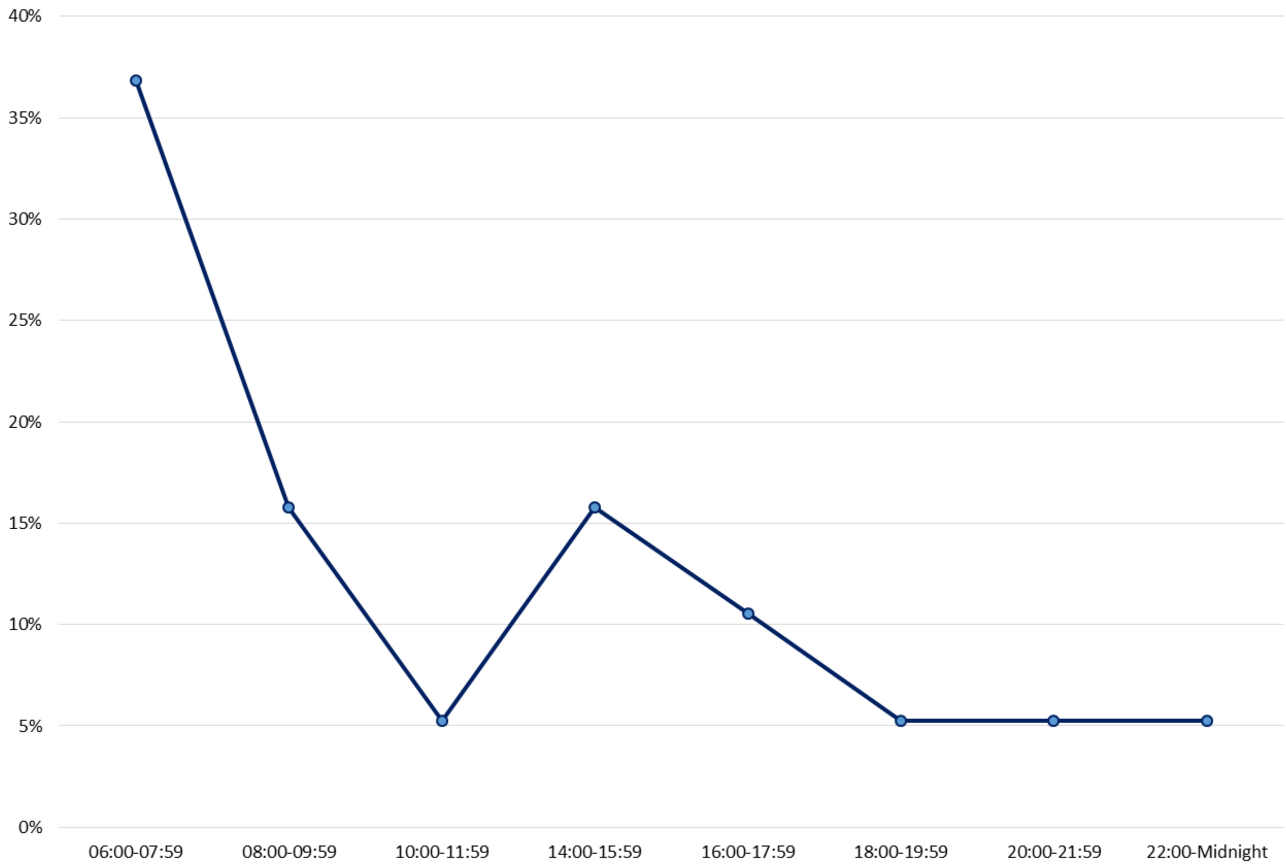
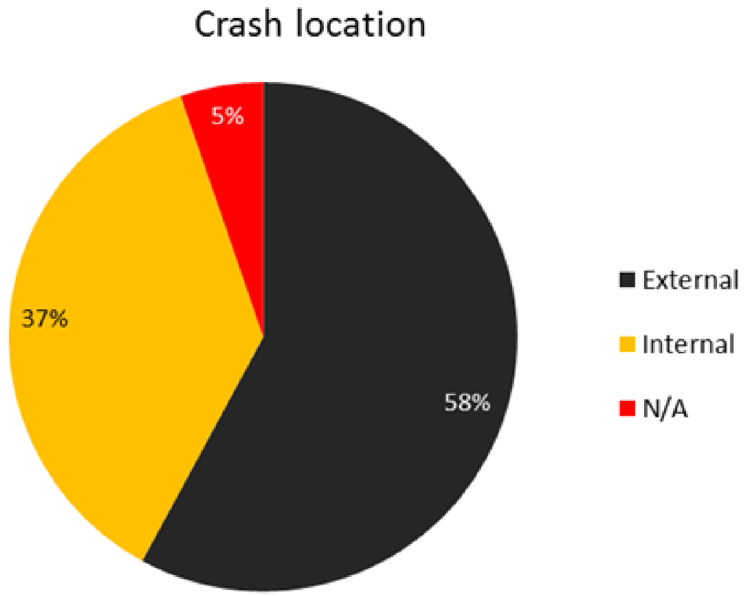


Figure 3.9: Crashes by location – Tunnel 4



3.1.5 Tunnel 5

Seventy-five crashes occurred in Tunnel 5 during the eight years and three months period between October 2007 and December 2015. Seventy-four (99%) of these crashes resulted in no injury. The analysis also found that the number of crashes increased each year over the evaluation period, increasing from two (3%) in 2007 to 14 (19%) in 2015 as shown in Figure 3.10. While the number of crashes steadily increased from 2007 to 2015 this may have been as a result, to a varying degree, of increased traffic over this period.

Forty-six (61%) of the crashes occurred on weekdays while 29 (39%) occurred during weekends. The analysis also indicated that 40 (73%) of the weekday crashes occurred during peak periods, mainly during the morning peak. Similarly, a higher proportion of weekend crashes occurred during peak hours compared to the off peak period, i.e. 52 (69%) and 23 (31%) respectively, as shown in Figure 3.11. Overall, 40 (53%) of all crashes occurred during the weekday peak periods, 20 (27%) during the weekend peak and 15 (20%) in the off peak period.

An analysis of pavement conditions showed that 63 (84%) of the crashes occurred on dry pavements while 12 (16%) occurred on wet pavements.

Figure 3.10: Crashes by year – Tunnel 5

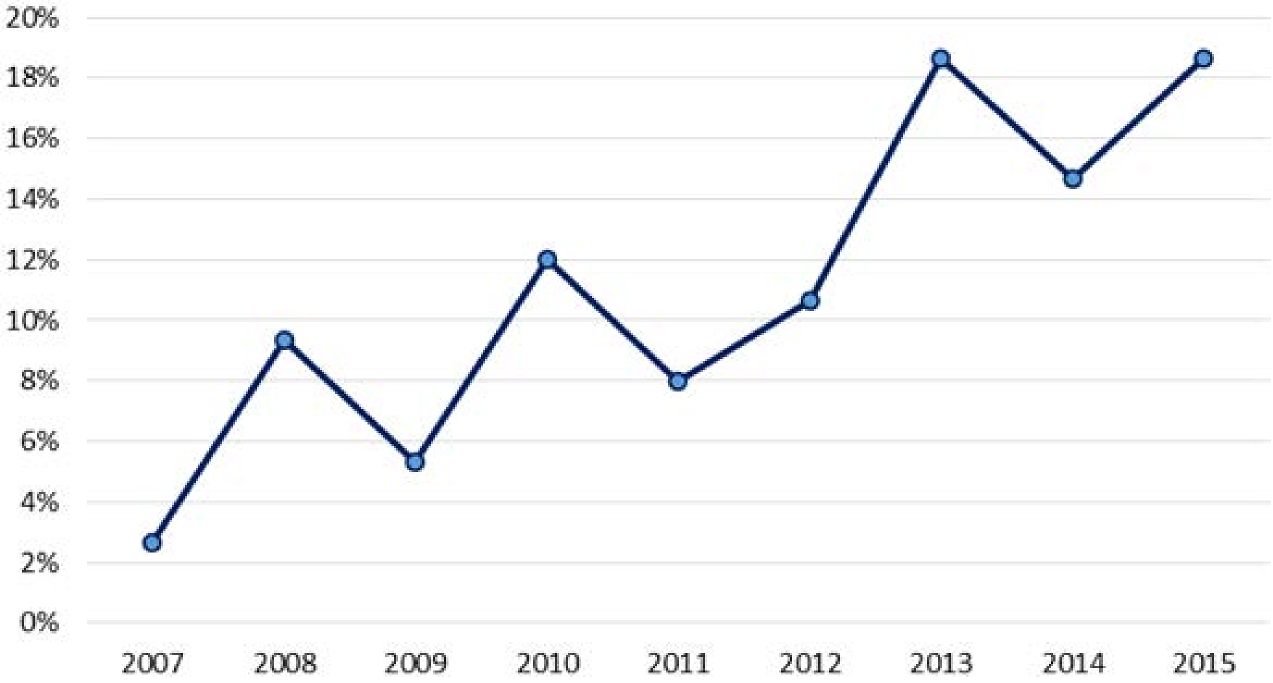
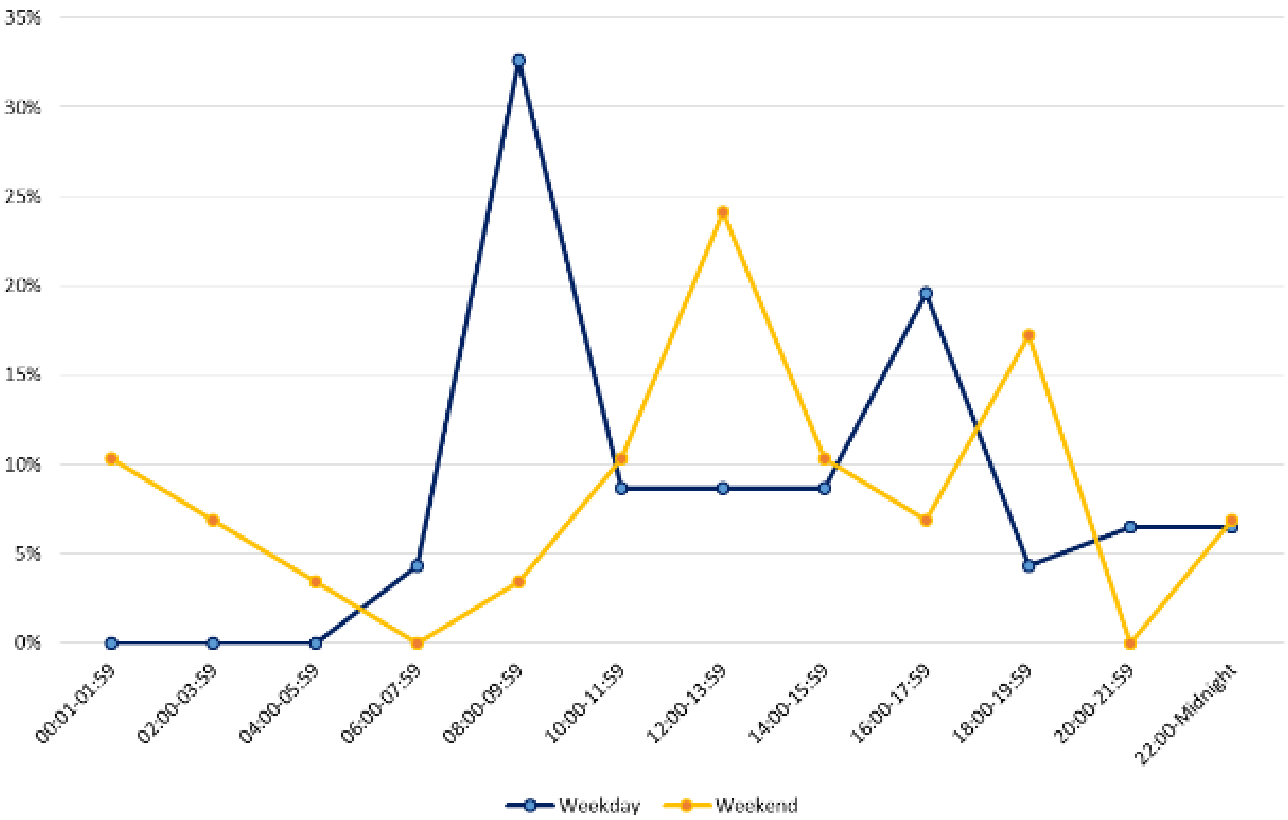


Figure 3.11: Crashes by time of day: weekday and weekend – Tunnel 5



The analysis also showed that 46 (61%) of the crashes involved single vehicles whilst 29 (39%) involving multiple vehicles. The highest proportion of multiple vehicle crashes occurred between 8 am and 10 am while the highest proportion of single-vehicle crashes occurred between noon and 2 pm as outlined in Figure 3.12.

Analysis of crashes according to crash type found that 43 (57%) of the crashes were ‘off-carriageway left on right bend’ followed by 19 (25%) rear-end crashes and four (5%) out-of-control on carriageway crashes as outlined in Table 3.4. Of the ‘off-carriageway left on right bend’ crashes, 25 (58%) occurred during weekends while 18 (42%) occurred on weekdays.

Figure 3.12: Single vehicle and multiple vehicle crashes by time of day – Tunnel 5

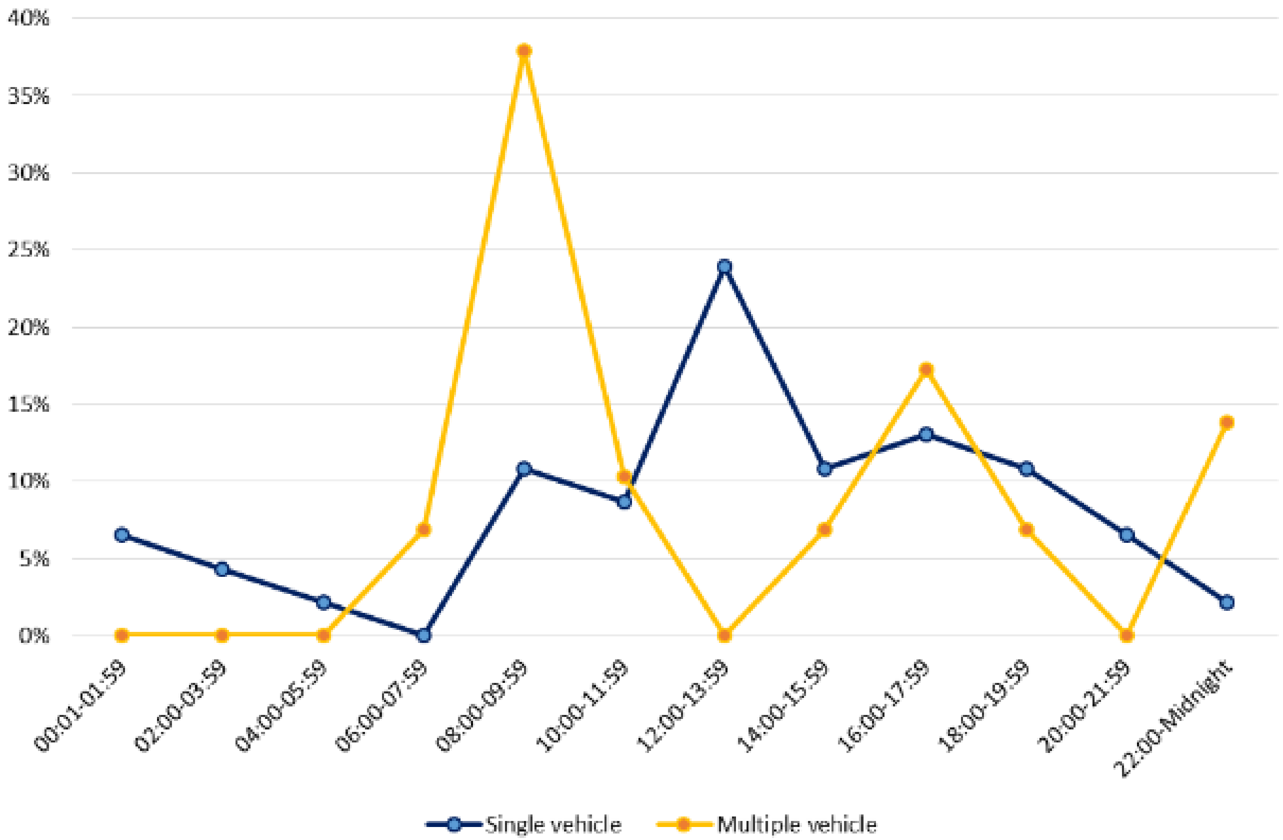


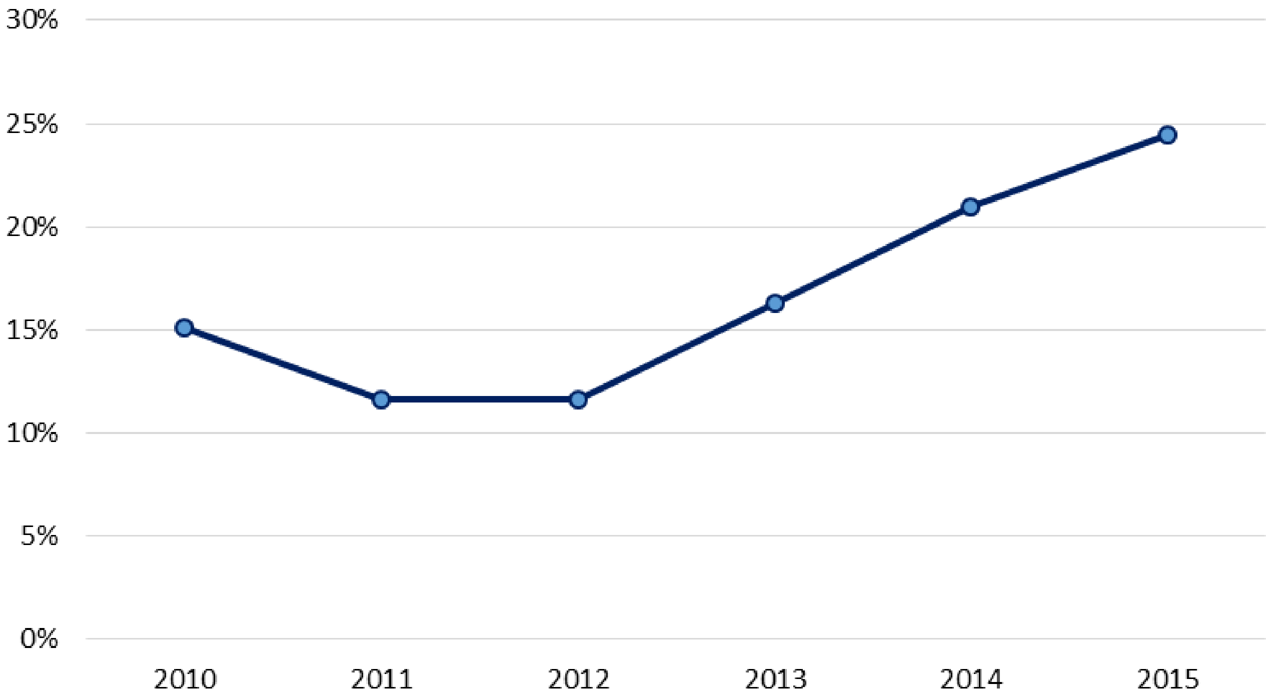
Table 3.4: Types of crashes – Tunnel 3

Types of crashes	Weekday	Weekend	Total crashes
Lane change left	2%	0%	1%
Lane side-swipe	7%	0%	4%
Off carriageway left on right bend	39%	86%	57%
Off carriageway right on right bend	0%	3%	1%
Out-of-control on carriageway	7%	3%	5%
Rear-end	41%	0%	25%
Struck object on motorway	2%	3%	3%
Unknown	2%	3%	3%
Total crashes	100% (46 crashes)	100% (29 crashes)	100% (75 crashes)

3.1.6 Tunnel 6

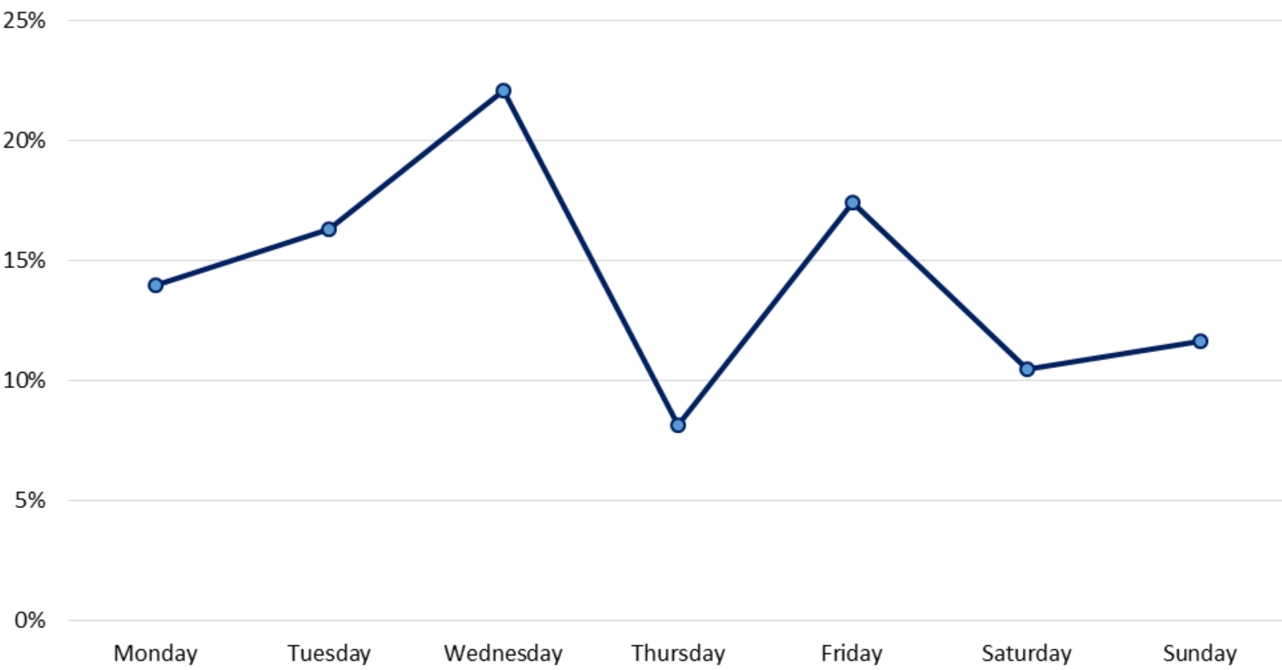
During the six year period between January 2010 and December 2015, there were 86 crashes in Tunnel 6. The analysis showed that there was a general upward trend in crashes during the analysis period, with crashes increasing from 13 (15%) in 2010 to 21 (24%) in 2015 as outlined in Figure 3.13. The analysis did not take into account changes in traffic volume over this period. Variations in crash occurrences may have, to a degree, reflected changes in the volume of traffic driving through the tunnel each year.

Figure 3.13: Crashes by year – Tunnel 6



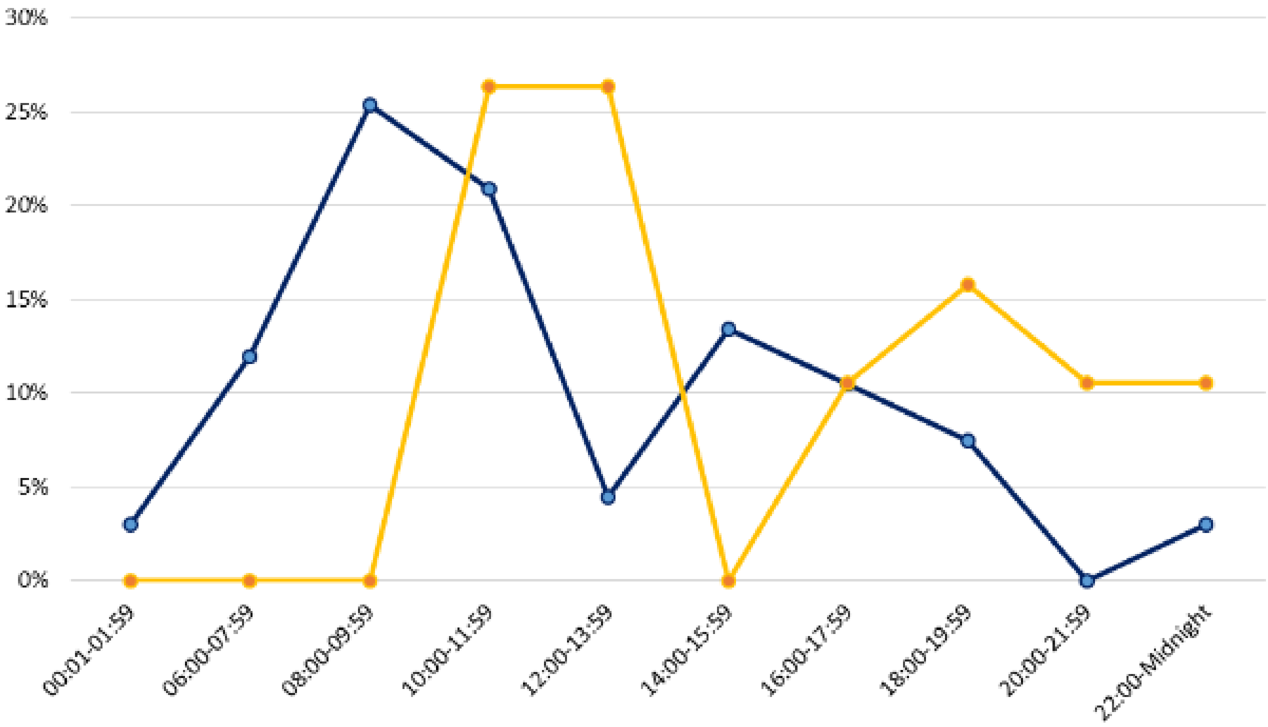
Sixty-seven (78%) of the crashes occurred during weekdays while 19 (22%) occurred during weekends (Figure 3.14). Of the weekday crashes 46 (69%) occurred in the northbound direction while 21 (31%) in the southbound direction. During the weekends 15 (79%) occurred in the northbound direction while four (21%) occurred in the southbound direction.

Figure 3.14: Crashes by day of week – Tunnel 6



In terms of time of day, 36 (42%) crashes occurred between 8 am and noon while 18 (21%) occurred between 2 pm and 6 pm. For weekday crashes, 34 (51%) occurred between 8 am and noon. Similarly, 10 (53%) of weekend crashes occurred between 10 am and 2 pm as shown in Figure 3.15.

Figure 3.15: Crashes by time of day, weekday and weekend – Tunnel 6



3.1.7 Tunnel 7

There were 97 crashes in Tunnel 7 during 2012, seven (7%) of which were serious injury crashes, four (4%) minor injury crashes with the remaining 86 (89%) being non-injury crashes. Figure 3.16 also shows that the vast majority of the crashes (87 (90%)) occurred during weekdays.

Figure 3.16: Crashes by day of week – Tunnel 7

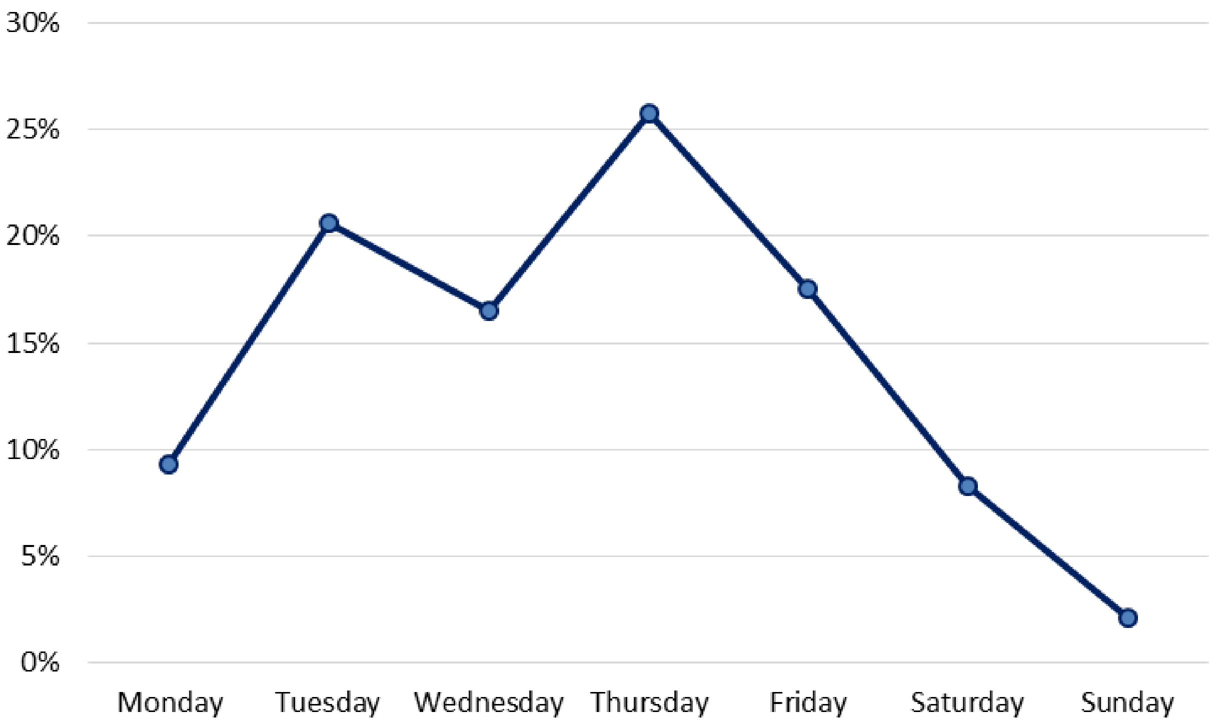


Figure 3.17 shows that 75 (78%) of the crashes involved a car colliding with another car, while 12 (12%) involved a vehicle striking a concrete New Jersey (NJ) barrier and eight (8%) involved a collision with a truck.

In terms of light conditions and crash location, 48 (49%) crashes occurred within the tunnel, 36 (37%) occurred in daylight conditions and 10 (10%) occurred at night (Table 3.5).

Figure 3.17: Crashes by object struck – Tunnel 7

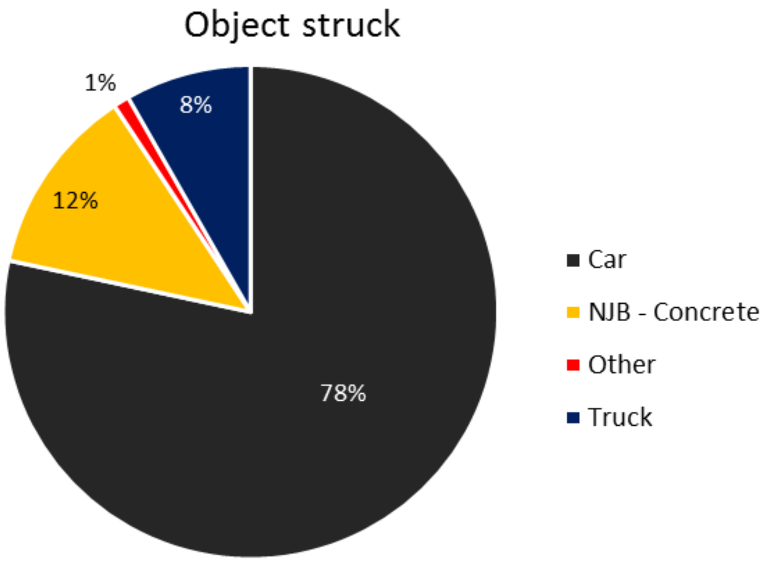


Table 3.5: Crashes by light conditions – Tunnel 7

Light condition	Total crashes
Dawn	1%
Day	37%
Dusk	2%
Night	10%
Tunnel	49%
Total crashes	100%

Analysis of the crash data by crash type found that 56 (58%) crashes were rear-end type, followed by 12 (12%) lane side-swipe crashes and 11 (11%) lane change left crashes. It is also of note that three (43%) of the seven serious injury crashes were of the 'lane change to the left' crash type (Table 3.6).

Table 3.6: Crash severity by crash type – Tunnel 7

Type of crash	Serious injury crashes	Minor injury crashes	Non-injury crashes	Total crashes
Vehicles same direction, rear-end	14%	25%	63%	58%
Vehicles same direction, lane side-swipe	0%	0%	14%	12%
Vehicles same direction, lane change right	0%	0%	5%	4%
Vehicles same direction, lane change left	43%	25%	8%	11%
Overtaking out-of-control	14%	0%	7%	7%
Overtaking cutting-in	0%	0%	1%	1%
On-path (struck) parked (vehicle)	0%	25%	0%	1%
Off-path on straight to left into object	14%	0%	0%	1%
Off-path on straight out-of-control	14%	0%	1%	2%
199 – Unknown	0%	25%	1%	2%
Total crashes	100%	100%	100%	100%

Table 3.7 outlines crash severity by time of crash. Overall, 19 (20%) of all the crashes occurred between 8:00 am and 10:00 am, followed by equal proportions of crashes between 2:00 pm and 18:00 pm. Most of the serious injury crashes occurred between 10:00 am and noon while the highest proportion of non-injury crashes occurred between 8:00 am and 10:00 am.

Table 3.7: Crash severity by time of crash – Tunnel 7

Time of crash	Serious injury crashes	Minor injury crashes	Non-injury crashes	Total crashes
00:01–01:59	0%	0%	1%	1%
04:00–05:59	14%	0%	2%	3%
06:00–07:59	0%	0%	10%	9%
08:00–09:59	0%	0%	22%	20%
10:00–11:59	43%	0%	10%	12%
12:00–13:59	14%	25%	9%	10%
14:00–15:59	0%	25%	15%	14%
16:00–17:59	0%	0%	16%	14%
18:00–19:59	14%	50%	8%	10%
20:00–21:59	14%	0%	2%	3%
22:00–Midnight	0%	0%	2%	2%
Total crashes	100%	100%	100%	100%

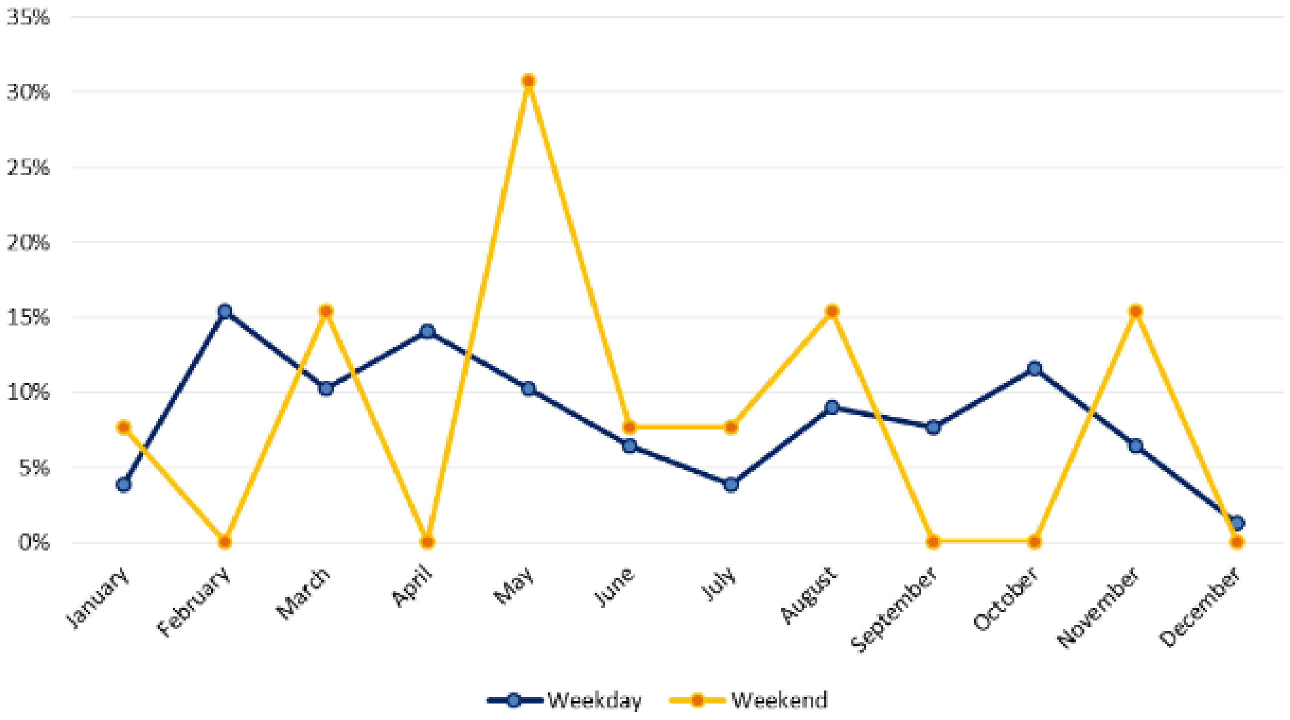
Analysis according to vehicle type revealed that 64 (66%) of the crashes involved cars while the remaining 33 (34%) crashes involved trucks. Further, 58 (91%) of crashes involving cars were non-injury crashes, followed by equal proportions of serious and minor injury crashes. When considering trucks, four (12%) crashes resulted in serious injury crashes, one (5%) in a minor injury crash, whilst the remaining 28 (83%) were non-injury crashes.

Seventy-one (73%) crashes occurred during fine weather conditions, 19 (20%) during overcast conditions and seven (7%) when it was raining. Of the crashes involving cars, 45 (70%) occurred during fine weather, 14 (22%) during overcast conditions and five (8%) when it was raining. In terms of trucks, 26 (79%) crashes occurred during fine weather, five (15%) during overcast conditions and two (6%) when it was raining.

3.1.8 Tunnel 8

During the three year period between January 2014 and May 2016 there were 91 crashes at Tunnel 8. Thirty-three (34%) occurred during 2014, 36 (40%) during 2015 and 22 (24%) in 2016, which is a substantial decline. Of these crashes, 78 (86%) occurred on weekdays while 13 (14%) occurred on weekends Figure 3.18.

Figure 3.18: Crashes by month of year – Tunnel 8

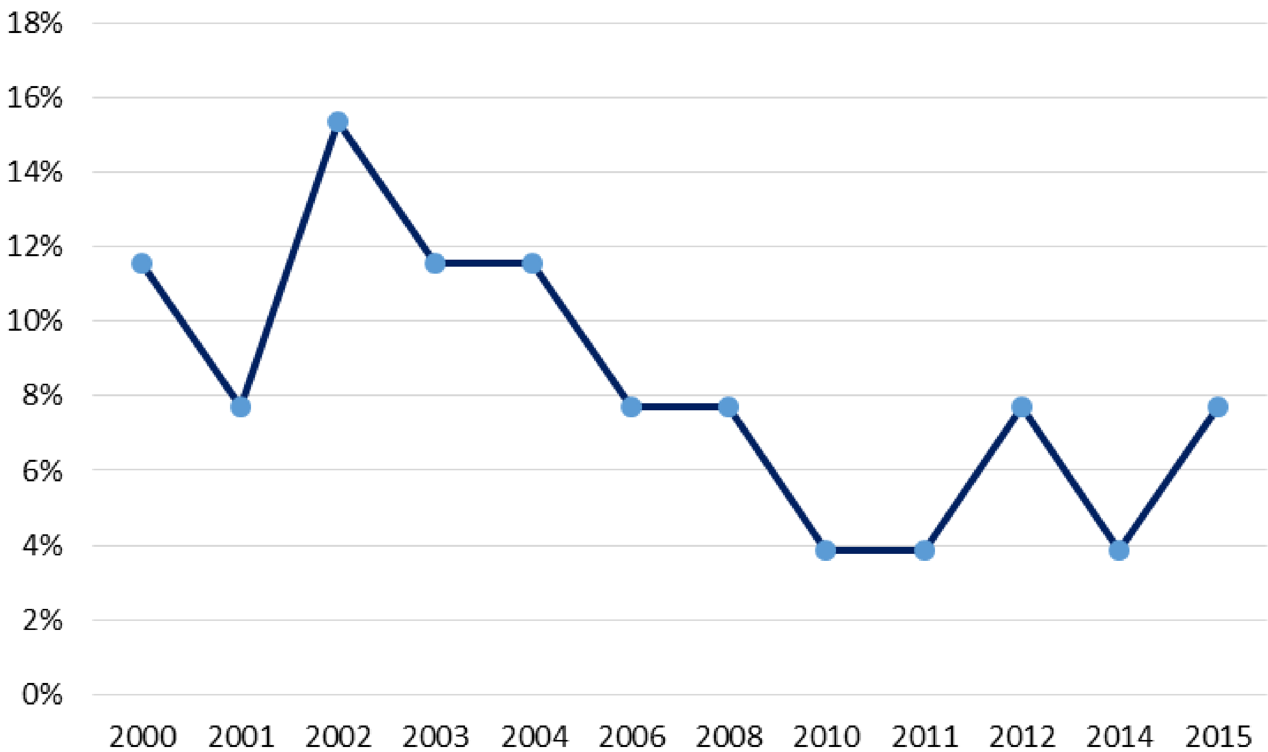


All the recorded crashes were rear-end collisions. Additionally, 88 (97%) of the rear-end crashes involved car-to-car crashes with the remaining three (3%) involving cars and trucks.

3.1.9 Tunnel 9

A total of 26 crashes occurred at Tunnel 9 during the 15 years and nine month period between March 2000 to November 2015. Nine (35%) crashes resulted in at least one person being injured, while conversely there were no injuries as a result of the remaining 19 (65%) crashes. It can be seen from Figure 3.19 that the number of crashes gradually declined from 2000 to 2006 (they appear to have plateaued to about per year). It should be noted that the analysis did not take into account changes in traffic volume over this period. Variations in crash occurrences may have been reflective of changes in the volume of traffic driving through the tunnel each year.

Figure 3.19: Crashes by year – Tunnel 9



Further analysis found that 17 (65%) crashes occurred on weekdays with the remaining nine (35%) occurring during weekends. It is also of note that six (86%) of the injury crashes occurred during weekends (Table 3.8).

Table 3.8: Crash severity by weekday and weekend – Tunnel 9

Crash severity	Weekday	Weekend	Total crashes
Serious	0%	11%	4%
Minor	24%	44%	31%
No injury	76%	44%	65%
Total crashes	100%	100%	100%

Analysis of crashes according to time-of-day showed that eight (31%) crashes occurred between 10 am and noon and five (19%) crashes occurred between 8 am and 10 am.

Analysis according to crash type revealed that 10 (38%) of the crashes involved vehicles cornering or manoeuvring to the left or right, four (15%) involved head-on collisions, while two (8%) were rear-end collisions (Table 3.9).

Further analysis showed that 13 (50%) crashes occurred in dry pavement conditions and 13 (50%) on wet or icy pavements. Eleven (42%) crashes occurred on straight sections of road, while 15 (66%) occurred on curved sections. All of the injury crashes occurred at curved sections (Table 3.10).

Table 3.9: Crash severity by crash type – Tunnel 9

Road user movement	Serious injury crash	Minor injury crash	Non-injury crash	Total crashes
Collision with obstruction, non-vehicular (including animals)	0	0	1	1
Collision with obstruction, other	0	0	2	2
Cornering, lost control turning left	0	2	1	3
Cornering, lost control turning right	0	6	1	7
Head-on, lost control on curve	1	0	0	1
Head-on, other	0	0	3	3
Lost control or off-road (straight roads), off-roadway to right	0	0	1	1
Lost control or off-road (straight roads),off-roadway to left	0	0	1	1
Manoeuvring, other	0	0	2	2
Manoeuvring, reversing along road	0	0	3	3
Rear-end, other	0	0	1	1
Rear-end, queue	0	0	1	1
Total crashes	1	8	17	26

Table 3.10: Crash severity by road curvature – Tunnel 9

Curve	Serious injury crash	Minor injury crash	Non-injury crash	Total crashes
Easy curve	0	1	3	4
Moderate curve	1	3	3	7
Severe curve	0	4	0	4
Straight road	0	0	11	11
Total crashes	1	8	17	26

In terms of the prevailing weather and light conditions, 18 (69%) crashes occurred in fine weather conditions, while the six (24%) occurred when it was raining. When considering light conditions 12 (46%) crashes occurred during overcast light conditions, nine (35%) during bright sun conditions and two (8%) at night.

3.1.10 Tunnel 10

There were 36 crashes at Tunnel 10 during the 13 years 11 months period between September 2000 and November 2014. Ten (28%) of the crashes resulted in at least one person being injured with the remaining 26 (72%) resulting in non-injuries. There was a substantial increase in tunnel crashes between 2000 and 2003, peaking at eight crashes in 2003. The number of crashes steadily declined after 2003, plateauing to one crash per year from 2009 to 2014 (Figure 3.20). It should be noted that variations in crash occurrences may to a degree been reflective of changes in the number of vehicles driving through the tunnel each year.

It was also found that 28 (78%) of the crashes occurred on weekdays while eight (22%) occurred during weekends (Figure 3.21).

Examination of crash occurrence according to time of day found that eight (22%) crashes occurred between 10 pm and midnight, seven (19%) occurred between 2 pm and 4 pm and four (11%) occurred between noon and 2 pm (Table 3.11).

Figure 3.20: Crashes by year – Tunnel 10

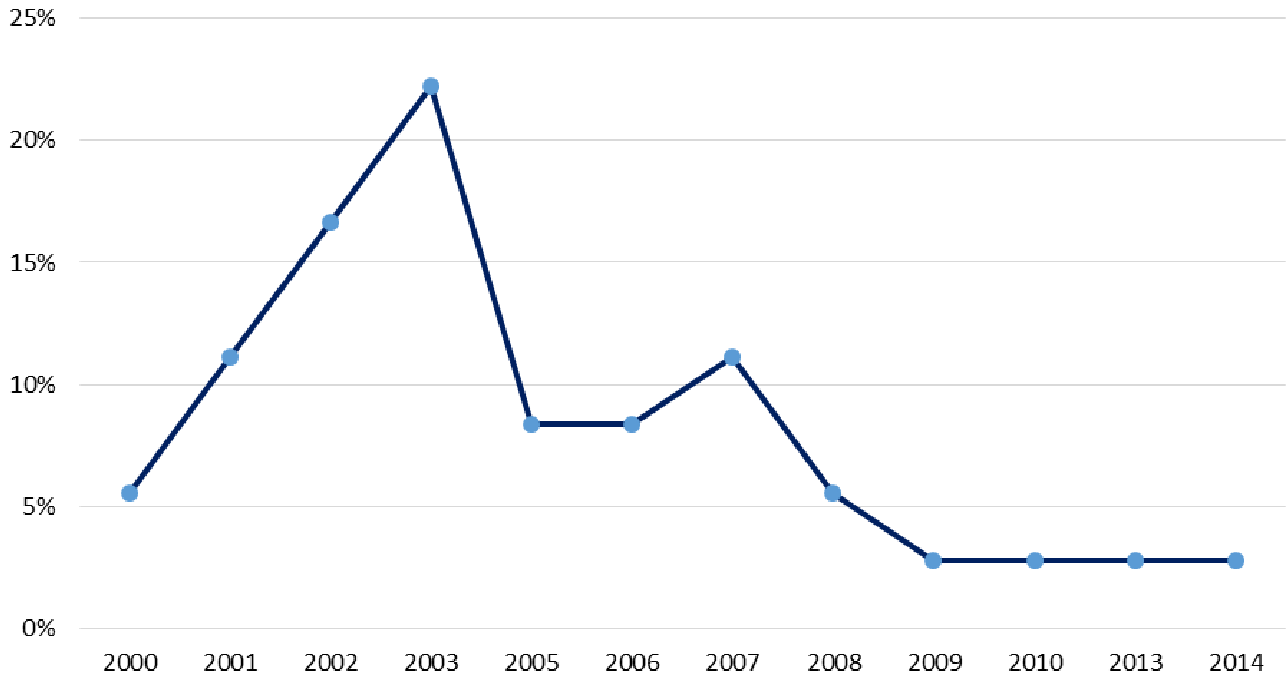


Figure 3.21: Crashes by day of week – Tunnel 10

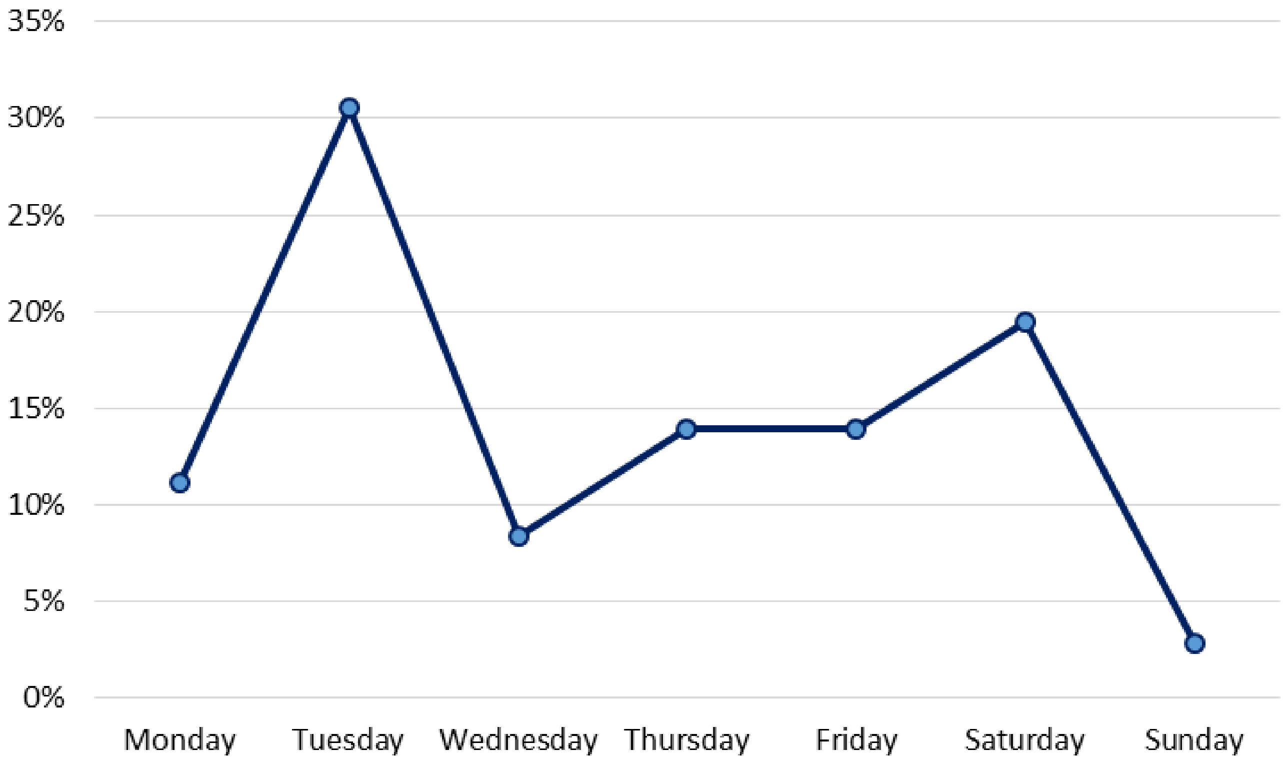


Table 3.11: Crashes by time of day and day of week – Tunnel 10

Time of day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Total crashes
00:01–01:59	0	1	0	0	1	1	0	3
02:00–03:59	0	0	0	0	0	1	0	1
04:00–05:59	0	0	1	0	1	0	0	2
06:00–07:59	0	1	0	0	0	1	0	2
08:00–09:59	1	0	0	0	1	0	0	2
10:00–11:59	0	1	0	0	0	0	0	1
12:00–13:59	0	2	0	0	1	1	0	4
14:00–15:59	1	1	0	3	0	2	0	7
16:00–17:59	0	2	1	0	0	0	0	3
18:00–19:59	0	0	0	1	0	0	0	1
20:00–21:59	1	0	0	1	0	0	0	2
22:00–Midnight	1	3	1	0	1	1	1	8
Total crashes	4	11	3	5	5	7	1	36

The analysis of crash data also showed that 18 (50%) of the crashes occurred in dark conditions, 11 (31%) during overcast conditions and seven (19%) during bright sun conditions. In terms of weather conditions, 31 (86%) crashes occurred in fine weather conditions and four (11%) when it was raining (Table 3.12).

Table 3.12: Crash severity by weather condition – Tunnel 10

Weather conditions	Serious injury crashes	Minor injury crashes	Non-injury crashes	Total crashes
Fine	100%	78%	88%	86%
Fine and strong winds	0%	0%	4%	3%
Heavy rain	0%	11%	0%	3%
Light rain	0%	11%	8%	8%
Total crashes	100%	100%	100%	100%

The analysis also found that 30 (83%) crashes occurred when the pavement was dry and six (17%) when the pavement was wet. In addition, 17 (47%) crashes occurred on straight sections of road, while 19 (53%) occurred on curved sections of road (Table 3.13).

Table 3.13: Crash severity by road curvature – Tunnel 10

Road curvature	Serious injury crashes	Minor injury crashes	Non-injury crashes	Total crashes
Easy curve	100%	44%	23%	31%
Moderate curve	0%	11%	23%	19%
Severe curve	0%	0%	4%	3%
Straight road	0%	44%	50%	47%
Total crashes	100%	100%	100%	100%

3.1.11 Tunnel 11

There were 136 crashes at Tunnel 11 during the 15 years and 6 months period between April 2000 and September 2015. Of these, one resulted in a fatal crash, there were two serious injury crashes, 34 (25%) minor injury crashes and 99 (73%) non-injury crashes. There was a substantial increase in the number of crashes from 2000 that peaked during 2007. There was a substantial decline in the number of crashes between 2007 and 2015, from 22 (16%) in 2007 to four (3%) in 2015 (Figure 3.22). Variations in crash occurrences, however, may have been as a result of changes in the number of vehicles driving through the tunnel each year.

A total of 100 (74%) crashes occurred on weekdays while 36 (26%) occurred during weekends. Thirty (81%) of the 37 injury crashes occurred on weekdays (Figure 3.23).

Figure 3.22: Crashes by year – Tunnel 11

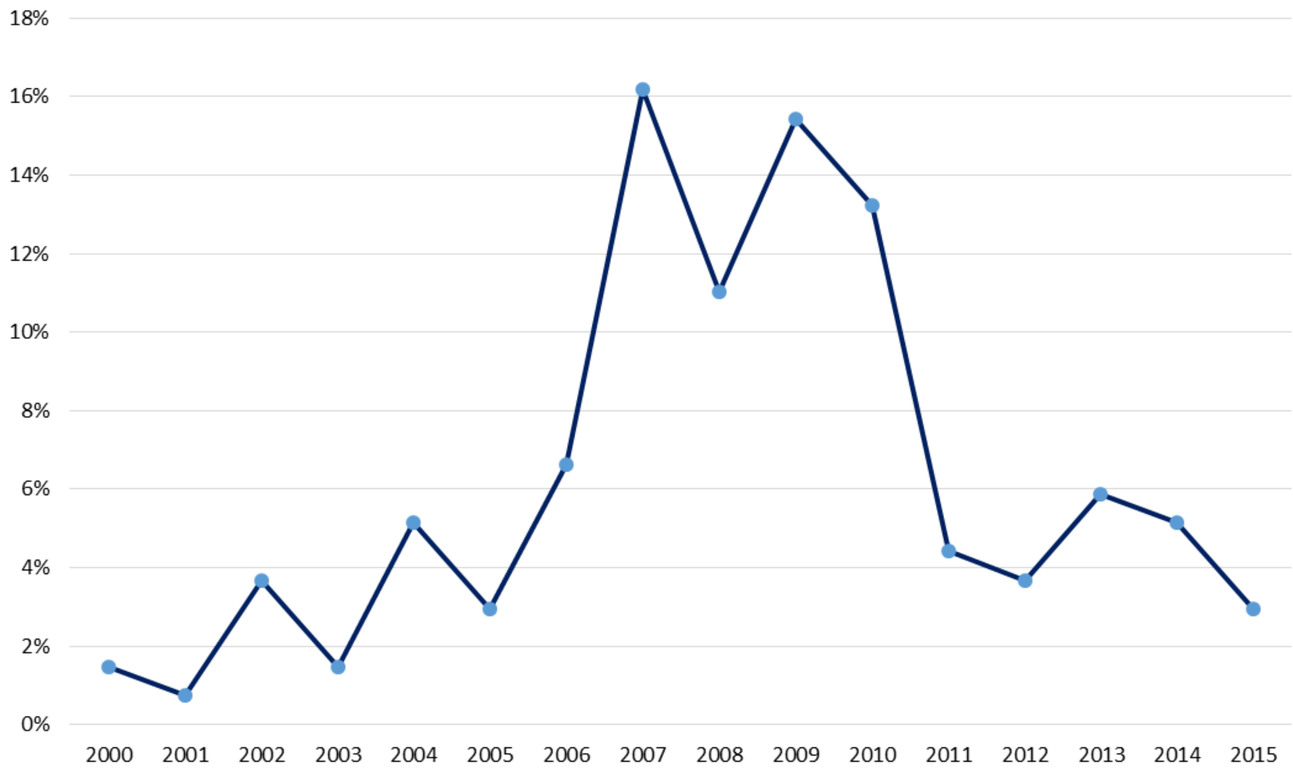
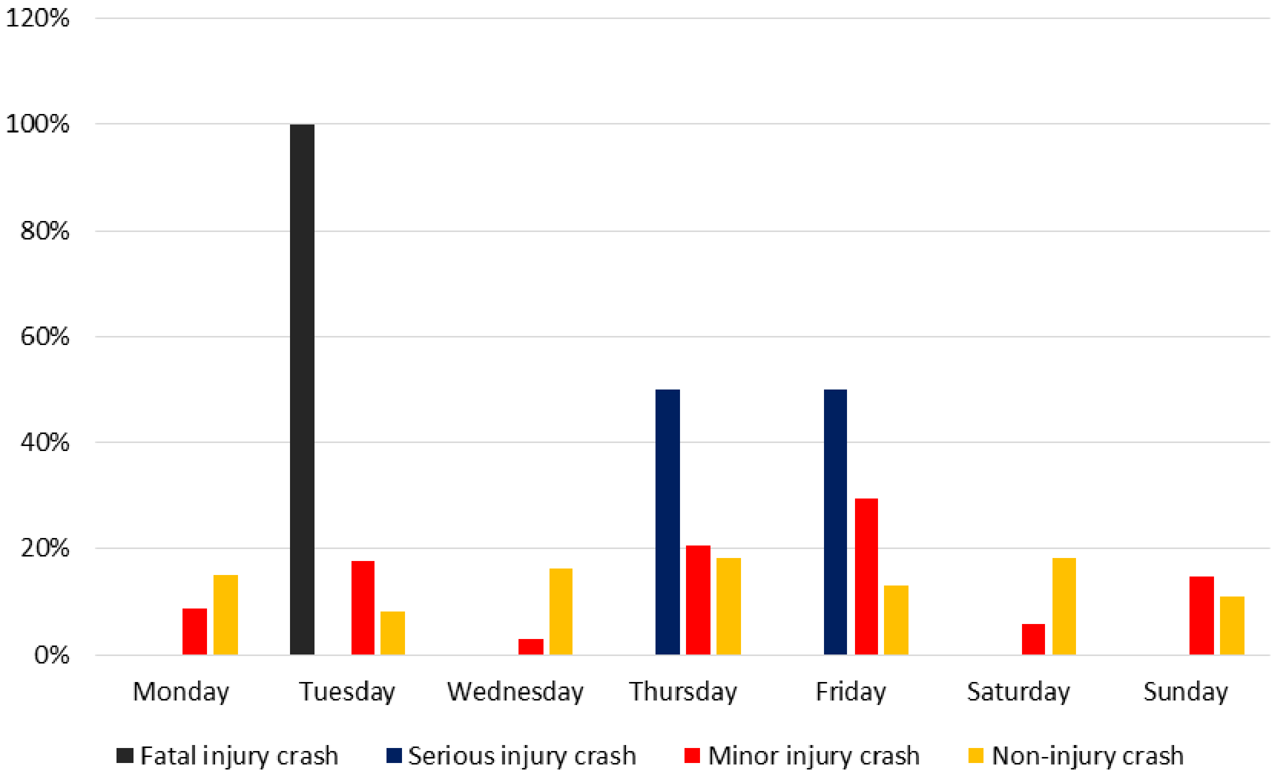


Figure 3.23: Crash severity by day of week – Tunnel 11



There were pronounced peaks in crashes during the morning and evening weekday peaks and weekend peaks, with 44 (32%) crashes occurring between 4 pm and 6 pm, 33 (24%) between 2 pm and 4 pm and 17 (13%) between 8 am and 10 am. The highest proportion of crashes on weekdays occurred between 4 pm and 6 pm; 37 (37%) and 33 (29%) crashes between 2 pm and 4 pm and 17 (19%) crashes between 10 am and noon and between 4 pm and 6 pm on weekends as shown in Figure 3.24.

One hundred and six (78%) crashes occurred in dry pavement conditions and 30 (22%) in wet pavement conditions. When considering weather conditions, 107 (79%) crashes occurred during fine weather conditions and 28 (21%) occurred when it was raining.

One hundred (74%) crashes were rear-end collisions, 12 (9%) involved overtaking and lane change collisions, eight (5%) head-on collisions and seven (4%) loss-of-control collisions.

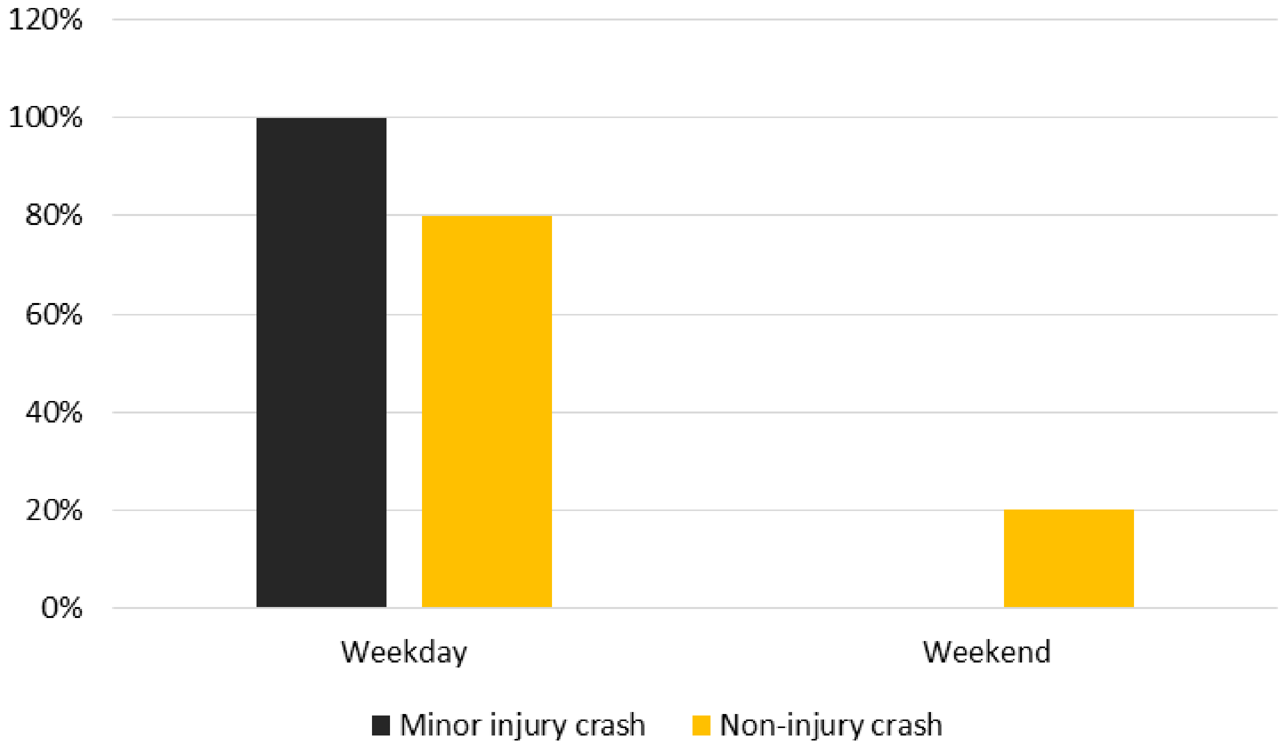
Analysis of road curvature and light conditions indicated that 118 (87%) crashes occurred on straight sections of road and 18 (13%) on curved sections of road. Fifty-two (39%) crashes occurred in overcast conditions, 40 (29%) in bright sun conditions, 31 (23%) in dark conditions and 12 (9%) in twilight conditions.

Figure 3.24: Crashes by time of day, weekday and weekend – Tunnel 11

3.1.12 Tunnel 12

There were 12 crashes at Tunnel 12 during the 15 years and three months period from August 2000 to October 2015. Of these, two (17%) crashes resulted in at least one injury while the remaining 10 (83%) were non-injury crashes. Overall, there was a near constant trend in crashes, with one crash a year between 2000 and 2015 and four crashes in 2014. Ten (83%) of the crashes occurred on weekdays while the remaining two (17%) occurred during weekends (Figure 3.25).

Figure 3.25: Crashes and crash severity by weekday and weekend – Tunnel 12

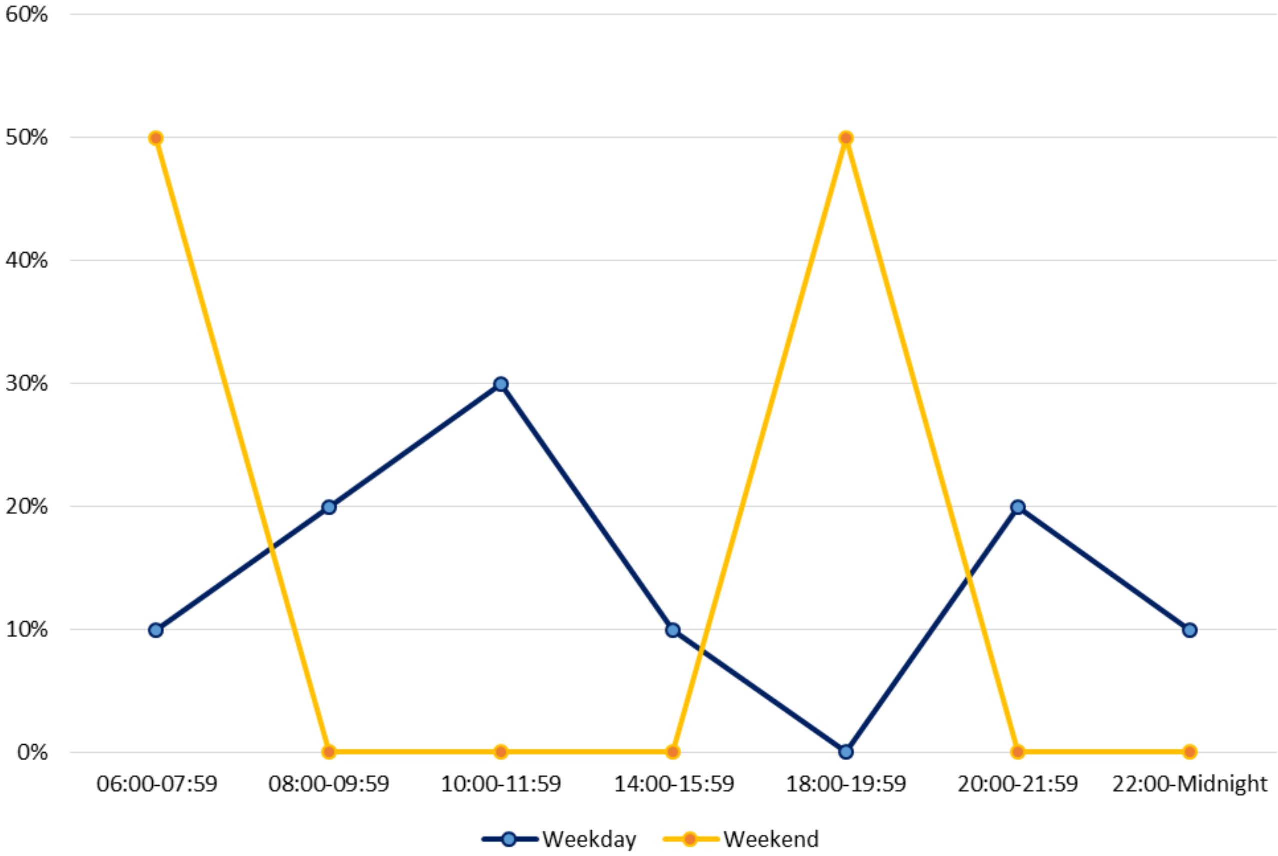


In terms of time of day, there were three (25%) crashes between 10 am and noon and two (17%) between 6 am and 10 am and 8 pm and 11 pm (Figure 3.26).

It was also found that seven (58%) crashes occurred in dry pavement conditions and five (42%) in wet pavement conditions. Nine (75%) crashes occurred in fine weather and three (25%) when it was raining.

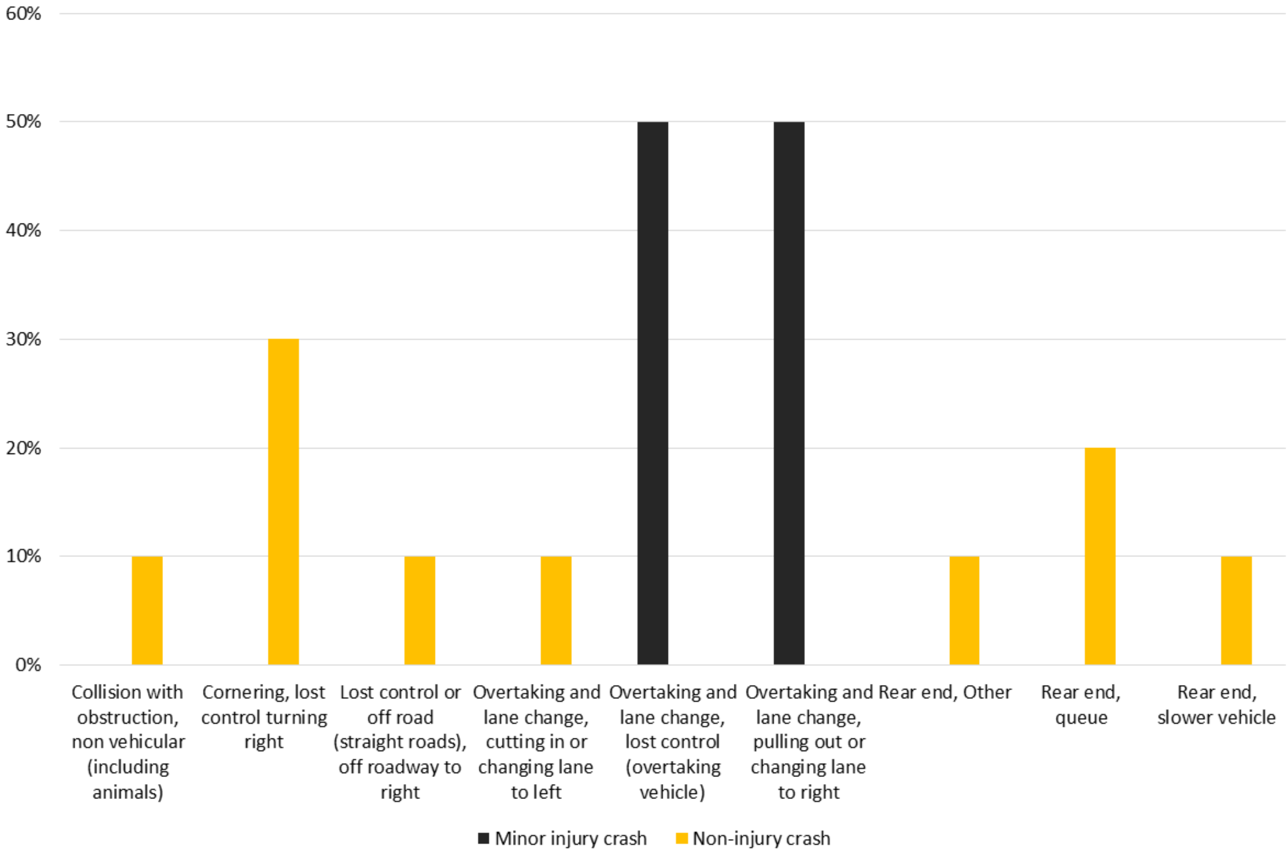
In terms of light conditions and road curvature, five (42%) crashes occurred during bright sun conditions, four (33%) during dark conditions and three (25%) in overcast conditions. Six (50%) crashes occurred on straight sections of road and six (50%) crashes occurred on curved sections of road.

Figure 3.26: Crashes by time of day, weekday and weekend – Tunnel 12



Further analysis showed that four (33%) crashes were rear-end type, three (25%) were cornering collisions, three (24%) involved overtaking and lane changes whilst the remaining crash involved a vehicle losing control as illustrated in Figure 3.27.

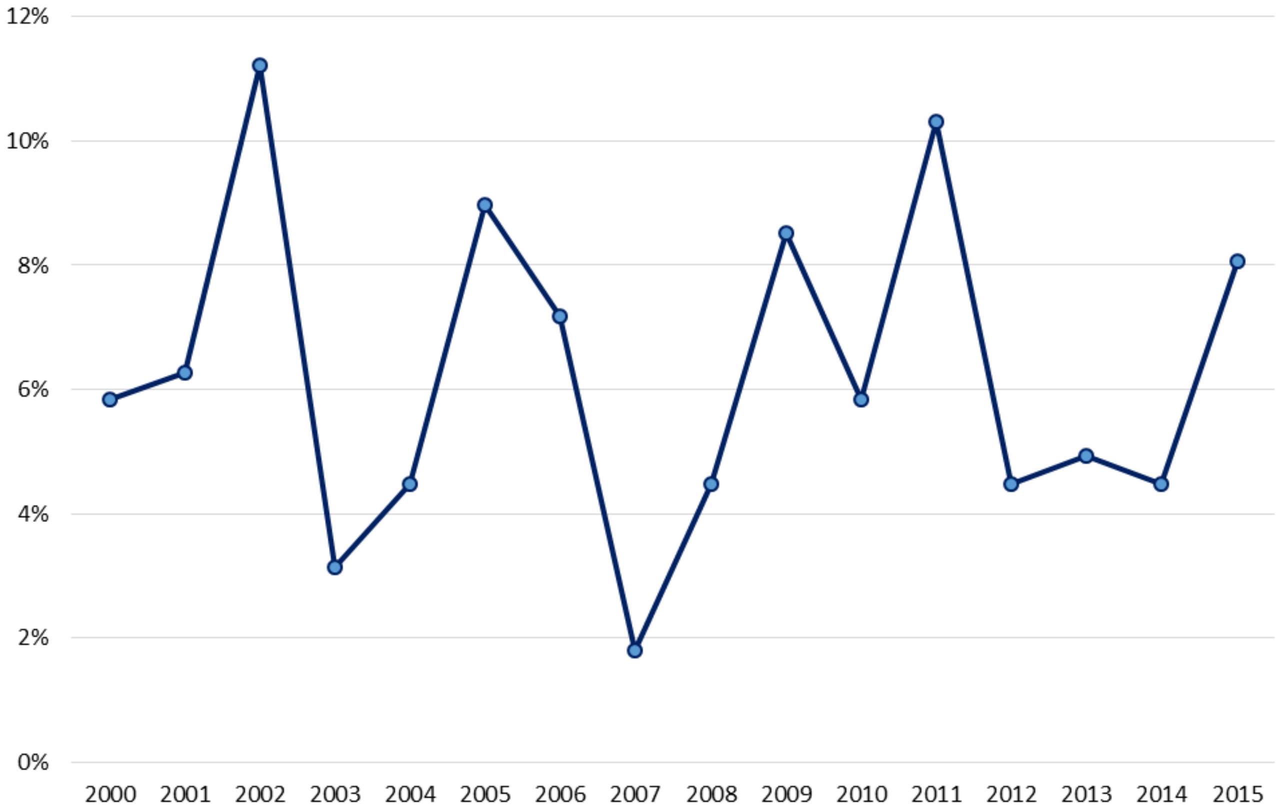
Figure 3.27: Crash severity by crash type – Tunnel 12



3.1.13 Tunnel 13

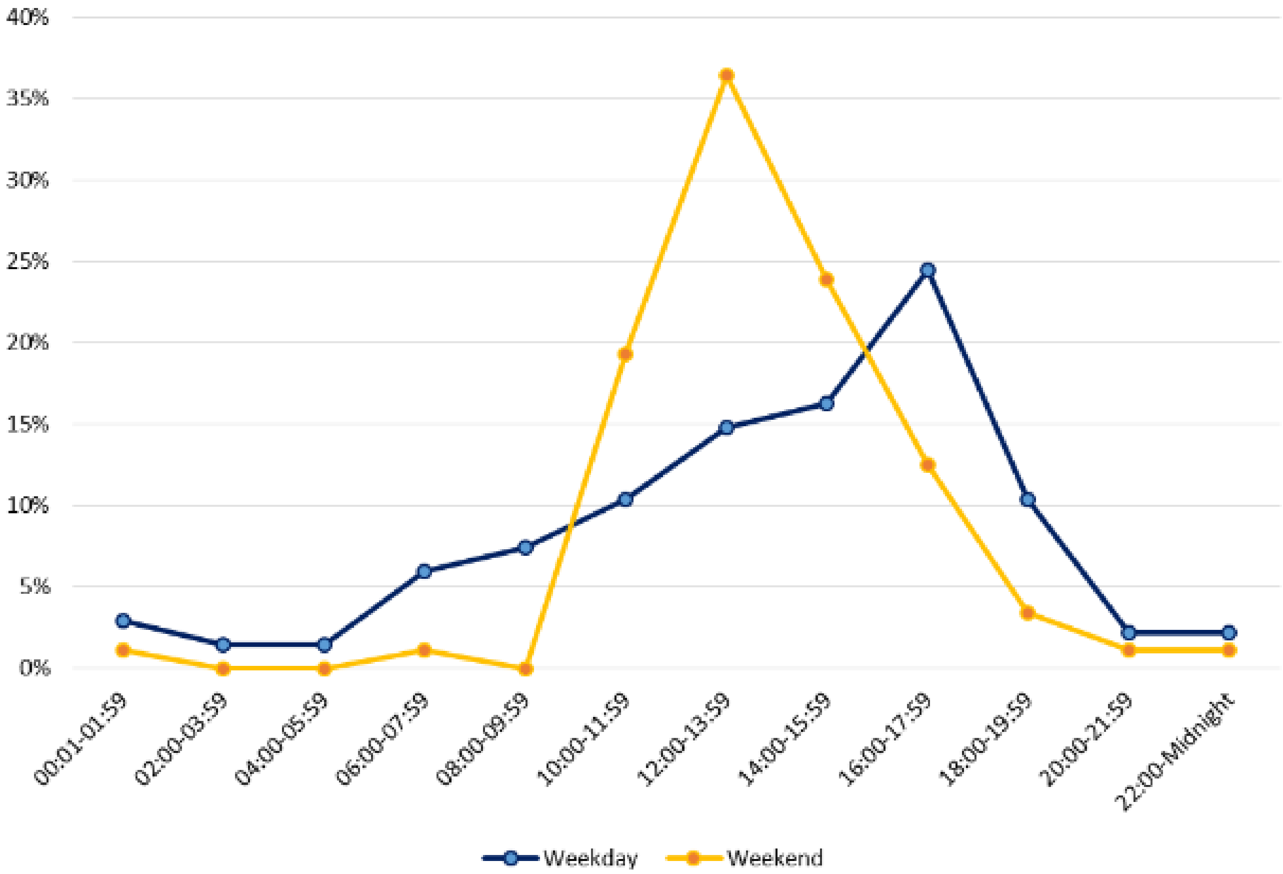
There were 223 crashes at Tunnel 13 during the 15 years and nine months between March 2000 and December 2015. Of these, 185 (83%) were non-injury crashes, while the remaining 38 (17%) resulted in a least one person being injured. There were overall fluctuations in crashes, increasing from 13 (6%) during 2000 to 24 (11%) in 2002 and falling to 18 (8%) in 2015 as shown in Figure 3.28. It should be noted that variations in crash occurrences may to a degree been reflective of changes in the number of vehicles driving through the tunnel each year.

Figure 3.28: Crashes by year – Tunnel 13



The analysis showed that 41 (18%) crashes occurred on Thursdays, 30 (13%) on Fridays and 26 (12%) on Tuesdays. Overall, 135 (61%) of the crashes occurred during weekdays and 88 (39%) on weekends. Of the weekend crashes, 52 (59%) occurred on Saturdays and 36 (41%) on Sundays. Further, 52 (23%) of the crashes occurred between noon and 2 pm, 32 (36%) of which were weekend crashes as illustrated in Figure 3.29.

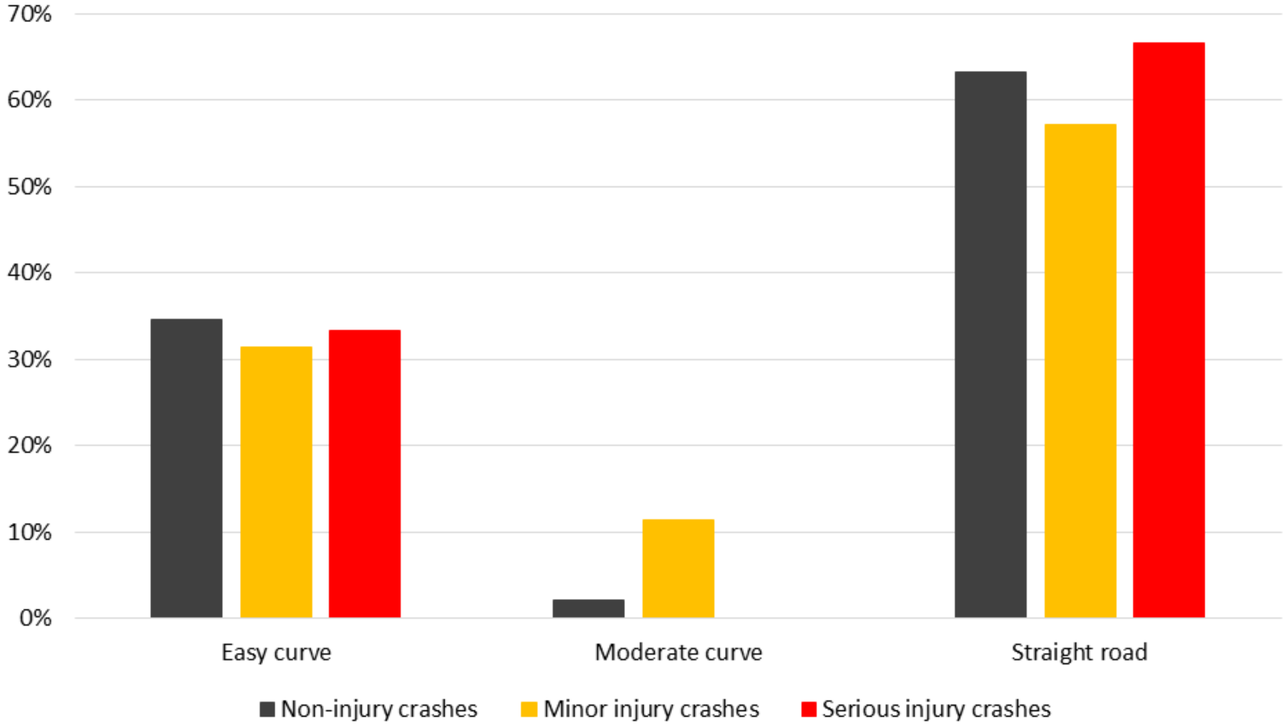
Figure 3.29: Crashes by time of day, weekday and weekend – Tunnel 13



One hundred and forty seven (66%) crashes occurred on dry pavements and 76 (34%) on wet pavements. In addition, 139 (62%) crashes occurred on straight sections of the road, while 84 (38%) occurred on curved road sections (Figure 3.30).

In terms of weather conditions, 144 (65%) crashes occurred during fine weather conditions and 76 (35%) when it was raining. Further analysis found that 173 (78%) crashes where rear-end types, 24 (11%) involved overtaking and lane changes and 14 (6%) involved cornering.

Figure 3.30: Crash severity by road curvature – Tunnel 13



3.2 Summary

As indicated earlier in this report comparisons of the safety performance between tunnels, and their crash records, should be treated with great caution. Tunnel attributes and age are unknown, and these may vary to large degrees, traffic volume and traffic compositions are unknown, while the recording of non-injury crashes in tunnels may vary markedly, being very dependent on their recording protocols.

Crash frequency and severity

Table 3.14 summarises from the data available for the 13 tunnels, including the number and severity of crashes, and the periods when they occurred.

When considering the number of crashes and their severities, the following was found:

- On average, each tunnel recorded 19 crashes per year.
- The tunnel with the poorest crash history recorded 97 crashes in the one year which is almost two crashes per week, while the tunnel with the best history recorded less than one crash per year.
- About 14% of crashes resulted in at least one person being injured, while about 2.3% of crashes resulted in at least one person being seriously injured or killed.

Time-of-day and day-of-week

Similar to the findings from the individual site analyses, most of the crashes (74%) occurred on weekdays. A breakdown by time-of-day using data for 11 of the 13 tunnels indicated the presence of notable peaks in crashes during the morning and evening peak periods and also the weekend peak period. About 26% of the weekday crashes occurred between 6 am and 09.59 am, while about 35% occurred between 2 pm and 5.59 pm. About 65% of the crashes during the weekends occurred between 10 am and 5.59 pm as shown in Figure 3.31.

Figure 3.31: Overall crashes by time-of-day

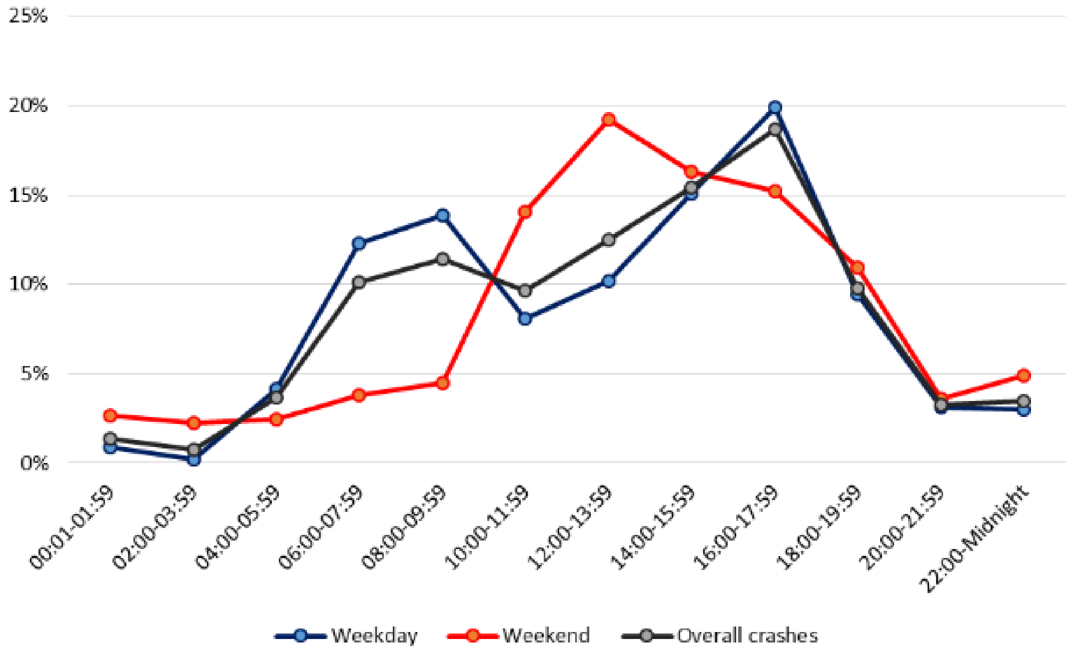


Table 3.14: Summary

Tunnel	Period	Tunnel crashes					
		Total crashes	Crashes/ year	Fatal	Serious injury	Minor injury	Non injury crashes
1	Jan 2010 to Dec 2015 (6 years)	206	34	0	10	14	182
2	Jan 2008 to Mar 2011 (4 years 3 months)	128	30	0	2	9	117
3	Oct 2011 to Dec 2015 (4 years 3 months)	26	6	0	0	1	25
4	Jan 2010 to Dec 2015 (6 years)	19	3	0	6[1]		13
5	Oct 2007 to Dec 2015 (8 years 3 months)	75	9	0	0	1	74
6	Jan 2010 to Dec 2015 (6 years)	86	14	Crash severity data unavailable			
7	Jan 2012 to Dec 2012 (1 year)	97	97	0	7	4	86
8	Jan 2014 to May 2016 (3 years)	91	30	0	0	0	91
9	Mar 2000 to Nov 2015 (15 years 9 months)	26	2	0	1	8	17
10	Sept 2000 to June 2014 (13 years 11 months)	36	3	0	1	9	26
11	April 2000 to Sept 2015 (15 years 6 months)	136	9	1	2	34	99
12	Aug 2000 to Oct 2015 (15 years 3 months)	12	1	0	0	2	10
13	Mar 2000 to Dec 2015 (15 years 9 months)	223	15	0	3	35	185
	Total	1161	19 (average /tunnel)	1	26[2]	117[2]	925[2]

1 *Severity level unavailable.*
2 *Excludes data from Tunnel 6.*

Crash type

Analysis of crash types at eight of the 13 tunnels (Table 3.15) found that 62% of the crashes were rear-end type, followed by overtaking and lane change crashes (11%) and off-path crashes (8%).

Table 3.15: Overall crash types

Crash type	Overall crashes	Percentage
Rear-end crashes	501	62%
Cornering	41	5%
Overtaking and lane change	92	11%
Manoeuvring	9	1%
Pedestrian	4	0%
Side-swipe	43	5%
Off-path	67	8%
Head-on	19	2%
Other	35	4%
Total	811	100%

Prevailing pavement conditions

Analysis of pavement conditions showed that a majority of the crashes occurred on dry surfaces (80%) while the remaining 20% of the crashes occurred on wet or icy surfaces (Table 3.16).

Table 3.16: Overall crashes by pavement conditions

Pavement condition	Total crashes	Percentage of crashes
Dry	671	80.2%
Wet	165	19.7%
Ice	1	0.1%
Total crashes	837	100%

Vehicle types involved in crashes

Analysis of vehicle type using data from 10 of the 13 sites showed that cars were involved in 78% of the crashes, followed by trucks (15%) and buses (1%) as outlined in Table 3.17.

Table 3.17: Overall crashes by vehicle type

Vehicle type	Total crashes	Percentage of crashes
Car	755	78%
Truck	148	15%
Bus	11	1%
Other	51	5%
Total crashes	965	100%

4. Site Investigations

4.1 Tunnel Selection and Investigation

The tunnel safety investigation was undertaken both on-site and at the control centre, utilising a tunnel checklist of crash-contributing and safety risk factors as the main assessment tool.

Four tunnels were selected by the Project Advisory Group (PAG), who as previously indicated, were members of the Austroads Road Tunnels Task Force (RTTF) and key stakeholders – for review. Two of these tunnels were designed to older standards, while the other two were designed to new standards. All were located within major Australian cities. Contacts were made with individual tunnel operators via the Austroads Project Manager. In the interest of maintaining a collaborative approach between stakeholders, the tunnel locations are not provided in this report.

The tunnel inspection involved a 'drive through' examination at normal traffic speeds using a digital video camera to record physical road and tunnel elements during peak and off-peak periods. The video footage was reviewed as part of completing a tunnel safety checklist for each tunnel.

4.2 Development of Tunnel Safety Checklist

The development of the tunnel safety checklist was based on findings from earlier stages of the project (literature review and crash data analysis) as well as consideration of relevant tools developed overseas.

The literature review revealed some of the leading causes of crashes in and around tunnels. Full details are provided in the literature review report (Task 1.2 of the project), but some key findings are as follows:

- The most common casualty crash types were same-direction crashes, mainly rear-end and side-swipe crashes.
- Increasing crash frequency correlated with increasing traffic volumes.
- Longer tunnels have greater crash rates per unit of traffic flow.
- The highest crash rates were observed at the tunnel entrance and exit points rather than within the tunnels. This may in part be due to the adjustment of lighting at these sections, and/or manoeuvring/lane changes. This is also the only sections of tunnels that experience wet pavements.
- The visual load for the vehicle driver when entering and exiting the tunnel is substantially higher than on the tunnel approach, or within the tunnel.
- Driver behaviour changes when entering tunnels, with vehicles moving laterally away from the wall and concentration being focused forward. Larger headways are introduced and speeds decrease.
- Weather conditions, alignment, grade and crash location all contribute to the severity of the crash.

The review findings were consistent with the outcome of the crash analysis. The analyses of data from 14 tunnels (Task 1.4 of the project) showed that:

- the prevalent crash types were rear-end, overtaking, lane change and side-swipe collisions
- most of the crashes were multiple vehicle crashes
- most of the crashes were non-injury or minor injury crashes
- a large proportion of crashes occurred on dry pavement surfaces
- more crashes occurred during the morning and evening peak periods.

A review was undertaken of existing road safety checklists and related documents. The Austroads *Guide to Road Safety Part 6: Road Safety Audit* (Austroads 2009) does not include any information specific to safety in or around tunnels, but some of the more generic content is informative. The *Guide to Road Tunnels Parts 1 to 3* (Austroads 2010a, 2010b, 2015) were also reviewed, and relevant factors relating to safety issues identified.

Safety experts in Europe were also contacted, and information was provided on the ECOROADS project. This project involves the development of assessment tools that would apply for both roads and tunnels. This is based on the recognition of a need for uniform safety measures to be planned and implemented both on open roads and in tunnels. Assessment tools are planned but have not yet been developed. However, information was provided on European guidance. The most relevant of these is the Norwegian Directorate of Public Roads manual *Road Safety Audits and Inspections* (2014), which includes specific provisions for road tunnel audits.

Based on this review, the crash factor analysis and the literature review, a tunnel safety checklist was produced (Appendix A). This focused on design and traffic management features that would be most likely to lead to crash types identified in the earlier review. The checklist divided the tunnel investigation into four sections, including the approach to the tunnel, the tunnel entry/portal, a section within the tunnel and the exit portal.

The checklist was intended to help identify ‘potential’ and ‘likely’ contributors to crashes within these distinctive zones. However, issues such as over-height vehicles and post-crash provision (such as evacuation, fire and smoke control) were not included.

4.3 Interviews with Tunnel Operators

The purpose of an interview at a control centre was to discuss safety and, to a lesser extent, operational and maintenance issues in and around the tunnel from the perspective of the tunnel operators. Specific activities during the semi-structured interview were:

- discussion on key crash types identified in and around tunnels
- discussion of crash risk factors, including driver behaviour and possible causes of the crashes in and adjacent to the tunnel, including (where relevant) a review of video footage of vehicles travelling through the tunnel
- identification of possible solutions to these issues
- identification of sources of data that might provide a better understanding of crash risk in tunnels, including crash history, vehicle speeds and volumes, and traffic composition.

4.4 Results and Discussion

The site inspections and control centre interviews were undertaken on 7 and 8 December 2016 for the Victorian and NSW tunnels.

4.4.1 Tunnel Safety Checklist and Drive-through Inspection

The checklist for each tunnel was completed during a drive-through inspection. The focus was to identify any potential factors that contribute to a crash (e.g. deficiency in design or traffic management implementation). As previously indicated, factors relating to tunnel evacuation and fire procedures were not included in the assessment. Issues and solutions relating to over-height vehicles were also excluded.

The factors were classified into higher likelihood (termed ‘crash contributing factors’) and lower likelihood (termed ‘potential crash factors’) categories. Only ‘potential crash factors’ were identified during the site inspections (i.e. there were no ‘contributing factors’ identified), and these are presented in Table 4.1.

Table 4.1: Crash factors identified in the four tunnels under investigation

Site	Location			
	Tunnel approach	Tunnel entry/portal	Within tunnel	Tunnel exit
Tunnel 1	• Merge/diverge area leading to additional vehicle manoeuvring	• Lighting differential between entry and tunnel	• Adverse alignment • Speed management deficient • Shoulder width	• Roadside protection at exit, which present a roadside hazard • Lighting differential between tunnel and exit • Wall brightness
Tunnel 2	• Adverse alignment	• Lighting differential between entry and tunnel	• Adverse alignment • Shoulder width	• Lighting differential between tunnel and exit • Adverse alignment • Glare due to sun
Tunnel 3	• Merge/diverge area leading to additional vehicle manoeuvring • Speed management deficient	• Lighting differential between entry and tunnel • Lane merge leaving to additional manoeuvring	• Adverse alignment • Merge/diverge area • Shoulder width	• Lighting differential between tunnel and exit • Adverse sight distance • Adverse alignment • Glare due to sun
Tunnel 4	• Merge/diverge area leading to additional vehicle manoeuvring • Speed management deficient	• Lighting differential between entry and tunnel • Lane merge leading to additional manoeuvring	• Speed management • Merge/diverge area leading to additional vehicle manoeuvring • Lighting deficient	• Lighting differential between tunnel and exit • Adverse alignment

At the tunnel approach, the road design elements of merge and diverge area and alignment were identified as potential factors contributing to a crash. This resulted in a great amount of vehicle manoeuvring at some locations. Speed management, and more specifically variable speed limit signs, were utilised on the approach to tunnels, but it was noted that in some locations this could have been used further in advance, and be more adaptive to lower operating speeds during congested periods. This comment is applicable to the area outside as well as within the tunnels.

Lighting differentials at the entry and exit portals were identified as a potential issue consistently across the four tunnels. Even with the dynamic lighting adjustment systems employed at some tunnels, the contrast of lighting levels was identified as an issue that might lead to driver confusion or slowing/braking, presenting a possible risk of rear-end crashes. At the exit point, the glare due to the sun was a potential crash-contributing factor for east-west aligned tunnels.

Narrow shoulder width and lack of shoulder with tunnels were identified as possible safety risk issues in several locations. Vehicle strike marks on the tunnel walls were apparent, highlighting the risks associated with this design element. Merge and diverge areas were also considered a potential crash contributor in some tunnels, particularly with the additional manoeuvring that these introduce. Vertical and horizontal alignments were identified as a potential risk, especially when speeds were higher (i.e. from reduced sight distance), or when trucks were present (in the case of gradient, this can also lead to speed differentials with faster vehicles).

4.4.2 Control Centre Interviews

The interviews with tunnel operators took place at three control centres; two in one and one in another (covering two separate tunnels). The summary of the interview responses are included in (Appendix B). The following key points relating to tunnel safety and crash contributing factors were identified from the interviews.

Key crash types:

- rear-end and side-swipe related collisions were identified as the major crash types
- most crashes occurred outside of the tunnel (i.e. on approach or departure) with very few actually inside tunnels
  - most collisions were of low severity, but these were identified as being potentially significant, particularly in terms of traffic delay.

Crash risk factors:

- differentials in vehicle speeds were noted as a likely contributor to crashes, and may be caused by tunnel gradient (especially for trucks travelling up-hill, but also noted for light vehicles, including when approaching the ‘dip’ where vehicles switched from descent to ascent)
- lane changing was noted as another contributor to risk leading to both rear-end and side-swipe crashes
- lane changing could be the result of speed differentials, positioning for a more appropriate lane (i.e. if needing to exit within or following the tunnel, or if just entering the roadway), debris on the road or broken down vehicles
- better lane discipline was observed for the sites without any merge/diverge area located within or adjacent to the tunnel
- lighting differentials were considered important at the transition areas to and from the tunnel, with some adjustment required by road users
  - narrow shoulders were noted, although side-swipes into barrier or tunnel walls were not thought to have resulted in high injury outcomes.

A number of possible solutions were discussed, including:

- improved lane management and discipline which could be achieved through
  - enhanced lane signing well in advance of the tunnel, and on approach
  - measures to discourage lane changing in tunnels, including the possible use of audio-tactile line marking
  - potentially banning trucks from the right lane either on a full or part-time basis
  - consider closing on or off-ramps where these are under-utilised
- encouragement of more regular vehicle speeds which could be achieved through some of the measures identified above as well as
  - more effective variable speed limit systems that operated further in advance of the tunnel, and at lower speeds
  - measures to improve lighting levels at tunnel entry and exit so as to reduce driver disorientation
  - perceptual countermeasures to encourage more regular traffic speeds, including at the ‘dip’
  - minimising gradient in tunnels during construction
- removal of distractions within tunnels
- possible ‘gating’ of traffic at peak periods when approaching tunnels
  - greater shoulder width within tunnels (it was noted that banning trucks from the right lane might allow narrower right lanes, potentially allowing greater shoulder widths.

It was noted that while some of the ‘solutions’ may produce limited safety benefits, when used in combination, a number of them had the potential to deliver significant safety improvements.

5. Guide to Road Tunnels: Areas for Review

5.1 Part 1: Introduction to Road Tunnels

Within the context of a *Safe System*, the underpinning philosophy of Australia and New Zealand's road safety strategies, Part 1 provides an overview of the objectives of road tunnels and the planning and design stages. Part 1 also describes the implementation process, the general planning and regulatory requirements needed.

Other relevant key areas generally covered include structural and geometric design considerations, functional safety and operations, and environmental considerations.

Specific areas that may be reviewed in light of conclusion drawn from the findings of study:

- Section 1.5.2: Design Objectives:
  - The section may be broadened to highlight the safety benefits of providing emergency breakdown lanes (i.e. provision of wide shoulders), and reducing grades within tunnels while also endeavouring to provide no adverse horizontal road alignments on the approaches to and within tunnels.
  - The geometric (e.g. lane widths and radius of road curvatures) and operational (e.g. travel lane requirements) design of tunnels should be reviewed to better consider truck movements through tunnels.
  - While the section indicates that the functional objectives of tunnels should provide adequately safe tunnels and roadways, there is scope to elaborate on these points with examples and details of what is meant.
- Section 3.3.4: Human Factors
  - This section may be expanded upon to describe the issues associated with factors within tunnels that may contribute to unsafe driver behaviour within tunnels; and to describe the means by which they may be addressed (i.e. providing transitional lighting upon tunnel entry and providing an internal tunnel environment that lessens the prospect of some driver from suffering anxiety attacks).
- Section 3.5.2: Risk Assessment
  - Should be reviewed to include crash risks on the approaches to and within tunnels.
- Section 3.5.3: Risk Register
  - May be revised to include crash risks observed or experience d through crash records.
- Section 5: Traffic Considerations
  - A section may be included in relation to the management of traffic conflicts within tunnels, particularly as they relate to trucks (e.g. preventing or minimising lanes changes, variable speed limits and dynamic unsafe headway warning systems).

5.2 Part 2: Planning, Design and Commissioning

Part 2 outlines more road safety detail in relation to general and geometric design requirements, environmental considerations, lighting design, and monitoring and control.

Sections within Part 2 that may be reviewed to include key study findings include:

- Section 2.1: Road Tunnel Characteristics
  - While the section briefly provides distinguishing tunnel characteristics, it would benefit from expanding and providing information as it relates to unsafe human behaviour.
  - The section while correctly indicating that road tunnels are generally safer than the open road it should recognise the importance of road tunnels as part of the road network; the fact that cashes do occur in tunnels, with a substantial proportion of these crashes involving trucks, and the potential sever consequences that may result from these crashes occurring.
  - The section could be broadened to provide basic safety principles (e.g. transitional lighting, and the placement and wording of static and variable messaging), together with practices to be avoided.
- Section 2.2 Overall Design Considerations
  - There is absence of safety considerations. This section may be revise to summarise general safety considerations as they relate to human behaviour, ‘safe’ road design, ‘safe’ traffic management (which includes singing, line-marking, regulatory and advisory signing, and VMS).
- Section 2.3: Risk Analysis in the Planning and Design Stage
  - A new subsection under this heading may be included to consider crash risk, particularly associated with trucks.
- Section 4: Geometric Design
  - Section 4.2: Sight Distance in Tunnels
    - While sight distance requirements adopted in tunnels is the same as for the open road, this area that should be reviewed in light of driver behaviours that vary when travelling through tunnels.
  - Section: 4.3 Operating Speed
    - In light of the application of speed detection technologies/cameras within tunnels the operating speed value adopted should be reviewed, i.e. instead of the posted speed limit plus 10 km/h the operating speed within tunnels will be expected to be close to the posted speed limit.
    - Consideration should be given to include variable speed limits and truck speed limits.
  - Section 4.6: Cross-section
    - Areas that should be reviewed include lanes and shoulder widths to better take into consideration changed human factor behaviours within tunnels (e.g. driving away from tunnel walls) and larger truck movements through tunnels.
    - More information is required to provide better guidance with respect to ramp and conflict zones.
  - Section 4.8.3: Emergency Services Access and Parking
    - As crash severity outcomes are highly dependent on the time medical assistance is provided to those involved a crash, the section could be expanded to provide guidance as to how delays may be prevented or minimised for emergency vehicles.
- Section 6: Environmental Considerations
  - Section 6.2.3: Transition Zone
    - Some basic design principles may be included in this section which recognise that some driver may be predisposed to anxiety and/or insecurity when traveling through tunnels, and which provide measures which are able to be implemented that will reduce the incidence and severity of these conditions.
  - Section 6.2.4: Internal Tunnel Design
    - As above but for the internal design of tunnels.

- Section 10: Lighting Design
  - Considerable amount of information based on evidence-based research related to lighting and crash risk should be incorporated into this section. While much of the information related to the research is expected to be provided within the AS and AS/NZ standard referenced in Part 2, the section would benefit from providing in a descriptive manner principles associated with ‘safe’ tunnels lighting design associated with the research (refer to Section 2.2).
- Section 12.3: Traffic Monitoring and Control Systems
  - 12.3.1: General

    Section may be revised to highlight the consequences of crashes in tunnels and the importance of traffic monitoring and control as it relate to

    - providing immediate medical assistance to reduce crash severity
    - effectively manage resultant traffic to reduce delays to as to minimise the migration of crash risk across the surrounding road network as driver seek alternative travel routes in attempt to avoid traffic congestion.
  - 12.3.2: Tunnel Information Signs System
    - The section should be reviewed to consider the safety implications associated with the placement of signs (static and dynamic), and the type and extent of messaging provided, as they relate to a drivers’ capacity to effectively view, comprehend and process information provided.
  - 12.3.4: Variable Speed Limit (VSL) System

    The section may be expanded to:

    - indicate the purpose of operating VSL (i.e. to provide less variability in travel speed amongst drivers which in turn will reduce the incidence of overtaking and therefore the risk of side-swipe, rear-end and overtaking types of crashes)
    - provide guidance with respect to what changed speed limits should be applied and under what circumstances (e.g. as an incident management measure and during changes in traffic volumes).
  - 12.3.6: Variable Message Signing (VMS) Systems
    - Those comment provided in relation to 12.3.2 are have similar relevance to this section.
  - 12.3.10: Closed Circuit Television
    - Information should be provided indicating how information under Section 12.3.11: Automated Incident Detection, is provided to the operators of the CCTV and/or an automated emergency medical emergency response centre, and the manner in which it is considered.

      Where a collision has occurred, a description may be provided of the response required in despatching medical assistance and to the tasks needed to manage traffic flow so as to provide unhindered or minimal delay to the medical service traveling to the crash site.
  - 12.3.11: Automated Incident Detection
    - Additional information may be provided to complement the comments provided under Section 12.3.10, particularly in related to the triggering of automatic responses.
  - General Comment:
    - While it is expected that road safety audits are conducted at all stages of the construction of a tunnel (i.e. feasibility to preliminary design to detailed design to pre-opening stages), the future review of Part 2 should consider providing commentary related to this topic with appropriate referencing to the Austroads *Guide to Road Safety, Part 6: Road Safety Audits* (Austroads 2009).
    - Consideration should also be given to how the different audit stage ‘check-lists’ may be revised so as to capture safety issues that are specific to tunnels for each of the key stages. This information may be contained in Part 2 and be considered as part of the road safety audit process detailed in *Part 6: Road Safety Audits*, of the Austroads Guide to Road Safety.

5.3 Part 3: Operation and Maintenance

Part 3 focus on the provision of guidance in managing the operations and maintenance of tunnels, including those factors that need to be considered when setting suitable performance standards.

- Section 1.4: Definitions of Operations and Maintenance.
  - The section defines the activities relevant to both tunnel operations and tunnel maintenance. It may be appropriate within the maintenance definition to elaborate on the safety implications associated with the importance of maintaining
    - a control system that monitors incidents and their triggering of remedial actions
    - road surfaces
    - road signs and line markings.
- Section 2.4: Risk Analysis
  - Consideration should be given expanding the section to provide more detail in relation to crash risks associated and proven measures that will reduce crash severity and crash occurrence.

6. Use a Perceptual Countermeasure to Improve Road Tunnels Safety

A workshop was held on the 8th March 2017 to discuss research priorities. Information on previous stages of work, including the literature review, data analysis and site investigations was presented. The workshop focused on issues that were associated with road crashes adjacent to and within tunnels, and solutions that had been identified. There was broad recognition from the group regarding the issues identified (i.e. many of these were familiar).

A further key focus of the work was to also consider and identify in-tunnel perception countermeasure treatment (PCT), which had the purpose of influencing lower driver speed behaviour, reduce variability in driver speeds, improve lane discipline and more uniform vehicle headways (both in time and distance).

The personation material is provided in Appendix C.

Based on the workshop discussions, the following summary table (Table 6.1) was produced.

Table 6.1: Summary from workshop

Issue	Treatment	Comment
Uniform speed	Vertical/horizontal elements on tunnel wall to facilitate more uniform vehicle speed	Some evidence that this has a positive impact on speed reduction/distribution
	Provide measures at sag to indicate need for acceleration	To address speed reduction at sag (leading to speed differential) which has been identified in some tunnels
	Reduce speed differential on approach to tunnel through perceptual means	Designed to address speed and lane change behaviour
	Reduced lighting contrast between tunnel and entry/exit portal	
	ITS – speed reduction at peak times – more dynamic control and provided further in advance	
Rear-end and gaps between vehicles	Measures to perceptually increase gaps between vehicles (e.g. chevrons)	Designed to increase spacing between vehicles
Lane discipline and lane change behaviour	Signing strategy to indicate appropriate lane further in advance of portal	
	Line marking/regulatory signs to prohibit lane change	
	Audio tactile line marking to reduce lane changing behaviour	

The Project Advisory Group (PAG) was asked to comment on the solutions identified and indicate a priority for each of the solutions. Responses to this survey were limited, and the results were conflicting. All of the solutions were of interest to at least one tunnel operator. Out of these solutions, all are amenable to simulator study.

In addition to the solutions identified above, one respondent requested information on technologies to disable mobile phone use in tunnels.

6.1 Driver Simulator Study Design

This section describes the design of a research study to be undertaken in the ARRB/C-MUARC advanced driving simulator located in Perth. The study will enable evaluation of the effectiveness of two perceptual countermeasures designed to affect speed and time headway between vehicles in tunnels. As yet these perceptual countermeasures have not been specified but will be selected based on future developed options.

This is a high-level experimental protocol that can be further refined in consultation with the Austroads Road Tunnels Task Force.

Table 6.2: Study Design

Study element	Comment
Participants	A total of 75 participants, randomly assigned to one of three treatment groups (see below). Will be broadly representative of driving population.
Design	A 3 (baseline, speed treatment, headway treatment) x 2 (congested, uncongested) mixed factorial experimental design will be utilised. Twenty-five participants per treatment group (i.e. baseline group, speed treatment group, headway treatment group). Relevant demographic variables will collected (e.g. age; driving experience) to allow a number of post hoc statistical analyses to be undertaken (e.g. to compare the impact of the perceptual countermeasure treatments between inexperienced and experienced drivers).
Simulator drive: Baseline	This will be the control group for the study. Twenty-five participants will drive through a simulated tunnel environment that contains no speed or headway perceptual countermeasure treatments. Will contain both congested and uncongested segments of roadway. The following critical measures of driving performance will be recorded and compared between this drive and the other two drives (see below): • mean speed; standard deviation (SD) speed • minimum time headway; mean time headway; SD time headway • lane discipline and overtaking (lane utilisation, amount of lane changing, lane position). Other behaviours of interest will be recorded.
Simulator drive: Speed/headway treatment	This drive will be identical to the Baseline Drive, except that it will contain a perceptual countermeasure (to be designed/agreed) designed to reduce speed, speed variability and headway. Twenty-five participants will drive through the same simulated tunnel environment which will contain the same congested and uncongested segments of roadway as the Baseline Drive. The same critical measures of driving performance will be recorded and compared between this drive and the other two treatment drives: mean speed; standard deviation (SD) speed; minimum time headway; mean time headway; SD time headway. Overtaking and other behaviours of interest will be recorded.
Simulator drive: Lane discipline treatment	This drive will be identical to the Baseline Drive, except that it will contain a perceptual countermeasure (to be designed/agreed) designed to reduce time headway and time headway variability. Twenty-five participants will drive through the same simulated tunnel environment which will contain the same congested and uncongested segments of roadway as the other two drives. The same critical measures of driving performance will be recorded and compared between this drive and the other two drives: mean speed; standard deviation (SD) speed; minimum time headway; mean time headway; SD time headway and overtaking/lane position behaviours. Other behaviours of interest will be recorded.

Study element	Comment
Procedure	The simulated tunnel will be designed, programmed and piloted. Participants will be invited to take part in the study via a number of methods (e.g. advertising on social media, Gumtree, word-of-mouth), and screened for motion sickness, epilepsy etc. Prior to undertaking a simulator experiment, participants will be briefed on the study, complete a demographic questionnaire, and complete a consent form. Participants will then complete a familiarisation drive, to get used to the look and feel of the simulator. Participants then complete the relevant drive to which they have been assigned (Baseline, Speed Treatment or Headway Treatment). Participants will be de-briefed, thanked and compensated for the participation with money or a gift voucher.
Data analysis	The data will be parsed, cleaned and coded. The following key analyses will be undertaken: • analysis of variance comparing across treatment conditions the mean values for the critical measures noted above • analysis of variance comparing, across traffic density conditions (congested versus uncongested), the mean values for the critical measures noted above • analyses of any interaction effects that derive from the analyses above • a qualitative analysis of overtaking and other behaviours of interest.

7. Key Findings

Outlined below are the key findings that have been drawn from the literature review, crash analysis and site investigations.

7.1 Crashes

- While road tunnels have lower crash rates than those on open roads, the severity of crashes in tunnels is greater.
- Crashes in tunnels are mostly rear-end or side-swipe types of crashes, followed-up by lane changing types of crashes.
- Crashes mostly occurred within about 100 m to the approach of a tunnel, within the tunnel 'entrance' zone of about 100 m, then followed by a subsequent 'transition' zone of up to 300 m.
- From a sample of 13 tunnels in Australia and New Zealand where available crash data was made available the following findings were made
  - On average each tunnel recorded 19 crashes per year.
  - The tunnel with the poorest crash history recorded 97 crashes in the one year which is almost two crashes per week, while the tunnel with the best history recorded less than one crash per year.
  - About 14% of crashes resulted in at least one person being injured, while about 2.3% of crashes resulted in at least one person being seriously injured or killed.
  - 75% of crashes occurred during weekdays, a reflection attributable to increased traffic flows through tunnels during the 'working' weekdays.
  - 62% of crashes were rear-end type, followed by overtaking and lane change (side swipe), types of crashes (11%) and off-path crashes (8%).
  - Cars were involved in 78% of the crashes, followed by trucks in 15% and buses in 1%.
  - The majority of the crashes occurred on dry surfaces (80%).
  - The types of crashes occurring in tunnels in Australia and New Zealand are similar to those experienced in tunnels in other countries. It is therefore expected that crash occurrence and severity factors are also similar.

7.1.1 Crash contributing factors

General

- It was noted that the proportion of 'large vehicles' were a major contributing factor to the increased severity of crashes in tunnels. Other factors reported as contributing to crash severity in an equal manner included weather conditions, horizontal alignment and grade.
- Road and operational factors identified as crash contributing factors included tunnel length and cross-section, lane widths, 'quality' of lighting, composition of traffic (i.e. proportion of trucks), traffic volume and vehicle speeds.
- At the tunnel approach, the road design elements of merge and diverge area and alignment were identified as potential factors contributing to a crash, which resulted in a great amount of vehicle manoeuvring at some locations.

- In-tunnel merge and diverge areas were also considered a potential crash contributor in some tunnels, particularly with the additional manoeuvring that these introduce.
- Within tunnels narrow shoulder width and lack of shoulder were identified as increasing crash risk.
- The vertical and horizontal alignments were identified as a potential risk, especially when speeds were higher or when trucks were present (in the case of gradient, this can also lead to speed differentials with faster vehicles).

Lighting

- While tunnels are generally lit at all times drivers may experience sudden lighting changes at tunnels portals which may increase crash risk.
- It was determined, using a driver simulator that wall colour and illumination have a large impact on the safety of the motorist as a lighter colour wall and greater illumination decreases the risk of a crash inside a tunnel. Brighter walls are more important for safety and comfort than a high illumination level, however only if the illumination was sufficiently bright.

Driver behaviour

- The driving task is complex and requires constant perception and the processing of information.
- Tunnels are structures that are enclosed that create a confined space which can affect driver behaviour when entered and driven along.
- A substantial proportion of drivers suffer from discomfort or anxiety when driving through tunnels.
- Providing stripes along the tunnel wall and decreasing the width of these gaps may cause drivers to unintentionally slow down which increases safety within the tunnel.
- Decision making in tunnels by drivers occurs in a short timeframe from what they are accustomed to on open roads. Furthermore, drivers are required to ‘perceive’, analyse and understand a different driving environment, which is unlike driving on open roads.
- The visual load for the vehicle driver when entering and exiting the tunnel is substantially higher than either side of these sections. A number of studies have been developed to determine accurate crash prediction measures within a tunnel.
- Some drivers may have a tendency to shy away (i.e. drive away), from tunnel walls, particularly when entering the tunnel which in turn create crash risk with motorists driving in adjacent lanes.

Measures to improve safety

- Increasing width of tunnel/lanes, decreasing gradient, doubling radius and introducing dual tubes produce a decrease in crashes when implemented correctly.
- It was also indicated that a general rule applied in a number of countries was that gradual levels of lighting change be provided within the first section of the tunnel (i.e. transitional zone), using as an example dimmers. It was further indicated that motorists should not be given information within the transition zone as driver’s experience a higher level of workload in this area which effects information processing.
- Near entry portals more lighting levels should be provided, while within the tunnel they may be generally lowered to two lighting levels. These levels may be chosen automatically in response to external sunlight, during day and night-time periods and on occasions on the basis of traffic conditions. Lighting levels also may be manually operated to increase in response to a crash or incident. The purpose of doing so is to increase the attention of drivers approaching the crash or incident, while also increasing the visibility of emergency exits and other safety elements near the occurrence.
- It was recommended in some literature that having stimulating lighting features would provide positive safety benefits within long tunnel sections.

- Intelligent transport systems (ITS) increases driver awareness of upcoming incidents prior to reaching them. It allows drivers to prepare for unexpected circumstances and provides guidance on how to deal with these situations, increasing safety within the tunnel environment.
- A driving simulator study that assesses driver performance and workload when subjected to lengths on tunnels found that signage indicating the remaining tunnel length, as well as the use of intelligent transport systems (ITS), increased safety within the tunnel.
- Provide emergency lanes/widen narrow shoulders to reduce the crash risk associated with vehicles that break down in a tunnel. This will also assist to overcome the crash risk resulting from drivers who shy away (i.e. drive away) from tunnel walls.
- As sight distances in tunnels are generally reduced special attention should be taken with the placement of and the characteristics of signs and signals.
- Providing the safety management systems in tunnels (e.g. signing, directional pavement markings, Variable Message Signing (VMS) and lane management control signals), reduce crash risk.
- The use of perceptual countermeasure treatments (PCT), which involved vertical lines on tunnels walls, in a tunnel simulation, in which the distance between lines and the thickness increased, decreased or remained constant, found that with decreasing gaps vehicles decreased their speed.
- Improve lane management and discipline which could be achieved through
  - enhanced lane signing well in advance of the tunnel, and on approach
  - measures to discourage lane changing in tunnels, including the possible use of audio-tactile line marking
  - potentially banning trucks from the right lane either on a full or part-time basis
  - consider closing on or off-ramps where these are under-utilised
  - minimising gradient in tunnels during construction.
- Removal of distractions within tunnels.

8. Conclusions and Recommendations

Analysis of available crash data found that the types of crashes occurring in tunnels are generally rear-end, side-swipe and lane changing types of collisions. While generally these types of crashes are of relatively low severity, when they do occur in a tunnel the consequences are potentially very severe, particularly when they involve multiple vehicles, trucks or when a fire results from a collision.

Major factors considered to contribute to the occurrence and severity of crashes were that:

- Driver behaviour is a major factor in occurrence of crashes on the approaches to and within tunnels. Such behaviours included driver lane discipline and lane changing (refer to Section 2.3 and Section 4.4.2 for further information).
- Most crashes involve vehicles travelling in the same direction (i.e. rear-end, side-swipe and lane changing); this is as a result of variations in driver speeds, unsafe vehicle headways (i.e. vehicles travelling too close to each other or inadequate travel time gaps between vehicles), poor lane discipline, unsafe passing and high speeds for the conditions.
- Changes in driving conditions pose the greatest crash risks as drivers approach a tunnel from about 100 m, travel through the tunnel portal along a distance of approximately 100 m and then drive through a transitional zone of up to a further 300 m.
- Variations in light levels when entering tunnels and the ‘quality’ of lighting within tunnels are considered as crash risk factors.
- Trucks traveling through tunnels increase crash risk, while also increasing the risk of high severity crash outcomes.
- The absence of a shoulder (or emergency lanes), or narrow shoulders and narrow lanes increase crash risk.
- Merge and diverge areas in tunnels increase crash risk as there is an increase in vehicle manoeuvring.

To address the factors that increase crash risk and cash severity the following conclusions and recommendations are provided for consideration:

- As information overload is a safety performance factor for some drivers approaching tunnel portals, signage and the placement of signage should be reviewed so as to simplify the driving task, thereby reducing crash risk for affected drivers.
- Review and regulate lighting levels upon entry to tunnels, and through the transition zone, so as to minimise variations in lighting that may occur over a short distances that are experienced by drivers and motorcycle riders.
- Particularly for long tunnels promote the usage for Variable Message Signing (VMS) as a means of informing and advising users of incidents and driving requirements.
- Review of truck access to tunnels, with the following potential measures implemented; discouraging truck access, restriction of truck access to select lanes, curfews for truck access or banning of truck access. The application of any of these options will be dependent on the tunnel location, its function as part of the road network and the viability of alternative route travel options and their crash risks.
- When trucks are permitted to travel through tunnels restrict the lanes they are permitted to travel in.
- To reduce unsafe speeding behaviour speed cameras should be considered for installation in all road tunnels.

- While overtaking in some circumstances in tunnels may be required, this manoeuvre should be discouraged using VMS or static signing, while similarly advising tunnel users to maintain a safe distance between themselves and the vehicle ahead. In the latter case the message may be symbolic showing consecutive vehicles having overtly a clear space between each other. In both cases more detailed examination of the signs and messages will be required to ensure the messaging and signage provided achieves the desired effect.
- If possible provide shoulders or breakdown bays. If these lanes are not able to be accommodated, ensure that safety management systems are provided to reduce crash risks associated with their absence.
- As a means of affecting safe driver speed behaviour, improving lane discipline and safe driver headways, investigate the application of low cost perceptual countermeasures treatments (PCT). In order to determine the potential benefits, while also detecting possible adverse unintended consequences of such treatments, it is recommended that the PCT be trialled and evaluated within a driver simulator, the study design of which is provided in Section 6 of this report.
- Review the Austroads Guide to Road Tunnels (GRT), to ensure that they reflect best practice in the construction of new tunnels and in the retrofitting of older tunnels (refer to Section 5 for areas of review).

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Appendix A Tunnel Safety Check-List

TUNNEL CRASH CONTRIBUTING FACTORS AND SAFETY CHECK

Tunnel / Road name .... Direction ....

Date .... Time .... Weather ....

Number of lanes .... Speed limit(s) ....

	Crash Contributing Factors (Y/N)	Potential Crash Factors (Y/N)
1.0 TUNNEL APPROACH		
1.1 Sight distance		
Comment..		
1.2 Alignment		
Comment..		
1.3 Merge / diverge areas (e.g. on-ramp / off-ramp)		
Comment..		
1.4 Speed management (e.g. variable or fixed speed limit)		
Comment..		
1.5 Advanced traffic management (e.g. lane management)		
a) not provided...		
b) insufficient..		
Comment..		
1.6 Advanced directional signing		
a) None..		
b) Existing signage ambiguous / unclear.................		
Comment..		
1.7 Linemarking		
a) not provided...		
b) insufficient..		
a) poorly maintained..		
Comment..		
1.8 Other delineation (e.g. RRPM's)		
b) not provided...		
c) insufficient..		
a) poorly maintained..		
Comment..		
1.9 Lighting		
a) not provided...		
b) insufficient..		
Comment..		

1

	Crash Contributing Factors (Y/N)	Potential Crash Factors (Y/N)
2.0 TUNNEL ENTRY / PORTAL		
2.1 Protection at entry (e.g. guardrail / attenuator)	☐	☐
Comment...		
2.2 Lighting differential	☐	☐
Comment...		
2.3 Wall brightness...	☐	☐
Comment...		
2.4 Sight distance	☐	☐
Comment...		
2.5 Lane merge		
a) just prior to portal...	☐	☐
b) inside tunnel..	☐	☐
Comment...		
2.6 Glare due to sun	☐	☐
Comment...		
3.0 WITHIN TUNNEL		
3.1 Sight distance...	☐	☐
Comment...		
3.2 Alignment		
a) vertical (i.e. grade)...	☐	☐
b) horizontal (i.e. curvature)...................................	☐	☐
Comment...		
3.3 Side protection		
a) tunnel wall left..	☐	☐
b) median..	☐	☐
c) at cross passages..	☐	☐
Comment...		
3.4 Advance directional signing		
a) None...	☐	☐
b) Existing signage ambiguous / unclear..................	☐	☐
Comment...		
3.5 Other signing (e.g. warning, regulatory)		
a) None...	☐	☐
b) Existing signage ambiguous / unclear..................	☐	☐
Comment...		

2

	Crash Contributing Factors (Y/N)	Potential Crash Factors (Y/N)
3.6 Linemarking		
a) not provided…………………………………………	☐	☐
b) insufficient…………………………………………	☐	☐
a) poorly maintained……………………………………	☐	☐
Comment………………………………………………………………………………………………		
3.7 Other delineation (e.g. RRPM's)		
a) poorly maintained……………………………………	☐	☐
b) not provided…………………………………………	☐	☐
c) insufficient…………………………………………	☐	☐
Comment………………………………………………………………………………………………		
3.8 Advanced traffic management (e.g. lane management)		
a) not provided…………………………………………	☐	☐
b) insufficient…………………………………………	☐	☐
a) poorly maintained……………………………………	☐	☐
Comment………………………………………………………………………………………………		
3.9 Speed management (e.g. speed limit; speed cameras)		
a) not provided…………………………………………	☐	☐
b) insufficient…………………………………………	☐	☐
a) poorly maintained……………………………………	☐	☐
Comment………………………………………………………………………………………………		
3.10 Merge / diverge areas (e.g. on-ramp / off-ramp)		
a) inadequate protection (e.g. attenuators)……………	☐	☐
b) poor sight distance……………………………………	☐	☐
c) poorly signed…………………………………………	☐	☐
d) poorly delineated……………………………………	☐	☐
Comment………………………………………………………………………………………………		
………………………………………………………………………………………………………		
3.11 Drainage	☐	☐
Comment………………………………………………………………………………………………		
3.12 Lane and shoulder width…………………………	☐	☐
Comment………………………………………………………………………………………………		
3.13 Lighting		
a) not provided…………………………………………	☐	☐
b) insufficient…………………………………………	☐	☐
Comment………………………………………………………………………………………………		

3

	Crash Contributing Factors (Y/N)	Potential Crash Factors (Y/N)
4.0 TUNNEL EXIT		
4.1 Roadside protection at exit (e.g. Guardrail / attenuator)	☐	☐
Comment………………………………………………………………………………		
4.2 Lighting		
a) not provided………………………………………………	☐	☐
b) insufficient………………………………………………	☐	☐
c) differential between tunnel and exit……………………	☐	☐
Comment………………………………………………………………………………		
4.3 Wall brightness	☐	☐
Comment………………………………………………………………………………		
4.4 Sight distance	☐	☐
Comment………………………………………………………………………………		
4.5 Alignment		
a) vertical (i.e. grade)…………………………………………	☐	☐
b) horizontal (i.e. curvature)……………………………………	☐	☐
Comment………………………………………………………………………………		
4.6 Glare due to sun	☐	☐
Comment………………………………………………………………………………		
………………………………………………………………………………………		

4

Appendix B Control Centre Interview Responses

B.1 Operator One for Case Study 1

B.1.1 Key Crash Types

Rear-end and sideswipe type crashes were confirmed as the most predominant crash types. A larger number of crashes occurred on the approach and beyond the tunnel exit. Very few of the collisions resulted in injury, and this might be related to the very low speeds during much of the day.

B.1.2 Crash Risk Factors

A large amount of weaving occurs prior to the tunnel due to the on-ramp preceding the tunnel, with motorists attempting to position themselves in appropriate lanes. There was also an off-ramp following the tunnel, and this also resulted in lane change manoeuvres.

It was noted that the tunnel gradient resulted in speed differentials between light vehicles and trucks, particularly for the uphill gradient. In addition, it has been observed that vehicles slowed approaching the dip in the middle of the tunnel (where it transitions from downhill to uphill). This also led to a speed differential.

It was thought that some drivers applied vehicle brakes, especially when travelling downhill to ensure they were in compliance with the speed cameras. This could also potentially lead to speed differentials.

It was thought that vehicle strikes against barriers were the result of motorists looking over their shoulder while changing lanes. It was noted that these barrier strikes did not usually result in loss of control.

B.1.3 Possible Solutions

Increasing lane discipline was thought to be problematic, as vehicles are needing to move lanes to position themselves for off-ramps following the tunnel. It may be possible to close an under-utilised off-ramp following the tunnel either on a full time or part time (e.g. during the peak) basis, and this would result in less lane changing behaviour. Trucks could potentially be banned from the right lane. If this was done, the lane could be narrowed, providing greater width for the other two lanes and/or the shoulder.

Better lane positioning could be achieved through improved advanced directional signing, and this is planned for this tunnel.

Illumination could be increased at the tunnel entrance and exits, but it is not known whether this would have much effect. It was noted that lighting is already graduated between the tunnel entrance and the rest of the tunnel. Similarly, the tunnel wall could be made a lighter colour to help increase illumination and reduce contrast with the tunnel exit.

It may be possible to use some sort of perceptual countermeasure within the tunnel to mitigate the slowing of vehicles at the dip in the tunnel. This might include some perceptual means to given the impression that the tunnel was wider at this point compared with others.

‘Gating’ was one solution that could be explored (i.e. freeway metering where only a set number of vehicles were able to enter the tunnel at peak times). It is understood that this has been undertaken in the USA.

It was considered that even though some measures might have only a small benefit in safety terms, if several treatments were used together, this might result in benefits that were more substantial.

B.2 Operator Two for Case Study 2

B.2.1 Key Crash Types

Rear-end and side-swipe type crashes were confirmed as the most predominant crash types. A breakdown of crashes was provided, and it was apparent that a large majority of crashes occurred not within the tunnel, but rather on approach and departure.

B.2.2 Crash Risk Factors

Lane changing and speed differential were discussed as factors in crash occurrence. Lane changing manoeuvres were often linked to slower vehicles. The differential in speed was related to slower speeds by trucks, especially on the uphill gradient. It was also considered that some drivers who were inexperienced at driving in tunnels slowed more than other drivers.

Lane discipline was considered to be poor in some cases, including drivers ignoring lane closure signs.

Debris on the roadway, including from unsecured loads, were identified as resulting in lane changing, breaking and other risk-related behaviours. Vehicle breakdowns (including from vehicles running out of fuel) were also identified as a factor.

Contrast in light between the outside of the tunnel and within the tunnel was recognised as an issue. This tunnel had dynamic systems to alter the level of lighting to better match the lighting levels from outside the tunnel. Glare when leaving the tunnel in one direction was acknowledge as an issue.

B.2.3 Possible Solutions

Solutions discussed included the following:

- Provision of clearer guidance on appropriate lane position in advance of the tunnel.
- Greater ability to manage speeds (including reduced speed differential) through VSL, including systems placed further in advance of the tunnel.
- Prohibition of heavy and slow moving vehicles from the right lane, or even at certain times of the day.
- Initiatives to ensure vehicles did not need to change lanes including education of drivers, additional warning, encouragement (including audio-tactile lane separators), and reducing the need for lane changes (e.g. reducing speed differential).
- Tunnels should be designed to minimise gradient due to the speed differential issue.
- Unnecessary signs within tunnels should be removed so as to remove distraction.

B.3 Operator Three for Case Studies 3 and 4

B.3.1 Key Crash Types

Rear-end and side-swipe type crashes were confirmed as the most common crash types in and adjacent to the tunnels. The majority of crashes occurred outside the tunnels.

B.3.2 Crash Risk Factors

Speed differentials and lane changing were identified as major crash contributing factors. Lighting at the tunnel entry and exit zones was considered a crash risk factor. An adaptive lighting system was employed to adjust the light level according to ambient natural light e.g. tunnel lighting is dimmed at night.

The video-based automatic incident detection system (including traffic loops, VMS, VSLS and CCTV) has been used to manage the operational and safety issues that may arise in the tunnels. The automatic system also detects any activities within the breakdown bays that are provided at regular intervals along the tunnels.

With its own dedicated lane and transition space, the merge or diverge area does not cause any operational concern. For one tunnel, flexible bollards have been used for lane management.

The variable speed limits can be adjusted from 80 to 60, 40 and 20 km/h depending on the level of incidents and safety risks. The speed change is applied to the entire tunnel section for speed consistency on each lane.

Additionally, the following points were discussed:

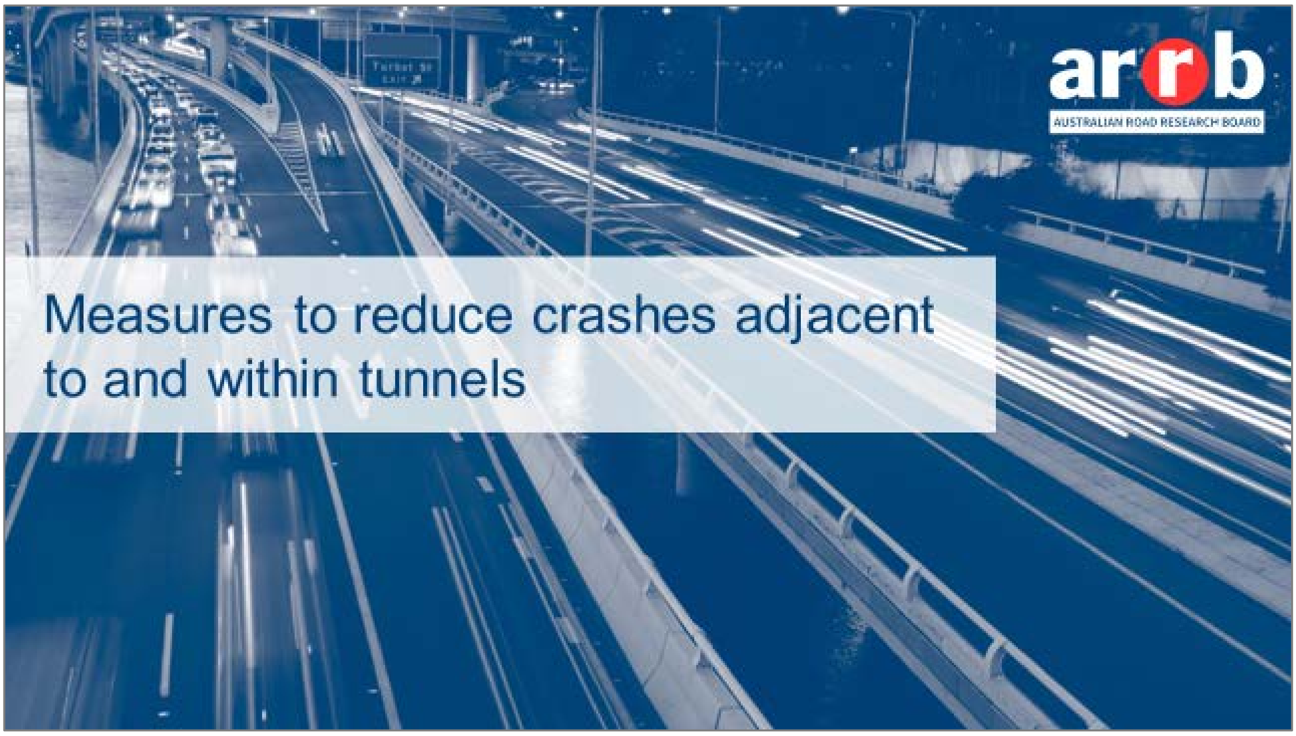
- No drainage or flooding issues in the tunnels.
- Over height detection system, using infrared beams.
- Tunnel walls are always in white or light cream colour to help with light reflection.
- The operation and maintenance responsibility of road transport infrastructure before and after the tunnels are of the government agency.

B.3.3 Possible Solutions

It was suggested that a tunnel should be designed with a minimum of three lanes not only for future proofing, but also for assisting in the tunnel traffic and safety management.

Without adequate infrastructure provisions, no pedestrian and cyclist should be allowed into the road tunnels.

Appendix C Workshop Presentation



Overview

- Workshop objective: Identify safety solutions for tunnels, and perceptual countermeasure options for trial
- Summary of previous stages
  - literature review
  - data analysis
  - site inspections
- Discussion on possible solutions to address safety in tunnels
- Discussion on perceptual countermeasure option for trial (2017/18)
  - In simulator
  - In tunnel(s)
- Not 'post crash' issues (e.g. emergency evacuation etc.).

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Context

Issue	Crashes within and adjacent to tunnels lead to trauma and delays
	Need to create a Safe System for road users
Objective	Identify factors contributing to crash risk and severity
	Identify solutions
	Review tunnel guides
Project tasks	Literature review
	Crash data analysis
	Site inspections
	Workshop

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Findings to date – literature review

- Lower number of crashes in tunnels than open roadways
- Collision in tunnels can have very severe consequences
- Rear-end and side swipe crashes most prevalent crash types
- Highest crash rate adjacent to entrance, exits
- Factors contributing to crash risk and severity include:
  - Number of lanes
  - Length of tunnel
  - Traffic volume – overall and per lane
  - Lighting

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Findings to date – literature review

- Number of lanes
  - Crash risk increases with number of lanes
  - Increased likelihood of side swipe crashes, lane changes and overtaking
- Length of tunnel
  - Higher crash risk in longer tunnels than shorter ones
  - Increased probability of lane changes
  - Higher risk of rear-end crashes
- Traffic volume
  - Higher volumes per lane increase crash risk
  - Increased volumes of heavy vehicles also increase crash risk

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Findings to date – literature review

- Lighting
  - Sudden transition in lighting on tunnel entry and exit – high visual demand
  - Glare from sun / reflection
  - Tunnel walls – bright walls reflect light, reducing crash risk
- Other factors
  - Alignment
  - Grade

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Findings to date – literature review

- Solutions identified include:
  - ITS (lane and speed management)
  - Lighting
  - increasing width of tunnel/lanes
  - decreasing gradient / improving curve radius

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Findings to date – crash data analysis

- Assessed safety performance at 14 case study locations, with over 1000 crashes
- Assessed key elements including
  - time of day
  - site characteristics (e.g. speed limit)
  - crash characteristics (e.g. DCA category, object struck)
  - environmental conditions (e.g. light conditions, weather conditions)
  - road user characteristics (e.g. vehicle type, number of vehicles involved).

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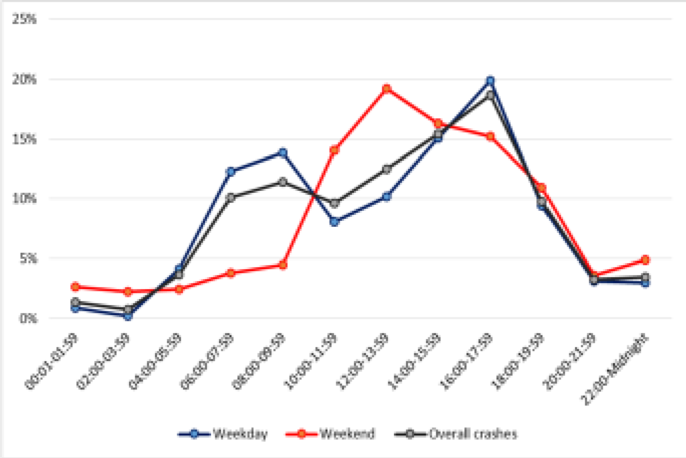
Findings to date – crash data analysis

- Most prevalent crash types
  - Rear-end crashes (62%)
  - Overtaking and lane change crashes (11%)
  - Side swipe crashes (5%)
- Most crashes involved multiple vehicles
- Mostly minor and non-injury crashes
- Higher proportion of crashes during weekday and weekend peaks



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Findings to date – site inspections

- Development of safety checklist
  - Based on work in Europe (Contact with safety experts, ECOROADS, Norwegian road safety audit guideline)
  - Austroads Guide to Road Safety Audit (Part 6)
  - Austroads Guide to Tunnels (Parts 1 – 3)
  - Findings from literature review and data analysis
- Visit to tunnels / video assessment
  - Two old standard, two new standard
  - Reviewed tunnel approach, tunnel entrance, within tunnel, tunnel exit
- Interviews with operators

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Findings to date – site inspections

- Tunnel approach
  - Merge and diverge areas increase risk
  - Adverse alignment
  - Speed management / variable speed limits – further in advance; more adaptive
- Entry and exit
  - Lighting differential including sun glare at exit
- Within tunnel
  - Narrow lanes and lack of shoulder
  - Merge and diverge areas contributed to manoeuvring
  - Lane changing behaviour
  - Speed differentials

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Findings to date – site inspections (interviews)

- Key crash types
  - Key crash types confirmed (rear end and manoeuvring)
  - Most crashes outside tunnel
  - Most crashes low severity, but significant delay
- Risk factors
  - Speed differentials (tunnel gradient / heavy vehicles uphill; approaching 'sag')
  - Lane changing due to speed differentials, positioning for lane, debris
  - Lighting differentials considered important
  - Narrow shoulder risk noted

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Synthesis of findings

- Crash characteristics
  - Rear-end, overtaking and lane change and side swipe crashes
  - Most crashes occur on entry, exit and adjacent to tunnels
  - Mostly non-injury crashes, but these are significant in terms of delay and potentially very high severity

- Crash risk factors
  - Lane changes, overtaking and weaving (differentials in speed)
  - Gradient – affecting vehicle speeds and speed differentials
  - Lighting conditions, especially on entry and exist to tunnel
  - Traffic volumes and mix
  - Narrow shoulder

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Synthesis of findings: Safety solutions

- Improved lane management and discipline
  - Enhanced lane signing in advance
  - Measures to discourage lane changing
    - Lane markings, signage, audio-tactile
  - Banning heavy vehicles in right lane on full-time or part-time basis
  - Consider closing on/off ramps where under-utilised
- Encourage more regular speed
  - More effective variable speed systems; operating further in advance
  - Adaptive lighting systems at entry and exit
  - Perceptual countermeasures to encourage more regular speed, including at 'sag' locations
- Removal of distraction in tunnel and on approach

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