TRAFFIC SAFETY IN URBAN
UNDERGROUND ROAD SYSTEMS

YEUNG JIAN SHENG

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

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TRAFFIC SAFETY IN URBAN
UNDERGROUND ROAD SYSTEMS

YEUNG JIAN SHENG

School of Civil and Environmental Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirements for the degree of
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In addition, I would like to extend my thanks to my family, friends, and colleagues. They have provided me with many insightful discussions, imparted me many useful knowledge, and helped me out in many ways.
PREFACE

This thesis was written in British English.

All the work presented henceforth was conducted in the Transportation and Geospatial Laboratory in the Nanyang Technological University (NTU), Singapore. The project (“Driver behavioural adaptation to underground road conditions”) that involved data collection from participants from actual on-road drive sessions was approved by NTU’s Institutional Review Board (Reference: IRB12/06/20), which serves as the university’s ethics committee.

A version of Chapter 4 has been published in a journal [Yeung, J.S., Wong, Y.D., 2013, “Road traffic accidents in Singapore expressway tunnels”, *Tunnelling and Underground Space Technology* 38, 534-541]. I was the lead investigator, responsible for all major areas of concept formation, data extraction, analysis, and manuscript composition. Wong Y.D. was the supervisory author on this project and was involved throughout in the concept formation and manuscript edits. The data were kindly provided by both the Singapore Traffic Police Department and the Singapore Land Transport Authority. Under the Journal Publishing Agreement (Retained Rights) with the publisher (Elsevier Ltd), I retain the rights (without the need to obtain further information) to use the article for personal use (including inclusion in this thesis).

A version of Chapter 5 has been published in a journal [Yeung, J.S., Wong, Y.D., 2014, “The effect of road tunnel environment on car-following behaviour”, *Accident Analysis and Prevention* 70, 100-109]. I was the lead investigator, responsible for all major areas of concept formation, data collection, analysis, and manuscript composition. Wong Y.D. was the supervisory author on this project and was involved throughout in the concept formation and manuscript edits. Partial data were kindly provided by the Singapore Land Transport Authority. Under the Journal Publishing Agreement (Retained Rights) with the publisher (Elsevier Ltd), I retain the rights (without the need to obtain further information) to use the article for personal use (including inclusion in this thesis).
An early version of Chapter 6 was presented in a conference [Yeung, J.S., Wong, Y.D., “Drivers’ visual attention in urban road tunnels”, Proceedings of the 14th World Conference of Associated research Centres for the Urban Underground Space, 119-124]. I was the lead investigator, responsible for all major areas of concept formation, data collection, analysis, and manuscript composition. Wong Y.D. was the supervisory author on this project and was involved throughout in the concept formation and manuscript edits. The project was jointly funded by the NTU Sustainable Earth Office and the Centre for Infrastructure Systems.

A version of Chapter 7.1 has been published in a journal [Yeung, J.S., Wong, Y.D., Xu, H., “Driver perspectives of open and tunnel expressways”, Journal of Environmental Psychology 36, 248-256]. I was the lead investigator, responsible for all major areas of concept formation, data collection, analysis, and manuscript composition. Wong Y.D. and Xu H. were supervisory authors on this project and were involved throughout in the concept formation and manuscript edits. Under the Journal Publishing Agreement (Retained Rights) with the publisher (Elsevier Ltd), I retain the rights (without the need to obtain further information) to use the article for personal use (including inclusion in this thesis).

The following is a list of my other relevant publications (both accepted and under review, as of 24 April 2015):


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ABSTRACT
As the urbanisation phenomenon continues to manifest itself, cities are faced with the challenge of urban sustainability. One key issue is the land space constraint, calling for urban space creation. To overcome space limitations, many cities are beginning to utilise urban underground space for various uses, and underground road systems are acknowledged to be a strategic use, especially in highly developed areas. As underground road systems become increasingly popular, it is important to understand how traffic performance is affected in a road tunnel environment. However, there is limited knowledge available in the literature, especially for traffic safety in urban road tunnels. Hence, the objective of this research is to investigate traffic safety in urban underground road systems.

The research adopted a multilevel approach to evaluating traffic safety in urban underground road systems. At the macroscopic level, studies in the literature suggest that traffic accident rates in road tunnels are lower than those on open roads but more information is needed to characterise traffic accidents in urban road tunnels. Road traffic accidents (RTAs) that occurred in urban expressway tunnels in Singapore were examined for a 3-year period (2009-2011) and interestingly it was found that after disaggregating the RTAs by zone, travel direction, and crash type, RTA rates were excessively higher at the tunnel portals, especially on tunnel entry. More than two in three tunnel RTAs were rear-end collisions, indicating that inter-vehicle interactions in urban road tunnels required further investigation at the mesoscopic and microscopic levels.

At the mesoscopic level, car-following behaviour and drivers’ visual attention were examined to establish the link between driver behaviour and RTA risk. Car-following behaviour in an urban expressway tunnel was compared with that in an urban open expressway and it was found that drivers had more conservative behaviour in the road tunnel environment. Headways were longer and overall safety margins were higher in the expressway tunnel. In addition, other factors affecting car-following behaviour such as lane, leader type, and speed were investigated in both open and tunnel road environments.
Drivers’ eye movement data in the same urban expressway tunnel were obtained from an on-road study. Glance behaviour was compared between the tunnel entry zone and the tunnel interior zone, based on one-minute epochs of data. The results revealed that drivers made more glances to the in-vehicle dashboard and the forward roadway in tunnel entry compared to the tunnel interior, resulting in shorter glances and overall glance time to the forward roadway. Less attention was paid to the forward roadway in tunnel entry, explaining the higher RTA risk at tunnel portal areas.

On the microscopic level, driver perception was investigated to understand how it may modulate driver behaviour. A free association study was conducted and driver perspectives of open and tunnel expressways were found to be different based on associations to various roadway qualities. Drivers perceived speed, traffic condition, and scenery to be most prevalent for open expressways; while lighting, enforcement, and safety were most prevalent for tunnel expressways. This implied that drivers in road tunnel environments were more likely to exhibit safer driving behaviour than in open road environments. However, the reported quality of experience in tunnel expressways was lower than that in open expressways, meaning that there is room for improvement for the design of urban road tunnels. Also, a driver task load index survey was conducted to find out how drivers perceived the driving task in the tunnel expressway. Compared to the open expressway, drivers perceived driving in road tunnels to be more mentally demanding and required more effort.

Overall, the findings show that the implementation of urban underground road systems is justifiable in term of traffic safety and should be recommended. Macroscopic evaluation revealed that RTA rates in road tunnels were lower than those in open roads, which was due to safer car-following behaviour as shown through mesoscopic analyses. The safer behaviour was likely the result of safety-oriented perspectives of the road tunnel environment and drivers being more vigilant in road tunnels, as found in the microscopic assessment. In addition, traffic safety at tunnel portals can be enhanced by improving the design of the road tunnel to help reduce the need for drivers to look away from the forward roadway.
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<tr>
<td>AADT</td>
<td>Annual Average Daily Traffic</td>
</tr>
<tr>
<td>ABX</td>
<td>Minimum desired following distance in Action Point Model</td>
</tr>
<tr>
<td>AOI</td>
<td>Area of Interest</td>
</tr>
<tr>
<td>AYE</td>
<td>Ayer Rajah Expressway</td>
</tr>
<tr>
<td>C</td>
<td>Car</td>
</tr>
<tr>
<td>CBD</td>
<td>Central Business District</td>
</tr>
<tr>
<td>CLDV</td>
<td>Threshold for perceiving small negative relative speeds in Action Point Model</td>
</tr>
<tr>
<td>CTE</td>
<td>Central Expressway</td>
</tr>
<tr>
<td>EMAS</td>
<td>Expressway Monitoring Advisory System</td>
</tr>
<tr>
<td>HGV</td>
<td>Heavy Goods Vehicle</td>
</tr>
<tr>
<td>HV</td>
<td>Heavy Vehicle</td>
</tr>
<tr>
<td>ITSC</td>
<td>Intelligent Transport Systems Centre</td>
</tr>
<tr>
<td>KPE</td>
<td>Kallang-Paya Lebar Expressway</td>
</tr>
<tr>
<td>LGV</td>
<td>Light Goods Vehicle</td>
</tr>
<tr>
<td>LTA</td>
<td>Land Transport Authority</td>
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<tr>
<td>MC</td>
<td>Motorcycle</td>
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<td>MCE</td>
<td>Marina Coastal Expressway</td>
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<td>MDS</td>
<td>Multidimensional Scaling</td>
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<td>MVC</td>
<td>Multi-vehicle Crash</td>
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<tr>
<td>N (prefix)</td>
<td>Northern</td>
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<td>NB</td>
<td>Northbound</td>
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<tr>
<td>OCC</td>
<td>Operations Control Centre</td>
</tr>
<tr>
<td>OPDV</td>
<td>Threshold for perceiving small positive relative speeds in Action Point Model</td>
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<td>RRHW</td>
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<td>Road Traffic Accident</td>
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<td>Time Exposed TTC</td>
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<td>Time Headway</td>
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<td>TIT</td>
<td>Time Integrated TTC</td>
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<td>Time-To-Collision</td>
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CHAPTER 1 INTRODUCTION

1.1 Background

The globalisation phenomenon has led to the world experiencing rapid urbanisation. Urbanisation arises from the migration of people to cities and primarily results in the continuous spatial expansion of urban agglomerations (Esch et al., 2014). Economic activities in the cities offer many investment and employment opportunities for people and hence migrants are attracted to the cities. Consequently, by 2014 more than half of the world’s population reside in urban areas, a significant proportion as compared to 30 per cent in 1950. It is projected that by 2050, two-thirds of the world’s population will consist of urban dwellers (United Nations Population Division, 2014).

“Megacities”, defined by United Nations (UN) as urban agglomerations with at least 10 million inhabitants, have increased from a total of three in 1975 to a total of 19 in 2007 (United Nations Population Division, 2008). In 2008, UN predicted that the number of megacities will increase to 27 by the year 2025. However, in 2014 there were already 28 megacities in the world and there was a new projection of 41 megacities by 2030 (United Nations Population Division, 2014). The premature realisation of the 2008 projection in merely six years clearly highlighted the underestimation of the urbanisation phenomenon.

As the world continues to urbanise, the key challenge faced by cities, both developed and developing, is sustainable development. Undoubtedly, the city is a complex system where its sustainability is primarily linked to its social, environmental, and economic needs. Each city has a different level of urbanisation and hence has varying priorities towards sustainable development. However, with the rapid pace of urbanisation, it is clear that cities in the world will reach a high level of urbanisation at some stage. While urbanisation is positively associated with developments such as employment, rising living standards, trade, and education, it is also associated with negative impacts such as environmental degradation, pollution, waste, social conflicts, and traffic congestion (Esch et al., 2014).
As highly urbanised cities struggle with environmental conservation and heritage preservation, one key challenge is the lack of urban space for infrastructural developments to meet the increasing demands of the people. For most cities, there are limits to horizontal expansion due to territorial and/or natural boundaries and there is also a limit to how high buildings can go due to engineering and air space/rights considerations. Hence, the only option left is to go underground – that is, to utilise the urban underground space (UUS).

1.2 Urban Underground Space
The utilisation of underground space is not a new idea. Tunnels had long been used by humans since early days, mainly for irrigation and drainage purposes. In the middle ages, tunnels were used primarily for mining and military engineering. Later in the 17th century, transport needs in Europe grew and major waterway tunnels started to appear. Since then, the use of tunnels had spread across the world for other uses such as railroads, highways and commercial activities. Tunnelling technology had improved tremendously over time and the construction and use of tunnels have become safer and more reliable.

In the urban context today, the utilisation of urban underground space (UUS) creates space for prospective developments and allows long-term environmental preservation. Utilisation of UUS also offers various other benefits such as protection from weather and better connectivity to existing underground facilities (Bélanger, 2007, Cui et al., 2013).

However, UUS is a non-renewable resource and has become increasingly valuable over time (Bobylev, 2009). UUS serves many functions and conflicting demands increase the competition for UUS. Hence, it is important for proper urban planning to be in place for efficient use of the non-renewable UUS. For instance, the use of utility tunnels instead of conventional burying of utilities can be properly planned to reduce long-term maintenance efforts and the need to divert surface traffic (Canto-Perello et al., 2009, Canto-Perello and Curiel-Esparza, 2013).

An early study on underground space in land-use planning (Ronka et al., 1998) highlighted the feasibility depths of different activities in the urban structure. In the
urban structure, surface space should be reserved for the most important functions such as work, recreation, and housing; while industrial functions, traffic functions, and technical infrastructure may be more suited for the deep underground.

One good use of UUS is the underground road system (URS). Roads are long, linear elements that are increasingly difficult to position in dense urban cities and often consume a substantial amount of valuable surface space (Sterling, 1997). Several studies (Sahlström, 1990, Sterling, 1997, Ronka et al., 1998, van der Hoeven, 2011) have acknowledged the strategic use of URS’s, especially in highly developed areas such as central business districts. The reason is that URS’s help to reduce traffic in important city streets and protect the surface environment from noise and emissions. Other advantages of URS’s include shielding motorists from adverse weather conditions and freeing up surface land for other quality uses.

The use of URS’s is increasingly popular and with URS’s becoming more extensive, motorists can expect to spend a greater amount of time in road tunnels.

1.3 Road Tunnels
Traditionally, road tunnels were used to overcome natural obstacles such as mountains and rivers. For example, the longest continuous road tunnel in the world, the Lærdal Tunnel, is a 24.51-km single-tube road tunnel cutting through a mountain range and connecting Lærdal and Aurland in Norway. Completed in 2000, the tunnel is divided into four sections by three large mountain caverns, with blue lighting and yellow lights as shown in Figure 1-1, to provide drivers with relief from mental strain due to long, monotonous driving. The Lærdal Tunnel is part of a road link between Oslo and Bergen, the two largest cities in Norway. The construction of the Lærdal Tunnel was chosen over the refurbishing of existing roads which were on difficult terrain with high risks of rock falls.

An example of a subsea tunnel is the North Cape Tunnel (see Figure 1-2) in Norway, or also known as Nordkapp Tunnel. Completed in 1999, it is a 6.875-km single-tube tunnel under the Magerøysundet Strait, reaching a depth of 212 m below sea level, and connecting Magerøya Island to the Norwegian mainland. Before the tunnel was built, traffic was carried across the sea using ferries.
Figure 1-1 Interior View of Lærdal Tunnel Cavern

Figure 1-2 Interior View of Nordkapp Tunnel

Source: Flam A.S. (n.d.)

Source: hartmut.breitling (2011)
In more recent times and in megacities, where space is a limited resource, road tunnels are used to overcome “urban obstacles”. For instance, Seoul (South Korea) has planned for an underground road network, U-SMART WAY, which consists of six highways in a lattice pattern with inter-connecting junctions (Kwon, 2009). The total tunnel length will be about 149 km with 37 entrance structures and 33 exit structures (Kim, 2012). Figure 1-3 illustrates the proposed network. The tunnel interior will be designed to have aesthetic lighting displays and some form of artwork on the tunnel walls, with the intention to keep the drivers attentive while driving in the tunnels. The U-SMART WAY is expected to be completed by 2019 or later, and will be the first of its kind.

Another example is the A86 Duplex Tunnel in Paris, France. The 10-km bi-level tunnel (Figure 1-4) is part of the 80-km long ring road around Paris, and is designed to accommodate up to three lanes of traffic moving in a different direction on each level (Reid, 2008). Similarly, artistic displays are mounted to the tunnel walls to improve the motorists’ driving experience in the A86. Completed in 2011, the A86 allows the journey from Malmaison to Versailles to take only 10 instead of 45 minutes. The A86 was built to ease traffic congestion and improve traffic links in Paris. In addition, the A86 Duplex Tunnel was ranked first in terms of safety in the 2010 European Tunnel Assessment Program (EuroTAP) evaluation.

The Lærdal Tunnel and Nordkapp Tunnel are examples of rural road tunnels where the tunnels are generally far away from the city, darker, moderately-designed, and accommodate light traffic volumes. On the other hand, the U-SMART WAY tunnels and A86 are examples of urban road tunnels where the tunnels are generally near or under the city, brighter, designed to a higher standard, accommodate heavier traffic volumes, and usually have numerous access ramps along the tunnel length.

It can be observed in the abovementioned examples that effort was made to improve the aesthetics of the tunnel interior in various ways. The purpose of these aesthetic improvements was to stimulate drivers’ attention while driving in these continuous tunnels, in order to reduce the likelihood of road traffic accidents (RTAs).
Figure 1-3 Seoul's Underground Road Plan

Figure 1-4 Cross-section of A86 Duplex
RTAs in road tunnels are of great concern to the authorities for various reasons. First, RTAs are often the cause for non-recurring traffic congestions because they greatly reduce the capacity of the roadways by creating bottlenecks. Second, RTAs can potentially be injurious and fatal, which results in the social trauma and grief to the affected road users and their families.

Most importantly, RTAs in road tunnels have strong potential to escalate into disasters on a catastrophic scale due to enclosure by the tunnel walls. Several road tunnel catastrophes have occurred over the past two decades, including the following:

- In 1999, a fire caused by a heavy goods vehicle (HGV) in the Mont Blanc Tunnel between France and Italy resulted in 39 deaths.
- Also in 1999, the collision between a truck and a column of queuing vehicles in the Tauern Tunnel in Switzerland resulted in 12 deaths (Leitner, 2001). Eight were killed by the impact of the collision while four were killed by the fire and smoke resulting from the collision.
- In 2001, the collision of two HGVs resulted in 11 deaths in the Gotthard Tunnel in Switzerland. The smoke and gases from the resulting fire was the main cause of death.
- In 2006, a fire broke out in the Viamala Tunnel in Switzerland, following a head-on collision between a bus and a car. Other vehicles were affected and a total of nine lives were lost.

Road tunnel safety has thus become a critical consideration in the planning and design of future road tunnels. In 2005, following a series of tunnel disasters, EuroTAP, with the backing of the European Commission, began to assess the safety standards of tunnels in Europe. Experts from automobile clubs inspected and evaluated the quality and safety of the tunnels. A shocking finding was that 21% of the tunnels that were evaluated did not meet the minimum standards specified by the European Tunnel Directive (Sauter and ADAC, 2007).

In these assessments, the “safety” potential of a tunnel is based on the capability to prevent emergencies and manage incidents (Sauter, 2010). In emergency
prevention, four categories are assessed: traffic and traffic control (17%), tunnel system (14%), lighting and energy supply (7%), and emergency management (8%). In incident management, four categories are assessed: fire protection (18%), escape and rescue routes (14%), communication (11%), and ventilation (11%).

The “safety” potential is then compared against the “risk” potential of the tunnel, which describes the likelihood of emergencies occurring and the expected severity. The assessment of “risk” potential considers the following parameters: annual traffic volume, share of heavy goods vehicles (HGVs), traffic type, vehicles per hour per lane, dangerous goods transport regulation, gradient, intersections, and entries/exits.

Ideally, the “safety” potential of a tunnel should be greater than its “risk” potential. The assessment methodology is based on an infrastructural perspective and determines the safety score of individual tunnels using a qualitative approach.

However, from a traffic safety perspective, it is difficult to determine whether URS’s are the best use of UUS. As urban road tunnels are relatively new compared to the rural road tunnels, there is limited knowledge on how urban road tunnel environments affect traffic safety.

1.4 Singapore Context

Singapore is an island state with a population of more than five million (National Population and Talent Division, 2011) and total land area of 712 km². By UN standards, Singapore is a large city (5 to 10 million inhabitants) and is highly urbanised (about 100% urban) (United Nations Population Division, 2014). Singapore’s strong economy and successful governance have attracted many migrants, resulting in accelerated population growth over the years despite low citizen birth rates. The population is expected to reach 6.9 million by 2030.

Urbanisation has a strong impact on car use and national transport and road energy use (Poumanyvong et al., 2012), especially for high income countries. Coupled with rapid population growth, the transport system in highly-urbanised Singapore has been under constant pressure.
1.4.1 Vehicle Growth
Rapid development and urbanisation has led to a growing demand for private transport over the years, as illustrated in Figure 1-5 (Land Transport Authority, 2011), causing traffic congestion to become a critical issue for planners and end-users due to land scarcity, especially in the city centre.

![Figure 1-5 Annual Vehicle Populations in Singapore](image)

The growth in vehicle population is not unique to Singapore. Most developing or developed countries also experience increased levels in motorisation. Figure 1-6 shows the growth rates in selected countries, based on figures obtained from international statistics (Organisation for Economic Co-operation and Development, 2012). More often than not, positive growth rates are observed for the six selected developed countries.

Studies have discussed that reasons for car usage are not only instrumental (as modes of transport) but affective (as symbols of social status) as well (Steg et al., 2001, Anable, 2005, Steg, 2005, Beirao and Cabral, 2007, Gardner and Abraham, 2007). This implies that despite various strategies to encourage people to commute
by public transport, it is likely that car usage will continue to increase in the foreseeable future.

![Figure 1-6 Annual Growth Rates of Private Cars from 1991 to 2010](image)

Although increasing the kilometre of roads is not the long-term solution to the traffic congestion, it is still essential to expand the current road network to accommodate the inevitable increase in transport demands. Land-scarce Singapore will thus need to address the transport issues along the scale of megacities.

### 1.4.2 Transport Infrastructure in Singapore

Traffic conditions are gradually worsening due to the development of road space being outpaced by vehicle growth. Figure 1-7 shows the overall growth of the vehicle population against the development of road space, from base year 2000. Over 11 years, the vehicle population grew four times as fast as the creation of road space. It would seem inevitable that more road infrastructure have to be built in order to support the growing vehicle population, especially in the central districts.

As of 2011, there were a total of 9,045 lane-km of roads in Singapore (Land Transport Authority, 2011). With 12% of Singapore’s land space already allocated to roads, the Land Transport Authority (LTA) is operating on the basis that future
roads may have to be partly or wholly built underground (Land Transport Authority, 2008). For instance, LTA has been considering the development of the Singapore Underground Road System (SURS), which is slated to consist of two 15-km inner ring roads circling under the city area, as shown in Figure 1-8.

![Figure 1-7 Vehicle growth and road space development, base year 2000](image1)

Source: Hulme and Burchell (1999)

![Figure 1-8 Proposed SUSR](image2)
1.4.3 Existing Road Tunnels in Singapore

As of 2014, there are six existing road tunnels in Singapore, namely the Kampong Java Tunnel, Chin Swee Tunnel, Kallang-Paya Lebar Expressway (KPE) Tunnel, Marina Coastal Expressway (MCE) Tunnel, Fort Canning Tunnel, and Woodsville Tunnel. In particular, the Kampong Java Tunnel, Chin Swee Tunnel, and KPE Tunnel will be looked at in the present research study. Figure 1-9 shows snapshots of typical open expressway and expressway tunnel in Singapore.

![Figure 1-9 Typical (a) open expressway; (b) expressway tunnel in Singapore](image-url)
Completed in 1991, Chin Swee Tunnel and Kampong Java Tunnel form part of the Central Expressway (CTE) and are separated from each other by a short open section. The two tunnels are often identified as the CTE Tunnel, despite being two separate tunnels. The CTE Tunnels are the first road tunnels in Singapore, freeing up land for the preservation of greenery and monumental buildings (Public Works Department, 1991).

The CTE was the only expressway connecting the city to the northern residential areas in Singapore. As a result, it carries greater traffic volumes and is often congested. The CTE Tunnels were the only underground roads in Singapore, until the opening of Fort Canning Tunnel in 2007.

![Figure 1-10 Kampong Java, Chin Swee, and KPE Tunnels](image-url)
The KPE Tunnel was completed in 2008. It forms the major part of the KPE, and is also the longest road tunnel in Singapore. Figure 1-10 shows the locations of the expressway tunnels.

The KPE is the ninth expressway built in Singapore, connecting the northern parts of Singapore to the central-southern region, easing the traffic on the CTE which runs parallel to the KPE. The KPE Tunnel has also been assessed as “very good” by EuroTAP (Land Transport Authority, 2009).

All three tunnels are dual tubes, carrying northbound (NB) and southbound (SB) traffic, and each tube carries three lanes, with the exception of NB Kampong Java Tunnel which has four lanes. Table 1.1 summarises the tunnel characteristics (as of 2013).

It should be noted that the southern end of the Chin Swee Tunnel is followed by a 300 m semi-tunnel (chainage CTE 1.75 – 2.05 km) by way of an open depressed section. Also, the speed limit in the KPE Tunnel was revised upwards to 80 km/h in 2014.

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Chainage</th>
<th>Length (m)</th>
<th>Direction</th>
<th>Lanes</th>
<th>Speed Limit (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kampong Java</td>
<td>CTE 4.40 – 5.15 km</td>
<td>750</td>
<td>NB</td>
<td>3 – 4</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SB</td>
<td>3</td>
<td>80</td>
</tr>
<tr>
<td>Chin Swee</td>
<td>CTE 2.05 – 3.85 km</td>
<td>1,800</td>
<td>NB</td>
<td>3</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SB</td>
<td>3</td>
<td>80</td>
</tr>
<tr>
<td>KPE</td>
<td>KPE 0.00 – 8.35 km</td>
<td>8,350</td>
<td>NB</td>
<td>3</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SB</td>
<td>3</td>
<td>70</td>
</tr>
</tbody>
</table>

In an earlier review of road traffic accidents (RTAs) in Singapore, it was found that the number of RTAs on expressways have increased by about 30% from 2004 to 2008, accounting for about 18% of RTAs in Singapore for the same period of time (Hau et al., 2010). It may hence be prudent to review RTAs occurring in the expressway tunnels, while bearing in mind that such accidents have greater potential for catastrophic consequences due to the enclosed road environment.
1.5 Objectives and Scope of Research

As more urban roads are being introduced underground, there is limited knowledge in the literature as to whether the implementation of urban URS’s is justifiable in terms of traffic safety, which has serious consequences on human lives. Hence, there is strong impetus for research in this area.

The main objective of this research is to investigate traffic safety in urban URS’s. Traffic safety can be represented in a multilevel framework. Huang and Abdel-Aty (2010) proposed a 5 × Spatiotemporal-level hierarchy to represent the general framework of data structures in traffic safety. The five levels are, in descending order of spatial level: geographic region level, traffic site level, traffic crash level, driver-vehicle unit level, and occupant level. The proposed framework is applied in the context of this research and the adopted framework is illustrated in Figure 1-11.

![Research Framework](image-url)
The goal is to assess whether URS’s are beneficial to traffic safety at the “city network” level but direct data are not available at the “city network” level. Consequently, data from the lower levels are investigated in this research to achieve the objective. Specific sequential goals pertaining to each level below the “city network” level are as follows:

- At the “urban URS” level, to find out whether RTA rates in road tunnels are lower than those on open surface roads;
- At the “accidentology in road tunnels” level, to characterise RTAs in road tunnels and identify key traffic safety concerns in URS;
- At the “driver behaviour” level, to examine how the driver-vehicle unit behaves and understand how the observed behaviour translates to the findings from the upper levels; and
- At the “driver perception” level, to investigate how drivers perceive the URS environment and understand how driver perception is linked to driver behaviour.

The research emphasises the human element in traffic engineering and does not cover the road geometrical design aspects.

Although freight vehicles, especially those carrying hazardous materials, can potentially lead to more disastrous outcomes in road tunnels, freight vehicles are not the main focus in this research. This is because in many states and cities, such as Singapore, there are strict regulations that do not permit freight vehicles carrying hazardous materials onto bridges and into tunnels for security reasons. This effectively reduces the explosion and fire risks of freight vehicles.

Hence, the aspects of driver behaviour and perception mainly focus on passenger car users and their behaviour, since passenger cars form a greater proportion of the vehicle population in highly urbanised cities.

It has long been known that most RTAs are caused by the driver in the driver-vehicle-environment interaction. Instead of just enhancing geometrical design principles based on physical laws, driver behaviour and perceptions should be
strongly considered as well. This research investigates at the driver-environment interaction, specifically in the road tunnel environment.

As tunnelling and underground construction technologies become more advanced, more urban road tunnels are being planned and constructed. The findings from this research will provide city planners and transport engineers with information on how urban road tunnels affect traffic safety and whether the implementation of URS’s are justifiable, in terms of traffic safety.

1.6 Thesis Outline

There are a total of eight chapters in this thesis. This thesis is structured as follows:

Chapter 1 covers the introduction. The need to utilise urban underground space and implement urban underground road systems is discussed. The chapter also mentions the motivation, approach, and significance of this research.

Chapter 2 discusses the literature review in the various aspects of underground road systems: accidentology, car-following behaviour, drivers’ visual attention, and driver perceptions.

Chapter 3 elaborates the methodology employed in this research, as per the multilevel approach. On the macroscopic level, road tunnel accidentology was examined; on the mesoscopic level, car-following behaviour was examined; on the microscopic level, drivers’ visual attention and drivers’ perceptions were examined. Each subsection elaborates on the methods and resources involved on each level.

Chapters 4 to 8 report the findings obtained from each of the levels and the implications. Chapter 4 pertains to accidentology; Chapter 5 pertains to car-following behaviour; Chapter 6 pertains to drivers’ visual attention; and Chapter 7 pertains to driver perceptions.

Chapter 8 summarises the research work done and reported in the preceding chapters. The chapter also concludes the research with regard to the initial objectives stated in Chapter 1. Recommendations arising from the research are also included in Chapter 8.
CHAPTER 2 LITERATURE REVIEW

2.1 Importance of Safety in URS

The design of underground facilities is multidisciplinary. Carmody et al. (1994) discussed that safety is an important issue in the use of underground facilities because of physical restraints in these facilities that require special design features to ensure basic safety in an emergency. In principle, two main aspects should be considered in the safety design of UUS facilities. First, emergency evacuation from the UUS facility should be efficient and safe. Visual egress information and voice communication need to be effective in order to minimise any delay in evacuation due to confusion. Second, UUS facilities have limited accessibility for fire-fighting. Hence, there should be a control centre constantly monitoring the UUS facility and there should be automatic fire suppression and smoke ventilation systems to control fires.

For URS, the primary concern is also fire and road user safety. Various evacuation models have been compared and consistent results are obtained from different models for similar tunnels (Ronchi et al., 2012, Alvear et al., 2013). The models estimate the evacuation times using different methodologies. Such models can assist tunnel operators in decision-making during stressful emergency situations. However, it should be noted that although various tunnel assessment models have been developed, these models need to be used with care, since each tunnel has its own unique issues (Beard, 2010).

In dealing with accident fires, various aspects have been studied. Aralt and Nilsen (2009) conducted fire detection experiments to find out whether smoke or heat detection systems were more effective for early fire detection. They found that the results from heptane pool fires differed from those from actual car fires and hence difference scenarios should be tested for optimality. Other researchers have worked on tunnel fires using both full-scale experiments (Tong et al., 2009, Ingason et al., 2012) and simulation (Hua et al., 2011, Caliendo et al., 2012, Caliendo et al., 2013), to develop ventilation models and smoke control strategies.
As observed, much of the considerations in the safety design of road tunnels are dealing with the occurrence of emergencies. While design standards can always be updated to ensure that design provisions are adequate in terms of safety potential, there exists a need for consideration in terms of risk potential.

Other simulator studies assessed various aspects of tunnel driving such as darkness-enhanced startle responses (Mühlberger et al., 2008), phobic fear (Mühlberger et al., 2007), perceptual speed regulation (Manser and Hancock, 2007), lighting, wall colour and driver inattention (Kircher and Lundkvist, 2011).

“As long as tunnels form only a small part of the roadway network, drivers tend to drive more carefully in tunnels.” (Lemke, 2000). As more underground road systems are being introduced, drivers will spend a greater portion of their time in road tunnel environments, and the ‘novelty’ effect may wear off. Hence, a holistic investigation into traffic safety in road tunnels is warranted.

2.2 Accidentology

Since RTAs are the primary index for traffic safety, RTA statistics serve as important tools for traffic safety evaluation. This section discusses the RTA rates in road tunnels as found in the literature.

2.2.1 RTAs in Road Tunnels

It is widely known that road tunnels have lower RTA rates compared to open surface roads (Amundsen and Ranes, 2000, Lemke, 2000, Nussbaumer, 2007, Ma et al., 2009). Nonetheless, traffic accidents in road tunnels are of great concern due to their potential for catastrophic outcomes.

Amundsen and Ranes (2000) analysed tunnel RTA data obtained from police records for 587 Norwegian road tunnels (lengths ranging from under 100 m to over 3 km, with most being 100-500 m) for a five-year study period (1992-1996). They found that the severity of injury RTA in road tunnels is greater than in open roads, with greater proportions of killed and seriously injured persons.

Nussbaumer (2007) analysed tunnel RTA that occurred in Austrian tunnels (18 bidirectional tunnels with average length of 4.79 km and 32 unidirectional tunnels
with average length of 2.01 km), using data obtained from the police database. The analyses revealed lower RTA rates but greater RTA severity in road tunnels compared to open roads. With regard to the tunnel type, fatality rates were found to be more than double in bi-directional tunnels as compared to in unidirectional tunnels, presumably due to a higher risk of head-on collisions with vehicles from opposing directions.

Lemke (2000) analysed the police accident database for 68 German tunnels (46 freeway tunnels with average length of 650 m and 22 tunnels on rural two-lane highways with average length of 800 m). The longest tunnel included in the study was 2.9 km long. It was found that injury RTA rates were highest in bidirectional tunnel highways while material damage RTA rates were highest in tunnel freeways without shoulder lanes. However, accident costs were found to be lower in road tunnels than open roads. The lower accident costs were likely due to the fact that there was no major accident that had occurred in the German tunnels in the study.

Evidently, RTA data from these studies reveal that RTAs are less likely to occur in road tunnels, compared to open surface roads. Also, bi-directional road tunnels have higher RTA risk. Fortunately, for practical reasons urban road tunnels are mostly dual-tube, carrying unidirectional traffic in each tube. As a result, rear-end collisions are the most prevalent RTA type in urban road tunnels. For unidirectional road tunnels, more than two in three RTAs are categorised as rear-end collisions (Lemke, 2000, Meng and Qu, 2012), while single vehicle crashes account for a small fraction of all reported tunnel RTAs (Amundsen and Ranes, 2000, Ma et al., 2009).

2.2.2 RTAs within Road Tunnels

Apart from the overall RTA rates in road tunnels as described in 2.2.1, studies have also examined the characteristics of the RTAs, particularly the RTA location within the road tunnel. Typically, these studies adopted a zonal analysis approach.

Amundsen and Ranes (2000) divided each tunnel into four zones and determined the RTA rates in each zone. The results revealed that RTA rates for Zone 1 (refer to Table 2.1) were highest, followed by Zones 2, 3, and 4. Also, longer tunnels were
found to have lower overall accident rates, possibly due to the longer interior zones with low RTA rates. Consistently, Nussbaumer (2007) also found RTA rates to be highest in the vicinity of the road tunnel portal, regardless of tunnel type (unidirectional or bi-directional).

<table>
<thead>
<tr>
<th>Study by</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amundsen and Ranes (2000)</td>
<td>First 50 m before/after tunnel</td>
<td>First 50 m inside tunnel</td>
<td>Next 100 m inside tunnel</td>
<td>Remainder of tunnel</td>
</tr>
<tr>
<td>Ma et al. (2009)</td>
<td>First 100 m before/after tunnel</td>
<td>First 100 m inside tunnel</td>
<td>Next 300 m inside tunnel</td>
<td>Remainder of tunnel</td>
</tr>
</tbody>
</table>

*some short tunnels may not consist of all four zones

Ma et al. (2009) analysed RTAs that occurred in four Chinese freeway tunnels, for a two-year study period (2003-2004), with RTA data obtained from police records. The four tunnels ranged from 0.2 km to 3.0 km in length. They investigated the monthly and hourly distribution characteristics of the RTAs but did not obtain significant findings. Similarly, each tunnel was divided into four zones but the zone definitions were different from those defined by Amundsen and Ranes (Table 2.1). Contrarily, they found the highest RTA and casualty rates in Zone 3 instead of the access zones as found by others.

### 2.2.3 Remarks

The studies conducted in the various countries are consistent in highlighting lower RTA rates in road tunnels compared to open roads, and a higher RTA risk in the tunnel portal vicinity. However, the results appeared contradictory to some extent, particularly RTA severity in tunnels compared to open roads, and RTA likelihood in the different tunnel zones. The contradiction may be due to different RTA reporting requirements and procedures in each jurisdiction. In addition, these
studies were mainly based on rural mountain road tunnels instead of the urban road tunnels, which have substantially different characteristics.

RTAs are the most direct measures of traffic safety and RTA data have typically been used in traffic safety analyses. However, it is difficult to base traffic safety analyses solely on RTAs because they are rare events (Laureshyn et al., 2010). This approach is also limited by the availability, level of detail and reliability of the RTA records (Lemke, 2000). Furthermore, RTA data may have issues such as under-reporting and lack of detailed causal information. Hence, evaluation of traffic safety should also be conducted with microscopic behavioural data, since driver behaviour and RTA likelihood would have a causal relationship.

2.3 Driver Behaviour
Driving is a complex task. Brain imaging studies (Calhoun et al., 2006, Beeli et al., 2008, Just et al., 2008, Mader et al., 2009) with driving simulators have shown that the driving task imposes high cognitive demands, and the level of brain activation varies with the situation. For example, driving along a familiar, monotonous route seemingly led to reductions in attention and perception processes. Driving is also a difficult task. In a driving simulator study involving 30 drivers (Dijksterhuis et al., 2011), it was found that the mean heart rate while driving was higher than the baseline resting condition.

Studies have shown that driver behaviour varies in different situations such as handling secondary tasks (Recarte and Nunes, 2003, Briggs et al., 2011, Metz et al., 2011), at intersections (Dukic and Broberg, 2012, Wenneke and Vollrath, 2012), different road widths (Dijksterhuis et al., 2011, Antonson et al., 2013), different road complexities (Cantin et al., 2009, Stinchcombe and Gagnon, 2010), different times of the day (Chipman and Jin, 2009), different luminance levels (Hogema et al., 2005), different weather conditions (Konstantopoulos et al., 2010), and even slight changes in the surrounding landscape including trees (Antonson et al., 2009) and crash barriers (Antonson et al., 2013). It can hence be expected that an entirely different road environment such as the urban road tunnel will also result in different driver behaviour.
2.3.1 Driving Behaviour in Road Tunnels

Several studies have investigated driving behaviour in road tunnels. In a series of driving simulator experiments (Calvi et al., 2012, Calvi and D’Amico, 2013), it was found that the road tunnel environment, as compared to a control open section, resulted in lower driving speeds and differences in average lateral position (further away from the tunnel walls). Lower pathologic discomfort was also found in the tunnel interior zones. Interestingly, pathologic discomfort in the tunnel portal areas was found to be higher in a tunnel scenario as compared to the control scenario, and this suggests a causal link with RTA rates.

In an experiment where six drivers drove through a two-lane highway tunnel in China, Zhao et al. (2011) found that heart rate was higher in tunnels than on open roads for all six subjects. This finding suggests that driving in tunnels was more taxing on the drivers.

In another study, He et al. (2010) studied drivers’ visual attention in various tunnel lengths in on-road trials and found indicative differences in the distribution of gaze time and fixation duration. However, the distribution of fixations was assessed within the road scene itself, which was likely to be strongly affected by the tunnel geometry and traffic conditions instead of the tunnel environment.

Several studies investigated the effect of various tunnel features. A driving simulator study by Shimojo et al. (1995) revealed that tunnel cross section and signage information indicating the remaining tunnel length had notable effect on driving performance and driving workload. Hirata et al. (2006) examined the effectiveness of accident information on drivers in a simulated tunnel and found that informing drivers about an accident that occurred in the tunnel had a positive effect on safety. Törnros (2000) assessed the effects of several tunnel wall patterns on simulated driving behaviour. Although no significant effect of wall pattern was found, drivers drove at significantly lower speeds in the tunnels compared to surface roads. Kircher and Ahlström (2012) investigated the effects of tunnel design and lighting on driver performance in a driving simulator and found light-coloured walls were more important than strong illumination to keep drivers’ visual attention on the road ahead.
However, most of these studies did not provide a comparative perspective in behaviour between open and tunnel road environments. Thus, they do not provide insight into how tunnels will impact traffic behaviour compared to the open roads. Furthermore, these studies were mostly based on single vehicles travelling through light traffic in the road tunnels, either in simulated or real world environments. Hence, there is also a lack of understanding in how the tunnel environment affects inter-vehicle interactions.

### 2.3.2 Car-Following

In unidirectional traffic streams, the most prevalent form of inter-vehicle interaction is car-following. Car-following behaviour refers to how drivers follow behind others in unidirectional travel and it is typically quantified by either headway or gap, which is expressed either spatially or temporally. Figure 2-1 illustrates the difference between headway and gap.

Car-following behaviour has a direct influence on traffic capacities. For instance, the traffic volume of a single lane of roadway can be described as:

\[
Q = (1000)v/S
\]

where \( Q \) refers to the traffic volume of a single lane (vehicles/h); \( v \) is the speed (km/h); and \( S \) is the average spacing (m).

![Figure 2-1 Illustration of headway, gap, and rear-to-rear headway](image)
The spacing $S$ (or spatial headway) is in turn dependent on three components: the effective vehicle length $L$; the reaction time $T$, and the maximum average deceleration of a following vehicle $a_f$ (Rothery, 2011), as given by:

$$S = L + Tv + \frac{v^2}{2a_f}$$

(2.2)

The first term represents the physical length of the vehicle which cannot be changed; the second term represents the distance to be travelled by the vehicle in the time the driver takes to react; and the third term represents the braking distance in which the vehicle decelerates to a complete stop. In theory, Equation 2.2 presents the safe following distance for vehicles.

### 2.3.2.1 Factors Affecting Car-Following

Interestingly, the spacing between vehicles is highly variable – each driver has his or her own perspective of a “safe distance” due to differences in perceived reaction times and braking abilities. Evans and Wasielewski (1982) found that accident-involved drivers and traffic violators tended to follow more closely than non-violators. This implies that drivers’ risk-taking profiles can be inferred from car-following behaviour – risk-averse drivers will drive with longer headways.

Many factors may affect drivers’ choice of headway, such as individual differences, situational factors, and other vehicles. Ranney (1999) suggested that as traffic tends towards congestion, the influence of individual and situational factors diminishes while the influence of other vehicles increases. A key factor influencing headway choice is vehicle speed. However, while some studies have found time headways to increase with speed (Colbourn et al., 1978, Puan, 2004, Broughton et al., 2007, Al-Kaisy and Karjala, 2010), other studies found otherwise (Taieb Maimon and Shinar, 2001, Marsden et al., 2003, Brackstone et al., 2009). Other factors include visibility (Broughton et al., 2007), lead vehicle type (Puan, 2004, Brackstone et al., 2009, Ossen and Hoogendoorn, 2011, Duan et al., 2013), driver culture (Marsden et al., 2003), driving experience (Colbourn et al., 1978), and intervention advisory signage (Michael et al., 2000).
Most of these studies on car-following were conducted on single-lane roads and the effect of the traffic lane travelled in a multilane roadway was not investigated, i.e. whether car-following behaviour in the fast lane is different from that in the slow lane. Also, none has investigated car-following behaviour in road tunnels.

2.3.2.2 Car-Following and Traffic Safety

As reviewed earlier, rear-end collisions are the most prevalent RTA type in unidirectional road tunnels. A rear-end collision occurs when a following vehicle fails to brake in time to avoid impact with a front vehicle. This is usually a result of inadequate following distance. Typically, the two safety indicators used in assessing imminent rear-end collisions are headway (or gap) and time-to-collapse (TTC) (Oh and Kim, 2010, Bella and Russo, 2011). TTC is defined as the time taken for a collision to occur, given that the vehicles of interest maintain their current states of motion which will result in a collision. Vogel (2003) surmised that short headways indicate potential danger while short TTCs represent actual danger. While vehicle speeds influence the severity of a collision, relative speeds influence the likelihood of a collision. Meng and Qu (2012) also demonstrated that rear-end crash rates can be estimated using the likelihood of TTC being below a certain threshold at different traffic volumes.

In order to assess the traffic safety, extended TTC measures such as the time exposed TTC (TET) and time integrated TTC (TIT) have been proposed (Minderhoud and Bovy, 2001). TET takes into account the amount of time that the TTC falls below a predetermined threshold. TIT takes into account both the duration and magnitude of which TTC falls below the threshold. These measures require the analyses of vehicular trajectories over time and are difficult to apply to spot measurements.

Bifulco et al. (2013) proposed the concept of car-following waves. Based on psychophysical models (also known as Action Point models), car-following waves in opening charts provide better regression results in the $DV/DX$ vs. $DV$ plane ($DV$ is the relative speed and $DX$ is the distance gap between two successive vehicles) than conventional interpretation of Action Point models in the $DV$ vs. $DX$ plane.
In each interpretation, the regression coefficient describes the TTC patterns observed in car-following.

Zhang et al. (2010) proposed the use of safety margin (SM) as an alternative risk indicator in car-following. The computation of SM considers distance gap, speed, and relative speed, which are the main macroscopic safety indicators (Qu et al., 2014). Lu et al. (2012) discussed that, out of three risk indicators (time headway, TTC, and SM), SM serves as a suitable quantitative indicator of homeostatic risk perception in car-following because it follows the normal distribution. They also found that professional drivers exhibited lower SM as compared to general drivers, which implies that professional drivers were willing to drive in a less safe manner.

2.3.2.3 Defining Car-Following

With regard to judging whether a vehicle is indeed impeded by the leading vehicle and is in “following” mode, varying thresholds have been adopted and proposed. In his study focussing on vehicles not impeded by other traffic, Wasielowski (1984) regarded vehicles with headways greater than four seconds to be in “free” mode. The four-second headway threshold was later also adopted by Michael et al. (2000) in their research on the effects of intervention on vehicle headways. On the other hand, in a Malaysian study on car-following headway (Puan, 2004), a five-second headway threshold was used alongside an additional speed ratio criterion.

In order to establish the threshold, several approaches have been proposed. Al-Kaisy and Karjala (2010) used empirical observations of smoothing average speeds in different headway thresholds, while Vogel (2002) used the correlations between leader and follower speeds in various headway groups for regression analysis. Interestingly, both approaches suggested that car-following interactions cease beyond time headways of six seconds on two-way two-lane roads.

With regard to safety thresholds, regulations for minimum following distances differ across different countries. For instance, the Road Safety Authority in Ireland and the SWOV Institute for Road Safety Research in The Netherlands recommend a minimum two-second gap, while the US National Safety Council recommends a minimum three-second gap. In some jurisdictions, it is a traffic violation if vehicles
are tailgating. In Singapore, the Traffic Police (TP) generally advises motorists to “keep a safe following distance and not to harass the vehicle in front by tailgating” (Singapore Police Force, 2009).

Overall, there is no definitive threshold for car-following. Studies have used various thresholds, or critical headways, but there are issues concerning the use of critical headways since some data will be truncated.

2.3.2.4 Car-Following Models

Car-following can be categorised into three subtasks: perception, decision making, and control.

In perception, the driver collects relevant visual information from the forward road scene. The information is primarily related to the motion of the vehicle in front and the driver’s vehicle, such as vehicle speeds, accelerations, relative speeds, inter-vehicle spacing.

Next, in decision making, the driver interprets the information collected, integrates the information over time, and develops a driving strategy, based on past driving experiences.

Then, in control, the driver executes control over the vehicle to act according to the driving strategy developed.

Car-following models aim to describe how the responses adopted by the driver, mostly acceleration decisions, is dependent on various stimuli presented to the driver. The concept is represented by:

\[
\text{Response} = \lambda \cdot \text{Stimulus} \tag{2.3}
\]

where \(\lambda\) is a sensitivity factor. It is also assumed in car-following modelling that the driver has two primary goals: (1) to keep up with the vehicle ahead; and (2) to avoid collisions.
Brackstone and McDonald (1999) reviewed the development of several car-following models, and it led to a discussion on car-following models by other experts (Boer, 1999, van Winsum, 1999). Some of the discussed models are mentioned below.

**Gazis-Herman-Rothery (GHR) Model**

The GHR model is one of the most well-known car-following models, proposed more than fifty years ago. It is represented by:

\[
a_n(t) = k v_n^m(t) \frac{\Delta v(t-T)}{\Delta x(t-T)}
\]

where \(a_n\) is the acceleration of vehicle \(n\) implemented at time \(t\) by a driver and is proportional to the speed \(v\) of the \(n^{th}\) vehicle, relative spacing \(\Delta x\), and relative speed \(\Delta v\) between the \(n^{th}\) and \((n-1)^{th}\) vehicles, assessed at an earlier time \(t-T\), where \(T\) is the driver reaction time. On the other hand, \(m\), \(l\) and \(k\) are constants to be determined.

**Safety Distance or Collision Avoidance Models**

This approach stems from Equation (2.2), with slight amendments to account for the different braking behaviour between the lead vehicle and following vehicle.

The component representing braking distance in Equation (2.2) is conservative, since it represents a situation where the leading vehicle comes to a complete stop instantaneously. However, in reality the leading vehicle also undergoes a braking process. A modified version of the safety distance is:

\[
S(t-T) = L + Tv(t) + \frac{v_{n-1}^2(t-T)}{2a_{n-1}(t-T)} + \frac{v_n^2(t)}{2a_n(t)}
\]

where the braking distance component is dependent on the braking behaviour of the leading vehicle (third term) and the reactive braking behaviour of the following vehicle (fourth term).
*Psychophysical or Action Point Models*

The Action Point Model is said to be the most justifiable formulation of car-following models (Brackstone *et al.*, 2002). The model is controlled by the presence of perceptual thresholds, based on changes in distance gaps/headways, relative speeds, and the visual angle of the vehicle ahead. These thresholds would then demarcate an area in the DX-DV space within which the driver is unable to pick up any changes in his dynamic state, and maintains a constant acceleration.

The model revolves around four thresholds (see Figure 2-2):

(a) Minimum desired following distance, termed $ABX$, under which drivers will find their vehicles too close with the leading vehicle. Following distance here can be defined as either the distance gap or headway (offset by leading vehicle length).

(b) Maximum desired following distance, termed $SDX$, beyond which drivers will find their vehicles too far away from the leading vehicle.

(c) Threshold for realising small negative relative speeds, termed $CLDV$, where drivers start to notice that they are closing in on the leading vehicle.

![Figure 2-2 Illustration of thresholds in Action Point Model](image)
(d) Threshold for realising small positive relative speeds, termed \( OPDV \), where drivers start to notice that they are lagging away from the leading vehicle.

When within the \( ABX \) and \( SDX \) thresholds, drivers find themselves to be following at an acceptable following distance. As pointed out by Boer (1999), drivers do not aim to optimise their driving behaviour but behave in a satisfying manner. Drivers are capable of evaluating and executing all possible driving strategies.

When within the \( CLDV \) and \( OPDV \) thresholds, the driver is unable to detect any changes in the visual angle of the leading vehicle and hence cannot tell if his vehicle is closing in to or lagging away from the leading vehicle. As such, he will maintain his current state of acceleration. Boer (1999) also pointed out that drivers use perceptual variables in decision making and control, instead of Newtonian variables which are key variables in other car-following models. It is logical that drivers can only react to changes only if they are able to perceive these changes.

The control of vehicle acceleration using the four action points result in a ‘spiralling’ behaviour in the \( \Delta v - \Delta x \) space, as shown in Figure 2-3.

![Figure 2-3 Car-following Spiral of the Action Point Model](source: Brackstone et al. (2002))
In addition, both $ABX$ and $SDX$ are functions of the dynamic speed of the vehicle, while $CLDV$ and $OPDV$ are functions of the spacing between the vehicles. When a threshold is reached, drivers start to perceive an unacceptable state of motion (too close, too far, too fast, or too slow) and reacts by changing the direction of acceleration (either accelerate or decelerate).

**Time Headway and TTC Model**

In a commentary by van Winsum (1999), he discussed drivers following a time headway that is independent of vehicle speed, and explained that the preferred following distance $D_p$ is given by:

$$D_p = t_p v_i$$  \hspace{1cm} (2.6)

where $t_p$ is the preferred time headway and $v_i$ is the vehicle speed. As long as the following distance is larger than $D_p$, there are no safety-related issues and drivers will travel at a preferred speed. However, once the following distance is smaller than $D_p$, there is a safety-related reason to decelerate to reach $D_p$. Thus, there should be distinction between the acceleration and deceleration states.

Deceleration behaviour is then dependent on TTC estimated by the driver, as given by:

$$a_i = cTTC_{est} + d + \epsilon$$  \hspace{1cm} (2.7)

where $a_i$ is the deceleration of the driver, $TTC_{est}$ is the TTC estimated by the driver, $c$ ($>0$) and $d$ ($<0$) are constants, and $\epsilon$ is a random error term. The equation is only valid for deceleration. The equation relates smaller $TTC_{est}$ with a larger negative $a_i$ (deceleration). The error term is due to the inaccurate prediction and control of the deceleration applied by the driver.
Again, the estimated TTC in the model is dependent on the driver’s judgement and may be different from the actual TTC.

2.3.2.5 Remarks
Car-following behaviour has direct implications on traffic safety and serves as an assessment basis that is more reliable than RTAs. The literature contains evidence that car-following behaviour is influenced by many factors but the effect of road tunnel environment has yet to be investigated. With the increasing implementation of underground road systems, it is timely to do so.

In order to evaluate traffic safety based on car-following behaviour, various extended-TTC measures of traffic safety have been proposed in the literature and car-following models can be derived. However, they require the analyses of individual vehicle trajectory data which are difficult and resource-intensive to obtain for a large number of vehicles to evaluate traffic safety.

Hence, for the assessment of traffic safety, extended-headway/gap measures such as opening charts and SM are more viable options.

2.3.3 Visual Attention
Humans are primarily receiving information about the environment from visual channels (Gifford and Ng, 1982). Driving is predominantly a visual task (Land, 2006, Owsley and McGwin, 2010) and safe driving requires drivers to allocate visual attention strategically (Crundall and Underwood, 2011). Experienced drivers have been found to scan the road scene more extensively than novice drivers in demanding dual-carriageways (Underwood et al., 2002) and this suggests that higher crash risk associated with novice drivers can be attributed to the inadequate allocation of visual attention. Apart from scanning the road scene, long glances away from the forward roadway (nominally more than two seconds) are also considered to be unsafe (Klauer et al., 2006, Kircher and Ahlström, 2012). In a study on change detection, it was found that drivers who took longer glances at road elements were more likely to detect changes and the greater the change was, the higher the rate of detection (Martens, 2011). This suggests that long glances to the forward roadway are also beneficial to hazard detection.
2.3.3.1 Visual Attention in Car-Following

For actual driving tasks in the real world, traffic conditions are varying and elements in the road scene are highly dynamic, thus it is important for drivers to pay attention to the road.

Many studies have investigated drivers’ eye movements in various contexts. Birrell and Fowkes (2014) evaluated the effects of using an in-vehicle driving aid on drivers’ glance behaviour on-road. They found that the use of the driving aid did not result in substantial deterioration of visual attention allocated to ‘critical’ areas in the road scene. ‘Critical’ areas are areas in the road scene where safety-relevant visual information can be found. However, they defined these ‘non-critical’ areas to be off-centre glances to the road scene, which is not necessarily true. As argued by Underwood and his colleagues in a series of studies on driver eye movement (Underwood et al., 2002, Underwood et al., 2003, Underwood, 2007), wider scanning of the road scene, as exhibited by experienced drivers compared to novice drivers, had positive effects of traffic safety, especially on urban streets. Hence, off-centre glances to the road scene should not be disregarded.

Driver eye glance behaviour during car-following was examined by Tijerina et al. (2004). Sixty participants drove an instrumented vehicle, without being supervised, on public roads and their eye movement behaviours were captured using video cameras. The results suggested that drivers did not take gaps or headways into account for deciding when to look away from the road ahead during car-following, implying that drivers believe the lead vehicle will not brake abruptly. The average duration of glances away from the forward roadway was 0.6 s and drivers glanced at the forward roadway 86% of the time (Tijerina et al., 2004). The distribution of glance locations were examined as well and it was found to vary with individual differences and speed regime.

Kircher and Ahlström (2012) conducted a driving simulator study to investigate the effects of tunnel design factors on driving performance. Eye tracker data from 28 participants were analysed and the glance behaviour was computed. The results suggested that light-coloured walls were more effective than strong illumination in keeping drivers’ visual attention to the forward roadway. In their experiment, the
participants were presented with scheduled incidents to observe the participants’
behaviour to these responses. However, general car-following behaviour was not
investigated in the study.

In a large scale 100-car naturalistic driving study, Klauer et al. (2006) analysed the
glance behaviour of the drivers in the five seconds prior and one second after the
onset of the precipitating factor in crashes and near-crashes. They found that
crashes/near-crashes were significantly more likely to occur if drivers had made off-
road glances in the 6-second interval, especially if the total off-road glance time was
longer than two seconds. This implies that RTA rates are related to the off-road
glance durations even in short 6-second intervals.

Wong and Huang (2013) examined data from the 100-car naturalistic driving study
and proposed the use of renewal cycles to analyse attention allocation. The renewal
cycle approach uses the forward roadway as the initial reference point, since
moving forward is the main activity of driving. A renewal cycle describes the driver
glancing at the forward roadway, making transitions to other focal points, and then
returning to the forward roadway. They found that 90.74% of drivers’ attention
allocations were 2-glance renewal cycles, suggesting that drivers separated lapses of
attention from the forward roadway into several sequences, a conscientious effort to
maintain a certain level of awareness to the forward roadway.

2.3.3.2 Remarks
Strategic allocation of visual attention is paramount to traffic safety. The literature
provides evidence that off-road glances are often related to RTAs – the longer the
off-road glance duration the more likely a RTA would occur. It is important for
drivers to have long glances to the forward roadway, especially in car-following. It
should also be noted that the forward roadway should be inclusive of off-centre
elements as well, since wide visual scanning is known to be beneficial to safety.

However, studies on driver visual attention in tunnels have not focussed on car-
following, which is most prevalent to rear-end collisions. Hence, there is a need to
address this gap in the literature and investigate how traffic safety in urban road
tunnels is related to drivers’ visual attention.
2.4 Driver Perception

In all driver behaviour models, driver perception plays an important role in modulating behaviour. Hence, it is essential to understand driver perception in order to explain driver behaviour. With regard to how drivers perceive the road tunnel environment, reference should be made to environmental psychology.

2.4.1 Environmental Psychology

Environmental psychology is the study of the interrelationships between environment and behaviour. Its work is stimulated by the existing problems in interactions between people and the environment they are in (Gifford, 2002). It was also mentioned that social design benefits the users of the particular facility by considering the needs and feedback of the users when designing the facility.

2.4.1.1 Environmental Perception

“Understanding how people perceive their environments is vital to the design process.” (Kopec, 2012).

Several texts on environmental psychology (Veitch and Arkkelin, 1995, Bell et al., 2001, Bechtel and Churchman, 2002, Kopec, 2012, Steg et al., 2013) agree that before an environment can be designed, it is important to understand how people perceive the environment.

Environmental perception is people’s general awareness and comprehension of the environment. It relies on experiences and psychological factors. Since humans are primarily visual by nature (Gifford and Ng, 1982), perceptions are highly dependent on vision and cues originating from the other senses. As a result, perception as a whole is more than the sum of its parts. Hence, the overall experience of a particular environment is difficult to fine-tune, and it may be sometimes difficult to explain why certain environments are preferred over others.

2.4.1.2 Landscape Preference Theories

Regarding landscape preferences, some evolutionary theories provide explanations linked to the landscape characteristics which enhanced the survival of early humans, while cultural theories relate preferences to social, cultural and personal traits (Tveit et al., 2013).
Three evolutionary theories state that (1) humans possess an ‘innate affinity for life and lifelike processes’ (known as biophilia hypothesis); (2) humans seek landscapes that serve as suitable habitats; and (3) humans seek places where they can see without being seen (known as prospect-refuge theory). As a result, humans have innate tendencies to seek contact with animals, plants, and natural landscapes.

Two cultural theories state that (1) humans prefer landscapes which they are familiar with and have experience in (known as topophilia); and (2) humans prefer landscape when they understand its ecological functions (known as the ecological aesthetic). As a result, humans prefer landscapes which they have learnt and understand.

In the context of road tunnels, it would be expected that road users do not prefer road tunnels due to the lack of nature (evolutionary theories) and familiarity (cultural theories).

2.4.1.3 Environment-Behaviour Theories
There are several environment-behaviour theories formulated since early days in the field of environmental psychology. Bell et al. (2001) discussed six perspectives on the environment-behaviour theories, which explain most of the important aspects.

First is the arousal perspective. Environments contain lots of stimuli which lead to arousal. Arousal also has influences on performance, as described by the Yerkes-Dodson law (see Figure 2-4). This law states that performance is maximal at a moderate, optimal level of arousal, and performance falls progressively when arousal falls or rises from this point. The rate at which performance deviates depends on the difficulty level of the task.

Second is the environmental load perspective. Humans have limited cognitive resources and when met with excessive amounts of information from the environment, humans experience information overload. The normal reaction to overload is ‘tunnel vision’, the devotion of available cognitive resources to the more relevant items while other inputs are ignored. Also, under prolonged periods of cognitive activity, cognitive resources are depleted temporarily and humans will experience directed attention fatigue, which is a state of mental exhaustion.
Third is the under-stimulation perspective. Apart from overload, humans can also suffer from the lack of sufficient stimulation. In this case the senses are deprived of stimuli, leading to boredom and errant behaviours.

Fourth is the adaptation level theory. The theory states that there are three categories of stimulation: sensory, social, and movement. And each category varies along three dimensions: intensity, diversity, and patterning. Each person has an optimal level of stimulation and when he is faced with a new environment, he is forced off the optimal point. However, after some time, the optimal point is shifted so that he feels comfortable in this new environment. This is called adaptation.

Fifth is the behaviour constraint perspective. When there is a loss of perceived control, humans feel discomfort and negative emotions. Initial reactions will be to reassert control over the situation. However, if it fails, learned helplessness is experienced.

Last is the environmental stress perspective. Among the many environmental stimuli exists stressors. Stimuli are first appraised. This primary appraisal evaluates impact or threat of the stimuli. Once a stimulus is recognised as a stressor, humans may experience stress in anticipation of danger (Veitch and Arkkelin, 1995), and the secondary appraisal takes place to assess coping strategies. In the meanwhile, stress responses involving the whole body occur to prepare to cope. Physiological changes are part of the stress responses.
Taking into consideration the six perspectives, Bell et al. (2001) came up with an eclectic model. Figure 2-5 illustrates the model, in a simplified interpretation.

![Figure 2-5 Eclectic model of environment-behaviour theories](Image)

Adapted from Bell et al. (2001)

In the urban setting, arousal and stimulus overload due to multiple stressors has been identified as a primary mechanism explaining negative responses (Bonnes et al., 2013). Bonnes et al. (2013) and van den Berg et al. (2007) also discussed that urban nature can help to reduce stress and mental fatigue and concluded that urban nature is a design option that promotes urban sustainability.
In addition, research also found that drivers have higher frustration tolerance levels in roads with more roadside vegetation, compared to a built-up environment (Cackowski and Nasar, 2003).

### 2.4.1.4 Theory of Planned Behaviour

The theory of planned behaviour (Ajzen, 2005, Steg and Nordlund, 2013) is one of the most popular models that explain environmental behaviour. It assumes that humans usually make reasoned choices and behave in a logical manner. An individual’s intention to perform a particular behaviour is the most influential determinant of that action. This intention is in turn dependent of three factors: attitude, subjective norms, and perceived behaviour control.

Attitude is the individual’s perception of the behaviour of interest, usually based on beliefs on the pros and cons of performing the behaviour. Positive attitudes towards certain behaviours increase the intentions to perform them.

Subjective norms reflect the individual’s beliefs regarding the expectations of others, and also the social costs and benefits of the behaviour. They are also based on the individual’s motivation to comply with these expectations. Greater motivation to comply with expectations influences the behaviour via intentions.

![Extended Theory of Planned Behaviour](image)

**Figure 2-6 Extended Theory of Planned Behaviour**
Perceived behaviour control refers to the individual’s perception of his ability to carry out the behaviour, taking into account various conditions which may affect his actions. Perceived behaviour control influences behaviour though intentions, as per the other two factors, and may also influence the behaviour directly.

Other than the three factors mentioned, the theory of planned behaviour has been extended by including personal norms as predictors. Personal norms refer to the feelings of moral obligation to adopt pro-environmental behaviour. Figure 2-6 illustrates the extended theory of planned behaviour model.

Hence, if the road tunnel environment is perceived as being different from typical open roads, it is very likely that the individual’s norms and attitude, and possibly the perceived control, will be different. Thus, to understand the behaviour of drivers in road tunnels, it would be necessary to investigate drivers’ perceptions of the road tunnel environment.

2.4.2 Tunnel Perception Studies

Several studies have examined drivers’ perceptions of the road tunnel environment. An early European study on tunnel driving (Serrano and Blennemann, 1992) reviewed that some drivers were nervous of driving too close to tunnel walls so they drove further out, thus increasing the risk of collision with oncoming vehicles in a two-way tunnel. There were instances of drivers not being able to continue driving due to claustrophobia. It was also reported that the average speed level in tunnels was lower than that of surface roads, though speeds still exceeded speed limits. One important observation was the distinct reduction of speed on the approach section due to a visual “narrowing-down” effect of massive portals. The same study also conducted an opinion poll on users of the Arlberg Tunnel. It was found that some drivers felt discomfort and “something special” while driving through tunnels. Reasons given by respondents included poor air quality, fatigue, boredom, poor lighting, claustrophobia and lack of safety. These findings were supported by another study of driver behaviour based on investigations in eight Norwegian road tunnels ranging from 2.3 km to 11.4 km, and road user interviews (Amundsen, 1994). In addition, a Singapore perception survey conducted on CTE users (Fan et al., 1992) reported that 25.8% of the tunnel users found driving in a tunnel
expressway more demanding than driving on an open expressway. Also, when there was a slowdown or a jam within road tunnels, motorists became worried very quickly, especially when the cause was unknown to them (Marec, 1996). This heightened sense of anxiety may result in unsafe and careless behaviour. Hence, it is important to make tunnels appear spacious to the motorists.

Following up on the opinion polls conducted by Serrano and Blennemann (1992) and Amundsen (1994), when road tunnels were still relatively new to motorists, a more recent survey (Arias et al., 2008) revealed that more than a decade later, motorists still experienced negative emotions when driving through tunnels. Arias et al. (2008) did questionnaire interviews on 458 drivers recruited from the city of Madrid (Spain). Darkness, noise and the geometry of tunnels were reported as stimuli that provoke unpleasant sensations, which then led to the perception that driving in tunnels was risky.

However, conventional perception surveys have usually involved the use of structured questionnaires and guided options. For instance, statements like “I feel safe driving in the tunnels” are usually followed by a five- or seven-point scaled option ranging from “Strongly Disagree” to “Strongly Agree”. In such questions, the category (feelings of safety) is stated upfront and respondents are only required to express their valence (level of agreeableness) towards the category. Although this type of question results in structured and objective responses which make the analysis procedure easier for the analyst, it does not take into consideration how strongly respondents associate to these categories or how strongly these categories are interconnected. The effectiveness of using scales is undermined when the predetermined categories do not reflect the underlying prevalence of each category. However, attempting to cover every plausible category would result in lengthy questionnaires and complicated analyses.

### 2.4.3 Free Association

One possible way to address the issue of predetermined categories is to employ the free association technique. The free association technique was first developed by Sigmund Freud as a therapeutic method to allow subjects to express their thoughts without any censorship by the rational mind (Rennison, 2001). The technique is
unrestrictive on the respondents and allows respondents to freely draw thoughts and recall relevant elements regarding the stimuli domain. The research will be able to measure the strength of the association between a given domain and the categories associated with it. The list of categories can also be used to portray the current perspective of the domain (Granié and Papafava, 2011). The responses provided by the respondents will be most strongly associated to the given domain and the most frequently associated categories can then be inferred to be the most prevalent characteristics of the domain to the respondents.

The technique and its variant forms: free listing and word association, have been used in various fields such as food quality (Rozin et al., 2002, Ares and Deliza, 2010, Guerrero et al., 2010, Hough and Ferraris, 2010), social science (Gaymard, 2006), and transport-related research (Granié and Papafava, 2011).

2.4.4 Remarks

Drivers’ perceptions of the road environment modulate their subsequent behaviours on the road. Thus, any differences in behaviour between different road environments can be attributed to differences in environmental perception. However, existing tunnel perception studies in the literature have employed conventional, close-ended survey approaches and hence the effectiveness of the surveys may have been undermined. Hence, open-ended survey approaches such as free association should be employed for road tunnel environments to add to the existing literature.

2.5 Summary

Two key concerns are found in the literature review regarding traffic safety in road tunnels. First, rear-end collisions are the most prevalent type of RTAs in unidirectional road tunnels. Second, RTA risk is highest at the tunnel portals. However, it is difficult to base traffic safety evaluations on RTAs alone and behavioural studies should be considered.

Driving is a complex task with real-world consequences. Driver behaviour was found to vary with different situations and it can be expected that drivers will behave differently in an entirely different road environment such as tunnels. A few
studies have examined driver behaviour in road tunnels but none have examined car-following behaviour, which is most relevant to rear-end collisions. In addition, drivers’ visual attention while driving is of paramount importance but so far there is yet any research on visual attention in urban road tunnels.

Driver behaviour models state that driver perception plays an important role in modulating behaviour. It is hence crucial to understand how motorists perceive road tunnels, since these environmental perceptions will be consequential to driver behaviour such as car-following and visual attention. However, conventional surveys use a bounded approach with predetermined categories and the effectiveness is undermined. Thus, alternative survey approaches should be explored.
CHAPTER 3 METHODOLOGY

This chapter will discuss the methods employed to carry out the various data collection and analyses to meet the research objectives laid out in Chapter 1. Overall, traffic safety will be holistically assessed on three levels: (1) accidentology; (2) driver behaviour; and (3) driver perception. The findings are presented in the following chapters.

3.1 Accidentology

RTAs are the most definitive indicators of traffic safety, i.e. traffic with fewer RTAs is safer. Hence, RTAs that occurred in urban road tunnels were examined.

3.1.1 Expressway tunnels

A study on RTAs that occurred along three expressway tunnels in Singapore (refer to 1.4.3) was conducted. Other road tunnels were not included in the study as their lengths were not substantial enough to be considered.

Figure 3-1 shows the individual tunnel geometries and locations of the on-off ramps, along with the indicative annual average daily traffic (AADT, based on available 2011 traffic data obtained from LTA). It should be noted that the southern end of the Chin Swee Tunnel is followed by a 300 m semi-tunnel (CTE 1.75-2.05 km). The semi-tunnel is in the form of an open depressed section and it is not considered as part of the tunnel in this study.

3.1.2 Data Basis

Conventionally, police accident records serve as fairly reliable sources of RTA data. Past RTA studies in Singapore (Halim, 2004, Thu, 2004, Kusumawati, 2008, Hau et al., 2010) had also been based on the police accident database. Police RTA data were obtained from the Traffic Accident Analysis and Management (TAAM) system, a GIS-based accident analysis software developed by the Singapore Land Transport Authority (LTA) to facilitate retrieval and analysis of RTA data obtained from the police. RTA data for CTE and KPE were extracted from TAAM, through a secure terminal located at LTA Road Safety Engineering Unit.
However, under the Non-Injury Accident Reporting Scheme in Singapore, motorists are only required to make a traffic accident report if the accident involves: (a) a government vehicle; (b) damage to government property; (c) a foreign vehicle; (d) a hit-and-run case; or (e) an injury where

- at least one person involved in the accident was taken to hospital from the accident scene by an ambulance; or
- at least one person involved was taken to hospital by other transport and subsequently hospitalised or given outpatient medical leave of three days or more; or
- no one was conveyed from accident scene to a hospital, but one or more persons involved subsequently required hospitalisation or outpatient medical leave of three days or more.

Figure 3-1 Plan views and indicative AADT of (a) Kampong Java; (b) Chin Swee; and (c) KPE Tunnels
Thus, police data do not contain most non-injury RTAs. In this study, RTA data were additionally obtained from incident records provided by LTA. The LTA Intelligent Transport Systems Centre (ITSC) and KPE Operations Control Centre (OCC) monitor traffic in the CTE and KPE Tunnels constantly through surveillance cameras installed throughout the tunnels.

Traffic incidents, which led to disruptions in traffic flow, were identified, investigated, and recorded. These incidents included road works, vehicle breakdowns, abandoned vehicles, vehicles out of gas, and RTAs. The police data containing information on RTA casualty were then merged with RTA data from these incident records, thus creating a more complete RTA database (especially for non-injury RTAs). Figure 3-2 illustrates the relationship between the two datasets.

![Figure 3-2 RTA data hierarchy](image)
The merging of the two datasets provided a complete record of all RTAs that occurred in the tunnels (all fatal, injury, and non-injury RTAs), with the most accurate injury reports (number of injured persons, fatalities, etc.). In this study, all RTAs were analysed. It should be noted that in Singapore, comprehensive incident records were only available for tunnel expressways and hence there is non-comparability between open and tunnel expressway accidents (from incident records).

Tunnel RTA data were provided for the study period of 2009 – 2011. In the three-year period, there were no notable changes to tunnel infrastructure or traffic management strategies. A total of 608 RTAs that occurred on the main expressway carriageways were examined in this study. RTAs that occurred on the slip roads (on-off ramps) along the corresponding carriageway were examined separately due to the varying characteristics of each slip road which may confound the results.

3.1.3 Zone Definition
The tunnel zones defined by Amundsen and Ranes (2000) and Ma et al. (2009) were likely to be applicable only for the specific tunnel contexts in their studies. Urban road tunnels may have different conditions which affect the length of the transition zones.

As such, a preliminary analysis of RTA rates in 50 m intervals was performed. It should be noted that the southern end of KPE Tunnel (chainage = 0 km) split into various slip roads. There was no observable increase in RTA rates in this area, suggesting that traffic safety was not significantly affected by such splitting.

It was observed that RTA rates begin to change significantly at some distance away from the tunnel portals, on both the inside and outside of the tunnels. Hence, three distinct zones were identified: (1) just outside the tunnel portal; (2) just inside the tunnel portal; and (3) the remainder of the tunnel. Figure 3-3 shows the plots from the 50 m-interval RTA rate analysis along the CTE and KPE Tunnels (vertical axes represent the number of RTAs in a 50 m interval).

However, the distance at which RTA rates changed significantly varied among the different tunnel portals (ranging from 50 to 200 m) and this suggested that a zonal
length of 250m would adequately encompass this distance. Also, 250 m is not excessively long such that the actual characteristics of each zone would be masked by overly averaged RTA rates.

![Diagram of RTA counts along CTE and KPE Tunnels](image)

**Figure 3-3 RTAs in 50 m intervals along (a) CTE and (b) KPE Tunnels**

Coincidentally, road signs informing motorists of the tunnel were placed about 250 m before the tunnel portal, which could be a possible trigger for the change in RTA rates in the defined zones. Tunnel zones in this study (see Figure 3-4) were defined as follows:

- **Zone 1 (Z1)**, exterior transition zone: 250 m in front of tunnel;
- **Zone 2 (Z2)**, interior transition zone: first 250 m into the tunnel; and
- **Zone 3 (Z3)**, interior zone: the remainder of the tunnel.
A fourth zone was not observed for the 50 m-interval RTA rate analysis and hence there was no Zone 4, unlike the other studies. Furthermore, Z2 already covers a substantial length of the tunnel adjoining the portal.

In addition, the 50 m-interval RTA rates did not appear to vary with the indicative AADT as shown in Figure 3-1. Hence, it was presumed that the varying traffic volumes along the length of the tunnel have negligible influence on the occurrence of tunnel RTAs.

### 3.1.4 Data Analysis

This study adopted a data mining approach to identify critical traffic safety areas in urban road tunnels. In this approach, no specific hypotheses were formulated or tested but instead the data were examined to discover consistent and noteworthy patterns of RTA occurrence in the road tunnels.

### 3.2 Driver Behaviour

Two key concerns were found in the literature review regarding RTAs in road tunnels. First, rear-end collisions are the most prevalent type of RTAs in unidirectional road tunnels. Second, RTA risk is highest at the tunnel portals. Hence, driver behaviour in the road tunnels was investigated to understand these concerns.

#### 3.2.1 Car-Following Behaviour

Car-following behaviour in both open and tunnel road environments was examined so as (1) to identify factors which affect how car drivers behave in unidirectional
car-following situations; and (2) to understand, from a microscopic behavioural perspective, how traffic safety in road tunnels is different from that in conventional open roads. Headways (temporal and spatial), TTC, and SM were applied in the analyses.

### 3.2.1.1 Data Basis

Traffic video footages were obtained for both open and tunnel expressways in Singapore. The main criterion for site selection was to have similar roadway characteristics in both environments. For open expressway, video footage was recorded from an overhead pedestrian bridge arching over the Ayer Rajah Expressway (AYE) at the 4.5 km mark (see Figure 3-5). This section of the AYE is relatively straight and consists of six lanes (three in each direction, separated by a central median). It is also relatively free from lane changing activity as the nearest intersection is more than one kilometre away. The speed limit of this road section was 90 km/h. Data were collected from a 25 frames-per-second video recorded on 18 September 2012, during the peak hour period from 1700 to 1900 h, for westbound traffic. The weather was good with no rain for the entire observation period. In order for the video camera recorder to be as inconspicuous as possible to minimise its influence on motorists’ behaviour, the “away” view was recorded (see Figure 3-6).

Figure 3-5 Data collection site for open road
For tunnel expressway, the selected site was the 5.4 km mark of the KPE Tunnel (see Figure 3-7). This section of the KPE is relatively straight and consists of three lanes in each tube – KPE Tunnel consists of dual unidirectional tubes. Lane changing activity was minimal since it is located mid-distance between an upstream off-ramp and a downstream on-ramp. The speed limit of this road section was 70 km/h at time of the data collection. The video footage was requested from the LTA KPE OCC, which monitors KPE traffic through 24-h traffic cameras. Data were collected from a 25 frames-per-second video recorded on 26 September 2012, during the evening peak hour period from 1700 to 1930 h, for northbound traffic. The external weather was good with no rain for the entire observation period. In the tunnels, the “away” view was also preferred (see Figure 3-8) because vehicle headlights in the frontal view tend to create a glare effect in the footage which compromises the quality of the video.
3.2.1.2 Data Extraction

A manual frame-by-frame approach was used for data extraction. Manual data extraction was performed for two reasons. First, the traffic cameras did not have sufficient height to provide an ideal plan view of the traffic. As a result, automated image processing/computer vision would not be able to detect vehicles properly. Second, existing automated methods were also unable to provide accurate vehicle classifications.
Two references lines 14 m apart were marked over the video image and the distance between the two lines was determined using the lane markings. The timestamps (with a resolution of 0.04 s) at which a vehicle passes each of the two reference markings were logged, along with the vehicle class (motorcycle MC, car, light goods vehicle LGV, or heavy vehicle HV) and the lane travelled. Rear-to-rear headways were used in this study instead of frontal headways (refer to Figure 2-1). In rare instances where the view of a vehicle was obscured, the timestamps were estimated by the observer. This video extraction approach had been validated in several traffic studies (Meng and Weng, 2011, Meng and Qu, 2012) and it was reported to effectively yield data of comparable quality to those obtained using the radar-speed measurement method (Strong et al., 2003).

3.2.1.3 Treatment of Lane Splitting Motorcycle (MC)
Lane splitting MC refers to a MC that travels in between traffic lanes (or in the case of exterior lanes, a MC that travels at the edge of the traffic lanes). It was assumed in this study that these MCs do not affect within-lane car-following behaviour in any significant way and were excluded from the analysis.

3.2.1.4 Identification of Car-Following Instances
Several studies used a critical headway approach to characterise car-following (Sayer et al., 2003, Brackstone et al., 2009, Shiomi et al., 2011). These studies only considered headways smaller than a defined threshold to represent car-following, while headways longer than the threshold were disregarded. However, critical headways were not suitable for application in this study due to several reasons. First, there is no evidence that a same critical headway applies to both open and tunnel road environments. Second, there is no evidence that the same critical headway applies to all vehicle classes, especially when heterogeneous traffic is being examined. Third, the study objective was to examine how various factors affect car-following and most of the measures would be derived from headways. By truncating the data based on headways, the results would be biased towards behaviour at smaller headways even though some drivers may choose to adopt larger headways in certain situations.
Instead, all headways were considered in this study and categorised by speed. When vehicle speed was lower than the imposed speed limit, it is reasonable to assume that the vehicle was experiencing some level of impedance and was in car-following mode. Furthermore, since the data were collected during peak hours when traffic flows were relatively heavy, the occurrence of non-car-following instances would be minimal.

### 3.2.1.5 Assessment of Headways

With the timestamps of two successive vehicles $t_n$ and $t_{n-1}$ ($n$ represents the order of the vehicle in which $n^{th}$ vehicle is the follower vehicle), the time headway $THW_n$ (refer to Figure 2-1) and vehicle speed $v_n$ can be determined:

\[
THW_n = t_{n,L1} - t_{n-1,L1}
\]

\[
v_n = D/(t_{n,L2} - t_{n,L1})
\]

where $n$ refers to the vehicle identification (assigned by the order of appearance), $L1$ the upstream reference line, $L2$ the downstream reference line, and $D$ the distance between the two reference markings. The length of $D$ used in this study was 14 m. Car-X (following leader, X denotes any vehicle class) headways were extracted from the entire dataset for analysis.

Data from both road environments were assessed using ANOVA to investigate whether the road tunnel environment has significant effects on headways. However, the data used in the ANOVA would depend on the data availability in various cells and consideration for the significance of underlying factors affecting headway choice. For this reason it was essential to identify these factors first.

The effects of speed, lane, and leader type were assessed using ANOVA in the first set of analyses.
### 3.2.1.6 Assessment of Time-To-Collision (TTC)

TTC is defined as the time taken for a collision to occur given that the vehicles of interest maintain their current states of motion which will result in a collision. Because vehicle lengths varied greatly among the different vehicle types, only TTC for cars as followers were considered. In order to determine TTC, the gap between vehicles was first obtained. The distance gap $DX$ between two vehicles is determined by:

$$DX_n = THW_n \times v_n - l_{car}$$

where the average car length $l_{car}$ is taken to be 4.5 m. TTC was then estimated using:

$$TTC_n = \begin{cases} 
\frac{DX}{DV}, & v_n > v_{n-1} \\
N.A., & \text{otherwise}
\end{cases}$$

where $TTC$ values are only existent in gaps where the follower’s speed is greater than the leader’s speed. If the leader is travelling faster than the follower, a rear-end collision between the two vehicles is rendered impossible.

The data points used in (Bifulco et al., 2013) were experimentally determined action points. However, the data points used in this observational study represent any point in the car-following spirals and not necessarily the action points. Nonetheless, these data points would statistically be spread symmetrically around the mean slope. Hence, a regression analysis of the slope would, in theory, produce a similar coefficient as compared to using action points only, with the main difference being a lower $R^2$ due to further spread of the data points around the regressed slope.
3.2.1.7 Assessment of Safety Margin (SM)

The determination of SM is given as:

\[
SM = 1 - \left( 0.15 \frac{v_n}{DX} + \frac{[v_n + v_{n-1}] |v_n - v_{n-1}|}{1.5g \times DX} \right)
\]  

(3.5)

where \(g\) is the acceleration due to gravity. The SMs for cars in each road environment were evaluated and the mean SM represents the desired SM of the drivers in the road environment. Furthermore, safe levels of headway are obtained when:

\[
\frac{v_n \times \tau_1}{DX} \leq SM
\]  

(3.6)

where \(\tau_1\) represents the driver’s response time, which is assumed to be one second. According to the studies on drivers’ brake reaction time (Warshawsky-Livne and Shinar, 2002, Makishita and Matsunaga, 2008), the average brake reaction time is close to one second.

The likelihood of ensured safety was also determined to evaluate traffic safety based on car-following. For each car-following instance, it was determined whether safe conditions were obtained. The likelihood was then derived as the proportion of car-following instances (car as followers) with safe levels of headway.

All statistical procedures were performed using IBM SPSS 21.

3.2.2 Drivers’ Visual Attention

Drivers’ visual attention in urban road tunnels was studied through a university-funded project entitled, “Driver behavioural adaptation to underground road conditions”.

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3.2.2.1 Participants

Participants were publicly recruited through flyers distributed at selected locations around Singapore. The flyers indicated that drivers had to have at least one year of driving experience, use their own cars for the experiment, and be in good physical and mental health. Drivers who met the requirements then registered their interest to participate either via a mail-back form or email address provided.

A total of 21 male drivers aged between 20 and 39 participated in the study. The mean age was 29.0 years (s.d. 4.35) and the mean reported driving experience was 6.9 years (s.d. 4.68).

3.2.2.2 Equipment

Eye tracker

In order to measure the participants’ eye movements while driving, a mobile eye tracker system was outfitted on the participants. Eye movement data were captured using the Mobile Eye XG (MEXG) developed by Applied Science Laboratories. The MEXG is a light-weight, head-mounted mobile eye tracker system, allowing the participant unrestricted head movements to carry out the driving task normally. It can be worn by subjects wearing glasses using an over-the-glasses frame. Figure 3-9 shows the MEXG glasses (weighs about 80 g) and over-glasses frame (about 95 g). Eye movement data were transmitted in real-time from the MEXG to an onboard laptop for remote recording.

The MEXG uses dark pupil tracking and has a sampling rate of 30 Hz. The MEXG relies primarily on two cameras – (1) an eye camera to capture images of the eye and (2) a scene camera to record the forward view of the subject. Three infra-red lights are beamed onto the cornea and their reflections, known as corneal reflections (CR), are captured along with the eye image, as shown in Figure 3-10 (a).
The system then detects the pupil and corneal reflections, through monochromic contrasts, as shown in Figure 3-10 (b). As the gaze location changes, the position of the pupil and CR changes as well, and the gaze position is determined using the positions of the pupil and CR.

Figure 3-11 shows the eye movements and relative positions of the pupil and CR, when the eye is looking towards various directions.

Upon calibration, the MEXG computes the participant’s point of gaze (POG) with an accuracy of one degree visual angle.
For more background information on eye tracking, refer to Appendix A.

![Figure 3-11 Image of eye looking to the: (a) right; (b) left; (c) top; (d) bottom](image)

**Vehicle**

Participants used their own vehicles in the study. It was reasoned that unfamiliarity with the vehicle environment may result in excessive allocation of visual attention to the vehicle environment such as the dashboard and controls. Hence, it was deemed necessary for the participants to be familiar with their vehicles when capturing eye movement data relevant to the actual visual attention behaviour while driving.

**3.2.2.3 Procedure**

Each participant first reported to NTU Transport and Geospatial Laboratory. The participant was given a Participant Information Sheet and received a briefing on the driving tasks that were required.
After written consent was obtained from the participant, the MEXG was mounted on the participant with the help of a researcher. The calibration of the MEXG was performed using the 9-point calibration procedure.

The participant and two researchers then proceeded to move into the car. One researcher was seated in the front passenger seat to provide driving instructions and help to look out for potential hazards. The other researcher was seated in the back passenger seat to monitor and manage the data acquisition equipment.

The participants were asked to drive along a predetermined route and were instructed to drive as they would normally, while directions and instructions would be given by the onboard researcher along the way. The route is shown in Figure 3-12. The route consisted of two legs. In the first leg, the participant drove from NTU campus (labelled ‘A’) to East Coast Parkway (ECP, labelled ‘G’), via various expressways including the full length of KPE (labelled ‘F’). The participant then rested for about 15 minutes at ECP, before commencing the second leg, which was from ECP back to NTU in the reverse direction. The total distance travelled per session was about 100 km.

For most parts of the route, except for the stretch between points ‘A’ and ‘B’ (familiarisation period), and location ‘C’ (lane changing required to stay on route) in Figure 3-12, the participants were asked to stay in the middle lane without making any lane changes.

Eye movement data were recorded for the roadway of interest, that is, the KPE Tunnel. Sample eye movement data can be found in Appendix B.

After returning to NTU, the MEXG was dismounted from the participant and the participant was asked to complete a NASA-TLX questionnaire, which will be described in the later Section 3.3.2.

At the end of the entire session, a S$100 honorarium was issued to the participant as a token of appreciation for his time. Each session lasted about 2.5 to 3 h, depending on traffic conditions and the rate at which equipment calibration was performed.
3.2.2.4 Data Analysis and Dependent Variables

Since the literature suggests that RTA risk is relatively higher in the tunnel portal areas (and especially at tunnel entry, as discussed later in Chapter 4), while RTA risk is significantly lower in the tunnel interior, this study examined drivers’ visual attention in two zones: (1) tunnel entry and (2) tunnel interior. And since rear-end collisions are the most prevalent crash type, only eye movements during car-following were considered for the analyses, as per Tijerina et al. (2004).

Glare is known to be a major issue in on-road studies (Taylor et al., 2013), due to the strong ambient light from the environment (eye tracking technologies rely heavily on the detection of reflections). Hence, it is difficult to record eye movement data in daytime open road environment. Fortunately, since the tunnel environment has relatively dimmer ambient light, recorded eye movement data would be highly stable and reliable.

As such, one-minute intervals (epochs) were extracted from the eye movement data for both the tunnel entry and interior zones. The onset of epochs in the tunnel entry zone was the northern portal of the KPE Tunnel during southbound travel (first leg of data collection). The onset of epochs in the tunnel interior zone was not limited to any specific location but was generally taken to be at least two minutes away...
from the tunnel portals, to avoid any confounding effects in transition. The southern end of the KPE Tunnel was not used because the main tunnel expressway diverged into smaller slip roads and did not provide consistency in the cross section of the roadway. Figure 3-13 illustrates the zone definition for the epochs extracted.

In addition, epochs for the tunnel interior zone were sampled twice (Tunnel Interior I and Tunnel Interior II) for each participant, whenever possible. Eye movement behaviour would be compared between tunnel entry zone and Tunnel Interior I to investigate any behavioural differences due to zonal effects. Also, eye movement behaviour would be compared between Tunnel Interior I and Tunnel Interior II to examine the relative behavioural consistency in the tunnel interior zones. No significant differences in behaviour would be expected between the two interior zones.

![Figure 3-13 Zone definition for epochs](image)

The data from all participants were examined for car-following instances in both tunnel entry and interior zones. However, one of the greatest limitations of controlled on-road studies (Carsten et al., 2013) is that it is not possible to absolutely control factors such as weather and traffic conditions. As such, if during the data collection there were no vehicles in front of the participant’s car in the defined zones, no car-following epochs would be available. Hence, only a subset of the participants provided valid data.
The eye movement data came in two forms: (1) the scene video; and (2) the data log file with coordinates of the point of gaze (POG) in the scene video. Playback in the ASL Plus analysis software allowed the POG to be overlaid in the scene video. A frame-by-frame glance analysis was performed in accordance to ISO 15007 (International Organisation for Standardisation, 2002), which defined glance duration as the time from the moment at which the POG moves towards an area-of-interest (AOI) to the moment it moves away from it. The defined AOIs in this study were the forward roadway (F), rear-view mirror (M), left mirror (L), right mirror (R), and in-vehicle dashboard (D). These AOIs are illustrated in Figure 3-14.

![Figure 3-14 Definition of AOIs](image)

Similar to Birrell and Fowkes (2014), the dependent variables considered in the glance analysis were glance frequency, glance duration, and glance transitions. Glance frequencies to each AOI were compared between the tunnel zones. Glances to the forward roadway were considered most critical in safe driving (on-road glances) while glances to other AOIs were considered as off-road glances. In the computation of average glance duration, glances to AOIs other than the forward roadway were aggregated as off-road glances (OFF).

As for glance transitions, the assessment was based on renewal cycles (Wong and Huang, 2013). A renewal cycle begins with a glance to the forward roadway and ends with the glance just before the next glance to the forward roadway.
3.3 Road User Perceptions

According to environment-behaviour theories, behaviour is a manifestation of the individual’s perspectives and perceptions of the environment. The theory of planned behaviour (Ajzen, 2005, Steg and Nordlund, 2013) indicates that behaviour is indirectly modulated through intention by personal norms, attitude, subjective norms, and perceived behavioural control.

This section covers a discussion of various methodologies adopted to investigate the effect of urban road tunnel environment on driver perspective and quality needs, and how it might be linked to driver behaviour in urban road tunnels.

3.3.1 Free Association Survey

3.3.1.1 Questionnaire and Dissemination

The two domains in this study were the open and tunnel expressways, and the categorical associations were to portray the most prevalent roadway qualities in the driver perspectives. Semi-open expressways were not considered due to the lack of substantial presence in the Singapore road network.

A questionnaire consisting of three sections was administered. Section I asked the respondent to imagine driving on an open expressway and to list the first five words, thoughts, feelings, or expressions that came to mind. Similarly, Section II required the respondent to imagine driving in a tunnel expressway and to list the first five responses that came to mind. However, it was not compulsory for respondents to list a total of five responses for each of Sections I and II.

Section III asked for the respondent’s age group, gender, driving experience, and frequency of road tunnel usage. As different from the approach used by Granié and Papafava (2011), where respondents were divided into two groups and each group provided responses to a single stimulus, this study required all respondents to provide responses to both stimuli of open and tunnel expressways. Also, respondents were asked to rate on a scale of one (dislike) to five (like) their overall experience in each of the road environments.
The questionnaire was disseminated via three modes, in sequential order: online open participation (respondents mostly aged 18 to 30 years), mail-back forms with URL link for online version (placed on the windshields of parked cars in various car parks, 4.5% mail-back response rate, respondents mostly aged 18 to 45 years), and face-to-face interviews (conducted near car-parks, aimed at respondents aged 31 to 60 years, with near-complete response rate). In all three modes, especially face-to-face interviews, it was ensured that the respondents were not provided with any form of guidance in their responses. These three modes were used in order to engage sufficient respondents for each age group.

To minimise order effects, respondents were randomly assigned questionnaires which presented sections in the order of either I-II-III or II-I-III, in an unsystematic manner.

3.3.1.2 Respondents
Since free association relies on a memory recall function based on the stimuli presented to the subject, only complete questionnaires filled in by drivers who drove on a regular basis (identified through the respondent particulars) were considered in this study.

After filtering the questionnaires, there were a total of 114 questionnaires completed by active drivers who drove on a regular basis. Table 3.1 shows the distribution of respondents by gender, age group, and tunnel usage frequency. No significant differences were found in the distribution of respondents between males and females, $\chi^2 = 1.658$ $df = 8$, $p = 0.9898$.

3.3.1.3 Data Analyses
A combined total of 1,107 responses were collected from both Sections I (551) and II (556), yielding an average of 9.884 responses per respondent, (4.92 for Section I, 4.96 for Section II). Also, out of the 114 respondents, 55 (47.3%) were presented Section I before Section II; while the other 59 (52.7%) were presented Section II first. These responses were coded into categories for analyses. First, the mean frequencies of associations to each domain were compared using paired two-tail t-
tests, for each category. Holm-Bonferroni corrections for multiple comparisons were made to control the family-wise error rate at $\alpha = 0.05$.

### Table 3.1 Distribution of Respondents by Gender, Age, and Tunnel Usage Frequency

<table>
<thead>
<tr>
<th>Tunnel Usage*</th>
<th>Male Age (Years)</th>
<th>Female Age (Years)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18-30 31-45 46-60</td>
<td>18-30 31-45 46-60</td>
<td></td>
</tr>
<tr>
<td>Frequent</td>
<td>15 8 3</td>
<td>5 3 1</td>
<td>35</td>
</tr>
<tr>
<td>Occasional</td>
<td>19 7 3</td>
<td>8 2 1</td>
<td>40</td>
</tr>
<tr>
<td>Rare</td>
<td>13 6 7</td>
<td>6 4 3</td>
<td>39</td>
</tr>
<tr>
<td>Total</td>
<td>47 21 13</td>
<td>19 9 5</td>
<td>114</td>
</tr>
</tbody>
</table>

*Frequent=Several times a week or more; Occasional=Several times a month; Rare=Several times a year or less

Second, multidimensional scaling analysis was performed to map the categories and their inter-correlations onto a two-dimensional plot.

Third, one-way ANOVA was performed on the response valences to investigate the effects of tunnel usage frequency on the tendency to provide positive or negative responses. In addition, the relationship between the respondent valences and self-reported ratings for each expressway type was investigated to find out if response valences could indeed be used to understand the respondents’ attitudes towards each domain.

### 3.3.1.4 Encoding

The responses from Sections I and II were encoded into their respective categories and valences. Similar to the free association study on food by Rozin et al. (2002), the categories were not determined before data collection. Instead, the categories were generated using the data collected. For each response, it was determined which existing category it would best belong to. If none of the existing categories sufficiently described the response, a new category was generated by the first encoder. Thus, the categories generated by this approach were, in principle, mutually exclusive.
Based on the responses from both Sections I and II for all respondents, 22 categories were generated. The individual categories, along with their definitions and some common responses associated with them are listed in Table 3.2. It should be noted that in rare cases where responses were considered to be associated to more than one category, multiple associations were coded for these responses.

In addition, the response valences were considered. Each response could either be a positive, neutral, or negative association to the categories. For instance, the response “traffic congestion” was assigned a negative valence in the category TRAFFIC CONDITION. On the other hand, “cruising” was assigned a positive valence in the same category. Neutral valences were assigned to responses such as “speed”, “safety”, “lights”, and “weather”, which were nouns which did not offer any description to the associated category.

The next part of the analyses considered the categorical valences. Positive associations were given each a valence of +1, negative associations each a valence of −1; and neutral associations valences of 0. The categorical valences were tallied to obtain the overall valences for individual respondents corresponding to each of the two road environments. The overall categorical valence measures the overall tendency of the respondent to give positive or negative responses.

Because the encoding process was dependent on the encoder’s judgement, it was prone to subjective bias. In order to account for subjective bias, the reliability of the encoding had to be examined. As in the study by Granié and Papafava (2011), after all the responses were encoded by the first encoder, a second encoder encoded 25% of the data (277 responses) selected at random. The second encoder categorised the responses using the definitions listed in Table 3.2.

An interrater reliability analysis using the Kappa statistic was performed to determine consistency among the encoders. The reliability analysis was performed twice – once for the categorical associations, and once for the response valences. For the categorical associations, it was found that Kappa = 0.803, p < 0.001. For the response valence, it was found that Kappa = 0.854, p < 0.001. The Kappa values of greater than 0.80 indicate good interrater reliability.
<table>
<thead>
<tr>
<th>Category</th>
<th>Definition</th>
<th>Common words</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SPEED</strong></td>
<td>Responses related to speed</td>
<td>fast, slow</td>
</tr>
<tr>
<td><strong>ROAD</strong></td>
<td>Responses related to the physical road pavement</td>
<td>smooth, bumpy, lanes, straight</td>
</tr>
<tr>
<td><strong>OTHER MOTORISTS</strong></td>
<td>Terms related to motorists other than the subject</td>
<td>reckless drivers, cars, inconsiderate drivers, road-hog</td>
</tr>
<tr>
<td><strong>TRAFFIC CONDITION</strong></td>
<td>Words describing the state of traffic</td>
<td>congestion, jam, cruising, too many cars</td>
</tr>
<tr>
<td><strong>SAFETY</strong></td>
<td>Words related to the act or state of safety</td>
<td>safe, dangerous, accident, caution</td>
</tr>
<tr>
<td><strong>EMOTION</strong></td>
<td>Feelings or expressions that describe an emotion</td>
<td>happy, uncertain, claustrophobic, relaxed</td>
</tr>
<tr>
<td><strong>PURPOSE</strong></td>
<td>Expressions related to the purpose of the trip</td>
<td>going to work, will I be late</td>
</tr>
<tr>
<td><strong>COST</strong></td>
<td>Terms that relate to the costs of travel</td>
<td>electronic road pricing (ERP), petrol, expensive</td>
</tr>
<tr>
<td><strong>SCENERY</strong></td>
<td>Items in peripherals &amp; words describing them</td>
<td>trees, wall, greenery, orangey (referring to colour of lighting at tunnel entrance)</td>
</tr>
<tr>
<td><strong>ENFORCEMENT</strong></td>
<td>Words related to traffic enforcement</td>
<td>traffic police, speed cameras, speed limit</td>
</tr>
<tr>
<td><strong>SPACE</strong></td>
<td>Words related to spatial dimensions</td>
<td>long, wide, narrow, width, enclosed, open</td>
</tr>
<tr>
<td><strong>TEMPERATURE</strong></td>
<td>Adjectives for temperature</td>
<td>hot, cooler</td>
</tr>
<tr>
<td><strong>LIGHT</strong></td>
<td>Words related to lighting</td>
<td>lighting, dark, brightness, headlight</td>
</tr>
<tr>
<td><strong>CONTROL</strong></td>
<td>Includes manoeuvres and vehicular control</td>
<td>overtake, slow down, accelerate, lane change</td>
</tr>
<tr>
<td><strong>SIGNAGE</strong></td>
<td>Words related to road signs &amp; traffic information</td>
<td>signage, EMAS (traffic information), blocked signs</td>
</tr>
<tr>
<td><strong>WEATHER</strong></td>
<td>Includes weather effects</td>
<td>raining, sheltered, flooding</td>
</tr>
<tr>
<td><strong>SIGHT DISTANCE</strong></td>
<td>Responses related to the ability to see</td>
<td>visibility, unobstructed, clearer view</td>
</tr>
<tr>
<td><strong>RECEPTION</strong></td>
<td>Words related to radio or GPS</td>
<td>radio, GPS, reception</td>
</tr>
<tr>
<td><strong>SOUND</strong></td>
<td>Includes sounds &amp; their adjectives</td>
<td>noisy, music, sound, echo</td>
</tr>
<tr>
<td><strong>EXITS</strong></td>
<td>Responses containing “exit”</td>
<td>exits, looking for exits, which exit to use</td>
</tr>
<tr>
<td><strong>AIR</strong></td>
<td>Words related to air quality</td>
<td>ventilation, smoky, fresh air</td>
</tr>
<tr>
<td><strong>OTHERS</strong></td>
<td>Uncommon words not in any other categories</td>
<td>food, wheel</td>
</tr>
</tbody>
</table>
3.3.2 Driver Task Load

In addition to the free association survey, a task load survey was conducted to investigate the perceived driver task load in open and tunnel expressways. Drivers were asked to complete the National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire after driving through open and tunnel expressways.

3.3.2.1 Participants

A total of 21 male drivers aged between 20 and 39 years completed the questionnaire. The mean age was 29.0 years (s.d. 4.35) and the mean reported driving experience was 6.9 years (s.d. 4.68). These participants were same as those described in Section 3.2.2.1.

3.3.2.2 NASA-TLX Questionnaire and Procedure

The NASA-TLX is a subjective, multidimensional psychometric assessment tool that was developed in the 1980s and refined over the years (Hart and Staveland, 1988, Hart, 2006). The current NASA-TLX consists of six dimensions: mental demand, physical demand, performance, temporal demand, effort, and frustration. The definitions of these dimensions and the questionnaire administered can be found in Appendix C.

At the end of the driving session as described in Section 3.2.2, the participants were asked to complete the questionnaire. The participants had carried out similar tasks on the open and tunnel expressways – remaining in the centre lane of a three-lane carriageway, without lane changing.

The evaluation procedure consisted of two parts. The first part required the participants to determine how much weightage each dimension should constitute for the driving task. This was achieved by doing pairwise comparisons for the six dimensions. For each pair of dimensions, participants selected the dimension which he felt contributed more to the workload of the task. After fifteen possible pairs had been completed, the number of selections for each dimension was tallied and its weight was computed by dividing the tallies by 15.
Since the task was the same for both open and tunnel expressways (normal driving activity), the component weights of workload for both environments would be the same for each participant. Thus, the first part of the evaluation procedure was required once and the computed dimension weights were applied to dimension ratings.

The second part required the participants to report numerical ratings for each dimension, to reflect the magnitudes of the dimensions experienced. Each dimension was represented by a horizontal scale divided into 20 equal intervals, anchored by bipolar descriptors. Subjects then marked out on each scale his rating for that dimension. The overall workload score was obtained by computing the sum of the weighted ratings for each dimension.

The dimension ratings were expected to be different between the two environments. Thus, the second part of the evaluation procedure was required twice – once for open expressways; and once for tunnel expressways.

Overall, two separate workload scores were then computed for each subject using the subjective weights and ratings, one for each environment.

3.3.2.3 Data Analysis

The average weight of each dimension was examined to understand how drivers perceived the driving task, and which dimensions served as the main sources of workload in the driving task.

In order to find out if there were any differences in the perceived workload between the two road environments, paired-sample $t$-test was performed on the overall workload scores.

In addition, the individual dimension ratings were also assessed to gain insight into the underlying sources of workload for the drivers. Again, paired-sample $t$-tests were performed for each dimension.
CHAPTER 4 ACCIDENTOLOGICAL ANALYSIS

A version of this chapter has been published in *Tunnelling and Underground Space Technology* (Yeung and Wong, 2013). The published version can be found in Appendix D.

This chapter will present the results and discussions obtained from the analysis of the RTA data. The methodological details can be found in Section 3.1. All of the RTA analyses were based on a data period of three years (2009 – 2011).

The aggregated (Zone 1 + Zone 2 + Zone 3) mean RTA rates (per year per km) for the Kampong Java, Chin Swee, and KPE Tunnels are 38.67, 26.52 and 10.85, respectively. It appears that the mean RTA rate decreases as tunnel length increases. The annual aggregated RTA rates for each tunnel were also used to compute the variance-to-mean ratios. The ratios for the Kampong Java, Chin Swee, and KPE Tunnels are 3.01, 1.87, and 2.36, respectively. The ratios are all within the 95% confidence interval [0.025, 3.689] (Nicholson and Wong, 1993) and hence the RTAs can be considered to follow a Poisson process, i.e. the occurrence of each RTA was independent of the preceding RTAs.

4.1 RTA Rates in each Zone

The definitions of the zones are found in Section 3.1.3.

The RTA rates (aggregated for both directions) in each of the defined zones for the CTE and KPE Tunnels were determined and are shown in Figures 4-1 and 4-2, respectively. It should be noted that the southern end of KPE Tunnel split into various slip roads and hence Z1 and Z2 were only defined for the northern end of KPE Tunnel. For convenience, zones with prefixes N and S will denote northern and southern zones, respectively.

Since the traffic conditions of each expressway were different (CTE Tunnels generally have higher AADT, refer to Figure 3-1), it was not appropriate for comparisons to be made for the respective zonal RTA rates between the two expressways. Hence, comparison was made only among the zones within each expressway.
RTA rates were generally higher in the transition zones (Z1 and Z2) than the interior zones (Z3). However, there was no consistent indication of whether Z1 or Z2 had higher RTA rates. Whereas Z1 exhibited substantially higher RTA rates than Z2 for the shorter CTE Tunnels, this pattern was somewhat reversed for the longer KPE Tunnel.

Figure 4-1 RTA rates for CTE tunnel group

Figure 4-2 RTA rates for KPE Tunnel
If the Kampong Java Tunnel and Chin Swee Tunnel are to be considered as a tunnel group, it is evident that RTA rates were relatively much higher at the two external transition zones of the tunnel group, as compared to the internal transition zones. This suggests that there are certain factors in the transition zones which lead to more RTA occurrences. In order to probe further, the RTA rates were disaggregated, by travel direction.

4.2 RTAs by Travel Direction

Chi-square tests were performed to investigate if there is any effect of travel direction on the RTA occurrences. If there was no effect of travel direction on the RTA occurrence, then the likelihood of the RTA occurring in the NB tube should be the same as the SB tube, i.e. \( H_0: p_{NB} = p_{SB} = 0.5 \). Chi-square tests were carried out for each expressway tunnel zone and the findings are presented in Table 4.1.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Kampong Java</th>
<th>Chin Swee</th>
<th>KPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NB</td>
<td>SB</td>
<td>( x^2 )</td>
</tr>
<tr>
<td>NZ1</td>
<td>6</td>
<td>44</td>
<td>28.88</td>
</tr>
<tr>
<td>NZ2</td>
<td>5</td>
<td>20</td>
<td>9.000</td>
</tr>
<tr>
<td>Z3</td>
<td>18</td>
<td>4</td>
<td>8.909</td>
</tr>
<tr>
<td>SZ2</td>
<td>15</td>
<td>4</td>
<td>6.368</td>
</tr>
<tr>
<td>SZ1</td>
<td>14</td>
<td>15</td>
<td>0.034</td>
</tr>
</tbody>
</table>

The results indicated that, at 5% significance level, RTAs occurred more often in the NB tube than SB tube at SZ1 of Chin Swee Tunnel, as well as SZ2 and Z3 of Kampong Java Tunnel. On the other hand, there was higher likelihood for RTA to occur in the SB tube than NB tube at NZ1 and NZ2 of the Kampong Java Tunnel and KPE Tunnel.

Figure 4-3 shows the disaggregated RTA rates in each zone for the three tunnels. Four observations can be made. First, RTA rates were notably the highest at the first instance of entry into the road tunnels. This implies that some conditions exist in the entry transition zones, resulting in the highest RTA rates across the tunnels.
Second, RTA rates were the lowest in the interior zones. This means that once drivers have passed the transition zones into the tunnel environment they seem to drive more carefully and are less prone to RTA. Comparison with open roads was not possible since there were no corresponding figures available for RTA rates on open roads which include non-injury RTA. However, since incident tracking by KPE OCC extended to the entire KPE, a limited comparison could be made to the

Figure 4-3 RTA rates by travel direction for (a) CTE Tunnels; (b) KPE Tunnel

Second, RTA rates were the lowest in the interior zones. This means that once drivers have passed the transition zones into the tunnel environment they seem to drive more carefully and are less prone to RTA. Comparison with open roads was not possible since there were no corresponding figures available for RTA rates on open roads which include non-injury RTA. However, since incident tracking by KPE OCC extended to the entire KPE, a limited comparison could be made to the

Figure 4-3 RTA rates by travel direction for (a) CTE Tunnels; (b) KPE Tunnel
open section of KPE, which has 108 RTAs (41 NB; 67 SB) over 3.15 km (KPE 8.60-11.75 km), aggregating to a mean RTA rate of 11.43 per year per km (4.34 NB; 7.09 SB). The KPE Tunnel interior zone had lower RTA rates (6.30 per year per km; 2.72 NB; 3.58 SB) than the open road sections. However, SZ2 and Z3 of the NB Kampong Java Tunnel had rather high RTA rates compared to the rest of the tunnel. This abnormality was likely related to the change in number of lanes from three to four beginning in SZ2, which was exclusive to the NB Kampong Java Tunnel.

Third, RTA rates increased slightly when exiting the tunnels. This implies that exit transition zones also contain some conditions which increase RTA likelihood, though the effect is not as strong as the entry transition zones. RTA rates during tunnel exit were several times lower than RTA rates during the first instance of tunnel entry.

Last, subsequent re-entry into an ensuing tunnel (for CTE Tunnels) was associated with relatively lower RTA rates as compared to the first instance of tunnel entry. This suggests that drivers may have retained certain levels of adaptation to the transition zones.

Figure 4-4 shows the mean zonal RTA rates for a unidirectional road tunnel, excluding data from the NB Kampong Java Tunnel as it had an additional lane as compared to the other tunnels in the study.

Based on the RTA data available, it was not possible to deduce the reasons for high RTA rates in the transition zones. However, crash factors were available in police data, which reported the causes for injury RTAs. The most common causes were (1) drivers failing to keep a proper lookout; (2) drivers following too closely to the vehicle in front; and (3) drivers changing lanes without due care. These causes provide indicative reasons for RTA occurrence but do not explain the localised RTAs that occurred in the transition zones.

Four possible explanations for the higher RTA rates in transition zones were explored: (1) differences in speed limits between the open and tunnel sections; (2) drivers having poor adaptation to different luminance levels; (3) difficult road
gradients in the transition zones; and (4) differences in driving behaviour between open and tunnel sections.

First, the speed limits in the open sections north of KPE Tunnel and Kampong Java Tunnel were 10 km/h higher than those in the tunnels. This might have resulted in greater speed differentials which are recognised as factors influencing RTA likelihood, between vehicles in the transition zones. However, the open sections between the CTE Tunnels and south of Chin Swee Tunnel have similar speed limits to the tunnels but the respective transition zones still exhibited high RTA rates. This renders the effects of differing speed limits questionable.

Second, drivers might be poor at adapting to the different luminance levels in the different environments, especially the black hole effect. The black hole effect refers to the impairment of visual perception, along with motor control, when transiting from an optically brighter region to a darker region. However, the expressway tunnels in Singapore were designed to address the black hole effect (NYX Hemera Technologies Inc., 2010). According to KPE Tunnel specifications, the design minimum luminance at road surface level is 5 lux during the day and 2.5 lux at night. However, in situ static luminance measurements were not feasible in the in-
operation tunnels. Instead, alternate measurements were performed using a light metre placed on top of a car (about 1.4 m above road surface) driving through the tunnels. Interior zone luminance was found to be 100-200 lux; luminance levels in transition zones were higher than interior zones but the reading were not stable due to high variation. Nonetheless, it can be observed in Figure 4-5 that the transition zones are adequately bright, thereby minimising the black hole effect. It should also be noted that, sun angle and direction were not considered to be critical since both tunnels ran in the North-South direction.

![Image of tunnel zones with labels](image)

Figure 4-5 Various tunnel zones: (a) Zone 1; (b) entry Zone 2; (c) Zone 3; and (d) exit Zone 2

Third, road gradients might be difficult for drivers to manage. Since the transition zones connect at-grade open road sections to subgrade tunnel sections, there will be road gradients. Steep roads may result in poor speed control due to gravitational
effect. However, the transition zones in Singapore are mild in gradient and impairment of speed control would be unlikely. All roads in Singapore are designed according to the LTA Civil Design Criteria (Land Transport Authority, 2010), which states that the absolute maximum grade for expressways is 5%.

Fourth, driver behaviour on open roads and tunnels may be different. It is possible that drivers perceive tunnels in ways different from open roads and adopt a set of different behaviours when they are in road tunnels, regardless of the luminance level or speed limits. The change in driving behaviour may occur in the transition zones and hence result in RTAs. However, little is known about driver behaviour in urban road tunnels and hence there is a need to conduct research in the area.

In the absence of additional data, the explanations are speculative and justifications will require in-depth analysis of RTA in the transition zones.

4.3 RTA Type in each Zone

To gain better perspective on the type of RTA in each zone, the RTAs were further disaggregated by crash type – single vehicle crash (SVC) or multi-vehicle crash (MVC). SVCs are RTAs due to self-skid, loss of vehicle control, without the involvement of other vehicles. MVCs are RTAs involving at least two colliding vehicles.

Figure 4-6 shows the SVC and MVC rates in the respective tunnels, disaggregated by travel direction. It is observed that SVC rates were fairly low and stable across the tunnel zones, averaging 3.76 RTA per year per km for the CTE Tunnel group and 0.91 for KPE Tunnel. Thus, the differences in RTA rates among the various zones could be attributed to MVCs. The transition zones appear to impair drivers’ ability to cope with inter-vehicle interactions.

Figure 4-7 shows the mean zonal SVC and MVC rates for a unidirectional road tunnel, excluding data from the NB Kampong Java Tunnel. About 21% of the RTAs were SVCs; the remaining 79% were MVCs. This suggests that interactions among vehicles, such as following too closely to each other, are important RTA contributory factors.
Figure 4-6 SVC and MVC rates for (a) CTE Tunnels; and (b) KPE Tunnel
4.4 RTA Casualty Likelihood

The severity of RTA is another aspect to be considered. There were only one fatal RTA and two serious injury RTAs in the entire data, while the rest of the injury RTAs involved only slight injuries. Thus, fatal and serious injury RTAs were not separately considered. Instead, casualty RTA likelihood was determined. The casualty RTA likelihood was estimated as the proportion of RTAs in each zone that were casualty RTAs. A casualty RTA was defined as a RTA where at least one person involved was injured or killed. Figure 4-8 shows the respective mean zonal casualty RTA likelihoods for the CTE Tunnel group and KPE Tunnel, disaggregated by travel direction.

![Figure 4-7 Mean SVC and MVC rates for a unidirectional road tunnel](image)

The RTA casualty likelihoods in the CTE Tunnels were generally higher than those in the KPE Tunnel. It was likely to be due to the lower speed limits in the KPE Tunnel. Vehicle collisions at slower speeds experience smaller impact forces and are less likely to suffer casualties.

Also, opposite patterns compared to the RTA rates can be observed. Casualty likelihood appeared to be higher in the interior zones and lower in the transition zones. The trend can be explained by the higher proportion of SVCs in the interior.
zones. Figure 4-9 illustrates the casualty RTA likelihoods of SVCs and MVCs in the respective tunnels – the casualty RTA likelihood for SVC was 0.291 while the casualty RTA likelihood for MVC was 0.128. Evidently, SVCs were more than twice as likely as MVCs to result in casualties. However, it should be noted that MVCs were three times more likely as SVCs to occur in unidirectional road tunnels.

![Casualty RTA likelihoods](image)

Figure 4-8 Casualty RTA likelihoods for (a) CTE Tunnels; (b) KPE Tunnel
After examining the RTAs that occurred on the main expressways, this section examines the RTAs that occurred on the tunnel slip roads, i.e. slip roads connecting to the road tunnels. However, every slip road was unique and their design was entirely dependent on the existing land infrastructure and terrain. Hence, their lengths, curvature, gradient, and number of lanes differed from one another. These characteristic data were not available in this study and thus the findings presented in this section are purely indicative and should be interpreted with caution.

The number of RTAs occurring on entrance and exit tunnel slip roads was compared, on the assumption that the amount of traffic utilising them were about the same. The proportions of RTAs that occurred on the entrance and exit slip roads were determined and shown in Table 4.2.

The difference in slip road characteristics might have resulted in the difference in RTA rates. For example, the tunnel slip roads in the Kampong Java Tunnel (eight RTAs) were relatively much shorter than the ones in Chin Swee Tunnel (138 RTAs).
Generally, there were significantly more RTAs on entrance slip roads than on exit slip roads, with the exception of Kampong Java Tunnel. Again, this implies that RTAs were more likely to occur on slip roads during tunnel entry. This is consistent with the earlier finding that drivers have transitional issues when entering the expressway tunnels.

Table 4.2 RTA on tunnel slip roads

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Numbers</th>
<th>RTA counts</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Entry</td>
<td>Exit</td>
<td>Entry</td>
</tr>
<tr>
<td>Kampong Java</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Chin Swee</td>
<td>2</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>KPE</td>
<td>8</td>
<td>9</td>
<td>70</td>
</tr>
</tbody>
</table>

In addition, unlike the expressway main carriageway which had a gentle grade, tunnel slip roads were likely to be steeper due to shorter transition distances to the surface connecting roadways. As such, the greater number of RTAs that occurred in tunnel entry slip roads might be attributed to steeper gradients. However, due to the lack of detailed information on these slip roads, no further analyses were performed.

4.6 Concluding Remarks

This study aimed to investigate the characteristics of RTAs in expressway tunnels. Three expressway tunnels were included in this study – CTE Kampong Java Tunnel, CTE Chin Swee Tunnel, and KPE Tunnel.

Each expressway tunnel was divided into three zones and it was found that the RTA rates were generally higher in the transition zones (Z1 and Z2). Upon disaggregation by travel direction, it was found that RTA rates were exceptionally much higher during tunnel entry at the first instance. Tunnel exit and re-entry zones, though lower than first-instance tunnel entry, also showed relatively higher RTA rates compared to the interior zones.

Next, RTA type was examined in each zone. It was found that MVC rates were generally higher in the transition zones, suggesting that drivers were less able to
manage inter-vehicular interactions in transition zones. The higher RTA rates in transition zones could be attributed to the increase in MVCs. SVC rates on the other hand remained stable across the zones.

Several explanations for the high RTA rates in transition zones have been discussed and the most likely explanation is a difference in driver perceptions of the environment and hence driving behaviour between open roads and tunnels. Research work on driver behaviour in road tunnels will help to address this issue.

It should be noted that, weather conditions such as rain might have affect RTA occurrences in the tunnel entry/exit zone but were not considered since it was not possible to account for the exposure to various weather conditions, with the available data.

The effect of travel direction has not been addressed by other RTA studies before. As other studies had used aggregated tunnel zone data, this aspect was often overlooked. Furthermore, in the analysis of RTA data from numerous road tunnels, since every road tunnel is unique in its location and design to some extent, it is extremely difficult to consider individuality of each tunnel and thus only the common characteristics can be compared.

Current tunnel RTA studies use zone definitions which assume that RTA distribution is longitudinally symmetrical, which is justifiable if RTAs in both travel directions were aggregated. However, it is shown in this study that travel direction plays a crucial role in RTA distribution. Hence, future RTA studies should consider individual tunnel tubes as separate road tunnels. Zone definitions in future studies should also account for the non-symmetrical RTA distribution in each unidirectional tube.

Furthermore, analysis of RTAs that occurred on tunnel slip roads also revealed that RTAs were proportionately more likely to occur on entrance than exit slip roads, supporting the supposition that drivers are less able to cope with entrance transition. However, the difference could also be due to varying slip road characteristics and the findings on tunnel slip roads should be interpreted with caution.
Also, RTA casualty likelihood was discussed. It was found that RTAs in interior zones were more likely to result in casualties than RTAs in the transition zones, due to higher proportion of SVCs. SVCs were more than twice as likely as MVCs to result in casualty RTAs.

Road tunnel design and implementation of speed limits need to be carefully planned in order to reduce the RTA rates at the transition zones. However, if enhanced tunnel designs are still unable to effectively reduce RTA rates in transition zones, authorities may need to consider other measures. Since the high RTA rates can be attributed to MVCs, which are mostly rear-end collision on expressways, authorities can consider making driver assistance systems (DAS) mandatory. These systems will monitor TTC and time-to-lane-crossing constantly, and will alert the driver when a forward collision or lane departure is imminent. DAS have shown promising results in pilot tests in countries such as USA and the Netherlands (Rijkswaterstaat, 2007, Federal Motor Carrier Safety Administration, 2009).

Overall, the analyses of RTA data revealed that urban road tunnels are safer road environments than open roads, while more attention needs to be paid to transition zones. However, it is difficult to base traffic safety analyses on RTAs because they are rare events (Laureshyn et al., 2010) and microscopic behavioural data should be examined as well. Hence, a subsequent driver behaviour study was conducted.

In retrospect, since transition zones present the highest RTA risk, short tunnels should serve as important case studies. However, at the time of the study, the only other road tunnel in Singapore was the Fort Canning Tunnel which was only 350 m in length. This length was not considered to be substantial enough to induce a road tunnel environment, since the end of the tunnel could be seen from the entrance portal. Hence, the Fort Canning Tunnel was not included in this study. Future studies can include short tunnels which are at least 500 m long to investigate tunnel effects on RTA rates.
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CHAPTER 5 CAR-FOLLOWING BEHAVIOUR

A version of this chapter has been published in Accident Analysis and Prevention (Yeung and Wong, 2014b). The published version can be found in Appendix E. The methodological details can be found in Section 3.2.1.

Due to the data available being greatly unbalanced, full factorial ANOVA could not be performed to assess the effects of lane, speed and leader type, in each road environment. As a result, piecewise evaluation of the factors using ANOVA was performed instead and careful inferences were made. In essence, seven ANOVAs (A through G) were performed.

Time headways (THWs) were computed using Equation (3.1) as described in Section 3.2.1.5. THW was observed to follow a lognormal distribution across the groups. In order to utilise ANOVA, THW was first treated with natural log transformation into log THW. In addition, continuous speed data were also categorised into speed bands of 10 km/h, indicated by their mid-point values, i.e. data falling between speeds of 50 and 60 km/h would be classified as 55 km/h.

In addition to THW, the analyses were repeated using distance headways (a through g, corresponding to A through G). Similarly, distance headways were observed to follow a lognormal distribution and natural log transformation was applied.

Distance headway for the \( n \)th vehicle was computed as the product of its time headway \( THW_n \) and speed \( v_n \):

\[
\text{Distance headway}_n = THW_n \cdot v_n \tag{5.1}
\]

The typical lane configuration for both expressway sites (open section in AYE and tunnel section in KPE) is illustrated in Figure 5-1. The expressways are designed according to the LTA Civil Design Criteria (Land Transport Authority, 2010), which states that the recommended expressway lane width is 3.7 m, while the width of the paved shoulders should be 2.75 m on the left-hand side of the carriageway.
and 0.9 m on the right-hand side. The road median is on the right-hand side of the carriageway.

![Figure 5-1 Typical lane configuration for expressways in Singapore](image)

5.1 Open Expressway

A total of 11,167 vehicles were observed for the open expressway condition. The traffic composition is presented in Table 5.1. For the three-lane expressways, Lane 1 is the fast lane, Lane 2 is the middle lane, and Lane 3 is the slow lane.

Table 5.2 presents a summary of the results from the various ANOVAs (A through D; a through d) for open expressway, using both the log-transformed time and distance headways. The mean time headways of groups evaluated in the ANOVAs for open expressway are illustrated in Figure 5-2, while the mean distance headways are illustrated in Figure 5-3.
Table 5.1 Traffic composition for observed open expressway section

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Lane 3</th>
<th>Lane 2</th>
<th>Lane 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycles (Mean Speed)</td>
<td>24</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>(Mean Speed)</td>
<td>(60.49 kph)</td>
<td>(67.67 kph)</td>
<td>(71.20 kph)</td>
</tr>
<tr>
<td>Cars (Mean Speed)</td>
<td>1179</td>
<td>2974</td>
<td>4342</td>
</tr>
<tr>
<td>(Mean Speed)</td>
<td>(52.26 kph)</td>
<td>(57.58 kph)</td>
<td>(63.32 kph)</td>
</tr>
<tr>
<td>Light Goods Vehicles (Mean Speed)</td>
<td>981</td>
<td>849</td>
<td>47</td>
</tr>
<tr>
<td>(Mean Speed)</td>
<td>(53.33 kph)</td>
<td>(58.40 kph)</td>
<td>(66.15 kph)</td>
</tr>
<tr>
<td>Heavy Vehicles (Mean Speed)</td>
<td>640</td>
<td>66</td>
<td>0</td>
</tr>
<tr>
<td>(Mean Speed)</td>
<td>(52.62 kph)</td>
<td>(61.50 kph)</td>
<td>(N/A)</td>
</tr>
</tbody>
</table>

5.1.1 Effect of Speed on Headways

To control for the effects of leader type and lane, four ANOVAs (A and B; a and b) were conducted. The ANOVAs found a consistent effect of speed on both time and distance headways. Post-hoc comparisons in ANOVAs A and B found time headways to be the shortest at 65 km/h (see Figure 5-2). Post-hoc comparisons in ANOVAs a and b found distance headways to increase with speed (see Figure 5-3).

5.1.2 Effect of Leader Type on Headways

Controlling for effect of speed and possible effects of lane, two ANOVAs (C and c) were conducted. Car-MC pairs were not considered due to their small sample size. Both ANOVAs were consistent in finding no significant effect of leader type. However, significant effect of speed was found on distance headways but not on time headways. The interaction term speed × leader type was not found to be significant in both cases, i.e. effect of speed was not dependent on leader type.

5.1.3 Effect of Lane on Headways

ANOVAs D and d effectively control for effects of speed and possible effects of leader type. Both ANOVAs found significant effects of lane and speed, while no significant interaction effects of speed × lane were found. This meant that the effect of speed was similar across the lanes. Post-hoc comparisons found both time and distance headways to be shortest in Lane 1 and longest in Lane 3.
<table>
<thead>
<tr>
<th>ANOVA</th>
<th>Headway type</th>
<th>Input factors</th>
<th>Leader type</th>
<th>Effect</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>time</td>
<td>45, 55, 65, 75, 85</td>
<td>1</td>
<td>Car</td>
<td>speed</td>
</tr>
<tr>
<td>B</td>
<td>time</td>
<td>45, 55, 65, 75, 85</td>
<td>2</td>
<td>Car</td>
<td>speed</td>
</tr>
<tr>
<td>C</td>
<td>time</td>
<td>45, 55</td>
<td>3</td>
<td>Car, LGV, HV</td>
<td>speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>type</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>speed × type</td>
</tr>
<tr>
<td>D</td>
<td>time</td>
<td>45, 55</td>
<td>1, 2, 3</td>
<td>Car</td>
<td>speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>lane</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>speed × lane</td>
</tr>
<tr>
<td>a</td>
<td>distance</td>
<td>45, 55, 65, 75, 85</td>
<td>1</td>
<td>Car</td>
<td>speed</td>
</tr>
<tr>
<td>b</td>
<td>distance</td>
<td>45, 55, 65, 75, 85</td>
<td>2</td>
<td>Car</td>
<td>speed</td>
</tr>
<tr>
<td>c</td>
<td>distance</td>
<td>45, 55</td>
<td>3</td>
<td>Car, LGV, HV</td>
<td>speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>type</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>speed × type</td>
</tr>
<tr>
<td>d</td>
<td>distance</td>
<td>45, 55</td>
<td>1, 2, 3</td>
<td>Car</td>
<td>speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>lane</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>speed × lane</td>
</tr>
</tbody>
</table>
Figure 5-2 Mean time headways evaluated for open expressway

Figure 5-3 Mean distance headways evaluated for open expressway
5.2 Tunnel Expressway

A total of 9,096 vehicles were observed for the tunnel expressway condition. The traffic composition is presented in Table 5.3.

Table 5.3 Traffic composition for observed tunnel expressway section

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Lane 3</th>
<th>Lane 2</th>
<th>Lane 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycles</td>
<td>167</td>
<td>179</td>
<td>71</td>
</tr>
<tr>
<td>(Mean Speed)</td>
<td>(57.86 kph)</td>
<td>(65.24 kph)</td>
<td>(72.44 kph)</td>
</tr>
<tr>
<td>Cars</td>
<td>1125</td>
<td>2703</td>
<td>3002</td>
</tr>
<tr>
<td>(Mean Speed)</td>
<td>(55.88 kph)</td>
<td>(61.33 kph)</td>
<td>(68.44 kph)</td>
</tr>
<tr>
<td>Light Goods Vehicles</td>
<td>895</td>
<td>451</td>
<td>25</td>
</tr>
<tr>
<td>(Mean Speed)</td>
<td>(53.05 kph)</td>
<td>(60.13 kph)</td>
<td>(68.70 kph)</td>
</tr>
<tr>
<td>Heavy Vehicles</td>
<td>440</td>
<td>37</td>
<td>1</td>
</tr>
<tr>
<td>(Mean Speed)</td>
<td>(52.23 kph)</td>
<td>(59.81 kph)</td>
<td>(70.00 kph)</td>
</tr>
</tbody>
</table>

Table 5.4 presents a summary of the results from the various ANOVAs (E through G; e through g) for tunnel expressway, using both the log-transformed time and distance headways. The mean time headways of group evaluated in the ANOVAs for tunnel expressway are illustrated in Figure 5-4, while the mean distance headways are illustrated in Figure 5-5.

5.2.1 Effect of Speed on Headways in Tunnel

To control for the effects of leader type and lane, two ANOVAs (E and e) were conducted. The ANOVAs found a consistent effect of speed on both time and distance headways. Post-hoc comparisons in both ANOVAs found headways to increase with speed.

5.2.2 Effect of Leader Type on Headways in Tunnel

Controlling for effects of speed and possible effect of lane, two ANOVAs (F and f) were conducted. Both ANOVAs were consistent in finding significant effect of leader type. Post-hoc comparisons found that both time and distance headways were largest for Car-HV (follower-leader), followed by Car-LGV, Car-Car, and then Car-MC.
### Table 5.4 Results from various ANOVAs for tunnel expressway

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>Headway type</th>
<th>Input factors</th>
<th>Leader type</th>
<th>Effect</th>
<th>Results</th>
<th>F-test</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>time</td>
<td>55, 65, 75, 85</td>
<td>1</td>
<td>Car</td>
<td>speed</td>
<td>F (3, 2894) = 41.975</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>F</td>
<td>time</td>
<td>55</td>
<td>3</td>
<td>MC, Car, LGV, HV</td>
<td>type</td>
<td>F (3, 721) = 4.107</td>
<td>0.007</td>
</tr>
<tr>
<td>G</td>
<td>time</td>
<td>55, 65</td>
<td>1, 2, 3</td>
<td>Car</td>
<td>speed</td>
<td>F (1, 4889) = 88.086</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>lane</td>
<td>F (2, 4889) = 52.321</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>speed × lane</td>
<td>F (2, 4889) = 2.915</td>
<td>0.054</td>
</tr>
<tr>
<td>e</td>
<td>distance</td>
<td>55, 65, 75, 85</td>
<td>1</td>
<td>Car</td>
<td>speed</td>
<td>F (3, 2894) = 82.722</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>f</td>
<td>distance</td>
<td>55</td>
<td>3</td>
<td>MC, Car, LGV, HV</td>
<td>type</td>
<td>F (3, 721) = 3.520</td>
<td>0.015</td>
</tr>
<tr>
<td>g</td>
<td>distance</td>
<td>55, 65</td>
<td>1, 2, 3</td>
<td>Car</td>
<td>speed</td>
<td>F (1, 4889) = 178.802</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>lane</td>
<td>F (2, 4889) = 40.784</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>speed × lane</td>
<td>F (2, 4889) = 3.979</td>
<td>0.019</td>
</tr>
</tbody>
</table>
Figure 5-4 Mean time headways evaluated for tunnel expressway

Figure 5-5 Mean distance headways evaluated for tunnel expressway
5.2.3 Effect of Lane on Headways

ANOVA G and g effectively control for effects of speed and possible effects of leader type. Both ANOVAs found significant effects of lane and speed. Near-significant effect of the interaction term speed × lane was found in ANOVA G while significant interaction effect was found in ANOVA g, i.e. effects of speed were significantly dependent on lane. Post-hoc comparisons found time and distance headways to be shortest in Lane 1 and longest in Lane 3.

5.3 Comparisons

5.3.1 Headways

Taking into consideration the data available and the significance of the factors affecting headways in each road environment, two three-way ANOVAs (one for time headway and one for distance headway) were performed for Car-Car headways at speeds of 55 and 65 km/h (2 speeds × 3 lanes × 2 road environments). Table 5.5 presents the ANOVA results. In both ANOVAs, significant effects of speed, lane, and environment were found. All the interaction terms were found to be significant as well, implying that the effects of speed, lane, and road environment were not independent from each other. In the tunnel environment, greater increases in headways were observed in the slower lanes and with increasing speeds.

5.3.2 Time-to-Collision (TTC) Measures

Car-following charts were produced in the \(-DV/DX\) vs. \(DV\) plane (opening chart), for both the open and tunnel expressways. Regression analysis was performed for both sets of data points, with the intercepts set to the origin. Figure 5-6 illustrates the opening chart and Table 5.6 summarises the regression results obtained.

The regression coefficients obtained were significantly different from each other. For the same closing relative speeds \((-DV)\), the TTC-inverse \((DV/IDX)\) was very likely to be higher in open expressways than in tunnel expressways, i.e. TTCs were lower in open expressways. The average closing relative speeds in the open and tunnel expressways were \(-1.24\) m/s and \(-1.62\) m/s, respectively. When the average relative speeds were applied to the model, a somewhat higher TTC value was obtained for tunnel expressway (22.09 s) compared to open expressway (21.75 s).
Table 5.5 ANOVA results for headway comparison between open and tunnel expressways

<table>
<thead>
<tr>
<th>Headway type</th>
<th>Input factors</th>
<th>Effect</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed (kph)</td>
<td></td>
<td>F-test</td>
</tr>
<tr>
<td></td>
<td>Lane</td>
<td>Leader type</td>
<td>Road env.</td>
</tr>
<tr>
<td>time</td>
<td>55, 65</td>
<td>1, 2, 3</td>
<td>Car</td>
</tr>
<tr>
<td></td>
<td>speed</td>
<td>F (1, 9884)</td>
<td>75.639</td>
</tr>
<tr>
<td></td>
<td>lane</td>
<td>F (2, 9884)</td>
<td>98.873</td>
</tr>
<tr>
<td></td>
<td>road env.</td>
<td>F (1, 9884)</td>
<td>83.670</td>
</tr>
<tr>
<td></td>
<td>speed × lane</td>
<td>F (2, 9884)</td>
<td>7.610</td>
</tr>
<tr>
<td></td>
<td>lane × road env.</td>
<td>F (2, 9884)</td>
<td>13.146</td>
</tr>
<tr>
<td></td>
<td>speed × road env.</td>
<td>F (1, 9884)</td>
<td>44.020</td>
</tr>
<tr>
<td></td>
<td>speed × lane × road env.</td>
<td>F (2, 9884)</td>
<td>4.111</td>
</tr>
<tr>
<td>distance</td>
<td>55, 65</td>
<td>1, 2, 3</td>
<td>Car</td>
</tr>
<tr>
<td></td>
<td>speed</td>
<td>F (1, 9884)</td>
<td>266.650</td>
</tr>
<tr>
<td></td>
<td>lane</td>
<td>F (2, 9884)</td>
<td>76.684</td>
</tr>
<tr>
<td></td>
<td>road env.</td>
<td>F (1, 9884)</td>
<td>99.100</td>
</tr>
<tr>
<td></td>
<td>speed × lane</td>
<td>F (2, 9884)</td>
<td>9.325</td>
</tr>
<tr>
<td></td>
<td>lane × road env.</td>
<td>F (2, 9884)</td>
<td>10.584</td>
</tr>
<tr>
<td></td>
<td>speed × road env.</td>
<td>F (1, 9884)</td>
<td>30.669</td>
</tr>
<tr>
<td></td>
<td>speed × lane × road env.</td>
<td>F (2, 9884)</td>
<td>4.093</td>
</tr>
</tbody>
</table>
Figure 5-6 Opening chart for open and tunnel expressways

<table>
<thead>
<tr>
<th>Road Type</th>
<th>Coefficient $(1/m)$</th>
<th>R-square</th>
<th>$t$-value</th>
<th>$p$-value</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Expressway</td>
<td>-0.037</td>
<td>0.603</td>
<td>-113.652</td>
<td>&lt; 0.001</td>
<td>(-0.038, -0.036)</td>
</tr>
<tr>
<td>Tunnel Expressway</td>
<td>-0.028</td>
<td>0.422</td>
<td>-70.581</td>
<td>&lt; 0.001</td>
<td>(-0.029, -0.027)</td>
</tr>
</tbody>
</table>

The TTCs in then open and tunnel expressways can be represented by the following equations:

\[
TTC_{open} = \begin{cases} 
\frac{1}{-(0.037)DV}, & DV < 0 \\
N.A., & \text{otherwise}
\end{cases} \tag{5.2}
\]

\[
TTC_{open} = \begin{cases} 
\frac{1}{-(0.028)DV}, & DV < 0 \\
N.A., & \text{otherwise}
\end{cases} \tag{5.3}
\]

where $DV$ is the relative speed between two successive vehicles (a negative value means the gap between the two vehicles is shrinking).
5.3.3 Safety Margin (SM) and Safe Headway Levels

The SM values were analysed on a lane basis, since earlier findings revealed lane effects. The SM values were determined using Equation (3.5) described in Section 3.2.1.7. Also, the likelihood of safe headway levels was computed. Table 5.7 presents the results.

The mean SMs in the tunnel expressway were slightly higher than those in the open expressway. As for the likelihood of safe headway levels, it was found that Lane 1 (fast lane) had the lowest likelihood of safe headway levels while Lane 3 (slow lane) has the highest proportion. It should be noted that the likelihood of safe headway levels was consistently higher in the tunnels.

<table>
<thead>
<tr>
<th>Lane</th>
<th>Mean SM (s.d.)</th>
<th>Likelihood of safe headway levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open</td>
<td>Tunnel</td>
</tr>
<tr>
<td>1</td>
<td>0.883 (0.146)</td>
<td>0.890 (0.183)</td>
</tr>
<tr>
<td>2</td>
<td>0.886 (0.124)</td>
<td>0.903 (0.179)</td>
</tr>
<tr>
<td>3</td>
<td>0.889 (0.109)</td>
<td>0.902 (0.159)</td>
</tr>
<tr>
<td></td>
<td>0.615</td>
<td>0.644</td>
</tr>
<tr>
<td>2</td>
<td>0.676</td>
<td>0.703</td>
</tr>
<tr>
<td>3</td>
<td>0.736</td>
<td>0.747</td>
</tr>
</tbody>
</table>

5.4 Discussion

The data were collected during peak hours from two sites that shared similar traffic compositions and average speeds. This section discusses the results and highlights the significant implications of the findings.

5.4.1 Factors Affecting Headway

The first part of the study identified factors that have effect on car-following headways. Car-following patterns in open and tunnel expressways were independently examined, using ANOVA for both time and distance headways. Factors considered include speed, leader type, and lane.

It was expected for distance headways to increase with speed due to longer braking distances at higher speeds. Taieb Maimon and Shinar (2001) and Duan et al. (2013),
based on experimental data, reported differences in distance headway at different speeds but insignificant differences in time headway. If time headways did not differ across speeds, it would imply that a driver’s perceived risk in car-following was mainly a function of the driver’s perceived reaction time and that distance headway was merely the product of speed and the desired time headway. However, the findings in this study provide evidence that speed had a significant effect on time headway, which implies that drivers’ perceived risk changes with speed. This will be discussed later with the comparison of headways with other studies.

The absence of speed effects in the many previous experimental studies may be due to the Hawthorne effect, an impact on behaviour due to the awareness of being studied. As discussed by Boer (1999) and Hancock (1999), drivers behave in a satisfying manner. Under normal driving situations, drivers behave in a manner well enough to meet their driving goals and do not seek to optimise their behaviour. In an experimental context, drivers may have unknowingly performed in an optimising manner. Naturalistic observations thus offer higher fidelity (Eby, 2011).

The lane travelled was also found to be a significant factor in both road environments. Consistent in both environments, headways in Lane 1 (fast lane) were the shortest while headways in Lane 3 (slow lane) were the longest. Lane effects were not unexpected – when lane speeds are similar with that in other lanes, “faster” vehicles in the fast lane may somewhat create the illusion of speed by travelling at shorter headways. The lane effects agree with the findings of Olcott (1955), who found that the fast lane in the Lincoln Tunnel had a different speed-density curve from the slow lane. A possible explanation for lane effect is that, in a traffic culture where lanes are associated with different speeds, drivers who opt to stay in the slow lane would be more conservative than those in the fast lane. The higher overall level of risk aversion in the slower lanes thus results in longer headways. If true, this has interesting implications on future research which may identify different driver groups (in terms of risk perception) based on lanes.

The effect of leader type was found to be significant in the tunnel expressway but not significant in the open expressway. In the tunnel, car drivers maintained longer headways behind larger vehicles. Intuitively, one would expect longer headways
when following behind larger vehicles due to the view of the road ahead being obscured, adding elements of uncertainty to the drivers’ perceived risk. However, in the open expressway drivers seem to disregard the leader type. Perhaps the obscuration of the road ahead has a greater effect in the tunnels due to the limited sight distances. Various studies had examined the effect of leader vehicle type but conflicting findings had been obtained. While Puan (2004) and Duan et al. (2013) observed larger headways behind trucks than cars, Ossen and Hoogendoorn (2011), Brackstone et al. (2009), and Sayer et al. (2003) observed the opposite. They reasoned that since trucks have lower braking power which results in longer braking distance, car drivers following behind them have more time and distance to react and hence are able to maintain shorter headways. On the other hand, Yousif and Al-Obaedi (2011) found no differences in car headways behind cars or trucks. With regard to the inconsistency in the various studies, it would appear that environmental and cultural factors might play important roles.

Overall, after controlling for speed, lane, and leader type, headways (both time and distance) were longer in the tunnel than in open expressways. The road environment also had significant interaction effects with the mentioned factors. In a practical sense, the conservative behaviour was amplified in situations where larger headways were deemed necessary by drivers, resulting in even safer car-following conditions. The findings in this study provide behavioural evidence of drivers perceiving higher risks in the tunnel environment (and hence maintaining relatively larger headways). This is consistent with perception studies in the literature (Serrano and Blennemann, 1992, Arias et al., 2008), where drivers were found to perceive road tunnels as hostile environments and experience unpleasant feelings while driving in tunnels. It is also possible that drivers perceive driving in tunnels as a novel experience and hence drive more conservatively (Lemke, 2000). It is certainly important to understand why drivers behave differently in urban road tunnels.

Another possible explanation for the more conservative car-following behaviour in tunnels is the presence of traffic cameras. A characteristic of urban road tunnels is the high density of traffic cameras to monitor traffic throughout the tunnel, unlike
open roads where traffic cameras are further apart. Drivers may adopt more “sociable” driving behaviour in tunnels due to the awareness of being monitored. However, this explanation is less likely to be true because behavioural differences have been demonstrated in simulator studies where the effect of traffic cameras is non-existent.

5.4.2 Comparison of Headways with Other Studies
The Car-Car distance headways in this study were compared to minimum safety distance and the two-second rule (see Figure 5-7). In the derivation of safety distances, driver reaction time was assumed to be one second, and the deceleration term coefficient (reciprocal of twice the maximum average deceleration of a following vehicle) adopted was 0.075 s²/m, as suggested by (Rothery, 2011) for the case when the leading vehicle comes to a full stop instantaneously. In the less conservative set of safety distances, the deceleration term was assumed to be absent, i.e. the following vehicle adjusts its deceleration synchronously with the leading vehicle. In addition, comparison was done with results from other studies (Brackstone et al., 2002, Puan, 2004).

![Figure 5-7 Comparison of car-following behaviour](image)

This study (Open)  
This study (Tunnel)  
Puan (2004)  
Brackstone et al. (2002)  
Safety distance (conservative)  
Safety distance (less conservative)  
2 s rule
The headways in this study, like those found in other studies, mostly fall between the conservative and less conservative safety distances. The minimum safety distances and two-second rule considered only the crash likelihood based on consistent driver reaction and braking times, i.e. constant time headway. The headways observed in this study were shown to become more conservative as speed increases. This can be explained by the higher perceived risk at higher speeds. If a consistent driver reaction time is assumed (controlling for crash likelihood), it is possible that perceived crash consequence is more severe at higher speeds. Higher speeds are associated with greater crash severity and higher crash rates (Aarts and van Schagen, 2006). As shown in Figure 5-7, headways in road tunnel are the highest, which is explained by higher perceived risk in the road tunnel environment. However, headways at speeds above 65 km/h should be interpreted with caution due to the 70 km/h speed limit of the tunnel being applicable in this study.

5.4.3 Rear-End Collision Risk
Headways indicate the potential danger while TTCs indicate actual danger (Vogel, 2003). Time-to-collision values in both road environments were assessed using car-following waves. The results, as shown in Figure 5-6, indicated that for the same relative speeds, TTC values will be larger in the tunnel. This is because of the overall longer headways in the tunnel. Safety margins in the tunnel expressway were higher than those in the open expressway. The mean SM values found in this study were consistent with those of Lu et al. (2012), who found mean SM values for professional and general drivers to be 0.862 and 0.896, respectively. This study shows that drivers desired higher safety margins in the road tunnel environment.

The likelihood of safe headway levels was also computed. The computation took into account the vehicle speeds, speed differentials, distance gap, and driver reaction time. Notably, instances of safe headway levels were more likely in the tunnels, suggesting that from a behavioural perspective, traffic is safer in the road tunnel environment.

5.4.4 Implications of Longer Headways
Traffic capacity is a key consideration for major roads with high traffic demand. In fact, it is common for very short headways to be observed in expressways due to
shorter commute times being prioritised over safety, especially in urban areas where lengthy commute time is a greater disutility.

The longer headways in road tunnels imply that traffic capacity is compromised. Although road tunnels are superior in terms of traffic safety from a behavioural perspective, capacity is expected to be lower than that of open roads. Thus, implementation of URS should take into account the reduced lane capacities in road tunnels. In order to provide similar traffic capacities, road tunnels may require more lanes than surface roads.

5.5 Concluding Remarks

This study assessed the car-following patterns observed in both open and tunnel expressways. Speed, lane, and leader type were found to have effects on headways to various extents. Overall, car-following behaviour (with car as the follower) in the road tunnel environment was found to be more conservative (longer headways and greater safety margins) than that in the open road environment. The likelihood of safe headway levels was also higher in the tunnels. Overall, from a microscopic behavioural perspective, traffic in tunnel expressways would be safer than the conventional open expressways. The conclusion is consistent with the lower accident rates in road tunnels, suggesting that microscopic behaviour studies can serve as reliable traffic safety assessments. The effect of road environment on drivers’ car-following behaviour was also found to be significant, given that other factors such as speed, lane, and leader type are controlled.
CHAPTER 6 VISUAL ATTENTION

An earlier version of this chapter was presented at the 14th World Conference of Associated research Centres for the Urban Underground Space (Yeung and Wong, 2014a). The methodological details leading to the findings in this chapter can be found in Section 3.2.2.

The indicators for glance behaviour in the tunnel entry zone and tunnel interior zone (see Figure 3-13) were assessed. However, not all the subjects provided car-following epochs in both tunnel zones. It was realised through preliminary analysis that individual glance behaviours varied substantially and hence there was no merit in aggregating glance behaviour data from all available epochs for each tunnel zone. Thus, paired-sample tests formed the basis of comparison between the tunnel zones (tunnel entry zone vs. tunnel interior zone I). In addition, for some participants the traffic conditions were such that multiple car-following instances occurred in the tunnel interior zone. The consistency of glance behaviour in the tunnel interior zone was also assessed by comparing two separate, randomly sampled epochs in the tunnel interior zones (tunnel interior zone I vs. tunnel interior zone II).

In light of the relatively small sample sizes in the comparisons, the paired-sample Wilcoxon signed rank test was used with a significance level of 0.05.

6.1 Tunnel Entry Zone vs. Tunnel Interior Zone I

Although 21 participants took part in the study, only ten participants provided comparable car-following epochs in both tunnel entry zone and tunnel interior zone I. Figure 6-1 exhibits the zone-wise comparisons of the glance behavioural measures. Overall, there were more glances in the tunnel entry zone. There were significantly more glances to the forward roadway ($p = 0.007$) and in-vehicle dashboard ($p = 0.013$) in the tunnel entry zone, while no significant differences were found in glances to other areas-of-interest (AOIs, refer to Figure 3-14). The average glance duration to the forward roadway was significantly shorter ($p = 0.005$) in tunnel entry, while the average glance durations to other AOIs appeared to be similar. With regard to the percent of time spent, glance time to the forward
roadway \((p = 0.007)\) was significantly less in the tunnel entry while glance time to the dashboard was significantly greater \((p = 0.028)\).

The distribution of renewal cycles shows a dominance of two-glance cycles (99.5\%) with only one three-glance cycle (F-R-L) in the tunnel entry.

![Figure 6-1 Comparison of glance behaviour between tunnel entry and interior zones (error bars show standard error of the mean; and * denotes significance)](image)

**6.2 Tunnel Interior Zone I vs. Tunnel Interior Zone II**

To examine the consistency of glance behaviour in the tunnel interior zone, two car-following epochs from each subject (where available) in the tunnel interior zone were compared. Eight subjects provided two car-following epochs within the tunnel interior zone. Figure 6-2 illustrates the results. No significant or near-significant differences were found.

Again, two-glance cycles dominated the share of renewal cycles (98.2\%). There were only two three-glance cycles (F-R-M and F-M-D).
6.3 Discussion

6.3.1 Glance Frequency
The results suggested drivers made about 45% more glances in the tunnel entry zone than in the tunnel interior zone.

Upon inspection of the glance distributions, the differences in glance frequencies could be mostly attributed to the number of glances to the forward roadway and dashboard. This might be explained by the stronger associations to “enforcement” in the tunnel expressway, which is likely due to the higher level of speed enforcement in the tunnel expressways (this will be discussed later in Section 7.1). This would have caused the drivers to be more conscious of their driving speed upon entering the road tunnel environment. Alternatively, the increase in glances to the dashboard (and forward roadway) could be a result of drivers attempting to adjust to the road tunnel environment by associating the visual perception cues
(such as tunnel walls, road markings, etc.) to the desired driving speed. It has been shown that drivers’ perception of speed was dependent on the visual patterns and presence of texture applied to the tunnel walls (Manser and Hancock, 2007). Both explanations would result in more glances between the dashboard and the forward roadway. Within the tunnel interior zone, drivers would have adapted to speed perception and hence required fewer glances to the dashboard.

Studies examining the eye movements of novice and experienced drivers (Falkmer and Gregersen, 2005, Nabatilan et al., 2012) have demonstrated that novice drivers, who are associated with higher crash risk, made more fixations to the dashboard under various driving conditions. Hence, a visual scanning strategy that involves more attention allocated to the dashboard can be considered to be detrimental to safety.

6.3.2 Glance Duration

Long glances away from the roadway (nominally more than two seconds) are considered to be detrimental to safety (Klauer et al., 2006, Kircher and Ahlström, 2012). None of the off-road glances in this study exceeded two seconds and the eye glance behaviour could be considered ideal. The average off-road glance duration in this study was 0.59 – 0.64 s, which is consistent with those found in other studies. Tijerina et al. (2004) found the average off-road glance duration to be 0.6 s in car-following situations; while Birrell and Fowkes (2014) found the average glance durations to the speedometer and mirrors to be 0.62 s and 0.5 s, respectively. The short off-road glance durations suggest that drivers were cautious about how long they look away from the road scene ahead and hence did not take long glances away from the roadway.

Furthermore, the examination of the glance durations revealed that the average off-road glance duration was insensitive to the tunnel zone, i.e. regardless of the tunnel zone there was no difference in the amount of time drivers took to obtain information from the off-road glances.

Since the glance frequencies among the different tunnel zones varied without significant variations in the average off-road glance duration, this meant that higher
glance frequencies occurred at the expense of shorter on-road glance durations. The results revealed that in the tunnel entry zone, the average on-road glance duration is about 30% shorter than that in the tunnel interior. This suggests that perhaps it is not long glances away from the forward roadway that is truly detrimental to safety but the shorter glances to the forward roadway that lead to increased crash risk, i.e. the shorter the glances to the forward roadway where hazards are most likely to appear, the more likely it is for the driver to miss the hazard. Therefore, it is important for drivers to spend an adequate proportion of visual attention to the forward roadway.

The analysis of the percentage of time spent on glances to each AOI shows that approximately 90% of the time was spent on glances to the forward roadway. This is notably higher than the 86% observed by Tijerina et al. (2004) for car-following epochs in open road environments, which was termed ‘safety-ideal’ eye glance behaviour during car-following. This helps to explain the relatively lower crash risks in the road tunnel environment, though it should be noted that the work by Tijerina et al. (2004) was carried out in the US and might not reflect driving behaviour in the Singapore context.

Within the tunnel, the percentage of time spent on glances to the forward roadway is the lowest in the tunnel entry (88%) and the highest in the tunnel interior (92%). The overall effect of the variations in glance frequency and average glance duration is a lower percent of time spent on on-road glances, and conversely a larger percent of time spent on off-road glances, in the tunnel entry and exit zones, as compared to the tunnel interior. Consistent with the earlier proposition, the lower amount of attention allocated to the forward roadway could explain the higher crash risk in the tunnel entry zones.

Overall, since the off-road glance durations were not significantly affected by the tunnel zones, the average on-road glance durations were modulated by the number of glances made by the driver. Thus, future traffic safety assessments based on driver eye glance behaviour should not only consider long glances away from the roadway, but also the duration of the on-road glances.
6.3.3 Glance Transitions

The results showed a high dominance of two-glance renewal cycles. This suggests that the drivers separated the lapses of attention from the forward roadway into several sequences by directing their attention back to the forward roadway after each attentional shift away from it (Wong and Huang, 2013). In the study by Wong and Huang (2013), glance data from the 100-car naturalistic driving study (Klauer et al., 2006) were examined and it was found that 90.74% of the drivers’ attention allocations were two-glance cycles, and the remaining 9.26% consisted of three or more glances. The 100-car study data presumably represented driver behaviour in open surface roads. In this study, the share of two-glance cycles was consistently higher than 95% in each zone, indicating that drivers exhibited higher attentional priority to the forward roadway. Again, the higher share of two-glance cycles in the road tunnel further explains the lower crash rates in tunnels.

6.3.4 Limitations

In order to conduct behavioural studies, it is important to control for various confounding factors so the factor of interest can be isolated. However, as discovered in this on-road study, factors such as the traffic conditions, the weather, the presence of a leading vehicle, etc. could not be controlled. As a result, about half of the participants did not provide data that could be used in the analyses. In the literature, many studies have adopted the use of driving simulators to overcome this issue but it should be noted that the findings obtained from driving simulator studies require validation and more often than not, only relative validity can be established. Essentially, on-road studies offer the most ecologically valid findings, especially when investigating the effects of environmental differences which cannot be fully replicated in a driving simulator.

Also, it was not known whether the presence of the observers had any effect on the drivers’ glance behaviour (Carsten et al., 2013). However, in the analysis of the data, there were no glances made to the observer and it can be reasonably assumed that the observers had minimal impact on the data. Furthermore, the researcher had to be onboard for ethical and safety reasons.
CHAPTER 7 DRIVER PERCEPTION

This chapter discusses the results and findings obtained from the various driver perception surveys conducted in the course of the research. The methodological details can be found in Section 3.3.

7.1 Free Association Survey

A paper based on the free association survey has been published in *Journal of Environmental Psychology* (Yeung et al., 2013). The published paper can be found in Appendix F.

7.1.1 Frequency of Categorical Association

From the 1,107 subject responses, 1,112 categorical responses were coded. Not all respondents listed responses associated to unique categories; some of the respondents had more than one response associated to a particular category. The mean frequencies of response association for each category, for both Sections I and II, are shown in Table 7.1. The mean response association is the average number of responses, which were associated to a particular category, generated by a respondent.

The results indicated that, for open expressways, the most frequently (more than 30%) associated categories were (in descending order) TRAFFIC CONDITION, EMOTION, SPEED, SAFETY, OTHER MOTORISTS, and SCENERY. For tunnel expressways, the most frequently associated categories were (in descending order) LIGHT, SAFETY, EMOTION, ENFORCEMENT, and SPEED. This suggests that the most prevalent roadway qualities to the drivers for open expressways are different from that for tunnel expressways. On an open expressway, drivers perceive traffic conditions and flow speeds to be the most prevalent elements but in a tunnel expressway, they perceive lighting conditions and tunnel safety to be more prevalent.

Next, t-tests were performed to compare the means for each category between open and tunnel expressways. The results revealed that associations to SPEED, OTHER MOTORISTS, TRAFFIC CONDITION, COST, and SCENERY were statistically
more frequent in open expressways (absolute $T$ values greater than 1.96). On the other hand, $SAFETY$, $LIGHT$, $RECEPTION$, $SOUND$, and $EXITS$ were statistically more frequent in tunnel expressways. However, after Holm-Bonferroni corrections, statistical significance was found only for $LIGHT$, $TRAFFIC\ \text{CONDITION}$, $RECEPTION$, $SOUND$, $EXITS$, and $COST$.

### Table 7.1 Mean Frequencies of Response Association (with Standard Deviation) for each Category

<table>
<thead>
<tr>
<th>Category</th>
<th>Mean response association (S.D.)</th>
<th>Section I - Open</th>
<th>Section II - Tunnel</th>
<th>T value</th>
<th>Holm-Bonferroni corrected p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$LIGHT$</td>
<td>0.105 (0.308)</td>
<td>0.868 (0.685)</td>
<td>-11.94</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>$TRAFFIC\ \text{CONDITION}$</td>
<td>0.649 (0.665)</td>
<td>0.237 (0.485)</td>
<td>5.96</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>$RECEPTION$</td>
<td>0.026 (0.161)</td>
<td>0.159 (0.368)</td>
<td>-3.62</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>$SOUND$</td>
<td>0.018 (0.132)</td>
<td>0.132 (0.365)</td>
<td>-3.29</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td>$EXITS$</td>
<td>0.018 (0.132)</td>
<td>0.140 (0.373)</td>
<td>-3.26</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>$COST$</td>
<td>0.167 (0.419)</td>
<td>0.035 (0.185)</td>
<td>3.26</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td>$OTHER\ \text{MOTORISTS}$</td>
<td>0.368 (0.812)</td>
<td>0.167 (0.459)</td>
<td>2.9</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$SCENERY$</td>
<td>0.368 (0.655)</td>
<td>0.167 (0.478)</td>
<td>2.81</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$SPEED$</td>
<td>0.579 (0.563)</td>
<td>0.412 (0.529)</td>
<td>2.58</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$SAFETY$</td>
<td>0.377 (0.586)</td>
<td>0.544 (0.706)</td>
<td>-2.23</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$ENFORCEMENT$</td>
<td>0.272 (0.599)</td>
<td>0.421 (0.677)</td>
<td>-2.18</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$AIR$</td>
<td>0.026 (0.209)</td>
<td>0.079 (0.302)</td>
<td>-1.92</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$SIGHT\ \text{DISTANCE}$</td>
<td>0.079 (0.380)</td>
<td>0.018 (0.132)</td>
<td>1.62</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$EMOTION$</td>
<td>0.605 (0.908)</td>
<td>0.465 (0.719)</td>
<td>1.59</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$PURPOSE$</td>
<td>0.149 (0.426)</td>
<td>0.088 (0.314)</td>
<td>1.41</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$TEMPERATURE$</td>
<td>0.018 (0.132)</td>
<td>0.044 (0.206)</td>
<td>-1.14</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$ROAD$</td>
<td>0.289 (0.606)</td>
<td>0.228 (0.516)</td>
<td>1.12</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$WEATHER$</td>
<td>0.088 (0.314)</td>
<td>0.053 (0.224)</td>
<td>1.07</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$CONTROL$</td>
<td>0.237 (0.599)</td>
<td>0.219 (0.545)</td>
<td>0.39</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$SIGNAGE$</td>
<td>0.105 (0.361)</td>
<td>0.114 (0.346)</td>
<td>-0.24</td>
<td>n.s.</td>
<td></td>
</tr>
<tr>
<td>$SPACE$</td>
<td>0.237 (0.503)</td>
<td>0.246 (0.525)</td>
<td>-0.18</td>
<td>n.s.</td>
<td></td>
</tr>
</tbody>
</table>

### 7.1.2 Multidimensional Scaling

Multidimensional scaling (MDS) analysis was performed to model the driver perception of open and tunnel expressways. The inter-correlation matrix served as a pseudo-similarity matrix for MDS, excluding the category $OTHERS$. The model shows the relative prevalence of each of the categories on a two-dimensional space.
The two-dimensional model was adopted according to Parsimony’s Law. Furthermore, the normalised raw stress value is low (Open 0.10; Tunnel 0.11), and the Dispersion Accounted For (Open 0.90; Tunnel 0.89) and Tucker’s Coefficient of Congruence (Open 0.95; Tunnel 0.94) are close to 1.

A stress value of zero would mean that the MDS map perfectly reproduces the input data, while a stress value of one would mean that the map perfectly distorts the input data. The Dispersion Accounted For and Tucker’s Coefficient of Congruence measure the proportion of the sum of squared disparities accounted for by the distances in the MDS map.

Figure 7-1 illustrates the two-dimensional models corresponding to driver perspectives of open expressways and tunnel expressways, respectively. Both maps show the more prevalent categories being positioned nearer to the perimeter. It should be noted that the dimensions on both maps are arbitrary, and may not be the same. The maps reflect the relative distance of one category to another, for the two different road environments. Note: OTHER_P in the maps refers to OTHER MOTORISTS, the rest are self-explanatory.

As observed in Figure 7-1, the driver perspectives of the open and tunnel expressways are rather different. For instance, the position of LIGHT (marked by solid circle) is in the middle for open expressways, while it is at the right-most for tunnel expressways, implying the increased prevalence of LIGHT in the tunnels. Inter-categorical distances are also different. For instance, the gap between SPEED and SPACE (marked by dashed ellipse) is shorter for tunnel expressways, i.e. the two categories are more likely to be associated with each other in tunnels.

7.1.3 Effect of Tunnel Usage Frequency on Categorical Valences
The next part of the analyses took into consideration the categorical valences. The mean valence for open expressway was 0.351 (s.d. 2.51), and –1.149 (s.d. 2.13) for tunnel expressway. Drivers had higher tendencies to provide negative responses for tunnel expressway, and this suggests that tunnel expressways are not as popular as open expressways. Table 7.2 shows the mean counts (with standard deviation) disaggregated by gender and tunnel usage frequency. One-way ANOVA was
performed on the mean valence and no significant effects of gender or tunnel usage frequency were found.

Figure 7-1 MDS analysis for (a) open and (b) tunnel expressways
Table 7.2 Disaggregated mean positive and negative associations (with s.d.)

<table>
<thead>
<tr>
<th></th>
<th>Open Positive</th>
<th>Open Negative</th>
<th>Tunnel Positive</th>
<th>Tunnel Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Female</td>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>2.12 (1.63)</td>
<td>1.44 (1.40)</td>
<td>0.76 (1.12)</td>
<td>2.00 (1.37)</td>
</tr>
<tr>
<td></td>
<td>1.30 (1.53)</td>
<td>1.28 (1.37)</td>
<td>0.73 (1.10)</td>
<td>1.84 (1.54)</td>
</tr>
<tr>
<td>Tunnel usage</td>
<td>... week or more</td>
<td>1.66 (1.71)</td>
<td>1.49 (1.46)</td>
<td>0.77 (1.11)</td>
</tr>
<tr>
<td>(Several times a …)</td>
<td>1.55 (1.26)</td>
<td>1.55 (1.26)</td>
<td>0.75 (1.19)</td>
<td>1.70 (1.49)</td>
</tr>
<tr>
<td></td>
<td>... month</td>
<td>... month</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.72 (1.54)</td>
<td>1.00 (1.17)</td>
<td>0.69 (1.00)</td>
<td>1.72 (1.34)</td>
</tr>
</tbody>
</table>

7.1.4 Response Valences as Attitude Indicators

The respondents also rated their experience in open and tunnel expressways. On a scale of one (dislike) to five (like), the mean rating was 3.73 \( (s.d. 0.989) \) for open expressway and 3.28 \( (s.d. 1.043) \) for tunnel expressway. The difference was found to be statistically significant \( (t = 3.519, df = 113, p = 0.001) \). ANOVA found no significant effects of gender or tunnel usage frequency.

Figure 7-2 shows a plot of the mean respondent valences for each rating. It can be observed that there is a linear relationship between the valences and the ratings, with high \( R^2 \) values. Respondents who liked that particular road environment were more likely to provide more positive associations (or less negative associations). Also, it would appear that drivers had lower expectations for tunnel expressways, as shown by the smaller slope gradient. Evidently, the overall response valence of a driver correlates to the driver’s attitude towards the domain, and serves as a valid measurement of driver attitudes.

7.1.5 Discussion

The study set out to find out (1) whether drivers perceived open expressways differently from tunnel expressways; and (2) whether frequent tunnel users perceived tunnel expressways more positively than infrequent users. The free association technique was used to collect information for this study. In addition, the study aimed to find out (3) whether there was any relationship between the categorical valences and the reported overall experiences in each domain.
7.1.5.1 Driver perspectives of Open and Tunnel Expressways

Based on 1,107 responses from 114 respondents, the results showed that driver perceptions for open expressways and tunnel expressways are indeed different to some extent. After coding the responses into their respective categories, the categorical associations found that the most prevalent items to the drivers differ for open and tunnel expressways, as shown in Table 7.1. Driver perspective models obtained through multidimensional scaling also illustrate the differences.

Prevalent roadway qualities in open expressways are more traffic-oriented and relate directly to the inter-vehicular interactions (SPEED, TRAFFIC CONDITION, SCENERY, and OTHER MOTORISTS). For tunnels, the prevalent qualities are more self-oriented and relate directly to the subjects’ individual interaction with the road environment (ENFORCEMENT, LIGHT, and SPEED). The most strongly associated qualities were found to be clearly different for the two expressway types. Multidimensional scaling analysis was used to model driver perspectives using the inter-correlation of the categorical associations. The models show the perceptual structure of each road environment, with the more prevalent items nearer to the perimeter. Visual comparisons show how each roadway characteristic varies in various environments in terms of prevalence (distance from centre) and relation to other characteristics (relative position of characteristics).

Figure 7-2 Mean respondent valence against rating for open and tunnel expressways
As shown in Table 7.1, associations to six categories were found to be significantly different between the two road environments. Decreased associations to TRAFFIC CONDITION for tunnel expressways were likely due to the traffic management policies resulting in low congestion rates in the tunnels. Thus, traffic conditions become seemingly ‘irrelevant’ in the tunnels.

Meanwhile decreased associations to COSTS were most likely due to the absence of Electronic Road Pricing (ERP) systems in the tunnels. In Singapore, ERP gantries are erected at roads leading to high congestion areas. During certain hours of the day, ERP gantries are activated and vehicles passing through these gantries will have the toll fees electronically deducted without having to stop.

There was an increase in associations to LIGHT in tunnel expressways. Drivers perceive tunnels as darker environments without natural lighting, and hence acknowledge the importance of lighting in tunnels, complemented by the road signs that advise drivers to switch on headlights when driving in the tunnels. Since driving depends on vision, it is likely for drivers to feel that their visual performance is impaired in the tunnels due to the lower luminance levels. In fact, LIGHT was expected to be the most prevalent road tunnel quality.

Also, increased associations to EXITS in tunnel expressways could be related to the absence of unique and distinctive landmarks in the tunnels. Studies have shown that landmarks are essential in efficient way-finding and environmental cognition (Burnett, 2000, Ross et al., 2004). When landmarks were used in navigational tasks, fewer directional errors were made and navigation performance was improved (Ishikawa et al., 2008, Roger et al., 2011). In the absence of navigational landmarks in the tunnels, geographic knowledge is not facilitated (Evans et al., 1984) and drivers may find it difficult to identify locations. As a result they are constantly looking out for their desired exits.

Alternatively, some drivers may be claustrophobic and wish to exit the tunnels as soon as possible. Marec (1996) mentioned that when there is an accident in road tunnels, drivers naturally prefer to escape through the tunnels instead of going into the ‘clearly indicated shelters provided inside the tunnels’. This suggests that
wanting to exit the tunnels is a safety-seeking behaviour. Further research is required to investigate claustrophobic behaviour in tunnels, so as to determine ways to mitigate claustrophobia-related problems.

Increased associations to *RECEPTION* and *SOUND* in tunnels are likely due to the tunnel infrastructure blocking out GPS reception and retaining sounds within, and also the instructions asking drivers to switch on their radios when entering the tunnel.

Other notable differences, though not shown to be significant, include increased associations to *ENFORCEMENT* and *SAFETY* in the tunnels. Speed limits in the tunnels are generally lower than open expressways in Singapore, and the speed cameras are hard to spot within the tunnels. As a result drivers are more constrained in driving within the speed limit and hence greater associations to *ENFORCEMENT*.

Increased associations to *SAFETY* may be due to feelings of insecurity and riskiness inside the tunnels, possibly attributed to elements of claustrophobia. Enclosed spaces, entrapment, darkness and a lower level of perceived control are said to induce fear and avoidance of underground space (Carmody *et al*., 1994, Ringstad, 1994). Other fears may stem from feelings of disorientation (Goel *et al*., 2012). This fear in turn translates to a “subjective risk” experienced by the drivers, affecting driver behaviour in a conservative manner (Näätänen and Summala, 1976). This is consistent with earlier findings where drivers were found to maintain larger headways in tunnels.

Judging by the relative prevalence of the roadway qualities in the two expressway types, it is interesting to note that *TRAFFIC CONDITIONS* and *SPEED* are placed higher than *SAFETY* and *ENFORCEMENT* in open expressways; while *SAFETY* and *ENFORCEMENT* are placed above *SPEED* and *TRAFFIC CONDITIONS* in tunnel expressways.

Capacity and safety do not complement each other – larger headways are safer but they consume more space and hence reduce traffic capacity. Conversely, shorter headways are potentially more dangerous but the smaller spacing required between
vehicles make it possible for higher traffic flow. Since drivers perceived capacity-related qualities to be more prevalent on the open expressways, it would be intuitive to say drivers in general drive faster and in a more aggressive manner on open expressways, in order to reduce travel time. On the other hand, since safety-related qualities were strongly associated with tunnel expressways, drivers in general would drive slower and be more compliant with traffic laws in the tunnels, in order to enhance road safety.

7.1.5.2 Categorical Valences
Considering the categorical valences, it is evident that most drivers perceived road tunnels with more negative associations and fewer positive associations than open expressways. This is consistent with the findings of Arias et al. (2008), who found that tunnels induce unpleasant feelings and greater levels of perceived risk than open roads. In the current study, more associations (mostly negative) to SAFETY were also found for tunnel expressways. Furthermore, self-reported ratings reveal that open expressways were preferred over tunnel expressways.

The findings from Antonson et al. (2009) suggest that driving speeds decrease, lateral positioning tends towards the road centre, and emotional stress increases, as the landscape settings deviate away from open landscapes in terms of “openness”. Road tunnels would then represent an extreme landscape setting where “openness” is at the minimum. The driver task load survey in this research had also found that drivers reported greater mental demand, effort, and temporal demand in the tunnel expressways, after performing the same tasks in both open and tunnel expressways. This exemplifies a difference in attitudes towards road tunnels.

The findings are generally consistent with the evolutionary theories on landscape preferences, especially the biophilia hypothesis, which states that humans have innate tendencies to seek contact with animals, plants, and natural landscapes. Presence of natural elements in the urban setting is said to help reduce stress and mental fatigue (van den Berg et al., 2007). Also, drivers have reported higher frustration tolerance in nature-dominated roads compared to completely built roads (Cackowski and Nasar, 2003).
7.1.5.3 Effects of Tunnel Usage Frequency

It was intuitive to think that drivers who use tunnels more frequently would perceive tunnels more positively due to the increased familiarity. However, it was found that tunnel usage frequency had no significant effects on the valence of the associations and the ratings. Despite being more familiar with the tunnels, frequent tunnel users did not perceive tunnels more positively than infrequent users. This means that roadway perspectives, in terms of categorical associations and valences, were consistent across various groups of tunnel users. Initial impressions of the tunnel environment persist over time.

7.1.6 Implications of the Findings

There are several practical implications of the findings obtained in this study. First, the difference in prevalent items implies that drivers perceive road tunnel differently from open roads. These differences may modulate driving behaviour, as observed in the earlier chapter.

Evidently, this study reveals that drivers perceive illuminating elements more importantly in the tunnels. Lighting in tunnels thus plays a crucial role affecting drivers, through visual influences. Since safe driving depends primarily on the driver’s visual perception and psychomotor skills, it is reasonable to argue that any factors affecting the driver’s vision will have impacts on road safety.

Studies involving visual scanning patterns (Harbluk et al., 2007, Konstantopoulos et al., 2010, Crundall and Underwood, 2011) generally agree that increased road scene scanning has a protective effect on driver safety. Scanning increases the likelihood of detecting hazards early and shorter reaction times. Hence, the influences of lighting on visual attention should be further investigated.

Second, it is discussed that road tunnel driving is likely to be more stressful than open road driving. Stress is associated with increased cognitive loading, which has a negative effect on road safety (Recarte and Nunes, 2002, Harbluk et al., 2007, Lee et al., 2007, Cantin et al., 2009, Stinchcombe and Gagnon, 2010). Most of these studies show that with high mental workload, driving performance deteriorates – reaction times increase, visual detection is impaired, road scene scanning is
reduced, and the number of hard braking events increases. This implies that road safety in road tunnels may be compromised. Thus, interior design concepts for tunnels need to be explored for optimal concepts that induce minimal stress in the drivers.

Interestingly, drivers exhibited more conservative car-following behaviour as reported in the earlier chapters. This is possibly a result of increased vigilance due to the increased subjective risk experienced by the drivers, a compensatory behaviour.

Also, the results revealed that frequent tunnel users were not more receptive towards the tunnels than infrequent users. Tunnel users generally responded with proportionately more negative than positive associations to tunnels, compared to the conventional open roads. This finding reinforces the importance of the tunnel architecture and interior design to alleviate negative associations to the tunnel infrastructure. This is especially important for city planners to mould liveable cities and meet the quality needs of the people. This study has successfully identified roadway qualities in open and tunnel expressways that are prevalent to drivers.

7.1.7 Free Association as a Valid Measurement of Driver Attitudes
The free association technique allows the analysis to be open to categories which are not predetermined. It is essentially a user-centric approach which does not limit respondents to providing feedback based on a predetermined scope. Furthermore, additional psychological constructs or situational models relative to traffic safety may also be found in the process. This study had demonstrated that drive attitudes can be understood through the response valences.

This approach may also be applied to various road settings such as intersections, arterial roads, etc., which can help identify important road elements or roadway qualities that road users perceive as important for the particular road setting so that enhancements can be made to improve the driving experience and road safety.

7.1.8 Interpretation of Analyses
Response biases may be observed in online open participation and mail-back questionnaires, where the respondents mostly belonged to the two younger groups
of the three predefined age groups. However, it was not possible to ascertain whether non-respondents were older persons, since information on the age distribution of active drivers was unavailable.

In addition, it was not possible to improve the response rates for mail-back questionnaires through reminders, in the absence of driver addresses. As a result, face-to-face interviews had to be conducted in order to engage older respondents. However, the overall proportion of older drivers in the 40–50 years age group remains relatively low (~ 15%).

Nonetheless, the interpretations of the analyses were unlikely to be affected since age is not considered as a factor. In a free-listing study by Schrauf and Sanchez (2010), it was found that differences in responses produced between old and young seemed to disappear when items were limited to those mentioned by at least two people or more. They noted that this applies to cases where different age groups have the same relative familiarity with the domains of interest (as was the case in this study).

It is thus possible for the results obtained in this study to be generalised to all drivers, on the presumption that age-related differences in free association are negligible. However, since free association is heavily dependent on the respondent’s direct experience in the particular domain, it should be noted that the results of this study might not generalise to freeways in other regions, where driving cultures and practices greatly differ. Furthermore, extensive research has shown that there are differences in driver attitudes across different countries and culture (Lajunen et al., 2006, Özkan et al., 2006, Warner et al., 2009, Nordfjærn et al., 2011, Warner et al., 2011). This means that although we can expect the prevalent categories to be largely similar across regions, the overall valences may vary.

7.2 Driver Task Load

7.2.1 TLX Dimensional Weights

The mean number of selections of each dimension is shown in Figure 7-3. Subjects \((N = 21)\) found mental demand to be the biggest source of driving workload, followed by (in descending order) effort, performance, temporal demand, physical
demand, and frustration. Descriptions of these dimensions can be found in Appendix C.

![Figure 7-3 Mean number of selections (with s.d.) for each dimension](image)

After normalising, the proportion of workload attributed to each of the dimensions is presented in Figure 7-4. Essentially, participants on average perceived driving to be mostly a cognitive task, and it required certain levels of effort (both mental and physical) to perform the task, since mental demand and effort accounted for close to 50% of the workload source. Negative emotions due to driving were perceived to attribute least to the driving workload, as frustration accounted only for 6% of the workload source.

### 7.2.2 Overall Workload Score

The overall workload scores based on the NASA-TLX questionnaire were computed and are presented in Figure 7-5.

The mean workload score was 41.56 (s.d. 16.48) for open expressway driving and 49.14 (s.d. 19.55) for tunnel expressway driving. Participants experienced greater workload when driving in the tunnel expressway, as compared to driving on open expressway. Paired t-test found the difference between the two environmental workloads to be significant ($p = 0.0025$).
Although the reported driving workload was found to be significantly higher in the tunnels, it was not possible to tell from the overall score how these differences could be explained. Hence, the composition of the overall score was explored.
7.2.3 TLX Dimensional Ratings

The individual dimensional ratings were examined. Unlike the overall workload scores, the ratings for the individual dimensions provided insight into the specific aspects from which differences were derived.

The mean ratings for each dimension and each road environment are shown in Figure 7-6. Generally, the mean ratings were higher for tunnels across all dimensions. However, paired t-tests, at 5% significance level, found no significant differences in physical demand ($p = 0.1623$), performance ($p = 0.1861$), and frustration ($p = 0.0712$). This was expected since the tasks in the two environments were similar in terms of physical activity (steering, applying the pedals) and driving outcome (traversed through roadways with no noteworthy mistakes).

![Figure 7-6 Mean Dimensional Ratings for Driving Task](image)

Significant differences were found in mental demand ($p = 0.0028$), temporal demand ($p = 0.0089$), and effort ($p = 0.0112$). Also, the $p$-value for frustration was close to significance. Although the tasks in the two environments were similar, subjects experienced differences in these dimensions. This implies that the road
tunnel environment does indeed have certain negative influence on driver’s workload.

Increased levels of mental demand and effort in the tunnels may be due to the extra cognitive resources spent in staying being extra vigilant in the tunnels.

In addition, although there were no time constraints imposed on the driver participants, they reported greater time pressure in the tunnels, implying that they had a greater desire to traverse the tunnel expressway section quickly. This desire could stem from the greater amount of negative emotions experienced by the drivers in the tunnels. The negative perceptions of the tunnels could have resulted in dislike towards the tunnel environment and thus greater urgency to leave the tunnels.

This is consistent with the findings from the free association survey, where respondents mostly perceived the tunnels negatively. This negative perception of the tunnels influences the driving workload in tunnels, both directly (frustration) and indirectly via time pressure.

Some participants had commented that they had difficulties trying to stay awake in the tunnels; found the tunnels boring; and were frustrated with the slow speeds (due to lower speed limits and slow travelling vehicles).

7.3 Summary
Two surveys were conducted to investigate how drivers perceive tunnel expressways, and how these perceptions are different from those for open expressways.

The free association survey found that drivers associated tunnel expressways with items differently from open expressways. Lighting, safety, and enforcement were more strongly associated to tunnel expressways than to open expressways. Also, drivers perceive the tunnels less positively than open expressways, and rated tunnels lower for likability.

The findings from the survey based on NASA-TLX confirmed that drivers indeed found driving in the tunnels to be more mentally demanding and required more
effort, although the tasks presented to them in the two road environments were fairly similar.

The findings from the surveys indicate that drivers indeed perceived road tunnels differently from open roads. Roadway qualities associated to open expressways differed substantially from those associated to tunnel expressways. Drivers associate tunnels with more safety-related categories and are likely to drive with more vigilance.
CHAPTER 8 CONCLUSION

This chapter concludes the work presented in this thesis, with regard to the research objectives.

8.1 Accidentology

On the macroscopic level, literature review and limited analyses of RTAs in this thesis revealed that RTA rates were generally lower in the road tunnels compared to open roads. RTAs are the most direct performance indicators of traffic safety and on the macroscopic level, there is evidence to support the proposition that underground road systems would be beneficial to traffic safety.

While aggregated tunnel RTA rates were favourable, localised RTA rates should be considered as well. On characterising RTAs that occurred in urban road tunnels, it was found that RTA rates were highly varied within the tunnel length, with disproportionately high RTA rates at tunnel portals, especially on tunnel entry. Also, these variations in RTA rates could be attributed to rear-end collisions which are failures in inter-vehicle interactions.

The differences in RTA rates between open and tunnel roads, and within the tunnel, suggest that there were driver behavioural differences between these environments as well. Subsequent driver behaviour studies were conducted.

8.2 Driver Behaviour

The results found that apart from factors such as speed, lane, and leader type, the road tunnel environment also had significant effects on car-following behaviour. Drivers were found to exhibit more conservative car-following behaviour in tunnel expressways, with longer headways and longer TTCs. The conservative car-following helps explain the overall lower RTA rates in road tunnels but does not provide insight into the high RTA rates at tunnel portals, especially tunnel entry. If car-following behaviour transits to become more conservative in tunnels, why are RTA rates higher at tunnel portals?

The analysis of drivers’ glance behaviour revealed that drivers had more off-road glances in the tunnel entry zone, and this had an overall significant effect of
reducing the total on-road glance duration. Hence, despite the intention to drive more conservatively in road tunnels, drivers fail to allocate adequate levels of visual attention to the forward roadway at tunnel portals. This is likely to be due to the need for drivers to make some adaptations to the new road environment by associating travelling speed (off-road) with visual perceptual cues (on-road).

Thus at the mesoscopic behavioural perspective, notwithstanding the design considerations for tunnel portals, road tunnel environments induce more conservative car-following behaviour and are beneficial to traffic safety. Longer headways and TTCs translate to lower likelihoods of rear-end collisions. This is consistent with the proposition at the macroscopic accidentology level.

However, it had been suggested that drivers perceive road tunnels as novel roads and hence drive more carefully. As more road tunnels are introduced in the road network, the ‘novelty’ effect wears off and drivers will start to drive carelessly, resulting in increased RTA rates in tunnels.

8.3 Driver Perception
At the microscopic level, a free association study was conducted and the results found that drivers perceived open and tunnel expressway environments differently. While drivers perceived the tunnel expressway environment less positively compared to the open expressway environment, none of the associations suggested any effects of novelty. Observed associations in open and tunnel expressways were mostly linked to inherent characteristics of the roadway. Hence, the differences in the roadway perspectives perceived by drivers are likely to remain. This implies that safety-oriented associations in the tunnel expressway environment will continue to lead to safer driver behaviour in the road tunnels.

Apart from more conservative car-following behaviour, the greater amount of cognitive resources utilised when driving in tunnels was confirmed by a driving workload survey, based on NASA-TLX. Subjects reported higher driving workloads in the tunnels as compared to open expressways, even though the tasks in both environments were the same. This implies that drivers made conscientious efforts to drive more safely in road tunnels.
At the microscopic driver perceptual level, safety was more regarded in the road tunnel environment and these safety-oriented perceptions are expected to be innate. This supports the pro-tunnel propositions at the macroscopic and mesoscopic levels.

8.4 Conclusion

A multilevel approach to assess traffic safety in urban road tunnels suggests that urban underground road systems are beneficial to traffic safety. The findings presented in the thesis present useful insight and evidence to support the implementation of underground road systems in major cities.

However, there is a need to look into the design of tunnel portals from a traffic safety perspective. Much effort has been put into minimising the ‘black hole’ effect in drivers by enhancing the illumination in tunnel portals but drivers spend too much time looking away from the forward roadway. Hence, tunnel interior design can be improved to reduce the drivers’ need to make frequent glances to the in-vehicle dashboards.

Also, the research found that drivers perceived the road tunnel environment less positively compared to the open road environment. Future research may look into improving drivers’ experience in urban road tunnels so that drivers will perceive urban underground road systems more positively.
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APPENDIX A

Eye Tracking Basics


To understand how eye tracking works, it is important to have a basic knowledge about the structure of the eye.

The pupil is an aperture, or opening, in the iris that allows light to enter into the eye. Unless viewed exactly on-axis with a light source, the pupil appears black.

The iris, which is the colored part of the eye, opens and closes to control the pupil size.

On its way to the pupil, light passes through the cornea, which is a thin film-like tissue that covers the eye. The cornea is mostly transparent, however, some light is also reflected from the cornea.

The sclera is the white part of the eye.

The MobileEye uses a technique of eye tracking known as “Pupil to CR” Tracking. This method uses the relationship between two eye features, the black pupil and mirror reflections from the front surface of the cornea (Corneal Reflections, or CRs), to compute gaze within a scene.

A set of three harmless near infrared (IR) lights is projected on the eye by a set of LEDs in the SMU. The near IR light is not visible to the user so it does not cause a distraction, however it is visible to the eye camera on the SMU. The mirror reflection of these three lights from the front surface of the cornea appears in the camera image as a triangle of three dots, at a fixed distance from each other, called the Spot Cluster.

When the eye rotates in its socket, the center of the pupil moves relative to the spot cluster. By comparing the vector (angle and distance) between the pupil and one of the CRs in the spot cluster, the eye tracking system can compute the pointing direction of the eye.

By teaching the system how these angles relate to an image on a second camera that is viewing the environment, the Scene Camera, the eye tracker can compute point of gaze with respect to the scene camera field of view.
APPENDIX B
Sample field survey eye movement data

Data is recorded in two files: (1) video clip and (2) log file.

(1) Snapshots of sample video clip. Red crosshair indicates where the participants’ point of gaze. The pink markers indicate the detection of the corneal reflection (small pink cross) and the pupil (larger pink circle with cross).

Above: Participant gazing at the forward roadway
Above: Participant gazing at the in-vehicle dashboard

Above: Participant gazing at the rear-view mirror
Above: Participant gazing at the left wing mirror

Above: Participant gazing at the right wing mirror
(2) Log file. The log file contains frame data, which includes the coordinates of the corneal reflection (‘Spot x’ and ‘Spot y’) and pupil centroid (‘Pupil x’ and ‘Pupil y’) with respect to the infrared camera, and the coordinates of the point of gaze (‘Scene x’ and ‘Scene y’) with respect to the scene camera. Detection lapses are indicated by -2000.

Above: Snapshot of log file
# APPENDIX C

## NASA-TLX Questionnaire

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MENTAL DEMAND</td>
<td>How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?</td>
</tr>
<tr>
<td>PHYSICAL DEMAND</td>
<td>How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?</td>
</tr>
<tr>
<td>TEMPORAL DEMAND</td>
<td>How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?</td>
</tr>
<tr>
<td>PERFORMANCE</td>
<td>How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?</td>
</tr>
<tr>
<td>EFFORT</td>
<td>How hard did you have to work (mentally and physically) to accomplish your level of performance?</td>
</tr>
<tr>
<td>FRUSTRATION LEVEL</td>
<td>How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?</td>
</tr>
</tbody>
</table>
## Source of workload chart

*For each pair, select the one that contributed more to the task workload*

<table>
<thead>
<tr>
<th>Effort or Performance</th>
<th>Temporal Demand or Frustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal Demand or Effort</td>
<td>Physical Demand or Frustration</td>
</tr>
<tr>
<td>Performance or Frustration</td>
<td>Physical Demand or Temporal Demand</td>
</tr>
<tr>
<td>Physical Demand or Performance</td>
<td>Temporal Demand or Mental Demand</td>
</tr>
<tr>
<td>Frustration or Effort</td>
<td>Performance or Mental Demand</td>
</tr>
<tr>
<td>Performance or Temporal Demand</td>
<td>Mental Demand or Effort</td>
</tr>
<tr>
<td>Mental Demand or Physical Demand</td>
<td>Effort or Physical Demand</td>
</tr>
<tr>
<td>Frustration or Mental Demand</td>
<td></td>
</tr>
</tbody>
</table>
Rating Sheet

Use ○ for OPEN ROAD, × for TUNNEL ROAD

Mental Demand
Low High

Physical Demand
Low High

Temporal Demand
Low High

Performance
Good Poor

Effort
Low High

Frustration
Low High
APPENDIX D

Road traffic accidents in Singapore expressway tunnels
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ABSTRACT
In rapidly growing economies with limited land space, underground road tunnels are becoming more prevalent, before the implementation of large-scale underground road systems. It is necessary to gain more knowledge on their implications and impacts. This study examined 688 road traffic accidents (RTAs) that occurred in the three Singapore expressway tunnels over 2009–2011. Each road tunnel was divided into three areas and RTA characteristics were evaluated for each area. The analysis revealed that RTA rates are higher in the transition zones compared to the interior zones, being mostly attributed to multi-vehicle crashes. However, more casualties per RTA were found to be higher in the interior zones. Upon disaggregation by travel direction, it was found that RTAs are more likely to occur when entering the tunnel than exiting. The implications of the findings are discussed.

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1. Introduction
One of the many challenges faced by the world today is urban sustainability. As megacities continue to develop, their growth is constrained by limited land space. To overcome this limitation, cities are beginning to utilize underground space for various uses, such as utility tunnels, pedestrian systems, rail systems, retail facilities, and more. Utilization of underground space also offers various other benefits such as protection from weather and improved connectivity to existing underground facilities. Several studies (Rokosa et al., 1998; Salzstein, 1959; Sterling, 1957; van der Heeres, 2001) acknowledge the use of underground transport solutions, especially at transport nodes and highly developed areas such as central business districts, saving surface land for other purposes, protecting the environment from noise and pollution, and reducing traffic in important city streets.

It is important for proper urban planning to be in place for efficient use of the non-renewable urban underground space. For instance, the use of utility tunnels instead of conventional burying of utilities can be properly planned to reduce long-term maintenance efforts and the need to divert surface traffic (Ganto-Perello and Casas-Espada, 2013; Ganto-Perello et al., 2009).

Road tunnels, especially recently, require even more planning due to the scale of construction and the amount of resources required. Researchers have studied the design of portals to integrate underground facilities with the existing surface landscape (Peña and Pelizza, 2002; Ye et al., 2011). It is also important, especially in urban areas, to have instrumentation for geometrical and structural monitoring during construction to prevent tunneling hazards (Gherardi et al., 2012).

In the operational space, it is important to have in place appropriate tunnel management strategies, especially in tunnel accidents and fire situations. As such, much research effort has been directed to the development of such strategies.

In dealing with accident fires, various aspects have been studied. Adult and Nelson (2009) conducted fire detection experiments to fill in whether smoke or heat detection systems were more effective for early fire detection. They found that the results from both smoke and fire detectors have both excellent fire alarm and hence different scenarios should be tested for optimality. Other researchers have worked on tunnel fires using both full-scale experiments (Ingaramo et al., 2002; Kong et al., 2009) and simulation (Calzadilla et al., 2012, 2013; Hua et al., 2011), to develop ventilation models and similar control strategies.

Liao et al. (2012) performed a simulation study to test various tunnel management strategies in the event of a tunnel incident and found that a combination of ramp control, using variable message signs and opening up with shoulder lanes was the most effective strategy. However, it was also concluded that if there are few alternative routes, it will be difficult to develop efficient strategies for traffic management.

Tunnel emergency evacuation is also an important issue. Various evacuation models have been compared and consistent results are obtained from different models for similar tunnels (Abeyar, 2002; Roko et al., 2012). This implies that these models can assist tunnel operators in decision-making during emergency
situations. However, it should be noted that although various tunnel assessment models have been developed, these models need to be used with care, since each tunnel has its own unique issues [Bar, 2010].

With the increasing utilization of urban road tunnels, it is essential to understand how road users are adapting to them. One effective way to understand road user adaptability is to investigate how frequently road traffic accidents (RTAs) occur. However, few studies have been conducted on the characteristics of tunnel RTAs.

Arramburu and Rames (2000) analyzed tunnel RTA data obtained from police records for 587 Norwegian road tunnels with lengths ranging from under 100 m to over 3 km, for a five-year study period (1992–1996). They found that the severity of many RTAs in road tunnels is greater than on open roads, with greater proportions of killed and seriously injured persons. Subsequently, they divided each tunnel into four zones (see Table 1) and determined the accident rates in each zone. The results revealed that accident rates for access zones are highest, followed by the interior zones. Also, longer tunnels are found to have lower overall accident rates.

Ma et al. (2009) analyzed tunnel RTAs that occurred in four Chinese freeway tunnels, for a two-year study period (2003–2004), using data obtained from police records. The four tunnels ranged from 0.2 to 3 km in length. They investigated the monthly and hourly distribution characteristics of tunnel RTAs but did not obtain significant findings. Similarly, each tunnel was divided into four zones, but the zone definitions are different from those defined by Arramburu and Rames (refer to Table 1). Ma et al. found highest accident and casualty rates in Zone 3, as compared to being highest in access zones for the Norwegian study.

Naslund et al. (2007) analyzed tunnel RTAs that occurred in 59 Austrian tunnels (18 bidirectional tunnels with average length of 4.29 km and 32 unidirectional tunnels with average length of 2.01 km) using data obtained from police databases, and found that greater RTA severity in tunnels compared to open roadways. He divided the tunnel into zones and found that accident rates are highest at the portal zone. Furthermore, he found that accident severity is greater in tunnels with bidirectional traffic than those with unidirectional traffic.

Levendosky (2000) analyzed police-accident database for 68 German tunnels (46 freeway tunnels with average length of 650 m and 22 tunnels on rural two-lane highways with average length of 800 m and found that injury RTA rates are highest in bidirectional tunnel highways while material damage RTA rates are highest in tunnel freeways without shoulder lanes. Also, RTA costs are lower in road tunnels than open roads.

The few studies that have been conducted in Norway, China, Austria, and Germany show varying results. The results appear contradictory to some extent in both tunnel RTA severity compared to open roads and RTA likelihood in different tunnel zones, which may be due to different reporting requirements in each region. However, these studies are mainly based on rural mountain road tunnels instead of urban road tunnels. Urban road tunnels are typically shorter, better-designed, and accommodate heavier traffic volumes.

In order to investigate RTA characteristics in urban road tunnels, a study was conducted in Singapore based on three expressway tunnels. Singapore is an island state with 712 km² of land and a population of 5.3 million. Its population density is among the highest in the region. In an earlier RTA review in Singapore, it was found that the number of RTAs on expressways have increased by about 30% from 2004 to 2008, and accounts for about 18% of RTAs in Singapore for the same period (Ho et al., 2010). It may hence be prudent to look closely at RTAs in expressway tunnels.

2. Methodology

2.1. Expressway tunnels

Expressway tunnels in Singapore currently consist of the Choa Swee, Kampung Java, and Kallang-Paya Lebar Expressway (KPE) tunnels. The Choa Swee and Kampung Java tunnels completed in 1991 are separated from each other by a short 550 m open section and form part of the Central Expressway (CE). The KPE tunnel completed in 2006 is a major part of the KPE and one of the longest road tunnels in the region. The KPE tunnel has also been assessed as "very good" by European Tunnel Assessment Programme (Transport, 2009). Both the CE and KPE serve to connect the northern region of Singapore to the city area in the south. All three tunnels are dual lanes, carrying northbound (NB) and southbound (SB) traffic. Each tunnel carries three lanes, with the exception of NB Kampung Java tunnel which has four lanes. Table 2 summarizes the tunnel characteristics, while Fig. 1 shows the individual tunnel geometries and locations of the on-off ramps, along with the indicative annual average daily traffic (AADT, based on available 2011 traffic data obtained from Land Transport Authority). It should be noted that the southern end of the Choa Swee tunnel is followed by a 550 m semi-tunnel (CTE 1.75–2.85 km). The semi-tunnel is in the form of an open depressed section and it is not considered as part of the tunnel in this study.

2.2. Data basis

Conventionally, police accident records serve as fairly reliable sources of accident data. Past studies on RTAs in Singapore (Hain, 2004; Hua et al., 2010; Kumaraswamy, 2008; Thu, 2004) have also been based on police accident database.

However, under the Non-Injury Accident Reporting Scheme, motorists are only required to make a traffic accident report if

Table 1

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Coverage</th>
<th>Length (km)</th>
<th>Direction</th>
<th>Lanes</th>
<th>Speed limit (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near</td>
<td>440–540</td>
<td>3–4</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oral</td>
<td>2,010–3,010</td>
<td>3</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KPE</td>
<td>220–2,820</td>
<td>3</td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Coverage</th>
<th>Length (km)</th>
<th>Direction</th>
<th>Lanes</th>
<th>Speed limit (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choa Swee</td>
<td>1,750–2,850</td>
<td>3</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kampung Java</td>
<td>2,000–3,000</td>
<td>3</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KPE</td>
<td>220–2,820</td>
<td>3</td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the accident involves: (a) a vehicle accident; (b) damage to government property; (c) a foreign vehicle; (d) a hit-and-run case; or (e) an injury where:

- at least one person involved in the accident was taken to hospital from the accident scene by an ambulance; or
- the injured was conveyed to hospitalising otherwise; but in subsequent hospitalisation or outpatient medical leave of 3 days or more; or
- no one was conveyed from accident scene to hospital, but one or more persons involved subsequently required hospitalisation or outpatient medical leave of 3 days or more.

Thus, police data do not contain most non-injury RTAs. In this study, RTA data is obtained from incident records provided by the Land Transport Authority (LTA). The LTA Intelligent Transport Systems Centre (ITSC) and KPE Operations Control Centres (OCC) monitor traffic in the CTE and KPE tunnels continuously through surveillance cameras installed throughout the tunnels. Traffic incidents which lead to disruptions in traffic flow are identified and recorded. The incident records will include RTAs that occurred within the tunnels. Police data containing information on RTA casualties is then merged into these incident records.

Tunnel RTA data was provided for the study period of 2009–2013. In the three-year period, there were no notable changes to tunnel infrastructure or traffic management strategies. A total of 699 RTAs that occurred on the main expressway carriageway are examined in this study. RTAs that occurred on on-off ramps along the corresponding carriageway are not included due to the varying characteristics of each on-off ramp which may confound the results.

2.3. Zone definition

The tunnel zones defined by Amuridou and Sideris (2000) and Ooi et al. (2000) are likely to be applicable only for peak-time tunnel conflicts in their studies. Urban road tunnels may have different conditions which affect the length of the transition zones.

As such, an analysis of RTA rates in 50 m intervals is performed and three distinct zones are identified: (1) just outside the tunnel portal; (2) just inside the tunnel portal; and (3) the remainder of the tunnel. It is observed that RTA rates begin to change significantly at some distance away from the tunnel portals, on both the inside and outside of the tunnel. However, this distance varies among the different tunnel portals (ranging from 500 to 2000 m) and this suggests that a total length of 250 m will adequately encompass this distance. Also, 250 m is not excessively long such that the actual characteristics of each zone are masked by overly averaged RTA rates.

Coincidentally, road signs informing motorists of the tunnel are placed about 250 m before the tunnel portal, which presents a possible cause for the change in RTA rates in the defined zones.

Tunnel zones in this study (see Fig. 2) are defined as follows:

- Zone 1 (Z1): exterior transition zone: first 250 m outside the tunnel;
- Zone 2 (Z2): interior transition zone: first 250 m into the tunnel;
- Zone 3 (Z3): interior zone: the remainder of the tunnel.

Fig. 3 shows snapshots of various tunnel zones. A fourth zone is not observed for 50 m interval RTA rate analysis and hence there is no Zone 4, unlike the other studies. Furthermore, Zone 2 has already covered a substantial length of the tunnel adjoining the portal.

In addition, the 50 m RTA rates do not appear to vary with the indication AADT. (See Fig. 1.) Hence, it is presumed that the varying traffic volumes along the length of the tunnels have negligible influence on the occurrence of RTAs in the tunnels.

3. Results and discussion

3.1. RTA rates in each zone

The RTA rates (aggregated for both directions) in each of the defined zones for the CTE tunnels and KPE tunnel are determined and shown in Figs. 4 and 5, respectively. It should also be noted that the southern end of KPE tunnel splits into various slip roads and hence Z1 and Z2 are only defined for the northern end of KPE tunnel. For convenience, zones with prefixes i and s will denote northern and southern zones, respectively.

Since the traffic conditions of each expressway are different, it is not appropriate for comparison to be made for the respective zo-
nal RIA rates between the two expressways. Hence, comparison is made only among the zones within each expressway.

RIA rates are generally higher in the transition zones (Z1 and Z2) than the interior zones (Z3). However, there is no consistent indication of whether Z1 or Z2 has higher RIA rates. Whereas Z1 exhibited substantially higher RIA rates than Z2 for the shorter CHI tunnels, this pattern is somewhat reversed for the longer KPI tunnel.

If the two CHI tunnels are considered as a tunnel group, it is evident that RIA rates are much higher at the two external transition zones of the tunnel group, as compared to the internal transition zones. This suggests that there are certain factors in the transition zones which lead to more RIA occurrences. In order to probe further, the RIA rates are disaggregated by travel direction.

3.2. RIA by travel direction

Chi-square tests are performed (see Table 3) and it was found that, at 5% significance level, RIA occurred more often in the shiny tube than the black tube at Z21 of Chin Swee tunnel, as well as Z21 and 2.1 of Kampung Java tunnel. On the other hand, there is higher like-

Fig. 2. Zone definitions for road tunnel.

Fig. 3. Various tunnel zones: (a) Zone 1; (b) Zone 2; (c) Zone 3; and (d) exit Zone 2.

Fig. 4. RIA rates for CHI tunnel group.

Fig. 5. RIA rates for KPI tunnel.
likelihood for RTA to occur in the SB lane than NB lane at NZ1 and NZ2 of the Kampung Java and KPE tunnels.

Figs. 6 and 7 show the disaggregated RTA rates in each zone for the CTE tunnels and KPE tunnel, respectively. Four observations can be made. First, RTA rates are notably the highest at the first instance of entry into the road tunnel. This implies that some conditions exist in the entry transition zones, resulting in the highest RTA rates across the tunnels.

Second, RTA rates are lowest in the interior zones. This means that once drivers have passed the transition zones into the tunnel environment, they seem to drive more carefully and are less prone to RTA. Comparison with open roads is not possible since there are no corresponding figures available for RTA rates on open roads which include no overlapaba RTA. Limited comparison can be made to the open section of IPE, which has 868 RTA (41 NR, 677 SB) over 31.15 km (IW 8.60-11.75 km), aggregating a mean RTA rate of 11.43 per year per km (4.86 NR, 7.57 SB). The SB tunnel interior zone has slightly lower RTA rates (6.50 per year per km; 2.72 NR, 3.76 SB) than the open road section. However, 25 and S2 of the SB Kampung Java tunnel have rather high RTA rates compared to the rest of the tunnels. This anomaly is likely related to the change in number of lanes from three to four beginning in S2, which is exclusive to the SB Kampung Java tunnel.

Third, RTA rates appear to increase slightly when exiting the tunnels. This implies that exit transition zones also contain some conditions which increase RTA likelihood, though the effect is not as strong as the entry transition zones. RTA rates during tunnel exit are several times lower than RTA rates during the first instance of tunnel entry.

Lastly, subsequent re-entry into an existing tunnel (for CTE tunnels) experienced relatively lower RTA rates compared to the first instance of tunnel entry. This suggests that drivers may have retained certain levels of adaptation to the transition zones.

Fig. 8 shows the mean RTA rates for a unidirectional road tunnel, excluding the NB Kampung Java tunnel as it has an additional lane as compared to the other tunnels in this study.

Based on the RTA data available, it is not possible to deduce the reasons for high RTA rates in transition zones. However, crash data is available in police data, which reports the causes for injury RTAs. The most common causes are (1) drivers failing to keep a proper lookout; (2) drivers following too closely to the vehicle in front; and (3) drivers changing lanes without due care. These causes provide indicative reasons for RTA occurrence, but do not explain the localized RTA that occurred in the transition zones.

The authors explore four possible explanations for the higher RTA rates in the transition zones: (1) differences in speed limits between the open and tunnel sections; (2) drivers having poor adaptation to different luminance levels; (3) different road gradients in the transition zones; and (4) differences in driving behaviour between open and tunnel sections.

First, the speed limits in the open sections north of KPE tunnel and Kampung Java tunnel are 10 km/h higher than those in the tunnels. This may have resulted in greater speed differentials, which are recognized as factors influencing RTA likelihood, between vehicles in the transition zones. However, the open sections between the CTE tunnels and south of Kampong Java tunnel have the same speed limits to the tunnels on the respective transition zones still exhibit high RTA rates. This renders the effects of differing speed limits questionable.

Table 4: Z-test results for distribution of RTA travel direction in each zone.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Kampung Java</th>
<th>CTE South</th>
<th>KPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NR</td>
<td>SB</td>
<td>p-value</td>
</tr>
<tr>
<td>NZ1</td>
<td>9</td>
<td>44</td>
<td>28.89</td>
</tr>
<tr>
<td>NZ2</td>
<td>5</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>23</td>
<td>18</td>
<td>4</td>
<td>0.0001</td>
</tr>
<tr>
<td>53</td>
<td>15</td>
<td>5</td>
<td>0.0001</td>
</tr>
<tr>
<td>S2</td>
<td>14</td>
<td>15</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

D5
Second, drivers may be poor at adapting to different luminance levels in different environments, especially the black hole effect. The black hole effect refers to the impairment of visual perception, along with motor control, when transitioning from an optically brighter region to a darker region. However, the expressway tunnels in Singapore have been designed to have brightly lit portal areas to minimise the black hole effect (NYK Herrera Technologies Inc., 2010). According to ITA tunnel specifications, the design minimum luminance at road surface level is 5 lux during the day and 2.5 lux at night. However, in situ static luminance measurements were not feasible in the in-operation tunnels. Instead, alternative measurements were performed using a light metre placed on top of a car (about 1.4 m above road surface) driving through the tunnels. Interior zone luminance was found to be 100–200 lux: luminance levels in transition zones are higher than interior zones but the readings are not stable due to high variation. Nonetheless, it can be observed in Fig. 7 that the transition zones are adequately bright, minimising the black hole effect.

Third, road gradients may be difficult for drivers to manage. Since transition zones connect at-grade open sections to subgrade tunnel sections, there will be road gradients. Roads which are steep enough may result in poor speed control due to gravitational effects. However, the transition zones in Singapore are mild to graduent and impairment of speed control would be unlikely. All roads in Singapore are designed according to the LTA Civil Design Criteria (Land Transport Authority, 2010), which states that the absolute maximum grade for expressways is 5%.

Fourth, driving behaviour on open roads and tunnels may be different, regardless of speed limits or luminance levels. Young (2013) conducted a prospective study and found that drivers perceived open expressways differently from tunnel expressways. As such, regardless of how the transition zones are designed, conflicting driving behaviour will still result in RTAs occurring at the transition zones. This explanation seems to be most likely.

In the absence of additional data, the explanations are speculative and justifications will require in-depth analysis of RTAs in transition zones

3.3. RTA type in each zone

To gain better perspective on the RTAs at each zone, the RTAs were segregated by crash type: single vehicle crash (SVC), multi-vehicle crash (MVC). SVCs are RTAs due to self-induced loss of vehicle control. In contrast, MVCs are RTAs involving at least two colliding vehicles. Figs. 9 and 10 show the breakdown of RTAs into SVCs and MVCs for the CET tunnels and KPE tunnel respectively. It can be observed that SVC rates are rather low and stable across the tunnel zones, averaging 1.76 per year per km for CET tunnels and 0.91 for KPE tunnel. Thus, the differences in RTA rates among the various zones can be attributed to MVCs. The transition zones appear to impact drivers' ability to cope with inter-vehicle interactions.

Fig. 11 shows the mean SVC and MVC rates for a unidirectional road tunnel, excluding the NE Kranji Road tunnel. About 21% of the RTAs are SVCs; the remaining 79% are MVCs. This suggests that interactions among vehicles, such as following too closely to each other, are important RTA contributing factors.

3.4. RTA casualty likelihood

The severity of RTAs is another aspect to be considered. There were only one fatal RTA and two serious injury RTAs in the entire data, while the rest of the injury RTAs involved only minor injuries. Thus, fatal and serious injury accidents are not separately considered. Instead casualty likelihood, i.e., the likelihood that a RTA will involve casualties, is considered. Figs. 12 and 13 show the casualty likelihoods, disaggregated by travel direction, for the CET tunnels and KPE tunnel respectively.

In general, the casualty likelihoods in the CET tunnels are higher than those in the KPE tunnel. This is likely due to the higher speed limits in the KPE tunnel. Vehicle collisions at slower speeds experience smaller impact forces and are less likely to offer casualties. Also, opposite patterns compared to RTA rates can be observed. RTA casualty likelihood appears to be higher in the interior zones than in the transition zones. The trend can be explained by the higher proportion of SVCs in the interior zones. Fig. 14 shows the casualty likelihoods of SVCs and MVCs in the respective tunnels - the mean number of casualty RTAs per SVC is 0.299 while the mean number of casualty RTAs per MVC is 0.126. Evidently, SVCs are more than twice as likely as MVCs to result in casualties.
4. Conclusion

The study aims to investigate the characteristics of RTAs in expressway tunnels, using the Singapore context. Three expressway tunnels are included in this study - CTE Sungai Jawi tunnel, CTE Chin Swee tunnel and SPE tunnel.

Each expressway tunnel was divided into three zones and it was found that the RTA rates are generally higher in the transition zones (Z1 and Z2). Upon disaggregation by travel direction, it was realised that RTA rates are exceptionally much higher during tunnel entry at the first instance. Tunnel exit and re-entry zones, though lower than first instance tunnel entry, also showed relatively higher RTA rates compared to the interior zones.

Next, RTA type is examined in each zone. It was found that MVC rates are generally higher in the transition zones, suggesting that drivers are less able to manage inter vehicular interactions in transition zones. The higher RTA rates in transition zones can be attributed to the increase in MVCs, while rates on the other hand remained stable across the zones.

Several explanations for the high RTA rates in transitions have been discussed and the most likely explanation is a difference in driver perceptions of the environment and hence driving behavior between open roads and tunnels. Research work on driver behavior in road tunnels will help to address this issue.

To the authors' knowledge, the effect of travel direction has not been addressed by other RTA studies before. As other studies have used aggregated tunnel zone data, this aspect is often overlooked. Furthermore, in the analysis of RTA data from numerous road tunnels, since every road tunnel is unique in its location and design to some extent, it is extremely difficult to consider the individuality of each tunnel and thus only the common characteristics can be compared.

Current tunnel RTA studies use zone definitions which assume that RTA distribution is longitudinally symmetrical, which is justifiable if RTAs in both travel directions are aggregated. However, it is shown in this study that travel direction plays a crucial role in RTA distribution. Hence, future RTA studies should consider individual tunnel zones as separate road tunnels such as in Figs. 8 and 11. Zone definitions in future studies should also account for the non-symmetrical RTA distribution in such multidirectional tube.

Also, RTA casualty likelihood was discussed. It was found that RTAs in interior zones are more likely to result in casualties than RTAs in the transition zones, due to the higher proportion of MVCs. MVCs are more than twice as likely as MVGs to result in casualty RTAs.

Road tunnel design and implementation of speed limits need to be carefully planned in order to reduce the RTA rates at the transition zones. However, if enhanced tunnel designs are still unable to effectively reduce RTA rates in transition zones, authorities may need to consider other measures. Since the high RTA rates can be attributed to MVCs, which are mostly rear-end collisions on expressways, authorities can consider installing driver assistance systems (DAS) mandatorily. These systems will monitor rear-end collision and time-to- lane-crossing constantly, and will alert the driver when a forward collision or lane departure is imminent. DAS have shown promising results in pilot tests in countries such as USA and the Netherlands (Federal Motor Carrier Safety Administration, 2009; Rijkswaterstaat, 2007).

Unlike open roads, road tunnels are extremely costly to modify or rebuild. As more road tunnels are being built as part of urban road networks, it is crucial for these tunnels to be properly designed and planned for. Although most studies have shown that RTA rate in tunnels is lower than open roads, the authors believe that as long as tunnels form only a small part of the roadway network, drivers tend to and are able to drive more carefully in tunnels (Iannic, 2005). There may be a point in time where tunnels take up a significant portion of the network and drivers are unable to maintain high levels of vigilance throughout the network - that will be when RTAs in road tunnels become a grave issue.

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References


APPENDIX E

The effect of road tunnel environment on car following behaviour

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ABSTRACT

In order to overcome urban space constraints, underground road systems are becoming popular options for cities. Existing literature suggests that drivers react to road tunnels are lower than those in open roads. However, there is a lack of understanding as to how the road tunnel environment affects inter-
vehicle interactions. In this study, car following data of a major multi-lane tunnel under an open and
tunnel expressway in Singapore. A total of 13,325 car following histories with car as the follower, are
analysed and significant factors affecting the speed are found to be speed, and lane. Significant effect of
street type is only found for minor expressway. Speeding, are generally less in the tunnel environment.
Comparison of collision times amongst and safety indices also reveal safer car following
behaviour in the tunnel environment. The results are discussed from a behavioural perspective. Overall,
the findings show that road tunnels are superior in terms of safety but at reduced traffic capacity.

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1. Introduction

Urbanisation is one of the major challenges faced by megacities today. As megacities continue to grow, more space is
required for supporting infrastructure. However, urban expansion is often constrained by limited land space in the city. In order
to overcome this limitation, cities have begun to utilise urban under-
ground space for various uses, such as pedestrian links, utility tunnels, rail facilities and rail systems.

In particular, underground road systems (URSs) have become increasingly popular. Several studies (Kahnt, 1999; Sterling, 1998; Pinkel et al., 1998; Van Der Hagen, 2001) acknowledged the strategic use of URSSs, especially in highly developed areas such as central business districts. The reason is that URSSs help to reduce traffic in important city streets and preserve the surface environment from noise and emissions. Other advantages of URSSs include reducing motorists from adverse weather conditions and freeing up valuable land for other quality uses. With URSSs becoming more extensive, drivers can expect to spend a greater amount of time in road tunnels. However, there is limited knowledge on the impact of urban road tunnel environment on microscopic driving behaviour, which in turn aggregates into macroscopic traffic performance and safety.

According to the environment-behavioural theories, behaviour is the manifestation of the individual’s perspectives and perceptions of the environment. The theory of planned behaviour (Ajzen, 1991, 2005; Steg and Vlek, 2012) suggests that behaviour is modulated indirectly through intention by personal norms, attitude, subjective norms, and perceived behavioural control. In a field association study by Yeung et al. (2013), it was shown that drivers perceived open and tunnel environments differently. Several studies had also found drivers to be less receptive towards road tunnels (Cervero and Blumstein, 1990; Adams, 1994; Ania et al., 2008; Yeung et al., 2013), with higher scores in negative emotions experienced in tunnels as compared to surface roads. Considering the differences in perceptions and attitudes towards road tunnels, it is reasonable to expect drivers to behave differently in a road tunnel environment.

2. Literature review

2.1 Driving behaviour in road tunnels

Several studies have investigated driving behaviour in road tunnels. A series of driving simulator experiments (Cabinet et al., 2012; Cavin and Blanck, 2013) it was found that the road tunnel envi-
ronment, as compared to a control open section, resulted in lower driving speeds and differences in average lateral position (farther

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away from tunnel walls). Lower pathologic discomfort was also found in the tunnel interior zones. Interestingly, pathologic discomfort in the tunnel portal areas was found to be higher in a tunnel scenario as compared to the control scenario, and this suggests a causal link with accident rates. In another study, He et al. (2013) studied drivers' visual attention in various tunnel lengths in real-world trials and found indicative differences in the distribution of gaze time and fixation duration.

Some other studies investigated the effect of various tunnel features. A driving simulator study by Shiroyagi et al. (1995) revealed that tunnel centerline and frame information indicated the remaining tunnel length had notable effects on driving performance and driving workload. Sema et al. (2009) examined the effectiveness of accident information on drivers in a simulated tunnel and found that informing drivers about an accident that occurred in the tunnel had a positive effect on safety. Tsiakas (2009) assessed the effects of several tunnel wall patterns on simulated driving behavior. Although no significant effect of wall patterns was found, drivers drove at significantly lower speeds in the tunnel compared to regular roads. Kocher and Abilkerou (2002) investigated the effects of tunnel design and lighting on driver performance in a driving simulator and found light-colored walls were more important than strong illumination to keep drivers' visual attention on the road ahead.

However, most of these studies do not provide a comparative perspective in behaviour between open and tunnel road environments. Thus, they do not give insight into how tunnels will impact traffic behaviour compared to open roads. Furthermore, these studies were mostly based on single vehicles commuting through light traffic in the road tunnels, either in simulated or real-world environments. Hence, there is a lack of information on how the tunnel environment affects inter-vehicle interactions.

2.2 Traffic safety on road networks

Road tunnels have lower crash rates compared to surface roads (Aramburo and Kimes, 2004; Leung, 2004; Ma et al., 2009; Young and Wong, 2013). Homolely, traffic accidents in road tunnels are of great concern due to their potential for catastrophic outcomes. Nussbaumer (2007) found fatality rates to be more than double in bi-directional tunnels as compared to unidirectional tunnels, primarily due to a higher risk of head-on collisions with vehicles from opposing directions. Fortunately, for practical reasons, urban road tunnels normally carry only one-directional traffic, which reduces the risk of head-on collisions.

As a result, rear-end collision is the most prevalent crash type in urban road tunnels. More than two in three tunnel crashes in Singapore are rear-end collisions (Ma and Qia, 2012), while single vehicle crashes account for almost 10% of all reported tunnel crashes (Aramburo and Kimes, 2004; Ma et al., 2009; Young and Wong, 2013). According to The Handbook of Travel Risk Safety (Rabaud and Carre, 2012), most tunnel fires are caused by such rear-end collisions.

Road traffic accidents are the most direct measures of traffic safety and accident data have typically been used in traffic safety analyses. However, it is difficult to base traffic safety analyses on accidents because they are rare events (Laureyns et al., 2010). Furthermore, accident data may have sources such as underreporting and lack of detailed causal information. Hence, estimations of traffic safety should be more reliant on microscopic behavioural data.

2.3 Traffic safety and car following

A rear-end collision occurs when a following vehicle fails to brake in time to avoid impact with the front vehicle. This is usually a result of inadequate following distance. Typically, the two safety indicators used in measuring injurious rear-end collisions are headway (or gap) and time-to-collision (TTC). Lin and Kim (2010) and Biehl and Rosso, 2011. Vogel (2002) suggested that short headways indicate potential danger while short TTCs represent actual danger. This is consistent with Biehl and Middendorf (1982) who found that accident-involved drivers were more likely to maintain shorter headways than accident-free drivers (Meng and Qi, 2012) also demonstrated that the rear-end crashes were estimated using the likelihood of TTC being below a certain threshold at different traffic volumes.

Many factors may affect drivers' choice of headway, such as individual differences, situational factors, and other vehicles. Ramsey (1990) suggested that traffic tends towards congestion, the influence of individual and situational factors diminishes while the influence of other vehicles increases. A key factor influencing multiple choices is vehicle speed. However, while some studies have found headway predictions in increased speed with depth (Colbourne et al., 1978; Preece, 1984; Broughton et al., 2007; Aslam and Kazim, 2008; other studies have found otherwise (Tabish-Ahmed and Shams, 2001; Mandem et al., 2003; Brackstone et al., 2009). Other factors include visibility (Broughton et al., 2007), lead vehicle class (Preece, 1984; Racicot et al., 2009; Que and Wu, 2012; Aare et al., 2013), driver culture (Mandem et al., 2003), driver experience (Colbourne et al., 1978), and intervention advisory signage (Michael et al., 2002). Interestingly, most of these studies were conducted on single-lane roads and the effect of the traffic flow rate used in a multiple lane road is yet to be investigated. In other words, car following behavior in a GIS is different from that in the slow lane.

In order to assess the traffic safety, extended TTC measures such as the time exposed TTC (TE TTC) and time interval TTC (TITC) have been proposed (Minderhoud and Boy, 2001). TITC takes into account the amount of time that the TTC falls below a predetermined threshold. TITC takes into account both the duration and magnitude of which TTC falls below the threshold. These measures require the analysis of behavioral trajectories over time and are difficult to apply to point measurements.

Nikolai et al. (2012) proposed the concept of the time-averaging waves. Based on psychological or Action Point models, car following waves in opening chains provide better regression results in the D/Dox vs Ox plane (D is the relative speed and D0 is the distance gap between two successive vehicles) than conventional interpretation of Action Point models in the D/Dox plane (Brock et al., 2009; Brackstone et al., 2002). In essence, the expansion coefficients describes the TTC pattern observed in car following.

Zhu et al. (2012) proposed the mean of safety margin (SM) as an alternative risk indicator in car following. The computation of SM condition distance gap, speed, and relative speed, which is an important microscopic safety indicators (Qu et al., 2014). (Lu et al., 2012) discussed that, out of three risk indicators (time headway, TTC, and SM), SM serves as a suitable quantitative indicator of homocentric risk perception in car following because it follows the normal distribution. They also found professional drivers to exhibit lower SM compared to general drivers, which implies that professional drivers are willing to drive in a safer manner.

3. Objectives of the study

As mentioned, there is a lack of understanding in how the tunnel environment affects inter-vehicle interactions. This study sets out to examine car following behaviour (with car as the follower) in both open and tunnel road environments to meet two primary objectives: (1) to identify factors which affect how car drivers behave in unidirectional car following situations; and (2) to understand the macroscopic, psychological and biological perspective on the traffic safety.
in road tunnels is different from that in conventional open roads. Headways (time and distance) TEC, TM and SM are considered in the analysis. Drawing reference from accident studies, it is hypothesised that drivers adopt softer microscopic behaviour in the tunnel than in the open road environment.

4. Methodology

4.1. Data basis

Traffic video footage is obtained for both open and tunnel expressways in Singapore. The main criteria for site selection is to have similar roadway characteristics in both environments. For open expressway, video footage is recorded from an overhead pedestrian bridge arching over the Ayer Rajah Expressway (ARE) at the 4.5km mark. This section of the ARE is relatively straight and consists of six lanes (three in each direction, separated by a central median). It is also relatively free from lane changing activity in the nearest intersection more than one km away. The speed limit of this road section is 90 km/h. Data are collected from 25 frames per second video recorded on 16 September 2012, during the peak hour period from 1700 to 1900 hours, for westbound traffic. The weather was good with no rain for the entire observation period. In order for the video camera to be in a position as possible to minimise its influence on microscopic behaviour, the "away" view is recorded (see Fig. 1a).

For tunnel expressway, the selected site is the 5.4km mark of Kololo-Punggol Expressway (KPE) tunnel. This section of the KPE is relatively straight and consists of three lanes in each direction to KPE tunnel consists of dual unidirectional tubes. Lane changing activity is minimal since it is located mid-distance between an upstream on-ramp and a downstream off-ramp. The speed limit of this road section is 70 km/h. The video footage is requested from the Land Transport Authority (LTA) Operation Control Centre, which monitors KPE traffic through 24h traffic cameras. Data are collected from 25 frames per second video recorded on 26 September 2012 during the evening peak hour period (1700 to 1900 hours) for southbound traffic. The external weather was good with no rain for the entire observation period. In the tunnels, the "away" view is also performed (see Fig. 1b) because vehicle headlamps in the facial view tend to cause glare effect in the footage which compromises the quality of the video.

4.2. Data extraction

A manual frame-by-frame approach is used for data extraction. Manual data extraction is performed for two reasons. First, the traffic cameras do not have sufficient height to provide an ideal view of the traffic. As a result, automated image processing computer vision will not be able to detect vehicles properly. Second, existing automated methods are also unable to provide accurate vehicle classifications.

Two reference lines are marked over the video image and the distance between the two lines can be determined using the lane markings. The data stream (with a resolution of 6044) is plotted at which a vehicle passes each of the two reference markings are logged, along with the vehicle class (motorcycle, MC, car, light goods vehicle (LGV), heavy goods vehicle (HGV), or heavy vehicle (HV)). This lane traversal data is used in this study instead of the frontal headways (see Fig. 2) in lane change scenarios where the flow of vehicles is obstructed, the headways are estimated by the observer. This video extraction approach had been validated in several traffic studies (Meng and Wong, 2011; Meng and Ouy, 2012) and it was reported to effectively yield data of comparable quality to those obtained using the radar-speed measurement method (Strong et al., 2003).

4.3. Treatment of lane-keeping MC

Lane-keeping MC refers to a MC that travels in between traffic lanes (as in the case of two-lane MC that travels at the edge of the traffic lane). It is assumed in this study that these MCs do not affect, with-in lane car following behaviour in any significant way and are excluded in the analysis.

4.4. Identification of car following instance

Several studies used a critical headway approach to characterise car following (Young et al., 2003; Brodersen et al., 2011; Shiu et al., 2011). These studies only considered headways smaller than a defined threshold to represent car following, while headways longer than the threshold are disregarded. However, critical headways are not suitable for application in this study due to several reasons. First, there is no evidence that the same critical headway applies to all vehicle classes, especially when heterogeneous traffic is being examined. Third, the study objective is to examine how various factors affect car following and in one of the measures will be derived from headways. By truncating the data based on headways, the results will be biased towards smaller headways, even though some drivers may choose to adopt larger headways in certain situations.

Instead, all headways are considered in this study and categorised by speed. When vehicle speed is lower than the imposed speed limit, it is reasonable to assume that the vehicle is experiencing some level of impedance and is in car following mode. Furthermore, since the data are collected during the peak hours, the occurrence of non-car following instances would be minimal.
4.5 Assessment of headways

With the timestamps of two successive vehicles $t_i$ and $t_{i+1}$ (in minutes), the headway ($\Delta t_{i}$) can be determined:

\[ \Delta t_i = t_{i+1} - t_i \]  

where $i$ refers to the vehicle identification number, $t_i$ is the timestamp, and $\Delta t_i$ is the headway in minutes. The mean headway ($\Delta t_{\text{mean}}$) is then calculated:

\[ \Delta t_{\text{mean}} = \frac{\sum \Delta t_i}{N} \]

where $N$ is the number of headways.

4.6 Assessment of TTC

TTC is defined as the time taken for a collision to occur given that the vehicles are at the current distance of separation. It is calculated as the ratio of the distance gap (D) to the relative velocity ($v_{rel}$) between the two vehicles:

\[ TTC = \frac{D}{v_{rel}} \]

where $D$ is the distance gap and $v_{rel}$ is the relative velocity.

The TTC is further divided into two categories:

- **Gap Outstanding (GO):** If the TTC is greater than 1.5, there is no collision risk.
- **Gap Critical (GC):** If the TTC is less than 1.5, a collision is likely.

4.7 Assessment of SM

The determination of SM is based on the average stopping distance $S$ and the reaction time $T_{\text{reaction}}$ of the driver:

\[ SM = \frac{S}{T_{\text{reaction}}} \]

where $S$ is the distance to stop the vehicle and $T_{\text{reaction}}$ is the time taken to react.

5. Results

The results indicate that the effects of speed, lane, and time of day are significantly different. The mean stopping distance increases with speed, while the reaction time remains constant. The gap critical thresholds are adjusted based on these findings to improve road safety.
Table 1
Traffic composition for observed open expressway section.

<table>
<thead>
<tr>
<th>Vehicle class</th>
<th>Lane 1</th>
<th>Lane 2</th>
<th>Lane 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycles (mean speed)</td>
<td>29.09 (85 km/h)</td>
<td>50.47 (80 km/h)</td>
<td>15.71 (85 km/h)</td>
</tr>
<tr>
<td>Cars (mean speed)</td>
<td>85.13 (85 km/h)</td>
<td>85.49 (85 km/h)</td>
<td>45.02 (85 km/h)</td>
</tr>
<tr>
<td>Heavy vehicles (mean speed)</td>
<td>66.17 (85 km/h)</td>
<td>66.17 (85 km/h)</td>
<td>66.17 (85 km/h)</td>
</tr>
</tbody>
</table>

5.1. Open expressway

A total of 11,167 vehicles are observed for the open expressway condition. The traffic composition is presented in Table 1. For the three-lane expressway, Lane 1 is the fast lane, Lane 2 is the middle lane, and Lane 3 is the slow lane.

Table 2 presents a summary of the effects from the various ANOVAs (A through D) conducted for open expressway using both the log-transformed time and distance headways. The mean time headways of groups evaluated in the ANOVAs for open expressway are illustrated in Fig. 3, while the mean distance headways are illustrated in Fig. 4.

5.1.1. Effect of speed on headways

To control for the effects of领导者 type and lane, four ANOVAs (A through D) are conducted. The ANOVAs find consistent effect of speed on both time and distance headways. Post-hoc comparisons in ANOVA A and B find time headways to be the shortest at 65 km/h (see Fig. 3). Post-hoc comparisons in ANOVA A and B find distance headways to increase with speed (see Fig. 4).

5.1.2. Effect of leader type on headways

Controlling for effects of speed and possible effects of lane, two ANOVAs (E and F) are conducted. Car-MC pair are not considered due to their small sample size. Both ANOVAs are consistent in finding no significant effect of leader type. However, significant effect of speed is found in distance headway but not on time headways. The interaction term speed * leader type is not found to be significant in both cases.

5.1.3. Effect of lane on headways

ANOVA D and (effectively) control for effects of speed and possible effects of leader type. Both ANOVAs find significant effects of lane and speed, while no significant interaction effects of speed * lane are found. Post-hoc comparisons find both time and distance headways to be shortest in lane 1 (longest in lane 3).

5.2. Tunnel expressway

A total of 10,005 vehicles are observed for the tunnel expressway condition. The traffic composition is presented in Table 3. Table 4 presents a summary of the results from the various ANOVAs (through G) (through H) for open expressway, using both the log-transformed time and distance headways. The mean time headways of groups evaluated in the ANOVAs for tunnel expressway are illustrated in Fig. 5, while the mean distance headways are illustrated in Fig. 6.

5.2.1. Effect of speed on headways in tunnel

To control for the effects of leader type and lane, two ANOVAs (E and F) are conducted. The ANOVAs find consistent effect of speed on both time and distance headways. Post-hoc comparisons in both ANOVAs find headway to increase with speed.

5.2.2. Effect of leader type on headways in tunnel

Controlling for effects of speed and possible effects of lane, two ANOVAs (F and G) are conducted. Both ANOVAs are consistent in finding significant effect of leader type. Post-hoc comparisons find that both time and distance headways are largest for Car-HV (follower-leader), followed by Car-LV, Car-LV 1, and finally Car-MC.

Fig. 3. Mean time headways evaluated for open expressway.

Fig. 4. Mean distance headways evaluated for open expressway.

Fig. 5. Mean time headways evaluated for tunnel expressway.
Table 2. Results from various ANOVAs for open expressway.

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>Headway type</th>
<th>Lane factors</th>
<th>Leader type</th>
<th>Effect</th>
<th>F-test</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Time</td>
<td>45.75, 50, 75, 85</td>
<td>1</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 13.93</td>
</tr>
<tr>
<td>B</td>
<td>Time</td>
<td>45.75, 50, 75, 85</td>
<td>2</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 11.32</td>
</tr>
<tr>
<td>C</td>
<td>Distance</td>
<td>45.75</td>
<td>5</td>
<td>Car, SGC, I-2</td>
<td>speed</td>
<td>F(4, 42) = 10.35</td>
</tr>
<tr>
<td>D</td>
<td>Distance</td>
<td>45.75</td>
<td>1, 2, 3</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 14.79</td>
</tr>
<tr>
<td>a</td>
<td>Distance</td>
<td>45.75, 50, 75, 85</td>
<td>1</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 10.79</td>
</tr>
<tr>
<td>b</td>
<td>Distance</td>
<td>45.75, 50, 75, 85</td>
<td>2</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 15.32</td>
</tr>
<tr>
<td>c</td>
<td>Distance</td>
<td>45.75</td>
<td>5</td>
<td>Car, SGC, I-2</td>
<td>speed</td>
<td>F(4, 42) = 14.93</td>
</tr>
<tr>
<td>d</td>
<td>Distance</td>
<td>45.75</td>
<td>1, 2, 3</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 14.79</td>
</tr>
</tbody>
</table>

Table 3. Traffic compensation for short of tunnel expressway section.

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Lane 3</th>
<th>Lane 2</th>
<th>Lane 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycles (mean speed)</td>
<td>167 (39.64 km/h)</td>
<td>172 (40.24 km/h)</td>
<td>71 (37.84 km/h)</td>
</tr>
<tr>
<td>Cars (mean speed)</td>
<td>112 (55.88 km/h)</td>
<td>236 (51.13 km/h)</td>
<td>50/2 (49.44 km/h)</td>
</tr>
<tr>
<td>Light goods vehicles (mean speed)</td>
<td>185 (39.65 km/h)</td>
<td>451 (41.59 km/h)</td>
<td>21 (41.54 km/h)</td>
</tr>
<tr>
<td>Heavy vehicles (mean speed)</td>
<td>466 (32.21 km/h)</td>
<td>57 (39.81 km/h)</td>
<td>117 (40.10 km/h)</td>
</tr>
</tbody>
</table>

Table 4. Results from various ANOVAs for tunnel expressway.

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>Headway type</th>
<th>Lane factors</th>
<th>Leader type</th>
<th>Effect</th>
<th>F-test</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Time</td>
<td>55, 65, 75, 85</td>
<td>1</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 14.93</td>
</tr>
<tr>
<td>F</td>
<td>Time</td>
<td>55, 65, 75, 85</td>
<td>2</td>
<td>Car, LGC, I-2</td>
<td>speed</td>
<td>F(4, 42) = 11.32</td>
</tr>
<tr>
<td>G</td>
<td>Time</td>
<td>55, 65, 75, 85</td>
<td>1, 2, 3</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 14.93</td>
</tr>
<tr>
<td>h</td>
<td>Distance</td>
<td>55, 65, 75, 85</td>
<td>1</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 14.93</td>
</tr>
<tr>
<td>i</td>
<td>Distance</td>
<td>55, 65, 75, 85</td>
<td>2</td>
<td>Car, LGC, I-2</td>
<td>speed</td>
<td>F(4, 42) = 14.93</td>
</tr>
<tr>
<td>j</td>
<td>Distance</td>
<td>55, 65, 75, 85</td>
<td>1, 2, 3</td>
<td>Car</td>
<td>speed</td>
<td>F(4, 42) = 14.93</td>
</tr>
</tbody>
</table>

5.23. Effect of lane on headways

ANOVA Cg and CgI, as well as control for effect of speed and possible effects of traffic type. Both ANOVAs find significant effects of lane and speed. Near-significant effect of the interaction term speed x lane is found in ANOVA Cg while significant interaction effect is found in ANOVA CgI. Post-hoc comparisons that both time and distance headways are shorter in lane 3, and longest in lane 1.

5.3. Comparison of headways between open and tunnel expressway

Taking into consideration the data available and the significance of the factors affecting headways in each environment, two three-way ANOVAs (one for time headway and one for distance headway) are performed for time and distance headways for Car-Car pairs at speeds of 55 and 65 km/h (2 speeds x 3 lanes = 6 combinations). Table 5 presents the ANOVA results. In both ANOVAs, significant effects of speed, lane, and environment are found. The interaction terms speed x lane, lane environment, speed environment, and speed x lane environment are found to be significant as well. In the tunnel environment, greater increases in headways are observed in the slower lanes and with increasing speeds.

5.4. Comparison of TTC measure

Car following charts are produced in the 45/90 vs. 45/90 plane (opening chart), for both the open and tunnel expressways.
Regression analysis is then performed for both set of data points, with the regression lines set to pass through the origin. Fig. 7 illustrates the opening chart and Table 6 summarizes the regression results obtained.

The regression coefficients obtained are significantly different from each other. For the same closing relative speed of 0.95, the TIC triense (DV/DG) is very likely to be higher in open expressways than in tunnel expressways, i.e. TICs are lower in open expressways. The average closing relative speeds in the open and tunnel expressways are -1.24 m/s and -1.62 m/s, respectively. When the average relative speed is applied to the regression model, a scene what higher TIC value is obtained for tunnel expressway (2.209) as compared to open expressway (2.175).

5.5. Comparison of SM and ensured safety

The SM values are analysed on a lane basis, since earlier findings revealed lane effects. Also, the likelihood of ensured safety is compared. Table 7 presents the results.

The mean SM in the tunnel expressway are slightly higher than those in the open expressway. As for the likelihood of ensured safety, it is found that Lane 1 (fast lane) has the lowest likelihood of ensured safety while Lane 3 (slow lane) has the highest likelihood. It should be noted that the likelihood of ensured safety is consistently higher in the tunnels.

6. Discussion

The data are collected during peak hours from two sites that share similar traffic composition and average speeds. This section discusses the results and highlights the significant implications of the findings.

6.1. Factors affecting roadway

The first part of the study identifies factors that have an effect on car following on roadways. Car following patterns in open and tunnel expressways have different speeds, examined using ANOVA for both time and distance headways. Factors considered include speed, leader type, and lane.

It is expected for distance headways to increase with speed due to longer breaking distances at higher speeds. Tache-Manzon and Shinar (2001) and Boan et al. (2011), based on experimental data, reported that differences in distance headway at different speeds but insignificant differences in time headway. If time headways do not differ across speeds, it would imply that a driver's perceived risk in car following is mainly a function of the driver's operational reaction time and that distance headway is merely the product of speed and the desired time headway. However, the findings in this study provide evidence that speed has a significant effect on time headway, which implies that drivers' perceived risk changes with speed.

This will be discussed later with the comparison of headways with other models.

Table 7

In Table 7, the SM values and likelihood of ensured safety are presented. The SM values show a trend of increasing from slow to fast lanes, with the highest SM values in the tunnel expressway. The likelihood of ensured safety also shows a trend, with the highest likelihood in Lane 3 (slow lane) and the lowest in Lane 1 (fast lane) in the open expressway. The table also includes a comparison of SM and likelihood values between open and tunnel expressways.
The absence of speed effects in the experimental studies may be due to Hawthorne effect, an impact behaviors due to the awareness of being studied. As discussed by Brier (1999) and Hancock (1999), driving is generally a satisfying task. Under normal driving situations, drivers behave in a manner well enough to meet their personal goals and do not seek to optimize their behavior. In an experimental context, drivers may have an unusually performed in an unusual manner. Naturalistic observations thus have higher validity (Bly, 2013).

The lane traveled is also found to a significant factor in both experimental and naturalistic studies. Consistent with both experimental and naturalistic studies, headways in lane 1 (fast lane) are the shortest while headways in lane 3 (slow lane) are the longest. Lane effects are therefore unexpected when lane lengths are similar, however, a significant difference in the last lane. The higher overall level of traffic in the slower lanes thus results in longer headways. A possible explanation for lane effect is that in a traffic culture where lanes are associated with different speeds, drivers who opt to stay in the slow lane would be more conservative than those in the fast lanes. The higher overall level of traffic in the slower lanes then results in longer headways. If true, this has interesting implications on future research as it may identify different driver groups by terms of risk perception based on lanes.

The effect of lead type is found to be significant in the naturalistic observations but not significant in the open expressway. In the tunnel, car drivers maintained a longer headways behind larger vehicles. Intuitively, one would expect longer headways when following behind larger vehicles due to the size of the vehicle ahead being obscured, adding elements of uncertainty to the driver's perceived risk. However, in the open expressway, drivers seem to disregard the lead vehicle type, and the advantage of the road ahead has a greater effect in the tunnels due to limited sight distances. Various studies have examined the effect of leader vehicle type on distinct driving behaviors, but the results have been mixed. White (2004) and Daux et al. (2012) observed larger headways behind trucks, in contrast, Vos and Hoogerbrugge (2011), Bade and Shinar (2008), and Kox et al. (2002) observed the opposite. They reasoned that since trucks have lower braking power which results in longer braking distances, drivers behind them have more time and distance to react and hence are able to maintain shorter headways. On the other hand, Vos and Hoogerbrugge (2011) found no differences in headways between cars and trucks. With regard to the inconsistency in the various studies, it would appear that environmental and cultural factors play an important role.

Overall, after speed, lane, and lead type, headways (both time and distance) are longer in the tunnel than in open expressway. The road environment also has significant interaction effects with the mentioned factors. The findings in this study provide behavioral evidence that drivers indeed perceive higher risks in the tunnel environment, (besides maintaining relatively larger headways). This is consistent with perception studies in the literature. However, it is also possible that drivers perceive driving in tunnels as a novel experience and therefore drive more conservatively (Leistikow et al., 2008). However, based on the free association study by Vos et al. (2002), drivers did not associate tunnels with novelty effects or unfamiliarity. Instead, drivers associated it more strongly with lighting, safety, and enforcement. This implies that novelty effects are insignificant and environmental effects are inherent.

Another possible explanation for the more conservative car following behavior in tunnels is the presence of traffic cameras. A characteristic of urban road tunnels is the high density of traffic cameras to monitor traffic throughout the tunnel, unlike open roads where traffic cameras are more sparse. Drivers may adopt more "conventional" driving behavior in tunnels due to the awareness of being recorded. However, this explanation is less likely to be true because behavioral differences have been documented in simulation studies where the effect of traffic cameras is non-existent.

6.2. Comparison of headways with other studies

The Car-Client distance headways in this study are compared to the minimum safe distances and the two-second rule (see Fig. 8). In the derivative of safety distances, driver reaction time is assumed to be 2 sec, and the deceleration is assumed to be 7 m/s². As shown in Fig. 8, the renal behavior of the lead vehicle is assumed to be slow, i.e., the following vehicle has its deceleration synchronized with the lead vehicle. In addition, comparison is done with results from other studies (Bade and Shinar, 2008; Daux et al., 2012).

The headways obtained in this study, like those found in other studies, mostly fall between the conservative and less conservative safety distances. The minimum safety distances and two-second rule are considered only the crash likelihood based on present driver reaction and braking distances. i.e., constant time headway. The headways observed in this study are shown to be more conservative as speed increases. This can be explained by the higher perceived risk at higher speeds. If a constant driver reaction time is assumed (controlling for crash likelihood), it is possible that perceived crash consequence is more severe at higher speeds. Higher speeds are associated with greater crash severity and higher crash rates (AFTF and JNCCE, 2004). As shown in Fig. 8, headways in our tunnel are the highest, which is explained by higher perceived risk in the tunnel environment. However, headways at speeds below 65 km/h should be interpreted with caution due to the 70 km/h speed limit of the tunnel being observed in this study.

6.3. Rear-end collision risks

Headways indicate the potential danger while TTC indicates actual danger (Vos, 2003). The minimum TTC values in both road environment are not assessed. In following waves, the results, as shown in Fig. 7, indicate that for the same relative speeds, TTC values will be larger in the tunnel. This is because of the overall longer headways in the tunnel. Safety margins in the tunnel environment are higher than those in the open environment.
mean SM local in this study are consistent with those of [10] who found mean SM values for professional and general drivers to be 0.872 and 0.860, respectively. This study shows that drivers display higher safety margins in the road-terrain environment, which is consistent with findings of small actions on safety in road networks [11].

The likelihood of an accident is also computed. The computation takes into account the vehicle speeds, speed differentials, distance gaps, and driver reaction times. By trials, instances of ensured safety are more likely in the terrain, supporting the hypothesis that traffic is safer in the road-terrain environment.

6.4. Implications of Longer Headways

Traffic capacity is a key consideration for major roads with high traffic density. Yeng et al. (2013) found that drivers strongly associated open expressways with speed and efficient traffic conditions. In fact, it is common in rural headways that the observed speeds are due to shorter commute time being prioritized over safety, especially in urban areas where commute time is a greater concern.

The longer headways in road tunnels imply that traffic capacity is compromised. Although road tunnels are superior in terms of traffic safety, capacity is expected to be lower than that of open roads. Thus, implementation of URS should take into account the reduced traffic capacities in road tunnels. In order to provide similar traffic capacities, road tunnels may require higher resistance than surface roads. From a land-use perspective, road tunnels may be less efficient use of space, compared to other uses for underground space such as shopping malls and warehousing. However, when considering the potential use of surface land, URS remains an attractive option. In a transit operation perspective, URS would ideally serve to supplement surface roads and not to replace them, at least in the near future.

7. Conclusion

This study assessed the car following patterns observed in both the open environment and the tunnel environment. Speed, lane, and leader type are found to have effects on headways to various extents. Overall, headways in tunnel environments are shorter than those in the open environment. The likelihood of an accident is also higher in tunnels. Overall, from a microscopic behavioral perspective, traffic in tunnel environments can be concluded to be safer than the conventional open expressways. The conclusion is consistent with the longer headways observed in road tunnels, suggesting that microscopic behavioral studies could be useful tools for assessing the effectiveness of road environments. This study is also extended to terrain-vehicle interaction in road tunnels and also the implications of implementing URS in future road networks.

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Driver perspectives of open and tunnel expressways

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ABSTRACT

Urban road tunnels are becoming more extensive due to land scarcity in city areas, and accident rates in these tunnels are comparatively lower than those on open roads. This study examines drivers’ perspectives of open and tunnel expressways for 114 active drivers in Singapore using the free association technique. The driver perspectives of open and tunnel expressways were found to be different using texts on the frequency of associations in each category, and through multidimensional scaling analysis. Drivers perceive speed, traffic condition, and scenery to be most prevalent for open expressways, while lighting, entertainment, and safety are more prevalent for tunnel expressways. Road quality is important to隧道 users identified in this study and the findings are discussed. Analysis of response variance shows that tunnels are generally perceived less positively compared to open expressways, and ANOVA found that frequent tunnel users do not perceive tunnel expressways more positively than infrequent users. The response variance is also found to correlate well with the reported quality of experience in such environments. The differences in driver perspectives may help explain differences in driver behavior. Findings from this study also provide insight to road planners in meeting quality needs of drivers. © 2013 Elsevier Ltd. All rights reserved.

I. Introduction

One of the many challenges faced by the world today is urban sustainability. As megacities continue to expand and develop, their growth is constrained by limited land space. To overcome this limitation, cities are beginning to utilise underground space, especially for transport systems. Several studies (Banks, Ikeda, & Raitha, 1998; Sallnäs, 1990; Sterling, 1997) acknowledge the use of underground transport solutions, which free up valuable land for other purposes, protects the environment from noise and pollution, and reduces traffic in important city streets. An underground road system (URS) becomes more efficient as drivers spend a greater portion of their driving time in road tunnels and it will be increasingly important to ensure that drivers are also able to drive comfortably and safely in the tunnels. Studies have shown that driver behavior and perception vary in different situations such as handling secondary tasks (Bridges, Hale, & Lord, 2011; Metz, Schrom, & Kruger, 2011; Recarte & Nanes, 2011), interactions (Dolce & Broberg, 2011; Weemde & Volvik, 2012), different road widths (Anderson, Abbott, Witzlind, Blomqvist, & March, 2012; Debertin, Badeau, & De Wadd, 2011), different road complexities (Cunial, Ladulanc, Serrano, & Tronci, 2009; Schröder & Gagnon, 2008), different times of the day (Champion & Jin, 2009), different luminance levels (Hagena, Veluur, & Hof, 2005), different weather (Kostadinopoulos, Chapman, & Crompton, 2010) and even slight changes in the surrounding landscape including trees (Anderson, March, Woods, & Blomqvist, 2009) and crash barriers (Arnold et al., 2012) can have a significant effect on how perception and behaviour is different in urban road tunnels.

In terms of safety, studies have shown that traffic accident rates in road tunnels are generally lower than those on open roads (Armstrong & Barnes, 2000; Lenke, 2010; Ma, Shao, & Zhang, 2009). However, there is limited knowledge on how perception and behaviour is different in urban road tunnels.

In the era of mass transport users, several researchers attempted to study traffic behaviour through tunnels such as candidate surveys (Astrand, 1994; Sörensson & Helenkamp, 1992) and questionnaires (Arto, López, Fernández, Martínez-Rubio, & Magallanes, 2008). These studies generally point towards negative
perceptions of the tunnels. Novel approaches, with the aid of improved technology, include those that study both driver and driving behaviour in real-world, using instrumented vehicles (H.-C. Chen, Wang, & Shi, 2010; Zhao, Jiang, & Hu, 2011; Zhou & Lin, 2011) and driving simulations (Hirata, Mohara, & Yile, 2006; Kircher & Landwehr, 2011; Mühlig-Bülow, Bülow, & Fahl, 2007; Mühlig-Bülow, Wiesen, & Fuhr, 2008; Sjunor, Talaj, & Olness, 1990; Kroustaki, 1994; Young, 2011) investigated the car-following patterns in urban tunnel expressway and found that drivers maintained larger gaps in the tunnels; as compared to open expressway, controlled for speed. This reflects a more conservative driving behaviour exhibited in tunnels.

According to environment-behaviour theories, behaviour is a manifestation of the individual's perspectives and perceptions of the environment. The theory of planned behaviour (Ajzen, 2002; Seg & Northcraft, 2003) indicates that behaviour is indirectly mediated through intention by personal norms, attitude, subjective norms, and perceived behavioural control.

In order to have a holistic understanding of driver behaviour, it is essential to investigate the effects of the road tunnel environment on driver perspectives and quality needs, and how they may affect drivers and driving behaviour.

Conventional perception surveys have usually involved the use of structured questionnaires and guided tours. For instance, statements like “I feel safe driving in the tunnels” are usually followed by a five- or seven-point scaled option ranging from “Strongly Disagree” to “Strongly Agree”. In such questions, the category feelings of safety is stated upfront and respondents are only required to express their valence (level of agreement) towards the category. Although this type of question relies in structured and objective responses which make the analysis procedure easier for the analyst, it does not take into consideration how strongly respondents associate to these categories or how strongly these categories are interconnected. The effectiveness of using scales is undermined when the predetermined categories do not reflect the underlying prevalence of each category, however, attempting to cover every plausible category would result in lengthy questionnaires and complicated analyses.

As such, the free association technique was used in this study. The technique is unrestrictive on the drivers and will allow drivers to freely give thoughts and recall relevant elements regarding the expressions. The researcher is able to measure the strength of the association between a given domain and the categories associated with it. The list of categories can also be used to portray the current perspective of the domain (Grant & Ragin, 2013). The responses provided by the respondent will be most strongly associated to the given domain and the most frequently associated categories can then be inferred to be the most prevalent domain characteristics to the respondents.

The technique and its variant forms, free listing and word association, have been used in various fields such as food quality (Aires & DeLo, 2008; Guerrero et al., 2010; Hough & Fernández, 2010; Rada, Kruiser, & Cohen, 2002), social science (Gouyand, 2008), and transport-related research (Grant & Ragin, 2011).

The study is conducted in Singapore and its main objective is to investigate driver perceptions of both open and tunnel expressways. Singapore is highly motorised island-state with a vehicle density of 100 vehicles per lane km, Figs. 1. and 2 show snapshots of typical open and tunnel expressways in Singapore, respectively. There are currently 61 km of expressways in Singapore, of which around 11 km are underground tunnel sections; 38 km semi-open sections; and the remaining open road sections.

In this study, three hypotheses are being tested: H1: drivers perceive open and tunnel expressways differently. This is expected to be true since driving behaviour in tunnels is found to be more conservative and behaviour is mediated by perspectives and perceptions.

H2: drivers who use tunnel expressways more frequently perceive the tunnels more positively than infrequent users due to increased familiarity. This will be of interest to road planners in understanding whether initial positive impressions of roads tunnels can be offset by tunnel usage frequency.

H3: drivers who feel more positively (or negatively) towards a particular domain will tend to provide a greater number of positive (or negative) responses for that domain. This implies that the free association technique serves as a valid measurement of driver attitudes.

The first two hypotheses directly relate to the main focus of the paper; while H3 is additional in understanding the usefulness of the free association technique.

2. Methodology

2.1. Questionnaire and data collection

The two domains in this study are the open and tunnel expressways, and the categorical associations are to portray the most prevalent roadway qualities in the drivers’ perspective. Semi-open expressways are not considered due to the lack of substantial presence in the Singapore road network.

Each questionnaire consists of three sections. Section I asks the subject to imagine driving on an open expressway and list the first five words, thoughts, feelings, or expressions that come to mind. Similarly, Section II requires the subject to imagine driving in a tunnel expressway and list the first five responses that come to
Table 2: Recession examples of coded categories of associations.

<table>
<thead>
<tr>
<th>Category</th>
<th>Definition</th>
<th>Common words</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMRD</td>
<td>Responses related to speed</td>
<td>Fast, slow, speed</td>
</tr>
<tr>
<td>I/RUDE</td>
<td>Responses related to the physical road pavement</td>
<td>Rough, bumpy, uneven</td>
</tr>
<tr>
<td>GENDER ROLES</td>
<td>Responses related to the role of the subject</td>
<td>Male, female, gender</td>
</tr>
<tr>
<td>PROSTHESIS</td>
<td>Words describing the nature of the body</td>
<td>Prosthetic, artificial limb</td>
</tr>
<tr>
<td>DEAFNESS</td>
<td>Words related to the act of being deaf</td>
<td>Hearing loss, deaf</td>
</tr>
<tr>
<td>CANCER</td>
<td>Words related to the disease</td>
<td>Cancer, oncology</td>
</tr>
<tr>
<td>COPD</td>
<td>Words related to the location of the issue</td>
<td>Asthma, lung disease</td>
</tr>
<tr>
<td>LUMBAR PAIN</td>
<td>Words related to the spine</td>
<td>Back pain, lumbago</td>
</tr>
<tr>
<td>DEPRESSION</td>
<td>Words related to emotional issues</td>
<td>Sadness, depression</td>
</tr>
<tr>
<td>ABDOMINAL PAIN</td>
<td>Words related to abdominal issues</td>
<td>Stomach pain, indigestion</td>
</tr>
<tr>
<td>PATIENT</td>
<td>Words related to hospitalization</td>
<td>Doctor, medication</td>
</tr>
<tr>
<td>DOCTOR</td>
<td>Words related to medical treatment</td>
<td>Surgery, medication</td>
</tr>
<tr>
<td>PHARMACY</td>
<td>Words related to medications</td>
<td>Prescription, pharmacy</td>
</tr>
<tr>
<td>RECEPTION</td>
<td>Words related to the reception of care</td>
<td>Reception, check-in</td>
</tr>
<tr>
<td>CHECK-OUT</td>
<td>Words related to discharge</td>
<td>Discharge, check-out</td>
</tr>
<tr>
<td>OBSERVATION</td>
<td>Words related to observation</td>
<td>Observation, inspection</td>
</tr>
<tr>
<td>RESULTS</td>
<td>Words related to test results</td>
<td>Results, outcome</td>
</tr>
<tr>
<td>FEEDBACK</td>
<td>Words related to feedback</td>
<td>Feedback, review</td>
</tr>
</tbody>
</table>

2.3. Responses

A combined total of 1017 responses are collected from both Sections 1 (551) and 2 (556) yielding an average of 3384 responses per subject (432 for Section 1, 436 for Section II). All subjects in the 140 questionnaire sessions, 55 (42.6%) presented Section I before Section II; while the other 35 (32.8%) presented Section I last. These responses are coded into categories for analysis. First, the mean frequencies of associations to each domain are compared using paired t-tests for each category. Holm-Bonferroni corrections for multiple comparisons are made to control the family-wise error rate at α = 0.05.

Second, multidimensional scaling analysis was performed to map the categories and their inter-relationships onto a two-dimensional plot. Third, one-way ANOVA was performed on the response valences to investigate if the effects of travel and/or usage frequency on the valence to provide positive or negative responses. In addition, the relationship between the response valences and the self-reported ratings for each expression type was investigated to find out if response valences could indeed be used to understand the respondents' attitudes toward each domain.
Table 3

<table>
<thead>
<tr>
<th>Category</th>
<th>Median frequency of response association (N=15)</th>
<th>Median frequency of response association (N=15)</th>
<th>Median association strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRAFFIC CONGESTION</td>
<td>0.549 (0.81)</td>
<td>0.157 (0.685)</td>
<td>0.43</td>
</tr>
<tr>
<td>RECESSION</td>
<td>0.738 (0.831)</td>
<td>0.119 (0.369)</td>
<td>0.16</td>
</tr>
<tr>
<td>REPAIR</td>
<td>0.543 (0.802)</td>
<td>0.106 (0.369)</td>
<td>0.16</td>
</tr>
<tr>
<td>COST</td>
<td>0.157 (0.875)</td>
<td>0.457 (0.857)</td>
<td>0.26</td>
</tr>
<tr>
<td>CIVIL DISOBEDIENCE</td>
<td>0.264 (0.84)</td>
<td>0.161 (0.459)</td>
<td>2.5</td>
</tr>
<tr>
<td>UNEMPLOYMENT</td>
<td>0.254 (0.859)</td>
<td>0.471 (0.676)</td>
<td>4.2</td>
</tr>
<tr>
<td>SPEED</td>
<td>0.479 (0.47)</td>
<td>0.12 (0.523)</td>
<td>0.5</td>
</tr>
<tr>
<td>SATISFY</td>
<td>0.297 (0.836)</td>
<td>0.24 (0.706)</td>
<td>1.1</td>
</tr>
<tr>
<td>ENRAGEMENT</td>
<td>0.277 (0.598)</td>
<td>0.421 (0.679)</td>
<td>0.18</td>
</tr>
<tr>
<td>AIR</td>
<td>0.104 (0.289)</td>
<td>0.478 (0.302)</td>
<td>0.12</td>
</tr>
<tr>
<td>SUGAR</td>
<td>0.297 (0.836)</td>
<td>0.24 (0.706)</td>
<td>0.12</td>
</tr>
<tr>
<td>OXYGEN</td>
<td>0.289 (0.448)</td>
<td>0.24 (0.706)</td>
<td>0.12</td>
</tr>
<tr>
<td>PAINFUL</td>
<td>0.149 (0.25)</td>
<td>0.488 (0.54)</td>
<td>1.4</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td>0.164 (0.72)</td>
<td>0.466 (0.506)</td>
<td>7.1</td>
</tr>
<tr>
<td>SLOW</td>
<td>0.289 (0.448)</td>
<td>0.24 (0.706)</td>
<td>0.12</td>
</tr>
<tr>
<td>TASTE</td>
<td>0.289 (0.448)</td>
<td>0.24 (0.706)</td>
<td>0.12</td>
</tr>
<tr>
<td>FRUITION</td>
<td>0.237 (0.875)</td>
<td>0.344 (0.525)</td>
<td>0.18</td>
</tr>
</tbody>
</table>

2.4. Encoding

The responses from Sections I and II are encoded into their respective categories and values. Similar to the free association study on food by Ross et al. (2002), the categories are not determined before data collection. Instead, the categories are generated using the data collected. For each response, it was determined which existing category it would best belong to. If none of the existing categories sufficiently describes the response, a new category will be generated by the first encoder. Thus, the categories generated by this approach are, in principle, mutually exclusive.

Based on the responses from both Sections I and II for all subjects, 22 categories were generated. The individual categories, along with their definitions and some common responses associated with them, are listed in Table 2. It should be noted that in rare cases where responses were considered by the encoder to be associated to more than one category, multiple associations were coded for those responses.

Also, the response valences were considered. Each response could either be a positive, neutral, or negative association to the category. For instance, the response "traffic congestion" will be assigned a negative valence in the category TRAFFIC CONGESTION. On the other hand, "coping" will be assigned a positive valence in the same category. Neutral valences are assigned to responses such as "speed", "safety", "light", and "weather", which are usually nouns which do not offer any description to the associated category. Each positive association is given a value of +1 while each negative association is given a value of -1, and neutral association are given a value of 0. The categorical valences are added up to obtain the overall valence for individual respondents corresponding to each of the two road environments. The overall categorical valence measures the overall tendency of the respondent to give positive or negative responses.

As in the study by Gusha & Popova (2011), after all the responses were encoded by the first encoder, a second encoder encoded 25% of the data (277 responses) selected at random, the second encoder categorized the responses using the definitions listed in Table 2. An inter-rater reliability analysis using the Kappa statistic was performed to determine consistency among the encoders. The reliability analysis was performed twice - once for the categorical associations and once for the response valences. For the categorical associations, it was found that Kappa = 0.803, p < 0.001. For the response valence, it was found that Kappa = 0.854, p < 0.001. The Kappa values of greater than 0.80 indicate good inter-rater reliability.
3. Results

3.2. Frequency of categorical association

From the 1,107 subject responses, 1,112 categorical associations were identified. The mean frequencies of response association for each category for both Sections I and II are shown in Table 3. The mean frequency of response association is the average number of responses which is associated to a particular category generated by a respondent.

The results indicate that, for open expressways, the most frequently (more than 30%) associated categories are (in descending order) TRAFFIC CONGESTION, EMOTION, SPEED, SAFETY, OTHER MOTORISTS, and SCENERY. For tunnel expressways, the most frequently associated categories are (in descending order) LIGHT, SAFETY, EMOTION, ENFORCEMENT, and SPEED. This suggests that most prevalent roadways qualities to the drivers for open expressways are different from that for tunnel expressways. On an open expressway, drivers perceive traffic conditions and flow speeds to be the most prevalent elements in a tunnel expressway, lighting conditions and tunnel safety take over.

Next, t-tests are performed to compare the means for each category between open and tunnel expressways. The results reveal that associations to SPEED, OTHER MOTORISTS, TRAFFIC CONDITION, COST, and SCENERY were statistically more frequent in open expressways (absolute values greater than 1.96). On the other hand, SAFETY, LIGHT, RECEPTION, SOUND, and ENFORCEMENT were statistically more frequent in tunnel expressways. However, after Holm-Bonferroni corrections for multiple comparisons, statistical significance was only found for LIGHT, TRAFFIC CONDITION, RECEPTION, SOUND, ENFORCEMENT, and COST.

3.2. Multidimensional scaling

Multidimensional scaling analysis was performed to model the driver perspectives of open and tunnel expressways. The intercorrelation matrix served as a pseudo-similarity matrix for multidimensional scaling, excluding the category OTHERS. The model shows the relative prevalence of each category on a two-dimensional space. The two-dimensional model is adopted according to Parkinson’s Law. Furthermore, the normalized root stress value is low (Open 0.06; Tunnel 0.11), and the Dispersion Accounted For (Open 0.40; Tunnel 0.30) and Tucker’s Coefficient of Congruence (Open 0.95; Tunnel 0.94) are close to 1.

Figs. 3 and 4 illustrate the two-dimensional models corresponding to driver perspectives of open expressways and tunnel expressways, respectively. Both maps show the same prevalent categories being positioned nearer to the periphery. It should be noted that the dimension on both maps are arbitrary, and may not be the same. The maps reflect the relative distance of each category to another for the two different road environments. Note OTHERS in the maps refers to OTHER MOTORISTS, the rest are self-explanatory.

As observed in Figs. 3 and 4, the driver perspectives of open and tunnel expressways are rather different. For instance, the position of LIGHT (marked by solid circle) is in the middle for open expressways, while it is at the rightmost for tunnel expressways, indicating the increased prevalence of LIGHT in the tunnels. Inter-categorical distances are also different. For instance, the gap between SPEED and SPACE (marked by dashed edges) is shorter for tunnel expressways, i.e., the two categories are more likely to be associated with each other in tunnels.

3.3. Effect of tunnel usage frequency on categorical valences

The next part of the analysis took into consideration the categorical valences. The mean valence for open expressway is 0.334 (± 0.251) and −1.140 (± 2.13) for tunnel expressway. Drivers had higher tendencies to provide negative responses for tunnel expressway, and this suggests that tunnel expressways are not as popular as open expressways. Table 4a shows the mean scores (with standard deviation) disaggregated by gender and tunnel usage frequency. One-way ANOVA is performed on the mean valence and no significant effects of gender and tunnel usage frequency are found.

3.4. Response valences as attitude indicators

The respondents also rated their experience in open and tunnel expressways. On a scale of one (drives) to five (likes), the mean

| Table 4 | Disaggregated mean positive and negative associations (standard deviations). |
|----------|------------------|------------------|------------------|---|
| Gender   | Open Positive    | Open Negative    | Tunnel Positive  | Tunnel Negative |
| Male     | 5.24 (1.52)      | 3.21 (1.35)      | 3.05 (1.32)      | 2.06 (1.37)     |
| Female   | 5.46 (1.46)      | 3.24 (1.37)      | 3.13 (1.30)      | 1.84 (1.36)     |
| Never or more month | 5.51 (1.38) | 3.27 (1.39) | 3.03 (1.32) | 2.20 (1.60) |
| Once or less | 5.2 (1.54) | 3.3 (1.17)  | 3.08 (1.08) | 1.72 (1.39) |
rating is 3.73 (s.d. 0.899) for open expressways and 3.28 (s.d. 1.049) for tunnel expressways. The difference is found to be statistically significant (t = 3.262, df = 113, p < 0.001). ANOVA found no significant effects of gender or tunnel usage frequency.

Fig. 5 shows a plot of the mean respondent valences for each rating. It is observed that there is an observed linear relationship between the valences and the ratings, with high ESP values. Respondents who like that particular road environment were more likely to provide more positive associations (or less negative associations). Also, it would appear that drivers have lower expectations for tunnel expressways, as shown by the smaller slope gradient. Evidently, the overall response valence of a driver correlates to the driver's attitude towards the domain, and serves as a valid measurement of driver attitudes.

4. Discussion

The study set out to find out 1) whether drivers perceived open expressways differently from tunnel expressways; and 2) whether frequent tunnel users perceived tunnel expressways more positively than infrequent users. The free association technique was used to collect information for this study. In addition, the study aims to find out 3) whether there is any relationship between the categorical valences and the reported overall experiences in each domain.

4.1. Driver perspective of open and tunnel expressways

The results show that drivers perceive open expressways and tunnel expressways are indeed different to some extent. After coding the responses into their respective categories, the categorical associations found that the most prevalent terms to the drivers differ for open and tunnel expressways, as shown in Table 3. Driver perspective models obtained through multidimensional scaling also illustrate the differences.

Prevalent roadway qualities in open expressways are more traffic-coordinated, and related directly to the interpersonal interactions (SPEED, TRAFFIC CONDITION, SCENERY, and OTHER MOVEMENTS). For tunnels, the prevalent qualities are more self-oriented and are related closely to the individual interaction with the road environment (ENFORCEMENT, LIGHT, and SPEED). The most strongly associated qualities tend to be clearly different for the two expressway types. Multidimensional scaling analysis is used to model driver perspective using the inter-correlation of the categorical associations. The models show the perceptual structure of each road environment, with the more prevalent terms moving to the periphery. Visual comparisons will show how each roadway characteristic varies in various environments in terms of prevalence (distance from centre of control) and relation to other characteristics (relative position of characteristics).

As shown in Table 3, associations to six categories were found to be significantly different between the two road environments. Increased associations to TRAFFIC CONDITION for tunnel expressways are likely due to the traffic management policies resulting in lower congestion rates in the tunnels. Thus, traffic conditions become seemingly "irrelevant" in the tunnels.

Meanwhile increased associations to CWIS are most likely due to the absence of Electronic Road Pricing (ERP) gates in the tunnels. In Singapore, ERP gates are erected at roads leading to high congestion areas. During certain hours of the day, ERP gates are activated and vehicles passing through these gates will have the toll fees electronically deducted without having to stop.

There is no increase in associations to LIGHT in tunnel expressways. Drivers perceive tunnels as darker environments without natural lighting, and hence acknowledge the importance of lighting in tunnels, complemented by the road signs that advise drivers to switch on headlights when driving in the tunnels. Since driving depends on vision, it is likely for drivers to feel that their visual performance is impaired in the tunnels due to the lower luminance levels. In fact, LIGHT was expected to be the most prevalent road tunnel quality.

Also, increased associations to ENVIRONMENT in tunnel expressways could be related to the absence of unique and distinctive landmarks in the tunnels. Studies have shown that landmarks are essential in efficient way-finding and environmental cognition (Barnett, 2008; May & Ross, 2006; Ross, May, & Grimley, 2004). When landmarks are used in navigational tasks, fewer directional errors are made and navigation performance is improved (Takimoto, Takayama, Inoue, & Ohtake, 2006; Chua, 2009). In the absence of navigational landmarks in the tunnels, geographic knowledge is not factored (Barnes, Skog, & Fitzgerald, 1984) and drivers may find it difficult to identify locations. As a result they are constantly looking out for their desired exits.

Alternatively, some drivers may be claustrophobic and wish to exit the tunnels as soon as possible. Moore (1996) mentioned that when there is an accident in road tunnels, drivers naturally prefer to escape through the tunnels instead of going to the clearly indicated shelter provided outside the tunnel. This suggests that when entering the tunnel is a stressful experience, future research is required to investigate claustrophobic behaviour in tunnels, so as to determine ways to mitigate claustrophobia-related problems.

Increased associations to SCENERY and SPEED in tunnels are likely due to the tunnel infrastructure, blocking out GPS reception and retaining sounds within, and also the instructions asking drivers to switch on their radios when entering the tunnel.

Other notable differences, though not shown to be significant, include increased associations to ENFORCEMENT and SAFETY in the tunnels. Speed limits in the tunnels are generally lower than open expressways in Singapore, and the speed cameras are fixed to spot within the tunnels. As a result drivers are more constrained in driving within the speed limit and hence greater associations to ENFORCEMENT.

Increased associations to SAFETY may be due to feelings of insecurity and awareness inside the tunnels, possibly attributed to elements of claustrophobia. Enclosed spaces, entrapment, darkness and a lower level of perceived control are said to induce fear and avoidance of underground spaces (Carnegie, Hart, & Sorell, 1994; Ringstad, 1994). Other fears may stem from feelings of disorientation (Lee, Simpkins, & Zhao, 2012). This fear in turn translates to a "subjective risk" experienced by the drivers, affecting driver behaviour in a conservative manner (Näätänen & Summala, 1996). This is consistent with findings of Yeung (2013), where drivers are found to maintain larger gaps in tunnels.

Judging by the relative prevalence of the roadway qualities in the two expressway types, it is interesting to note that TRAFFIC CONDITIONS and SPEED are placed higher than SAFETY and
ENFORCEMENT on open expressways, while SAFETY and ENFORCEMENT are placed above SPEED and TRAFFIC CONDITIONS in tunnel expressways.

Capacity and safety are known to be two conflicting aspects in traffic management—the enhancement of a single aspect would mean the compromise of the other. Since drivers perceive capacity-related qualities to be more relevant on open expressways, it would be intuitive to say drivers in general drive faster and in a more aggressive manner on open expressways, in order to reduce travel time. On the other hand, speed and distance-related qualities are strongly associated with tunnel expressways, drivers in general would drive slower and be more compliant with traffic laws in the tunnels, in order to enhance road safety.

4.2. Categorical valences

Considering the categorical valences, it is evident that most drivers perceived road tunnels with more negative associations and fewer positive associations than open expressways. This is consistent with the findings of Adams et al. (2008), who found that tunnels induce unpleasant feelings and greater levels of perceived risk than open roads. In the current study, more associations (mostly negative) to SAFETY were also found for tunnel expressways. Furthermore, self-reported ratings revealed that open expressways are preferred over tunnel expressways.

The findings from Peterson et al. (2009) suggest that driving speeds decrease lateral positioning tends towards the road centre, and emotional stress increases, as the landscape settings deviate away from open landscapes in terms of “openness.” Road tunnels would then represent an extreme landscape setting where “openness” is at the minimum. Young (2013) found that drivers reported greater mental demand, effort, and temporal demand in the tunnel expressway after performing the same tasks as in both open and tunnel expressways. This exemplifies a difference in attitudes towards road tunnels.

The findings are consistent with the evolutionary theories on landscape preferences, especially the “drift hypothesis,” which studies that humans have innate tendencies to seek contact with animals, plants, and natural landscapes. Presence of natural elements can help reduce stress and mental fatigue (van den Berg, Hartig, & Stadler, 2007). Also, drivers have reported higher frustration in reliance in nature-dominated roads compared to completely built roads (Cadwallach & Nastic, 2003).

4.3. Effect of tunnel usage frequency

It was hypothesized that drivers who use tunnels more frequently would perceive tunnels more positively due to the increased familiarity. To test this hypothesis, ANOVAs are performed for categorical valences and respondent ratings.

It was found that tunnel usage frequency had no significant effects on the valence of the association and the ratings. Despite being more familiar with the tunnels, frequent tunnel users did not perceive tunnels more positively than infrequent users. This means that, from a psychological perspective, in terms of categorical associations and valences, are consistent across various groups of tunnel users. Initial impressions of the tunnel environment are retained over time and do not improve.

4.4. Implications of the findings

There are several practical implications of the findings obtained in this study. First, the difference in prevalent traits implies that drivers perceive road tunnels differently from open roads. These differences may modulate driving behavior.

Indeed, this study reveals that drivers perceive illuminating elements more important in the tunnels, while lighting in tunnels that plays a crucial role affecting drivers, through visual influences. Since safe driving depends primarily on the driver’s visual perception and psychomotor skills, it is reasonable to argue that any factors affecting the driver’s vision will have impacts on road safety.

Studies involving visual scanning patterns (Crandall & Underwood, 2011; Hartikka, Tykkö, & Harman, 2007; Kyzar & Zdaniuk, 2009) generally agree that increased road scene scanning has a protective effect on driver safety. Scanning increases the likelihood of detecting hazards early and shorter reaction times. Hence, the influence of lighting on visual attention should be further investigated.

Second, it is also observed that road tunnel driving is likely to be more stressful than open road driving. Stress is associated with increased cognitive loading, which has a negative effect on road safety (Caracci et al., 2009; Hartikka et al., 2007; Lee, Kim, & Boyle, 2007; Recarte & Nunes, 2002; Sincock & Gagnon, 2010). Most of these studies show that with high mental work load, driving performance deteriorates reaction times increase, visual detection is impaired, road scene scanning is reduced, and the number of hard braking events increases. This implies that road safety in road tunnels may be compromised. Thus, interior design concepts for tunnels need to be explored for optimal concepts that induce minimal stress in the drivers.

Interestingly, studies have also found that accident rates in road tunnels are generally lower than those in open roads (Aamodt & Ranes, 2000; Martin et al., 2003; Young & Young, 2013), possibly because of increased vigilance due to the increased subjective risk experienced by drivers’ compensatory behavior.

Also, the results reveal that non-tunnel users are not more receptive towards the tunnels than infrequent users. Tunnel users generally respond with significantly more negative than positive associations to tunnels. This finding reinforces the importance of the tunnel architecture and interior design to alleviate negative associations to the tunnel infrastructure. This is especially important for cities planners to model future cities and meet the quality needs of the people. The study has successfully identified roadway qualities in open and tunnel expressways that are prevalent to drivers.

4.5. Free association as a valid measure of driver attitudes

The free association technique allows the analysis to open to categories which are not predetermined. It is essentially a more centric approach which does not limit respondents to providing feedback based on a predetermined scope. Furthermore, additional psychological constructs or situational models relative to traffic safety may also be found in the process. This study has demonstrated that driver attitudes can be understood through the response valences.

This approach may also be applied to various road settings such as intersections, arterial roads, etc., which can help identify important road elements or roadway qualities that read users perceive as important for the particular road setting so that enhancements can be made to improve the driving experience and road safety.

4.6. Interpretation of analysis

Response biases may be observed in online open participation and mail-back questionnaires, where the respondents mostly belonged to the two younger groups of the three predefined age groups. However, it was not possible to ascertain whether non-
respondents were older persons, since information on the age distribution of active drivers is unavailable.

It was not possible to establish the response rates for mail-back questionnaires through reminder letters, in the absence of driver addresses. As a result, face-to-face interviews had to be conducted in order to engage older respondents. However, the overall proportion of older drivers in the 40–60 years age group remained relatively low (16%).

In the absence of the analyses are unlikely to be affected since it is not considered a factor. In a free-living study by Schaal and Sanchez (2001), it was found that differences in production between older and younger subjects decreased when items were limited to those mentioned by at least two people or more. Thus, this indicates that it applies to cases where different age groups have the same relative familiarity with the demand of interest (as was the case in this study).

It is thus possible for the results obtained in this study to be generalised to all drivers, on the presumption that age-related differences in free association are negligible. However, since free association is heavily dependent on the respondent’s direct experience in the particular domain, it should be noted that the results of this study may not generalise to keepers in other regions, where driving conditions and practices differ greatly. Furthermore, extensive research has shown that there are differences in driver attitudes across different countries and cultures (Lajunen, O’callaghan, Parker, & Summala, 2007; Nordfjærn, Jørgensen, & Randrup, 2001; Ökman, Lajunen, Chalidouki, Parker, & Summala, 2004; Warner, O’callaghan, & Lajunen, 2009; Warner, Ökman, Lajunen, & Tramniska, 2011). This means that although we can expect the prevalent categories to be largely similar across regions, the overall contents may vary.

5. Conclusion

This study attempted to investigate the differences in driver perspectives of open and tunnel expressways, in terms of associations to various roadway qualities, and the salience of these associations. The free association technique has, together with test-set PMMA, been proven to be useful when investigating the roadway qualities prevalent to drivers. The results are based on the most accessible memory of the road environments and gives insight into how driver perspectives are shaped.

With regard to the three hypotheses set out, this study has managed to show insightful results: (1) as expected, drivers indeed perceived tunnel expressways as more complex than the open expressways – self-oriented items are found to be more prevalent in the tunnel environment; (2) drivers had significantly more negative associations to the tunnel environment as compared to the open expressways, and unexpectedly, drivers who use the tunnels more frequently did not perceive the tunnel more positively compared to less frequent users; and (3) unsupervised drivers who reported better experiences tend to have more positive associations.

The results can serve as the basis for further research in road tunnel design. The various roadway qualities identified to be prevalent to the drivers can be set as variables to determine the optimal design parameters, where road safety and quality of driving are optimized. For instance, this study found that lighting, feelings of safety, and the type of enforcement/intelligence systems are important to the drivers and are the most likely factors to modulate drivers’ behavior in the road tunnel environment and the quality of driving.

Lowest driver perspectives are likely to lead to different driving behaviors in the two road environments, which might explain the differences in driving behavior and accident rates between the two road environments. Increased association to unstructured categories and increased negative associations may imply that drivers perceive the tunnels as hostile environments with higher levels of risk. As a result, drivers adopt safer driving behaviors, such as maintaining larger gaps and being more vigilant, as a form of risk compensation. On a macroscopic level, this translates to overall lower accident rates in tunnels.

Although evidence shows that current road safety levels in tunnels are generally higher, this has been a result of research and development to improve the current standards. Limm (2005) pointed out that "as long as tunnels remain only a small part of the road network, drivers tend to drive more carefully in tunnels." As more cities begin to utilize urban underground road systems, it is increasingly important to understand how drivers perceive these new environments and how their behavior may be affected.

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