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Title	The effect of road tunnel environment on car following behaviour
Author(s)	Yeung, Jian Sheng; Wong, Yiik Diew
Citation	Yeung, J. S., & Wong, Y. D. (2014). The effect of road tunnel environment on car following behaviour. <i>Accident Analysis &amp; Prevention</i> , 70, 100-109.
Date	2014
URL	<a href="http://hdl.handle.net/10220/19809">http://hdl.handle.net/10220/19809</a>
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# The effect of road tunnel environment on car following behaviour

By

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Article Submission to Accident Analysis and Prevention

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1 According to environment-behaviour theories, behaviour is the manifestation of the individual's  
2 perspectives and perceptions of the environment. The theory of planned behaviour (Ajzen, 1991; 2005; Steg  
3 and Nordlund, 2013) suggests that behaviour is modulated indirectly through intention by personal norms,  
4 attitude, subjective norms, and perceived behavioural control. In a free association study by Yeung *et al.*  
5 (2013), it was shown that drivers perceive open and tunnel expressways differently. Several studies had also  
6 found drivers to be less receptive towards road tunnels (Serrano and Blennemann, 1992; Amundsen, 1994;  
7 Arias *et al.*, 2008; Yeung *et al.*, 2013), with higher scores in negative emotions experienced in tunnels as  
8 compared to surface roads. Considering the differences in perceptions and attitudes towards road tunnels, it is  
9 reasonable to expect drivers to behave differently in road tunnel environment.

## 10 **2. Literature review**

### 11 **2.1. Driving behaviour in road tunnels**

12 Several studies have investigated driving behaviour in road tunnels. In a series of driving simulator  
13 experiments (Calvi *et al.*, 2012; Calvi and D'Amico, 2013), it was found that the road tunnel environment, as  
14 compared to a control open section, resulted in lower driving speeds and differences in average lateral position  
15 (further away from tunnel walls). Lower pathologic discomfort was also found in the tunnel interior zones.  
16 Interestingly, pathologic discomfort in the tunnel portal areas was found to be higher in a tunnel scenario as  
17 compared to the control scenario, and this suggests a causal link with accident rates. In another study, He *et al.*  
18 (2010) studied drivers' visual attention in various tunnel lengths in on-road trials and found indicative  
19 differences in the distribution of gaze time and fixation duration.

20 Some other studies investigated the effect of various tunnel features. A driving simulator study by Shimojo  
21 *et al.* (1995) revealed that tunnel cross section and signage information indicating the remaining tunnel length  
22 had notable effects on driving performance and driving workload. Hirata *et al.* (2006) examined the  
23 effectiveness of accident information on drivers in a simulated tunnel and found that informing drivers about  
24 an accident that occurred in the tunnel had a positive effect on safety. Törnros (2000) assessed the effects of  
25 several tunnel wall patterns on simulated driving behaviour. Although no significant effect of wall pattern was  
26 found, drivers drove at significantly lower speeds in the tunnels compared to surface roads. Kircher and  
27 Ahlstrom (2012) investigated the effects of tunnel design and lighting on driver performance in a driving

1 simulator and found light-coloured walls were more important than strong illumination to keep drivers' visual  
2 attention on the road ahead.

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

## 8 **2.2. Traffic safety in road tunnels**

9 Road tunnels have lower crash rates compared to surface roads (Amundsen and Ranes, 2000; Lemke,  
10 2000; Ma *et al.*, 2009; Yeung and Wong, 2013). Nonetheless, traffic accidents in road tunnels are of great  
11 concern due to their potential for catastrophic outcomes. Nussbaumer (2007) found fatality rates to be more  
12 than double in bi-directional tunnels as compared to unidirectional tunnels, presumably due to a higher risk of  
13 head-on collisions with vehicles from opposing directions. Fortunately, for practical reasons urban road  
14 tunnels mainly carry unidirectional traffic in each tube, thus greatly reducing the possibility of head-on  
15 collisions.

16 As a result, rear-end collision is the most prevalent crash type in urban road tunnels. More than two in  
17 three tunnel crashes in Singapore are categorised as rear-end crashes (Meng and Qu, 2012), while single  
18 vehicle crashes account for a small fraction of all reported tunnel crashes (Amundsen and Ranes, 2000; Ma *et*  
19 *al.*, 2009; Yeung and Wong, 2013). According to *The Handbook of Tunnel Fire Safety* (Beard and Carvel,  
20 2012), most tunnel fires are caused by such rear-end collisions.

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

## 26 **2.3. Traffic safety and car following**

27 A rear-end collision occurs when a following vehicle fails to brake in time to avoid impact with the front  
28 vehicle. This is usually a result of inadequate following distance. Typically, the two safety indicators used in

1 assessing imminent rear-end collisions are headway (or gap) and time-to-collision (TTC) (Oh and Kim, 2010;  
2 Bella and Russo, 2011). Vogel (2003) surmised that short headways indicate potential danger while short  
3 TTCs represent actual danger. This is consistent with Evans and Wasielewski (1982) who found that accident-  
4 involved drivers are more likely to maintain shorter headways than accident-free drivers. Meng and Qu (2012)  
5 also demonstrated that rear-end crash rates can be estimated using the likelihood of TTC being below a certain  
6 threshold at different traffic volumes.

7 Many factors may affect drivers' choice of headway, such as individual differences, situational factors, and  
8 other vehicles. Ranney (1999) suggested that as traffic tends towards congestion, the influence of individual  
9 and situational factors diminishes while the influence of other vehicles increases. A key factor influencing  
10 headway choice is vehicle speed. However, while some studies have found time headways to increase with  
11 speed (Colbourn *et al.*, 1978; Puan, 2004; Broughton *et al.*, 2007; Al-Kaisy and Karjala, 2010), other studies  
12 found otherwise (Taieb-Maimon and Shinar, 2001; Marsden *et al.*, 2003; Brackstone *et al.*, 2009). Other  
13 factors include visibility (Broughton *et al.*, 2007), lead vehicle class (Puan, 2004; Brackstone *et al.*, 2009;  
14 Ossen and Hoogendoorn, 2011; Duan *et al.*, 2013), driver culture (Marsden *et al.*, 2003), driver experience  
15 (Colbourn *et al.*, 1978), and intervention advisory signage (Michael *et al.*, 2000). Interestingly, most of these  
16 studies were conducted on single-lane roads and the effect of the traffic lane travelled in a multilane roadway  
17 is yet to be investigated, i.e. whether car following behaviour in the fast lane is different from that in the slow  
18 lane.

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

24 Bifulco *et al.* (2013) proposed the concept of car following waves. Based on psychophysical or Action  
25 Point models, car following waves in opening charts provide better regression results in the  $DV/DX$  vs  $DV$   
26 plane ( $DV$  is the relative speed and  $DX$  is the distance gap between two successive vehicles) than conventional  
27 interpretation of Action Point models in the  $DV$  vs  $DX$  plane (Brackstone and McDonald, 1999; Brackstone *et*  
28 *al.*, 2002). In essence, the regression coefficient describes the TTC patterns observed in car following.

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

### 8 **3. Objectives of the study**

9 As mentioned, there is a lack of understanding in how the tunnel environment affects inter-vehicle  
10 interactions. This study sets out to examine car following behaviour (with car as the follower) in both open  
11 and tunnel road environments to meet two primary objectives: 1) to identify factors which affect how car  
12 drivers behave in unidirectional car following situations; and 2) to understand from a microscopic behavioural  
13 perspective how traffic safety in road tunnels is different from that in conventional open roads. Headways  
14 (time and distance), TTC, and SM are considered in the analyses. Drawing reference from accident studies, it  
15 is hypothesized that drivers adopt safer microscopic behaviour in the tunnel than in the open road  
16 environment.

## 17 **4. Methodology**

### 18 **4.1. Data basis**

19 Traffic video footages are obtained for both open and tunnel expressways in Singapore. The main criterion  
20 for site selection is to have similar roadway characteristics in both environments. For open expressway, video  
21 footage is recorded from an overhead pedestrian bridge arching over the Ayer Rajah Expressway (AYE) at the  
22 4.5 km mark. This section of the AYE is relatively straight and consists of six lanes (three in each direction,  
23 separated by a central median). It is also relatively free from lane changing activity as the nearest intersection  
24 is more than one km away. The speed limit of this road section is 90 kph. Data are collected from a 25 frames-  
25 per-second video recorded on 18 September 2012, during the peak hour period from 1700 to 1900 h, for  
26 westbound traffic. The weather was good with no rain for the entire observation period. In order for the video  
27 camera recorder to be as inconspicuous as possible to minimise its influence on motorists' behaviour, the  
28 "away" view is recorded (see Figure 1a).

1 For tunnel expressway, the selected site is the 5.4 km mark of Kallang-Paya Lebar Expressway (KPE)  
 2 tunnel. This section of the KPE is relatively straight and consists of three lanes in each direction – KPE tunnel  
 3 consists of dual unidirectional tubes. Lane changing activity is minimal since it is located mid-distance  
 4 between an upstream off-ramp and a downstream on-ramp. The speed limit of this road section is 70 kph. The  
 5 video footage is requested from the Land Transport Authority KPE Operations Control Centre, which  
 6 monitors KPE traffic through 24-h traffic cameras. Data are collected from a 25 frames-per-second video  
 7 recorded on 26 September 2012, during the evening peak hour period from 1700 to 1930 h, for northbound  
 8 traffic. The external weather was good with no rain for the entire observation period. In the tunnels, the  
 9 “away” view is also preferred (see Figure 1b) because vehicle headlights in the frontal view tend to create a  
 10 glare effect in the footage which compromises the quality of the video.



13 Figure 1. Snapshot from video footage for (a) open expressway and (b) tunnel expressway

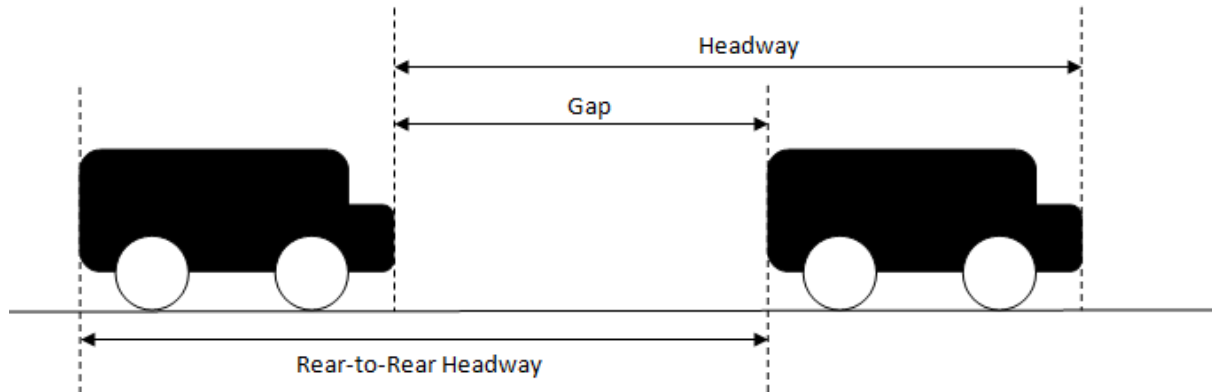
#### 14 4.2. Data extraction

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

19 Two reference lines are marked over the video image and the distance between the two lines can be  
 20 determined using the lane markings. The timestamps (with a resolution of 0.04 s) at which a vehicle passes  
 21 each of the two reference markings are logged, along with the vehicle class (motorcycle MC, car, light goods  
 22 vehicle LGV, or heavy vehicle HV) and the lane travelled. Rear-to-rear headways are used in this study  
 23 instead of the frontal headways (see Figure 2). In rare instances where the view of a vehicle is obscured, the



1 timestamps are estimated by the observer. This video extraction approach had been validated in several traffic  
 2 studies (Meng and Weng, 2011; Meng and Qu, 2012) and it was reported to effectively yield data of  
 3 comparable quality to those obtained using the radar-speed measurement method (Strong *et al.*, 2003).



4  
 5 Figure 2. Illustration of headway, gap, and rear-to-rear headway

#### 6 **4.3. Treatment of lane splitting MC**

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

#### 10 **4.4. Identification of car following instances**

11 Several studies used a critical headway approach to characterise car following (Sayer *et al.*, 2003;  
 12 Brackstone *et al.*, 2009; Shiomi *et al.*, 2011). These studies only considered headways smaller than a defined  
 13 threshold to represent car following, while headways longer than the threshold are disregarded. However,  
 14 critical headways are not suitable for application in this study due to several reasons. First, there is no  
 15 evidence that the same critical headway applies to both open and tunnel road environments. Second, there is  
 16 no evidence that the same critical headway applies to all vehicle classes, especially when heterogeneous  
 17 traffic is being examined. Third, the study objective is to examine how various factors affect car following and  
 18 most of the measures will be derived from headways. By truncating the data based on headways, the results  
 19 will be biased towards behaviour at smaller headways even though some drivers may choose to adopt larger  
 20 headways in certain situations.

21 Instead, all headways are considered in this study and categorised by speed. When vehicle speed is lower  
 22 than the imposed speed limit, it is reasonable to assume that the vehicle is experiencing some level of

1 impedance and is in car following mode. Furthermore, since the data are collected during the peak hours, the  
 2 occurrence of non-car following instances would be minimal.

### 3 **4.5. Assessment of headways**

4 With the timestamps of two successive vehicles  $t_n$  and  $t_{n-1}$  ( $n$  represents the order of the vehicle), the time  
 5 headway  $THW_n$  (refer to Figure 1) and vehicle speed  $v_n$  can be determined:

$$6 \quad THW_n = t_{n,L1} - t_{n-1,L1} \quad (1)$$

$$7 \quad v_n = D / (t_{n,L2} - t_{n,L1}) \quad (2)$$

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

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

16 The effects of speed, lane, and leader type are assessed using ANOVA in the first analyses.

### 17 **4.6. Assessment of TTC**

18 TTC is defined as the time taken for a collision to occur given that the vehicles of interest maintain their  
 19 current states of motion which will result in a collision. Again, only TTC for cars as followers are considered.  
 20 In order to determine TTC, the gap between vehicles is first obtained. The distance gap  $DX$  between two  
 21 vehicles is determined by:

$$22 \quad DX_n = THW_n \cdot v_n - l_{car} \quad (3)$$

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

$$24 \quad TTC_n = \begin{cases} \frac{DX}{DV} = \frac{DX}{v_n - v_{n-1}}, & v_n > v_{n-1} \\ N.A. & , \text{ otherwise} \end{cases} \quad (4)$$

25 where TTC values are only existent in gaps where the follower's speed is greater than the leader's speed. If  
 26 the leader is travelling faster than the follower, a collision is rendered impossible.

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

#### 7 **4.7. Assessment of SM**

8 The determination of SM is given as:

$$9 \quad SM = 1 - \left\{ \frac{0.15v_n}{DX} + \frac{[v_n + v_{n-1}][v_n - v_{n-1}]}{1.5g.DX} \right\} \quad (5)$$

10 where  $g$  is the acceleration due to gravity. For its theoretical development and mathematical formulation, refer  
 11 to Lu *et al.* (2012). The SMs for cars in each road environment will be evaluated and the mean SM represents  
 12 the desired SM of the drivers in the road environment. Furthermore, safety is ensured when

$$13 \quad \frac{v_n \cdot \tau_1}{DX} \leq SM \quad (6)$$

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

17 The likelihood of ensured safety is also determined to evaluate traffic safety based on car following. For  
 18 each car following instance, equation (6) is applied to determine whether safety is ensured. The likelihood is  
 19 then derived as the proportion of car following instances (car as followers) where equation (6) is satisfied.

20 All statistical procedures are performed using *IBM SPSS 21*.

#### 21 **5. Results**

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

26 *THW* is observed to follow a lognormal distribution across the groups. In order to utilise ANOVA, *THW* is  
 27 first treated with natural log transformation into *log THW*. In addition, continuous speed data are also

1 categorised into speed bands of 10 kph, indicated by their mid-point values, i.e. data falling between speed of  
2 50 and 60 kph will be classified as 55 kph.

3 In addition to *THW*, the analyses are repeated using distance headways (a through g, corresponding to A  
4 through G). Similarly, distance headways are observed to follow a lognormal distribution and natural log  
5 transformation is applied.

### 6 **5.1. Open expressway**

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

10 Table 1. Traffic composition for observed open expressway section

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

11

12 Table 2 presents a summary of the results from the various ANOVAs (A through D; a through d) for open  
13 expressway, using both the log-transformed time and distance headways. The mean time headways of groups  
14 evaluated in the ANOVAs for open expressway are illustrated in Figure 3, while the mean distance headways  
15 are illustrated in Figure 4.

#### 16 **5.1.1. Effect of speed on headways**

17 To control for the effects of leader type and lane, four ANOVAs (A, B, a, and b) are conducted. The  
18 ANOVAs find a consistent effect of speed on both time and distance headways. Post-hoc comparisons in  
19 ANOVAs A and B find time headways to be the shortest at 65 kph (see Figure 3). Post-hoc comparisons in  
20 ANOVAs a and b find distance headways to increase with speed (see Figure 4).

21

22

### 1 5.1.2. Effect of leader type on headways

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

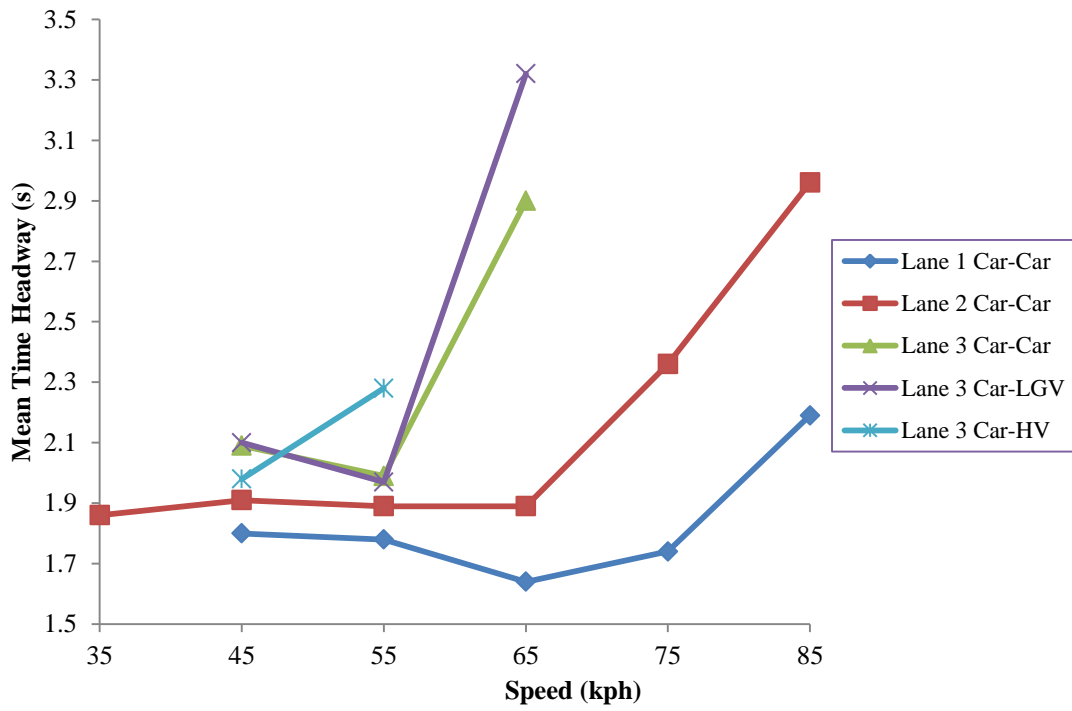
7 Table 2. Results from various ANOVAs for open expressway

ANOVA	Headway type	Input factors			Effect	Results	
		Speed (kph)	Lane	Leader type		F-test	p-value
A	time	45, 55, 65, 75, 85	1	Car	speed	F (4, 4242) = 17.454	< 0.001
B	time	45, 55, 65, 75, 85	2	Car	speed	F (4, 2233) = 11.002	< 0.001
C	time	45, 55	3	Car, LGV, HV	speed	F (1, 1012) = 0.063	0.802
					type	F (2, 1012) = 1.843	0.159
					speed*type	F (2, 1012) = 2.884	0.056
D	time	45, 55	1, 2, 3	Car	speed	F (1, 3967) = 3.903	0.048
					lane	F (2, 3967) = 14.975	< 0.001
					speed*lane	F (2, 3967) = 0.254	0.776
a	distance	45, 55, 65, 75, 85	1	Car	speed	F (4, 4242) = 148.750	< 0.001
b	distance	45, 55, 65, 75, 85	2	Car	speed	F (4, 2233) = 102.565	< 0.001
c	distance	45, 55	3	Car, LGV, HV	speed	F (1, 1012) = 40.666	< 0.001
					type	F (2, 1012) = 2.023	0.133
					speed*type	F (2, 1012) = 2.653	0.071
d	distance	45, 55	1, 2, 3	Car	speed	F (1, 3967) = 98.421	< 0.001
					lane	F (2, 3967) = 9.312	< 0.001
					speed*lane	F (2, 3967) = 0.643	0.526

8

### 9 5.1.3. Effect of lane on headways

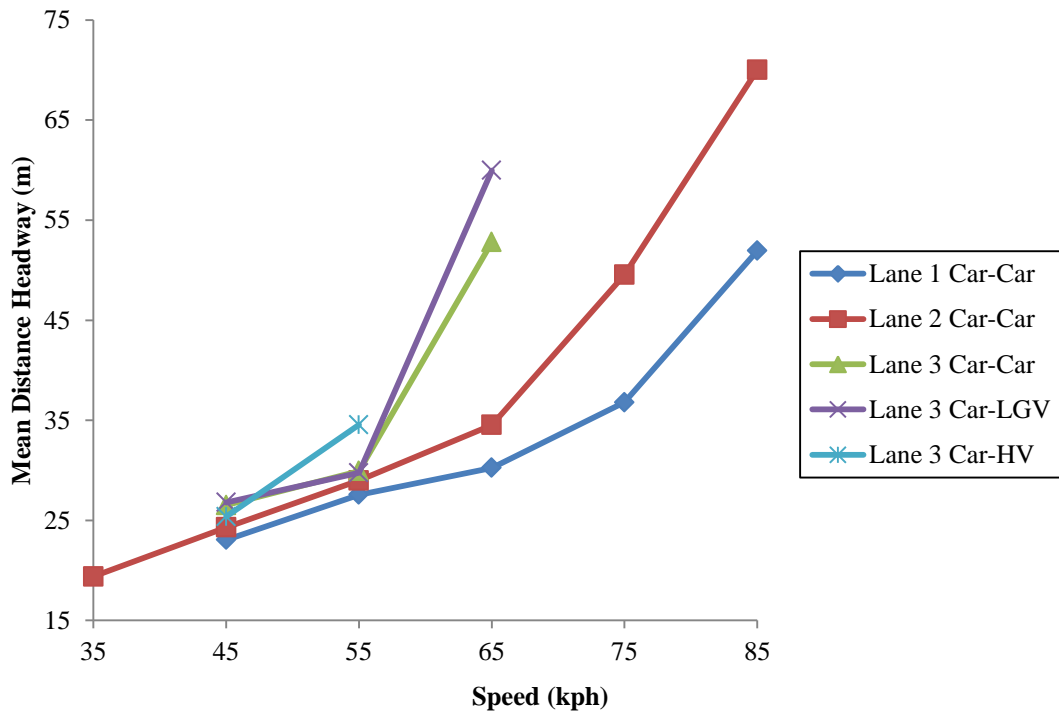
10 ANOVAs D and d effectively control for effects of speed and possible effects of leader type. Both  
 11 ANOVAs find significant effects of lane and speed, while no significant interaction effects of speed\*lane are  
 12 found. Post-hoc comparisons find both time and distance headways to be shortest in Lane 1 and longest in  
 13 Lane 3.



1

2

Figure 3. Mean time headways evaluated for open expressway



3

4

Figure 4. Mean distance headways evaluated for open expressway

5

6

## 1 5.2. Tunnel expressway

2 A total of 9,096 vehicles are observed for the tunnel expressway condition. The traffic composition is  
3 presented in Table 3.

4 Table 3. Traffic composition for observed tunnel expressway section

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

5

6 Table 4 presents a summary of the results from the various ANOVAs (E through G; e through g) for open  
7 expressway, using both the log-transformed time and distance headways. The mean time headways of groups  
8 evaluated in the ANOVAs for tunnel expressway are illustrated in Figure 5, while the mean distance  
9 headways are illustrated in Figure 6.

10

11 Table 4. Results from various ANOVAs for tunnel expressway

ANOVA	Headway type	Input factors			Effect	Results	
		Speed (kph)	Lane	Leader type		F-test	p-value
E	time	55, 65, 75, 85	1	Car	speed	F (3, 2894) = 41.975	< 0.001
F	time	55	3	MC, Car, LGV, HV	type	F (3, 721) = 4.107	0.007
G	time	55, 65	1, 2, 3	Car	speed	F (1, 4889) = 88.086	< 0.001
					lane	F (2, 4889) = 52.321	< 0.001
					speed*lane	F (2, 4889) = 2.915	0.054
e	distance	55, 65, 75, 85	1	Car	speed	F (3, 2894) = 82.722	< 0.001
f	distance	55	3	MC, Car, LGV, HV	type	F (3, 721) = 3.520	0.015
g	distance	55, 65	1, 2, 3	Car	speed	F (1, 4889) = 178.802	< 0.001
					lane	F (2, 4889) = 40.784	< 0.001
					speed*lane	F (2, 4889) = 3.979	0.019

12

13

14

### 1 5.2.1. Effect of speed on headways in tunnel

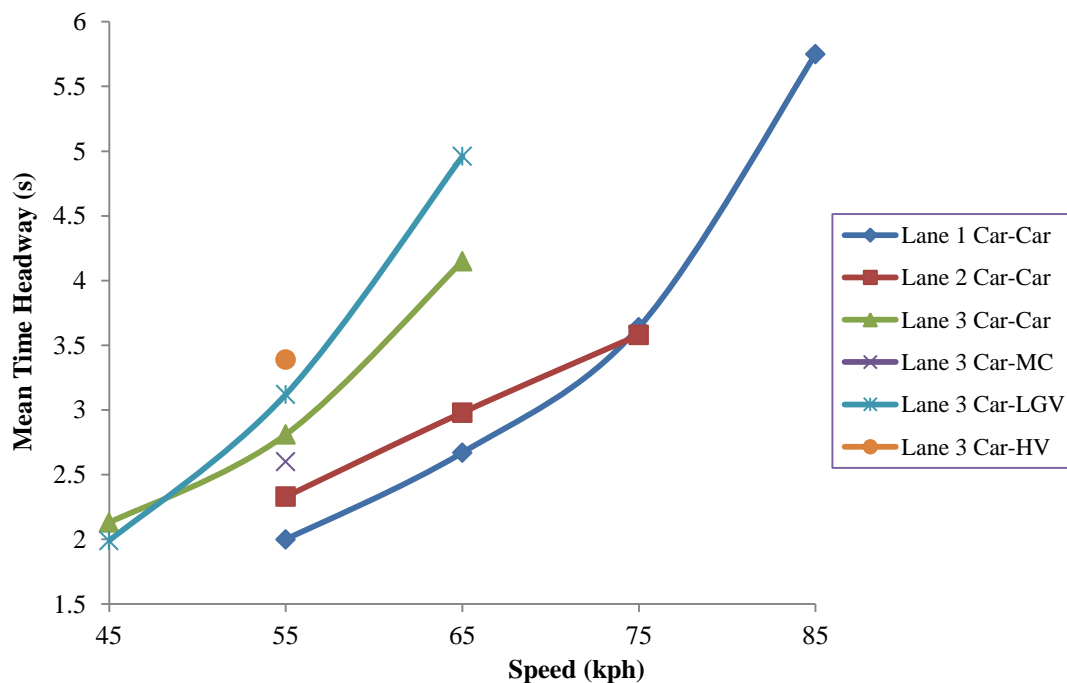
2 To control for the effects of leader type and lane, two ANOVAs (E and e) are conducted. The ANOVAs  
3 find a consistent effect of speed on both time and distance headways. Post-hoc comparisons in both ANOVAs  
4 find headways to increase with speed.

### 5 5.2.2. Effect of leader type on headways in tunnel

6 Controlling for effects of speed and possible effects of lane, two ANOVAs (F and f) are conducted. Both  
7 ANOVAs are consistent in finding significant effect of leader type. Post-hoc comparisons find that both time  
8 and distance headways are largest for Car-HV (follower-leader), followed by Car-LGV, Car-Car, and then  
9 Car-MC.

### 10 5.1.3. Effect of lane on headways

11 ANOVAs G and g effectively control for effects of speed and possible effects of leader type. Both  
12 ANOVAs find significant effects of lane and speed. Near-significant effect of the interaction term speed\*lane  
13 is found in ANOVA G while significant interaction effect is found in ANOVA g. Post-hoc comparisons find  
14 both time and distance headways to be shortest in Lane 1 and longest in Lane 3.



15  
16 Figure 5. Mean time headways evaluated for tunnel expressway



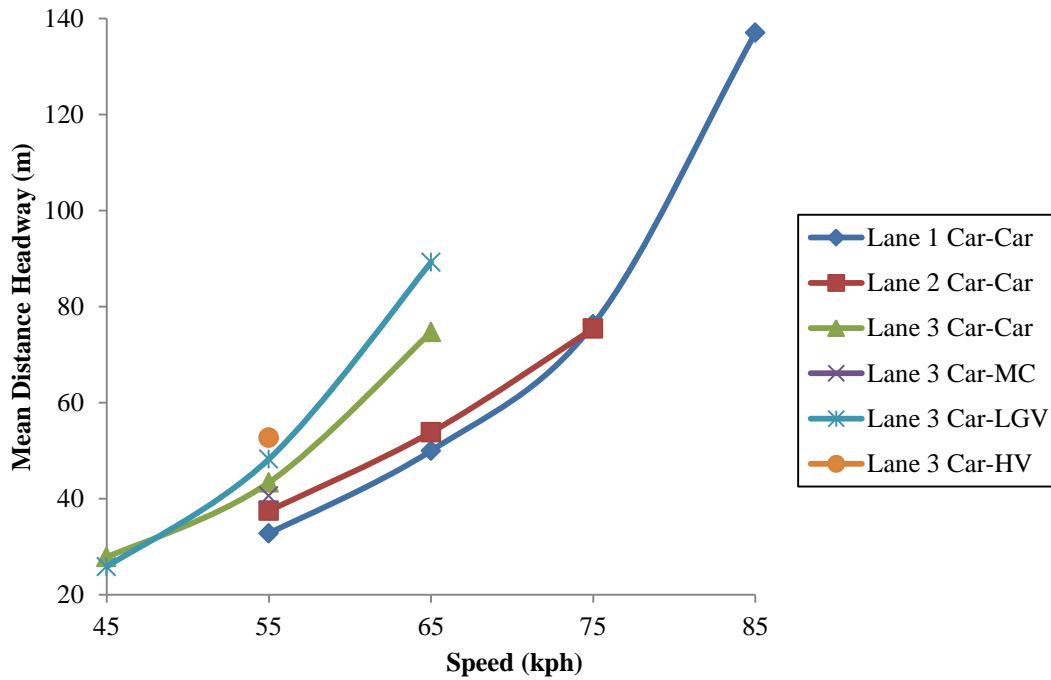


Figure 6. Mean distance headways evaluated for tunnel expressway

### 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 road 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 kph (2 speeds x 3 lanes x 2 environments). Table 5 presents the ANOVA results.

In both ANOVAs, significant effects of speed, lane, and environment are found. The interaction terms speed\*lane, lane\*environment, speed\*environment, and speed\*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.

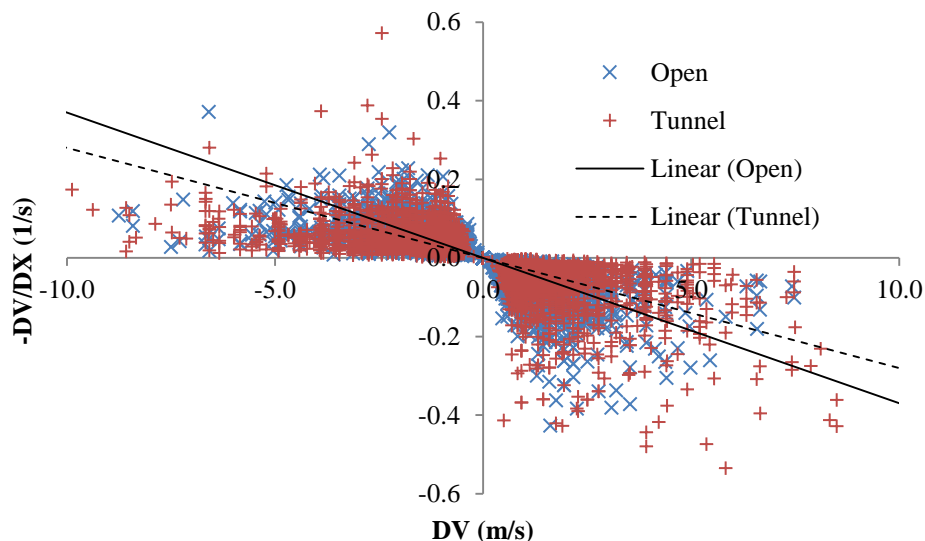
1 Table 5. ANOVA results for headway comparison between open and tunnel expressways

Headway type	Input factors				Results		
	Speed (kph)	Lane	Leader type	Road env.	Effect	F-test	p-value
time	55, 65	1, 2, 3	Car	Open, Tunnel	speed	F (1, 9884) = 75.639	< 0.001
					lane	F (2, 9884) = 98.873	< 0.001
					env.	F (1, 9884) = 83.670	< 0.001
					speed*lane	F (2, 9884) = 7.610	< 0.001
					lane*env.	F (2, 9884) = 13.146	< 0.001
					speed*env.	F (1, 9884) = 44.020	< 0.001
					speed*lane*env.	F (2, 9884) = 4.111	0.016
					distance	55, 65	1, 2, 3
					lane	F (2, 9884) = 76.684	< 0.001
					env.	F (1, 9884) = 99.100	< 0.001
					speed*lane	F (2, 9884) = 9.325	< 0.001
					lane*env.	F (2, 9884) = 10.584	< 0.001
					speed*env.	F (1, 9884) = 30.669	< 0.001
					speed*lane*env.	F (2, 9884) = 4.093	0.017

2

3 **5.4. Comparison of TTC measures**

4 Car following charts are produced in the  $-DV/DX$  vs.  $DV$  plane (opening chart), for both the open and  
5 tunnel expressways. Regression analysis is then performed for both set of data points, with the regression lines  
6 set to pass through the origin. Figure 7 illustrates the opening chart and Table 6 summarises the regression  
7 results obtained.



8

9 Figure 7. Opening chart for open and tunnel expressways

10

1 Table 6. Regression results for car following waves

Road Type	Coefficient (1/m)	R-square	t-value	p-value	95% Confidence Interval
Open Expressway	-0.037	0.603	-113.652	< 0.001	(-0.038, -0.036)
Tunnel Expressway	-0.028	0.422	-70.581	< 0.001	(-0.029, -0.027)

2

3 The regression coefficients obtained are significantly different from each other. For the same closing  
4 relative speeds ( $-DV$ ), the TTC-inverse ( $DV/DX$ ) is very likely to be higher in open expressways than in tunnel  
5 expressways, i.e. TTCs are lower in open expressways. The average closing relative speeds in the open and  
6 tunnel expressways are -1.24 m/s and -1.62 m/s, respectively. When the average relative speeds are applied to  
7 the regressed model, a somewhat higher TTC value is obtained for tunnel expressway (22.09 s) as compared  
8 open expressway (21.75 s).

### 9 5.5. Comparison of SM and ensured safety

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

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

16 Table 7. Mean SM values and likelihood of ensured safety

	Lane	Open	Tunnel
Mean SM (s.d.)	1	0.883 (0.146)	0.890 (0.183)
	2	0.886 (0.124)	0.903 (0.179)
	3	0.889 (0.109)	0.902 (0.159)
Likelihood of ensured safety	1	0.615	0.644
	2	0.676	0.703
	3	0.736	0.747

17

## 18 6. Discussion

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

21

22

## 1 **6.1. Factors affecting headway**

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

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

13 The absence of speed effects in the experimental studies may be due to Hawthorne effect, an impact on  
14 behaviour due to the awareness of being studied. As discussed by Boer (1999) and Hancock (1999), driving is  
15 generally a satisficing task. Under normal driving situations, drivers behave in a manner well enough to meet  
16 their driving goals and do not seek to optimise their behaviour. In an experimental context, drivers may have  
17 unknowingly performed in an optimising manner. Naturalistic observations thus offer higher fidelity (Eby,  
18 2011).

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

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

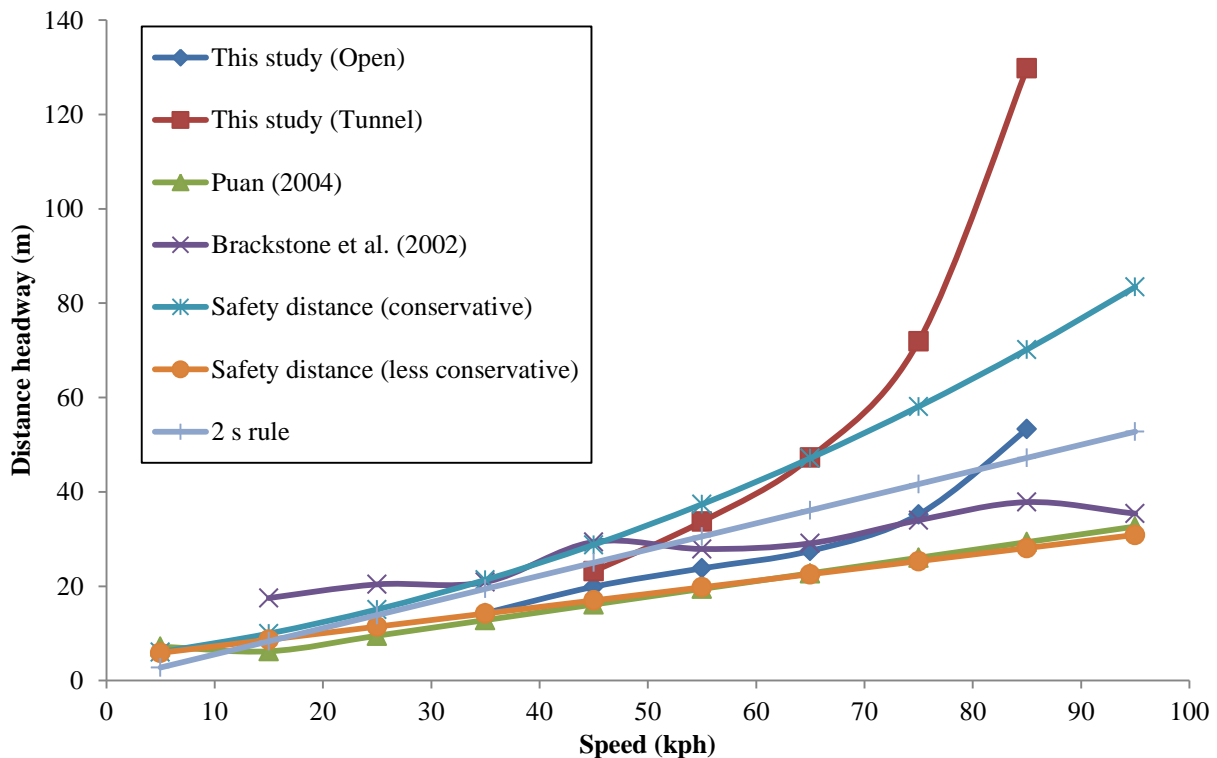
14 Overall, after controlling for speed, lane, and leader type, headways (both time and distance) are longer in  
15 the tunnel than in open expressways. The road environment also has significant interaction effects with the  
16 mentioned factors. The findings in this study provide behavioural evidence that drivers indeed perceive higher  
17 risks in the tunnel environment (hence maintaining relatively larger headways). This is consistent with  
18 perception studies in the literature (Serrano and Blennemann, 1992; Arias *et al.*, 2008), where drivers were  
19 found to perceive road tunnels as hostile environments and experience unpleasant feelings while driving in  
20 tunnels. It is also possible that drivers perceive driving in tunnels as a novel experience and hence drive more  
21 conservatively (Lemke, 2000). However, based on the free association study by Yeung *et al.* (2013), drivers  
22 did not associate tunnels with novelty effects or unfamiliarity. Instead drivers associated more strongly with  
23 lighting, safety, and enforcement. This implies that novelty effects are insignificant and environmental effects  
24 are inherent.

25 Another possible explanation for the more conservative car following behaviour in tunnels is the presence  
26 of traffic cameras. A characteristic of urban road tunnels is the high density of traffic cameras to monitor  
27 traffic throughout the tunnel, unlike open roads where traffic cameras are further apart. Drivers may adopt  
28 more "sociable" driving behaviour in tunnels due to the awareness of being monitored. However, this

1 explanation is less likely to be true because behavioural differences have been demonstrated in simulator  
 2 studies where the effect of traffic cameras is non-existent.

### 3 6.2. Comparison of headways with other studies

4 The Car-Car distance headways in this study are compared to minimum safety distances and the two-  
 5 second rule (see Figure 8). In the derivation of safety distances, driver reaction time is assumed to be one  
 6 second, and the deceleration term coefficient (reciprocal of twice the maximum average deceleration of a  
 7 following vehicle) adopted is  $0.075 \text{ s}^2/\text{m}$ , as suggested by Rothery (2011) for the case when the leading  
 8 vehicle comes to a full stop instantaneously. In the less conservative set of safety distances, the deceleration  
 9 term is assumed to be absent, i.e. the following vehicle adjusts its deceleration synchronously with the leading  
 10 vehicle. In addition, comparison is done with results from other studies (Brackstone *et al.*, 2002; Puan, 2004).



11  
 12 Figure 8. Comparison of car following behaviour

13 The headways in this study, like those found in other studies, mostly fall between the conservative and less  
 14 conservative safety distances. The minimum safety distances and two-second rule considers only the crash  
 15 likelihood based on consistent driver reaction and braking times, i.e. constant time headway. The headways  
 16 observed in this study are shown to become more conservative as speed increases. This can be explained by  
 17 the higher perceived risk at higher speeds. If a consistent driver reaction time is assumed (controlling for crash

1 likelihood), it is possible that perceived crash consequence is more severe at higher speeds. Higher speeds are  
2 associated with greater crash severity and higher crash rates (Aarts and van Schagen, 2006). As shown in  
3 Figure 8, headways in road tunnel are the highest, which is explained by higher perceived risk in the road  
4 tunnel environment. However, headways at speeds above 65kph should be interpreted with caution due to the  
5 70 kph speed limit of the tunnel being observed in this study.

### 6 **6.3. Rear-end collision risk**

7 Headways indicate the potential danger while TTCs indicate actual danger (Vogel, 2003). Time-to-  
8 collision values in both road environments were assessed using car following waves. The results, as shown in  
9 Figure 7, indicate that for the same relative speeds, TTC values will be larger in the tunnel. This is because of  
10 the overall longer headways in the tunnel. Safety margins in the tunnel expressway are higher than those in the  
11 open expressway. The mean SM found in this study are consistent with those of Lu *et al.* (2012), who found  
12 mean SM values for professional and general drivers to be 0.862 and 0.896, respectively. This study shows  
13 that drivers desire higher safety margins in the road tunnel environment, which is consistent with findings of  
14 strong associations to safety in road tunnels (Yeung *et al.*, 2013).

15 The likelihood of ensured safety is also computed. The computation takes into account the vehicle speeds,  
16 speed differentials, distance gap, and driver reaction time. Notably, instances of ensured safety are more likely  
17 in the tunnels, supporting the hypothesis that traffic is safer in the road tunnel environment.

### 18 **6.4. Implications of longer headways**

19 Traffic capacity is a key consideration for major roads with high traffic demand. Yeung *et al.* (2013) found  
20 that drivers strongly associated open expressways with speed and traffic conditions. In fact, it is common for  
21 unsafe headways to be observed in expressways due to shorter commute times being prioritised over safety,  
22 especially in urban areas where commute time is a greater disutility.

23 The longer headways in road tunnels imply that traffic capacity is compromised. Although road tunnels are  
24 superior in terms of traffic safety, capacity is expected to be lower than that of open roads. Thus,  
25 implementation of URS should take into account the reduced lane capacities in road tunnels. In order to  
26 provide similar traffic capacities, road tunnels may require more lanes than surface roads. From a land-use  
27 perspective, road tunnels may be a less efficient use of space, compared to other uses for underground space  
28 such as shopping malls and warehousing. However, when considering the potential use of surface land, URS

1 remains an attractive option. From a transportation perspective, URS should ideally serve to supplement  
2 surface roads and not to replace them, at least in the near future.

### 3 **7. Conclusion**

4 This study assessed the car following patterns observed in both open and tunnel expressways. Speed, lane,  
5 and leader type are found to have effects on headways to various extents. Overall, car following behaviour  
6 (with car as the follower) in the road tunnel environment is found to be more conservative (longer headways  
7 and greater safety margins) than that in the open road environment. The likelihood of ensured safety is also  
8 higher in the tunnels. Overall, from a microscopic behavioural perspective, traffic in tunnel expressways can  
9 be concluded to be safer than the conventional open expressways. The conclusion is consistent with the lower  
10 accident rates in road tunnels, suggesting that microscopic behavioural studies can serve as reliable traffic  
11 safety assessments. The effect of road environment is also discussed to be inherent.

12 With the increasing demand for urban space, URS is one of the proposed solutions. This study has shown  
13 that, in terms of traffic safety, road tunnels perform better than open roads. However, enhanced traffic safety  
14 implies that traffic capacity is compromised. This study provides useful insight into inter-vehicle interactions  
15 in road tunnels and also the implications of implementing URS's in future road networks.

### 16 **Acknowledgements**

17 The tunnel traffic video footage is provided by the Land Transport Authority of Singapore. In particular,  
18 the authors would like to thank KPE OCC for facilitating the video extraction from the traffic surveillance  
19 cameras. This study is part of a research project, "Driver behavioural adaptation to underground road  
20 conditions", which is jointly funded by the Nanyang Technological University Sustainable Earth Office and  
21 Centre for Infrastructure Systems.

22 The authors would also like to thank two anonymous reviewers for their comments which have helped to  
23 improve the manuscript.

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