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Safety of Professional Drivers in an Ageing Society – A Driving Simulator Study

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Abstract

Of the road crashes involving personal injury in Hong Kong, over 70% involved at least one commercial vehicle. Besides, the proportion of older drivers in the transport sector has been increasing due to the shortage of labor and aging population. It is believed that increase in age can have adverse impact on driving performance, even that professional drivers may possess better driving skill than non-professional drivers and the age-related impairment can be offset by task familiarity of professional drivers. In this paper, a driving simulator experiment was conducted to address this question. Additionally, possible factors that affect the driving performance of professional drivers and that of non-professional drivers were examined. A total of 50 participants were recruited and 94 tests were completed. Driving performance was assessed in terms of standard deviation of lateral position (*SDLP*), standard deviation of heading error (*SDHE*), mean heading error (*MeanHE*) and standard deviation of speed (*SDspeed*). Results of random intercept models indicate that lateral and speed control performances of mid-aged drivers were better than those of older drivers. Then, disaggregated models were established for professional and non-professional drivers respectively based on the results of market segmentation analysis. It was found that lateral and speed control performance of mid-aged professional drivers were better than that of older professional drivers. In contrast, older non-professional drivers were more likely to have degraded steering performance under the high traffic condition. Results of this study are indicative to the driver management strategies of the transport operators for sustained safety improvement of commercial vehicle fleet.

Keywords: Professional driver, ageing population, driving performance, driving simulator, driver management

1. INTRODUCTION

Economic losses attributed to road injuries cost the society around 3% of the national income. The share of these losses contributed by road crashes involving commercial vehicles are considerable (Health and Safety Commission, 2001; WHO, 2018). It is because the crashes involving passenger (e.g. light bus, bus and taxi) and goods vehicles do not only result in the severe injury and death of the convicted drivers, but also those of other innocent road users including passengers on the vehicles and pedestrians on roads (Barua and Tay, 2010; Mooren et al., 2014; Meng et al., 2019). In Hong Kong, the commercial vehicles only constitute to about 20% of total registered vehicles. However, over 70% of the road crashes involve at least one commercial vehicle. Crash involvement rates (per million vehicle-km) of commercial vehicles, particularly taxi, light bus and bus, are higher than that of the private car in Hong Kong (Transport Department of HKSAR, 2017). It is of essence to identify the factors contributing to higher crash rates of commercial vehicles.

Indeed, driving under the influence of fatigue has been a significant safety issue (Bunn et al., 2005; Duke et al., 2010; Rosenbloom and Shahar, 2007). Professional drivers are more vulnerable to the fatigue as they have to drive for longer time, as compared to the general drivers. Also, aggressive driving behavior (attributed to desire for higher revenue and expectation from the customers/employers) can contribute to higher crash rates (Matthews et al., 1999; Sullman et al., 2002; Kontogiannis, 2006, Öz et al., 2010). In addition, increase in the exposure of professional drivers is also correlated to the increase in crash involvement rate. Regarding the difference in the behaviors between professional and non-professional drivers, one possible factor is the vehicle ownership. Professional driver who does not own the vehicle may have a higher propensity of committing convicted driving behavior. Hence, moral hazard may occur since the driver (who is not the owner) has less incentive to avoid any risky event (Tay and Choi, 2016).

However, professional drivers are believed to have better driving skills (Andrews and Westerman, 2012; Borowsky and Oron-Gilad, 2013). It is therefore crucial to assess the driving performance of professional drivers (i.e. whether it is better than that of non-professional drivers), and the possible contributory factors.

On the other hand, the proportion of older drivers in the transport sector has been increasing because of the ageing population, shortage of labor and economic incentives (Duke et al., 2010). In Hong Kong, the percentage of the population aged 60 or above increased from 16.8% in 2008 to 23.6% in 2017 (Census and Statistics Department of HKSAR, 2017). Accordingly, the percentage of the full driving license holders aged above 60 in Hong Kong increased from 8% in 2008 to 16% in 2017 (Transport Department of HKSAR, 2017). The effect of age on driving performance is of increasing concern. Driving performance is recognized to be deteriorated with age (Islam and Mannering, 2006; Shanmugaratnam et al., 2010). It in turn increases the associated crash and injury risks (Hole, 2007). Increase in the accident risk of older driver is found to be associated with the degradation in physical, mental and cognitive conditions of human being (Lundberg et al., 1998). These associations have been examined using the driving simulator experiments. For example, older drivers generally show a degraded neuropsychological performance, which is in turn associated with the degraded lateral control performance (Andrews and Westerman, 2012; Shanmugaratnam et al., 2010). Also, older drivers perceive greater mental workload from driving (Cantin et al., 2009), and perform worse at controlling the vehicle simultaneously than younger drivers (Bélanger et al., 2010). Despite that there is negative correlation between age and driving performance, professional drivers tend to have better driving skills since they have more on-road experience. It is controversial that whether the age-related impairments on driving performance could be offset by the driving experience and task familiarity of professional drivers (Andrews and Westerman, 2012). On the other hand, older (non-professional) drivers tend to drive less and the reduction in exposure could be a more significant factor to crash risk, compared to driving experience and task familiarity (Tay, 2006, 2008). Therefore, the interaction between driver type (i.e. professional driver or not) and age on the driving performance is of our interest.

In addition, environmental factors including road type and traffic flow condition can also affect the association between crash and possible risk factors. For examples, sleep-related road crashes are more prevalent on the motorways, as compared to the urban roads (Horne and Reyner, 1999; Maycock, 1996). Crash risks on the rural roads are also higher than that on the urban roads because of the monotonous road environments and limited stimuli on roads (Blower et al., 1993). For the traffic flow condition, increase in traffic volume and presence of moderate traffic congestion are correlated to the reduction in crash risk and crash severity (Martin, 2002; Yau, 2004). The association between road environment, traffic flow condition and crash risk could be attributed to the variation in driving performance across different environments. For instances, variation in the steering and lateral stability are correlated to the complexity of driving task (e.g. reduced horizontal and vertical curvatures, traffic interactions and roadside stimuli) (Thiffault and Bergeron, 2003; Jamson and Merat, 2005; Arnedt et al., 2005; Boyle et al. 2008; Teh et al., 2014).

Driving simulator experiment is a safe and cost-effective approach to evaluate the driving performance. In particular, the effects of road design and traffic condition on the driving performance could be assessed in a controlled manner (Boyle et al., 2010; Lee et al., 2003). Effects of age, road environment and traffic condition on the driving performance have been attempted in a number of studies. However, the moderating effect by the (better) driving skill of professional drivers because of the driving experience and task familiarity has yet to be explored. In this study, we hypothesize that: (1) age-related impairments on driving performance can be offset by the driving experience and task familiarity of professional drivers; and (2) contributory factors to driving performance of professional drivers are different from that of non-professional drivers. It is anticipated that the results will be indicative to the dispatch policies and driver management strategies of the transport operators. This is particularly important to a compact and ageing society like Hong Kong, where the public transport usage is very high.

The remaining parts of the paper are organized as follows. Section 2 will provide the details of experimental design, procedures of driving simulator test and the method of analysis. The results and implications will be discussed in Section 3 and 4 respectively. Eventually, Section 5 will provide the concluding remarks and recommendations for future research.

2. METHOD AND DATA

2.1 Participants

A total of 50 male drivers were recruited for the driving simulator study. The selection criteria were: (1) holding a valid full driving license; (2) driving for at least 5 hours a week; and (3) having good health condition. Of the 50 participants, 26 were professional drivers and 24 were non-professional drivers respectively. For the professional drivers, one must be a full-time driver of taxi, public light bus, bus or goods vehicle. In the subsequent analysis, the professional drivers will be stratified into two groups: (i) passenger vehicle (i.e. taxi, light bus and bus) drivers and (ii) goods vehicle drivers. It is because the difference in the experience and driving skills between vehicle types may moderate the association between driving performance and possible factors. Age of the participants ranged from 40 to 69 years. The participants were classified into two categories by age: (i) "mid-aged" referred to the drivers of age from 40 to 55 years; and (ii) "older" referred to the drivers of age from 56 to 69 years. Such classification was consistent to that of previous study (Li et al., 2016). Informed consent of the participation was obtained, and monetary reward was provided. US$50 and US$25 were paid to the professional drivers and non-professional drivers respectively for the participation. All participants were required to have a good rest and abstain from the consumption of alcohol and caffeinated beverages on the day before the experiment. **Table 1** provides the summary of the participants. Overall, the mean age was 53.2 years and the mean driving experience (year holding driving license) was 29.0 years respectively.

Table 1 Summary of the participants of driving simulator study

Driver Group	Number of participant	Age	Year holding full driving license	Annual driving distance (10^3 km)
			Mean (s.d.)	
Older professional	12	63.7 (2.9)	41.3 (4.3)	35.4 (10.1)
Mid-aged professional	14	43.9 (2.8)	22.1 (4.7)	51.6 (13.2)
Older non-professional	12	59.4 (3.3)	31.9 (6.7)	7.3 (2.1)
Mid-aged non-professional	12	47.2 (4.8)	21.7 (8.5)	10.7 (4.5)
Overall	**50**	**53.2**	**29.0**	**27.3**

A number of driving simulator studies have been carried out to examine the effects of fatigue induced by prolonged driving time on driver performance. The duration of driving tests varied from 30 minutes to 2 hours (Thiffault and Bergeron, 2003; Filtness et al., 2012; Ahlström et al., 2018). In this study, duration of 60 minutes is adopted for each simulated driving test. This is consistent to the time duration of a typical bus or goods vehicle trip in Hong Kong. Also, according to the results of pilot tests, 60-minute driving is long enough to reveal the driving performance under the influence of fatigue, while avoiding the simulator sickness.

2.2 Apparatus, Driving Scenario and Test Procedures

The apparatus is a fix-based driving simulator - OKTAL CDS-650. The apparatus is depicted in **Figure 1**. As shown in Figure 1, three 32'' full HD LED displays were set up to provide 100º horizontal field of view. The simulator is equipped with clutch, brake and throttle pedals, steering wheel (real Peugeot wheel with OKTAL force-feedback system), signaler, dashboard and a sound system. They are expected to provide realistic feedback to the participants.

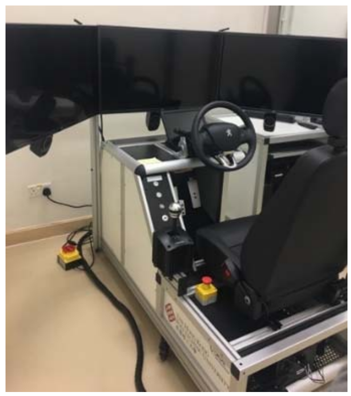

Figure 1 OKTAL CDS-650 driving simulator

The simulated driving scenario is generated by the SCANeR™ studio software. The scenarios are depicted in **Figure 2**. The typical road environments in Hong Kong are simulated. In particular, two distinct road environments are set out: (1) Inner city road with numerous roadside activities including but not limited to off-street parking, cyclists, and pedestrians (walking or standing); and (2) Dual carriageway three-lane motorway with no roadside activity. Speed limits of inner city road and motorway are 50km/h and 80km/h respectively, which are consistent to the actual driving environment in Hong Kong.

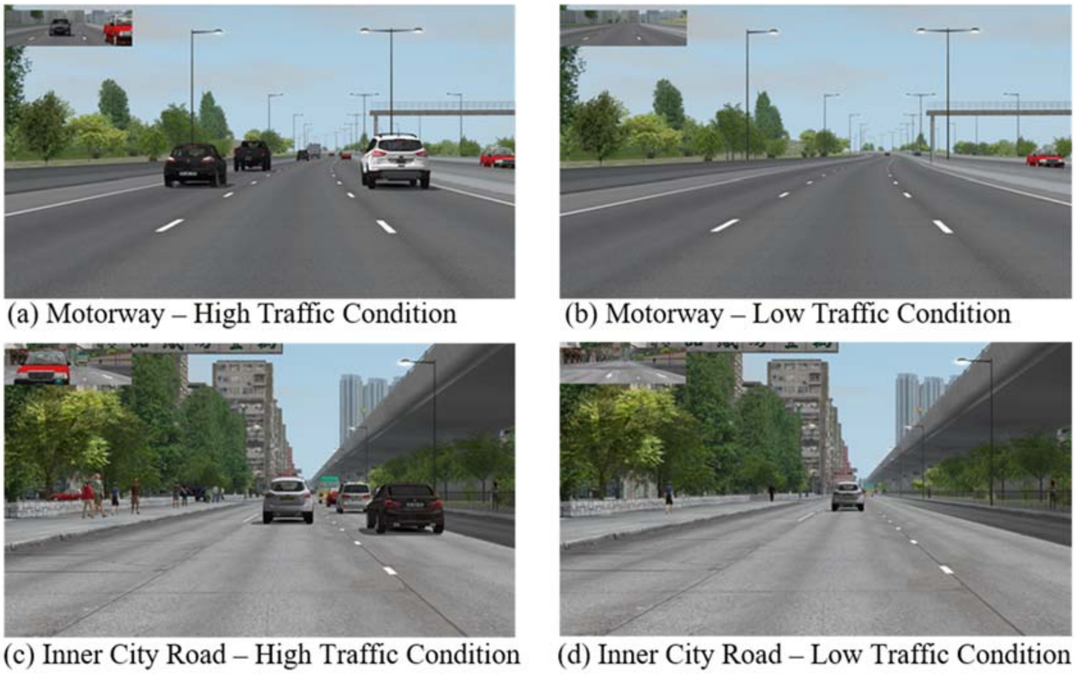

Figure 2 Typical scenarios for the simulated driving experiment

There are four types of simulated driving scenarios, with respect to road environment and traffic flow condition, namely (i) Motorway – high traffic flow condition (**Figure 2a**); (ii) Motorway – low traffic flow condition (**Figure 2b**); (iii) Inner city road – high traffic flow condition (**Figure 2c**); and (iv) Inner city road – low traffic flow condition (**Figure 2d**). Each participant was asked to complete two driving simulator tests. In the experiment, a private car was simulated. Drivers were asked to drive on the middle lane and were not allowed to make any overtake. In the low traffic flow condition, two vehicles travelling around the subject vehicle were simulated. In the high traffic flow condition, ten vehicles travelling around the subject vehicle were simulated. Also, a car would be following the subject vehicle, while a safe following distance should be maintained. For the geometric design, average lane width of the motorway is 3.5 m, and that of the inner city road is 3.3 m respectively. To simulate the environment of urban area, a grid street network in Shum Shui Po district, with traffic signals, buildings and shops, were presented in the inner-city scenario. Also, walking and standing pedestrians (number of pedestrians varied with traffic volume) on the footpaths would be simulated. To simulate the environment of motorway, a highway section with bridges, interchanges, and roadside features like plantation and slopes were presented. Also, the horizontal curvature and vertical grade could vary. It is expected that the road environment (motorway versus inner-city road) and traffic condition (low versus high traffic conditions) could moderate the association between driver type, age and driving performance.

Table 2 provides the distribution of the simulated driving tests by driver group, road environment and traffic flow condition. Because of the simulator sickness and unavailability, some participants only completed one simulated driving test. Hence, a total of 94 tests (instead of 100) were completed. Also, the distribution of the tests by road environment, traffic flow condition and driver group, were not perfectly balanced (as shown in Table 2).

Table 2 Distribution of the completed driving simulator tests

Driver Group	Inner city road: High traffic flow	Inner city road: Low traffic flow	Motorway: High traffic flow	Motorway: Low traffic flow	Total
	Number of tests				
Older professional	5	6	6	6	**23**
Mid-aged professional	7	7	7	7	**28**
Older non-professional	5	5	6	6	**22**
Mid-aged non-professional	5	5	6	5	**21**
Overall	**22**	**23**	**25**	**24**	**94**

Prior to the experiment, a 15-minute practice was provided to help the participants familiarize with the control of simulator and detect the possible syndromes of simulator sickness. After the practice, each participant was asked to complete the two 60-minute driving simulator tests: one was on the motorway and the other was on the inner city road respectively. The driving tasks were similar for the two tests. Between the tests, a 30-minute break was given. In addition, the orders of the tests were randomized and counterbalanced. Furthermore, the experiment would be stopped immediately when a participant felt unwell.

2.3 Driving Performance Indicator

Four indicators are used to assess the driving performance. They are standard deviation of lateral position (***SDLP***), standard deviation of heading error (***SDHE***), mean heading error (***MeanHE***), and standard deviation of speed (***SDspeed***). In particular, lateral position is defined as the perpendicular distance between the centerlines of a traffic lane and the vehicle. On the other hand, as shown in **Figure 3**, the heading error is defined as the angular deviation of the vehicle centerline from the tangent to the (curved) road centerline (Mollenhauer et al., 1994; Comte et al., 2000). Increases in *SDLP, SDHE, MeanHE* and *SDspeed* imply the prevalence of lateral instability, steering control instability, steering error and inability of speed control respectively (Shanmugaratnam et al., 2010; Li et al., 2016; Meng et al., 2019).

Additionally, these indicators also imply the existence of driver fatigue and sleepiness, especially after the prolonged driving (Boyle et al., 2008; Meng et al., 2019). Furthermore, they are sensitive to the interactions between road environment, driver fatigue and driving performance (Thiffault and Bergeron, 2003; Ahlström et al., 2018). In this study, all the driving performance indicators were recorded at a very high frequency (100Hz) throughout the test. In addition, the data was aggregated into twelve time periods, i.e. [0-5) minute, [5-10) minute, [10-15) minute, [15-20) minute, [20-25) minute, [25-30) minute, [30-35) minute, [35-40) minute, [40-45) minute, [45-50) minute, [50-55) minute, [50-60) minute respectively. Therefore, there were 1128 observations (94 tests x 12 time periods) in total for each driving performance indicator.

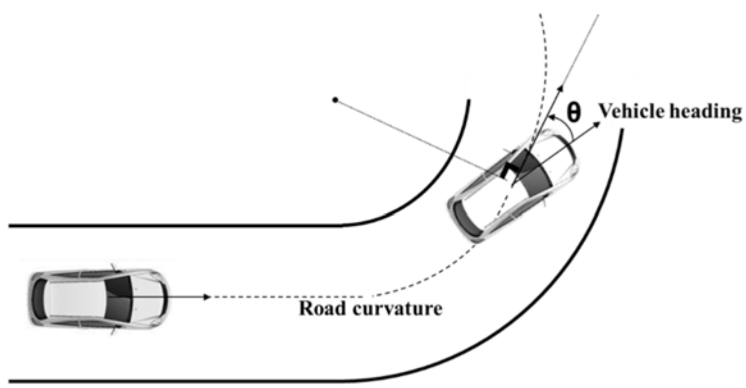

Figure 3 Illustration of the Heading Error θ

Table 3 Summary statistics for the simulated driving tests (Total observation = 1128)

Variable	Number of observations	SDLP	SDHE	MeanHE	SDspeed
			Mean (s.d.)		
Professional driver	612	0.20 (0.08)	0.33 (0.21)	0.33 (0.14)	3.49 (1.59)
Passenger vehicle driver	408	0.21 (0.07)	0.32 (0.20)	0.34 (0.13)	3.59 (1.45)
Goods vehicle driver	204	0.19 (0.08)	0.33 (0.22)	0.33 (0.15)	3.29 (1.61)
Non-professional driver	516	0.21 (0.07)	0.32 (0.21)	0.36 (0.13)	3.52 (1.49)
Older driver	540	0.22 (0.08)	0.34 (0.21)	0.36 (0.14)	3.76 (1.69)
Mid-aged driver	588	0.20 (0.06)	0.32 (0.20)	0.33 (0.13)	3.26 (1.34)
High traffic flow	564	0.21 (0.08)	0.32 (0.20)	0.35 (0.11)	3.56 (1.54)
Low traffic flow	564	0.21 (0.08)	0.34 (0.21)	0.34 (0.16)	3.44 (1.56)
Motorway	588	0.26 (0.05)	0.51 (0.12)	0.44 (0.11)	4.43 (1.38)
Inner city road	540	0.15 (0.05)	0.13 (0.02)	0.24 (0.05)	2.49 (0.95)
Time period 1 (0-5 min)	94	0.20 (0.07)	0.28 (0.16)	0.31 (0.10)	3.13 (1.19)
Time period 2 (6-10 min)	94	0.20 (0.07)	0.28 (0.17)	0.32 (0.11)	3.26 (1.37)
Time period 3 (11-15 min)	94	0.18 (0.06)	0.29 (0.16)	0.32 (0.11)	3.36 (1.45)
Time period 4 (16-20 min)	94	0.19 (0.07)	0.28 (0.16)	0.32 (0.11)	3.63 (1.60)

Time period 5 (21-25 min)	94	0.21 (0.08)	0.35 (0.23)	0.35 (0.14)	3.35 (1.49)
Time period 6 (26-30 min)	94	0.22 (0.08)	0.34 (0.22)	0.35 (0.14)	3.54 (1.48)
Time period 7 (31-35 min)	94	0.20 (0.07)	0.33 (0.20)	0.35 (0.12)	3.52 (1.57)
Time period 8 (36-40 min)	94	0.20 (0.06)	0.31 (0.19)	0.33 (0.12)	3.62 (1.68)
Time period 9 (41-45 min)	94	0.21 (0.08)	0.36 (0.23)	0.36 (0.14)	3.55 (1.53)
Time period 10 (46-50 min)	94	0.22 (0.08)	0.35 (0.23)	0.37 (0.17)	3.50 (1.55)
Time period 11 (51-55 min)	94	0.22 (0.08)	0.38 (0.24)	0.38 (0.15)	3.65 (1.57)
Time period 12 (56-60 min)	94	0.23 (0.08)	0.37 (0.24)	0.38 (0.15)	3.88 (1.76)

Table 3 summarizes the data collected in the simulated driving tests. As shown in Table 3, the professional drivers may have better driving performance than the non-professional drivers, as the average *SDLP, MeanHE* and *SDspeed* of professional drivers are lower than that of the counterpart. On the other hand, performances of the mid-aged drivers are better than that of the older drivers. For the road environment, driving performances on inner city road are better than that on motorway, given that the average *SDLP*, *SDHE*, *MeanHE* and *SDspeed* are lower on inner city road, as compared to that on motorway. Furthermore, the driving performance tends to degrade over time in general, as the average *SDLP*, *SDHE, MeanHE* and *SDspeed* in the last two time periods are all higher than that in the first two time periods, and so on and so forth.

2.4 Statistical Method

Multiple regression approach is applied to measure the effects of driver type, age, road environment, traffic flow condition and driving time on driving performance. Also, the interaction effect between driver type and age is considered. Then, disaggregated models by driver type (i.e. professional and non-professional drivers) are developed based on the results of market segmentation analysis (Wong et al., 2008; Szeto et al., 2013).

In this study, each participant was asked to complete two simulated driving tests (each for 60 minutes). On the other hand, there were twelve observations (by twelve time periods) for each test. The observations within the same test and of the same participant would be correlated because they shared the common (unobserved) random effect. To allow for the correlation between observations, the panel random intercept regression approach was applied to measure the association between driving performance and possible factors, including road environment, traffic flow condition, driver occupation, age and driving time. The random intercept models (θ_1 for *SDLP*, θ_2 for *SDHE*, θ_3 for *MeanHE* and θ_4 for *SDspeed* respectively) are specified as follows,

$$\theta_{1it} = \beta_{10} + \mu_{1i} + \sum x_{itj}\beta_{1j} + \varepsilon_{1it} \qquad (1)$$

$$\theta_{2it} = \beta_{20} + \mu_{2i} + \sum x_{itj}\beta_{2j} + \varepsilon_{2it} \qquad (2)$$

$$\theta_{3it} = \beta_{30} + \mu_{3i} + \sum x_{itj}\beta_{3j} + \varepsilon_{3it} \qquad (3)$$

$$\theta_{4it} = \beta_{40} + \mu_{4i} + \sum x_{itj}\beta_{4j} + \varepsilon_{4it} \qquad (4)$$

where *i* refers to the test (*i* = 1, 2, 3, …, and 94); *t* refers to the time period (*t* = 1, 2, 3 … 12); μ refers the independent residual (between tests); ε_{it} refers to the independent residual (between observations); *x* is the value of explanatory variable (including road environment, traffic flow condition, driver type, age, and time period) and β is the corresponding coefficient respectively.

The coefficients were estimated using the maximum likelihood approach. To assess the goodness-of-fit of the proposed model, the likelihood ratio test statistics are given by,

$$LR = -2\,[LL(\beta_{H0}) - LL(\beta_{ML})] \qquad (4)$$

where $LL(\beta_{H0})$ is the restricted log likelihood function and $LL(\beta_{ML})$ is the unrestricted log likelihood function respectively. Under the null hypothesis, *LR* is χ^2 distributed with *q* degree of freedom (*q* is the difference in the number of parameters between the restricted and unrestricted models). A good fit was indicated by a statistically significant *LR*. In this study, the statistical package *NLOGIT 5.0* was used to establish the proposed random intercept models.

3. RESULTS

In this study, the random intercept approach was used to measure the effects of factors including driving time, age, driver type, road type and traffic flow condition on the driving performance, with which the unobserved effect of correlation between observations of the same participant and in the same test was controlled for. There were 1128 observations for each model (*SDLP*, *SDHE, MeanHE* and *SDspeed*).

Table 4 presents the results of parameter estimation of the overall models. Since driver type, age, traffic flow condition and driving time are the variables of interest in this study, they are all considered in the proposed models, even no evidence can be established for significant correlation with the driving performance indicators. Additionally, two types of professional drivers (i.e. passenger vehicle and goods vehicle drivers) are considered. This is to control for the effects of differences in experience and skills between vehicle types. For the interaction effect, focus was paid on the two interested variables (i.e. older and professional driver). However, no significant evidence related to the driving performance of older professional drivers could be established.

Table 4. Results of parameter estimates of the (overall) random intercept models

Variable	SDLP		SDHE		MeanHE		SDspeed	
	Coeff.	(z-stat.)	Coeff.	(z-stat.)	Coeff.	(z-stat.)	Coeff.	(z-stat.)
Constant	0.140	(14.26)**	0.098	(7.16)**	0.206	(12.61)**	1.875	(8.00)**
High traffic flow	-0.0005	(-0.06)	-0.031	(-3.00)**	0.004	(0.32)	0.115	(0.59)
Motorway	0.109	(13.24)**	0.370	(35.70)**	0.204	(14.98)**	1.946	(9.95)**
Goods vehicle driver	-0.027	(-2.37)*	-0.011	(-0.79)	-0.031	(-1.63)	-0.264	(-0.97)
Passenger vehicle driver	-0.005	(-0.58)	-0.010	(-0.90)	-0.023	(-1.52)	0.085	(0.39)
Older driver	0.023	(2.70)**	0.017	(1.66)	0.021	(1.52)	0.472	(2.40)*
Time period 2 (5-10 min)	0.001	(0.14)	0.006	(0.65)	0.005	(0.71)	0.105	(1.07)
Time period 3 (10-15 min)	-0.020	(-4.92)**	0.016	(1.66)	0.006	(0.86)	0.201	(2.04)*
Time period 4 (15-20 min)	-0.007	(-1.65)	0.002	(0.21)	0.010	(1.40)	0.471	(4.79)**
Time period 5 (20-25 min)	0.015	(3.59)**	0.076	(7.67)**	0.041	(5.84)**	0.194	(1.97)*
Time period 6 (25-30 min)	0.015	(3.75)**	0.062	(6.31)**	0.040	(5.72)**	0.384	(3.91)**
Time period 7 (30-35 min)	0.004	(0.92)	0.054	(5.47) **	0.039	(5.47)**	0.362	(3.68)**
Time period 8 (35-40 min)	-0.0002	(-0.04)	0.037	(3.76)**	0.019	(2.74)**	0.469	(4.77)**
Time period 9 (40-45 min)	0.015	(3.60)**	0.079	(7.96)**	0.050	(6.95)**	0.399	(4.05)**
Time period 10 (45-50 min)	0.015	(3.73)**	0.077	(7.84)**	0.065	(9.19)**	0.344	(3.50)**
Time period 11 (50-55 min)	0.022	(5.33)**	0.098	(9.95) **	0.066	(9.41)**	0.491	(4.99)**
Time period 12 (55-60 min)	0.028	(6.85)**	0.097	(9.87)**	0.070	(9.98)**	0.761	(7.72)**
Goodness-of-fit								
Unrestricted loglikelihood	2281.89		1348.18		1671.35		-1299.14	
Restricted loglikelihood	1320.83		178.47		671.08		-2084.54	
Likelihood ratio test	1922.12**		2339.42**		2000.54**		1570.80**	

*** Statistical significance at the 1% level*

** Statistical significance at the 5% level*

In addition, the market segmentation analysis using the Watson and Westin pooling approach (Wong et al., 2008; Szeto et al., 2013) was conducted to examine the possible intervention effect by driver type (i.e. professional versus non-professional drivers) on the relationship between driving performance and possible factors. Disaggregated models for professional and non-professional drivers were then established based on the results of market segmentation analysis (shown in **Table 5)**. Therefore, differences in possible factors between professional and non-professional drivers could be assessed. **Table 6** presents the results of the disaggregated analyses. Overall, the proposed models fit well with the observations, all at the 1% level of significance. Results of parameter estimation for each of the four driving performance indicators (i.e. *SDLP*, *SDHE*, *MeanHE and SDspeed*) are described one by one in the following **Section 3.1**, **3.2**, **3.3** and **3.4**.

Table 5. Results of market segmentation analysis

Indicator	$LL(\beta_{H0})$	$LL(\beta_{ML})$	**Degrees of freedom**	**Likelihood Ratio**
SDLP	2280.24	2294.37	16	28.26*
SDHE	1348.18	1379.61	16	62.86**
MeanHE	1671.27	1684.44	16	26.34*
SDspeed	-1299.90	-1280.12	16	41.38**

*** Significant at the 1% level*
** Significant at the 5% level*

Table 6 Results of parameter estimates for professional and non-professional drivers

Variable	**SDLP**		**SDHE**		**MeanHE**		**SDspeed**	
	Pro	**Non-Pro**	**Pro**	**Non-Pro**	**Pro**	**Non-Pro**	**Pro**	**Non-Pro**
Constant	0.121**	0.148**	0.095**	0.101**	0.180**	0.226**	2.026**	1.668**
High traffic flow	0.001	0.000	-0.040*	-0.051**	-0.002	-0.026	-0.142	0.443
Motorway	0.117**	0.098**	0.365**	0.379**	0.205**	0.206**	1.803**	2.094**
Older driver	**0.021***	**0.021**	0.006	0.001	0.023	-0.021	**0.690****	**0.212**
Older x High traffic flow	--	--	**--**	**0.060***	**--**	**0.076***	--	--
Time period 2	0.006	-0.005	0.018	-0.008	0.017	-0.009	0.032	0.193
Time period 3	-0.016**	-0.025**	0.026	0.005	0.011	-0.001	0.143	**0.271***
Time period 4	-0.003	-0.011	0.001	0.003	0.012	0.008	**0.391****	0.567**
Time period 5	**0.020****	0.009	**0.097****	**0.050****	**0.043****	**0.038****	0.071	0.342**
Time period 6	0.015*	**0.016****	0.068**	0.055**	0.039**	0.042**	0.326*	0.455**
Time period 7	0.001	0.007	0.056**	0.051**	0.042**	0.035**	0.345*	0.385**
Time period 8	-0.005	0.005	0.030*	0.046**	0.019	0.019*	0.425**	0.523**
Time period 9	0.015**	0.014*	0.074**	0.084**	0.043**	0.056**	0.214	0.619**
Time period 10	0.021**	0.008	0.076**	0.079**	0.071**	0.057**	0.253	0.454**
Time period 11	0.026**	0.017**	0.106**	0.088**	0.072**	0.060**	0.314*	0.671**
Time period 12	0.031**	0.024**	0.104**	0.090**	0.070**	0.070**	0.689**	0.849**
				Goodness-of-fit				
Unrestricted Loglikelihood	1228.76	1065.61	670.85	711.28	868.62	818.49	-752.79	-527.33
Restricted Loglikelihood	711.38	613.19	93.37	85.22	341.32	336.59	-1121.04	-963.07
Likelihood ratio test	1034.58**	904.84**	1154.96**	1252.12**	1054.60**	963.80**	736.50**	871.48**

Notes:
*** Statistical significance at the 1% level*
** Statistical significance at the 5% level*
"Pro" refers to professional driver and "non-Pro" refers to non-professional driver respectively

3.1 Lateral stability

Standard deviation of lateral position is widely used to reflect the driver's ability to maintain the lateral stability (Boyle et al., 2008). Increase in *SDLP* implies the degradation in lateral control performance. As shown in **Table 4**, for the main effect, driver type, driver age, road type and driving time are found correlated to *SDLP*. In particular, *SDLP* of older driver is higher than that of the mid-aged driver. *SDLP* of goods vehicle driver is lower than that of the non-professional driver. Also, *SDLP* tends to increase when driving on the motorway. In addition, *SDLP* increases remarkably when the driving time is greater than 25 minutes (Time period 5).

As shown in **Table 6**, driver age, road type and driving time significantly affected the lateral stability of professional driver. SDLP of older professional driver tends to be higher than that of the mid-aged professional driver. Also, remarkable increase in SDLP could be observed after driving for 25 minutes (Time period 5). On the other hand, no evidence could be established for the association between driver age and SDLP of non-professional driver. Yet, obvious increase in SDLP of non-professional driver could be observed after 30 minutes (Time period 6).

3.2 Stability of steering control

Standard deviation of heading error reflects the driver's stability of steering wheel control. Increase in *SDHE* indicates the degradation in steering performance. As shown in Table 4, for the main effects, traffic flow condition, road type and driving time are found correlated to *SDHE*, all at the 1% level of significance. In particular, *SDHE* increases when driving on the motorway and decreases when driving under the high traffic flow condition. In addition, *SDHE* increases remarkably when the driving time is greater than 25 minutes (Time period 5).

For the disaggregated analyses, as shown in **Table 6**, traffic flow condition, road type and driving time significantly affected the *SDHE*, both of professional and non-professional drivers. However, the interaction effect between driver age and traffic flow condition was significant only among non-professional drivers. In particular, steering stability of older non-professional driver tends to be worse than that of the mid-aged non-professional drivers, when driving under the high traffic flow condition.

3.3 Steering error

Mean heading error refers to the mean angular deviation of the vehicle trajectory from that of the road centerline. Increase in *MeanHE* indicates the degradation in steering accuracy. As shown in Table 4, for the main effects, road type and driving time are found correlated to *MeanHE* at the 1% level of significance. In particular, *MeanHE* increases when driving on the motorway. Also, *MeanHE* increases remarkably when the driving time is greater than 25 minutes (Time period 5).

For the disaggregated analyses, as shown in **Table 6**, main effects of road type and driving time on *MeanHE* were found significant both for the professional and non-professional drivers. However, the interaction effect between driver age and traffic flow condition on *MeanHE* is significant only among the non-professional drivers. In particular, steering error of older non-professional driver was greater than that of the mid-aged non-professional driver, when driving under the high traffic flow condition.

3.4 Speed stability

Standard deviation of speed is widely used to reflect the driver's ability to maintain the stability of driving speed. Increase in *SDspeed* implies the degradation in speed control performance. As shown in **Table 4**, for the main effect, driver age, road type and driving time are found correlated to *SDspeed*. In particular, *SDspeed* of older driver is higher than that of the mid-aged driver. Also, *SDspeed* tends to increase when driving on the motorway. In addition, *SDspeed* increases remarkably when the driving time is greater than 15 minutes (Time period 3).

For the disaggregated analyses, as shown in **Table 6**, driver age, road type and driving time all affect the speed control performance of professional drivers. *SDspeed* of older professional driver tends to be higher than that of the mid-aged professional driver. Also, significant increase in the *SDspeed* of professional driver could be observed after 20 minutes (Time period 4). On the other hand, no evidence could be established for the association between driver age and *SDspeed* of non-professional driver. Yet, remarkable increase in the *SDspeed* could be observed for non-professional driver after 15 minutes (Time period 3).

4. DISCUSSION

In this study, we hypothesized that (1) the age-related impairments on driving performance could be offset by the driving experience and task familiarity of professional drivers; and (2) contributory factors to the driving performance of professional drivers were different from that of non-professional drivers. Results of overall model indicate that increase in age and driving on the motorway are correlated to the degradation of lateral and speed control stability. In addition, road type and traffic flow condition are correlated to the steering performance. Furthermore, results of disaggregated models indicate that effects of possible environmental factors on the driving performances of professional drivers are similar to that of non-professional drivers. Nevertheless, interaction effect by driver age on the association between traffic flow condition and driving performance is remarkable exclusively for the steering performance of non-professional drivers. In particular, the older non-professional drivers tend to have higher *MeanHE* and *SDHE* when driving under the high traffic flow condition. On the other hand, effect of age is exclusive for the lateral and speed control performances of professional drivers.

4.1 Effect of age on driving performance

Overall, older drivers show poorer lateral and speed control performance than the mid-aged drivers in this study. It is consistent to the findings of previous studies that driving performance deteriorates with age (Islam and Mannering, 2006; Shanmugaratnam et al., 2010). This could be attributed to the degraded physical, mental and cognitive capabilities (Lundberg et al., 1998; Andrews and Westerman, 2012). In addition, older people have higher perceptual sensitivity to the mental workload induced by driving, as compared to the younger counterpart (Cantin et al., 2009).

Estimation results for non-professional driver indicate that interaction between age and traffic condition is statistically significant. For non-professional driver, degradation in steering performance by age is found remarkable under the high traffic flow condition. Such findings in line with that of previous studies (Cantin et al., 2009; Trick et al., 2010). In particular, older drivers often consider driving under the high traffic flow condition as a challenging task (with higher mental workload). Since older drivers tend to be risk averse, they would avoid driving under the unfavorable road environment and traffic condition

(Molnar and Eby, 2008; Cantin et al., 2009; Trick et al., 2010; Teh et al., 2014). In contrast, no evidence could be established for the degraded driving performance of older professional drivers under the high traffic flow condition. This could be attributed to the task familiarity of older professional drivers (Andrews and Westerman, 2012). Yet, it is recommended that more rigorous medical assessment should be implemented for the renewal of driving license of older drivers, considering their high crash involvement rates. Also, the moderating effects by other environmental conditions, such as lighting and weather, on the association between age and driving performance must be explored in the extended study.

4.2 Performance of professional drivers

Results of overall model indicate that goods vehicle drivers have better lateral control performance than the non-professional drivers. This can be attributed to the higher driving experience and better driving skill of goods vehicle drivers (Borowsky and Oron-Gilad, 2013). Seemingly, goods vehicle drivers in Hong Kong demonstrate better driving skills and attitudes. Indeed, the crash involvement rate (per million vehicle-km) of goods vehicle was lower than that of other commercial vehicles (i.e. taxi, light bus and bus) in Hong Kong (Transport Department of HKSAR, 2017). Yet, no evidence can be established for significant difference in driving performance between passenger vehicle drivers and non-professional drivers. Seemingly, superior driving skill of passenger vehicle drivers related to driving experience on different types of the roads, vehicle size relative to road width, and work-related trips could be offset by the aggressive driving behaviors (Kontogiannis, 2006; Öz et al., 2010; Li et al., 2019). Examples of aggressive driving behaviors include but are not limited to speeding, red light running, and improper lane changing. They are indeed more prevalent for passenger vehicle drivers because of the desire for higher revenues and expectations of the employers/customers (Wong et al., 2008). In this study, effects of operation characteristics and attitudes of the drivers on the driving performance are however not considered. It is worth exploring the effects of driver perceptions and characteristics (e.g. risk-taking behavior, traffic offenses, and crash involvement) on the driving performance using the attitudinal survey. Furthermore, it is of essence to measure the association between the road geometry, driving performance (especially on steering performance) and crash risk, when comprehensive vehicle trajectory and crash data of professional drivers are available (Ahlström et al., 2018).

For the difference in effects of possible factors between professional and non-professional drivers, age effect was found significant only among the professional drivers. In particular, lateral and speed control performances of mid-aged professional drivers are better than that of the older professional drivers. Seemingly, the reduction in exposure by age could be a significant contributory factor to the degraded performance of professional drivers. Older professional drivers have lower annual driving distance that their mid-aged counterparts. It could be because the working and/or driving hours of older professional drivers tend to be lower. It is likely that the older professional drivers proactively reduce their exposure on road to mitigate the elevated crash risk due to age-related impairments. On the other hand, the driving hours of older professional drivers can be limited by the safety management policy of the transport operators. To this end, it is proposed that additional driver training, particularly on lateral stability and speed control, could be provided to the older professional drivers to mitigate the age-related impairments.

4.3 Effect of other factors on driving performance

As revealed in this study, the lateral performance of driver degrades over the 60-minute drive in general. It is consistent to the findings of previous studies (Oron-Gilad and Ronen, 2007; Ting et al., 2008; Farahmand and Boroujerdian, 2018). This could reflect the increase in fatigue level resulted from the prolonged driving (Du et al., 2015; Ahlström et al., 2018). Degradation of speed control, lateral stability and steering performance are correlated to the increase in driver sleepiness and fatigue, particularly after prolonged driving (Boyle et al., 2008; Meng et al., 2019). In addition, the results of overall and disaggregated models show that degraded lateral, steering and speed control performances tend to occur when driving on the motorways. This could be attributed to the drowsiness due to the monotonous driving environment, and limited roadside activities and interactions with other road users (Oron-Gilad and Ronen, 2007; Williamson et al., 2014; Du et al., 2015; Ahlström et al., 2018). Yet, such findings could be verified when information on both subjective and physiological indicators are available in the extended study (Oron-Gilad et al., 2008). On the other hand, the degraded driving performance on the motorways could also be attributed to the geometric and operational characteristics of the roadway. Indeed, degradation of lateral and speed stabilities could be profound when speed limit and road width increase (Ahlström et al., 2018; Meng et al., 2019). It would be worth exploring the effect of road curvature (in term of the number of curves, interval between curves and radius of curvature), road width and speed limit on the association between driving performance and driving time in the extended study.

It was expected that the effect of driving time on driving performance should be different between professional and non-professional drivers, since the professional drivers are more skillful in general. Results of disaggregated model indicated that onset of the significant degradations in lateral and speed control performance are different between professional and non-professional drivers. Moreover, the lateral and steering performance of professional drivers started to degrade after driving for 25 minutes. This should be indicative to the safety management strategies of the transport operators, especially the design and development of in-vehicle driver monitoring and assistance system on the commercial vehicle fleets (Davidse et al., 2009). For example, eye tracking unit for the detection of driver fatigue, and electronic stability control system could be installed on the passenger vehicles (for franchised buses in Hong Kong, a subsidization scheme has been introduced to retrofit smart safety devices including electronic stability control on the existing bus fleets).

5. CONCLUSION

Professional drivers are considered more skillful and experienced. However, the overall crash involvement rate of professional drivers is higher than their counterparts in Hong Kong. Also, the population of older professional driver is increasing because of the ageing population. In this study, we hypothesized that the impairment of driving performance by age could be offset by the driving experience and task familiarity of professional drivers. Additionally, we hypothesized that the contributory factors to the driving performance of professional drivers should be different from that of non-professional drivers. The driving performance indicators considered are standard deviation of lateral position, standard deviation of heading error, mean heading error and standard deviation of driving speed.

Results of overall model indicate that goods vehicle drivers tend to have better lateral stability than the non-professional drivers. Driving performances of mid-aged drivers tend to be better than that of the older drivers. Based on the results of disaggregated analysis, the impairments on driving performance by age (i.e. older) are more prevalent when driving under the high traffic flow condition among non-professional drivers. No evidence could be established for the degraded driving performance of older professional drivers under the high traffic flow condition. Although older drivers are often risk averse and would avoid driving under the high traffic flow condition, age-related impairments could be offset by the driving experience and task familiarity of professional drivers. Therefore, for the driver recruitment and management, decision making of transport operators should not be solely based on driver age. Instead, rigorous assessment of driving skills and enhanced training could be provided for the older drivers. Furthermore, results of the disaggregated models indicate that the effect of age was found prevalent only among the professional drivers. Lateral and speed control performance of mid-aged professional drivers were superior than that of older professional drivers. Seemingly, reduction in exposure could be a contributory factor to the impaired driving performance of older professional drivers. It is recommended that driver training could be provided to the older drivers, particular on vehicle control. This is to mitigate the increase in collision risk attributed to reduced exposure. As for the second hypothesis, results of disaggregated analyses indicate that effects of possible environmental factors (i.e. motorway and high traffic flow condition) of professional drivers are similar to that of non-professional drivers. However, the interaction between age and traffic flow condition are exclusive to the non-professional drivers only.

In this study, the interaction effects by the driver perception and attitude on the association between driving performance and driver characteristics are not considered. Additionally, the driving performances of male drivers only are assessed in the driving simulator experiment, given the relatively small sample size. Effect of gender on driving performance is therefore not attempted. It is worth exploring the effects of driver characteristics (in term of crash involvement, traffic offense and risk perception) on the driving performance when the comprehensive information is available from the attitudinal survey (Wong et al., 2008; Li et al., 2014). Furthermore, effects of road design and environmental condition (e.g. lighting and weather) on the crash risk of professional driver can be revealed based on comprehensive vehicle trajectory and crash data in extended study.

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