# Temporal patterns of driving fatigue and driving performance among male taxi drivers in Hong Kong: A driving simulator approach

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Abstract

This study uses a questionnaire survey and a driving simulator test to investigate the temporal patterns of variations in driving fatigue and driving performance in 50 male taxi drivers in Hong Kong. Each driver visited the laboratory three times: before, during, and after a working shift. The survey contained a demographic questionnaire and the Brief Fatigue Inventory. A following-braking simulator test session was conducted at two speeds (50 and 80 km/h) by each driver at each of his three visits, and the driver's performance in brake reaction, lane control, speed control, and steering control were recorded. A random-effects modeling approach was incorporated to address the unobserved heterogeneity caused by the repeated measures. In the results, a recovery effect and a lagging effect were defined for the driving fatigue and performance measures because their temporal patterns were concavely quadratic and had a 1-hour delay compared to the temporal patterns of occupied taxi trips and taxi crash risk in Hong Kong. Demographic variables, such as net income and driver age, also had significant effects on the measured driving fatigue and performance. Policies regarding taxi management and operation based on the modeling results are proposed to alleviate the taxi safety situation in Hong Kong and worldwide.

*Keywords*: Temporal pattern, driving fatigue, driving performance, taxi safety, driving simulator

## 1. Introduction

As one of the most important modes of public transport, taxis play a key role in the modern transportation system by offering passengers flexible, comfortable, point-to-point travel service (Wu *et al.* 2016). As the global taxi industry's revenues have grown, serious safety concerns regarding taxi trips have been raised (Baker *et al.* 1976, Meng *et al.* 2017b). According to the Transport Department of Hong Kong (2016), 3928 crashes involving taxis occurred in Hong Kong in 2016, resulting in 5352 casualties in the taxis involved. Both figures rank second among the 17 classes of vehicles, trailing only private cars. From 2007 to 2016, the number of crashes involving taxis in Hong Kong rose by 18.3%. Although the efficiency and the comfort level of trips were enhanced by improvement of taxi services, the frequent taxi crashes and the large number of casualties still puzzle transport managers in Hong Kong and worldwide (Meng *et al.* 2017b).

Taxi drivers' aggressive driving attitudes and risky driving performance have apparently led to an increase in hidden crash risk and have been frequently investigated (Machin and De Souza 2004, Rosenbloom and Shahar 2007, Shams *et al.* 2011, Cheng *et al.* 2016). Rosenbloom and Shahar (2007) studied the attitudes toward traffic violation penalties between male taxi drivers and nonprofessional drivers in Israel and thus measured their legal obedience levels. The results of a survey with 80 participants showed that taxi drivers judged the penalties as less severe than nonprofessional drivers, especially those with penalty conditions of low and medium severity, possibly as a result of different driving attitudes: taxi drivers may be willing to risk violating traffic rules to increase their profits. This hypothesis was verified in a more recent study by Cheng *et al.* (2016), in which impulsivity and risky decision-making tendencies were compared in 30 taxi drivers, including 15 traffic offenders and 15 non-offenders. The taxi drivers with traffic offence records were found to be less sensitive to the consequences of risky behavior and were more profit-driven than their non-offending counterparts. These findings not only unveiled the possible causes of taxi drivers' aggressive attitudes as hypothesized by Rosenbloom and Shahar (2007) but also further proved that the profit-making nature of taxi services resulted in taxis drivers' risky decision-making and driving performance. To more specifically investigate taxi drivers' driving performance, Wu *et al.* (2016) conducted a driving simulator study with two simulated scenarios: red-light running violation and crash avoidance at intersections. Taxi drivers ran red lights with a significantly greater frequency than non-professional drivers, indicating that taxi drivers were more inclined to cross the intersection during amber light and thus displayed more violating behaviors; however, taxis drivers showed better crash avoidance behavior at the simulated intersections.

It has long been argued that fatigued driving may lead to risky driving performance and aggressive driving attitudes because driving fatigue can reduce a driver's alertness and cause poor psychometric conditions (Dalziel and Job 1997, Merat and Jamson 2013, Wu *et al.* 2016). Indeed, professional drivers such as taxi drivers commonly drive at a high fatigue level because they tend to drive continuously for long hours with a high working intensity because of the profit-driven nature of their driving. Dalziel and Job (1997) examined the relationships between fatigue-related variables and traffic crash involvement in a survey of 42 taxi drivers in Sydney, Australia, and concluded that longer driving hours produced higher crash risks and that taking longer breaks during a shift could help alleviate the situation. Similarly, prolonged driving hours were found to contribute to driving fatigue among taxi drivers by Meng *et al.* (2015) based on a survey in which taxi drivers' fatigue perception was compared with that of truck drivers. The researchers also found that taxi drivers reported significantly more fatigued driving experiences and greater crash involvement rates than truck drivers. In addition to the fatigue gained through driving, disordered night-time sleep was also found to contribute to drivers' daytime driving fatigue (May *et al.* 2016). Firestone *et al.* (2009) surveyed 241 taxi drivers in Wellington, New Zealand, and showed that obstructive sleep apnea syndrome was prevalent among taxi drivers, especially among the Maori and Pacific ethnicities.

Although it seems plausible that longer driving hours may cause greater driving fatigue in taxi drivers, the pattern of driving fatigue and driving performance along with driving hours in a working shift has never been investigated. The origins of driving fatigue have been shown to be comprehensive (Meng *et al.* 2015), and continuous long-hour driving is not its only cause. Sleep disorders, taking breaks during driving, driving intensity, and self-perceived fatigue can all affect drivers' fatigue levels and fatigued driving performance (Ting *et al.* 2008, Merat and Jamson 2013, Huffmyer *et al.* 2016, May *et al.* 2016). Moreover, taxi services in Hong Kong are rather flexible, so each driver can take a break whenever he feels fatigued and may thus seek his own balance between making profits and maintaining alertness and driving safety. Therefore, taxi drivers' fatigue levels and driving performance over time during a shift remain subtle if not quantitatively modeled.

According to Transport Department of Hong Kong, approximately 15% of taxi drivers in Hong Kong are female (6,000 of 40,000 valid taxi driver licenses), but a large majority are part-time drivers who drive taxis infrequently. Moreover, according to the road traffic crash records of the Hong Kong Police Force, 4163 taxis were involved in road traffic crashes in 2011, of which 98.2% (4088 taxis) were driven by a male driver when the crash occurred. Therefore, considering the low percentage of female taxi drivers and the much higher rate of crash involvement of male taxi drivers in Hong Kong, this study focused on male taxi drivers only. In this paper, a driving simulator experiment and a fatigue survey were conducted among male taxi drivers to identify the role of driving hours in taxi drivers' fatigue levels and driving performance. A following-braking scenario was applied, and the drivers' driving and reaction behaviors were recorded and analyzed. The Brief Fatigue Inventory (BFI) was used to evaluate the drivers' fatigue levels. Each taxi driver was required to participate at three points: before, during, and after a normal work shift, to account for the effects of driving/working hours on their driving performance and fatigue levels. Policy implications were proposed based on the results of the analyses to cope efficiently with the taxi drivers' driving fatigue and further alleviate the taxi safety situation in Hong Kong.

## 2. Methods

### 2.1. Participants

Fifty male taxi drivers between 23 and 66 years of age (mean 45 years) were recruited in Hong Kong. All recruited drivers were legal Hong Kong residents with a valid taxi driving license issued by the Transport Department of Hong Kong. Each driver was asked to visit the laboratory three times: before, during, and after their normal working shifts. All drivers were asked to refrain from consuming caffeinated drinks and alcohol during the 24 hours before their scheduled experiments. Free parking services were provided if participants needed to drive their taxis to the experiment venue.

## 2.2. Apparatus

The taxi drivers' driving performance was tested on a driving simulator in the Transport Laboratory at the University of Hong Kong. An XP-300 desktop driving simulator (XPI Simulation Ltd., U.K.) was used for all of the tests. Three 19-inch LCD monitors and a three-way video splitter were used to display the driving scenarios and enhance the simulation quality. A Logit G27 steering wheel and pedal kit were also connected as the control module of the simulator. The driving scenarios inserted in the simulator included Emergency Braking, Following-Braking (FB), Two-Second Rule, Hazard Perception, and Free Drive. In this study, the experiment and further data analyses were based on a FB test. In all simulated scenarios, data were automatically logged in a text file with a 30-Hz sampling frame. The recorded information included vehicle speed, acceleration, lane position, direction, and steering angle.

## 2.3. Design and procedure

The survey and experiment took a 3 (time) × 2 (speed) within-subjects design. Each driver's three visits at different times of their working shift formed the design's longitudinal dimension, and the simulator test scenario included two speed levels (i.e., 50 and 80 km/h).

A questionnaire including two sections, a demographics survey and a fatigue questionnaire, was completed by each driver at all three visits. Ethical approval for the questionnaire was acquired from the Human Research Ethics Committee of The University of Hong Kong before the study began. The demographic questionnaire recorded each driver's basic information, such as age, daily net income, daily driving hours, daily sleeping hours, and full- or part-time status. Notably, the driver's number of driving hours in the shift on the day of experiment before the experiment started was also recorded to represent his working hours in that shift (to facilitate further discussion, this variable is abbreviated as *DrHr* in this paper). By definition, the DrHr should be zero for all before-shift experiments. The drivers' fatigue levels were measured by a fatigue questionnaire using the BFI, which was originally invented to measure the fatigue level in cancer patients (Mendoza *et al.* 1999) and was later applied to various medical and social science studies (Lavoie *et al.* 2004, Davis *et al.* 2013). The BFI has nine items measured on a 10-point Likert scale. The BFI was able to efficiently measure and quantify the subjects' self-perceived fatigue level, and the scores were ready for further analyses such as statistical testing and modeling.

In the driving simulator tests, a classic FB test session was applied as the main body of the experiment (Figs. 1 and 2). The FB test includes three phases. First, the driver was instructed to follow the leading car and maintain a certain speed; when the leading car began to brake, the test driver should detect it at his fastest speed and make an emergency brake using his fastest reaction until the car completely stops. Each phase of an FB test was used to examine certain driving abilities: the ability to control the car at a given speed, the ability to detect a hazard in front acutely, and the ability to brake and stop the car safely. Hypothetically, if a driver was fatigued, these abilities could be weakened and detected through his driving performance during the three phases. Two speed levels were incorporated in the FB tests (50 and 80 km/h) because the same driver may have different driving, reaction, and braking features in different speed conditions (Yan *et al.* 2015, Li *et al.* 2016). The two speed levels reflect the average driving speeds of Hong Kong's city roads and highways, respectively.

During the FB tests, both the front car and the test car's performance, such as coordinates, speed, acceleration, lane position, and steering, were recorded at 30-Hz. To evaluate the participant's driving performance, the following measures were calculated for data analyses for both speed levels:

a). brake reaction time (BRT),
b). braking distance (BD),
c). standard deviation of speed (SDSpeed),
d). standard deviation of lane position (SDLane), and
e). variance of the steering wheel angle (VarSteer).

Each taxi driver was required to visit three times: before, during, and after his normal working shift. Upon his first arrival, a briefing session introduced the aims, contents, and requirements of the survey and the experiment, and the questionnaire followed. A warm-up driving session was then conducted with a 10-min free drive on both urban roads and expressways to familiarize the participant with the driving simulator, and an emergency braking session was conducted to familiarize him with the braking system in particular. After the warm-up session, the main body of the simulator experiment began. The FB test was conducted six times at each speed level. The order of the scenarios was counterbalanced across participants. At the participant's second and third visits, the briefing session was omitted, but the other procedures, including the warm-up session, the questionnaire, and the simulator tests, remained the same.

Fig. 1. FB scenario at 50 km/h.

Fig. 2. FB scenario at 80 km/h.

## 2.4. Modeling unobserved heterogeneity

Because repeated measures were conducted with each participant at three different times, the dataset was considered to be panel data (Washington *et al.* 2010). To account for longitudinal unobserved effects and explore the temporal patterns of driving fatigue and driving performance, a random-effects (RE) approach was applied to model both the drivers' fatigue levels and various driving performance measures. In a RE modeling framework, the dependent measure $y_{it}$ can be specified as (Wooldridge 2013):

$$y_{it} = \boldsymbol{\beta}\boldsymbol{X_{it}} + a_i + v_{it} \quad (1)$$

where $i$ is the cross-sectional index representing each participant (i.e., $i = 1,2,3,\ldots,50$); $t$ is the longitudinal index that refers to the time of each driver's three experiments (i.e., $t = 1,2\ or\ 3$); $\boldsymbol{X_{it}}$ is a vector of independent variables, including the number of driving hours and demographic factors of participant $i$ at time $t$; $\boldsymbol{\beta}$ is a vector of the coefficients to be estimated; $a_i$ is a variable that varies across participants to account for unobserved heterogeneities; and $v_{it}$ is a random error term. In this study, there were two choices for the dependent variable $y_{it}$: the BFI score at the time of the experiment and the driving performance measures defined in Section 2.3. Table 1 summarizes the descriptive statistics of the dependent and independent variables applied to the modeling process.

The designed modeling scheme contained two steps. The first modeled the relationship between the driving performance measures and the taxi drivers' self-reported fatigue (with other demographic variables), and the second captured the effects of DrHr and the demographic variables on BFI and driving performance. The first step explored the effect of the taxi drivers' self-reported driving fatigue on their driving performance, and the second step was used to discover the temporal patterns of the taxi drivers' fatigue levels and driving performance variation during a working shift.

Table 1. Descriptive statistics for dependent and independent variables in RE modeling.

| Variable | Description | Mean | S.D. | Min. | Max. |
|---|---|---|---|---|---|
| **Dependent variable:** | | | | | |
| BFI | BFI score at time of experiment | 3.83 | 2.24 | 0 | 8 |
| BRT_50 | Brake reaction time at 50 km/h (s) | 0.86 | 0.26 | 0.40 | 1.84 |
| BRT_80 | Brake reaction time at 80 km/h (s) | 0.85 | 0.27 | 0.42 | 2.14 |

| | | | | | |
|---|---|---|---|---|---|
| BD_50 | Braking distance at 50 km/h (m) | 15.39 | 1.50 | 12.85 | 24.23 |
| BD_80 | Braking distance at 80 km/h (m) | 38.97 | 2.78 | 31.18 | 55.55 |
| SDSpeed_50 | SD of speed at 50 km/h | 2.46 | 0.86 | 0.96 | 5.83 |
| SDSpeed_80 | SD of speed at 80 km/h | 2.46 | 0.94 | 1.24 | 8.08 |
| SDLane_50 | SD of lane position at 50 km/h | 0.48 | 0.46 | 0.05 | 2.41 |
| SDLane_80 | SD of lane position at 80 km/h | 1.27 | 1.35 | 0.13 | 6.04 |
| VarSteer_50 | Variance of steering wheel angle (°) at 50 km/h | 2.13 | 0.91 | 0.85 | 7.84 |
| VarSteer_80 | Variance of steering wheel angle (°) at 80 km/h | 1.67 | 0.67 | 0.75 | 4.72 |
| | | | | | |
| **Independent variable**: | | | | | |
| Serious fatigue | 1 = BFI score >3, 0 = other | 0.52 | 0.50 | 0 | 1 |
| DrHr | No. of driving hours from start of shift | 4.80 | 4.00 | 0.00 | 12.00 |
| Sleeping hours | Daily number of sleeping hours | 6.99 | 1.17 | 5.00 | 10.00 |
| Net income | Net income per shift, HKD[a] | 817.9 | 265.8 | 410.0 | 1540.0 |
| Full-time driver | 1 = Full-time driver, 0 = other | 0.57 | 0.50 | 0 | 1 |
| Young driver | 1 = age ≤35 y, 0 = other | 0.24 | 0.43 | 0 | 1 |
| Middle-age driver | 1 = age between 35 and 60 y, 0 = other | 0.60 | 0.49 | 0 | 1 |

[a] 1 HKD ≈ 0.78 USD.

## 3. Results

### 3.1. Modeling driving performance with driving fatigue

To investigate the effect of the taxi drivers' fatigue level on their driving performance with unobserved heterogeneities, various measures dependent upon driving performance recorded in the driving simulator experiments were modeled with the participants' self-reported fatigue at the time of the experiment and their demographic factors using RE models. A dummy independent variable, *serious fatigue*, was adopted to represent the driver's level of fatigue. The value of this variable was 1 if the BFI score was higher than 3 and 0 if the BFI score was 3 or lower (Mendoza *et al.* 1999, Cheng *et al.* 2017). Among the driving performance-dependent measures proposed in Table 1, four were found to have a significant ($p < 0.05$) association with the drivers' fatigue levels: BRT_50, SDLane_50, SDLane_80, and VarSteer_80. Table 2 presents the coefficient estimation results of these four measures with the fatigue levels and other demographic variables.

## 3.2. Modeling temporal patterns of driving fatigue and driving performance

The BFI scores at the time of the three experiments for each participant were modeled as a function of DrHr and other demographic variables using a RE model. To explore the temporal pattern of the BFI, various forms of DrHr (including linear, quadratic, and exponential) were explored, and the Akaike Information Criterion (AIC) was used to evaluate the goodness-of-fit of various model forms (Akaike 1971). Keeping the other independent variables the same, a quadratic form of DrHr best explained its effect on the BFI score based on its lower AIC value (635.323). Table 3 shows the RE modeling results of the BFI scores with a quadratic form of DrHr. Both DrHr (coefficient = 0.820) and DrHr square (coefficient = −0.062) were significant ($p < 0.05$). In addition to DrHr, one of the driver age groups, young driver (coefficient = 1.717), also had a significant positive effect on driving fatigue when compared with drivers at or above 65 years of age.

Table 2. Modeling results of driving performance measures with self-reported driving fatigue.

| Variable names | BRT_50 | | SDLane_50 | | SDLane_80 | | VarSteer_80 | |
|---|---|---|---|---|---|---|---|---|
| | Coefficient | p value | Coefficient | p value | Coefficient | p value | Coefficient | p value |
| **Serious fatigue** | **0.096*** | **0.008** | **0.216*** | **0.007** | **0.799*** | **0.000** | **0.230*** | **0.023** |
| Young driver | -0.217* | 0.001 | -0.029 | 0.819 | 0.168 | 0.643 | -0.645* | 0.000 |
| Middle-aged driver | -0.157* | 0.003 | 0.157 | 0.122 | 0.833* | 0.004 | -0.495* | 0.001 |
| Sleeping hours | 0.048* | 0.002 | 0.007 | 0.802 | 0.163 | 0.051 | 0.011 | 0.797 |
| Net income | $-2.42\times10^{-4*}$ | 0.001 | $-3.53\times10^{-4*}$ | 0.007 | $-7.03\times10^{-4*}$ | 0.044 | $-2.58\times10^{-4}$ | 0.149 |
| Full-time driver | 0.001 | 0.970 | 0.129 | 0.067 | 0.475* | 0.017 | -0.303* | 0.003 |
| Constant | 0.818* | 0.000 | 0.434 | 0.079 | -0.068 | 0.922 | 2.454* | 0.000 |
| | | | | | | | | |
| No. of observations | 150 | | 150 | | 150 | | 150 | |
| Log-likelihood at zero | -7.47 | | -95.23 | | -257.04 | | 686.77 | |
| Log-likelihood at convergence | 17.22 | | -81.64 | | -238.24 | | 703.19 | |
| AIC | -16.44 | | 181.29 | | 494.48 | | -1388.38 | |

* Significant at the 0.05 level.

Table 3. Coefficient estimates for the RE model of the BFI scores with a quadratic form of DrHr.

| Variable names | Coefficient | Standard Error | z | P>z |
|---|---|---|---|---|
| DrHr | 0.820* | 0.286 | 2.89 | 0.004 |
| DrHr square | -0.062* | 0.023 | -2.67 | 0.008 |
| Sleeping hours | -0.237 | 0.130 | -1.82 | 0.068 |
| Net income | $-0.773\times10^{-4}$ | 0.001 | -0.14 | 0.888 |
| Full-time driver | 0.380 | 0.313 | 1.21 | 0.226 |
| Young driver | 1.717* | 0.560 | 3.06 | 0.002 |
| Middle-aged driver | 0.718 | 0.456 | 1.21 | 0.226 |
| Constant | 3.020* | 1.263 | 2.39 | 0.017 |
| | | | | |
| No. of observations | 150 | | | |
| Log-likelihood at zero | -321.60 | | | |
| Log-likelihood at convergence | -307.66 | | | |
| AIC | 635.323 | | | |

* Significant at the 0.05 level.

Given that the estimated coefficient of DrHr square was significantly negative (−0.062), the quadratic function was concave, which indicates that as the driving hours increased, the BFI score first increased, and then decreased after it reached its maximum value. Eq. (2) describes the concavely quadratic effect of DrHr to the BFI:

$$\mathrm{BFI}_{it} = -0.062\mathrm{DrHr}_{it}^{2} + 0.820\mathrm{DrHr}_{it} + \boldsymbol{\beta X_{it}} \quad (2)$$

where the variable names carry the same meanings as defined before.

To explore the temporal patterns of the taxi drivers' driving performance, the five proposed driving performance measures at two different speed levels were modeled directly with DrHr and the demographic variables (without quantifying the effect of the BFI) using RE models. The same three forms of DrHr were tested for all models, including linear, quadratic, and exponential, to investigate the role of DrHr in affecting driving performance. Two driving performance measures were found to have significant associations with DrHr: BD_80 and VarSteer_50. In both models, the quadratic form of DrHr performed the best among the tested three forms based on their lower AIC values (733.130 for BD_80 and −1264.683 for VarSteer_50). Tables 4 and 5 present the estimation results for BD_80 and VarSteer_50 with DrHr and other demographic variables. In the model of BD_80, the coefficients of four variables were significant at the 0.05 level: DrHr (coefficient = 0.365), DrHr square (coefficient = −0.036), net income (coefficient = −0.002), and middle-aged driver (coefficient = 1.941). In the model of VarSteer_50, the coefficients of DrHr (0.126), DrHr square (−0.011), and net income (−0.001) were significant at the 0.05 level.

Table 4. Coefficient estimates for the RE model of BD_80 with a quadratic form of DrHr.

| Variable names | Coefficient | Standard Error | z | P>z |
|---|---|---|---|---|
| DrHr | 0.365* | 0.173 | 2.10 | 0.035 |
| DrHr square | -0.036* | 0.017 | -2.16 | 0.031 |
| Sleeping hours | -0.263 | 0.184 | -1.43 | 0.153 |
| Net income | -0.002* | $7.74\times10^{-4}$ | -2.28 | 0.023 |
| Full-time driver | 0.341 | 0.443 | 0.077 | 0.441 |
| Young driver | 0.973 | 0.791 | 1.23 | 0.219 |
| Middle-aged driver | 1.765* | 0.643 | 2.75 | 0.006 |
| Constant | 40.410* | 1.524 | 26.52 | 0.000 |
| | | | | |
| No. of observations | 150 | | | |
| Log-likelihood at zero | -365.70 | | | |
| Log-likelihood at convergence | -356.57 | | | |
| AIC | 733.130 | | | |

* Significant at the 0.05 level.

Table 5. Coefficient estimates for the RE model of VarSteer_50 with a quadratic form of DrHr.

| Variable names | Coefficient | Standard Error | z | P>z |
|---|---|---|---|---|
| DrHr | 0.126* | 0.054 | 2.33 | 0.020 |
| DrHr square | -0.011* | 0.005 | -2.11 | 0.035 |
| Sleeping hours | -0.013 | 0.058 | -0.22 | 0.824 |
| Net income | -0.001* | $2.54\times10^{-4}$ | -3.99 | 0.000 |
| Full-time driver | -0.005 | 0.138 | -0.03 | 0.974 |
| Young driver | -0.172 | 0.246 | -0.70 | 0.483 |
| Middle-aged driver | -0.378 | 0.199 | -1.90 | 0.057 |
| Constant | 0.011* | 0.002 | 6.26 | 0.000 |
| | | | | |
| No. of observations | 150 | | | |
| Log-likelihood at zero | 642.83 | | | |
| Log-likelihood at convergence | 657.39 | | | |
| AIC | -1264.683 | | | |

* Significant at the 0.05 level.

Eq. (3) and (4) show the temporal effects of BD_80 and VarSteer_50, respectively:

$$\mathrm{BD\_80}_{it} = -0.036\mathrm{DrHr}_{it}^{2} + 0.365\mathrm{DrHr}_{it} + \boldsymbol{\beta X_{it}} \tag{3}$$

and

$$\mathrm{VarSteer\_50}_{it} = -0.011\mathrm{DrHr}_{it}^{2} + 0.126\mathrm{DrHr}_{it} + \boldsymbol{\beta X_{it}}. \tag{4}$$

# 4. Discussion

## 4.1. Effect of driving fatigue on driving performance

Based on the results shown in Table 2, male taxi drivers' self-reported fatigue levels were significant when modeling BRT_50, SDLane_50, SDLane_80, and VarSteer_80, whereas other confounding demographic variables were incorporated and unobserved heterogeneities were considered. The coefficients of serious fatigue were all significantly positive in the four listed models, which means that in general, the more seriously fatigued drivers tended to have worse driving performance than the drivers with mild fatigue (BFI <4). Specifically, the taxi drivers with higher fatigue levels had slower brake reaction times at 50 km/h, greater lane deviation at both speeds, and greater steering variance at 80 km/h.

BRT was a classical dependent measure of the drivers' level of alertness and ability to take action in simulated braking or hazard avoidance scenarios (Li *et al.* 2016, Wu *et al.* 2016). In this study, taxi drivers with a BFI score higher than 4 had a slower BRT when driving at 50 km/h (coefficient = 0.096), indicating that mildly fatigued drivers can react more quickly to the braking of the front car and take action to brake. Moreover, the drivers' standard deviation of lane position was significantly associated with serious fatigue at both speeds when confounding variables and unobserved heterogeneities were addressed (coefficient = 0.216 [50 km/h] and 0.799 [80 km/h]). The positive relationships between lane deviation and driving fatigue were intuitive: the more fatigued the driver is, the less lane stability he can maintain. Because lane position stability has long been incorporated in driving simulator studies as a measure of the participant's car control ability (Merat and Jamson 2013, Li *et al.* 2016, May *et al.* 2016, Wu *et al.* 2016), we have sufficient evidence to conclude that at any speed, male taxi drivers' ability to control a car deteriorates as they become fatigued from driving. In addition, the taxi drivers' steering variance was also shown to be significantly greater if their BFI score was higher than 3 (coefficient = 0.230). The results match the relationships between steering control and driving fatigue in previous studies (Ingre *et al.* 2006, Boyle *et al.* 2008, Merat and Jamson 2013).

For the taxi drivers' demographic factors, full-time taxi drivers (coefficient = 0.475) had significantly greater variability in lane position than part-time drivers at 80 km/h. Similar results were observed by Wu et al. (2016), who noted that taxi drivers were more prone to steer out of their lane to avoid a crash than non-professional drivers, which resulted in greater lane deviation before the crash. Full-time taxi drivers are more alert to hazards than part-time taxi drivers, thus they tend to be more overly prepared and overly alert, which might produce hidden traffic hazards. Moreover, given the same fatigue level, the drivers with a higher net income (coefficient = −8.72e-4) in their shifts had a slower BRT and weaker lane drifting behavior. Given that the taxi rental fee for each shift was similar for all drivers (around 450 HKD during a day shift and 400 HKD during a night shift), a higher net income corresponds to a longer time and distance serving passengers. When serving a passenger, a taxi driver tends to drive more carefully and stably than when driving a vacant taxi, to secure the safety and comfort level of the passengers. Hence, better driving performance in terms of reaction acuteness and lane control can be achieved by a driver with healthier driving habits who serves more passengers and thus reaches a higher net income in a working shift.

### 4.2. Temporal patterns of driving fatigue and driving performance

The temporal pattern of the taxi drivers' fatigue levels is depicted by the model of BFI with DrHr and the other demographic variables shown in Table 3. For each driver, the highest BFI score occurred 6.6 hours into his working shift, according to the parameters of DrHr and DrHr square in Eq. (2). The standard deviation of lane position at 80 km/h reached its peak at the same time, because SDLane_80 had a positive linear association with the BFI score.

The DrHr were found to have a direct significant effect on two dependent measures of driving performance in the FB tests—BD_80 and VarSteer_50—in a quadratic manner, as shown in Tables 4 and 5, respectively. The coefficients of DrHr square in both models were negative, meaning that the quadratic models were both concave. The results indicate that in a taxi driver's working shift, both driving performance measures increased with driving hours, reached a peak value, and then gradually decreased. According to the estimated parameters, the maximum braking distance occurred 5.1 hours into the working shift, and the maximum steering variance occurred 5.7 hours into the working shift.

The temporal patterns of driving fatigue and performance of taxi drivers in Hong Kong can be explained by the working intensity in a typical day. In Hong Kong, the taxi day-shift normally starts at 4 or 5 AM and ends at 4 or 5 PM. Based on the modeling results, the peak of taxi driving fatigue and driving performance occurred between 10 and 11 AM. According to the traffic characteristics survey in 2011 (TCS2011), a peak in the distribution of occupied taxi trips was observed between 7 and 10 AM (Fig. 3). Because the working intensity of taxi drivers is extremely high during peak hours, they are unlikely to be able to rest during these hours, and thus their fatigue levels continue to accumulate. Therefore, a lagging effect of driving fatigue and performance could be concluded: the peaks of the driving fatigue and performance measures were observed around 1 hour after the peak of the taxi drivers' working intensity. After the hours with extremely high working intensity, the taxis had fewer passengers to serve, which enabled the drivers to relax and take breaks if needed. Hence, their fatigue level gradually decreased accordingly, which we called a recovery effect.

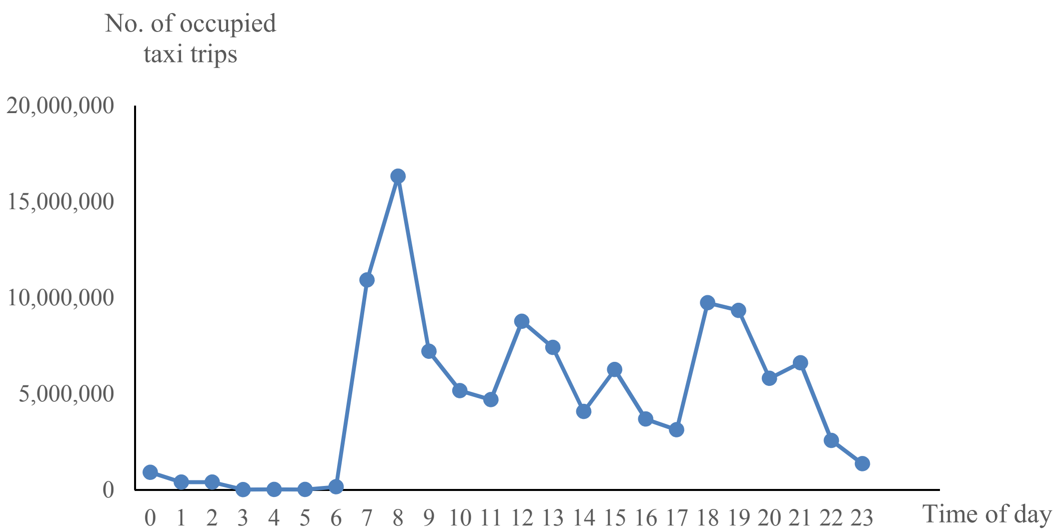


Fig. 3. Temporal distribution of number of occupied taxi trips in a typical day in Hong Kong.

To verify the temporal pattern and the recovery effect of male taxi drivers' driving fatigue and driving performance in Hong Kong, the distribution of taxi crash risk over a typical day was calculated (Fig. 4). The taxi crash risk was defined as the frequency of crashes involving taxis in Hong Kong in 2011 divided by the gas-dynamic-analogous-exposure (GADE) proposed by Meng *et al.* (2017a). A morning peak was observed from 8 to 10 AM from the taxi crash risk distribution. For day shift taxis, the highest crash risk occurred at the same time (around 10 AM) as the worst driving performance based on the models (i.e., BD_80 and VarSteer_50) indicates that poor driving performance may be the main cause of the high crash risk.

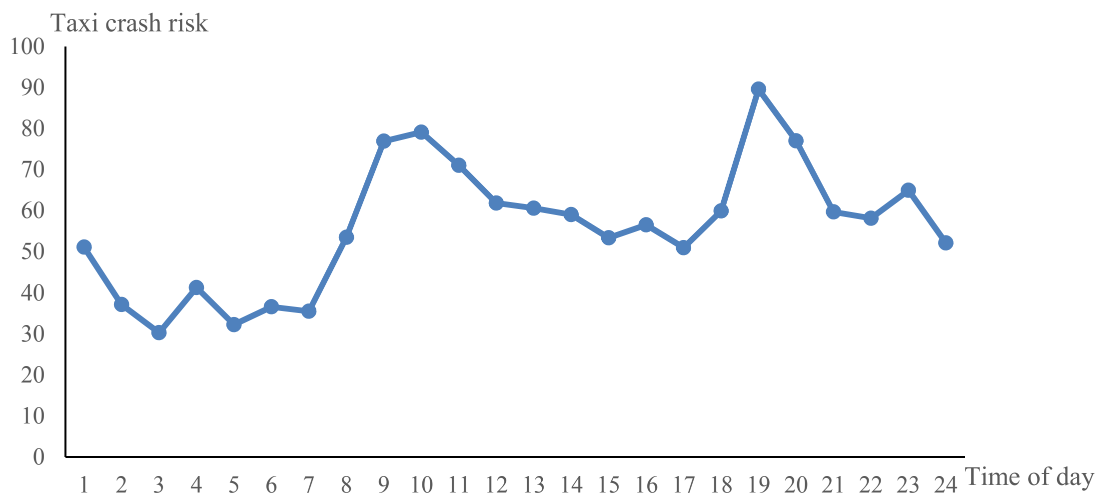


Fig. 4. Temporal distribution of taxi crash risk in a typical day in Hong Kong.

4.3. Other influential factors in the quadratic functions

Age was the only demographic factor that made a significant contribution to the taxi drivers' self-reported fatigue levels. Drivers 35 years of age or younger (coefficient = 1.717) were found to have higher BFI scores than their older counterparts. In the collected data, the average daily gross income of the younger drivers was 1537.5 HKD, which was significantly higher than that of the older drivers (1105.0 HKD). The relatively higher gross income indicated that the young taxi drivers served more passengers and had a relatively higher working intensity level than the elderly drivers, which may have resulted in the younger drivers' higher fatigue level.

Age also played a crucial role in the taxi drivers' braking distance at 80 km/h; meaningful differences as a result of age can be observed in Table 5. Drivers between 35 and 60 years of age had a relatively longer braking distance (coefficient = 1.765) at 80 km/h than the drivers older than 60 years of age. Chin and Huang (2009) concluded that older taxi drivers are more likely to be responsible for a crash and to have greater difficulty judging traffic conditions, which is consistent with our results about their steering instability. In our study, the older taxi drivers' mean BRT was 1.074 s—more than 0.2 s longer than that of the middle-aged drivers (0.846 s) and more than 0.3 s longer than that of the young drivers (0.739 s). Given the drivers' crash-avoidance intuition, the older drivers' prolonged reaction time to the hazards at the front may result in more urgent and emergent braking action, especially at high speeds, leading to a shorter braking distance.

## 5. Conclusions

In this study, a questionnaire and a driving simulator experiment with FB scenarios were designed to define the temporal patterns of the fatigue levels and driving performance of 50 male Hong Kong taxi drivers in their working shifts. The same measurements were conducted for each participant at three times: before, during, and after his working shift. The questionnaire recorded the drivers' demographic information, such as age, daily net income, and daily sleeping hours, and their BFI scores at the three times. Driving simulator tests measured the drivers' driving performance, including BRT, BD, lane variability, speed variability, and steering control, at 50 and 80 km/h. A RE modeling approach was then applied to model the relationship between driving fatigue and driving performance and the temporal patterns of driving fatigue and performance while addressing any unobserved heterogeneity that might exist via repeated measures. A relatively higher level of driving fatigue was found to increase the driver's lane deviation, steering variance, and reaction time to sudden braking. Linear, quadratic, and exponential forms of the driving hours were then tested in the models of the BFI and various driving performance measures, and the quadratic function was the best fit for BFI. A recovery effect was then concluded from the results: in a working shift, the drivers' fatigue level first increased, reached a peak, and then dropped to a certain level. Similarly, a recovery effect was also shown in the models of braking distance at 80 km/h and steering variability at 50 km/h.

The temporal patterns of taxi drivers' driving fatigue and performance can be justified by the distribution of taxi trips in Hong Kong: a high working intensity during the peak hours increases the taxi drivers' driving fatigue with a lagging effect, and the fatigued driver can possibly recover after relaxation after the shift's peak hours. The taxi crash risk distribution in Hong Kong over a day verifies the recovery effect and lagging effect of the male taxi drivers' fatigue levels and driving performance.

To alleviate the fatigued driving situation among taxi drivers in Hong Kong, some policies regarding taxi management and regulations can be implemented. Because taxi drivers' driving fatigue was concavely quadratic rather than monotonously incremental, a simple reduction in their working hours is not efficient. A reasonable number of rush hour taxis can be deployed from 7 to 9 AM and from 6 to 8 PM to cover the two peak hours to handle the high working intensity. In addition, a peak-load taxi pricing scheme could be applied based on detailed survey and economic calculation to balance the taxi drivers' work load and revenue. Moreover, taxi drivers' continuous driving duration can be monitored, and they can be required to take a break when this duration reaches a threshold value, especially during peak hours. In this way, the recovery effect can be used to enable the drivers to relax and recover from fatigue before they reach a dangerous fatigue level.

This study is limited to its samples and experimental conditions; the pool of subjects could be expanded, and the experimental design could be further improved. The gender difference in taxi drivers' driving fatigue could be explored with a more abundant driving simulator experiment design. Taxi drivers' driving behavior in specific situations, such as signalized intersections, s-curve roads, and taxi stations (i.e., passenger pick-up locations), can be investigated. Moreover, future studies could apply similar approaches to other professional drivers, such as truck and bus drivers, because their working patterns and natures may differ from those of taxi drivers, to extend the policy implications to other professional drivers.

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