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Investigating the effect of blood alcohol concentration on motorcyclist's riding performance using an advanced motorcycle simulator

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ABSTRACT

It is largely accepted that drink-driving significantly increases the likelihood that a driver may engage in risk-taking behavior and thus road crash. Although there have been a few studies examining the effect of blood alcohol concentration (BAC) on rider performance in developed countries, there has not been any research on the effect of BAC levels on motorcycle rider's performance in developing countries. This study is attempted to evaluate the effect of low BAC levels (i.e., ≤0.05 g/dL or 0.05) on riding performance of motorcycle riders in Vietnam using an advanced motorcycle riding simulator. Thirty-four motorcycle riders aged 18–40 complete simulated rides on three BAC levels, namely 0.00, 0.02, and 0.05. Riding performance indicators are measured and compared at different BAC levels. These indicators include average speed, average lateral overtaking distance, brake reaction time, acceleration, deceleration, and frequency of lane change. At the level BAC = 0.02 or lower, the negative effects on the rider's ability to control a motorcycle safely are statically insignificant. At the level BAC = 0.05, all the performances are impaired and the negative effects become statistically significant. In comparison of between novice participants and experienced participants at the same level of BAC, mean speed and acceleration rates of novice participants are significantly higher than the experienced participant. Based on the findings, the paper further discusses empirical relationships between reduced riding performances and road crash risk, and insights into drink-riding deterrence policy-making with regard to motorcycle riders.

1. Introduction

This study distinguishes the term "rider" from the term "driver". Driver refers to a person who drives or controls a car, while rider or so-called motorcyclist refers to a person who rides or controls a motorcycle or scooter or moped. Alcohol is a significant risk factor for drivers, and the effect of alcohol on car drivers has been well known (Compton et al., 2002; Moskowitz, 2002; Moskowitz & Florentino, 2000). It is largely accepted that drink-driving significantly increases the likelihood that a driver may engage in risk-taking behavior (Li et al., 2016). Many studies have reported that alcohol-impaired drivers pose a higher crash risk, particularly when the drivers are killed or seriously injured, than those who have not

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consumed alcohol (Mounce and Pendleton, 1992; Robertson and Drummer, 1994; Tsui et al., 2010; Li et al., 2013). In the past two decades, there were many studies using a driving simulator to examine the effect of blood alcohol concentration on drivers' driving performance (Bernosky-Smith et al., 2011; Li et al., 2016; Rakauskas et al., 2008; Veldstra et al., 2012; Verster et al., 2009). The previous studies revealed that alcohol intake could harm driving skills, such as vehicle speed, braking, steering while passing, overtaking time, and choosing the inappropriate distance with surrounding vehicles. Lane position, line crossing, speeding time, and collision number could be other essential indicators to assess drivers' driving performance (Martin et al., 2013; Rezaee-Zavareh et al., 2017). Such effects are explained by the distraction caused by alcohol (Rakauskas et al., 2008). Previous studies concluded that alcohol consumption could impair neurological and cognitive functions of drivers (Bernosky-Smith et al., 2011; Eckardt et al., 1998; Rakauskas et al., 2008; Verster et al., 2009), and alcohol intake may lead to an increase in reaction time to on-road hazards (Marple-Horvat et al., 2008; Veldstra et al., 2012; Verster et al., 2009). Furthermore, other demographic information of drivers, such as age, gender, and driving experience, may affect the alcohol-related driving performance (Rezaee-Zavareh et al., 2017; WEST et al., 1993).

From the best of our understanding, up to now there is sparse research on the impairing effects of alcohol on motorcycle control skills. In fact, there have been only three studies to date examining the effect of blood alcohol concentration on rider performance, and all such studies were conducted in developed countries. Using a motorcycle riding simulator to examine riding skills under different levels of BAC in experienced riders, Colburn et al. (1993) found that increased BAC levels up to 0.1% were associated with increased riding errors, particularly "running off the road". The study compared riding performance and hazard response under three low-dose alcohol conditions (sober, 0.02% and 0.05%). The results showed a significant increase in the standard deviation of lateral position in the urban road scenario and peripheral detection task reaction time in the rural road scenario under 0.05% BAC compared with zero-alcohol. Participants were most likely to collide with an unexpected pedestrian in the urban scenario at 0.02% BAC, with novice participants at a greater relative risk than experienced riders. Creaser et al. (2009) used a test track method to examine the effects of alcohol on riding skills. Experienced riders completed riding tasks under zero-alcohol, 0.02%, 0.05% and 0.08% BAC conditions in a repeated measures design. Across almost all tasks, a BAC of 0.08% resulted in greater riding impairment compared with the other conditions. In particular, participants were significantly impaired at performing an offset weave task with a BAC of 0.08%. In Australia, Filtness et al. (2013) used a riding simulator to test the effects of low-dose alcohol on riding behavior. The study result revealed that the rider's ability to perceive and handle dangerous situations decreases when alcohol concentration increases. The study suggested modifying the law to prove that blood alcohol content below 0.05% is reasonable. In the two studies (Filtness et al., 2013; Colburn et al., 1993) that used a motorcycle simulator to investigate the effects of alcohol on riders' performance, the indicators of study were limited. These studies did not consider other key indicators, such as lane position, line crossing, number of collisions, vehicle's speed, overtaking time, braking, steering, and the distance to surrounding vehicles. Until recently, there has not been any research on the effect of blood alcohol concentration on riding performance of motorcycle riders in developing countries, where motorcycles are numerous.

In Asian developing countries, rapid growths in motorcycle ownership and use and alcohol consumption have made drink-riding behavior a serious road safety concern as it has contributed to an increased number of road crashes, fatalities and injuries. In Vietnam, for example, drinking alcoholic beverages has been traditionally accepted in the local culture as a part of creating a friendship and cheering a successful business. As the economy is growing, alcohol consumption is increasing even faster in Vietnam than in the other parts of the world. For the period of 2009–2019, Vietnam had lost around 10,000 people on roads each year (MoS, 2019). An analysis of data collected at three hospitals in Vietnam during July 2009 and September 2010 revealed that about 28% of the 10,566 motorcycle drivers hospitalized due to road crash injuries were tested with BAC levels higher than the legal limit ($\leq$50 mg/dL) (Nguyen et al., 2013). In 2016, fatal road crashes involving alcohol in Thailand and Combodia was about 14% and 13%, respectively, while the figure in Japan was just 6% (WHO, 2018a). Obviously, Vietnam has experienced a higher share of alcohol-impaired road accidents than other Asian countries. In addressing alcohol-related driving accidents and fatalities, the Government of Vietnam imposed the zero-tolerance regulation on car drivers, but not on motorcycle riders. License suspensions and monetary fines were imposed to combat drink-driving offenses and address the problem of car driver's drink-driving. The government had allowed people to ride a motorcycle in the condition of BAC level below 50 mg/dL. Since 2020, the new law on prevention and control of harms of liquor and beer abuse has set a solid ground for enforcing the zero-tolerance regulation on motorcycle riders. However, many other developing countries have still been facing a critical debate on whether and to what extent to reduce legal BAC levels on motorcyclists for significant road safety improvements.

Less than half of countries worldwide (i.e., 88 countries) have set in their drink-driving laws blood alcohol concentration limits are equal to or less than 0.05 g/dL, as recommended in the World report on road traffic injury prevention (WHO, 2018b). However, it is important to investigate whether such BAC limits are appropriate for motorcycle riders as they are involved in road crashes more often at lower BAC levels than car drivers (Sun et al., 1998). BAC limits ranged from zero-tolerance and 0.02 to 0.10% constitutes prima facie evidence in most countries for 'Driving under Influence of Alcohol'. This latter standard is too permissive, as driving skills deteriorate and crash involvement risk increases beginning at 0.02% (Desapriya et al., 2003). A review of published studies found that laws establishing a lower BAC limit – of between zero and 0.02 g/dL – for young or inexperienced drivers can lead to crash reduction of between 4% and 24% (Shults et al., 2001). The best practice for drink–driving laws includes a BAC limit of 0.05 g/dL for the general population and a BAC limit of 0.02 g/dL for young or novice drivers or riders (WHO, 2018a). Furthermore, our in-depth interview survey on the effects of alcohol abuse on motorcycle riding in Vietnam in 2018 found an interesting fact that more than 60% the rider respondents

(N = 309) strongly believed that after drinking a little alcohol they can ride a motorcycle without or with a very little impact on their ability to control the vehicle. Clearly, people are not aware of the negative influence of low-dose alcohol on safe riding. Therefore, the results of literature review and the interview survey call for a distinction between zero-tolerance and a BAC limit of 0.02 g/dL to significantly improve road safety and enhance the riders 'awareness about alcohol effects.

Driving and riding simulators have been used in a wide range of research settings to help develop an understanding of drivers and riders' behavior in complex environments (Irwin et al., 2017), including investigating the effect of alcohol on driving and riding performance of drivers and riders (Creaser et al., 2011). Driving and riding simulators are also a key element in regional, national, and international efforts to probe the efficacy of and behavioral adaptation induced by advanced technologies being used or introduced into the vehicle, such as foward collision warning system, lane departure warning system, adaptive cruise control system, and navigation aids (Fisher et al., 2011). In recent years, driving/riding simulators have commonly been used to monitor the effects of alcohol on driving/riding performance in road safety research. A modern driving/riding simulator provides a flexible experimental setup and well-controlled environment that allow for a safe, comfortable, and relatively realistic investigation of driving/riding behaviors. A major advantage of using a driving/riding simulator is that hazardous situations or events can be systematically designed, presented, and reproduced. Furthermore, compensatory behavior can be experienced as if participants were in realistic traffic environment. Current technological advancements have supported driving/riding simulators being developed into complex multi-functional components of apparatus, with abilities to test different scenarios and relatively real-world driving/riding environment experiences. A large amount of critical driving/riding behavior data can be collected and recorded by the simulator systems. One disadvantage of using a driving simulator is, however, that drivers may experience simulator sickness. Roughly about 40% and 50% of test drivers who are not familiar with driving simulator report symptoms of simulator sickness. This disadvantage is easily remedied, however, if drivers complete familiarization sessions with the simulator; 90% of all test drivers who completed such sessions do not experience any symptom of the sickness (Hoffmann et al., 2006).

2. Objectives and structure

This study is attempted to evaluate the effect of low BAC levels on riding performance of Vietnamese motorcycle riders using an advanced riding simulator. The outcomes would be a reference to determining a proper legal limit of BAC on motorcyclists and set forth a follow-up study on quantifying relative changes in road crash risk due to alcohol-impaired riding performance changes and suggesting solutions to prevention of drink-driving behavior.

Based on the literature review, it is hypothesized that increasing BAC level (<0.05%) would impair riding performance (i.e., average speed, average lateral overtaking distance, brake reaction time, acceleration/deceleration, and frequency of lane changes) in both novice and experienced riders. It is further hypothesized that the riding effects of low-dose alcohol would be more significant for novice riders than experienced ones. Riding experiments are designed and conducted to test these hypotheses.

This paper is structured as follows. Section 3 presents a method for the study. It describes the characteristics of the participants, apparatus, and materials, designing an experimental session with three test BAC levels, defining driving performance measures, and simulated riding environment. The procedure and data analysis method are briefly explained. Section 4 presents the results of analysis on the effects of low BAC levels on riding performance of motorcyclist participants. Section 5 discusses the results of the study with reference to relevant studies. Section 6 provides insights into policy-making for drinking and driving deterrence ce in Vietnam. Section 7 concludes with key findings, policy considerations, limitations and further studies.

3. Method

3.1. Participants

Nagoshi et al. (1991) found that male drivers would be sensation-seeking and more impulsive under the effects of drinking and driving than females. At the same BAC level, young drivers would have a higher relative crash risk than older ones (Mayhew et al., 1986; Zador, 1991). To capture riders types, 34 Vietnamese motorcycle riders, including 28 males and 6 females, are recruited based on a voluntary manner. The participants were from the Vietnamese German University, the Eastern International University and local communities via word of mouth, advertisements on notice-boards at university campus and on the university's e-learning platform. Interested individuals emailed or phoned to the study team to receive detailed information about the experiment. The recruitment required that participants experienced drinking alcohol. Participants who reported previous alcohol or substance abuse or any psychiatric disorder were excluded. For interested female volunteers who were pregnant or breastfeeding by self-report were not permitted to participate. All the participants hold a riding license to ensure that they are legal road users. All riders who participated in this study ride their motorcycles of the same type with the riding simulator at the laboratory (i.e., Honda Wave, Yamaha Sirius, Suzuki Viva, and so forth). All volunteers provided informed consent information about the study prior to participation. They were presented a gift valued at VND500.000 (equivalent to US$22) for appreciation of their deliberate participation in the experiments.

Table 1
Participant characteristics.

	Novice rider	Experienced rider	Pooled
The number of participants	17	17	34
In which, the number of female participants	4	2	6
Age (Mean, SD)	20.3 (1.3)	29.3 (3.0)	24.8 (5.1)
The number of years of holding a riding license (Mean, SD)	1,9 (0.8)	9.6 (2.6)	5.7 (4.3)

The characteristics of the participants are described in Table 1. The experienced participants are significantly older than the novice ones and have significantly longer riding experience expressed by the number of years of holding a riding license. Age is not included as a covariate as it is highly correlated with riding experience. There are seventeen experienced riders, including four females, aged 24–37 (mean = 29.3, SD = 3.0) having held a driving license for 9.9 years on average, and seventeen novice riders, including two females, aged 18–23 (mean = 20.3, SD = 1.3), who have been holding the license for more or less two years. All the participants hold a riding license to ensure that they are legal road users, as previously mentioned.

3.2. Apparatus and materials

3.2.1. Riding simulator

At the Vietnamese-German Transport Research Centre within the Vietnamese German University, an advanced riding simulator is specially developed for in-depth researches on riding behaviors of motorcyclists. It is an interactive riding simulator developed from a real Honda Future 125 motorcycle. Participants are able to enjoy real feelings of controlling the throttle, hand and foot brake, and steering. The simulated scenario is displayed on a curved projection screen providing a 180 degrees horizontal and 40 degrees vertical field of view with an additional screen for the rearward view (Fig. 1). The motorcycle is fixed in a vertical position to allow participants to have both feet on the foot pegs, emulating a real riding position. A digital speedometer is presented on the instrument panel of the motorcycle to allow participants to read speed. Lateral position, speed, throttle, and brake use are recorded automatically by the system. Speed is recorded from the moment when a participant has run 500 m from the start point (to exclude acceleration up to speed) until the end of the ride. In this study, the data logging frequency rate of the riding simulator system is at 0.1 s per time.

3.2.2. Breathalyzer

The Draeger Alcotest 7410 Plus is a portable breathalyzer system using a heat and temperature-controlled electrochemical fuel cell, which is certified for the U.S. Department of Transportation (DOT) alcohol testing. This device measures Breath Alcohol Content (BrAC), and BrAC is converted to BAC using a BrAC-BAC ratio of 1:2100. To ensure an accuracy, the breathalyzer is calibrated by Ho Chi Minh City Traffic Police prior to study commencement.

3.3. Experimental design

3.3.1. Level of alcohol consumption

The study examines the effect of three BAC levels ranging from sober up to the per se legal limit (0 mg/dL, 20 mg/dL, and 50 mg/dL). During the experiment, the alcohol dose for each participant is calculated according to Watson's research (Watson, 1989). Equation (1) is used to calculate the dose for the targeted BAC level as follow:

Fig. 1. An advanced riding simulator used for the experiment.

$$\text{Alcohol dose (g)} = \frac{10 \times \text{BAL} \times \text{TBW}}{0.8} + 10 \times \text{MR} \times (\text{DDP} + \text{TPB}) \times \frac{\text{TBW}}{0.8} \quad (1)$$

$$\text{Men's TBW} = 2.447 - 0.09516 \times \text{Age} + 0.0174 \times \text{Height(cm)} + 0.3362 \times \text{Weight(kg)} \quad (2)$$

$$\text{Women's TBW} = 2.097 + 0.1069 \times \text{Height(cm)} + 0.2466 \times \text{Weight(kg)} \quad (3)$$

where *BAL* is the target blood-alcohol level, *TBW* is the total body water amount calculated differently for males and females using Equation (2) and (3), respectively; *MR* is the metabolic rate (generally 0.015 g/100 ml/h); *DDP* is the duration of the drinking period; and *TPB* is the time to peak *BAL* (generally 0.5 h).

3.3.2. Experimental session design

The experiment was conducted from October to December 2018. A 3 × 2 mixed design is utilized with alcohol dose ('Dose') as the within-subjects 0 mg/dL, 20 mg/dL, and 50 mg/dL and riding experience ('Experience') as the between-subjects factor (experienced, novice). In addition to participant's gender and riding experience, BAC level is a key factor to the riding performance. Each participant experiences all three designated BAC conditions in an orthogonal counter-balanced order. Each participant pays four visits to the laboratory in four days, for each visit he or she follows two or three steps of experiment as shown in Table 2. By reducing the number of test days per participant to four days, this incomplete design helps reduce the probability of attrition while retaining 90% of the statistical efficiency of a complete design. This study follows the experimental design for using a driving simulator to study the impact of alcohol consumption on driver's performance as summarized in Rezaee-Zavareh et al. (2017). In previous studies, the indicators of study include participant's demographic information, driving experience, average speed, average lateral overtaking distance, frequency of lane change, reaction time, acceleration, and deceleration. In Vietnam, lunch time is usually from 11:00 AM to 13:00 PM and Vietnamese people usually do not drink in the morning, but they drink during lunch and dinner times. Following the local practice, the participants are instructed to drink alcohol after 10:00 AM on the experiment day.

3.3.3. Driving performance measures

The process of vehicle control is divided into three levels, namely strategic, tactical, and operational levels (Michon, 1985; and Ranney, 1994). At the strategic level, the journey goals are selecting a safe and as fast as possible path and arriving at the destination in time. The driver shall control the time for competitive activities, which are not related to the control of the vehicle, and the decision at this level occurs in a wider time window, such as in minutes, a day, or a week. At the tactic level, the goals involve the selection of lane, velocity, and spacing. The driver shall control the time for performing the vehicle control operations in seconds to minutes. At the operational level, vehicle control involves controlling the horizontal and vertical position of the vehicle. The driver shall focus on the operations to control the vehicle, such as accelerating, braking, steering, etc. Any action or decision at the three levels can be applied to the operations necessary to drive safely (Lee & Strayer, 2004).

There is no standard set of driving performance measures used for testing alcohol-impaired driving (Creaser et al., 2011). As measures shall provide a track record of driving behaviors impaired by alcohol intoxication, they should be selected on the basis of their sensitivity to the disruptive effects of alcohol (Harrison & Fillmore, 2005). Recently, various studies have considered the standard deviation of lateral position (SDLP) as an outcome measure in driving simulator tests. This measure of vehicle control presents the amount of "weaving" of the car in a car-following traffic environment in Western countries. However, in a motorcycle-dominant traffic environment like the one in Vietnam motorcycles often do not follow the lane discipline. For example, there are several motorcycles running in parallel on the same lane of 3.0–3.5 m wide. Therefore, the SDLP indicator might be not applicable in a motorcycle-dominant traffic environment. As noted, the two simulator studies used a number of indicators for measuring motorcycle riding performance. Filtness et al. (2013) used lateral position of the motorcycle within the lane, standard deviation of lateral position (SDLP), speed, hazard perception ability and reaction time. Colburn et al. (1993) used riding errors and reaction time as performance indicators. In the test-track study, Creaser et al., 2009) used minimum passing distance, lane crossings, maximum speed in straight section, maximum deceleration,

Table 2
The number of visits for the experiment per participant.

	Visit 1	Visit 2	Visit 3	Visit 4
BAC level	0.00	0.00	0.02	0.05
Arrival time at laboratory	8:00 AM	8:00 AM	8:00 AM	8:00 AM
Drinking period	–	10 AM – 12 PM	10 AM – 12 PM	10 AM – 12 PM
Step 1	Measuring BAC before drinking	Measuring BAC before drinking	Measuring BAC before drinking	Measuring BAC before drinking
Step 2	Getting familiar with the simulator	Simulated riding about 15 min	Drinking to reach BAC = 0.02	Drinking to reach BAC = 0.05
Step 3	Driving training about 60 min		Simulated riding about 15 min	Simulated riding about 15 min

Table 3
Definition of selected motorcycle riding performance measures.

Riding task	Performance measure	Definition
Speed control in straight road	Average speed	Average riding speed of the vehicle (km/h)
Overtaking vehicles	Average lateral overtaking distance	An average lateral distance of overtaking between the motorcycle and other vehicle (m)
Keeping lane	Frequency of lane change	A lane change is counted when the vehicle moves outside the lane, either crossing the center line into the oncoming traffic lane or crossing the road shoulder. An average number of lane-crossings per kilometer is recorded as a frequency of lane change (times/km)
Responding to unexpected incidents	Brake reaction time	Response time to braking for an unexpected incident (s)
Responding to traffic signal lights	Acceleration	At an intersection, when the green light turns on, acceleration is measured in a distance of 50 m after the stop line (m/s2)
	Deceleration	At an intersection, when the red light turns on, deceleration is measured in a distance of 50 m before the stop line (m/s2)

response time, count of times feet leave pedals, and lane crossings (count). From the literature review, this study selectively chooses six measures at the operational levels, including average riding speed, average lateral overtaking distance, brake reaction time (BRT), acceleration, deceleration, and frequency of lane change. In this study, SDLP is not considered as it might be unsuitable for the context of mixed and motorcycle-dominant traffic environments. As briefly defined in Table 3, these measures are widely used in driving simulator and test-track studies aimed to examine the effect of low-dose alcohol on vehicle handling skills (Creaser et al., 2009; Colburn et al., 1993). The driver' hazard perception ability is measured by braking reaction time to an unexpected incident, such as a car suddenly brakes in front of the driver's car (Rudin-Brown et al., 2010). In the experiment, BRT is the time (in seconds) from the appearance of the braking event, T_{Event}, to the brake onset, T_{Brake}, as expressed by Equation (4).

$$\mathrm{BRT} = \mathrm{T_{Brake}} - \mathrm{T_{Event}} \tag{4}$$

3.3.4. Subjective measures

Perceived levels of intoxication and performance impairment are assessed immediately after riding. Participants selected a point along a line to describe how intoxicated they felt and how impaired they felt their riding performance was based on how they felt at that moment. The lines were anchored with "not at all" (rating = 0) on the left and "extremely" (rating = 10) on the right.

3.3.5. Simulated riding environment

The simulated riding environment is a four-lane bidirectional urban road of 5 km long, having three curves and two traffic signal lights. The width of a lane is 3.5 m. The straight roadway and curve are alternant in three scenarios to avoid participants' familiarity with only one route. A snapshot of the simulated riding environment is shown in Fig. 2. The participants randomly participate in the three scenarios across their visits to the laboratory.

Fig. 2. Simulated riding environment.

Table 4
BAC level reading.

BAC target	Acceptable range	Pre-ride mean (SD)
0.02 (N = 34)	0.01–0.03	0.022 (0.003)
0.05 (N = 34)	0.04–0.06	0.051 (0.003)

3.4. Procedure

3.4.1. Training session

All participants are requested to complete a simulator familiarization session by default with instructions in the first visit. The goal of training is to extinguish learning effects by establishing "error-free" performance on the course for each rider prior to beginning experimental tasks. This is essential not only to help participants establish a more natural way of driving in the simulator but also to prevent simulator sickness (Hoffmann et al., 2006).

3.4.2. Alcohol administration and experimental trials

Each participant performs three riding sessions in three days. Participants are instructed not to drink alcohol the night before and not to eat for at least two hours prior to a riding session. They are also instructed to get a good night's sleep the night before the session so that they are rested. They are advised to take a complimentary taxi to and from a session. Upon arrival at the laboratory, participants are breathalyzed to ensure that they have not consumed any alcohol. After completion of filling a demographic and riding experience questionnaire, participants are then brought to another room where they consume an alcohol dose relevant to the target condition. The alcohol dose (vodka, 37.5% alcohol) is administered as a beverage made up to 480 ml with chilled orange juice. Participants are blind to the BAC condition. In the zero-alcohol condition, a nominal amount (one ml) is floated atop the beverage to make it smell like it might contain alcohol. Participants are required to drink 30 ml (a "sip") of liquid every minute for 16 min. Twenty minutes post the drinking, participants are instructed to rinse their mouth with water to remove residual alcohol, and they are breathalyzed again. This is a common approach to administering alcohol and creating a zero-alcohol condition (Oxley et al., 2006). For a participant, the BAC level could be within the range of assigned condition (Table 4) 30 min since he or she began drinking.

3.5. Data analysis

The ANOVA test with an alpha level of 0.05 is deployed to determine statistical significance. Differences in the mean value of riding performance measures are determined using a mixed ANOVA with the within-subject factor of alcohol dose (i.e., zero-alcohol, 20 mg/dL or 0.02, and 50 mg/dL or 0.05) and the between-subject factor of riding experience (i.e., the novice and the experienced rider). First, the comparisons are conducted between within alcohol conditions (BAC = 0.02, 0.05) and non-alcohol condition (BAC = 0.00) to identify the lowest level of BAC that significantly affect the participants' riding performance. Second, the comparison is performed between the BAC conditions (BAC = 0.05 versus BAC = 0.02) to examine impairment differences between these two levels.

4. Results

Riding performance data are recorded and analyzed to reveal the effects of drink-driving conditions. Means and standard deviations of the six riding performance measures are used to explain the signatures of riding performance impaired by BAC levels. Values of the riding performance indicators at different BAC levels are presented in Table 5 and Table 6.

4.1. Blood alcohol concentration

In the condition BAC = 0.02, the participants start riding at mean BAC = 0.022 (SD = 0.003). In the condition BAC = 0.05, the participants start riding at mean BAC = 0.051 (SD = 0.003) (Table 4).

4.2. Subjective ratings of intoxication

Fig. 3 shows subjective ratings of intoxication (out of 10) at three BAC levels.

The mixed ANOVA analysis reveals significant differences in the rating at different BAC level, $F(2, 99) = 173.93$, $p < .000$. Pairwise comparisons reveal the condition BAC = 0.02 is associated with significantly higher ratings than the zero-alcohol condition, and the condition BAC = 0.05 is associated with significantly higher ratings than zero-alcohol and BAC 0.02 conditions ($p < .05$). The rating of subjective intoxication reported by participants in the condition BAC = 0.00 is significantly above zero. This implies that the method for administrating the placebo beverage is successful in term of generating an expectation that alcohol is possible in any drink.

Table 5
Comparison of riding performance by BAC level and riding experience.

	Novice participant (N = 17)				Experienced participant (N = 17)				Pooled (N = 34)			
BAC	0.00	0.02	0.05	Overall effect	0.00	0.02	0.05	Overall effect	0.00	0.02	0.05	Overall effect
Average speed (km/h)	45.39 (4.57)	45.65 (3.88)	52.75 (4.17)	F(2,48) = 16.64, p = .000	39.94 (8.27)	34.77 (8.95)	44.04 (11.33)	F(2,48) = 3.9, p = .025	42.66 (7.13)	40.21 (8.76)	48.39 (9.49)	F(2,99) = 8.26, p = .000
Average lateral overtaking distance (m)	1.49 (0.16)	1.48 (0.19)	1.22 (0.25)	F(2,48) = 10.10, p = .000	1.31 (0.25)	1.15 (0.29)	1.12 (0.30)	F(2,48) = 2.37, p = 0.104	1.40 (0.23)	1.32 (0.29)	1.17 (0.28)	F(2,99) = 684, p = .002
Brake reaction time (s)	1.25 (0.03)	1.31 (0.03)	1.46 (0.04)	F(2,48) = 168.59, p = .000	1.24 (0.07)	1.31 (0.05)	1.46 (0.07)	F(2,48) = 304.51, p = .000	1.25 (0.03)	1.31 (0.03)	1.46 (0.03)	F(2,99) = 447.93, p = 000.
Acceleration (m/s2)	2.31 (0.23)	2.69 (0.22)	3.87 (0.24)	F(2,48) = 215.58, p = .000	2.03 (0.39)	1.89 (0.62)	3.13 (0.93)	F(2,48) = 17.33, p = .000	2.17 (0.35	2.29 (0.60)	3.50 (0.76)	F(2,99) = 52.241, p = 000.
Deceleration (m/s2)	1.77 (0.22)	1.76 (0.26)	2.58 (0.27)	F(2,48) = 58.69, p = .000	1.50 (0.35)	1.91 (0.58)	2.35 (0.37)	F(2,48) = 15.24, p = .000	1.63 (0.32)	1.84 (0.45)	2.47 (0.34)	F(2,99) = 45.36, p = 000.
Frequency of lane change (time/km)	0.49 (0.12)	0.63 (0.24)	0.79 (0.20)	F(2,48) = 10.04, p = .000	0.53 (0.19)	0.58 (0.02)	0.73 (0.28)	F(2,48) = 3.29, p = .046	0.51 (0.16)	0.60 (0.22)	0.76 (0.24)	F(2,99) = 11.84, p = 000.

Table 6
Comparison of riding performance by riding experience at the same BAC level.

Performance measure	BAC = 0.02			BAC = 0.05		
	Novice participant (N = 17)	Experienced participant (N = 17)	Overall effect	Novice participant (N = 17)	Experienced participant (N = 17)	Overall effect
Mean speed (km/h)	45.65 (3.88)	34.77 (8.96)	F(1,32) = 21.15, p = .000	52.75 (4.17)	44.04 (11.33)	F(1,32) = 8.82 p = .006
Average lateral overtaking distance (m)	1.48 (0.19)	1.15 (0.29)	F(1,32) = 15.83, p = .000	1.22 (0.25)	1.12 (0.30)	F(1,32) = 1.13, p = .295
Brake reaction time (s)	1.31 (0.03)	1.31 (0.02)	F(1,32) = 0.32, p = .573	1.46 (0.04)	1.46 (0.03)	F(1,32) = 0.06 p = .807
Acceleration (m/s2)	2.69 (0.22)	1.89 (0.60)	F(1,32) = 26.59, p = .000	3.87 (0.24)	3.13 (0.93)	F(1,32) = 10.12 p = .003
Deceleration (m/s2)	1.76 (0.26)	1.91 (0.60)	F(1,32) = 0.92, p = .344	2.58 (0.27)	2.35 (0.37)	F(1,32) = 4.46, p = .042
Frequency of lane change (time/km)	0.63 (0.24)	0.58 (0.20)	F(1,32) = 0.401, p = .531	0.79 (0.20)	0.73 (0.28)	F(1,32) = 0.552 p = .462

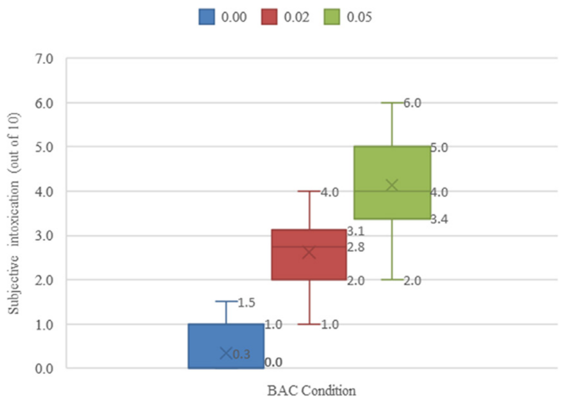

Fig. 3. Subjective ratings of intoxication (out of 10) (error bars represent standard error).

4.3. Motorcycle riding performances

4.3.1. Average speed

There is a statistically significant effect of BAC condition on mean riding speed (Table 5). As BAC level increases, the mean speed of the novice participants and the experienced ones increases, F (2,48) = 16.64, p = .000 (the novice), and F (2,48) = 3.9, p = .025 (the experienced). For all participants, the alcohol conditions (BAC = 0.02, 0.05) result in higher mean speeds than the zero-alcohol condition. At the same BAC level, the novice participants' mean speed is always significantly higher than the experienced ones 'mean speed, F (1,32) = 21.15, p = .000, and F (1,32) = 8.82 p = .006 (Table 6).

4.3.2. Average lateral overtaking distance

Among the novice participants, the average lateral overtaking distance significantly decreases as the BAC level increases, F (2,48) = 10.10, p = .000 (Table 5). Comparison tests reveal that there is no statistically significant difference between the level BAC = 0.00 and the level BAC = 0.02, but significant difference between the level BAC = 0.02 and the level BAC = 0.05. The participants tend to make a smaller lateral overtaking distance when BAC increases from the level BAC = 0.02 to the level BAC = 0.05, hence getting a higher risk of road crash with the vehicle being overtaken. Among the experienced participants, there is, however, no statistically significant effect of BAC level on the lateral overtaking distance, F (2,48) = 2.37, p = 0.104 (Table 5). At the condition BAC = 0.05, the novice participants' lateral overtaking distance seems significantly greater than the experienced participants', F (1,32) = 8.82 p = .006 (Table 6).

4.3.3. Brake reaction time

There is a statistically significant effect of BAC condition on brake reaction time to both the groups; the reaction time increases with BAC level, F (2,48) = 168.59, p = .000 and F (2,48) = 304.51, p = .000 (Table 5). There is no statistically significant difference in the reaction time between the groups at either the condition BAC = 0.02, F (1,32) = 0.92, p = .344, or the condition BAC = 0.05, F (1,32) = 0.06 p = .807 (Table 6).

4.3.4. Acceleration

Among the novice participants, there is a statistically significant effect of BAC level on the acceleration at the traffic green light, $F(2,48) = 215.58$, $p = .000$ (Table 5). The acceleration is much higher in the condition BAC = 0.05 than the condition BAC = 0.02. Among the experienced participants, there is also a significantly effect of BAC level on the acceleration, $F(2,48) = 17.33$, $p = .000$ (Table 5). The acceleration is much higher at the level BAC = 0.05 than at the level BAC = 0.02 or the zero-alcohol condition. Comparisons at the same BAC level show that the novice participants perform significantly higher acceleration rates than the experienced ones, $F(1,32) = 26.59$, $p = .000$ at the condition BAC = 0.02 and $F(1,32) = 10.12$ $p = .003$ at the condition BAC = 0.05 (Table 6).

4.3.5. Deceleration

There is a statistically significant effect of BAC level on the deceleration at the traffic red light, $F(2,48) = 58.69$, $p = .000$ for the novice group, and $F(2,48) = 15.24$, $p = .000$ for the experienced group. Among the same group, the deceleration is much higher at the condition BAC = 0.05 (Table 5). At condition BAC = 0.02, there is no statistically significant difference between the two groups (Table 6). At the condition BAC = 0.05, the novice group, however, tends to perform higher decelerations than the experienced group, $F(1,32) = 4.46$, $p = .042$.

4.3.6. Frequency of lane change

In both groups, there is a statistically significant effect of BAC level on the frequency of lane change, $F(2,48) = 10.04$, $p = .000$ for the novice participants and $F(2,48) = 3.29$, $p = .046$ for the experienced ones. However, there is no significant difference in the measure between the two groups, $F(1,32) = 0.401$, $p = .531$ at the condition BAC = 0.02 and $F(1,32) = 0.552$ $p = .462$ at the condition BAC = 0.05.

5. Discussion

The ingestion of the low alcohol doses (i.e., BAC = 0.02, 0.05) results in riding impairments expressed by significant changes in vehicle controlling skills as compared to the zero-alcohol condition. In this research, the effects become significant at the condition BAC = 0.05. As BAC level increases, the average speed increases, the average lateral overtaking distance decreases, the deceleration at the red light increases, the acceleration post the green light increases, and the lane change becomes more frequent. Especially, as BAC level increases, the brake reaction time is significantly lengthened. Such changes, if combined, would expose the driver himself to a significantly higher risk of a road crash. These findings are consistent with previous studies investigating low doses of alcohol in motorcyclists (Colburn et al., 1993; Creaser et al., 2009). Subsequent paragraphs discuss how changes in each of the riding performances may contribute to a higher risk of road crash and the necessity for reconsidering lower legal BAC limits in motorcycle dominant countries.

This research shows that motorcycle riders tend to ride faster on straight road segments and the speeds tend to be more variable as the BAC level increases, suggesting that the riders become more confident in speeding due to alcohol impairment. The speed is an essential factor to the risk and the severity of a road crash (Elvik et al., 2004). At a higher speed, the time the driver reacts to a change in the environment is shorter, the stopping distance is longer, and maneuverability is smaller (Yeh et al., 2015). If the average speed increases by one kilometer per hour, the risk of a crash involving injuries typically increases by 3%, and the risk of a crash involving fatalities increases by 4% or 5% (WHO, 2020). Increases in the crash risk at the conditions BAC = 0.05 and 0.08 would be equivalent to the ones caused speed increase by 10% and 20% above the average road speed, respectively (Patterson et al., 2000; Kimber, 2001). The crash risk increases faster with speed increase on minor roads than on major roads (Aarts & Van Schagen, 2006) and larger speed differences between vehicles are related to a higher crash risk (McLean and Kloeden, 2002). In Vietnam, Phan (2016) found that if the average speed of motorcycle-dominant traffic flows increases from 35 km/h to 50 km/h, the relative rear-end crash risk value would increase from 1.0 to 1.6, and the relative side wipe crash risk value may increase from 1.0 to 7.0. The author further found that if the speed difference changes from zero to 10 km/h, the relative side wipe crash risk value may increase from 1.0 to 7.0.

The rider's ability to respond to an unexpected event, as measured by brake reaction time, is impaired by BAC condition. The experiment shows that the response times are significantly slower in the condition BAC = 0.05 as compared to the zero-alcohol condition and the condition BAC = 0.02. This finding supports previous researches. Creaser et al. (2009) applied a test track protocol to demonstrate impaired reaction times as a result of alcohol consumption at similar tasks. Leung and Starmer (2005) examined the effects of higher BAC levels by using simulated car driving. The time delay in brake reaction leads to a higher risk of road crash. Cheng et al. (2011) found that in rear-end near-crash cases if the delay is 0.2 s, about 18% of the near-crashes would become crashes; if the delay is 1.0 s, about 59% of the near-crashes would become crashes.

The effects of alcohol are manifested in poorer lane control. As evidenced by the experiment, at the conditions BAC = 0.02 and 0.05, the number of times a rider crosses outside the boundaries of the riding lane significantly increase. Lane changing is one of the most dangerous maneuvers in riding. While changing lanes, a vehicle maneuvers in such a way that it may involve substantial crash risks for several reasons. First, it causes the individual to straddle traffic flows and be exposed to two streams of vehicles. Second, it requires the rider to make rapid, often incorrect judgments about sufficient spacing. Third, it increases the hazard related to other vehicles approaching along with the rider's blind spot. Fourth, it disrupts the traffic pattern for the following vehicles that may, in turn, have an accident. Mao et al. (2019) indicated that weaving ratio of greater than 41% has the highest possibility of bringing about a side wipe collision. NRSPP (2017) reported that due to constant lane changing behavior as congestion builds up, the likelihood of road crash increases by 5 to 6 times in peak hours compared to off-peak hours.

While overtaking other vehicles, the novice riders tend to keep smaller distances or gaps laterally to the other vehicles as the BAC level increases from 0.02 to 0.05. Phan (2016) developed a crash risk model for motorcycle-dominated traffic environment in Vietnam and determined the relative risk value of risk factors, including average speed, speed difference, traffic density, the front distance, the lateral clearance, and pavement surface condition. Interestingly, as the lateral clearance decreases from 2.0 m to 1.0 m, the relative rear-end crash risk value would change from 2.2 to 3.1, equivalent to an increase of 41%. Clearly, this alcohol-impaired behavior increases the risk of crashing with the other vehicles being overtaken.

The task of reaction to traffic signals requires the riders to control acceleration and deceleration of the motorcycle. The results show that at the higher BAC levels, the participants perform significantly higher accelerations when the green light is turned on to quickly clear the intersection. They also make significantly higher decelerations by hard braking when the red light turns on. The hard braking can cause the front wheel locked up, and the rider may lose control of his/her motorcycle. Late braking or hard braking and rapid start or rapid acceleration are called the elevated g-force events (Toledo et al., 2008; Simons-Morton et al., 2011; and Wåhlberg, 2007). These behaviors are dangerous because it increases the potential for loss of vehicle control, reduces the time available to respond to hazards, and render a vehicle less predictable for other road users, thereby reducing safety margins.

In general, relative crash risk and BAC level have an exponential relationship (Compton et al., 2002; Compton and Berning, 2015). The relative crash risk adjusted for age and gender for drivers at the level BAC = 0.05 is approximately twice that of the zero-alcohol condition. At the level BAC = 0.08 the adjusted relative crash risk is approximately 4 times higher, at the level BAC = 0.10 and BAC = 0.15 the adjusted risk increases by 6 times and 12 times, respectively. Zador (1991) found that fatal crash risk increases with increasing BAC level for all drivers, regardless of gender and age. The crash risk may double with each 0.02 increase in the driver's BAC. Drivers at the condition BAC = 0.05–0.09, regardless of age, are 9 times more likely to have a fatal crash than drivers without alcohol. All age drivers with BAC $\geq$ 0.02 are at a significantly increased risk of single-vehicle and multiple-vehicle crash fatalities. Evidences from collected crash data indicate that the risk of crash increases with alcohol consumption, especially for underage drivers and for all drivers at the level BAC $\geq$ 0.03 (Blomberg et al., 2005; Peck et al., 2008; Voas et al., 2012; Zador, 1991).

6. Policy recommendation

Although the relationships between the BAC levels and road crash risk are examined in the car dominant environment, it may be applicable to the motorcycle dominant environment. Considering the fact that motorcycle riders are much less protected than car occupants at the occurrence of a crash, it is very important to reexamine the legal BAC limits in motorcycle dominant societies. Recently, about half of World Health Organization member countries (i.e., 88 countries) have set BAC limits equal to or below 0.05 (WHO, 2018b). It is time to consider lowering the legal BAC limit imposed on motorcycle riders to help reduce alcohol-related road crashes. In 1970, Japanese Road Traffic Law regulated that nobody under the influence of alcohol could drive any vehicle; illegality was set at 0.25 mg/L as measured by breath alcohol tests (approximately BAC = 0.05). The new law led to a remarkable drop in the number of traffic accident fatalities from 16,765 in 1970 to 10,792 in 1975. In 2002, the illegality was further decreased to 0.15 mg/L (approximately BAC = 0.03), keeping a continuous decrease in the total numbers of road accidents and drink-driving related fatalities in the country. The reductions seemed to reach its rock-bottom level post the law revision in 2007 (Nishitani, 2019). In Southeast Asia, where motorcycles are a dominant mode, drink-riding have significantly contributed to fatal road crash rates. United Nations (2018) reported that in Cambodia and Thailand the legal BAC limit is 0.05 and the percentage of drink-driving related accidents is 13% to 14%. In Vietnam, the legal limit for motorcycle riders was 0.05 and nearly 28% of the motorcycle-involved crashes was associated with alcohol impairment (Nguyen et al., 2013).

The findings of this study suggest to reduce the legal BAC limit for motorcyclists to zero. At first, this new regulation would be applied against motorcycle riders who had a riding license for less than two years and motorcycle-taxi riders. Then, the zero-tolerance regulation would be imposed on the whole population. Challenges to the zero-tolerance law are building a consensus in societies and enhancing capacity for law enforcement forces. Innovations in public awareness campaigns and road traffic education programs would certainly help improving the understanding of the public and thus contributing to building the societal consensus. Such innovations shall be designed upon scientific research and international experience to help the public understand fully about the crash risk associated with the low BAC levels. As a next step, this study would be focused on experimentally quantifying the relationship between the low BAC level and relative crash risk involving motorcycle riders.

7. Conclusion

Overall, at the level BAC = 0.02 or lower, the negative effects on the rider's ability to safely control a motorcycle are insignificant. However, as the BAC level increases, the effects become consistently significant; at the level BAC = 0.05, all the riding performance measures are impaired, and the rider performance is significantly reduced. Key findings on riding performance measures from this study can be summarized as follows. The results indicate a tendency to ride faster in straight road segments and to have more variations in running speed as the BAC level increases. Rider's responding to incidents, as measured by braking reaction time, is impaired by increased BAC level; the brake reaction is significantly slower at the level BAC = 0.05 as compared to zero-alcohol and BAC = 0.02. The lane change, as measured by the number of times the rider crosses outside the lane boundaries, becomes more frequent at the levels BAC = 0.02 and BAC = 0.05. While overtaking other vehicles, the riders tend to make a smaller lateral distance as the BAC level increases from 0.02 to 0.05. At intersections, the riders always perform significantly higher accelerations when the green light turned on, meaning that they tend to revved up for crossing the intersection. These key findings could be an essential reference for the discrimination of drunk riding state and the formulation of countermeasures. The zero-tolerance enforcement on motorcycle riders should be implemented for road safety.

The results of this study support the application of an advanced riding and/or driving simulator as an effective tool to deeply analyze rider/driver behavior and calibrate performance models for riding or driving safety. As the most relevant results of this study are based on riding simulator experiments, field experiment studies would be required to validate the key findings from the simulator-based study. In addition, as data used in the study are collected from a male dominated sample of rider participants, the observed effects of alcohol may not be applicable to female riders. Therefore, further studies are needed to focus the investigation on female rider participants. Further studies should aim to investigate the relationship between the low BAC levels and road crash risk involving motorcycle riders to help advocate drink-riding deterrence policies and programs.

CRediT authorship contribution statement

Anh Tuan Vu: Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Minh Thong Nguyen:** Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Dinh Vinh Man Nguyen:** Resources, Writing - original draft. **Viet Hung Khuat:** Writing - review & editing, Funding acquisition.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2020.06.010.

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