Effects of alcohol on speeding and road positioning among young drivers: a driving simulator study

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ABSTRACT
Young people who drink and drive have a relatively higher risk of crash involvement for all BrAC ranges. However, not all aspects of alcohol consumption on young driver behavior have been sufficiently addressed, especially the differentiated effect of alcohol on their driving performance. Young driver behavior under the influence of alcohol is explored within this research by the use of a driving simulator experiment where participants were subjected to a common pre-defined dose of alcohol consumption. Comparing behavior before and after consumption as well as across individuals and different BrAC levels allows for interesting insights on driver behavior, as well as for suggestions regarding policy interventions. Results indicate strong differences across individuals mainly because of differentiated driving experience and baseline driving skills. They also designate reaction time and speeding as the most robust alcohol impairment indicators affecting driver choices directly. Most importantly, results suggest that the BrAC-speed curve across individuals is not monotonic over all BrAC intervals.

Keywords: alcohol; impaired driving; simulator; speed; road positioning

INTRODUCTION

Alcohol consumption results in the annual death of 2.5 million people either from alcohol-related diseases or from accidents related to alcohol-impaired behavior *(1)*. Alcohol impaired driving has been repeatedly linked to high accident involvement rates and severities (*2,3,4*). In Sao Paolo for example, 39.4% of crash victims were found to test positive to previous alcohol consumption (*5*), whereas in Canada, alcohol-related accidents account for 35% of total crashes (*6*). In the US, alcohol-related accidents account for over 40% of total road accidents (*7*), while 32% of the fatally injured drivers have blood alcohol concentrations (BACs) over 0.08% (*8*). External costs of driving while intoxicated (DWI) include rescue and hospitalization expenses, property damages and loss of productivity, quality of life, and future earnings; Miller et al. (*9*) estimated the cost/km driven sober to be at $0.07, while for BAC over 0.08 g/dL at $3.40.

Alcohol absorption rates and BACs vary widely across individuals with age being an important differentiating factor (*10*). Younger individuals are characterized by greater levels of impulsivity that lead to increased risk-taking and sensation-seeking (*11*).Young people who drink and drive have a relatively higher risk of crash involvement for all BAC ranges (*12,13,14*). Because of this, lower BAC limits often apply for young and inexperienced drivers since there exists strong empirical evidence indicating higher vulnerability to legal changes than older drivers (*15*). Jenigan (*16*) reports that drivers between 20 and 29 have a three times higher crash risk involvement compared to drivers over 30, possibly a result of relative inexperience with drinking, with driving, and with combining these two (*17*).

Alcohol consumption and impaired driving have been extensively linked (*18*). Alcohol consumption causes longer reaction times and breaking distances, inaccurate steering, difficulties in perceiving roadway information and so on (*19*); combining alcohol with drugs or fatigue further intensifies these effects (*20,21*). Alcohol's changes in cognitive reaction include exacerbation of fatigue (*22*), decreased attention (*23*), changes in risk perception (*24*), and modification of cerebral activity (*25*). The magnitude of alcohol-related effects also depends on driver attributes such as weight, gender, drinking experience (*26*), and beverage type (*27*).

Despite the obvious interest in driving while intoxicated (DWI) and in the factors that affect driver behavior while under the influence of alcohol, few studies have focused on the differentiated effect of alcohol on driving performance among young people, possibly because of the difficulty in collecting the necessary data. We explore young driver behavior under the influence of alcohol by means of a driving simulator experiment that allows for the comparison of behavior before and after consumption, and for interesting insights to be made regarding alcohol impaired driving. In this paper, we extend our previous research on alcohol effects upon reaction time (*28*) by considering important measures of impairment related to speeding and road positioning.

BACKGROUND

Early experimental studies that investigate drinking and driving have been scarce because of technological limitations. Lately, technological advancements have allowed for the conduction of numerous driving simulator experiments that can shed light on the effects of alcohol on driving impairment. Table 1 includes a comprehensive list of relevant research.

TABLE 1 Overview of Driving Simulator Studies on DWI

Author	Study Objective	Subjects ID	Main Performance Measurements	Major Findings
Arnedt et al. (*29*)	Effects of alcohol vs. prolonged wakefulness on driving (Canada)	-N=18 - all males - aged 18-35 - students	1. speed maintenance 2. number of off-road occurrences 3. road position (within- lane)	-Even modest BAC levels involve driving impairment. -3h of prolonged wakefulness produces impairment as serious as 0.05% BAC. -Combination of the 2 effects explains high crash rates at nighttime.

Banks et al. (*30*)	Combined effects of light doses of alcohol and sleep deprivation (Australia)	- N=20 - 9 men - aged 18-30 - volunteers	1. braking reaction time 2. steering deviation 3. speed variability 4. crashes	-Even legal BACs combined with sleep deprivation increase sleepiness and impair driving -Both alcohol and fatigue imply a poorest ability to predict crash risk -Alcohol eliminates sex differences concerning the willingness to drive under sleep deprivation
Ellingstad and Struckman (*31*)	Sex differences and driving performance (USA)	- N=24 - 12 men	1. steering wheel 2. road positioning 3. speed	-No sex differences in DWI -BAC levels impaired all measures of performance
Fillmore et al. (*32*)	Alcohol and response conflict effect on risky driving behaviors (USA)	- N=14 - 7 men - aged 21-30 - volunteers	1. road positioning (within-lane position) 2. steering rate 3. speed and acceleration 5. brake onset distance 6. failures to stop	- Alcohol promotes impulsive actions by impairing basic inhibitory mechanisms that normally serve to suppress inappropriate behavior. -Personal factors increasing crash risk-taking interact with alcohol consumption.
Gawron and Ranney (*33*)	Efficiency of spot treatments as alcohol countermeasure (USA)	- N=12 - all male - aged 21-55	1. speed 2. lateral position 3. lateral acceleration in curves	-Spot treatment effect is relatively weak
Harrison and Fillmore (*34*)	Effect of alcohol on driver distraction (USA)	- N=40 -20 men - aged 21-35	1. variability of lateral position 2. speed 3. failures at stop signals 4. reaction time	-While sober: divided attention does not impair driving. - DWI: divided attention exacerbates the impairing alcohol effects.
Harrison and Fillmore (*18*)	Driving skills and impairment level due to alcohol consumption (USA)	- N=28 - 14 men - aged 21-31	1. road positioning (within-lane) 2. speed	-Individuals with poorer baseline skills are more impaired by alcohol -Within-lane variation increases with alcohol consumption
Horne and Baumber (*35)*	Effects of the circadian propensity for sleepiness in combination with alcohol sedating effects (GB)	- N=12 - all women - aged 20-25	1. steering angle 2. average and variance of headway	-Self-rated alcohol impact is higher in the early afternoon compared to early evening. - Alcohol significantly increases average headway and its variance, especially during the early afternoon.
Howard et al. (*36*)	Combined effect of low-dose alcohol and extended wakefulness (Australia)	- N=19 - all men - aged 18-65 -professional drivers	1. road positioning 2. reaction time 3. crashes	-The combined effect of extended wakefulness and low-dose alcohol increases accident risk, reaction times and variation in lane position and speed.
Howland et al. (*37*)	Effects of caffeinated vs. non-caffeinated	- N=121 -62 men - aged 21-30	1. reaction time 2. speed 3. speed	-Alcohol significantly impaired driving performance and sustained

	alcohol beverages (USA)	- heavy episodic drinkers	variability 4. lane position and variability 5. off-the-road	reaction time -Addition of caffeine had no influence on performance
Lenné et al. (*38*)	Effects of alcohol, time of day, driving experience on driving performance (Australia)	- N=28	1. reaction time 2. speed average and variation	-Driving performance was highest at 11:00 p.m., despite the highest levels of subjective sleepiness and low motivation at this time. -Reaction times were significantly impaired after alcohol consumption at all times of day.
Lenné et al. (*39*)	Combined effect of opioid pharmacotherapies and alcohol (Australia)	- N=10 methadone (aged 33.4, 67% male) - N=13 LAAM (aged 31.2, 48% male) - N=11 buprenorphine (aged 31.4, 73% male) - N=21 non-using (aged 34.1, 41% male)	1. lateral position 2. speed 3. steering wheel angle 4. reaction time	-Alcohol at 0.05% impairs all measurements of driving performance. -Alcohol has a more detrimental effect on speed and steer deviation in straight road sections.
Lenné et al. (*40*)	Effects of alcohol and cannabis on arterial driving (Australia)	- N=22/25 - aged 18-21/ 25-40	1. speed 2. headway 3. steering 4. reaction time 5. lateral position	-Alcohol results to increases in speed and lateral position variation. -Alcohol has no effect on reaction time -Alcohol effect is more severe for inexperienced drivers regarding speed deviation and vehicle control.
Leung and Starmer (*41*)	Effect of age and alcohol on driving performance (Australia)	- N=16 / 16 - aged 18-21/ 25-35	1. reaction time for other-vehicle detection 2. overtaking 3. time-to-collision	-Alcohol impairs driver ability to divide attention, but has little effect on decision-making. -Young drivers show a greater tendency to engage in risky driving. -Other vehicle detection time increases with alcohol consumption and maturity
Liu and Ho (*42*)	Effects of different BACs, post-alcohol impairment on driving behavior and subsidiary cognitive task performance (Taiwan)	- N=8 - 6 men	1. longitudinal speed 2.lateral acceleration 3. traffic signs distance estimation	-Higher BACs are associated with lower driving performance -Distance estimation is impaired by alcohol -No significant differences between impaired driving and post-alcohol driving, similar consequences on road safety
Marczinski et al.(*43*)	Effects of alcohol on driving and	- N=40 adults - 24 binge drinkers	1. road positioning (within-lane) 2. speed average	-DWO: difficulties to maintain speed and position, more mistakes.

	perceived impairment (USA)	- aged 21-29	and variability 3. incidents (speeding, line crossing, edge excursion and accident).	-Binge drinkers feel less sedated and having a better ability to drive. -Reduced perceived drinking impairment accounts for the greater accident risk among binge drinkers.
McMillen et al. (*44*)	Effects of both actual and expected alcohol consumption on driving (USA)	- N=96 - 64 men - aged 21+ - students	1. time elapsed at maximum speed 2. number of cars passed 3. lane changes	-High sensation seekers drive more dangerously if believing to have consumed alcohol - Low sensation seekers drive more carefully if believing to have consumed alcohol
Moskowitz et al. (*45*)	Influence of age, gender and drinking practice at various BAC levels (USA)	- N=168 - 884 men - 4 age groups - 3 drinking categories	1. reaction time 2. incorrect responses to peripheral signals 3. speed variation 4. lane position variation 5. collisions 6. time over speed limit	-Impairment found even at the lowest level tested (0.02%) -Impairment magnitude increases consistently with BAC from 0.02% to 0.10% -No significant differences between age, gender and drinking practice groups
Oei and Kerschbaumer (*46*)	Effects of peer attitude, gender, and BAC (Australia)	- N=36 - 18 men - aged 18-25	1. speed 2. off-road errors	-Impaired subjects perceived themselves as being more capable than they actually were. -Impaired subjects drove faster and made more mistakes. -Males tend to engage in more risk-taking and more dangerous behavior.
Quillian et al. (*47*)	Combined effects of age and alcohol intoxication (USA)	- N=28 - all men - 14 middle aged / 14 older	1. steering deviation 2. time at stop signs 3. left-turning time 4. speed 5. number of off-road events 6. wrong turns 7. crashes	- Middle-aged: when sober, better performance vs. older. -Older: no more sensibility to alcohol in terms of peak BACs, driving performance or awareness of the impairment vs. middle-aged. -Older men are less likely to DWI.
Rakauskas et al. (*48*)	Combined effects of distraction and the intoxication	-N=48 -all men - 21-29	1. correlation between speed and front vehicle's speed 2. headway average and variance 3. steering reversals 4. lane position variability	- Distraction exacerbates alcohol impairment - Distractive tasks are more impairing than intoxication at BACs of 0.08%.
Rimm et al. (*49*)	Effect of alcohol expectancies on driving errors (USA)	- N=44 - all men - students	1. break operation 2. steering	-Alcohol impairs abilities critical to driving. - Alcohol expectancy does not affect driving.

Ronen et al. (*50*)	Effects of THC vs. alcohol on driving performance and subjective feelings (Israel)	- N=14 - aged 26.1±1.3 - recreational marijuana and alcohol users	1. reaction time 2. collisions 3. average speed 4. lane position 5. steering variability	-The effects of 0.05% BAC are similar to low-level THC cigarettes. -Alcohol consumption causes speed and reaction time increase, sleepiness, and lack of attention.
Ronen et al. (*51*)	Combined effects of alcohol and THC on willingness to drive and driving performance (Israel)	- N=12 - 7 men - aged 24-29 - recreational marijuana and alcohol users	1. reaction time 2. collisions 3. average speed 4. lane position 5. steering variability	-Consuming THC increases alcohol impairment. -Alcohol consumption increases speed. -No effects are observed 24h after consumption.
Stein and Allen (*52*)	Combined effects of alcohol and marijuana on driving performance (USA)	- N=12 - all males - heavy drinkers and marijuana users	1. accidents 2. speed 3. steering	-Alcohol at a 0.10 BAC impairs significantly driving performance (increasing accident rate, speed, and steering variability). -Combined effects of alcohol and marijuana lead to the highest increase of accident rates. -The majority of observed impairment is linked to alcohol consumption.
Vakulin et al. (*53*)	Combined effects of moderate sleep deprivation and low-dose alcohol (Australia)	- N=22 - all men - aged 18-30 - without sleep disorder	1. steering deviation 2. braking reaction time 3. collisions	- Increased steering deviation, subjective sleepiness and subjective negative performance - Significant decrease in alertness and driving performance
Weafer et al. (*54*)	Comparison between effects of alcohol and attention deficit/ hyperactivity disorder (USA)	- N=15 adults with ADHD -N= 23 adult without ADHD	1. lane position 2. duration of steering maneuvers 3. speed variance	- ADHD produces similar impairments to alcohol. -Alcohol could impair the ADHD drivers in an additive way.
Wester et al. (*55*)	Effects of alcohol on attention orienting and dual-task performance (Netherlands)	- N=32 participants -16 men - aged 21-50.	1. reaction times 2. steering errors	-Alcohol increases distractibility and reduces attention capacity and dual-task performance.
Williamson et al. (*56*)	Effects of fatigue vs. alcohol effects (Australia)	- N=20 / 19 - all male - truck drivers/ non-professional drivers	1. reaction time 2. unstable tracking 3. visual search 4. sequential spatial memory	-Professional drivers have more accurate but slower traction times. -Alcohol produces impairment in all measurements. -Fatigue does not impair all measurements.

Frequently used driving performance indicators include within-lane position (for example *18,29,32*); off-road events (for example *29,37,46*); headways (for example *40,48*); average travelling speed (for example *39,46,47*); speed deviation (for example *38,43,54*); road incidents (for example *52,53*); steering wheel angle (for example *39,51,52*); and reaction time (for example *34,39,50*). These measures are commonly averaged for each individual and over a driving session of several minutes. They are automatically registered and are readily available by most driving simulators.

In general, there is strong empirical evidence indicating that higher alcohol consumption increasingly impairs driving performance (*31,39,42,45,49*). Some performance measurements are impaired even at modest or legal BAC levels, particularly when combined with other factors such as fatigue (for example *29,30*). Higher BACs are associated with slower reaction times (*38*), speeding and speed variation (*39,40*), increased lateral position variation (*40*) and steering variability (*52*).

Some researchers compared the effects of alcohol consumption with other driving impairment factors (*29*), while others investigated the combined effects of alcohol with other impairment driver-related factors such as fatigue (*56*), sleep deprivation or extended wakefulness (*29,30,36,53*), distraction (*34,48,54,55*), and drug consumption (*39,40,50,51,52*). Most empirical results indicate that these factors exacerbate alcohol driving impairment.

Driver attributes have also been considered in an effort to explain the differentiated effects of alcohol driving impairment across individuals. Factors considered include baseline driving skills and experience (*18,38*); gender (*31,45,46*); time of the day (*35,38*); beverage type (*37*); driver age (*41,45,47*); perceived impairment (*43*); drinking habits (*45*). Young drivers show a higher tendency to engage in risky driving (*41*), while males tend to engage in more risk-taking and more dangerous behavior (*46*). There are, however, some authors who reported no significant differences between age, gender, and drinking habits (*45*).

In summary, despite the possible advantages of a controlled environment for such investigations, contributing driver-related factors have not been thoroughly examined. Further, despite the work done using simulators and the various aspects of drinking and driving investigated, few – if any - studies considered the differential effects of BrAC levels and other driver-related factors upon driving performance such as previous accident involvement.

EXPERIMENTAL DESIGN

Participants

Participants were voluntarily subjected to a common pre-defined dose of alcohol consumption, underwent two driving sessions, and completed a questionnaire. All subjects (N=49, F(male)=53.1%)) were non-abstaining drinkers holding a valid driving license, followed no medical treatment and were between the ages of 20 and 30 (mean age=23.2, SD=2.7). Other authors have also concentrated on the same age group for studying young driver alcohol impairment (*18*, as an example). The racial makeup of the sample was 100% Caucasian and consisted of 32.7% self-reported heavy drinkers (alcohol consumption higher than 3 times a week), 47.0 % light drinkers (consumption lower that twice a week), and 8.2% occasional-drinkers (consumption less than twice a month). Females were not screened for menstrual cycle (*57*). We note that all drivers provided informed consent prior to participating and did not leave the laboratory before their Breath Alcohol Concentration (BrAC) level was zero. Participants were also requested to abstain from consuming drugs or alcohol for a minimum of 18h prior to the experiment. Any subject who tested positive for the presence of alcohol prior to the experiment was excluded from the study. All sessions took place during late evening hours to approximate actual drinking and driving conditions.

Laboratory Settings

The experiment was held at the Department of Transportation Planning and Engineering of the National Technical University of Athens, Greece. We used a driving simulator (Foerst F12PT-3L40), along with a certified breath alcohol test device (Lion SD-400). The simulator includes a full car cabin with visual images projected onto three monitors resulting in a field view of 135^0. The driving cabin is equipped with usual functional car commands and features such as indicators, pedals, steering wheel, gearbox, dashboard, handbrake, car seat, and seatbelt.

Experimental procedure

The experiment was designed following a 4-stage procedure.

1. Subjects were briefed on the experimental procedure and requirements. They were introduced to the testing equipment (alcoholmeter and simulator), and had 3 minutes of free driving to get familiarized with the simulator. They were also instructed to complete a questionnaire regarding their physical state (e.g. fatigue, hours of nighttime sleep), personal attributes (age, weight, gender, and so on), travel habits (e.g. annual mileage), crash involvement history (e.g. number of accidents, whether at fault, severity outcome), drinking habits (e.g. frequency, quantity), and driving behavior (average travelling speed on highways, drink-driving, and so on).

2. Subjects underwent a 4-minute session of free driving under normal weather conditions, in the presence of on-coming traffic, and in a small-sized city environment. Predefined events (such as, for example, sudden opening of the door of a parked vehicle, animal entering suddenly the road, and so on) - triggered randomly by the operator - allowed for reaction times estimation. This driving test served as a baseline measure to assess driving skills and performance while sober.

3. Subjects ingested 100 ml of liquor (approximately 40ml of ethanol) within a short period (about 10 minutes; liquor included vodka, whisky or gin, diluted (e.g. with fruit juice) or straight, according to personal preferences). However, all such differentiations were recorded and statistically examined for possible influences on BrAC and driving performance. All participants were administered equal ethanol quantity regardless of their physical characteristics (weight), so as to obtain a range of BrACs. After a 20 min post-ingestion interval, subjects provided breath samples every 20 minutes and over a 1.3 hour period (4 times overall), to observe BrAC variation overtime.

4. Subjects repeated the – stage 2 - driving session one hour after liquor administration and while still intoxicated. Triggering events were again used to estimate reaction times. We note that simulator driving only approximates actual road and driving conditions and is unable to capture the complexity of real-life procedures such as decision-making, hazard perception, and so on. However, it can be reasonably assumed that relative performance (sober vs. intoxicated for example) on the simulator can reflect alcohol impairment.

Performance measures

Table 2 summarizes all driving performance indicators. Driving performance (before and after intoxication) was assessed using the following six indicators:

i) average travelling speed and speed variation after intoxication

Speed is commonly used as a driving performance indicator in simulator studies (*32,38,43*). Intoxicated drivers usually drive faster and show lower speed variability because of decreased risk perception and lower response to external stimuli. At lower speeds, speed S.D. may also indicate worse driving performance compared to smooth driving. Thus, speed variation is not a stand-alone indicator; average speed should also be considered.

ii) within-lane position and variation in within-lane position

The distance to the road axis is measured by simulators on a continuous basis and averaged over each driving session. Given the lane width, it is possible to measure the distance to the middle of the lane. Typically, DWI is linked to longer average distances to the middle of the lane and to larger position variability. We note that many studies involving simulated driving have used road positioning as an indicator of driving performance (*18,36,54*).

iii) safe distance keeping while intoxicated and while sober

Time or distance headway to the front vehicle is critical to road safety and has been used as a performance measure in previous simulator experiments (*35,40,48*). Alcohol consumption has been found to increase average headway and its variability may be due to driver risk counter-balance (*35*). We believe that headways should not be considered alone as their effect on safety is strongly related to speed. Consequently, in our analysis, we compared (distance) headway to safe distance and obtained the percentage of driving time when distance headway is longer than the safe distance.

TABLE 2 Driving Performance Indicators

Indicator	Type	Summary Statistics[1]	Description
Speed_a	Continuous	M=8.53 S.D.=1.79 Min=4.91 Max =12.74	Longitudinal average speed per individual while intoxicated ($m*s^{-1}$)
Speed_SD_a	Continuous	M= 5.57 S.D=1.15 Min=3.39 Max=7.56	*Speed_a* S.D. per individual
Track_a	Continuous	M=1.18 S.D.=0.26 Min=0.71 Max=2.31	Average distance to the middle of the lane per individual while intoxicated (in m)
Track_SD_a	Continuous	M= 0.77 S.D=0.37 Min=0.31 Max=2.91	*Track_a* S.D. per individual
HWTA	Continuous	M=0.949 S.D.=0.020 Min=0.87 Max=0.97	% of driving time when safety distance is kept (after intoxication)
DHRW	Continuous	M=-7.12 S.D=2.12 Min=-11.8 Max=-3.26	relative difference in time % of safety distance keeping after-before intoxication

[1]SD =standard deviation, M=mean, Min=minimum, Max=maximum, F=frequency

DATA AND METHODOLOGY

The Data

The driving performance measures of Table 2 were used as dependent variables in our analyses. Additional driving performance measures along with questionnaire data and breath test results served as independent variables. Table 3 provides a description of all independent variables considered along with summary statistics.

TABLE 3 Explanatory Variables

Variable	Type	Summary Statistics[1]	Description
Self-reported experimental-specific driver data			
sleep_hours	continuous	M=7.7, SD=2.1	hours of nighttime sleep
wake_hours	continuous	M=7.8, SD=2.6	hours since morning wake-up
meal	continuous	M=6.5, SD=6.6	hours since last meal
fatigue	dummy	F(1)=53.1%	=1 if tired; =0 otherwise
Driver attributes from questionnaire			
weight	continuous	M=71.1, SD=14.9	weight in kg
age	continuous	M=23.2, SD=2.6	age in years
gender	dummy	F(0)=46.9%	=0 if female; =1 otherwise
exercise	ordinal	F(1)=40.8%, F(2)=26.5%, F(3)=16.3%	=1 if physical exercise<1h/week; =2 if 1-2h/week; =3 if 3-5h/week; =4 if >5h/week
test	dummy	F(1)=46.9%	=1 if previous breath test experience; =0 otherwise
alc_con	ordinal	F(1)=6.1% F(2)=79.6%	=1 if <1 drink/week; =2 if 1-2 drinks/week; =3 if >2drinks/week
alc_con_2	ordinal	F(1)=10.2% F(2)=6.1%	=1 if drinking<once/month; =2 if once/month; =3 if>once/month
nights	ordinal	F(1)=6.1%, F(2)=38.8%, F(3)=40.8%	=1 if <one night out/week; =2 if 1-2/week; =3 if 3-5/week; =4 if >5/week
Self-reported Driving Behavior			

driv_ex	continuous	M=4.4, SD=3.1	years since driving license
violation	continuous	M=0.48, S.D.=0.85	Number of traffic violations/infractions
acc_inv	dummy	F(1)=53.1%	=1 if previous accident involvement; =0 otherwise
attitude	dummy	F(1)=42.9%	=1 if never trust other drivers after alcohol consumption; =0 otherwise
self_conf	dummy	F(0)=20.4%	=0 if low and average; =1 otherwise
neverDD	dummy	F(1)=28.5%	=1 if never drink and drive; =0 otherwise
someDD	dummy	F(1)=61.2%	=1 if sometimes drink and drive; =0 otherwise
speed_hi	continuous	M=105.4, SD=24.8	average travel speed on highways (km/h)
Breath test results			
BrAC1	continuous	M=0.3, SD=0.1	first breath test (mg/lt)
BrAC2	continuous	M=0.3, SD=0.1	second breath test (mg/lt)
BrAC3	continuous	M=0.2, SD=0.1	third breath test (mg/lt)
BrAC4	continuous	M=0.2, SD=0.1	fourth breath test (mg/lt)
BrAC3/1	continuous	M=1.2, SD=0.6	ratio of third to first breath test results
Simulator Measurements			
RT_a	continuous	M=1.2, SD=0.3	Average reaction time when intoxicated (sec)
Track_s	continuous	M=1.2, SD=0.2	Average distance from the middle of the lane (m) before alcohol consumption
Track_SD_s	continuous	M=0.6, SD=0.2	*Track_s* S.D. per individual
AANGTA	continuous	M=0.1, SD=0.0	Average steering angle (rad) after intoxication
STSDAT	continuous	M= 0.121 S.D=0.046	*AANGTA* S.D. per individual

[1]SD =standard deviation, M=mean, Min=minimum, Max=maximum, F=frequency

The Methodology

Multiple linear regression is commonly used to model the relationship between a continuous dependent variable and several regressors that are thought to covary. All six driving performance measures are continuous nonnegative variables and can be reasonably assumed to covary with experimental data (such as BrACs, subject age and physical condition, and so on). Following Washington et al. (*58*), performance indicators can be modeled as follows:

$$Y_i = \beta_0 + \beta_j X_{ij} + \varepsilon_i \qquad (1)$$

where Y_i is the indicator for subject i=1,2,…,49, β_0 is the constant term, β_j stands for the coefficients to be estimated for the j=1,2,…,ρ independent variables considered, and ε_i is the disturbance term for individual i.

EMPRIRICAL RESULTS

Model estimation results are shown in Tables 4 to 6; some variables were excluded from the final models because of low statistical significance. All estimated parameters included in the final models are statistically significant at the 95% level. Elasticities are estimated for all continuous variables to assess independent variable sensitivity with respect to changes in the regressors. We assume that alcohol's driver impairment is directly reflected on reaction time adjustment (*28*); in essence, drivers choose travel speed based on reaction times, BrAC, and other personal data (risk-taking behavior, fatigue, and so on). Headway and track are indirectly 'chosen' by drivers with regards to all previous variables as, for example, speed, reaction time, BrAC, and personal data. We also assume that alcohol does not have a direct proportional effect on driving impairment; individuals react differently to alcohol in terms of resulting BrAC levels and personal attributes and driving behavior.

TABLE 4 Model Estimation Results for Speed Indicators

	Model 1 *Speed_a*			Model 2 *Speed_SD_a*		
variables	coefficient	t-statistics	elasticity	coefficient	t-statistics	elasticity
constant	5.187	4.63		4.332	5.66	
meal				0.067	2.23	0.18
exercise				0.355	3.80	
violations				-0.311	-1.95	
acc_inv				-0.595	2.12	
fatigue	-0.396	2.06				
someDD	-0.659	1.73		0.444	-1.73	
nights	-0.398	-2.07		-0.421	-4.22	
self_conf	-1.321	-2.82				
attitude	-0.503	1.36				
speed_s	0.623	6.59	0.57	0.108	1.70	0.14
BrAC3	-4.908	-2.52	0.14	-3.244	-2.48	0.13
RT_a				1.459	3.05	0.27
Model Performance						
Number of observations			49			49
Number of estimated parameters			8			10
R^2			0.61			0.51

TABLE 5 Model Estimation Results for Track

	Model 3 *Track_a*			Model 4 *Track_sd_a*		
Variables	coefficient	t-statistics	elasticity	coefficient	t-statistics	elasticity
Constant	1.329	4.32		1.25	5.53	
wake_hours	0.020	1.58	0.22			
Exercise	-0.020	-1.56	0.31	-0.18	-1.67	0.43
alc_con2	-0.120	-2.26		-0.271	-3.71	
neverDD	0.127	-1.55		0.197	-1.85	
Meal				0.018	1.65	0.34
Violations				-0.134	-2.37	
BrAC3	-0.947	-2.52	0.19	-1.023	-2.10	0.35
track_s	0.309	2.08	0.33			
track_sd_s				0.496	2.45	0.75
speed_a	-0.035	-1.61	0.25	-0.039	-1.55	0.43
RT_a	0.213	1.63	0.19	0.309	1.87	0.43
Model Performance						
Number of observations			49			49
Number of estimated parameters			9			10
R^2			0.39			0.50

TABLE 6 Model Estimation Results for Safe Distance Keeping

	Model 5 *HWTA*			Model 6 *DHWR*		
Variables	coefficient	t-statistics	elasticity	coefficient	t-statistics	elasticity
Constant	1.013	5.01		0.772	5.70	
driv_ex	0.001	1.63	0.02	0.001	1.79	6.36
acc_inv	0.014	-2.86				
Exercise	-0.007	-3.89		-0.004	-2.10	
Nights	0.006	3.37		0.003	1.50	
Attitude	0.007	-1.43				
RT_a	-0.043	-4.81	0.05			

speed_a	-0.003	-2.25	0.03	
BrAC3/1	0.012	1.86	0.01	
Model Performance				
Number of observations			49	49
Number of estimated parameters			9	6
R^2			0.52	0.50

Self-reported experimental-specific driver data

Among self-reported experimental-specific and driver-related variables, the time elapsed since last meal (*meal*), the time since morning wake-up (*wake_hours*), and *fatigue* were found to significantly affect performance indicators. In particular, empirical results indicate that self-reported tired drivers travel at lower speeds compared to self-reported non-tired drivers while intoxicated. Drivers feeling tired seem to counter-balance the risk of fatigue by adjusting their speed accordingly. This is also the case for sober driving (*59*). On the contrary, actual fatigue (as approximated by time since morning wake-up and time lag since last meal) appears related to increased driving impairment (greater distances to the middle of the driving lane, higher speed and track variation). The latter is also the case for sober driving (*60*).

Driver attributes from questionnaire

Regular physical exercise (*exercise*) is related to shorter distances to the middle of the lane, less track variability, and mitigated alcohol effects on road positioning; all such effects come to verify the rather intuitive finding suggesting that 'fit' individuals respond better to alcohol intoxication (better absorption and reaction) compared to individuals that do not exercise regularly (61). Nevertheless, results also indicate that regular physical exercise is related to worse safe distance keeping and higher speed variation; the latter can be directly interpreted by previous findings suggesting that fit people have significantly shorter reaction times when intoxicated *(28)*.

Additionally, the frequency of going out at night (*nights*) was found to positively affect safe distance keeping, to aggravate alcohol effects on headways, and to decrease travel speeds and speed variability. Regular alcohol consumption (*alc_con2*) is shown to be linked with better lane positioning. Other driver attributes such as age, weight, and gender, were not found to statistically affect impaired driving performance. Similar were the findings of Moskowitz et al. (*45*). We believe that measured BrAC 'absorbs' all relative variance and indirectly – at least - captures such driver attributes.

Self-reported Driving Behavior

Model results suggest that generic driving experience (*driv_ex*) helps impaired drivers in better keeping safe distances. Also, drivers that report having 'excellent' driving skills (*self_conf*) travel at lower speeds. Regarding DWI experience, individuals that sometimes drink and drive (*someDD*) travel at lower speeds and show higher speed variability. On the other hand, individuals that never drink and drive (*neverDD*) show worse road positioning. All these findings imply that baseline driving skills, driving experience while sober, and driving 'experience' while intoxicated may help drivers in better dealing with DWI. Drivers that never trust other intoxicated drivers (*attitude*) better respect safety distances and travel at lower speeds. These drivers are the so-called in 'low-sensation seekers' that have more 'conservative' driving patterns *(44)*.

Previous accident involvement (*acc_inv*) significantly affects speed variation and safe distance keeping. In particular, drivers that had been involved in accidents show better driving performance. Interestingly, more past infractions (*violations*) has a decreasing effect on both speed and track variability; it may be the case that accident involvement and effective enforcement make drivers more cautious.

Breath test results

As anticipated, alcohol-related variables were statistically significant in most modeling efforts. In particular, increased values for BrAC immediately before the DWI session (*BrAC3*) appear related to lower speeds and speed variations, better lateral positioning, and less within-lane variation. This interesting finding suggests that drivers with more intense alcohol effects (higher BrACs) counter-balance the risk by adjusting their speed. Slow alcohol absorption (low *BrAC3/1* values) is found to have a negative impact on safe distance keeping; individuals with BrAC close to its maximum value, fail to estimate distances and actual travel speeds.

Simulator Measurements

Model results indicate that speeding before alcohol consumption (*speed_s*) is strongly related to speeding after alcohol consumption (*speed_a*). Also, better lateral vehicle position while sober (*track_s*) is related to better lateral position while intoxicated (*track_a*); higher lateral position variability while sober (*track_sd_s*) is related to higher variability during DWI (*track_sd_a*). These rather intuitive findings come to verify the important effect of baseline driving behavior upon DWI for all performance measurements (*18*). Noticeably, the corresponding elasticities are higher than BrAC-elasticity indicating that the sheer alcohol influence may be less important than baseline driving patterns.

Speeding during the DWI session (*speed_a*) appears associated with lower safe distance keeping but improved lane positioning. Brookhuis et al. (*62*) reached similar conclusions when studying MDMA effects on simulated driving.

Slower reaction times during DWI are a strong impairment indicator as they result in higher speed variability, poor safety distance keeping and lateral positioning. Drivers that generally have better reaction times maintain their speed and react smoothly to external stimuli.

CONCLUSIONS

We explored alcohol impairment through a driving simulator experiment and focused on younger drivers as there is empirical evidence indicating a significantly stronger effect of alcohol on young driver behavior as well as a higher rate of accident involvement due to relative inexperience. In contrast to most studies where behavior has been studied under an equal-BrAC-level hypothesis, we instead administrated the same alcohol quantity to all subjects leading to a wide range of BrAC levels. This approximates actual drinking habits of social drinkers who consume alcohol based on socially prevalent drinking patterns and not their body weight. Driving performance was measured in terms of speed, speed variation, lateral vehicle position, and lateral vehicle position variation as the relationship between these measurements and driving impairment has been well documented in the literature. In addition, we extend previously used driving performance indicators by introducing HWTA, that is the percentage of simulated driving time when the distance headway to the front vehicle is above safe distance.

We made the hypothesis that personal data (drinking and driving habits, driver attributes) and BrAC level explain post-consumption driving performance. We didn't limit our research to the relationship between pre- and post-consumption driving performance indicators because we assume a non-linear relationship between personal data, resulting BrAC and impaired driving performance. Following our previous research findings (*28*), we also assumed that alcohol impairment is directly (i.e. unconsciously) reflected upon driver reaction time. Drivers then choose (consciously) travelling speed based on reaction times, BrAC, and other personal data (risk-taking behavior, fatigue, and so on). Headway and lateral position are indirectly 'chosen' by drivers with regards to all previous variables i.e. speed, reaction time, BrAC, and personal data.

We statistically explored the relationship between driving performance indicators based on the aforementioned assumptions; empirical results came to verify our initial hypotheses. In particular, drinking, driving, driving after drinking experience, as well as baseline driving behavioral patterns are all crucial to post-alcohol consumption driving performance. Their effect appears to be even stronger than sheer alcohol influence as reflected in resulting BrAC levels (at least for this experiment). Also, driver reaction time while intoxicated appears to be a robust impairment indicator followed by speeding. Indeed, we found an increase in average speed when comparing pre- and post-alcohol consumption per individual, the latter being well-documented in the literature (*40,51,52*). However, for the same alcohol quantity consumed (resulting in differentiated BrACs), individuals with higher BrACs travel at lower speeds and closer to the middle of the lane. We can, thus, rationally infer that BrAC-speed curve is not monotonic over the BrAC intervals considered. For the lowest BrACs considered (~0.1 mg/lt), drivers do not seem to realize alcohol's effects on their driving behavior and make no adjustments. For higher BrAC values (~0.3mg/lt), drivers start to realize the impairment and counter-balance risks by reducing their speed. We note however that all BrAC levels considered are rather low; it is possible that for higher levels drivers adopt more risk-taking behaviors or fail in counter-balancing the risk and speed-BrAC curve changes accordingly. Further research should focus on this important issue.

Overall, our findings suggest that there exist significant differentiations among individuals and BrAC levels regarding driving performance while intoxicated. These differentiations need to be investigated further, while individual drinking, driving, and driving after drinking behavioral patterns significantly affect actual performance. Reaction time and speeding appear as the most robust alcohol impairment indicators as they affect directly driver choices. As a caveat, we note that our research suffers from some limitations that need to be considered in interpreting the results including limited sample size, low BrAC levels, and the inherent shortcomings of driving simulators.

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