YOUNG DRIVERS AND ALCOHOL IMPAIRED DRIVING: A DRIVING SIMULATOR EXPERIMENT

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ABSTRACT

Young individuals who drive under the influence of alcohol have a higher relative risk of crash involvement; as such, the literature has extensively investigated the factors affecting such involvement through post-accident surveys. The effects of alcohol consumption on young driver behavior, however, have been largely unaddressed, mainly as a result of the difficulty in collecting the necessary data. We explore young driver behavior under the influence of alcohol using a driving simulator experiment where 40 participants were subjected to a common pre-defined dose of alcohol consumption. Comparing driver behavior before and after consumption allows for interesting insights and suggestions regarding policy interventions. As expected, the results indicate that increased reaction times before consuming alcohol strongly affect post-consumption reaction times, while increased BAC levels increase reaction times; a 10% increase in BAC levels results in a 2% increase in reaction time. Interestingly, individuals with faster alcohol consumption times perform better regardless of absolute BAC level, while recent meals lead to higher reaction times and exercising to lower

Keywords: alcohol, impaired driving, reaction times, simulator, random-parameter regression

INTRODUCTION

Alcohol impaired driving has been repeatedly linked to high accident involvement rates and severities (Mann et al. 2010; NHTSA, 2005; Williams, 2006). In the US, for example, alcohol-related accidents account for over 40% of total road accidents, while 32% of the fatally injured drivers have blood alcohol concentrations (BACs)over 0.08%. (NHTSA, 2004).External costs of DWI include rescue and hospitalization expenses, property damages and loss of productivity, quality of life, and future earnings; Miller et al. (1999) estimated the cost/km driven sober to be $0.07, while at Blood Alcohol Concentration (BAC)over 0.08 g/dL at $3.40.Young people who drink and drive have a relatively higher risk of crash involvement compared for all BAC ranges (Mayhew et al., 1986; Peck et al., 2008; Zador, 2000), and as a result lower BAC limits often apply. Jenigan (2001) reports that drivers between 20 and 29 have a three times higher crash risk involvement compared to drivers over 30, a possible result or relative inexperience with drinking, with driving, and with combining these two (Williams, 2003).

Alcohol consumption and impaired driving have been extensively linked (Harrison and Fillmore, 2005). Alcohol consumption causes longer reaction times and breaking distances, inaccurate steering, difficulties in perceiving roadway information and so on (Kuypers et al., 2006); combining alcohol with drugs or fatigue further intensifies these effects (Banks et al., 2004; Ramaekers et al., 2000).Alcohol's changes in cognitive reaction include exacerbation of fatigue (NHTSA, 1998), decreased attention (Exum, 2006), changes in risk perception (Frick et al., 2000), and modification of cerebral activity (Aires Dominges et al., 2009). The magnitude of alcohol-related effects also depends on driver attributes such as weight, gender, drinking experience (Hiltunen 1997), and beverage type (Richman and Warren, 1985).

Despite the obvious interest in DWI and in the factors that affect driver behavior under the influence of alcohol, very 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.

BACKGROUND

Various road surveys, cross-sectional and case-control studies have shed light on the factors that influence alcohol-related fatalities (Annex I includes a complete list of research on driving under the influence of alcohol). Significant predictors include road and driving conditions such as road type, lighting, and number of passengers; de Carvalho Ponce et al. (2011) found that most alcohol-related accidents in Brasiloccur at nighttime and on weekends. In New Zealand, higher traffic volume and illuminated roads appear to be significantly safer (Keall et al., 2005), while the risk of fatal crashes at nighttime increases with the number of passengers for all BAC levels (Keall et al., 2004). Novice drivers are more affected by alcohol consumption (Peck et al., 2008), particularly during nighttime (Keall et al., 2004), while general risk-taking driver behavior aggravates alcohol impairment (Horwood and Ferguson, 2000). Authors focusing on the general tendency to drink and drive argue that in the US, members of fraternities, heavy drinkers, and people with a history of alcohol abuse are more likely to drink and drive (LaBrie et al. 2011).

Studies using driving simulators to investigate drinking and driving have been scarce, particularly considering the possible advantages of a controlled environment for such investigations. Early simulator experiments in the US explored the effects of alcohol consumption on driving behavior among University students. Alcohol was found to impair abilities that are critical to driving such as braking and steering (Rimm et al., 1982), while "*high sensation seekers*" were more likely to drive dangerously compared to "*low sensation seekers*" while intoxicated (McMillen et al., 1989). The authors argued that "*high sensation seekers*" interpret alcohol consumption as a justification for risk-taking. Gawron and Ranney (1990) extended the age group to 55 to study the efficiency of spot treatments as potential alcohol countermeasures; however, their results did not support this hypothesis.

In 2001, Arnedt et al. studied the effects of prolonged sleeplessness versus alcohol impairment among eighteen Canadian males 19 and 35.Driving performance was measured in terms of speed deviation, lane position, and off-road occurrences. The experiment showed that impairment is evident even for low BACs. The authors suggest that extending sleeplessness by 3hours can result to a reduced ability to maintain speed and road position equal to those found at the legal BAC limits

Lenné et al. (2003) designed a simulator experiment to study the effects of the opioid pharmacotherapies methadone, LAAM and buprenorphine, by themselves, as well as combined with alcohol (around the 0.05% BAL). Participants were 10methadone, 13 LAAM, 11 buprenorphine stabilized clients, and 21 non-drug Australians. Simulated driving skills were measured through standard deviations of lateral position, speed and steering wheel angle, and reaction time. The authors argue that BAC at 0.05% impairs all measurements of driving performance. Surprisingly, alcohol was found to have a more detrimental effect on speed and steer deviation on straight road sections.

In another study, Leung and Starmer (2005) examined gap acceptance and risk-taking by young and mature drivers using a simulator. 16 young and 16 mature drivers in Sydney were recruited for the experiment; they consumed 0.6 g (if female) or 0.7 g (if male) of alcohol per kg of weight. Driving tasks included other-vehicle detection, overtaking, and time-to-collision estimation. Detection times were significantly lower with age, alcohol consumption and lower approaching vehicle speeds particularly on curved road sections. Young drivers showed a greater tendency to engage in risky driving. In similar line of reasoning, Harrison and Fillmore (2005) tested the driving performance of 28 adults (21-31) in the US, under either an active dose of alcohol (0.65 g/kg) or a placebo. The objective was to examine whether 'bad' drivers are more likely to be impaired by alcohol. In parallel, a personal drinking habits questionnaire was completed, and a subjective intoxication degree was estimated. Significant within-lane deviation confirmed alcohol impairment; however, individuals with poorer baseline skills appeared to be more impaired by alcohol.

Ronen et al. (2008) assessed the effects of marijuana compared to alcohol ingestion on driving performance, physiological strain, and subjective feelings. They recruited 14 students (25-27) in Israel, that were recreational marijuana and alcohol users. Active and placebo dosages were administrated to identify differences in reaction time, number of collisions, average speed, lane position and steering variability. Alcohol consumption caused speed and reaction time increase, sleepiness, and lack of attention. Following the same protocol and using similar equipment, Ronen et al. (2010) further investigated the effects of alcohol (BAC=0.05%), marijuana, and their combined consumption. Alcohol consumption was found to increase speed, while the combination of alcohol and THC appeared to have the most intense effect following intake. Lenné et al. (2010) designed a simulator experiment to study the combined effects of cannabis and alcohol (vs. only cannabis) on driving impairment. To this end, they recruited both novice and experienced Australian drivers having a history of alcohol and cannabis consumption. Speed, headway, steering, reaction time, and lateral position data were used as driving performance indicators. Results showed that alcohol consumption is associated with speed increases and lateral position variability, but it does not affect reaction time nor does it produce synergistic effects when combined with cannabis. The authors attribute the latter to the relatively low alcohol dosage (ethanol of app. 0.5g/kg).

Despite the work done using simulators and the various aspects of driving after drinking investigated, few – if any - studies have considered the differential effects of BAC levels and other important factors upon driver reaction times.

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 (Harrison and Fillmore, 2005, 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).We note that all drivers provided informed consent prior to participating and did not leave the laboratory before their BAC 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, while visual images are 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. 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 BAC and driving performance. All participants were administered equal ethanol quantity regardless of their physical characteristics (weight), so as to obtain a range of BACs. 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 BAC 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

Driving performance (before and after intoxication) was assessed by driver reaction times to triggering events. Average time lag (in milliseconds) between triggering event occurrences and driver reaction (braking or steering) served as driving performance indicator. We note that reaction time (RT) is critical to road safety and has been used as a performance measure in previous simulator experiments (Lenné et al, 2003; Leung and Starner, 2005; Ronen, 2008).

DATA AND METHODOLOGY

The Data

Reaction time (M=1.1 sec, SD=0.3) while intoxicated was used as the dependent variable in our analysis. Questionnaire data and breath test results served as independent variables. Table 2 provides a description of all independent variables considered along with summary statistics. We created a dummy variable '*Alc1/3*'to capture the absolute difference between the third (right before the driving while intoxicated session) and the first (immediately following alcohol ingestion) breath test results. Interestingly, the positive sign for 41% of the cases indicates that BAC may continue to rise for as long as 1h following ingestion; the average value of 1.2 and S.D. of 0.6 indicate strong heterogeneity across individuals regarding BAC time variation.

Table 1.Explanatory variables in reaction time analysis

Variable	Type	Summary Statistics[1]	Description
experiment data			
Sleeping time (*sleep*)	continuous	M=7.7, SD=2.1	hours of nighttime sleep
Awake time (*awake*)	continuous	M=7.8, SD=2.6	hours since morning wake-up
Last meal (*meal*)	continuous	M=6.5, SD=6.6	hours since last meal
Fatigue (*tired*)	dummy	F(0)=53.1%	=0 if tired; =1 otherwise
personal data			
Weight (*weight*)	continuous	M=71.1, SD=14.9	weight in kg
Age (*age*)	continuous	M=23.2, SD=2.6	age in years
Height (*height*)	continuous	M=174.3, SD=9.4	height in cm
Driving experience (*exper*)	continuous	M=4.4, SD=3.1	years since driving license
Gender (*female*)	dummy	F(0)=46.9%	=0 if female; =1 otherwise
Eyesight (*problem*)	dummy	F(0)=53.1%	=0 if yes; =1 otherwise
Physical exercise (*no_ex*)	dummy	F(0)=40.8%	=0 if no regular exercise; =1 otherwise
(*12_ex*)	dummy	F(0)=26.5%	=0 if 1-2h weekly; =1 otherwise
(*4_ex*)	dummy	F(0)=16.3%	=0 if over 4h weekly; =1 otherwise
Alcohol consumption (*alc_2*)	dummy	F(0)=85.7%	=0 if 1- 2 drinks/week; =1 otherwise
Breath test experience (*test*)	dummy	F(0)=46.9%	=0 if previous experience; =1 otherwise
driving behavior			
Traffic violation *(infra)*	dummy	F(0)=26.5%	=0 if previous infraction; =1 otherwise
Accident involvement *(acc)*	dummy	F(0)=53.1%	=0 if previous acc involvement; =1 otherwise
Speeding *(speed)*	continuous	M=105.4, SD=24.8	average travel speed on highways (km/h)
Speed limit violation *(sp_viol)*	dummy	F(0)=12.2%	=0 if ‘*speed*’>130; =0 otherwise
Low self-confidence (*low_self*)	dummy	F(0)=20.4%	=0 if low and average; =1 otherwise
Drink and drive *(ndd)*	dummy	F(0)=28.5%	=0 if never; =1 otherwise
(sdd)	dummy	F(0)=61.2%	=0 if sometimes; =1 otherwise
breath test			
Breath test results (*Alc-1*)	continuous	M=0.3, SD=0.1	first breath test (mg/lt)
(*Alc-2*)	continuous	M=0.3, SD=0.1	second breath test (mg/lt)
(*Alc-3*)	continuous	M=0.2, SD=0.1	third breath test (mg/lt)
(*Alc-4*)	continuous	M=0.2, SD=0.1	fourth breath test (mg/lt)
(*Av_Al*)	continuous	M=0.2, SD=0.1	average result for all breath tests
Comparison between results			

(*Alc3-1*)	dummy	F(0)=59.2%	=0 if (‘*Alc3*’-‘*Alc1*’)<0; =1 otherwise
(*Alc1/3*)	continuous	M=1.2, SD=0.6	ratio of third to first breath test results

[1] F: frequency
M: average value
SD: Standard Deviation

Methodology

Multiple linear regression is commonly used to model the relationship between a continuous dependent variable and several regressors that are thought to covary. Subject reaction time following alcohol administration is a continuous nonnegative variable and can be reasonably assumed to covary with experimental data (such as BACs, subject age and physical condition, and so on). Following Washington et al. (2010), reaction time can be modeled as follows

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

where Y_i is reaction time 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.

The functional form of the multiple linear regression in Eq. (1) assumes that the estimated parameters are the same for all observation; however, initial regression results indicated significant heterogeneity among subjects and raised certain questions regarding the validity of such a fixed parameter assumption which, if violated, may result in inconsistent estimates. To relax the fixed-parameter restriction, a random parameter linear regression model was instead used (Washington et al. 2010)

$$Y_i = \beta_{0i} + \beta_{ij} X_{ij} + \varepsilon_i \qquad (2)$$

$\beta_{ij} = \beta_j + \varphi_i$, with φ_i a randomly distributed term. The distribution of the φ termacross individuals is to be specified along with the other model parameters (possible distributions include Normal, Uniform and Triangular). The random-parameter model randomizes the parameters to allow for the influence of the independent variables affecting reaction time to vary across individuals (for more information and a detailed discussion on random parameter models see Anastasopoulos and Mannering 2009 and 2011).

RESULTS

Two fixed- and two random-parameter models were used to model reaction times and alcohol-related variables while controlling for driver attributes. We also estimated two separate models; in the first type, the BAC level was the value obtained at the third breath test was used (right before driving while intoxicated and 1h following alcohol ingestion). In the second, variable ‘*alc1/3’* was used in order to observe differences with respect to alcohol absorption rates for the subjects (joint consideration of all alcohol-related variables was rejected because of multicollinearity concerns). The fixed-parameter specification was estimated using ordinary least squares (OLS), while maximum likelihood estimation was used to estimate the underlying population parameters for the random parameters model. We note that simulations were based on random draws with OLS parameter estimates serving as starting values. Normal, triangular and uniform distributions were considered for the functional form of the random parameter density functions.

Model estimation results are shown in Tables 2 and 3; 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% confidence level. The standard deviation for the distribution of the random parameters was significantly different from 0 for all the variables included in the random-parameter models. Elasticities are estimated for all continuous variables to assess reaction time sensitivity with respect to changes in the regressors.

In all cases, random-parameter models significantly outperform fixed-parameter models based on the likelihood ratio test. The test yields values higher than the X^2critical values, indicating a confidence that the random parameter models outperform the fixed parameter specification. We also note that, besides statistical fit, the two model specifications yield – in some cases - qualitatively and quantitatively different results for the parameter estimates. For example, variables '*alc_2'* and '*low_self*' were found to be statistically significant only in the random-parameter analysis.

Table 2. Model Estimation Results for Model Type 1

	Fixed Parameters			Random Parameters			
Variables	coefficient	t-statistics	elasticity	coefficient	t-statistics	S.D.[a]	elasticity
constant	0.41	1.94		0.93	16.21	0.04	
RT-bef	0.47	3.83	0.54	0.10	2.56	0.18	0.12
Alc-3	0.38	0.95	0.08	0.89	7.08	0.06	0.20
4_ex	0.15	1.87		0.15	7.95	0.03	
sp_viol	0.14	-1.33		0.15	-6.31	0.11	
meal	-0.01	-1.12	0.03	-0.01	-3.68	0.01	0.04
low_self	-0.01	0.09		0.21	-9.37	0.05	
alc_2	0.09	1.08		-0.10	-4.34	0.26	
Number of observations							49
Log-likelihood at zero LL(0)							-3.32
Log-likelihood at convergence LL(β)			12.1				28.81
Number of parameters			8				17
R-squared			0.47				
Likelihood-ratio test				*Random vs. fixed parameters*			
X^2=-2(LL(β_{fixed})-LL(β_{random}))					33.42		
Critical X^2 (0.9995 level of confidence and v=9 d.o.f.)					29.67		

[a]Standard deviation of parameter distribution

Table 3. Model Estimation Results for Model Type 2

Variables	Fixed Parameters			Random Parameters			
	coefficient	t-statistics	elasticity	coefficient	t-statistics	S.D.[a]	elasticity
constant	1.47	8.09		1.36	21.66	0.04	
Alc1/3	-0.14	-2.36	0.14	-0.13	-8.10	0.04	0.14
ndd	0.21	-2.76		0.11	-6.20	0.11	
4_ex	0.31	3.36		0.29	10.17	0.05	
sp_viol	0.25	-2.32		0.22	-5.57	0.16	
meal	-0.01	-1.62	0.42	0.01	1.83	0.00	0.02
low_self	0.08	-1.01		0.17	-6.59	0.02	
alc_2	0.03	0.29		0.06	1.50	0.12	
Number of observations		49					
Log-likelihood at zero LL(0)		-3.32					
Log-likelihood at convergence LL(β)			8.05				23.71
Number of parameters			8				17
R-squared			0.37				
Likelihood-ratio test					*Random vs. fixed parameters*		
X^2=-2(LL(β_{fixed})-LL(β_{random}))					31.32		
Degrees of freedom					v=17-8=9		
Critical X^2 (0.9995 level of confidence)					29.67		

[a]Standard deviation of parameter distribution

In the first model type, we focus on the relationship between reaction time while intoxicated (*RT_after*), reaction time before drinking (*RT_bef*) and BAC level (*Alc-3*). Results indicate that light drinkers (*alc_2*), having low or average – self assessed - driving skills (*low_self*), driving at speeds beyond the legal limits (*sp_viol*), and exercising for less than 4h per week (*4_ex*) significantly increase reaction time while intoxicated. Increased BAC levels are related to increased reaction times with an elasticity of -0.2. Reaction time decreased with lower times since the last meal (*meal*), but with lower elasticity than the BAC levels. Finally, increased reaction times while driving without alcohol (*RT_bef)* is strongly related to increased reaction times when driving under the influence (*RT_after*). All regressors were significant in the random parameter model with '*RT_bef', '4_ex', 'meal', 'low_self', and 'alc_2'* following the normal distribution, '*alc-3'* following the uniform distribution, and '*sp_viol'* following the triangular distribution.

In the second model type, we focus on the relationship between reaction time while intoxicated ('*RT_after'*), and the ratio of breath test results ('*Alc1/3'*). Empirical results suggest that low or average – self assessed - driving skills *('low_self'),*driving at speeds beyond legal limits ('*sp_viol'*), exercising for less than 4h per week ('*4_ex'*), and never driving after drinking ('*ndd'*) significantly increase reaction times while intoxicated. In contrast to the first model type, light drinkers and recent meals seem to result in decreased reaction times. Further, increasing BAC ratios ('*Alc1/3'*) result in lower reaction times; all regressors were found to have random parameters.

Experiment-specific driver data

Among all the variables related to experiment-specific data, reaction time before intoxication (‘*RT-bef’*) and the time elapsed since the last meal (‘*meal’*) were found to be significant; instead, hours of nighttime sleep and hours since morning wake-up do not appear to statistically influence reaction time. This finding contradicts some previous research (Arnedt et al., 2001), where prolonged sleeplessness was found to increase alcohol’s effects; we do note however that in this research we also considered additional fatigue-related variables such as ‘*meal*’ and ‘*RT-bef’*.

Empirical results from the first model type indicate that ‘*meal*’ has a random parameter with a mean of-0.006 and a SD of 0.009; this implies that for 75% of the subjects recent meal has an increasing effect on reaction time. This finding can be explained by the overall fatigue resulting from the additive effect of alcohol and a meal. Interestingly, in the second model type, ‘*meal*’ has a positive random coefficient of 0.003 and an SD of 0.004; this suggests a possibly strong heterogeneity between individuals and would have been neglected under a fixed-parameter approach; however, further investigation is needed in order to fully interpret the relationship between meal and reaction times.

Empirical results also indicate that ‘*RT-bef’* significantly influences reaction time while intoxicated. This clearly suggests that higher baseline reaction times correspond to higher reaction times after drinking. The corresponding random coefficient is normally distributed with a mean value of 0.102 and an SD of 0.181; the latter indicates that for 75% of the sample, increased values for initial reaction times are related to increased reaction times following intoxication. Similar findings were reported by Harrison and Fillmore (2005) where individuals with poorer baseline skills were found to be more affected by alcohol. For the remainder 25% of the subjects, increased baseline reaction times resulted in decreased reaction times after drinking; this rather counter-intuitive finding may be a result of low-dosage (a similar hypothesis was formulated by Lenné et al. (2010). We also note that the elasticity of ‘*RT-bef’* is lower than‘*alc-3’*,indicating that changes in BAC levels have a stronger effect on reaction times compared to baseline driving skills.

Personal data

Regarding personal data, two variables were found to significantly affect reaction times in all random-parameter models: physical exercise and drinking frequency. Both variables were not statistically significant under the fixed-parameter modeling approach. Variables related to weight, age, and sex were not found to be significant; measured BAC is believed to ‘absorb’ all relative variance and indirectly – at least - capture such driver attributes.

Exercising for over 4hrs per week (‘*4_ex’*) reduces reaction times. This is a rather intuitive finding suggesting that ‘fit’ individuals respond quicker to external stimuli even when intoxicated. The corresponding coefficient was found to follow the normal distribution with a relatively low SD compared to the mean, suggesting that this finding holds for the entire sample.

In both model types, being a light drinker (*alc_2*) was found to have a significant impact on reaction times. In the first model type, light drinkers show reduced reaction times compared to all other drinking frequencies (both occasional and heavy). This implies that drivers used to driving under the influence negotiate better with unexpected road hazards; however, the latter is restrained by an upper limit of two drinks per week. The random coefficient has a mean of -0.103 and an SD of 0.255, indicating that the distribution is positive only for 66% of the subjects. The second model type indicates that light drinkers show increased reaction times when compared to all other drinking frequencies. Again, the corresponding random coefficient is normally distributed with a mean of 0.062 and an SD of 0.120 indicating that the latter holds for 65% of the subjects.

Driving Behavior

Several variables related to self-reported driving behavior were examined regarding their influence on reaction times following intoxication. Results suggest that a – self-reported - average highway travelling speed over the maximum legal limit seems to correspond to longer reaction times. This finding suggests that driving while intoxicated is related to general risk-taking behaviors as suggested by Horwood and Ferguson (2000). In all random parameter models we find that drivers who self-assess their skills as low or average (*low_self*), have longer reaction times compared to more self-confident drivers. We finally find that drivers who report to never driving while intoxicated have significantly longer reaction times compared to drivers that drive while intoxicated on a 'regular' basis.

BAC

Breath tests enable us to consider several BAC-related variables; '*Alc-3'* and '*Alc1/3*' were found to be significant. As expected, the concentration of alcohol appears to have a strong relationship with driving performance as it directly affects cognitive abilities by exacerbating the effects of fatigue (NHTSA, 1998), decreased attention (Exum, 2006), changing risk perception (Frick et al., 2000), and modifying cerebral activity (Aires Dominges et al., 2009). The Elasticities for both variables are rather high (0.2 and 0.14 respectively), verifying the increased sensitivity of reaction time with changes in alcohol dosage and consequent BAC increases. Results suggest that increased BAC level as measured 1 hour after alcohol consumption and just before driving ('*Alc-3'*) is linked to longer reaction times. Tzambazis and Stough (2000) conducted a psychometric experiment and concluded that increasing BACs impair speed of information processing, simple reaction time, choice reaction time and higher-order cognitive abilities; similar findings can be found in other medicine-oriented experiments. Results also indicate ('*Alc1/3'*) to also be significant; increased values for the BAC ratio are related to lower reaction times. Increased values for '*Alc1/3*' imply that the initial BAC level has been significantly changed towards lower values, while the opposite is implied by lower BAC values. Figure 1 depicts probable BAC time evolution with a biphasic effect on cognitive abilities for the ascending and the descending parts (King et al., 2002; Pihl et al., 2003). Increased BAC ratios indicate narrower BAC curves and quicker BAC evolution overtime; the corresponding coefficient has a mean of -0.133 and an SD of 0.044, with this finding suggesting that individuals with narrower curves (faster alcohol absorption) show better driving performance regardless of their absolute BAC level.

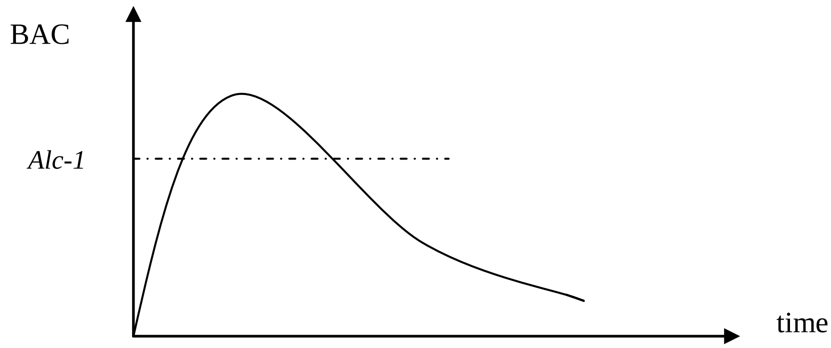

Figure 1. Qualitative BAC curve

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, and a higher rate of accident involvement due to relative inexperience. In contrast to most studies where behavior has been studied under an equal-BAC-level hypothesis, we instead administrated the same alcohol quantity to all subjects leading to a wide range of BAC levels. This better 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 reaction time to unexpected events as the relationship between longer reaction times and driving impairment has been well documented in the literature. We make the hypothesis that personal data (drinking and driving habits, driver attributes) and BAC level explain post-consumption reaction times. We didn't limit our research to the relationship between pre- and post-consumption reaction times because we assume a non-linear relationship between personal data, resulting BAC and impaired driving performance.

We explored the relationship between driver reaction times and BAC-related variables using random parameters linear regression models to account for the strong heterogeneity between individuals. Results indicate that exercising for less than 4h per week significantly increase reaction times while intoxicated, while increased reaction times during the baseline driving task are related to increased reaction times after drinking; elasticity estimates suggest that 10% faster reaction times for the baseline task lead to 5.4% faster reaction times while intoxicated. The effect of being a light drinker and having had a recent meal is largely differentiated across individuals. Most importantly, increasing BACs seems to relate strongly to slower reaction times, while quick reduction in BACs relates strongly to faster reaction times. In general we note that increased BAC levels increase reaction times; a 10% increase in BAC levels results in a 2% increase in reaction time. We finally note that individuals with faster alcohol consumption times perform better regardless of absolute BAC levels.

Overall, our findings suggest that there exist significant differentiations among individuals 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. 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, the lack of additional performance measures such as average travel speed and vehicle positioning, and the inherent shortcomings of driving simulators.

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Annex 1.Overview of alcohol impairment studies

Author	Date	Study objective	Method	Cases	Main results
Aires Dominges et al.	2009	Influence of alcohol on executive frontal functions among nighttime drivers (Brazil).	Road survey	389 drivers randomly recruited by police agents in Vitoria	- Increasing BAC decreases frontal activity. - Alcohol-induced impairment particularly important among young drivers (20-30 years)
Arnedt et al.	2001	Effects of alcohol vs. prolonged wakefulness on driving (speed maintenance and road position) in Canada	Driving simulator	18 males aged 18-35 (psychology students)	-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.
Beirness	1987	Pattern identification in BAC self-estimations (Canada).	Drinking sessions. (breath measures, BAC self-estimation)	72 volunteers aged 20-57 (38 males, 34 females)	-the pattern of BAC estimation errors is related to the decision to drive after drinking. -3 groups were identified. -'Underestimators' are most likely to drive while impaired.
Beirness et al. (Traffic Injury Research Foundation)	2005	People perception and driving behavior (Canada).	Telephone interview	1,209 randomly sampled households interviewed by Opinion search inc.	-88% of all impaired driving trips are made by 4% of the drivers. -Young drivers account for small% of the impaired driving trips.
Compton and Berning (NHTSA)	2009	Alcohol use by drivers in the US.	National roadside survey	9,413 randomly sampled nighttime drivers	-Males, motorcycle and pickup drivers are more likely to drink and drive. -The % of drivers above illegal BAC is higher at late nighttime. -Impaired drivers % has decreased over 1973-2007.
Dawson	1999	Alcohol consumption and impaired driving patterns in the US.	National longitudinal epidemiology survey	18,352 drinkers out of 42,862 randomly sampled households	-Impaired driving is higher among individuals with high-risk drinking patterns
De Carvalho Ponce et al.	2011	Relate fatal accident victims with alcohol consumption (Brazil)	Cross-sectional study	Crash reports from 907 accident victims in Sao Paulo (2005)	-39.4% of the victims were positive to alcohol. - Most accidents occur at night and weekends and involve males aged 25-54. -No age-related differentiation among women.
Dols et al.	2010	Prevalence and predictor factors for driving after alcohol and drug use (Spain).	Cross-sectional survey	Questionnaires from 11,239 students aged 14-18 in Valencia. Stratified sampling.	-45% reported drink-driving. - Alcohol dependence, being male, having poor family relationship increase the likelihood of driving after drinking.
Frick et al.	2000	Light alcohol	Double-blind	104 students aged 19-24	-Light alcohol consumption

		consumption and crash risk perception (German)	block-randomized experiment		does not influence risk perception and has a positive influence on the ability to detect traffic hazards.
Gawron and Ranney	1990	Efficiency of spot treatments as alcohol countermeasure (US).	Driving simulator	12 licensed male drivers aged 21-55	-Spot treatment effect was relatively weak.
Harrison and Fillmore	2005	Driving skills and impairment level due to alcohol consumption (US)	Driving simulator, questionnaire, subjective impairment measurement	28 volunteers (21-31 years of age)	-Individuals with poorer baseline skills are more impaired by alcohol -Within-lane variation increased with alcohol consumption
Horwood and Ferguson	2000	Relationship between drink driving behavior and accident rate (New Zealand).	Birth cohort study (interview)	907 drivers in Christchurch aged 21	-Drink-driving is related to higher crash risk and to general risk-taking driving behaviors.
Keall et al.	2005	Influence of alcohol and other risk factors on nighttime crash occurrence (New Zealand).	Case-control study (logistic regression)	23,912 crash records (1997-1998) vs. 14,000 interviews from randomly sampled households.	-Risk at night decreases with increasing age. -Higher volume roads are not preferred by drinking drivers. -Drivers under 40, weekend trips and drink driving are risk factors.
Keall et al.	2004	Influence of alcohol, age and number of passengers on nighttime crash risk (New Zealand).	Case-control study (logistic regression)	103 fatal crash date and 14,000 interviews from randomly sampled households vs. 85,163 police BAC controls (1995-2000)	-Risk is five times higher for drivers aged under 20 and three times higher for drivers aged 20-29 for all BAC levels. -Risk increases with the number of passengers -Fatal injury risk increases exponentially with BAC.
LaBrie et al.	2011	Predictors of driving after drinking among college students (US).	Survey (interviews)	3,753 from a randomly degenerated list of students from 2 West Coast Universities	-Significant predictors include: being male or member of fraternities, having alcohol abuse history, being heavy drinker, showing higher approval of drink-driving, having alcohol expectancies for sexual enhancement.
Lenné et al.	2010	Effects of alcohol and cannabis on arterial driving (Australia)	Driving simulator (main effects models)	22 novice drivers (aged 18-21) and 25 experienced drivers aged (25-40)	-Alcohol results to increases in speed and lateral position variation. -Alcohol had no effect on reaction time -Alcohol effect was more severe for inexperienced drivers regarding speed deviation and vehicle control.
Lenné et al.	2003	Combined effect of opioid pharmacotherapies and alcohol	Driving simulator (main effects model)	10 methadone, 13 LAAM, 11 buprenorphine stabilised clients, 21 non-using	-Alcohol at 0.05% impaired all measurements of driving performance. -Alcohol had a more

		(Australia)			detrimental effect on speed and steer deviation in straight road sections.
Leung and Starmer	2005	Effect of age and alcohol on driving performance (Australia)	Driving simulator	16 young (18-21), 16 mature (25-35) drivers recruited in Sydney	-Alcohol impaired driver ability to divide attention, but had little effect on decision-making. -Young drivers showed a greater tendency to engage in risky driving. -Other vehicle detection time increases with alcohol consumption and maturity.
Mann et al.	2010	Alcohol and driving factors that increase collision risk (Canada)	Cross-sectional telephone survey	8,542 Ontario adults. (random digit-dialing method)	-Drink-driving behavior, high alcohol consumption and alcohol problems are crash risk predictors.
McCartt et al.	2010	Effects of raising the minimum legal drinking age on drink-driving in the US.	Descriptive meta-analysis	Fatal crash reports, road surveys and alcohol consumption epidemiology survey.	-Raising the legal drinking age reduces alcohol related crashes on highways.
McMillen et al.	1989	Effects of both actual and expected alcohol consumption on driving (US)	Driving simulator and questionnaire	96 undergraduate (64 males, 32 females) psychology students aged 21+	-High sensation seekers drive more dangerously if believing to have consumed alcohol - Low sensation seekers drive more carefully if believing to have consumed alcohol
Miller et al.	1999	Extent, risks, and cost of driving while alcohol-impaired (US)	Case control study	Crash reports vs. roadside survey	-The number of drink-driven kilometers declines. - Driving at BALs > 0.08% costs 50 times compared to sober driving
Peck et al.	2008	Relationship between BAC, age, and crash risk (US)	Case control study (logistic regression)	3,791 crash reposrts vs. 7,582 controls from road surveys.	-age-BAC interaction is highly significant -Novice drivers are more affected by alcohol consumption. -Drink drivers aged under 21 show pre-existing characteristics that predisposed them to risk
Rimm et al.	1982	Effect of alcohol expectancies on driving errors (US)	Driving simulator	44 male students from a Texas University, social drinkers	-Alcohol impairs abilities critical to driving. -No alcohol expectancy affects driving.
Ronen et al.	2008	Effects of THC vs. alcohol on driving performance and subjective feelings (Israel)	Driving simulator (factor analysis)	14 students (aged 26.1±1.3), recreational marijuana and alcohol users	-the effects of 0.05% BAC are similar to low-level THC cigarettes. -Alcohol consumption caused speed and reaction time increase, sleepiness, and lack of attention.
Ronen et al.	2010	Combined effects of alcohol and THC on willingness to drive	Driving simulator	12 students (7 males, 5 females), recreational marijuana and alcohol	-Consuming THC increases alcohol impairment. -Alcohol consumption

		and driving task performance (Israel)		users, aged 24-29	increases speed. -No effects were observed 24h after consumption.
Vollrath et al.	2005	Consequences of relaxing the BAC limit in East Germany	Roadside surveys and interviews	21,198 drivers randomly stopped by police mostly at nighttime and on weekends in Thüringen and Unterfranken	-Raising BAC limit increases BAC of drink-drivers, but not their number. -Young drivers are more vulnerable to legal changes than other drivers.