

Do driver monitoring technologies improve the driving behaviour of distracted drivers? A simulation study to assess the impact of an auditory driver distraction warning device on

*Original*

Do driver monitoring technologies improve the driving behaviour of distracted drivers? A simulation study to assess the impact of an auditory driver distraction warning device on driving performance / Bassani, M.; Catani, L.; Hazoor, A.; Hoxha, A.; Lioi, A.; Portera, A.; Tefa, L.. - In: TRANSPORTATION RESEARCH PART F: TRAFFIC PSYCHOLOGY AND BEHAVIOUR. - ISSN 1369-8478. - 95:(2023), pp. 239-250. [10.1016/j.trf.2023.04.013]

*Availability:*

This version is available at: 11583/2978411 since: 2023-05-09T12:57:46Z

*Publisher:*

Elsevier

*Published*

DOI:10.1016/j.trf.2023.04.013

*Terms of use:*

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

*Publisher copyright*

(Article begins on next page)

1 **Do driver monitoring technologies improve the driving behaviour of**  
2 **distracted drivers? A simulation study to assess the impact of an**  
3 **auditory Driver Distraction Warning device on driving performance.**

4  
5 **Bassani, M.\*, Catani, L., Hazoor, A., Hoxha, A., Lioi, A., Portera, A., Tefa, L.**

6  
7 **Marco BASSANI**, [marco.bassani@polito.it](mailto:marco.bassani@polito.it) (\* = corresponding author)

8 **Lorenzo CATANI**, [lorenzo.catani@polito.it](mailto:lorenzo.catani@polito.it)

9 **Abrar HAZOOR**, [abrar.hazoor@polito.it](mailto:abrar.hazoor@polito.it)

10 **Adem HOXHA**, [adem.hoxha@studenti.polito.it](mailto:adem.hoxha@studenti.polito.it)

11 **Alessandra LIOI**, [alessandra.lioi@polito.it](mailto:alessandra.lioi@polito.it)

12 **Alberto PORTERA**, [alberto.portera@polito.it](mailto:alberto.portera@polito.it)

13 **Luca TEFA**, [luca.tefa@polito.it](mailto:luca.tefa@polito.it)

14

15

16 Department of Environment, Land and Infrastructure Engineering

17 Politecnico di Torino

18 24, c.so Duca degli Abruzzi

19 Torino – 10129 (Italy)

20 **ABSTRACT**

21 Being distracted while driving is a major cause of road crashes. To help prevent this particular type of crash,  
22 new driver monitoring technologies track ocular and head movement and alert drivers when periods of  
23 prolonged distraction are detected, thus preventing hazardous situations on the road. In this mixed-factorial  
24 multi-level experiment, the behaviour of drivers was measured as they performed a secondary task while  
25 being monitored via an auditory Driver Distraction Warning (A-DDW) device which reminded them to  
26 look at the road ahead and cease the activity which was the source of distraction. Here, we evaluated the  
27 effectiveness of this type of DDW device by measuring longitudinal and lateral behaviour in situations  
28 where the driver is intentionally distracted for a significant period of time, and when the device repeatedly  
29 reminds the driver of his/her primary task.

30 Forty-two participants were randomly stratified into three groups and subjected to the following  
31 distraction levels: (i) not distracted (baseline), (ii) distracted, and (iii) distracted but interacting with the  
32 A-DDW device. All participants drove in (i) free-flowing and (ii) stable traffic conditions along straight  
33 motorway segments. Speed and speed deviation values for distracted drivers were lower than for  
34 undistracted ones but they also experienced a significant deterioration in vehicle lateral control. Conversely,  
35 drivers assisted by the A-DDW device experienced a considerable improvement in their lateral control even  
36 though their speed and speed deviation values were higher. The reaction times of distracted drivers  
37 interacting with the A-DDW device deteriorated as revealed in cognitive tests conducted before and after  
38 the driving task.

39

40 **Keywords:** crash prevention, distraction, driver behaviour, Driver Distraction Warning device, driving  
41 simulation.

42

43

## 44 1. INTRODUCTION

45 Driver distraction is a serious road safety issue accounting for up to 25% of road crashes in Europe (ERSO,  
46 2018). In the recent three-year period 2016-2018, distracted driving caused circa 3,000 deaths per year in  
47 the United States, with more than a quarter of the distracted drivers in the 20 to 29-year-old age group  
48 (National Highway Traffic Safety Administration, 2018; 2019; 2020a). Distraction diverts drivers from  
49 primary driving-related activities towards secondary tasks (Regan *et al.*, 2011), which can be  
50 driving-related, e.g., focusing on onboard instruments, or non-driving-related, e.g., texting with a  
51 smartphone (Stutts *et al.*, 2005). Mind wandering while driving results in poor driver vigilance, and often  
52 occurs when the driver is familiar with the route (Baldwin *et al.*, 2017; Burdett *et al.*, 2016). There are four  
53 categories of distraction: (i) visual (Bakhit *et al.*, 2018; Kuo *et al.*, 2019), (ii) manual (Stutts *et al.*, 2005;  
54 Klauer *et al.*, 2006), (iii) auditory (Strayer *et al.*, 2003; European Road Safety Observatory, 2018), and (iv)  
55 cognitive (Strayer *et al.*, 2015). The use of a mobile phone involves a combination of these (Kircher, 2007)  
56 as does interaction with the centre console (Kuo *et al.*, 2019), with the driver repeatedly switching attention  
57 between the driving (primary) and the secondary task (Kaber *et al.*, 2012). A more demanding secondary  
58 task leads to a higher number of off-road glances, both for purely visual (Metz *et al.*, 2011) and  
59 visual-manual tasks (Tivesten & Dozza, 2014), while a complex driving task including both visual and  
60 auditory stimuli from in-vehicle systems forces drivers to concentrate more on the road ahead and keep  
61 their eyes focused spatially on the central part of the road (Victor *et al.*, 2005).

62 It is well established that distraction affects longitudinal and lateral vehicle control as well as driver  
63 reaction times (Papantoniou *et al.*, 2017; Young *et al.*, 2009). Driving simulation studies show that speed  
64 ( $S$ ) decreases when the driver is using a cell phone (Alm & Nilsson, 1994; Reed & Robbins, 2008) and the  
65 standard deviation of speed ( $SDS$ ) increases as the difficulty of the secondary task increases (Rakauskas *et*  
66 *al.*, 2004). A reduction in speed (Papantoniou *et al.*, 2017) and/or an increase in the distance between the  
67 driver and the vehicle in front (Strayer & Drews, 2004) are generally adopted as countermeasures to ensure  
68 increased reaction times in response to a potential hazardous event requiring an evasive manoeuvre like  
69 steering and/or braking. It should be noted that distracted drivers do not always deteriorate their  
70 performance levels. As reported by Oviedo-Trespalacios *et al.* (2018), when the distraction is self-inflicted,  
71 drivers select lower speeds to compensate for the risk(s) they are taking.

72 Regarding transversal control, lateral position ( $LP$ ) and standard deviation of lateral position ( $SDLP$ ) are  
73 the most common parameters employed to evaluate the ability to maintain appropriate position and control  
74 of the vehicle within the lane (Papantoniou *et al.*, 2017). However, any distractions while driving adversely  
75 affect the ability of drivers to maintain their vehicle correctly positioned in the lane (Choudhary & Velaga,  
76 2019; Rumschlag *et al.*, 2015). Furthermore, some studies showed that visual and manual tasks cause more  
77 lane deviations, steering errors and higher  $SDLP$  values than cognitive distractions (Engström *et al.*, 2005;  
78 Kaber *et al.*, 2012).

79 Driver monitoring technologies were introduced more than a decade ago, first as a driver behavioural  
80 research tool (May & Baldwin, 2009; Taylor *et al.*, 2013), then as in-vehicle technology to alert drivers to  
81 inappropriate driving practises and hazardous situations (Reagan *et al.*, 2018; Mase *et al.*, 2020). Recently,  
82 the European Parliament (European Parliament & Council of the European Union, 2019) approved  
83 Regulation No. 2019/2144 in an effort to protect vehicle occupants and other road users from distraction.  
84 The 2019/2144 Regulation imposes the adoption of Driver Distraction Warning (DDW) systems on new  
85 vehicles by 2026. These devices were originally introduced to the automotive aftermarket and to new  
86 vehicle models afterwards (Doudou *et al.*, 2020). They emit auditory and/or vibratory warnings when the  
87 driver is distracted, with the aim of ensuring that the driver is alert and retains or regains full control of the  
88 vehicle. The majority of current DDW devices process data relating to the eye region (gaze tracking, eye  
89 closure, percentage of eyelid closure over time, etc.) and face monitoring (Sigari *et al.*, 2014).  
90 Anti-distraction applications were also introduced on smartphones as low-cost DDW systems (Bergasa *et*  
91 *al.*, 2014). The technical documents in support of the 2019/2144 Regulation (European Parliament &  
92 Council of the European Union, 2021) indicate that DDW systems are expected to be more effective outside  
93 urban zones, e.g., on motorways, where long-distance driving at a constant speed together with less  
94 interesting surrounding environments can result in drivers becoming more distracted (Huemer & Vollrath,  
95 2011).

96 Despite the effectiveness of DDW technologies in detecting distraction being well recognized (Dumitru  
97 *et al.*, 2018; Gallahan *et al.*, 2013), their effects on driver behaviour and performance are still the subject  
98 of debate. Donmez *et al.* (2006) investigated the effects of an advisory mitigation strategy used to  
99 discourage off-road eye glances while drivers were interacting with an in-vehicle information system, but  
100 no relevant advantages in braking and steering performance were observed. Ahlstrom *et al.* (2013) used a  
101 seat vibrating DDW system based on a remote eye tracking (AttenD) algorithm to evaluate changes in  
102 driving behaviour in field tests under uncontrolled traffic conditions, but it did not result in significant  
103 changes in global glance behaviour. The uncertainty regarding the impact of DDW devices on driver  
104 performance in controlled traffic conditions suggests that more research is needed.

105 In this driving simulation study, we evaluated the effectiveness of an auditory DDW (A-DDW) device  
106 currently available on the automotive aftermarket, which can track eye and head movements and alert  
107 drivers if and when their visual behaviour deviates from the reference front position for at least 3 s.  
108 Participants were asked to perform a secondary task which involved a cognitive, visual and manual  
109 distraction. We were then able to assess the effectiveness of the warning system by measuring driver  
110 behaviour when subject to a state of intentional distraction.

111

112 **2. METHODS**

113 **2.1 Experimental design and hypotheses**

114 A multi-level mixed-factorial design with varying levels of distraction and traffic density was considered.  
115 Longitudinal and lateral behavioural indicators were monitored under two different traffic scenarios, while  
116 the participants were subjected to one of the following three states: not distracted, distracted, or distracted  
117 but with the support of the A-DDW device. This experiment was conducted under the hypothesis that the  
118 A-DDW device counteracts the negative impact of the distraction experienced when drivers persist in  
119 performing a secondary task.

120 Although this specific secondary task is not likely in ordinary driving, we considered it because of the  
121 conclusions reached by Shinar *et al.* (2005), who observed that solving mathematical operations  
122 significantly degraded driving performance compared to a distraction caused by conversation. On the other  
123 hand, the simultaneous activation of an alert system that detects distraction and the persistence of a  
124 distracted state is likely when A-DDW systems are installed on the next generation of vehicles in 2026.

125 We also evaluated the effect of the A-DDW device on mental workload by measuring the change in the  
126 perception and reaction times (PRT) of participants to visual and auditory stimuli before and after driving.  
127 The hypothesis tested in this experiment is that the A-DDW device requires a more demanding driving task,  
128 with an increment in the PRT after driving.

129 The experiment combines distraction as a between-subject factor, and traffic density (i.e., the level of  
130 service, LOS) as a within-subject factor (Table 1). The stimulus combined visual, cognitive, and manual  
131 distractions and was dispensed along straight segments of 2 km (see Section 2.2).

132

133 **TABLE 1. Synthesis of the design factors.**

<b>Experimental factors</b>	<b>Levels</b>			<b>Type</b>
Distraction level (Group No.)	No Distraction (0)	Distraction (1)	Distraction + A-DDW (2)	Between-subject
Traffic density (Level of Service, LOS)	7 pc/km/lane (A)	14 pc/km/lane (C)	-	Within-subject

134

135 **2.2 Road scenario**

136 The road scenario consisted of a rural motorway consistent with Italian technical standards (*Ministero delle*  
137 *Infrastrutture e dei Trasporti*, 2001). As the scenario was designed to favour distractions (see Figures 1a  
138 and 1b), long straights to increase the feeling of monotony were adopted (Huemer & Vollrath, 2011;  
139 Papantoniou *et al.*, 2016; Slootmans & Desmet, 2019). As depicted in Figure 1, the immediate surroundings  
140 were slightly hilly with the presence of vegetation, trees, and some buildings in the distance. The weather  
141 and visibility conditions for driving were optimal. The carriageway had a width of 7.5 m with 2 lanes  
142 (3.75 m each) per direction, a 3 m wide emergency lane, and a 0.7 m wide left shoulder. Horizontal  
143 markings and vertical signals conformed to the Italian Highway Code (*Nuovo Codice della Strada*, 1992).

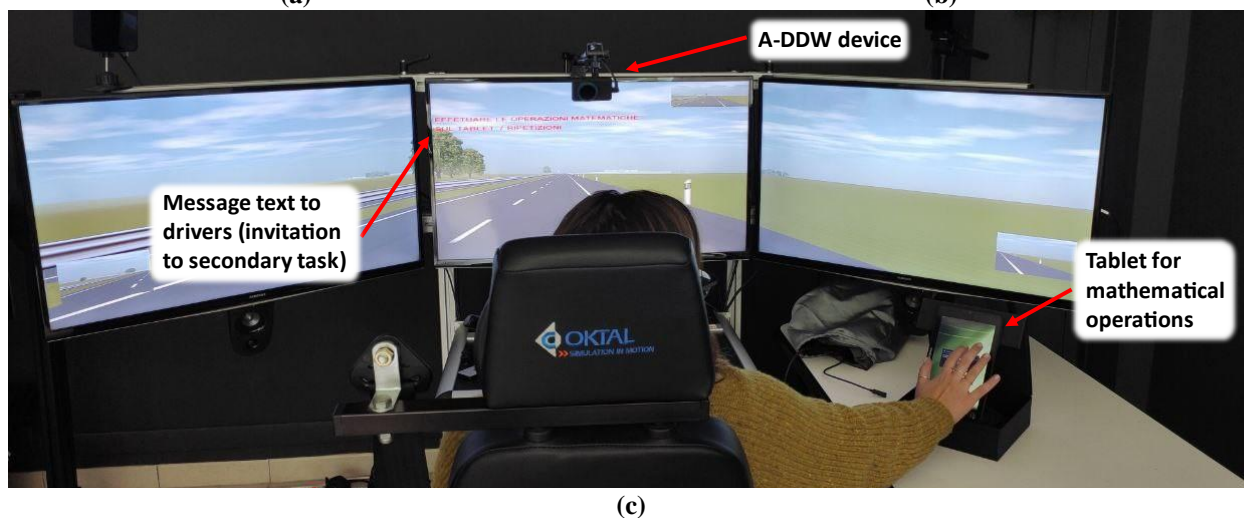
144 The posted speed limit was set at 130 km/h. A safety barrier of 850 mm in height was selected for the  
145 median while the barrier along the right roadside was omitted.

146 Drivers started the experiment from a lay-by before merging onto the motorway from a direct ramp.  
147 After merging, each participant drove on three long motorway tangents connected by circular arcs of  
148 1200 m in radius. The level of service (LOS) was set at A, i.e., free flow conditions, and C, i.e., stable flow  
149 with the reduced ability to change lane requiring greater awareness. The randomized order of administration  
150 of the LOS along the 2<sup>nd</sup> and the 3<sup>rd</sup> straights was adopted. Hence, a number of circulating vehicles  
151 corresponding to an average vehicle density of 7 pc/km/lane (LOS A, Figure 1a) and 14 pc/km/lane (LOS  
152 C, Figure 1b) was adopted (Transportation Research Board, 2016).

153



154  
155



156  
157

158 **FIGURE 1. Experimental set-up and scenarios: (a) straight segment under LOS A, and (b) LOS C. Simulation**  
159 **setting (c) with tablet for the secondary task and the A-DDW device.**

160

### 161 2.3 Equipment

162 Experiments were conducted using the fixed-base driving simulator with SCANeR Studio™ software  
163 (AV Simulation) at the Road Safety and Driving Simulation (RSDS) laboratory of the Politecnico di Torino  
164 (Figure 1c). With this simulator, the driver has a 130° horizontal and around 30° vertical field of view  
165 through three 32-inch full HD screens (1920×1080 pixels each). Together with the video card, the monitors  
166 update the images at a frequency higher than 50 Hz and are equipped with rear and side view mirrors. The  
167 simulator hardware consists of a cockpit complete with steering wheel, manual gearbox, pedals and

168 dashboard. The speedometer, rev counter and other onboard displays are on the small monitor mounted on  
 169 the back of the steering wheel but in a position where they are always visible to drivers during experiments.  
 170 The steering wheel is equipped with a force feedback sensor to simulate wheel spin and impacts. Vehicle  
 171 and traffic sound effects are reproduced through five speakers located behind the screens and a subwoofer  
 172 under the driver's seat. The simulator repeatedly reached relative validation for longitudinal (Bassani *et al.*,  
 173 2018), transversal (Catani and Bassani, 2019), and driving operations (Karimi *et al.*, 2020).

174 An A-DDW device available in the automotive aftermarket (Figure 1c), i.e., an infrared camera that  
 175 detects eye pupil and head movements, was used. It determines whether pupils dilate or blink, and if the  
 176 head position changes with respect to the initial calibration. As soon as any such change is detected, the  
 177 sensor alerts the driver in real-time to help maintain a condition of safe driving. When the gaze is directed  
 178 downwards or the pupils constrict, a continuous beep sounds and alerts the driver in less than 2 s. Following  
 179 3 s of persistent distraction, i.e., head and gaze not directly focused on the road, a warning voice message  
 180 informs the driver that he/she has to look ahead. Preliminary tests established that the ideal camera position  
 181 is close to the rear-view mirror and at a distance of  $60 \pm 5$  cm from the driver's head (see Figure 1c).

182

## 183 2.4 Participants

184 A hundred participants were contacted via email, and since the study was conducted in line with the Code  
 185 of Ethics of the World Medical Association (World Medical Association, 2018), all participants signed an  
 186 informed consent form before starting the experiments. Based on an expected effect size ( $f$ ) of .30, a  
 187 significance level of .05, and a power of .90, forty-two out of one hundred were involved. Drivers were  
 188 aged between 24 and 63, and were divided into three groups according to the between-subject factor  
 189 (Table 1) in order to avoid any learning effect in the data, while the duration of a driving session was limited  
 190 to no more than 15 min along the 25 km of the experimental track, so as to keep any fatigue phenomena to  
 191 a minimum. Groups were stratified by age and gender, with five females and nine males in each group  
 192 (Table 2).

193

194 **TABLE 2. Descriptive statistics for participant characteristics.**

<b>Participant characteristics</b>	<b>Group</b>	<b>N</b>	<b>Mean</b>	<b>SD</b>	<b>Minimum</b>	<b>Maximum</b>
<b>Driver age</b>	0	14	43.8	11.9	24	64
	1	14	43.0	11.3	23	61
	2	14	43.4	15.1	23	64
<b>Experience (km/y)</b>	0	14	14,857	10,516	1,000	30,000
	1	14	14,607	12,783	1,500	40,000
	2	14	11,429	9,764	2,000	35,000
<b>Experience (license y)</b>	0	14	25.1	11.9	5	45
	1	14	23.1	10.7	4	43
	2	14	23.7	14.7	4	45

195

196 **2.5 Protocol**

197 Each participant filled out a pre-drive questionnaire on their general health before driving on a test circuit  
198 to get familiar with the simulator commands. Drivers were instructed to drive as they would in a real  
199 motorway setting, while respecting traffic regulations. Those supported by the A-DDW device (Group 2)  
200 were instructed to complete the secondary task regardless of the fact that they were advised by the device  
201 to desist from doing so. After that, each participant drove for a maximum of 20 minutes. Before and after  
202 the driving task, participants completed two visual and auditory stimuli PRT tests using the online tool  
203 *Cognitive Fun!* (retrieved from <https://new.cognitivefun.net/>). We collected data with this online platform  
204 through a computer with a high-speed internet connection without conducting any validation tests.

205 During the distraction phase, a written message on the central windscreen invited participants to perform  
206 simple mathematical operations (Figure 1c). A random sequence of simple, solvable in your head additions,  
207 subtractions, multiplications, and divisions was proposed to influence driving performance (Shinar *et al.*,  
208 2005) through *MathGames* (retrieved from <https://www.mathplayground.com/math-games.html>) installed  
209 on a 7" tablet positioned 55 cm to the right of the steering wheel (Figure 1c). The A-DDW device was  
210 activated each time drivers looked at the tablet for more than 3 seconds and it remained active until drivers  
211 reverted their gaze from the tablet back onto the road for a while. Once they had regained full control of  
212 the vehicle, drivers were able to continue with the secondary task. No driver performed any incorrect  
213 manoeuvres, or crashed into road installations or surrounding vehicles.

214 Finally, each driver filled out a post-drive questionnaire to provide feedback on the simulation and the  
215 anti-distraction device. The responses to the questionnaire demonstrated that the presence of the A-DDW  
216 device did not irritate or annoy the drivers during the test. Positive responses were received on the realistic  
217 nature of the simulation when compared to real driving conditions.

218

219 **2.6 Observed variables, data collection and statistical analysis**

220 Data for speed and lane position were collected at a frequency of 10 Hz for all testing configurations. Any  
221 outcomes relating to sections in which drivers were engaged in lane change manoeuvres were excluded  
222 from the database and the results. In accordance with the SAE J2944 standard (Society of Automotive  
223 Engineers, 2015), the following dependent variables depicting the longitudinal and lateral behaviour of  
224 drivers were measured:

- 225 (i) average speed ( $S$ ),
- 226 (ii) standard deviation of speed ( $SDS$ ),
- 227 (iii) average lateral position ( $LP$ ), and
- 228 (iv) standard deviation of lateral position ( $SDLP$ ).

229  $LP$  indicates the distance from the vehicle centre of gravity to the lane centreline of both lanes in the  
230 carriageway. Positive  $LP$  values signify that the centre of gravity (CoG) was on the left side of the lane

231 centreline. *SDS* and *SDLP* values reflect the ability of the driver to remain in control of the vehicle vis-à-vis  
232 use of the throttle and the steering wheel, respectively (Verster & Roth, 2011).

233 PRT tests were conducted to determine if the cognitive performance of participants suffered during the  
234 simulation due to the increased mental workload caused by the distracting secondary task (Group 1) and  
235 the simultaneous interaction with the A-DDW device (Group 2).

236 Linear mixed-effects models (LMM) and the generalized linear models (GLM), in the case of violation  
237 of LMM assumptions, were considered. Among the fixed effects of both LMM and GLM, the two  
238 experimental factors (distraction level, and level of service) and gender were included as categorical, while  
239 age and driving experience (average distance travelled in a year, and number of years holding a licence)  
240 were included as covariates. In the LMM, random effects (RE) accounted for the unobserved heterogeneity  
241 due to participants' subjective characteristics. Therefore, the *Test driver ID* was used as a cluster variable  
242 in the analysis. Clinical research (Pietrzak *et al.*, 2010) demonstrates that the LMM rather than other  
243 statistical methods like RM-ANOVA, reduces the standard error in the estimation, and increases the effect  
244 size (i.e., lower *p*-value), and the reliability of results, especially in mixed experimental designs. LMM is  
245 used with datasets including repeated measurements, as in this investigated case where each driver was  
246 monitored under two different traffic density scenarios.

247 Statistically non-significant variables and relative interactions were removed in accordance with the  
248 backward elimination technique. By minimizing the Akaike Information Criterion (AIC, Eq. 1) (Akaike,  
249 1974) and the Bayesian Information Criterion (BIC, Eq. 2) (Stone, 1979):

$$250 \quad AIC = -2\ln(L) + 2k \quad (1)$$

$$251 \quad BIC = -2\ln(L) + \ln(n) \times k \quad (2)$$

252 where *L* is the model likelihood parameter, *k* is the number of parameters estimated, and *n* is the number of  
253 observations, the model performance was improved. When statistically significant effects and interactions  
254 were detected in LMM and GLM, post-hoc tests with Holm correction were performed. The significance  
255 level was always set at 5%. Statistical data analyses and modelling were carried out with Jamovi ver. 2.3.18  
256 (The Jamovi Project, 2021).

257

### 258 **3. RESULTS**

#### 259 **3.1 Descriptive statistics**

260 Table 3 provides the average and standard deviation of the experimental outcomes. The results have been  
261 grouped by distraction level and traffic density conditions.

262

263

264 **TABLE 3. Mean (and standard deviation) of outcomes for average speeds (*S*), standard deviation of speeds**  
 265 **(*SDS*), average lateral position (*LP*), and standard deviation of lateral position (*SDLP*).**

Groups No. (Distraction level)	Level of Service (LOS)	<i>S</i> (km/h)	<i>SDS</i> (km/h)	<i>LP</i> (m)	<i>SDLP</i> (m)
<b>0 (Baseline)</b>	A	123.3 (9.1)	4.71 (1.45)	0.123 (0.199)	0.223 (0.076)
	C	122.5 (11.9)	4.14 (2.42)	0.124 (0.245)	0.217 (0.063)
<b>1 (Distraction)</b>	A	114.4 (18.3)	2.81 (2.23)	0.175 (0.413)	0.344 (0.140)
	C	114.8 (15.3)	3.01 (1.68)	-0.061 (0.407)	0.420 (0.235)
<b>2 (Distraction + A-DDW)</b>	A	123.3 (18.9)	5.14 (4.35)	0.176 (0.375)	0.315 (0.130)
	C	128.3 (20.8)	3.39 (2.70)	-0.055 (0.335)	0.330 (0.169)

266

267 **3.2 Models estimation**

268 Table 4 shows the estimated parameters for the four dependent variables investigated. *S* and *LP* data were  
 269 used to calibrate LMM, while *SDS* and *SDLP* data were used to calibrate GLM since (i) no significant  
 270 impact of the *Test driver ID* as a cluster variable was observed after a preliminary analysis with LMM, and  
 271 (ii) to avoid any violation of assumptions on residuals for LMM. In Table 4, all models have the lowest  
 272 AIC and BIC values possible. The assumption checks carried out by the Kolmogorov-Smirnov test  
 273 confirmed the normality of residuals of the LMM for *S* and *LP* (*p*-values always higher than .05).

274

275 **TABLE 4. LMM and GLM for driver behavioural outcomes.**

	Effect	Estimate ( <i>p</i> -value)			
		LMM		GLM	
		<i>S</i> (km/h)	<i>LP</i> (m)	<i>SDS</i> (km/h)	<i>SDLP</i> (m)
<b>Factors, covariates (fixed effects):</b>					
Intercept		119.884 (<.001)	0.0810 (.057)	3.8654 (<.001)	0.3082 (<.001)
Distraction level	1-0	-8.4658 (.119)	-0.0638 (.497)	-1.3988 (.045)	0.1462 (<.001)
	2-0	1.9054 (.726)	-0.0655 (.522)	-0.0778 (.910)	0.0894 (.014)
LOS	C-A	-	-0.1574 (.018)	-	-
Gender	F-M	-8.4705 (.097)	-	-	-
Gender * Distraction level	F-M*1-0	0.8575 (.937)	-	-	-
	F-M*2-0	-23.3404 (.054)	-	-	-
LOS * Distraction Level	C-A*1-0	-	-0.2311 (.148)	-	-
	C-A*2-0	-	-0.2255 (.158)	-	-
Driver age (y)		-0.5621 (.019)	-	-	0.0197 (.001)
Experience (km/y)		7.64 · 10 <sup>-4</sup> (.010)	-	-	-
Experience (licence y)		-	-	0.0607 (.011)	-0.0162 (.008)
<b>Cluster variable for LMM (random effect):</b>					
Test driver ID		(<.001)	(.109)	-	-
<b>Summary statistics</b>					
AIC		649.64	63.50	402.25	-95.20
BIC		660.04	101.16	414.41	-80.61
R <sup>2</sup> marginal		.339	.082	-	-
R <sup>2</sup> (conditional for LMM)		.879	.314	.139	.349
Observations / Drivers				84/42	
Kolmogorov-Smirnov test for normality of residuals		.457	.913	-	-

276

277 **3.3 Longitudinal behaviour**

278 Regarding *S* (Table 4), the LMM explains around 88% of the total variance, with most of this ascribable to  
 279 the random effect associated with the *test driver ID* (54% of the total variance in the data), thus indicating  
 280 the predominant effect of subjective behaviour. Distraction level and LOS were not significant in explaining

281 S. In fact, LMM did not reveal any significant differences when comparing undistracted drivers with both  
282 distracted groups. Estimated marginal means revealed that distracted drivers ( $M_1 = 113.6$  km/h,  
283  $SE_1 = 3.67$  km/h) adopted lower speeds than undistracted ones ( $M_0 = 122.1$  km/h,  $SE_0 = 3.79$  km/h), and  
284 that drivers who interacted with the A-DDW device drove at speeds similar to those of the undistracted  
285 drivers in Group 0 ( $M_2 = 124.0$  km/h,  $SE_0 = 3.86$  km/h). A post-hoc test revealed that distracted males  
286 supported by the A-DDW device (Group 2) drove at significantly higher speeds than male drivers in  
287 Group 1 ( $S_{1M} - S_{2M} = -22.47$  km/h,  $t_{37} = -3.26$ ,  $p\text{-value}_{Holm} = .037$ ). Moreover, when distracted while under  
288 the influence of the A-DDW device, females drove at lower speeds with respect to males  
289 ( $S_{2M} - S_{2F} = 24.32$  km/h,  $t_{37} = 2.97$ ,  $p\text{-value}_{Holm} = .069$ ), a fact that explains why gender and distraction level  
290 interact in the model (Table 4). LMM results also indicate that participants used to driving more kilometres  
291 per year also drove faster than those used to driving less, while older drivers behaved more cautiously than  
292 younger ones.

293 *SDS* was marginally influenced by distraction. Distracted drivers reduced speed variation more than  
294 non-distracted drivers did ( $SDS_0 - SDS_1 = 1.40$  km/h,  $z = 2.04$ ,  $p\text{-value}_{Holm} = .134$ ). However, distracted  
295 drivers supported by the A-DDW (Group 2) device exhibited speed variations similar to undistracted ones  
296 ( $SDS_0 - SDS_2 = 0.8$  km/h,  $z = 0.11$ ,  $p\text{-value}_{Holm} = .910$ ). Experienced drivers also exhibited greater speed  
297 variations than novice drivers. As before though, no significant differences were imputable to the LOS.

298

### 299 **3.4 Lateral behaviour**

300 The LMM for *LP* revealed that it was significantly influenced by LOS ( $LP_A - LP_C = 0.157$  m,  $t_{41} = 2.44$ ,  
301  $p\text{-value}_{Holm} = .019$ ), and marginally by the driving style of participants ( $p\text{-value} = .141$ ) which, nevertheless,  
302 accounts for circa 23% of the total variance in the model. As shown in Table 3, distracted participants  
303 generally drove more on the right side of the centreline under denser traffic conditions (i.e., LOS C) than  
304 those undistracted and those distracted but operating under free-flow conditions (LOS A) did. However,  
305 LMM did not reveal a significant difference in *LP* ascribable to distraction levels and the covariates.

306 Conversely, *SDLP* was heavily influenced by distraction levels, driver age and experience. Distracted  
307 drivers increased their *SDLP* notably more than undistracted ones ( $SDLP_0 - SDLP_1 = -0.146$  m,  $t_{37} = -3.97$ ,  
308  $p\text{-value}_{Holm} < .001$ ). However, Group 2 drivers showed only a marginally better level of lateral control  
309 whilst performing the secondary distracting task than that shown by their Group 1 counterparts  
310 ( $SDLP_1 - SDLP_2 = 0.057$  m,  $t_{37} = 1.57$ ,  $p\text{-value}_{Holm} = .125$ ), albeit not enough to reduce their *SDLP* values  
311 to those of undistracted drivers ( $SDLP_0 - SDLP_2 = -0.089$  m,  $t_{37} = -2.44$ ,  $p\text{-value}_{Holm} = .039$ ). LMM revealed  
312 that free- and stable-traffic conditions had no significant effect on *SDLP*. As shown by the estimates for  
313 model coefficients, younger drivers maintained better lateral control than older ones, thereby demonstrating  
314 the significant effect of age on *SDLP* ( $p\text{-value}_{Holm} = .002$ ). However, more experienced drivers performed  
315 fewer corrections along the trajectory, i.e., had lower *SDLP* values.

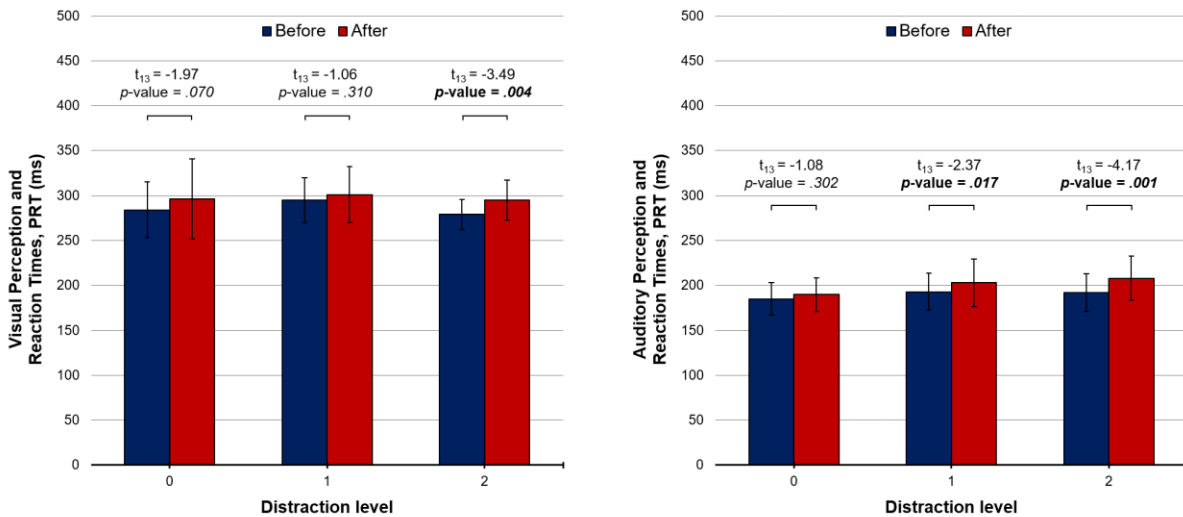
316

### 317 3.5 Visual and auditory PRT tests

318 The comparison between data for the visual and auditory PRT tests carried out before and after the driving  
 319 test for the three groups of participants is shown in Figure 2. For each group of drivers (i.e., undistracted,  
 320 distracted, and distracted but interacting with the A-DDW device), PRT data were found to be Gaussian  
 321 distributed according to outputs from Kolmogorov-Smirnov tests for normality (all  $p$ -values larger than  
 322 .05). The average visual and auditory PRT values after the experiments were always higher than the PRTs  
 323 measured before. Moreover, data confirmed that the visual stimuli led to longer PRTs, because of the longer  
 324 time required for the transmission of the photoreception signal to the brain compared to that required for  
 325 the auditory stimulus (Kemp, 1973).

326 The results obtained revealed no significant differences between before and after visual and auditory  
 327 PRT values for the undistracted drivers (Group 0). In contrast, significant statistical differences were  
 328 observed for the distracted drivers in Groups 1 and 2. While the change in PRT within Group 1 was only  
 329 significant for the auditory values ( $t_{13} = -2.37$ ,  $p$ -value = .017), both visual and auditory tests revealed that  
 330 distracted drivers who interacted with the A-DDW device experienced a statistically significant change in  
 331 their PRT values after the driving test (visual:  $t_{13} = -3.49$ ,  $p$ -value = .004; auditory:  $t_{13} = -4.17$ ,  
 332  $p$ -value = .001).

333



334

335 **FIGURE 2. Visual and auditory perception and reaction times (mean and standard deviation) before (blue**  
 336 **bars) and after (red bars) the driving session.**

337

338

#### 339 4. DISCUSSION

340 We examined the effect of an A-DDW device on driver performance while he/she is distracted by having  
341 to perform a secondary task along a motorway. In doing so, we took the performance of drivers distracted  
342 by the same task and non-distracted drivers as benchmarks.

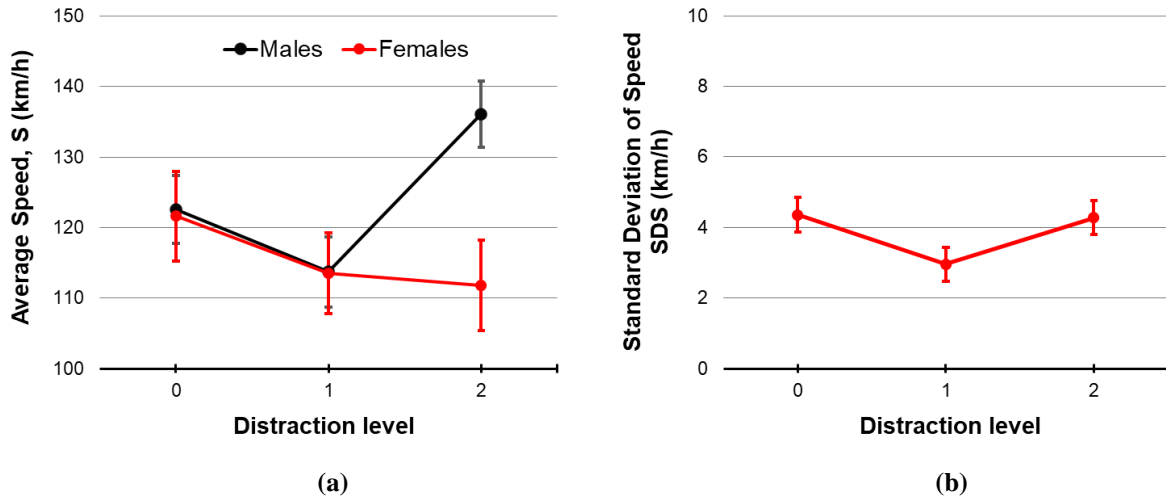
343 The results with the LMMs and GLMs indicate that along motorways the personal characteristics of  
344 drivers have a significant influence over speed and a marginal influence over lateral position in the lane. In  
345 contrast, longitudinal and transverse control ability are mainly influenced by the level of driver distraction  
346 and age.

347 As depicted in Figure 3a, drivers slightly reduced their speed when distracted to compensate for the risk  
348 associated with continuing to perform the secondary task. In this study, this reduction did not prove to be  
349 statistically significant, while the same trend but statistically significant in difference was observed by  
350 Choudhary and Velaga (2019) in a driving simulation study on a four-lane (two lanes per direction)  
351 undivided carriageway with a posted speed limit of 110 km/h. Similar outcomes were registered by  
352 Rakauskas *et al.* (2004) for a simulation study in a two-lane rural road setting. Based on our results, we can  
353 confirm that, when distracted, drivers prudently maintain a lower speed than they do when focused on the  
354 primary driving task only.

355 We also observed that the behaviour of distracted drivers interacting with the A-DDW device differed  
356 with gender. Whereas males drove significantly faster than the distracted-only drivers in Group 1, females  
357 reduced their speed to levels lower than males operating under the same conditions. The prudent nature of  
358 female drivers was observed by Onate-Vega *et al.* (2020), while Choudhary *et al.* (2022) confirmed that  
359 females demonstrated a greater perception of the risk associated with distracting secondary activities than  
360 their male counterparts. However, care must be taken not to generalise this result, as the study had an  
361 unbalanced composition of males (65%) and females (35%). LMM outcomes also reveal that drivers with  
362 greater driving experience in terms of distance travelled adopted higher speeds. This is consistent with the  
363 results from Oviedo-Trespalacios *et al.* (2017), who observed that inexperienced drivers reduced their speed  
364 more than experienced ones when distracted.

365 Figure 3b shows the impact of the different distraction levels on the standard deviation of speed (*SDS*).  
366 Distracted drivers reduced their speed variation, while those distracted but interacting with the A-DDW  
367 assumed speed variation values comparable to those of undistracted drivers. This outcome contrasts with  
368 that observed by Rakauskas *et al.* (2004) who measured an increment of 0.5-1 mph (0.8-1.6 km/h) in the  
369 *SDS* of drivers talking on their cell phones in realistic driving conditions. The differences between these  
370 two studies are attributable to the difference in distraction type, which was solely cognitive in Rakauskas  
371 *et al.* (2004), while cognitive, manual and visual in the present study. However, the not statistically  
372 significant increment observed for drivers interacting with the A-DDW device with respect to those simply  
373 distracted is consistent with the results from Rakauskas *et al.* (2004) who observed larger speed variation

374 values in tasks requiring a higher mental workload such as participation in mobile phone conversations.  
 375 Furthermore, the higher *SDS* values recorded for more experienced drivers indicate that they tended to  
 376 adjust speed more frequently when alerted by the A-DDW device, which emitted a “beep” sound and some  
 377 warning messages. This result is in line with that of Donmez *et al.* (2006), who observed that older drivers  
 378 accept and trust strategies to combat distraction more than young drivers do.  
 379

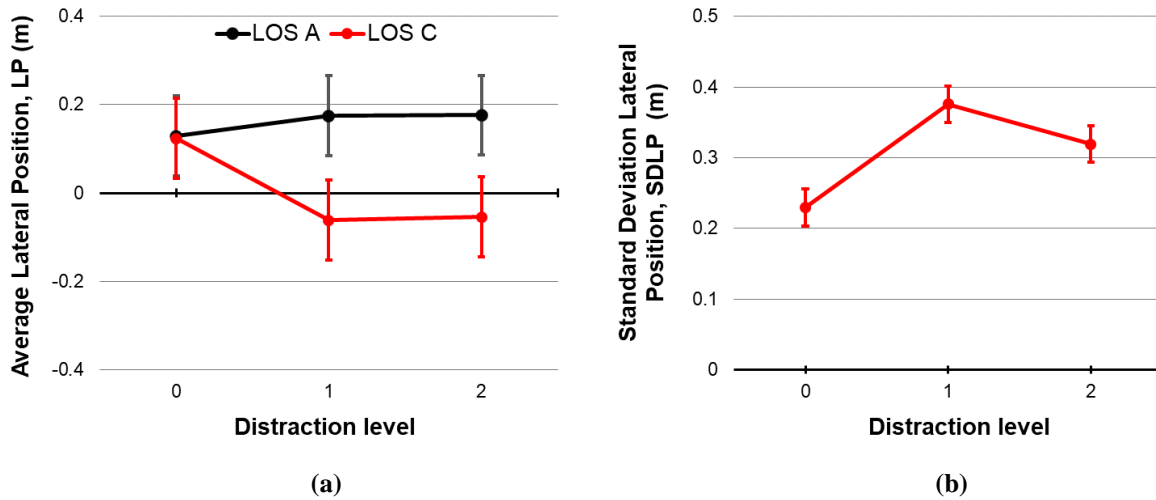


380  
 381  
 382 **FIGURE 3. Effect plots of the LMM and GLM analyses for the effect of distraction level on (a) average speed**  
 383 **(*S*), and (b) standard deviation of speed (*SDS*), respectively. Bars indicate the standard error.**  
 384

385 Significant differences in lane position were attributable to traffic density, as supported by the  
 386 observations from Mecheri *et al.* (2017) and Dijksterhuis *et al.* (2011), although their studies were  
 387 conducted on two-lane rural roads. In the case investigated here (Figure 4a), the average lateral position  
 388 values for distracted drivers in both Groups 1 and 2 were negative under LOS C conditions (see Table 3).  
 389 The higher the traffic density (Figure 1b), the farther to the right the position of the vehicle driven by  
 390 distracted participants. This clearly indicates the propensity of distracted drivers to occupy the right side of  
 391 the lane to limit the degree of interaction with any faster vehicles arriving from behind when occupying the  
 392 rightmost lane, or to increase the distance from a fixed installation like the traffic barrier when driving in  
 393 the leftmost lane. This can be seen as a risk compensation strategy to counteract the impact of distraction  
 394 in a more dangerous environment with vehicles on a multi-lane road, a strategy which was also observed  
 395 by Oviedo-Trespalcacios *et al.* (2020).

396 In terms of lateral control, distracted drivers exhibited higher *SDLP* values than undistracted ones  
 397 (Figure 4b) consistent with the studies of Engstrom *et al.* (2005) and Kaber *et al.* (2012), who claimed that  
 398 tasks combining visual and manual actions like texting with a smartphone cause more lane deviation and  
 399 result in higher *SDLP* values than distractions which are purely cognitive in nature. Nevertheless, when  
 400 comparing distracted drivers, the A-DDW device improved lateral behaviour (i.e., lower *SDLP*). Although  
 401 distracted, Group 2 drivers were invited by the A-DDW device to look at the road ahead, thus maintaining

402 better lateral control. The observation study carried out by Wang *et al.* (2019) in real driving conditions  
 403 corroborates this hypothesis, with distracted drivers reducing the number and duration of glances required  
 404 to perform the secondary distraction task so as to remain more focused on the road ahead.  
 405



406  
 407 (a) (b)  
 408 **FIGURE 4. Effect plots of the LMM and GLM analyses for the effect of distraction level on (a) the average**  
 409 **lateral position (*LP*), and (b) the standard deviation of lateral position (*SDLP*), respectively. Bars indicate the**  
 410 **standard error.**  
 411

412 Cognitive tests carried out before and after the driving task revealed a significant increase in PRTs for  
 413 drivers that used the A-DDW device. While the distracted drivers in Group 1 exhibited a significant  
 414 reduction in their auditory performances only, Group 2 drivers experienced a significant deterioration in  
 415 PRT values for both visual and auditory stimuli on completion of the driving session. It is worth noting that  
 416 while visual information is the most important type for drivers (Sivak, 1996), the noise level also impacts  
 417 the driving task (Denjean *et al.*, 2012), and auditory reactivity is inversely proportional to the cognitive  
 418 workload while driving (Reimer & Mehler, 2011). These results concur with those obtained by Chen *et al.*  
 419 (2005) regarding the increase in driver perception and reaction times while they are engaged in a series of  
 420 mental processing tasks. In this study, we measured the difference before and after the driving session, and  
 421 drivers who were exposed to distraction and interaction with the A-DDW device experienced a significant  
 422 deterioration in their cognitive performances. Milosevic (1997) observed that a driver's mental workload  
 423 leads to excessive fatigue which in turn leads to an increase in visual and auditory PRT values. Since  
 424 simulated driving is much more demanding than real driving (Philip *et al.*, 2005), it cannot be excluded that  
 425 the observed differences were attributable to the simulation effect, while in real driving conditions the same  
 426 cognitive deterioration can be observed after a prolonged exposure to the A-DDW interaction (Engström *et*  
 427 *al.*, 2005).  
 428

429 **4. CONCLUSIONS**

430 Carmakers and automotive companies are introducing new driver monitoring systems which use  
431 communication apparatuses to draw attention to and contrast the unsafe behavioural habits of distracted  
432 drivers, thus helping to reduce the number of road crashes. However, their effectiveness on driver  
433 performance has yet to be established.

434 In this study, the effectiveness of an auditory driver distraction warning (A-DDW) device was tested  
435 under motorway driving conditions by measuring longitudinal and lateral behaviour indicators when drivers  
436 are deliberately distracted for a sustained period of time with the device repeatedly reminding them to  
437 concentrate on their primary task. The longitudinal and transversal behaviour patterns of forty-two  
438 volunteers spanning a wide spectrum of ages and levels of driving experience were monitored.

439 Based on statistical data modelling, the main outcomes of this investigation were as follows:

- 440 1. in cars equipped with an A-DDW device and travelling along motorways, drivers experience a  
441 marginal improvement in their lateral control when distracted with respect to those who are not  
442 supported by such a device;
- 443 2. distracted male drivers interacting with an A-DDW device react differently to female drivers; while  
444 males tend to travel at higher speeds, females reduce their speed to levels lower than those of  
445 distracted and non-distracted drivers;
- 446 3. distracted drivers interacting with an A-DDW operate with a higher mental workload;
- 447 4. stable and free-flow traffic conditions impact the lateral position in the lane of distracted drivers  
448 irrespective of the presence of an A-DDW device;
- 449 5. the individual personality traits of drivers affect speed and to a lesser extent their position within  
450 the lane, while longitudinal and lateral control indicators are mostly influenced by the level of  
451 distraction and the countermeasures used to contrast same.

452 The hypothesis being tested is only partially confirmed in terms of average speed, since female drivers  
453 supported by the A-DDW device behave differently from males, a finding which merits further  
454 investigation, since we have adopted an unbalanced composition of males and females. However, the  
455 hypothesis is confirmed for lateral control. We observed that distracted drivers interacting with the A-DDW  
456 device reduce their lateral weaving movement within the lane more than that of simply distracted drivers.  
457 Hazardous interactions with fixed installations (e.g., safety barriers, vertical signals) and surrounding  
458 vehicles are reduced with the presence of an A-DDW device onboard. In conclusion, the use of an A-DDW  
459 device only partially contrasts driving impairments caused by deliberate distraction.

460 The results of this study should be considered by those who are developing anti-distraction systems of  
461 the type investigated here. Although their use should serve to discourage anyone from engaging in  
462 secondary activities that divert attention from the (primary) driving task, the possibility that drivers will  
463 persist in such safety-threatening behaviour must, nevertheless, receive serious consideration. In addition,

464 this study emphasises the need to explore the safety implications when drivers adopt improper driving  
465 behaviour despite the influence of technological countermeasures that promote better driving practises but  
466 which do not override their actions.

467 However, the results obtained must also be viewed in the light of five shortcomings. First, we used only  
468 one A-DDW device which uses an acoustic message to alert the driver. A different warning interface design,  
469 e.g., with visual or haptic warnings of different intensity, duration and/or repetition, could have a different  
470 impact on driver behaviour. Similarly, the timing and reliability of warnings determine their effectiveness.  
471 If drivers receive false warnings, they may begin to ignore the information and fail to respond quickly and  
472 appropriately. Therefore, visual and haptic modes should also be tested in the short and long term to see  
473 which of them are the most effective in terms of driving performance, subjective acceptance and usability.  
474 Second, the nature of the secondary task (i.e., doing math while driving) may imply external validity issues  
475 since such a scenario does not occur in real driving. Third, due to the differences in driving behaviour  
476 between males and females highlighted here and also reported in the literature, especially in terms of speed  
477 (Reed and Robbins, 2008; Li *et. al.*, 2015), gender must also be considered among the experimental factors.  
478 For this reason, balanced groups consisting of equal numbers of males and females should be adopted in  
479 the future. Fourth, the extension of this observation to other road types and environmental contexts should  
480 be the subject of future investigations. Finally, this study was conducted on a fixed-base driving simulator  
481 with drivers encouraged to perform a secondary task while driving; future studies should be conducted in a  
482 more ecological way with real vehicles running on testing tracks and with the secondary task also performed  
483 on a voluntary basis. The issue of how to directly measure crash risk should also be addressed in addition  
484 to driving performance measurements.

485

## 486 **FUNDING**

487 This research did not receive any funds from public, commercial, or not-for-profit sectors. All activities  
488 were conducted in the Laboratory of Road Safety and Driving Simulation (RSDS Lab) at the Department  
489 of Environment, Land and Infrastructure Engineering (Politecnico di Torino, Torino, Italy).

490

## 491 **REFERENCES**

- 492 Ahlstrom, C., Kircher, K., & Kircher, A. (2013). A Gaze-Based Driver Distraction Warning System and  
493 Its Effect on Visual Behavior. *IEEE Transactions on Intelligent Transportation Systems*, 14(2),  
494 965-973. doi: 10.1109/TITS.2013.2247759.
- 495 Akaike, H. (1974). A new look at the statistical model identification. *IEEE transactions on automatic*  
496 *control*, 19(6), 716-723.
- 497 Alm, H., & Nilsson, L. (1994). Changes in driver behaviour as a function of handsfree mobile phones – A  
498 simulator study. *Accident Analysis & Prevention*, 26(4), 441-451. [https://doi.org/10.1016/0001-](https://doi.org/10.1016/0001-4575(94)90035-3)  
499 [4575\(94\)90035-3](https://doi.org/10.1016/0001-4575(94)90035-3).
- 500 Bakhit, P. R., Guo, B., & Ishak, S. (2018). Crash and Near-Crash Risk Assessment of Distracted Driving  
501 and Engagement in Secondary Tasks: A Naturalistic Driving Study. *Transportation Research*  
502 *Record*, 2672(38), 245-254. <https://doi.org/10.1177/0361198118772703>.

- 503 Baldwin, C. L., Roberts, D. M., Barragan, D., Lee, J. D., Lerner, N., & Higgins, J. S. (2017). Detecting  
504 and Quantifying Mind Wandering during Simulated Driving. *Frontiers in Human Neuroscience*,  
505 *11*, 406. <https://doi.org/10.3389/fnhum.2017.00406>.
- 506 Bassani, M., Catani, L., Ignazzi, A.A., & Piras, M. (2018). Validation of a Fixed-Base Driving Simulator  
507 to Assess Behavioural Effects of Road Geometrics. Proceedings of the 17th Driving Simulation &  
508 Virtual Reality Conference, Antibes (France), 101–108.
- 509 Bergasa, L. M., Almería, D., Almazán, J., Yebes, J. J., & Arroyo, R. (2014). Drivesafe: An app for  
510 alerting inattentive drivers and scoring driving behaviors. In *2014 IEEE Intelligent Vehicles*  
511 *Symposium Proceedings*, 240-245. doi: 10.1109/IVS.2014.6856461.
- 512 Burdett, B. R., Charlton, S. G., & Starkey, N. J. (2016). Not all minds wander equally: The influence of  
513 traits, states and road environment factors on self-reported mind wandering during everyday  
514 driving. *Accident Analysis & Prevention*, *95*, 1-7. <https://doi.org/10.1016/j.aap.2016.06.012>.
- 515 Catani, L., & Bassani, M. (2019). Anticipatory Distance, Curvature, and Curvature Change Rate in  
516 Compound Curve Negotiation: A Comparison between Real and Simulated Driving. Proceedings  
517 of the 98th Transportation Research Board Annual Meeting, Washington D.C. (US).
- 518 Chen, W. H., Lin, C. Y., & Doong, J. L. (2005). Effects of Interface Workload of In-Vehicle Information  
519 Systems on Driving Safety. *Transportation Research Record*, *1937*(1), 73-78.  
520 <https://doi.org/10.1177/0361198105193700111>.
- 521 Choudhary, P., & Velaga, N. R. (2019). Effects of phone use on driving performance: A comparative  
522 analysis of young and professional drivers. *Safety Science*, *111*, 179-187.  
523 <https://doi.org/10.1016/j.ssci.2018.07.009>.
- 524 Choudhary, P., Gupta, A., & Velaga, N. R. (2022). Perceived risk vs actual driving performance during  
525 distracted driving: a comparative analysis of phone use and other secondary distractions.  
526 *Transportation Research Part F: Traffic Psychology and Behaviour*, *86*, 296-315.  
527 <https://doi.org/10.1016/j.trf.2022.03.001>
- 528 Denjean, S., Roussarie, V., Kronland-Martinet, R., Ystad, S., & Velay, J.-L. (2012). How does interior car  
529 noise alter driver's perception of motion? Multisensory integration in speed perception. *Acoustics*.  
530 *Acoustics*, Nantes, France. <https://hal.archives-ouvertes.fr/hal-00811257>.
- 531 Dijksterhuis, C., Brookhuis, K. A., & De Waard, D. (2011). Effects of steering demand on lane keeping  
532 behaviour, self-reports, and physiology. A simulator study. *Accident Analysis & Prevention*, *43*(3),  
533 1074-1081. <https://doi.org/10.1016/j.aap.2010.12.014>
- 534 Donmez, B., Boyle, L. N., Lee, J. D., & McGehee, D. V. (2006). Drivers' attitudes toward imperfect  
535 distraction mitigation strategies. *Transportation Research Part F: Traffic Psychology and*  
536 *Behaviour*, *9*(6), 387-398. <https://doi.org/10.1016/j.trf.2006.02.001>.
- 537 Doudou, M., Bouabdallah, A., & Berge-Cherfaoui, V. (2020). Driver Drowsiness Measurement  
538 Technologies: Current Research, Market Solutions, and Challenges. *International Journal of*  
539 *Intelligent Transportation Systems Research*, *18*(2), 297-319. [https://doi.org/10.1007/s13177-019-](https://doi.org/10.1007/s13177-019-00199-w)  
540 [00199-w](https://doi.org/10.1007/s13177-019-00199-w).
- 541 Dumitru, A. I., Gîrbacia, T., Boboc, R. G., Postelnicu, C. C., & Mogan, G. L. (2018). Effects of  
542 smartphone based advanced driver assistance system on distracted driving behavior: A simulator  
543 study. *Computers in Human Behavior*, *83*, 1-7. <https://doi.org/10.1016/j.chb.2018.01.011>.
- 544 Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and  
545 simulated motorway driving. *Transportation Research Part F: Traffic Psychology and Behaviour*,  
546 *8*(2), 97-120. <https://doi.org/10.1016/j.trf.2005.04.012>.
- 547 European Parliament & Council of the European Union (2019). Regulation (EU) 2019/2144 of the  
548 European Parliament and of the Council of 27 November 2019 on type-approval requirements for  
549 motor vehicles and their trailers, and systems, components and separate technical units intended for  
550 such vehicles, as regards their general safety and the protection of vehicle occupants and vulnerable  
551 road users. Retrieved from Official Journal of the European Union:  
552 <http://data.europa.eu/eli/reg/2019/2144/oj>.
- 553 European Parliament & Council of the European Union (2021). Regulation (EU) 2021/1341 of 23 April  
554 2021 supplementing Regulation (EU) 2019/2144 of the European Parliament and of the Council by

555 laying down detailed rules concerning the specific test procedures and technical requirements for  
556 the type-approval of motor vehicles with regard to their driver drowsiness and attention warning  
557 systems and amending Annex II to that Regulation. Retrieved from Official Journal of the  
558 European Union: [http://data.europa.eu/eli/reg\\_del/2021/1341/oj](http://data.europa.eu/eli/reg_del/2021/1341/oj).

559 European Road Safety Observatory (2018). *Driver distraction Summary 2018*. European Commission,  
560 Directorate General for Transport. Retrieved from  
561 [https://ec.europa.eu/transport/road\\_safety/system/files/2021-07/ersosynthesis2018-](https://ec.europa.eu/transport/road_safety/system/files/2021-07/ersosynthesis2018-driverdistraction-summary.pdf)  
562 [driverdistraction-summary.pdf](https://ec.europa.eu/transport/road_safety/system/files/2021-07/ersosynthesis2018-driverdistraction-summary.pdf).

563 Gallahan, S. L., Golzar, G. F., Jain, A. P., Samay, A. E., Trerotola, T. J., Weisskopf, J. G., & Lau, N.  
564 (2013). Detecting and Mitigating Driver Distraction with Motion Capture Technology: Distracted  
565 Driving Warning System. In *2013 IEEE Systems and Information Engineering Design Symposium*,  
566 76-81. doi: 10.1109/SIEDS.2013.6549497.

567 Huemer, A. K., & Vollrath, M. (2011). Driver secondary tasks in Germany: Using interviews to estimate  
568 prevalence. *Accident Analysis & Prevention*, 43(5), 1703-1712.  
569 <https://doi.org/10.1016/j.aap.2011.03.029>.

570 Kaber, D. B., Liang, Y., Zhang, Y., Rogers, M. L., & Gangakhedkar, S. (2012). Driver performance  
571 effects of simultaneous visual and cognitive distraction and adaptation behavior. *Transportation*  
572 *Research Part F: Traffic Psychology and Behaviour*, 15(5), 491-501.  
573 <https://doi.org/10.1016/j.trf.2012.05.004>.

574 Karimi, A., Bassani, M., Boroujerdian, A.M., & Catani, L. (2020). Investigation into passing behavior at  
575 passing zones to validate and extend the use of driving simulators in two-lane roads safety analysis.  
576 *Accident Analysis & Prevention*, 139, 105487. <https://doi.org/10.1016/j.aap.2020.105487>.

577 Kemp, B. J. (1973). Reaction time of young and elderly subjects in relation to perceptual deprivation and  
578 signal-on versus signal-off conditions. *Developmental Psychology*, 8(2), 268-272.  
579 <https://doi.org/10.1037/h0034147>.

580 Kircher, K. (2007). *Driver distraction: A review of the literature* (Final Report VTI rapport 594A).  
581 Swedish National Road and Transport Research Institute.

582 Klauer, C., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). *The Impact of Driver*  
583 *Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study*  
584 *Data* (Final Report DOT HS 810 594). Virginia Tech Transportation Institute and National  
585 Highway Traffic Safety Administration.

586 Kuo, J., Lenné, M. G., Mulhall, M., Sletten, T., Anderson, C., Howard, M., Rajaratnam, S., Magee, M., &  
587 Collins, A. (2019). Continuous monitoring of visual distraction and drowsiness in shift-workers  
588 during naturalistic driving. *Safety Science*, 119, 112-116.  
589 <https://doi.org/10.1016/j.ssci.2018.11.007>.

590 Mase, J. M., Majid, S., Mesgarpour, M., Torres, M. T., Figueredo, G. P., & Chapman, P. (2020).  
591 Evaluating the impact of heavy goods vehicle driver monitoring and coaching to reduce risky  
592 behaviour. *Accident Analysis & Prevention*, 146, 105754.  
593 <https://doi.org/10.1016/j.aap.2020.105754>.

594 May, J. F., & Baldwin, C. L. (2009). Driver fatigue: The importance of identifying causal factors of  
595 fatigue when considering detection and countermeasure technologies. *Transportation Research Part*  
596 *F: Traffic Psychology and Behaviour*, 12(3), 218-224.

597 Mecheri, S., Rosey, F., & Lobjois, R. (2017). The effects of lane width, shoulder width, and road cross-  
598 sectional reallocation on drivers' behavioral adaptations. *Accident Analysis & Prevention*, 104,  
599 65-73. <https://doi.org/10.1016/j.aap.2017.04.019>.

600 Metz, B., Schömig, N., & Krüger, H. P. (2011). Attention during visual secondary tasks in driving:  
601 Adaptation to the demands of the driving task. *Transportation Research Part F: Traffic Psychology*  
602 *and Behaviour*, 14(5), 369-380. <https://doi.org/10.1016/j.trf.2011.04.004>.

603 Milosevic, S. (1997). Drivers' fatigue studies. *Ergonomics*, 40(3), 381-389.  
604 <https://doi.org/10.1080/001401397188215>.

605 *Ministero delle Infrastrutture e dei Trasporti* (2001). *Norme Funzionali e Geometriche per la Costruzione*  
606 *delle Strade*, D.M. 5 novembre 2001, n. 6792, Gazzetta Ufficiale n.3 del 4-1-2002 Suppl. Ordinario  
607 n.5 D.M. 5 Novembre 2001, n. 6792.

608 National Highway Traffic Safety Administration (2018). Traffic Safety Facts. Research Note: Distracted  
609 Driving 2016 (Document No. DOT HS 812 517). Washington, D.C.: U.S. Department of  
610 Transportation. Retrieved from <https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812517>.

611 National Highway Traffic Safety Administration (2019). Traffic Safety Facts. Research Note: Distracted  
612 Driving in Fatal Crashes, 2017 (Document No. DOT HS 812 700). Washington, D.C.: U.S.  
613 Department of Transportation. Retrieved from  
614 <https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812700>.

615 National Highway Traffic Safety Administration (2020). Traffic Safety Facts. Research Note: Distracted  
616 Driving 2018 (Document No. DOT HS 812 926). Washington, D.C.: U.S. Department of  
617 Transportation. Retrieved from <https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812926>.

618 *Nuovo Codice della Strada* (1992). Decreto Legislativo 30 aprile 1992, n. 285 (Gazzetta Ufficiale n.114,  
619 18-5-1992, Suppl. Ordinario n.74).

620 Onate-Vega, D., Oviedo-Trespalacios, O., & King, M. J. (2020). How drivers adapt their behaviour to  
621 changes in task complexity: the role of secondary task demands and road environment factors.  
622 *Transportation Research part F: Traffic Psychology and Behaviour*, 71, 145-156.  
623 <https://doi.org/10.1016/j.trf.2020.03.015>

624 Oviedo-Trespalacios, O., Haque, M. M., King, M., & Washington, S. (2017). Self-regulation of driving  
625 speed among distracted drivers: An application of driver behavioral adaptation theory. *Traffic*  
626 *Injury Prevention*, 18(6), 599-605. <https://doi.org/10.1080/15389588.2017.1278628>.

627 Oviedo-Trespalacios, O., Haque, M. M., King, M., & Demmel, S. (2018). Driving behaviour while self-  
628 regulating mobile phone interactions: A human-machine system approach. *Accident Analysis &*  
629 *Prevention*, 118, 253-262. <https://doi.org/10.1016/j.aap.2018.03.020>.

630 Oviedo-Trespalacios, O., Afghari, A. P., & Haque, M. M. (2020). A hierarchical Bayesian multivariate  
631 ordered model of distracted drivers' decision to initiate risk-compensating behaviour. *Analytic*  
632 *Methods in Accident Research*, 26, 100121. <https://doi.org/10.1016/j.amar.2020.100121>.

633 Papantoniou, P., Papadimitriou, E., & Yannis, G. (2017). Review of driving performance parameters  
634 critical for distracted driving research. *Transportation Research Procedia*, 25, 1796-1805.  
635 <https://doi.org/10.1016/j.trpro.2017.05.148>.

636 Papantoniou, P., Yannis, G., Antoniou, C., Papadimitriou, E., Pavlou, D., & Golias, J. (2016).  
637 Investigating the effect of area type and traffic conditions on distracted driving performance.  
638 *Transportation Research Procedia*, 14, 3839-3848. <https://doi.org/10.1016/j.trpro.2016.05.469>.

639 Philip, P., Sagaspe, P., Taillard, J., Valtat, C., Moore, N., Åkerstedt, T., ... & Bioulac, B. (2005). Fatigue,  
640 Sleepiness, and Performance in Simulated Versus Real Driving Conditions. *Sleep*, 28(12),  
641 1511-1516. <https://doi.org/10.1093/sleep/28.12.1511>.

642 Pietrzak, R. H., Fredrickson, A., Snyder, P. J., & Maruff, P. (2010). A comparison of statistical  
643 approaches used to evaluate change in cognitive function following pharmacologic challenge: an  
644 example with lorazepam. *Human Psychopharmacology: Clinical and Experimental*, 25(4),  
645 335-341. <https://doi.org/10.1002/hup.1121>.

646 Rakauskas, M. E., Gugerty, L. J., & Ward, N. J. (2004). Effects of naturalistic cell phone conversations  
647 on driving performance. *Journal of Safety Research*, 35(4), 453-464.  
648 <https://doi.org/10.1016/j.jsr.2004.06.003>.

649 Reed, N., & Robbins, R. (2008). *The effect of text messaging on driver behaviour: A simulator study*.  
650 Transportation Research Laboratory, Published Project Report No. 367, Berkshire, UK.

651 Reagan, I. J., Cicchino, J. B., Kerfoot, L. B., & Weast, R. A. (2018). Crash avoidance and driver  
652 assistance technologies – Are they used? *Transportation research part F: traffic psychology and*  
653 *behaviour*, 52, 176-190. <https://doi.org/10.1016/j.trf.2017.11.015>.

654 Regan, M. A., Hallett, C., & Gordon, C. P. (2011). Driver distraction and driver inattention: Definition,  
655 relationship and taxonomy. *Accident Analysis & Prevention*, 43(5), 1771-1781.  
656 <https://doi.org/10.1016/j.aap.2011.04.008>.

- 657 Reimer, B., & Mehler, B. (2011). The impact of cognitive workload on physiological arousal in young  
658 adult drivers: a field study and simulation validation. *Ergonomics*, 54(10), 932-942.  
659 <https://doi.org/10.1080/00140139.2011.604431>.
- 660 Rumschlag, G., Palumbo, T., Martin, A., Head, D., George, R., & Commissaris, R. L. (2015). The effects  
661 of texting on driving performance in a driving simulator: The influence of driver age. *Accident*  
662 *Analysis & Prevention*, 74, 145-149. <https://doi.org/10.1016/j.aap.2014.10.009>.
- 663 Shinar, D., Tractinsky, N., & Compton, R. (2005). Effects of practice, age, and task demands, on  
664 interference from a phone task while driving. *Accident Analysis & Prevention*, 37(2), 315-326.  
665 <https://doi.org/10.1016/j.aap.2004.09.007>.
- 666 Sigari, M. H., Pourshahabi, M. R., Soryani, M., & Fathy, M. (2014). A Review on Driver Face  
667 Monitoring Systems for Fatigue and Distraction Detection. *International Journal of Advanced*  
668 *Science and Technology*, 64, 73-100. <http://dx.doi.org/10.14257/ijast.2014.64.07>.
- 669 Sivak, M. (1996). The information that drivers use: is it indeed 90% visual?. *Perception*, 25(9), 1081-  
670 1089. <https://doi.org/10.1068/p251081>.
- 671 Sloomans, F., & Desmet, C. (2019). *Distraction. Thematic File Road Safety N°5* (2nd edition, 2019)  
672 (Research Report No. 2018-T-07-SEN). Vias institute -Knowledge Centre Road Safety.
- 673 Society of Automotive Engineers (2015). *Operational definitions of driving performance measures and*  
674 *statistics*. Surface Vehicle Recommended Practice J2944.
- 675 Stone, M. (1979). Comments on model selection criteria of Akaike and Schwarz. *Journal of the Royal*  
676 *Statistical Society. Series B (Methodological)*, 276-278.
- 677 Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone-induced failures of visual attention  
678 during simulated driving. *Journal of Experimental Psychology: Applied*, 9(1), 23.  
679 <https://doi.org/10.1037/1076-898X.9.1.23>.
- 680 Strayer, D. L., & Drews, F. A. (2004). Profiles in Driver Distraction: Effects of Cell Phone Conversations  
681 on Younger and Older Drivers. *Human Factors*, 46(4), 640-649.  
682 <https://doi.org/10.1518/hfes.46.4.640.56806>.
- 683 Strayer, D. L., Turrill, J., Cooper, J. M., Coleman, J. R., Medeiros-Ward, N., & Biondi, F. (2015).  
684 Assessing Cognitive Distraction in The Automobile. *Human Factors*, 57(8), 1300-1324.  
685 <https://doi.org/10.1177/0018720815575149>.
- 686 Stutts, J., Feaganes, J., Reinfurt, D., Rodgman, E., Hamlett, C., Gish, K., & Staplin, L. (2005). Driver's  
687 exposure to distractions in their natural driving environment. *Accident Analysis & Prevention*,  
688 37(6), 1093-1101. <https://doi.org/10.1016/j.aap.2005.06.007>.
- 689 Taylor, T., Pradhan, A. K., Divekar, G., Romoser, M., Muttart, J., Gomez, R., Pollatsek, A., & Fisher, D.  
690 L. (2013). The view from the road: The contribution of on-road glance-monitoring technologies to  
691 understanding driver behavior. *Accident Analysis & Prevention*, 58, 175-186.  
692 <https://doi.org/10.1016/j.aap.2013.02.008>.
- 693 The Jamovi Project (2021). Jamovi. (Version 2.3.18) [Computer Software]. Retrieved from  
694 <https://www.jamovi.org>.
- 695 Transportation Research Board (2016). *The Highway Capacity Manual: A Guide for Multimodal Mobility*  
696 *Analysis*. Transportation Research Board of the National Academies, 6th Edition.
- 697 Tivesten, E., & Dozza, M. (2014). Driving context and visual-manual phone tasks influence glance  
698 behavior in naturalistic driving. *Transportation Research Part F: Traffic Psychology and*  
699 *Behaviour*, 26, 258-272. <https://doi.org/10.1016/j.trf.2014.08.004>.
- 700 Verster, J. C., & Roth, T. (2011). Standard operation procedures for conducting the on-the-road driving  
701 test, and measurement of the standard deviation of lateral position (SDLP). *International Journal of*  
702 *General Medicine*, 4, 359. doi: 10.2147/IJGM.S19639.
- 703 Victor, T. W., Harbluk, J. L., & Engström, J. A. (2005). Sensitivity of eye-movement measures to in-  
704 vehicle task difficulty. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(2),  
705 167-190. <https://doi.org/10.1016/j.trf.2005.04.014>.
- 706 Wang, C., Li, Z., Fu, R., Guo, Y., & Yuan, W. (2019). What is the difference in driver's lateral control  
707 ability during naturalistic distracted driving and normal driving? A case study on a real highway.  
708 *Accident Analysis & Prevention*, 125, 98-105. <https://doi.org/10.1016/j.aap.2019.01.030>.

- 709 World Medical Association (2018). *WMA Declaration of Helsinki–Ethical Principles for Medical*  
710 *Research Involving Human Subjects*, 9 July 2018. Retrieved from: [https://www.wma.net/what-we-](https://www.wma.net/what-we-do/medical-ethics/declaration-of-helsinki/)  
711 [do/medical-ethics/declaration-of-helsinki/](https://www.wma.net/what-we-do/medical-ethics/declaration-of-helsinki/).
- 712 Young, K. L., Regan, M. A., & Lee, J. D. (2009). Measuring the effects of driver distraction: Direct  
713 driving performance methods and measures. In *Driver Distraction: Theory, effects and mitigation*,  
714 85-105.