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1 **Do driver monitoring technologies improve the driving behaviour of**
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3 **auditory Driver Distraction Warning device on driving performance.**

4
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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.**

Experimental factors	Levels			Type
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).

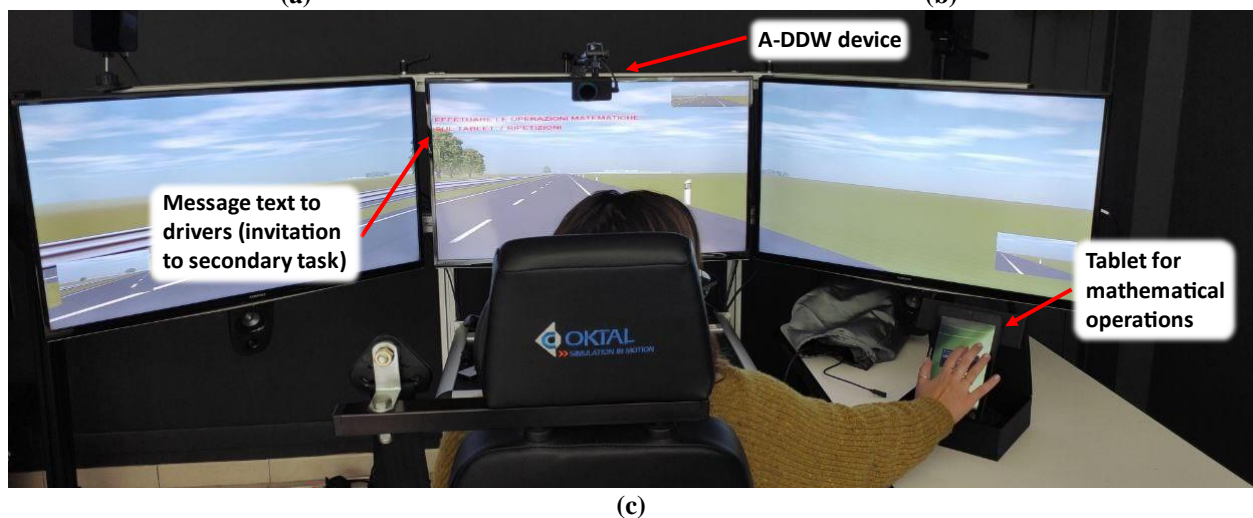
144 The posted speed limit was set at 130 km/h. A safety barrier of 850 mm in height was selected for the
145 median while the barrier along the right roadside was omitted.

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 2nd and the 3rd 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 ± 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.**

Participant characteristics	Group	N	Mean	SD	Minimum	Maximum
Driver age	0	14	43.8	11.9	24	64
	1	14	43.0	11.3	23	61
	2	14	43.4	15.1	23	64
Experience (km/y)	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
Experience (license y)	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)
0 (Baseline)	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)
1 (Distraction)	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)
2 (Distraction + A-DDW)	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)
Factors, covariates (fixed effects):					
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 ⁻⁴ (.010)	-	-	-
Experience (licence y)		-	-	0.0607 (.011)	-0.0162 (.008)
Cluster variable for LMM (random effect):					
Test driver ID		(<.001)	(.109)	-	-
Summary statistics					
AIC		649.64	63.50	402.25	-95.20
BIC		660.04	101.16	414.41	-80.61
R ² marginal		.339	.082	-	-
R ² (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.

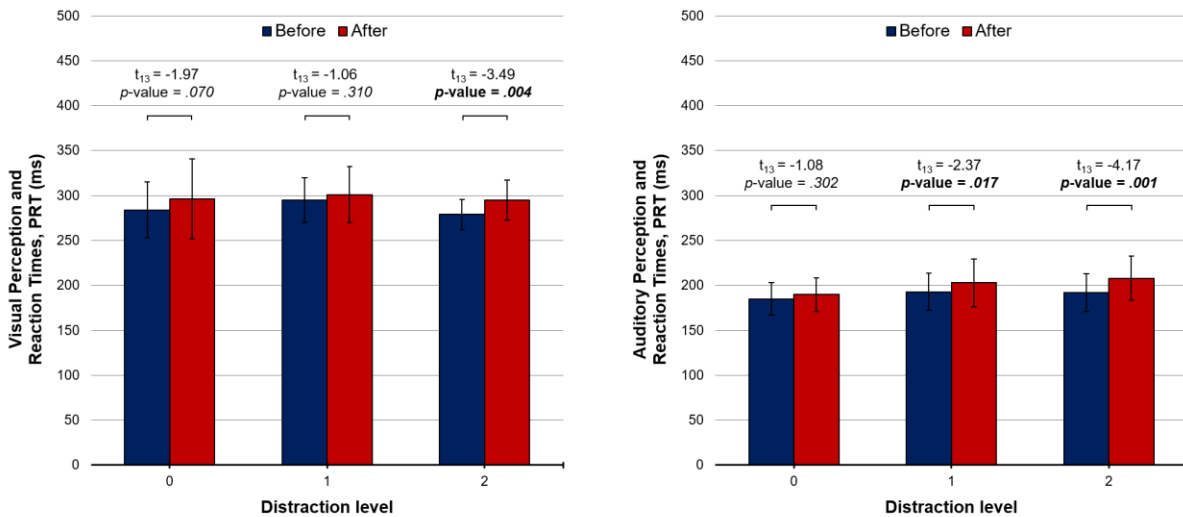
316

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.

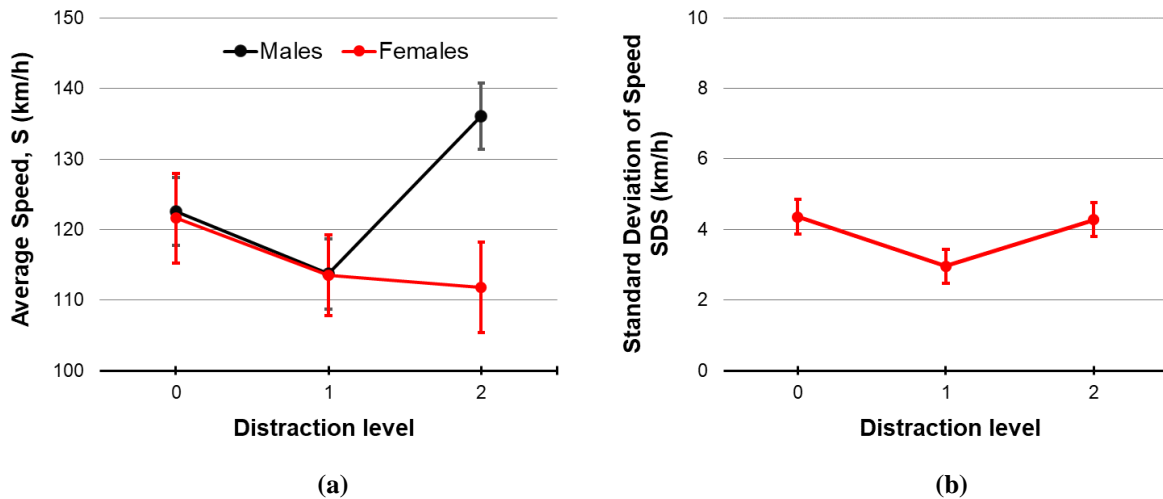
343 The results with the LMMs and GLMs indicate that along motorways the personal characteristics of
344 drivers have a significant influence over speed and a marginal influence over lateral position in the lane. In
345 contrast, longitudinal and transverse control ability are mainly influenced by the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

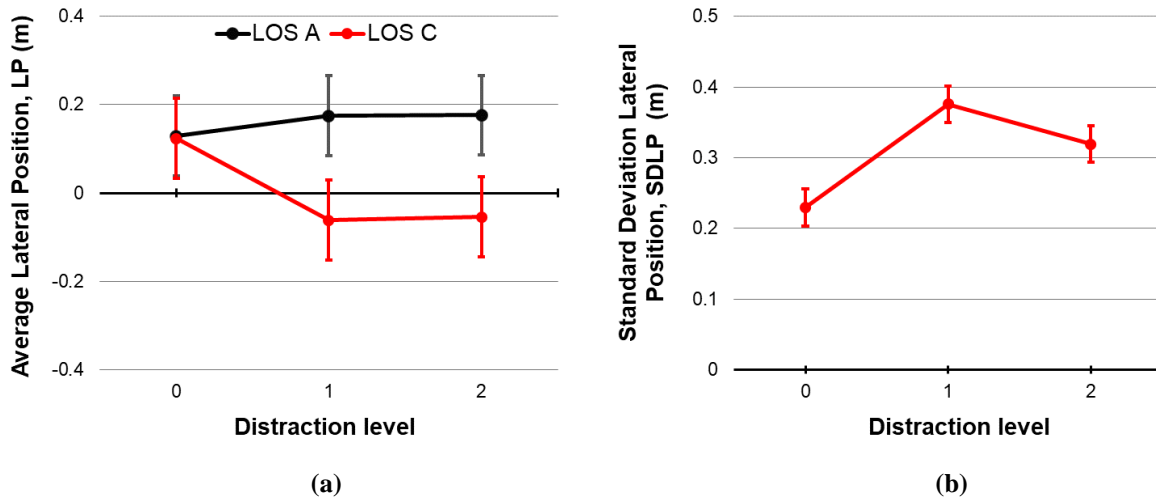


380
 381
 382 **FIGURE 3. Effect plots of the LMM and GLM analyses for the effect of distraction level on (a) average speed**
 383 **(*S*), and (b) standard deviation of speed (*SDS*), respectively. Bars indicate the standard error.**
 384

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

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490

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