

Investigation into passing behavior at passing zones to validate and extend the use of driving simulators in two-lane roads safety analysis

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1 **INVESTIGATION INTO PASSING BEHAVIOR AT PASSING ZONES TO VALIDATE**
2 **AND EXTEND THE USE OF DRIVING SIMULATORS IN TWO-LANE ROADS SAFETY**
3 **ANALYSIS**

4
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10

11 **ABSTRACT**

12 A passing maneuver allows drivers to maintain their desired speed on two-lane highways. However, it entails
13 a high risk of collision with vehicles traveling in the opposite direction. Investigating drivers' behavior while
14 performing passing maneuvers could provide helpful information on the factors that influence this process.
15 Driving simulators have become important tools for driving behavior research studies as they are safe, facilitate
16 the controlled use of experimental variables, and generate detailed output data. It remains to be seen whether
17 simulator results can be considered representative of real-life driving conditions. With respect to passing
18 maneuvers, no study has made a comprehensive and direct comparison between drivers' passing behavior in
19 the field and driver behavior observed in a simulated environment.

20 In this validation study, a fixed-base interactive simulator was used to collect data from fifty-four
21 participants (eighteen Iranians and thirty-six Italians) involved in several traffic scenarios on a two-lane rural
22 highway segment (obtained by varying the speed of opposing vehicles, lead vehicles and headways in the
23 opposite direction). A 3D model and its environmental characteristics were realized from the real segment
24 which had previously been surveyed with drones to collect videos and derive data on real passing maneuvers.

25 The results for the two-sided K-S test revealed no statistically significant difference in the accepted
26 gap, effective accepted gap, perception reaction time, and time to collision variables between the field and the
27 simulator at the 95% confidence level. However, when conducting a one-sided K-S test, some statistical
28 directional differences were found in the cases of the accepted gap and perception reaction time variables,
29 which exhibited lower values in the field compared to the simulator again at the 95% confidence level.
30 Although the passing duration was statistically higher in the simulator than in the field, the shape of the two
31 distributions was not statistically different. Analysis showed that differences in the passing duration are due to
32 the lower passing vehicle speed and lower speed difference with the simulator than in the field, which are
33 caused by truncating headways in the subject direction in the simulator. The cultural background of participants
34 did not result in any discernible difference in passing behavior. The results would support a more extensive
35 use of driving simulators in future passing behavior studies.

36

37

38 **Keywords:**

39 Passing maneuver, Driving simulator, Simulator validity, Two-lane rural highway, K-S test

40

41

42 **HIGHLIGHTS**

43 1. The validity of the driving simulator for studies of passing behavior was investigated.

44 2. Significant similarities in gap acceptance and perception-reaction time behavior in the simulator and
45 in the field were found.

46 3. Level of risk-taking by drivers using the driving simulator was similar to that in the field.

47 4. Although drivers passed at slower speeds in the simulator than in the field, the distribution shapes
48 were similar.

49 5. Iranian and Italian drivers showed similar passing behaviors.

50 1. INTRODUCTION

51 Two-lane rural roads are the main infrastructure type in most countries, especially in developing ones. On
52 two-lane rural roads, vehicles travel in one lane, but they may use the opposite lane to pass slower vehicles
53 ahead where admitted. The passing maneuvers could reduce the delay and improve traffic performance (TRB,
54 2010). However, a passing maneuver is one of the most demanding driving tasks; hence, human error is more
55 likely. Shariat-Mohaymany et al. (2013) found that although passing maneuvers accounted for only 20% of
56 total accidents on two-lane rural highways, they were responsible for 30% of injuries and 50% of fatalities. In
57 Italy, about 37% of rural highway fatalities occurred on two-lane rural highways (Cafiso et al., 2010). About
58 13.9% of passing-related accidents resulted in either a serious injury or fatality (Harwood et al., 2008)

59 Passing maneuvers occur if three conditions are satisfied: first, the driver should be willing to pass
60 (desire to pass); second, an accepted gap is necessary to pass slower vehicles (the gap acceptance); finally, the
61 passing maneuver has to be performed and completed (Farah and Toledo, 2010). The scenario that favors the
62 occurrence of these three conditions has been investigated at driving simulators by a few authors. To better
63 understand the drivers' desire to pass, Bar-Gera and Shinar (2005) studied the most appropriate speed
64 differential between the leading and the passing vehicles. Farah and Toledo (2010) modeled the passing
65 decision choice on two levels. The first level captured the drivers' desire to pass and the second level measured
66 the driver's acceptance of an available passing gap. To identify the important variables that affect gap
67 acceptance behavior (the second stage of a passing maneuver), some simulator studies were carried out in the
68 past (Leung and Starmer, 2005, Farah et al., 2007, Hegeman et al., 2007, Farah et al., 2009b, Toledo and Farah,
69 2011). The last stage of a passing maneuver was analyzed in the past (Jenkins and Rilett, 2005, Charlton, 2007,
70 Farah et al., 2008, Farah et al., 2009a, Bella, 2011, Jamson et al., 2012, Farah, 2013, Vlahogianni, 2013, Levulis
71 et al., 2015, Farah, 2016). However, the main question regarding simulator-based studies is whether their
72 results can be used to predict driver behavior in the real world.

73 In general, data collection with a driving simulator is cheaper and safer than in the field, and it also
74 provides more detailed data on vehicle speed and trajectories and driver behavioral factors. Furthermore, the
75 same scenario can be used for several drivers with full control of the variables involved in the study. That said,
76 the behavioral validity value for the driving simulator has to be reached; otherwise the findings cannot be
77 representative of real-life driving conditions (Lee, 2011).

78 There has been just one study comparing field and simulator passing maneuver data (Llorca and Farah,
79 2016). Some similarities were found between the passing time and passing distance for completed maneuvers.
80 However, drivers passed faster, and the passing end clearance was greater in the simulator than in the field.
81 They observed similar distributions of accepted gaps, and a significant difference between rejected gap
82 distributions, and also between critical gaps in the simulator and in the field. This validation study had some
83 shortcomings: (i) the participants did not have the same characteristics as the drivers in the field study, i.e.,
84 simulator participants and field drivers were from two different countries, and simulator participants were
85 younger than those in the field; (ii) the distribution of gaps was different from those observed in the field, and

86 they also truncated the distribution for small and large values; finally, (iii) all simulation scenarios were
87 designed with no sight distance limitations.

88 As regards shortcoming (ii), it should be pointed out that as the opposite gaps decrease, the probability
89 of having unsafe passing maneuvers will increase (Mwesige et al. (2016). As a result, when drivers face short
90 headways, they will accept more critical gaps. Therefore, the gaps in the opposite direction should have the
91 same distribution as those of the field study to get reliable outputs from the simulation. Concerning the
92 shortcoming (iii), Llorca et al. (2013) observed that the sight distance limitation has a significant effect on
93 drivers' passing performance. Hence, the simulated scenario and the real one should exhibit the same sight
94 conditions and limitations if they are to be compared.

95 This study explores the similarities and differences in driver passing behaviors between real and
96 simulated environments for two-lane rural highways. With care taken to address the shortcomings of previous
97 studies, field observations and simulator experiments for the same scenarios were carried out and the results
98 compared. In this experiment, traffic conflict indicators were used as surrogate measures in road safety
99 evaluation. Traffic conflicts may be divided into serious, slight, and, potential conflicts (Laureshyn et al.,
100 2010). Similar to a traffic accident, road users do not consciously want to put themselves into a serious conflict
101 (Uzondu et al., 2018). Hence, serious traffic conflicts could better reflect the level of safety for a road section
102 or intersection. Serious traffic conflicts are determined using the critical value of indicators.

103 For example, Time-to-Collision (*TTC*) has been widely used in a number of safety evaluation studies.
104 Based on the area of study and facility type, the critical value of *TTC* varies between 1.5 and 5 s (Boroujerdian
105 et al., 2014). Several studies have used *TTC* to evaluate the safety of passing maneuvers. Khoury and Hobeika
106 (2007) employed a 2 s critical value of *TTC* for passing maneuvers. Some other studies (Farah et al., 2009a,
107 Shariat-Mohaymany et al., 2013, Mohaymany et al., 2015) adopted a 3 s critical value. Mwesige et al. (2016)
108 applied both the 2 s and 3 s critical value in their study; they eventually proposed a 3 s as the critical value.
109 However, the use of traffic indicators in road safety studies using a simulator needs to be validated in this
110 environment, especially for serious traffic conflicts.

111 The paper is organized as follows: Section 2 presents the methodology which includes the objectives
112 of the study, test track characteristics, materials and equipment used, experimental design, information on
113 participants, variables for comparing passing behavior, data collection and manipulation. Section 3 includes a
114 comparison of the two outputs (from field and simulator experiments), while Section 4 provides a discussion
115 of results, and Section 5 presents the conclusions and the implications of this work.

116

117 **2. METHODOLOGY**

118 Field observations were conducted with a drone (Phantom 4 Pro). The simulator study was conducted using a
119 fixed-base driving simulator, where the same road geometry and traffic conditions of the field study were
120 replicated with a dedicated software.

121 In the following, different variables, each representing a particular aspect of passing behavior, are
122 analyzed and compared in the field (Section 2.1) and at the simulator (Section 2.2). For example, the variable

123 for speed difference can measure the desire of drivers to pass; accepted gap, and effective accepted gap show
 124 the gap acceptance behavior of drivers; perception-reaction time and passing duration represent the passing
 125 performance of drivers; and the time-to-collision measures the risk perception of drivers.

126

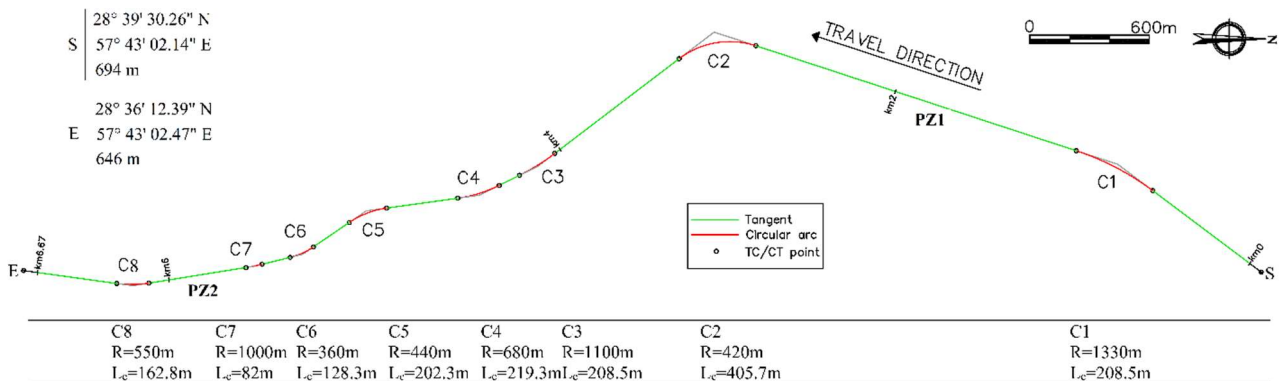
127 **2.1 Field investigation**

128 **2.1.1 Test track**

129 The test track forms part of a 100 km long two-lane highway that connects Jiroft and Faryab (Iran). Figure 1
 130 shows the characteristics of the horizontal alignment of the section used in the experiment. The alignment
 131 consists of eight horizontal curves with a radius between 360 and 1330 m. The lane width is 3.45 m. The road
 132 marking width is 15 cm, and there is no paved shoulder. In Figure 1, PZ1 and PZ2 indicate the first and the
 133 second passing zones that were monitored by the drone.

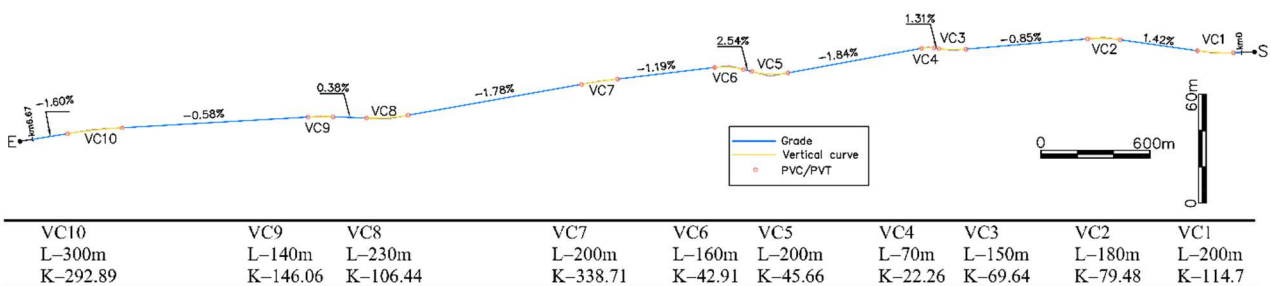
134 Figure 2 shows the vertical profile of the road track. The absolute vertical grade ranges from 0.38 to
 135 2.54%. The test track consists of ten vertical curves all with a length of between 70 and 300 m. All the data
 136 were taken from as-built surveys and then used to build a 3D highway model with the simulator software.
 137 Video records taken from the drivers' point of view were collected in both directions of the test track. Videos
 138 also provided spatial information such as marking details, vertical signs, roadside objects, and terrain features.
 139 Figure 3 shows pictures of both the simulated and real 3D test track.

140



141 **Figure 1: Horizontal alignment of road track (PZ1: passing zone 1, PZ2: passing zone 2)**

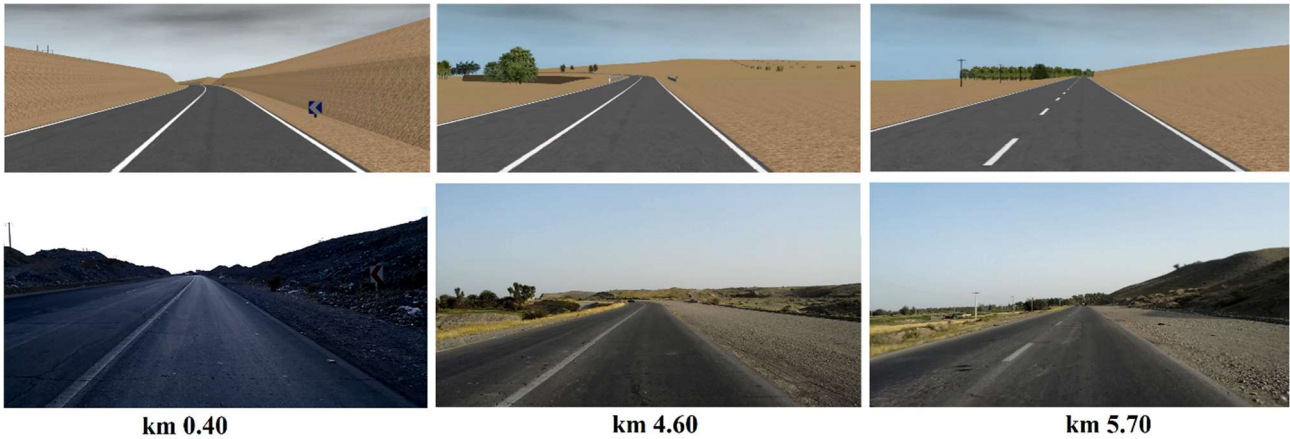
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143

144 **Figure 2: Vertical profile of test track (PVC: Point of vertical curvature, PVT: Point of vertical tangency)**

145



146
147 **Figure 3: Pictures of 3D simulated (above) and real (below) environments at three sections of the test track**
148

149 **2.1.2 Field study equipment**

150 Field data were collected using a Phantom 4 Pro drone on working days between 8:00 AM to 6:00 PM. The
151 drone was equipped with a 1-inch 20-megapixel sensor capable of shooting UHD 4K (4096×2160) video at
152 60 fps, and a 3-axis gimbal to minimize camera oscillations. The maximum resistance to wind speed was
153 10 m/s and the flight time was about 30 min. The minimum altitude of the drone during video recording was
154 150 m. As a result, there was no impact on driver behavior. The total length of the passing zone together with
155 about 50 m of the adjacent no passing zones were covered by the video camera.

156 The field data was collected by the drone over the course of fifteen flights. The video recording time
157 for each flight was between 15 and 20 min. The videos were recorded in both PZ1 and PZ2 (Figure 1) The
158 timestamps for vehicle positions were extracted from the field recording videos using the open source video
159 analysis software *Kinovea* (Charmant, 2016). As a result, the observed variables were calculated from the
160 timestamps of vehicle positions.

161

162 **2.2 Laboratory investigation**

163 **2.2.1 Driving simulator equipment**

164 The simulation study was conducted using the fixed-base driving simulator at the Politecnico di Torino. The
165 device, manufactured by Oktal (now *AV Simulation*, France) was equipped with a dedicated software and the
166 components listed in Table 1.

167

168 **Table 1: Specifications of the fixed-base driving simulator.**

Computers and monitors	
CPU	Quad-core
Video card	NVIDIA GeForce® GTX 780 Ti
Memory	8 Gb of random-access memory
Monitor	Three 32-inch full HD (cover approximately 130° of driver field of view)
Hardware	
Cockpit	Car seat, steering wheel, manual gearbox, pedals, and dashboard
Interactions between vehicle and road	Steering wheel returns active force feedback to the driver, simulating wheels' rolling, pavement roughness, and shocks. Vibration pads return vehicle vibrations on the seat and pedals
Software	
SCANeR™studio	Design tracks, manage the vehicle parameters, generate the experimental scenarios, run the simulations, collect and extract data

169

170 **2.2.2 Driving simulator experimental design**

171 All scenarios were designed with daytime and good weather conditions. The speed and path of all simulated
 172 vehicles were programmed and set at constant values in order to generate traffic with the desired distribution
 173 of headways.

174 As shown in Table 2, the three factors considered in the experimental design were headways of
 175 opposite vehicles, the speed of opposite vehicles, and the speed of lead vehicles. These factors include three
 176 levels (denoted by the values -1, 0, and +1) reported in Table 3. Three Gamma distributions were fitted on the
 177 observed headways data of the field study at the starting point for the passing zones for the three traffic volume
 178 levels for the opposite direction (minimum equal to 128 veh/h, median equal to 268 veh/h, and maximum equal
 179 to 332 veh/h). Figure 4a, 4b, and 4c show these fitted gamma distributions. The 15th, 50th and 85th percentiles
 180 of speeds for opposing vehicles from the field data were assumed to generate the simulated vehicles in the
 181 simulation. The speed levels of lead vehicles were assumed again as 15th, 50th and 85th percentiles of speeds
 182 observed in the 71 passing maneuvers surveyed in the field study along the travel direction. The headways in
 183 the subject direction were drawn from an exponential distribution by the parameter $\lambda = 13.094$ that truncated
 184 from 5 to 20 s intervals. As shown in Figure 4d, the exponential distribution is fitted on field headways in the
 185 subject direction. The truncation of lower headways was done to avoid the formation of platoons. Since the
 186 experiment time was limited, headways longer than 20 s were truncated.

187 To design experiments, a full factorial 3³ design, i.e. twenty-seven scenarios, was used. Based on a
 188 pilot study performed in advance, a maximum of four scenarios per driver was assumed. By assigning three
 189 scenarios per driver, nine blocks with a block size of 3 were adopted. Since the block size was lower than the
 190 combinations of the factors, the partial confounding method of Wilkie (1961) was used to assign the three
 191 scenarios to each driver, thus six main effects did not confound, while the other twenty interactions were
 192 confounded. Hence, a single replicated 3³ confounded factorial design in 9 blocks size was used as shown in
 193 greater detail in Table 3Table . By considering six replicates, the total number of participants was fifty-four.
 194 Each participant carried out a block of three specific scenarios; blocks were assigned randomly to participants
 195 in each replicate. In addition, the order of scenarios in each block was randomly assigned to each participant.

196

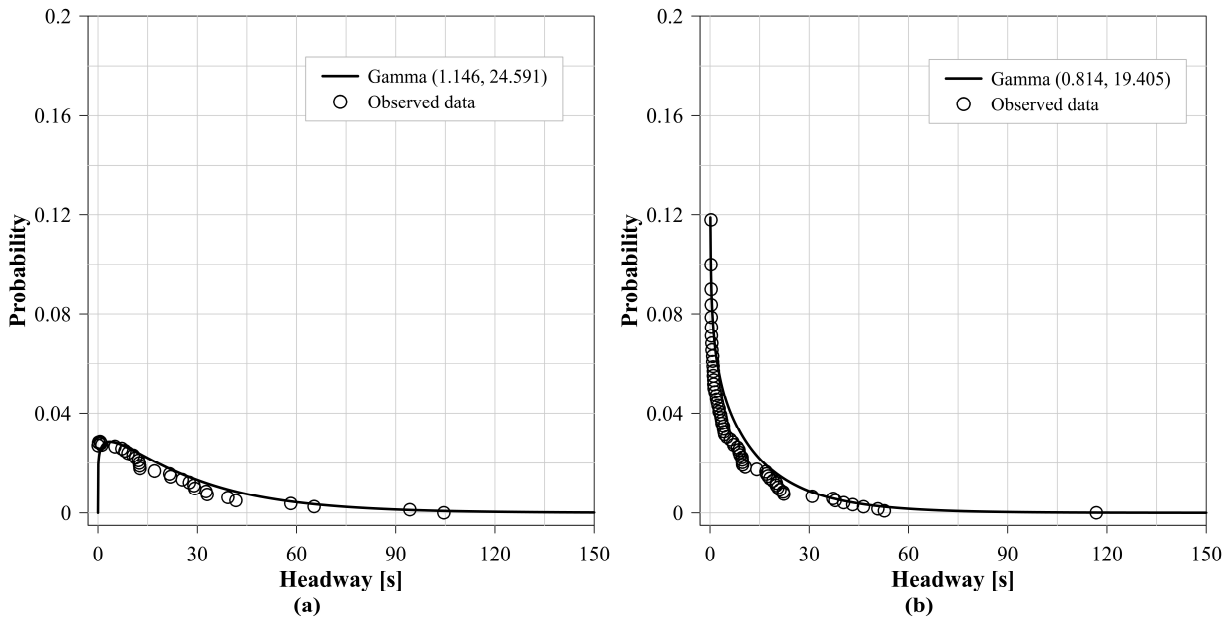
197 **Table 2: Factors included in the experimental design.**

Factors	Levels		
	-1	0	1
Headways of opposite vehicles (A) drawn from	Gamma distribution ($\alpha=0.844, \beta=12.956$)	Gamma distribution ($\alpha=0.814, \beta=19.405$)	Gamma distribution ($\alpha=1.146, \beta=24.591$)
Speed of opposite vehicles (B)	65.2 km/h	81.5 km/h	96.4 km/h
Speed of lead vehicles (C)	48.5 km/h	68.5 km/h	77.6 km/h

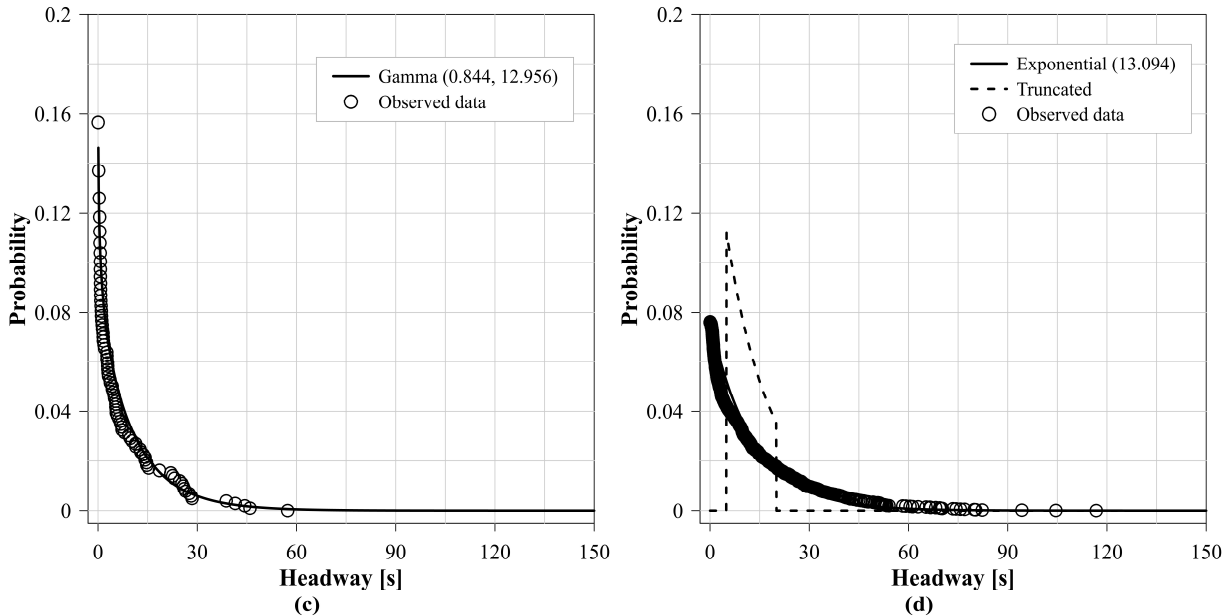
198
199 **Table 3: Twenty-seven different scenarios and factor variations included in the study. The values -1, 0 and +1 are**
200 **depicted in Table 2.**

Blocks	1			2			3			4			5			6			7			8			9			
Scenarios	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
Factors	A	-1	1	0	1	0	-1	0	-1	1	0	-1	1	0	-1	1	0	-1	1	0	-1	0	-1	1	-1	1	0	
	B	-1	0	1	0	1	-1	1	-1	0	-1	0	1	0	1	-1	-1	0	-1	0	1	0	1	-1	1	-1	0	
	C	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1

201



202



203
204 **Figure 4: Fitted distributions on headway data in the opposite direction (Gamma distributions for three traffic**
205 **levels: (a) lowest traffic level (i.e., highest headway level), (b) median traffic level, and (c) highest traffic level**
206 **(i.e., lowest headway level). Fitted distributions (d) on headway data in the subject direction: exponential and**
207 **truncated Exponential distributions (dashed line).**

208 2.2.3 Participants

209 In accordance with the Code of Ethics of the World Medical Association (Williams, 2008), fifty-four licensed
210 drivers were involved in the experiment on a voluntary basis without receiving any benefit or payment. All
211 participants signed an informed consent form prior to the experimental session. Thirty-six individuals were
212 Italian (22 males and 14 females) aged between 21 and 61 years old with a mean 40.4 and a standard deviation
213 of 11.8 years. The other 18 were Iranian (14 males and 4 females) aged between 23 and 37 years old with a
214 mean of 29.1 and a standard deviation of 4.0 years. Prior to the main experiment, all participants attended a
215 training session and drove for at least 10 minutes to familiarize themselves with the simulator. Each driver
216 completed three scenarios out of 27. With the simulation study being conducted in Italy, the Iranian participants
217 were chosen from candidates who had recently come to Italy and did not have any driving experience in the
218 country.

219

220 2.2.4 Experiment protocol, data collection, and manipulation

221 The longitudinal and lateral position, speed and acceleration of the subject and all simulated vehicles in the
222 simulated scenario were collected at the frequency of 10 Hz. From this raw data, passing maneuver related
223 variables were calculated based on the definition provided in the previous section.

224 The simulator experimental protocol included:

- 225 i. completion of a pre-drive questionnaire;
- 226 ii. performance of pre-drive cognitive tests (visual and auditory);
- 227 iii. driving experience in three scenarios with two-minute rest intervals;
- 228 iv. performance of post-driving cognitive tests; and
- 229 v. completion of a post-drive questionnaire.

230 The pre-drive questionnaire was designed to assess participants' health and physical condition levels.
231 In pre- and post-cognitive tests, reaction times to visual and auditory stimuli of participants were measured
232 using an online platform to detect induced mental fatigue in participants after the tests. In the first part of the
233 post-drive questionnaire, participants reported on the precision levels of on-board devices. In the second part,
234 the design of which was based on a suggestion from (Kennedy et al., 1993), participants declared whether they
235 had suffered from any kind of simulation sickness.

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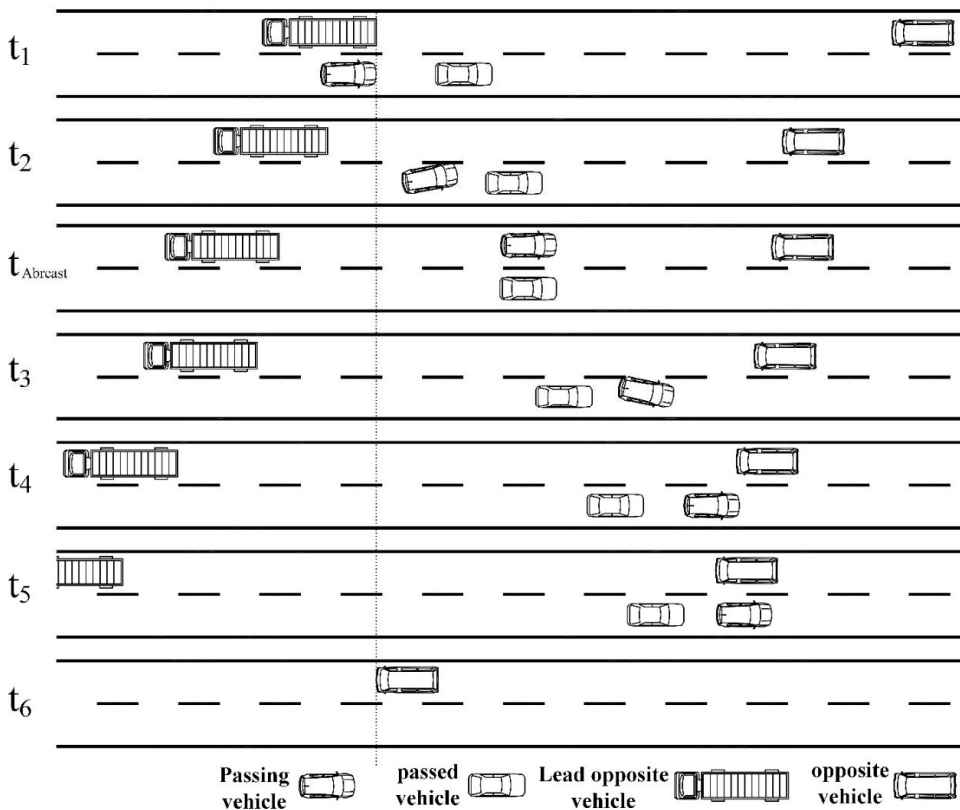
237 2.3 Observed variables

238 To validate behavior in passing maneuvers, the following variables were selected and extracted from the field
239 and simulator studies (the visual definition of variables are presented in Figure 5):

- 240 i. **passing duration** ($PD = t_3 - t_2$), as the time when the first wheel of the passing vehicle crossed
241 the centerline at the initiation of maneuver up to the time when the last wheel crossed the
242 centerline again to end the maneuver,
- 243 ii. **effective accepted gap** ($EAG = t_4 - t_2$), as the time between the initiation of a passing
244 maneuver and the arrival of the passing vehicle to the opposing vehicle,

- 245 iii. **time-to-collision** ($TTC = t_5 - t_3$), equal to the time necessary for an opposing vehicle to collide
 246 with the passing vehicle while the latter is completing a takeover maneuver,
 247 iv. **accepted gap** ($AG = t_6 - t_1$), the time gap between subject vehicle and the nearest vehicle
 248 moving in the opposite direction,
 249 v. **perception-reaction time** ($PRT = t_2 - t_1$), as the difference in time when the passing vehicle
 250 and the lead opposite vehicle are side by side up to the point of initiation of the passing
 251 maneuver,
 252 vi. **acceleration phase time** ($t_{accel.} = t_{Abreast} - t_2$), the time from the beginning of passing maneuver
 253 to when the vehicles are abreast of one another,
 254 vii. **back-to-lane phase time** ($t_{bit} = t_3 - t_{Abreast}$), the time frame from abreast position to when the
 255 passing vehicle returns to proper lane.

256 The speed of passing vehicles ($S_{passing}$) and speed difference in passing and passed vehicles (dS) from
 257 the onset of passing zones were also compared for field and simulator situations. Figure 5 indicates different
 258 timestamps on which the variables were defined.
 259



260
 261
 262 **Figure 5: Timestamps for definition of passing maneuver variables**
 263

264

265 2.4 Statistical comparison between field and simulator data

266 A two-sample Kolmogorov–Smirnov (K-S) test was used to investigate the significance of the differences
267 between two data populations, based on the two sample distributions obtained from field and simulator
268 investigations. The best results are achieved when the sample sizes are sufficiently large, at least 15 (Kanji,
269 2006).

270 Let $x;(x_1, x_2, \dots, x_m)$ and $y;(y_1, y_2, \dots, y_n)$ be two independent random samples of sizes m and n which
271 were drawn from populations with F and G cumulative distribution functions (CDFs). The null hypothesis (H_0)
272 can be tested against the two-sided alternative hypothesis (H_a) (Berger and Zhou, 2014):

$$273 H_0 : F(t) = G(t), \text{ for every } t \quad (1)$$

$$274 H_a : F(t) \neq G(t), \text{ for at least one value of } t \quad (2)$$

275 The null hypothesis (H_0) can also be tested against one of the following one-sided alternative (H_a) hypotheses:

$$276 H_a : F(t) > G(t), \text{ for all values of } t, \text{ strictly greater for at least one value of } t \quad (3)$$

$$277 H_a : F(t) < G(t), \text{ for all values of } t, \text{ strictly smaller for at least one value of } t \quad (4)$$

278 The statistic of the test for the alternative hypothesis of $F(t) \neq G(t)$ was calculated as follows:

$$279 D = \max | F_m(t) - G_n(t) |, \min(x, y) \leq t \leq \max(x, y) \quad (5)$$

280 where $F_m(t)$ and $G_n(t)$ are empirical CDFs for the x and y samples, respectively. For the two alternative
281 hypotheses of $F(t) > G(t)$ and $F(t) < G(t)$ for some value(s) of t , the statistic of the test was calculated as per
282 eq. 6 and eq. 7, respectively:

$$283 D^+ = \max [F_m(t) - G_n(t)], \min(x, y) \leq t \leq \max(x, y) \quad (6)$$

$$284 D^- = \max [G_n(t) - F_m(t)], \min(x, y) \leq t \leq \max(x, y) \quad (7)$$

285 To test H_0 at the significance level of 0.05, H_0 could be rejected in favor of H_a if the calculated p -value is lower
286 than 0.05.

287

288 3. RESULTS

289 Table 6 presents a summary of the variables observed in the field and driving simulator studies. The simulation
290 data are presented in three age groups (Iranian younger than 45, Italian younger than 45, and Italian older than
291 45). Furthermore, the effect of age on passing behavior was measured by comparing the young and old groups.
292 A comparison between Iranian and Italian drivers also provided a more comprehensive view of the universality
293 of results. A cursory examination of the results of the post-drive simulator sickness questionnaire revealed
294 eyestrain and sweating to be the most commonly reported ailments affecting participants. The incidence of
295 sickness or discomfort was, however, limited (low) and did not appear to influence drivers' behavior during
296 the experiment. It should be noted that two participants failed to complete the experiment, thus their data were
297 removed from the database.

298 The results of the t -test for visual (p -value = 0.705) and auditory (p -value = 0.839) tests before and
299 after driving with the simulator show that there is no statistically significant difference between the cognitive
300 status of drivers before and after driving. Since drivers did not change their cognitive performances during the
301 tests, it is clear that the collected data were not affected by changes in psychomotor skills. The results of the

302 post-drive questionnaire which provided driver feedback on the devices show that most of the test drivers
 303 perceived the on-board equipment (acceleration, pedal, and gearbox) to be similar to that used in real-life.
 304 However, they were not fully satisfied with the brake response which did not correspond with real-life
 305 conditions.

306 The total number of passing maneuvers recorded in the field study along the travel direction (PZ1 and
 307 PZ2 in Figure 1) was 71. However, the number of observations for each variable presented in Table 6 is not
 308 equal to that of the field study. This is because the road coverage and recording time of the drone were limited.

309

310 **Table 6: Descriptive statistics of variables in field and driving simulator (# indicates the number of data)**

Sample	variable	#	Mean	SD	Min.	Max.
Field (Iranian)	<i>AG</i> (s)	65	45.96	25.71	16.45	132.6
	<i>EAG</i> (s)	43	26.16	19.83	5.77	90.62
	<i>PRT</i> (s)	45	6.161	9.873	0.20	49.99
	<i>TTC</i> (s)	68	12.55	13.48	0.63	70.70
	<i>PD</i> (s)	47	7.74	2.46	3.07	14.68
	<i>t_{accel.}</i> (s)	50	3.97	1.63	1.70	8.40
	<i>t_{bit}</i> (s)	52	4.55	2.31	1.30	12.80
	<i>S_{passing}</i> (m/s)	71	23.63	5.11	9.52	37.43
Simulator (Iranian younger than 45 years)	<i>dS</i> (m/s)	71	5.12	4.13	-0.69	18.14
	<i>AG</i> (s)	31	70.65	50.57	17.16	163.53
	<i>EAG</i> (s)	31	23.00	13.64	9.50	65.80
	<i>PRT</i> (s)	31	11.14	15.74	0.50	60.50
	<i>TTC</i> (s)	31	12.99	12.96	1.07	57.00
	<i>PD</i> (s)	31	10.82	2.91	5.60	16.80
	<i>t_{accel.}</i> (s)	31	4.82	1.47	2.40	9.70
	<i>t_{bit}</i> (s)	31	6.00	2.49	2.70	11.90
Simulator (Italian younger than 45 years)	<i>S_{passing}</i> (m/s)	31	18.07	4.29	12.02	29.66
	<i>dS</i> (m/s)	31	1.38	2.65	-1.46	10.54
	<i>AG</i> (s)	32	61.28	46.16	13.36	163.53
	<i>EAG</i> (s)	32	20.64	12.73	5.10	63.20
	<i>PRT</i> (s)	32	8.77	12.33	0.60	48.50
	<i>TTC</i> (s)	32	11.16	12.16	1.10	54.20
	<i>PD</i> (s)	32	9.58	2.55	4.10	16.00
	<i>t_{accel.}</i> (s)	32	4.64	2.00	2.10	11.90
Simulator (Italian older than 45 years)	<i>t_{bit}</i> (s)	32	4.94	1.82	2.00	8.70
	<i>S_{passing}</i> (m/s)	32	20.19	5.57	12.82	32.88
	<i>dS</i> (m/s)	32	3.27	4.11	-1.41	11.89
	<i>AG</i> (s)	25	59.81	45.45	22.59	163.47
	<i>EAG</i> (s)	25	20.11	10.32	7.80	44.20
	<i>PRT</i> (s)	25	8.32	11.50	0.40	46.90
	<i>TTC</i> (s)	25	10.18	8.83	0.40	33.30
	<i>PD</i> (s)	25	10.05	2.52	5.80	14.40
Simulator (All participants)	<i>t_{accel.}</i> (s)	25	4.28	1.52	2.10	7.00
	<i>t_{bit}</i> (s)	25	5.76	2.49	1.20	10.80
	<i>S_{passing}</i> (m/s)	25	19.99	4.42	13.54	32.16
	<i>dS</i> (m/s)	25	3.29	3.84	-4.68	13.01
	<i>AG</i> (s)	88	64.16	47.27	13.36	163.53
	<i>EAG</i> (s)	88	21.32	12.36	5.10	65.80
	<i>PRT</i> (s)	88	9.48	13.33	0.40	60.50
	<i>TTC</i> (s)	88	11.52	11.55	0.40	57.00
Simulator (All participants)	<i>PD</i> (s)	88	10.15	2.70	4.10	16.80
	<i>t_{accel.}</i> (s)	88	4.60	1.69	2.10	11.90
	<i>t_{bit}</i> (s)	88	5.55	2.29	1.20	11.90
	<i>S_{passing}</i> (m/s)	88	19.39	4.87	12.02	32.88
	<i>dS</i> (m/s)	88	2.61	3.65	-4.68	13.11

311 In the simulator study, a total of 373 passing maneuvers were recorded; however, only 88 of these
312 were in the same passing zones considered in the field observations (PZ1 and PZ2 in Figure 1). To compare
313 maneuvers performed with the same sight distance limitation and road geometry, only these 88 passing
314 maneuvers were used in the analyses. Table 6 shows that, out of these 88 passing maneuvers, 31 were
315 conducted by Iranian participants and 57 by Italian participants (32 by those younger than 45, 25 by those
316 older than 45).

317 Cumulative probability distributions of the passing variables resulting from field and simulator
318 investigations were evaluated and compared. In the case of the simulator, four categories, including Iranians
319 younger than 45, Italians younger than 45, Italians older than or equal to 45, and pooled Italian participants
320 were defined to check passing behavior differences in terms of nationality and age.

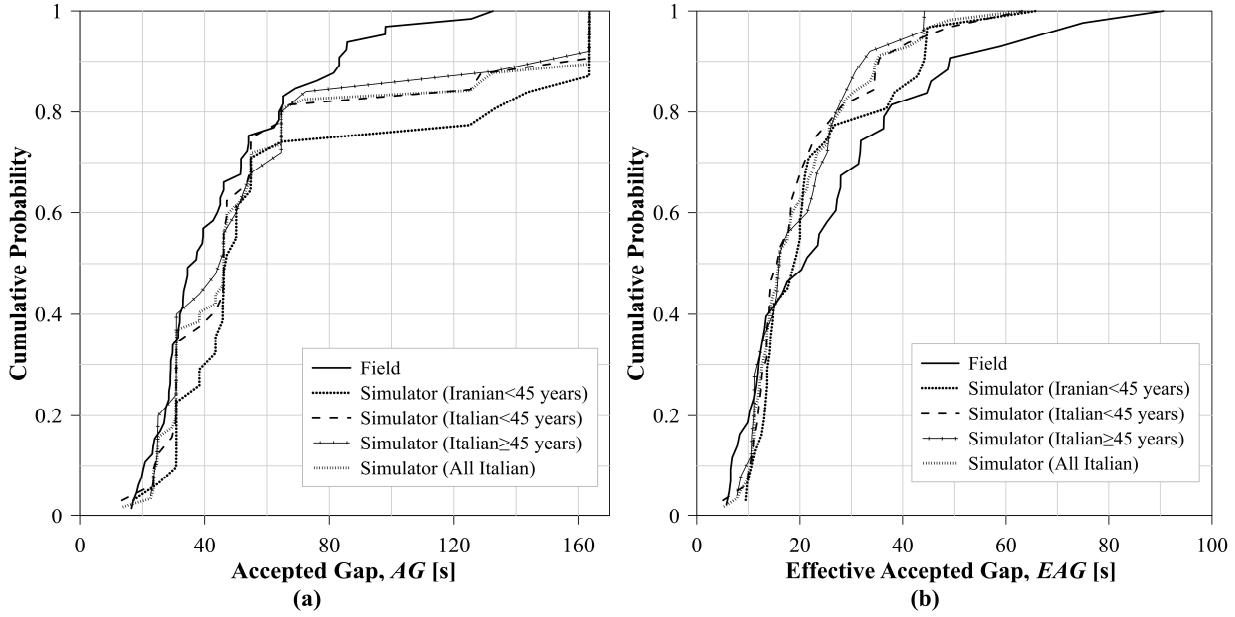
321

322 **3.1 Accepted (*AG*) and effective accepted gap (*EAG*)**

323 Figure 6a indicates the cumulative probability distributions for the *AG*. The distributions for young
324 (< 45 years) and old (≥ 45 years) Italian drivers' behaviors are very similar as confirmed by the K-S test results
325 presented in Table 7 ($D = 0.1100$, p -value = 0.996). Iranians accepted slightly greater, albeit insignificant, gaps
326 compared to Italians in the simulator ($D = 0.1720$, p -value = 0.592). As shown in Table 7, there are no
327 significant differences between field and simulator accepted gap distributions at the 95% confidence level.
328 However, it seems that field distribution values are lower than those for the simulator, a finding which might
329 be of practical significance. Hence, the null hypothesis was tested against a one-sided alternative hypothesis.
330 The results show that the *AG* distribution for Iranians was lower in the field than at the simulator at the 95%
331 confidence level ($D = 0.2973$, p -value = 0.025). The outcomes of one-sided tests for other *AG* distributions
332 did not reveal any significant differences. If there is a type II error (unable to reject the wrong null hypothesis)
333 during the conduct of statistical tests, the differences suggest that the *AG* field values are lower than the
334 simulator. An increase in sample size leads to a reduction in the probability of type II errors. The differences
335 in *AG* distributions between field and simulator studies were more evident in the right tails. Recorded videos
336 in the field were short (about 15 minutes), and some of the large accepted gaps in the initial part or end of the
337 videos were not recorded, which could explain the lower frequency of large accepted gaps in the field study.

338 A variable that provides a more direct measure of the risk taken by drivers in accepting a gap is the
339 effective accepted gap (*EAG*). The distributions of *EAG* are shown in Figure 6b. Even though the *AG*
340 distribution of Iranian participants in simulator has the biggest divergence from the field ($D = 0.2973$,
341 p -value = 0.050), the distribution of *EAG* of Iranians in the simulator is the closest to field data ($D = 0.2384$,
342 p -value = 0.248). The results for the one-sided K-S test also show no significant differences between the field
343 study and simulator *EAG* distributions. However, these insignificant differences were bigger between field and
344 simulator distributions in the tails of distribution, especially in the right tail, which represents the high values
345 of *EAG*. The high values of *EAG* are less important from a safety perspective.

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Figure 6: Comparison of driver gap acceptance behavior in field and simulator: (a) accepted gap (AG), and (b) effective accepted gap (EAG)

Table 7: The results of the K-S test for each pair of distribution functions of Figure 6a (below the diagonal) and Figure 6b (above the diagonal)

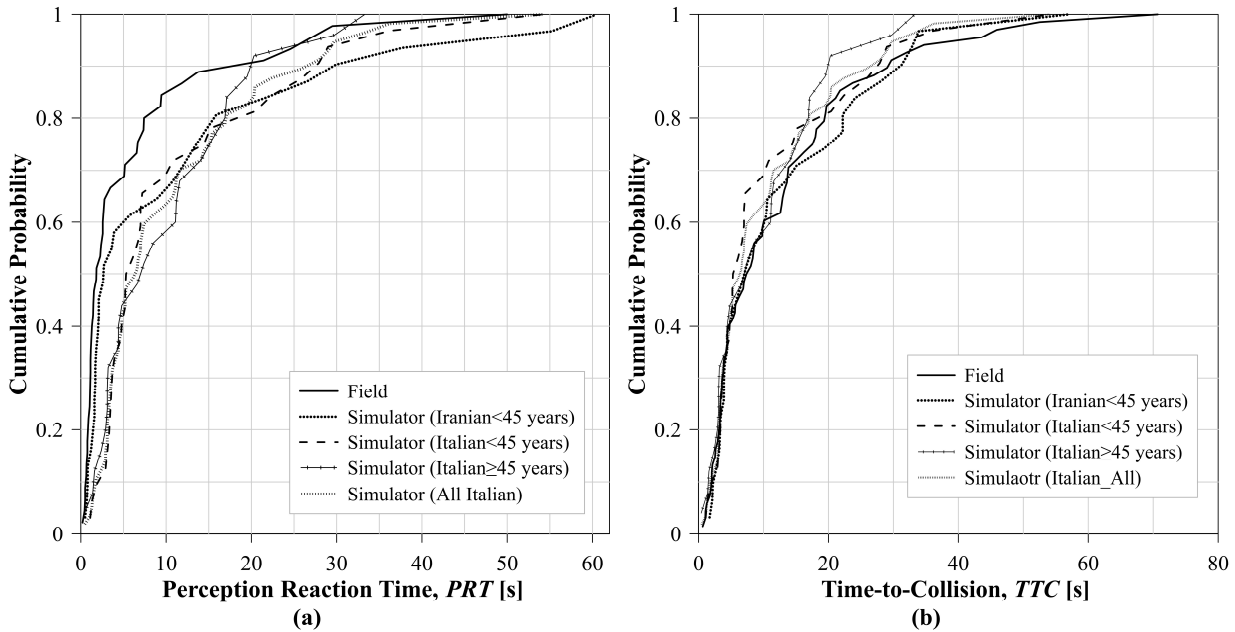
	Field	Simulator (Iranian < 45)	Simulator (Italian < 45)	Simulator (Italian ≥ 45)	Simulator (All Italian)
Field		D=0.1980 <i>p</i> -value=0.480	D=0.2384 <i>p</i> -value=0.248	D=0.2056 <i>p</i> -value=0.516	D=0.2077 <i>p</i> -value=0.241
Simulator (Iranian < 45)	D=0.2973 <i>p</i> -value=0.050		D=0.1734 <i>p</i> -value=0.731	D=0.1910 <i>p</i> -value=0.694	D=0.1517 <i>p</i> -value=0.745
Simulator (Italian < 45)	D=0.2245 <i>p</i> -value=0.230	D=0.1845 <i>p</i> -value=0.657		D=0.1275 <i>p</i> -value=0.976	D=0.0559 <i>p</i> -value=1.000
Simulator (Italian ≥ 45)	D=0.1508 <i>p</i> -value=0.806	D=0.1742 <i>p</i> -value=0.795	D=0.1100 <i>p</i> -value=0.996		D=0.0716 <i>p</i> -value=1.000
Simulator (All Italian)	D=0.1922 <i>p</i> -value=0.212	D=0.1720 <i>p</i> -value=0.592	D=0.0482 <i>p</i> -value=1.000	D=0.0618 <i>p</i> -value=1.000	

354

3.2 Perception and reaction time (*PRT*), time-to-collision (*TTC*)

356 The results of the two-sided K-S test in Table 8 show there are no significant difference between any *PRT*
357 distributions for field and simulator groups (*p*-values > 0.05). However, Figure 7a shows that the *PRT*
358 distributions in the simulator could be lower in the field. By conducting the one-sided K-S test, the largest
359 difference between the *PRT* distributions in the field and young Italians at the simulator, in the direction that
360 simulator have larger value than field study ($D^+ = 0.3104$). This implies that this difference in this direction is
361 significant (*p*-values = 0.027). The results of the one-sided K-S test between the field and Iranians in the
362 simulator show that there was no significant difference at the 95% confidence level ($D^+ = 0.2731$,
363 *p*-values = 0.065). However, the results for the one-sided K-S test in the direction that *PRT* values in simulator
364 are smaller than the field show that very low and highly insignificant differences. This implies that the
365 probability of an existence type II error occurring in this direction is low. Hence, if there are differences in the
366 distribution, it will be that the *PRT* simulator values are higher than those observed in the field.

367 The risk of a head-on collision with a vehicle travelling in the opposing direction at the end of a passing
 368 maneuver was evaluated using *TTC*. Figure 7b shows how *TTC* values are similar in the field and simulator
 369 for different groups of drivers. According to Table , profiles of the level of risk taken on by drivers in both the
 370 field study and at the simulator (all *p*-values were found to be larger than 0.5) show a strong resemblance,
 371 especially for Iranians ($D = 0.1110$, p -value = 0.956). Young and old Italian drivers took the comparable level
 372 of risk for completing a passing maneuver ($D = 0.1763$, p -value = 0.776). Also, Iranians and Italians showed
 373 an identical distribution for *TTC* ($D = 0.1177$, p -value = 0.944).
 374



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 376
 377 **Figure 7: Probability distributions of (a) perception-reaction time, and (b) time-to-collision**
 378

379 **Table 8: The results of the K-S test for each pair of distribution functions presented in Figure 7a (below the**
 380 **diagonal) and Figure 7b (above the diagonal)**

	Field	Simulator (Iranian < 45)	Simulator (Italian < 45)	Simulator (Italian ≥ 45)	Simulator (All Italian)
Field		D=0.1110 <i>p</i> -value=0.956	D=0.1710 <i>p</i> -value=0.548	D=0.1288 <i>p</i> -value=0.922	D=0.0988 <i>p</i> -value=0.923
Simulator (Iranian < 45)	D=0.2731 <i>p</i> -value=0.129		D=0.1724 <i>p</i> -value=0.738	D=0.1781 <i>p</i> -value=0.773	D=0.1177 <i>p</i> -value=0.944
Simulator (Italian < 45)	D=0.3104 <i>p</i> -value=0.054	D=0.1663 <i>p</i> -value=0.776		D=0.1763 <i>p</i> -value=0.776	D=0.0773 <i>p</i> -value=1.000
Simulator (Italian ≥ 45)	D=0.2178 <i>p</i> -value=0.431	D=0.3110 <i>p</i> -value=0.138	D=0.3150 <i>p</i> -value=0.123		D=0.0989 <i>p</i> -value=0.966
Simulator (All Italian)	D=0.2234 <i>p</i> -value=0.162	D=0.1471 <i>p</i> -value=0.777	D=0.1382 <i>p</i> -value=0.829	D=0.1768 <i>p</i> -value=0.649	

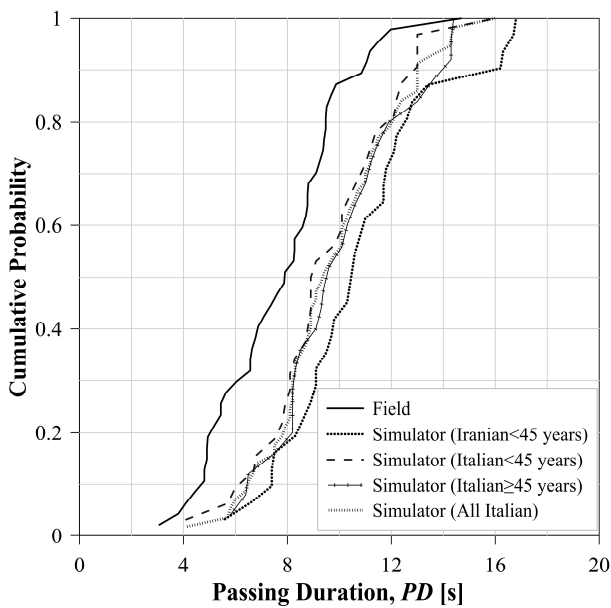
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382 **3.3 Passing duration (PD) and speed difference (dS)**

383 Figure 8 shows the distribution of PD. As shown in this figure and based on the results of the K-S test in
 384 Table 9, the different participants' simulator groups (Iranians, young and old Italians) had similar distributions
 385 (p -values > 0.30). However, there are significant differences between field and simulator PD distributions
 386 (p -values < 0.05). According to the graph, participants in the simulator took longer to complete a passing
 387 maneuver than drivers in the field. By moving field distribution by the difference of PD mean for the simulator
 388 and the field (adding 2.41 s to all field observations) and conducting a K-S test ($D = 0.1030$, p -value = 0.901),
 389 the shape of the field distribution appears to be strongly similar to the simulator one.

390 PD was then divided into two parts: the acceleration phase time ($t_{accel.}$) and the back-to-lane phase time
 391 (t_{btl}). The distributions of these two factors are shown in Figure 9a and Figure 9b. The $t_{accel.}$ values for the
 392 simulator are slightly greater than those in the field, albeit the difference between them is insignificant
 393 ($D = 0.2309$, p -value = 0.067). The significant duration differences occurred at the back-to-lane phase of
 394 passing maneuvers with shorter durations for the field compared to the simulator ($D = 0.2561$,
 395 p -value = 0.027).

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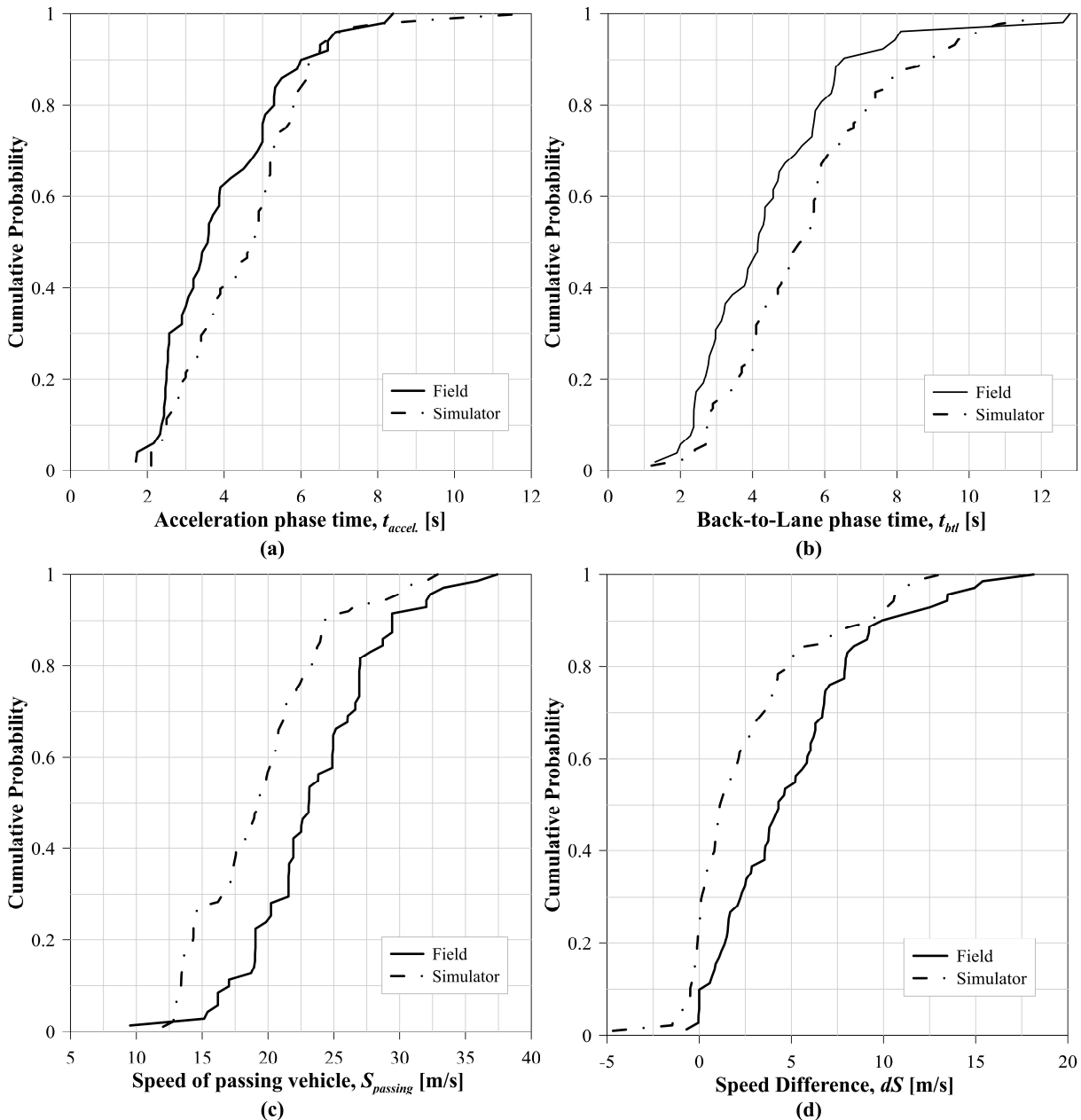
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Figure 8: Passing duration probability distributions for the field and simulator studies.

401 **Table 9: The results of the K-S test for each pair of distribution functions presented in Figure 8.**

	Field	Simulator (Iranian < 45)	Simulator (Italian < 45)	Simulator (Italian ≥ 45)	Simulator (All Italian)
Field		-	-	-	-
Simulator (Iranian < 45)	D=0.4962 p -value=0.000		-	-	-
Simulator (Italian < 45)	D=0.3198 p -value=0.041	D=0.2419 p -value=0.315		-	-
Simulator (Italian ≥ 45)	D=0.3523 p -value=0.035	D=0.1665 p -value=0.838	D=0.1525 p -value=0.900		-
Simulator (All Italian)	D=0.3285 p -value=0.008	D=0.1862 p -value=0.489	D=0.0669 p -value=1.000	D=0.0856 p -value=1.000	

402 The shape of the two distributions is similar, and there is almost a constant difference between field
 403 and simulator observations. To discover the possible cause source for this difference, the distributions for the
 404 speed of passing vehicle and speed difference (dS) between passing and passed vehicles at the beginning of
 405 the passing zones are shown in Figure 9c and Figure 9d. They show the speed of passing vehicles ($D = 0.4342$,
 406 p -value < 0.001), and it is apparent that the speed difference between passing and passed vehicles in the field
 407 is significantly greater than at the simulator ($D = 0.3510$, p -value < 0.001).
 408



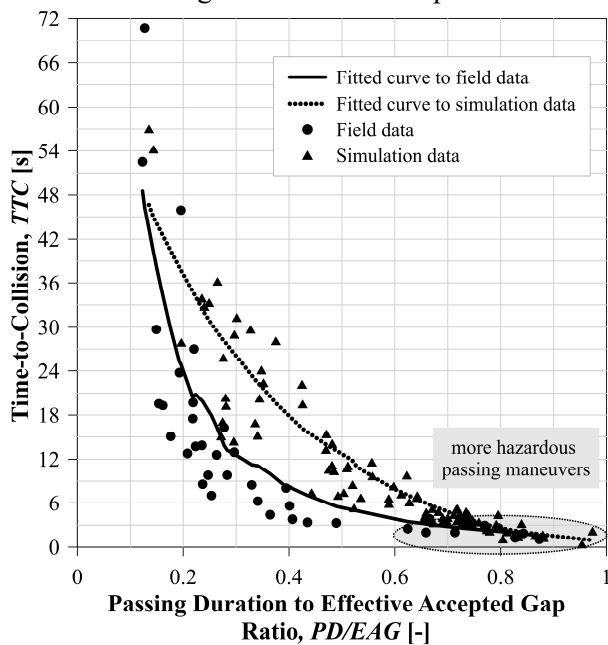
410
 411 **Figure 9: Probability distribution of (a) acceleration phase time, (b) back-to-lane phase time, (c) speed of passing**
 412 **vehicle, and (d) speed difference**
 413

414 One possible reason for these differences is the truncation of large headways (more than 20 s) in the
 415 subject lane in the simulation study. Drivers did not have enough time to increase their speed to the desired
 416 value when approaching a lead vehicle. Farah (2013) concluded that by decreasing passing vehicle speed and
 417 speed difference between the passing and passed vehicles the *PD* would be increased. Moreover, a study
 418 conducted by Vlahogianni (2013) showed that longer durations for the acceleration and back-to-lane phases
 419 are anticipated in the case of low-speed differences. Hence, the difference between field and simulator passing
 420 duration time is reasonable.

421

422 3.4 Relationship among *TTC*, *PD*, and *EAG*

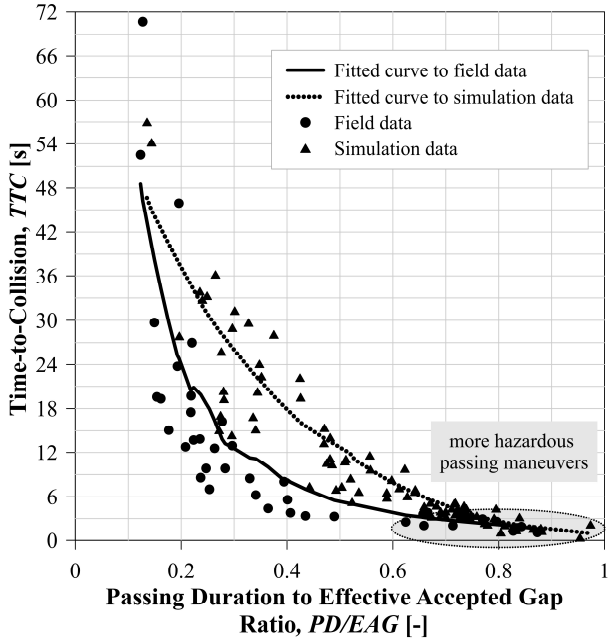
423 Mwesige et al. (2016) observed that the *TTC* decreases by increasing the *PD* and decreasing the *EAG*. They
 424 also showed a significant relationship between *TTC* and the ratio of *PD* to *EAG*. Figure 10



425

426 shows the scatter plots of *TTC* against the ratio of *PD* to *EAG* in the field and simulation environments.
 427 Using nonparametric Lowess regression (Cleveland, 1979), two curves were fitted to field and simulation
 428 data. Figure 10 shows that passing maneuvers with a certain *PD/EAG* ratio were completed with higher *TTC*

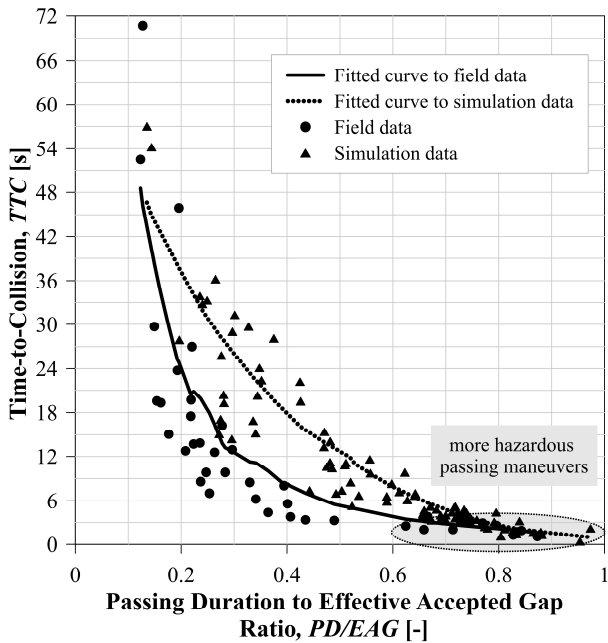
429 values in the simulator compared to in the field. However, Figure 10



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431 also shows that serious passing maneuvers (those with $TTC \leq 3$ s) had more similar results. Figure 7b also
432 shows that the distributions for TTC in the field and at the simulator are closer for serious passing maneuvers.
433 The t-test results show that serious passing maneuvers had statistically the same mean values for the PD/EAG
434 ratio in the field and at the simulator (t-value = -1.8661, p-value = 0.0829).

435



436

437 **Figure 10: Relationship between TTC and PD/EAG ratio**

438 4. DISCUSSION

439 In this work, the gap acceptance behavior of drivers involved in a passing maneuver in the field and at the
440 driving simulator was compared by using the accepted gap (*AG*) and the effective accepted gap (*EAG*)
441 variables. The results show that there are no statistically significant differences between them. However, some
442 statistical directional differences were found based on a one-sided K-S test. The results imply that the drivers
443 accepted lower gaps in the field, although most of these differences proved statistically insignificant. This
444 could be because of higher significant speeds for passing vehicles and also a higher speed difference (*dS*)
445 between passing and passed vehicles in the field and their equivalent values at the simulator, which increase
446 the desire (on the part of drivers) to accept lower gaps. Llorca and Farah (2016) showed that *AG* values in the
447 field and simulator were not significantly different, but their rejected gap distribution was statistically different.
448 They had different gap distributions in the opposite direction for the two databases (field and simulator). In
449 this study, the opposite gap distribution was selected based on the field data. Hence, as there was not
450 statistically significant difference in the accepted gap, there was not also statistically significant difference in
451 the rejected gaps.

452 The Perception-reaction times (*PRT*) for starting a passing maneuver in the field and simulator had
453 statistically no different distributions. However, in some cases a statistical directional difference occurred,
454 which implies that *PRT* values are lower in the field than at the simulator. The collision risk taken on by the
455 driver to complete a passing maneuver is measured by the time-to-collision (*TTC*). The result indicates a
456 statistical similarity between field and simulator *TTC* distributions. The *TTC* distributions were more
457 statistically similar in the serious passing maneuvers ($TTC \leq 3$ s). The result also showed that the mean values
458 of *PD/EAG* ratio were statistically similar for serious passing maneuvers. These results imply that the simulator
459 could be used to evaluate road safety using traffic conflict indicators like *TTC*. Llorca and Farah (2016) divided
460 *TTC* values into less than 10 s and greater than 10 s groups. In the case of the group with values lower than 10
461 s, which is important from a safety perspective, they observed a highly significant difference between simulator
462 and field studies, unlike current results. Drivers took a higher risk at the simulator than in the field. Reasons
463 for this change in risk taking behavior by participants in the simulation study may be:

- 464 i. the use of a gap distribution for opposing traffic based on the field data without truncating
465 large gaps; lower opposite headways could lead to higher risk-taking when passing (Mwesige
466 et al., 2016);
- 467 ii. the application of sight distance limitations equal to those measured in the field;
- 468 iii. using a simulator with a cockpit and wider display equipped with side mirror with acceptable
469 fidelity; based on the feedback from participants' reports, greater fidelity could have
470 influenced the driver's performance (Wynne et al., 2019).

471 Passing duration (*PD*) values at the simulator were significantly higher than those in the field. By
472 dividing passing duration into two parts: the acceleration and back-to-lane phase, a more in-depth analysis was
473 performed on passing duration. In the first part of the passing (acceleration phase), drivers passed at a slightly
474 lower speed, but this was not statistically significant. The major difference was observed in the back-to-lane

475 phase, in which drivers took longer in the simulator to move back to their original lane compared to in the
476 field. Vlahogianni (2013) concluded that lower speed differences would increase the durations of the
477 acceleration and back-to-lane phases. Farah (2013) also showed that by decreasing passing vehicle speed and
478 the speed difference between passing and passed vehicles the *PD* would increase. Based on results and previous
479 works, it can be concluded that the higher passing duration in the simulator was the result of the lower speed
480 of passing vehicles and the speed difference between passing and passed vehicles at the simulator. This
481 reduction in simulator speeds could be due to truncating headways in the subject lane, hence drivers could not
482 find the gap required to increase their speed to the level desired. The comparison conducted by Llorca and
483 Farah (2016) showed that the *PD* at the simulator was significantly lower than in the field. Also, the speed
484 difference (*dS*) was higher at the simulator, in contrast with the results for this current research.

485 To make the findings more general, a comparison between Iranian and Italian participants was also
486 drawn. The results showed that there were no statistically significant differences between the passing variable
487 distributions for Iranian and Italian participants at the simulator. A comparison between young and old
488 participants showed no significant difference between passing variables. A comparison between the field data
489 and the pooled simulation data (Iranian and Italian), reveal no significant differences for variables *AG*
490 ($D = 0.2217, p\text{-value} = 0.051$), *EAG* ($D = 0.2125, p\text{-value} = 0.149$), *PRT* ($D = 0.2167, p\text{-value} = 0.122$), and
491 *TTC* ($D = 0.0789, p\text{-value} = 0.971$). However, there is a significant difference between distributions of *PD*
492 between field and pooled simulation data ($D = 0.3504, p\text{-value} = 0.001$). While the results of this study indicate
493 no statistically difference between the driving behaviors of drivers from Iran and Italy, further research is
494 necessary to confirm the results obtained here in the case of drivers from different countries.

495

496 5. CONCLUSIONS

497 This study drew a comparison between drivers' behavior and performance when conducting passing
498 maneuvers in real-life and driving simulator environments. The purpose of this comparison was to validate the
499 driving simulator and also to contribute to improving its use for behavioral studies on the passing maneuver.

500 The field environment (a segment of an Iranian two-lane rural highway) was reconstructed as a 3D
501 virtual environment. Similar traffic conditions (headway and speed) were applied to simulator scenarios. The
502 same variables were defined and measured in both environments in order to be compared. To provide a more
503 comprehensive insight into the universality of results, in addition to the Iranian group, Italian participants also
504 took part in the simulation at the driving simulator.

505 The results served to confirm the suitability of using the driving simulator for the study of passing
506 behavior on two-lane rural highways. In this regard, statistical similarities were observed for the gap
507 acceptance behavior and perception-reaction times, however some statistical directional differences were
508 found compared to the field. The risk-taking behavior of drivers in passing maneuvers were measured using
509 the surrogate safety measure of *TTC*. The statistical significant similarity was found for *TTC* in real and virtual
510 environments, especially for serious passing maneuvers, which is more important in road safety evaluation.
511 The results showed significant differences for the passing duration, speed of passing vehicle and speed

512 differences between passing and passed vehicles; however, results from the field and simulator showed
513 statistical similarities in their shape of distributions. A comparison was also made between simulator
514 participants with different backgrounds, cultures and age groups, and no statistical significant differences were
515 observed between them. However, the age threshold in this study was 45 years. The results would be different
516 in the case of other age thresholds.

517 The main outcome of this study is the need to define a simulation framework for future studies on
518 passing maneuvers. Researchers could produce their scenarios based on the results of this work.

519 To improve and generalize the results of future studies, some suggestions and recommendations are
520 put forward. The generation of headways, with the large ones being truncated, in the subject traffic flow,
521 affected driver speed choice behavior as drivers could not accelerate enough to achieve their desired speed.
522 Hence, it is better to utilize actual (not truncated) distributions of field headways in simulators in future studies.
523 This study was conducted based on a field study with a traffic volume of 332 veh/h in the opposite direction.
524 The risk-taking and gap acceptance behaviors of drivers might be different at higher traffic volumes because
525 the existing gaps are smaller and present fewer passing opportunities. When studying passing behavior at
526 passing zones, the validation of simulators for studying illegal passing maneuvers is also necessary.

527 Although this study considered participants with the same nationality (Iranians) as those in the field
528 but with a wider range of ages, some limitations have to be acknowledged since the age and gender distribution
529 of field drivers and simulator participants should be similar. Consequently, the findings of this paper should
530 be treated with caution in future passing behavior studies with other types of driving simulators. Finally, each
531 simulator should be validated separately, so this study cannot be used to validate other similar simulators.

532 All passing variables employed in this research for validating the simulator were time-based and
533 validating spatial variables might help to better understand driving behavior in simulator versus real-life
534 scenarios. In this study, the speed and path of all vehicles involved in the simulation were programmed and set
535 constant. However, the interaction between vehicles (and drivers) operating at different speeds plays an
536 important role when performing passing maneuvers. Unfortunately, this is not captured within a driving
537 simulator experiment with only one human driver, which is an issue that should be considered in future studies
538 and applications.

539

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547

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