Learning by message passing in networks of discrete synapses

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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ABSTRACT

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

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

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

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

HIGHLIGHTS

1. The validity of the driving simulator for studies of passing behavior was investigated.
2. Significant similarities in gap acceptance and perception-reaction time behavior in the simulator and in the field were found.
3. Level of risk-taking by drivers using he driving simulator was similar to that in the field.
4. Although drivers passed at slower speeds in the simulator than in the field, the distribution shapes were similar.
5. Iranian and Italian drivers showed similar passing behaviors.

1. INTRODUCTION

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

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

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

There has been just one study comparing field and simulator passing maneuver data (Llorca and Farah, 2016). Some similarities were found between the passing time and passing distance for completed maneuvers. However, drivers passed faster, and the passing end clearance was greater in the simulator than in the field. They observed similar distributions of accepted gaps, and a significant difference between rejected gap distributions, and also between critical gaps in the simulator and in the field. This validation study had some shortcomings: (i) the participants did not have the same characteristics as the drivers in the field study, i.e., simulator participants and field drivers were from two different countries, and simulator participants were younger than those in the field; (ii) the distribution of gaps was different from those observed in the field, and they also truncated the distribution for small and large values; finally, (iii) all simulation scenarios were designed with no sight distance limitations.

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

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

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

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

2. METHODOLOGY

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

In the following, different variables, each representing a particular aspect of passing behavior, are analyzed and compared in the field (Section 2.1) and at the simulator (Section 2.2). For example, the variable for speed difference can measure the desire of drivers to pass; accepted gap, and effective accepted gap show the gap acceptance behavior of drivers; perception-reaction time and passing duration represent the passing performance of drivers; and the time-to-collision measures the risk perception of drivers.

2.1 Field investigation

2.1.1 Test track

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

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

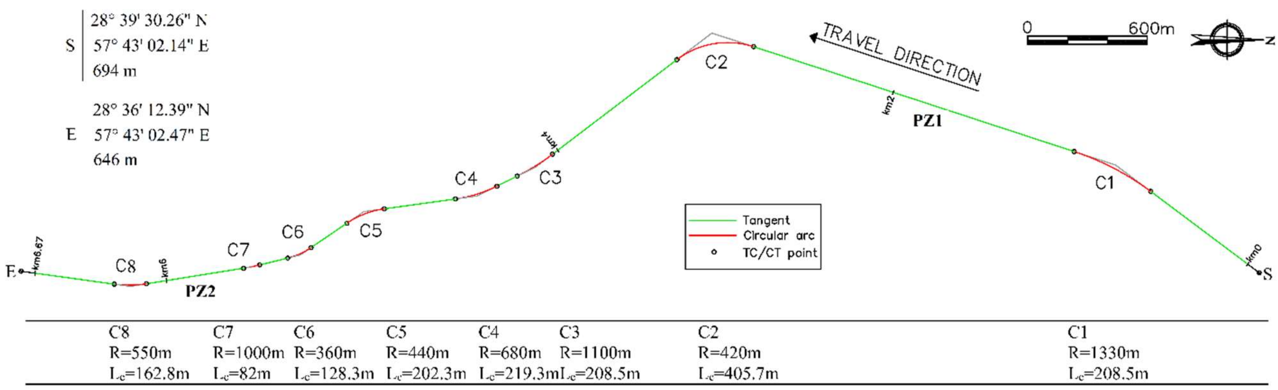


Figure 1: Horizontal alignment of road track (PZ1: passing zone 1, PZ2: passing zone 2)

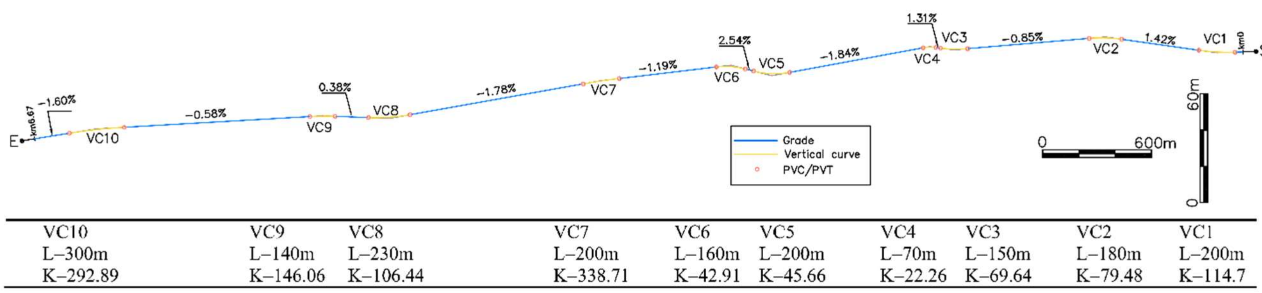


Figure 2: Vertical profile of test track (PVC: Point of vertical curvature, PVT: Point of vertical tangency)

km 0.40 **km 4.60** **km 5.70**

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

2.1.2 Field study equipment

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

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

2.2 Laboratory investigation

2.2.1 Driving simulator equipment

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

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

2.2.2 Driving simulator experimental design

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

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

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

Table 2: Factors included in the experimental design.

Factors	Levels		
	-1	0	1
Headways of opposite vehicles (A) drawn from	Gamma distribution (α=0.844, β=12.956)	Gamma distribution (α=0.814, β=19.405)	Gamma distribution (α=1.146, β=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

Table 3: Twenty-seven different scenarios and factor variations included in the study. The values -1, 0 and +1 are 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	-1	1	0	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	-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

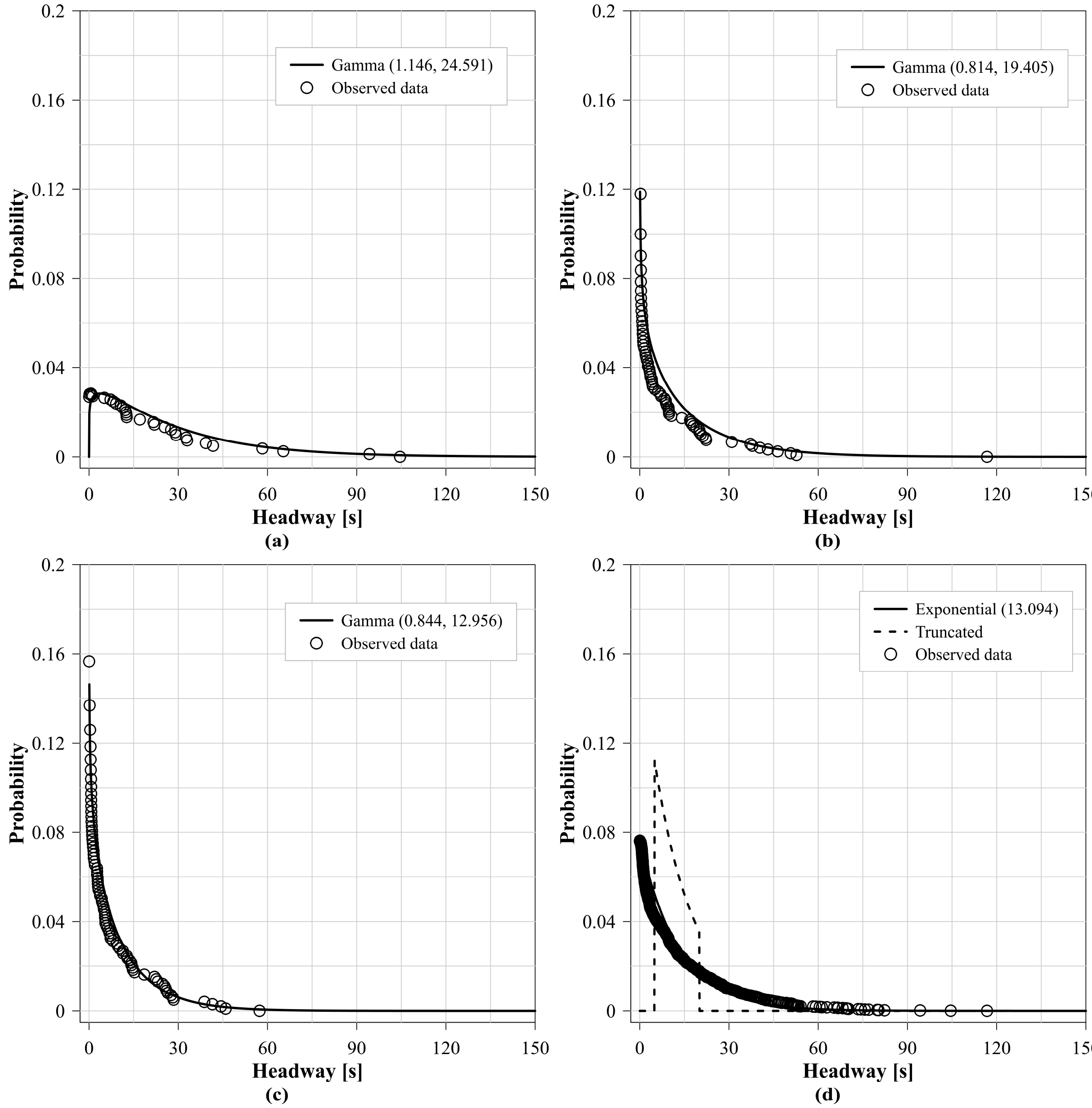


Figure 4: Fitted distributions on headway data in the opposite direction (Gamma distributions for three traffic levels: (a) lowest traffic level (i.e., highest headway level), (b) median traffic level, and (c) highest traffic level (i.e., lowest headway level). Fitted distributions (d) on headway data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

2.2.3 Participants

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

2.2.4 Experiment protocol, data collection, and manipulation

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

The simulator experimental protocol included:

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

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

2.3 Observed variables

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

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

iii. **time-to-collision** ($TTC = t_5 - t_3$), equal to the time necessary for an opposing vehicle to collide with the passing vehicle while the latter is completing a takeover maneuver,

iv. **accepted gap** ($AG = t_6 - t_1$), the time gap between subject vehicle and the nearest vehicle moving in the opposite direction,

v. **perception-reaction time** ($PRT = t_2 - t_1$), as the difference in time when the passing vehicle and the lead opposite vehicle are side by side up to the point of initiation of the passing maneuver,

vi. **acceleration phase time** ($t_{accel.} = t_{Abreast} - t_2$), the time from the beginning of passing maneuver to when the vehicles are abreast of one another,

vii. **back-to-lane phase time** ($t_{btl} = t_3 - t_{Abreast}$), the time frame from abreast position to when the passing vehicle returns to proper lane.

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

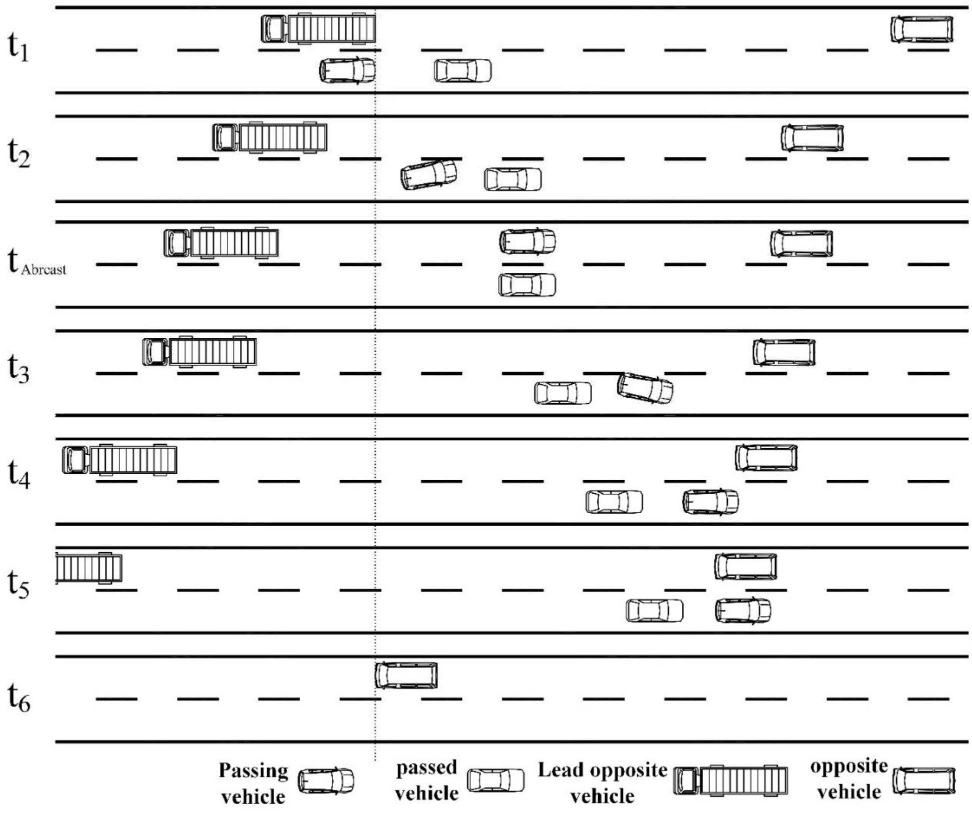


Figure 5: Timestamps for definition of passing maneuver variables

2.4 Statistical comparison between field and simulator data

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

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

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

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

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

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

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

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

$$D = \max|\ F_m\ (\text{t}) - G_n\ (\text{t})\ |,\ \min(x, y) \leq t \leq \max(x, y) \tag{5}$$

where F_m (t) and G_n (t) are empirical CDFs for the x and y samples, respectively. For the two alternative 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 eq. 6 and eq. 7, respectively:

$$D^{+} = \max[\ F_m\ (\text{t}) - G_n\ (\text{t})\ ],\ \min(x, y) \leq t \leq \max(x, y) \tag{6}$$

$$D^{-} = \max[\ G_n\ (\text{t}) - F_m\ (\text{t})],\ \min(x, y) \leq t \leq \max(x, y) \tag{7}$$

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 than 0.05.

3. RESULTS

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

The results of the t-test for visual (p-value = 0.705) and auditory (p-value = 0.839) tests before and after driving with the simulator show that there is no statistically significant difference between the cognitive status of drivers before and after driving. Since drivers did not change their cognitive performances during the tests, it is clear that the collected data were not affected by changes in psychomotor skills. The results of the post-drive questionnaire which provided driver feedback on the devices show that most of the test drivers perceived the on-board equipment (acceleration, pedal, and gearbox) to be similar to that used in real-life. However, they were not fully satisfied with the brake response which did not correspond with real-life conditions.

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

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

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

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

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

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

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

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

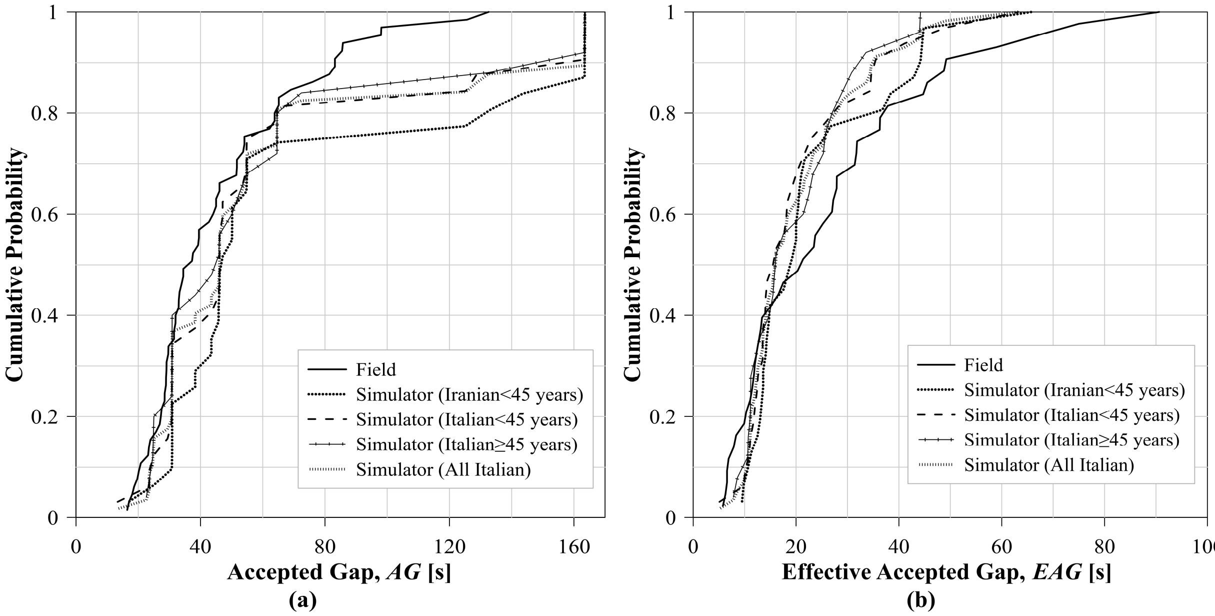


Figure 6: Comparison of driver gap acceptance behavior in field and simulator: (a) accepted gap (AG), and (b) effective accepted gap (EAG)

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

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

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

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

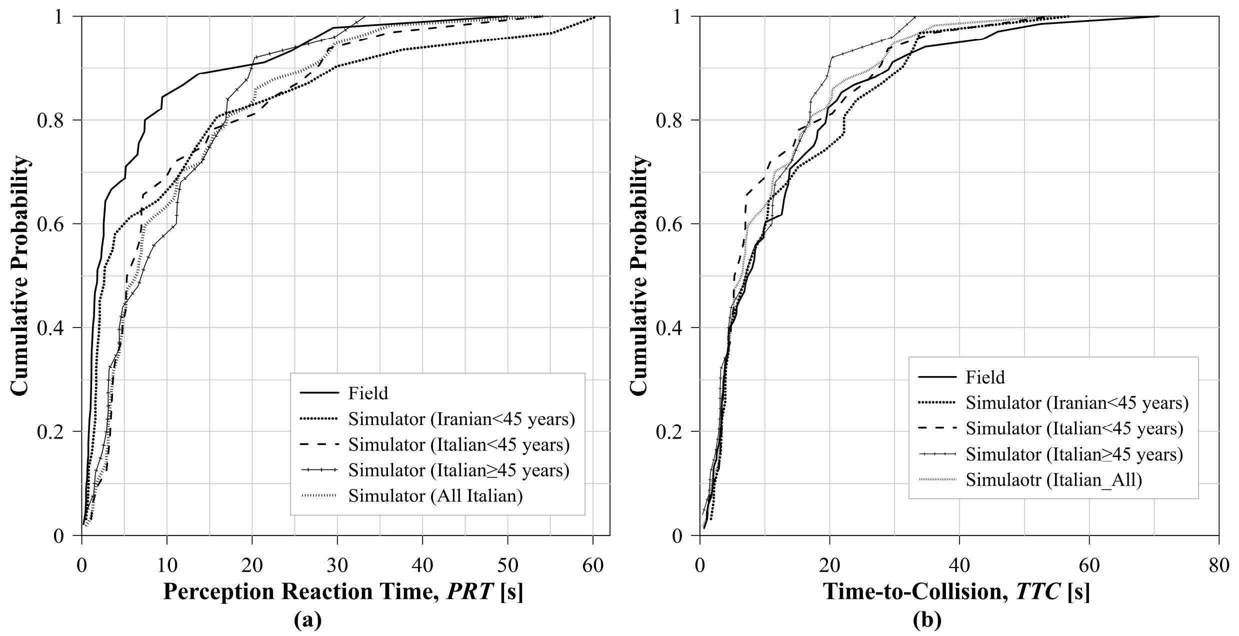


Figure 7: Probability distributions of (a) perception-reaction time, and (b) time-to-collision

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

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

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

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

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

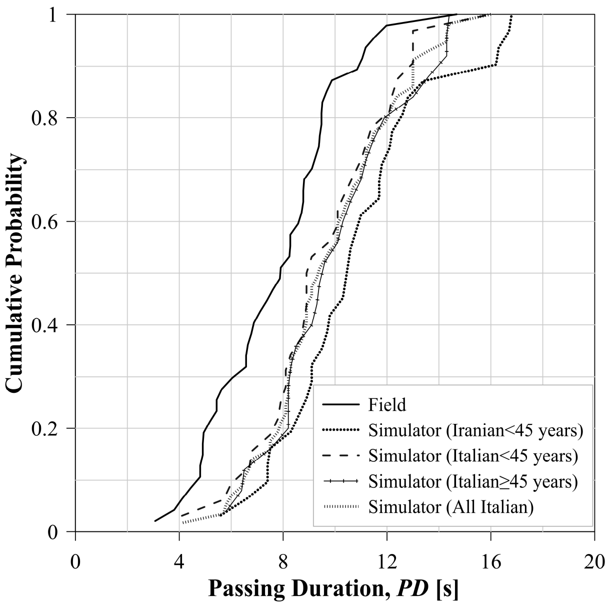


Figure 8: Passing duration probability distributions for the field and simulator studies.

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	

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

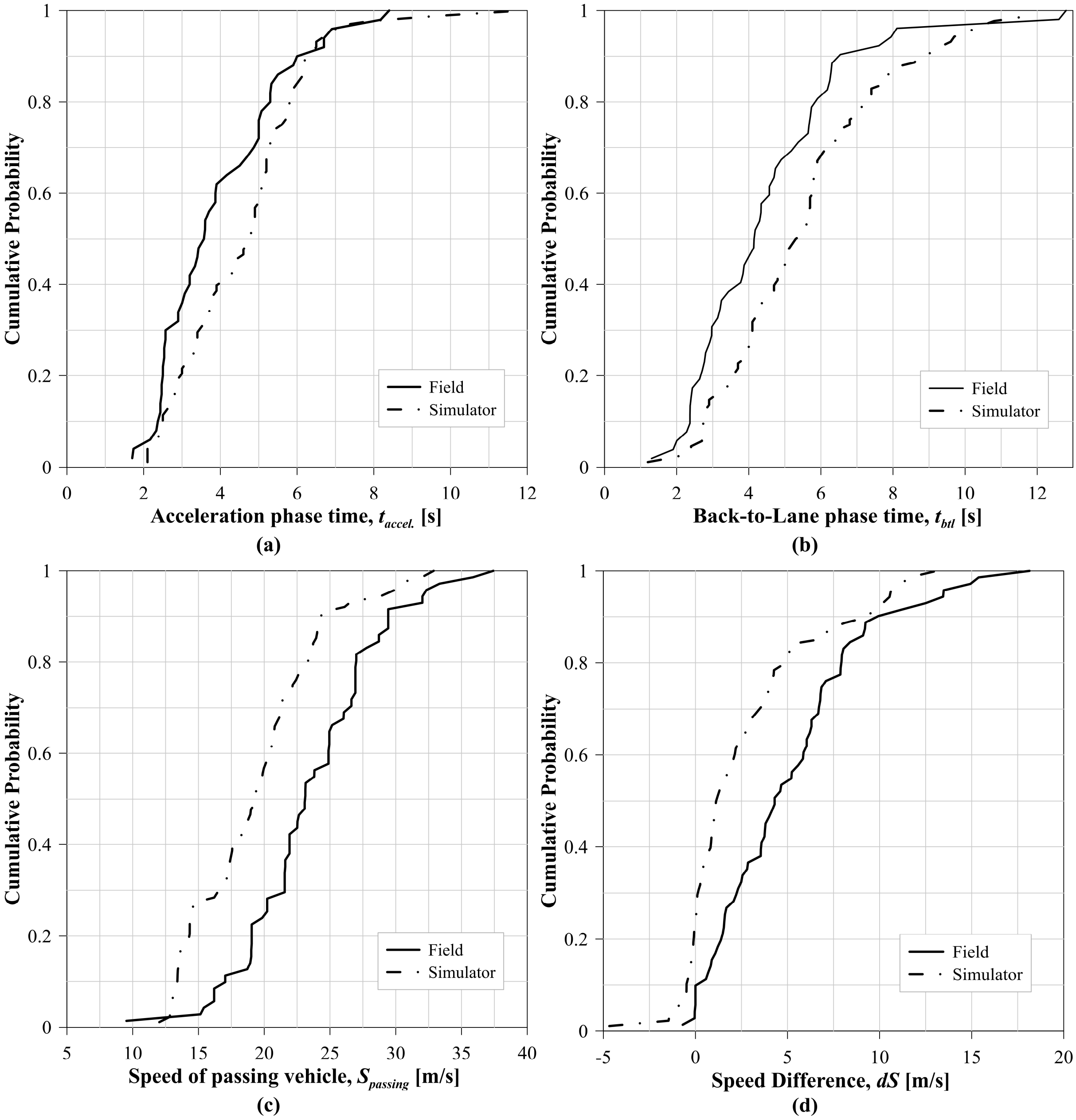
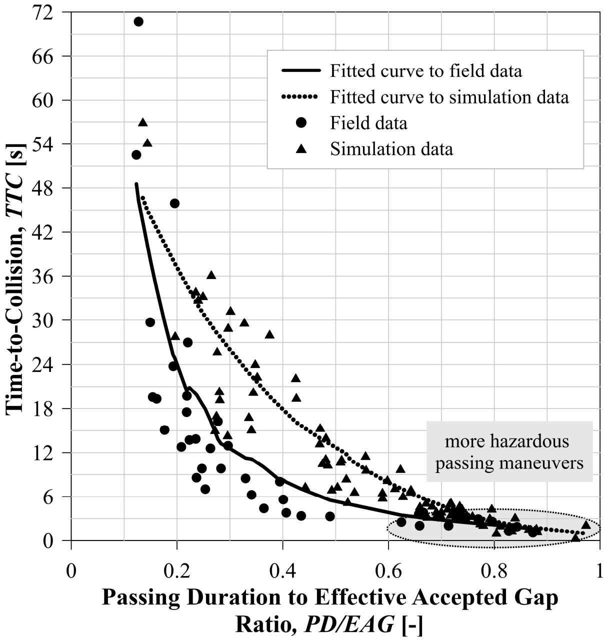


Figure 9: Probability distribution of (a) acceleration phase time, (b) back-to-lane phase time, (c) speed of passing vehicle, and (d) speed difference

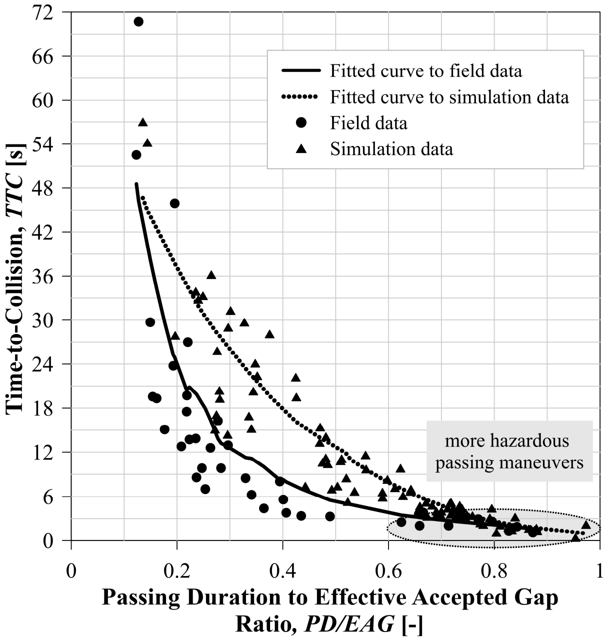
One possible reason for these differences is the truncation of large headways (more than 20 s) in the subject lane in the simulation study. Drivers did not have enough time to increase their speed to the desired value when approaching a lead vehicle. Farah (2013) concluded that by decreasing passing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

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

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



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



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

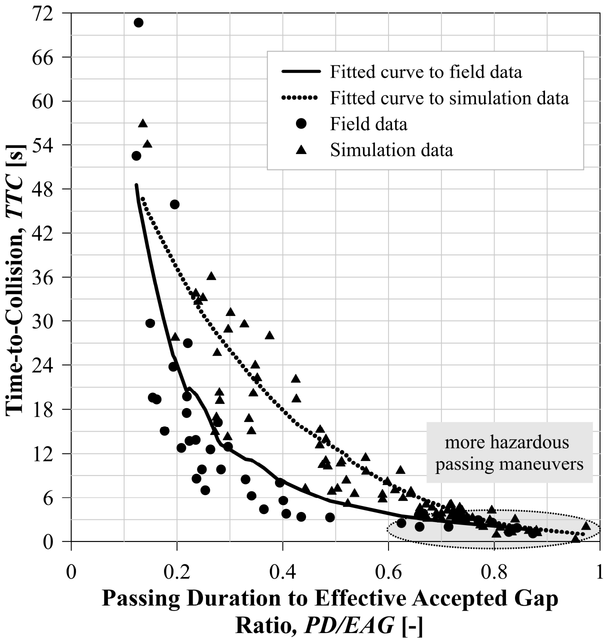


Figure 10: Relationship between *TTC* and *PD*/*EAG* ratio

4. DISCUSSION

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

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

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

Passing duration (*PD*) values at the simulator were significantly higher than those in the field. By dividing passing duration into two parts: the acceleration and back-to-lane phase, a more in-depth analysis was performed on passing duration. In the first part of the passing (acceleration phase), drivers passed at a slightly lower speed, but this was not statistically significant. The major difference was observed in the back-to-lane phase, in which drivers took longer in the simulator to move back to their original lane compared to in the field. Vlahogianni (2013) concluded that lower speed differences would increase the durations of the acceleration and back-to-lane phases. Farah (2013) also showed that by decreasing passing vehicle speed and the speed difference between passing and passed vehicles the *PD* would increase. Based on results and previous works, it can be concluded that the higher passing duration in the simulator was the result of the lower speed of passing vehicles and the speed difference between passing and passed vehicles at the simulator. This reduction in simulator speeds could be due to truncating headways in the subject lane, hence drivers could not find the gap required to increase their speed to the level desired. The comparison conducted by Llorca and Farah (2016) showed that the *PD* at the simulator was significantly lower than in the field. Also, the speed difference (*dS*) was higher at the simulator, in contrast with the results for this current research.

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

5. CONCLUSIONS

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

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

The results served to confirm the suitability of using the driving simulator for the study of passing behavior on two-lane rural highways. In this regard, statistical similarities were observed for the gap acceptance behavior and perception-reaction times, however some statistical directional differences were found compared to the field. The risk-taking behavior of drivers in passing maneuvers were measured using the surrogate safety measure of *TTC*. The statistical significant similarity was found for *TTC* in real and virtual environments, especially for serious passing maneuvers, which is more important in road safety evaluation. The results showed significant differences for the passing duration, speed of passing vehicle and speed differences between passing and passed vehicles; however, results from the field and simulator showed statistical similarities in their shape of distributions. A comparison was also made between simulator participants with different backgrounds, cultures and age groups, and no statistical significant differences were observed between them. However, the age threshold in this study was 45 years. The results would be different in the case of other age thresholds.

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

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

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

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

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