PASSING BEHAVIOR ON TWO-LANE ROADS IN A REAL AND IN A SIMULATED ENVIRONMENT

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ABSTRACT

Passing maneuvers allow faster drivers to continue driving at their own desired speeds without being delayed behind an impeding vehicle. On two lane rural roads, this requires from the passing driver to occupy the opposing lane. This has tremendous implications on safety and operation of two-lane roads. In the literature, several studies investigated the passing behavior of drivers, and some have used driving simulators to analyze drivers' behavior during following and passing maneuvers. However, the validity of simulators has not been ensured, as their results have rarely been compared with real data.

The objective of this study is to compare drivers' passing behavior as observed in the field with passing behavior in a driving simulator. This may improve both methods to validate the use of simulation instead of observations. For this purpose, data on passing performance and passing gap acceptance decisions is required. This paper carried out a comparative analysis of the most significant variables related to passing behavior.

The results showed similarities between passing time and passing distance of completed maneuvers (during the occupation of the opposing lane). However, drivers passed faster in the driving simulator, keeping higher clearances. Gap acceptance decisions were also found to be similar, as the distributions of both accepted and rejected gaps were similar, although critical gaps were found to be lower in the driving simulator. This might be explained by the absence of objective risks. Consequently, the applicability of driving simulation seems reasonable, although some improvements are still possible, in order to account for sight distance limitations, replicate age and gender distributions, and reproduce better the opposing traffic flow.

INTRODUCTION

On two-lane rural roads, vehicles travelling at lower speeds cause delays to faster vehicles. Passing maneuvers allow faster drivers to travel at their own desired speeds minimizing these delays. However, it is necessary to occupy the opposing lane to pass a slower vehicle. As a result, an interaction with the opposing traffic has both operational and safety implications.

Drivers make passing decisions based on their own behavior, experience, vehicle, as well as the road, traffic and environmental conditions. Traditionally, passing process has been divided into three consecutive stages *(1)*: passing desire, passing decision (namely passing gap acceptance) and passing performance. The severity of accidents related to passing maneuvers is usually higher than in other maneuvers *(2)*. To ensure road safety, roads are provided at certain locations with sufficient passing sight distance, which is the distance required to pass a slower vehicle when an opposing vehicle is approaching. The determination of the minimum passing sight distance as well as the characterization of passing gap acceptance has been widely explored. However, there is a high dispersion in design and marking standards *(3)*, as well as within research studies *(4)*.

Some authors proposed theoretical models, which described the trajectories of the vehicles by equations. They assumed different hypotheses, such as uniform speed of the impeding vehicle *(5–7)*, uniform acceleration of the passing vehicle *(6, 7)*, or linear relationships between the acceleration rate and the speed of the passing vehicle *(8)*. However, to ensure the validity of those assumptions it was required to collect data of passing maneuvers. Several studies focused on observing passing maneuvers on real roads. Some of them obtained video data from external, static positions, in order to extract the trajectories of the vehicles *(9–11)*. Those authors calibrated passing sight distance models, by characterizing the opposing lane occupation time as well as the speeds of both impeding and passing vehicles. Additionally, static observations were used to describe the operational effects of passing zones *(12, 13)*, as this method has no intervention of the researchers on traffic flow. Other researchers observed passing maneuvers from an instrumented vehicle that acted as impeding vehicle *(14–16)*. The advantages of instrumented vehicle compared to conventional video data are the higher accuracy and better level of detail of the measurements, which included in certain cases even the age and gender of the following drivers.

Generally, collecting data from the field is costly and time-consuming. The use of driving simulators has been proposed as an alternative to obtain detailed data of passing maneuvers. Driving simulators have several advantages, including the ability to control the intervening variables and as well to repeat the same exact scenario for several participants in the experiment and to collect personal information on drivers. Furthermore, the driving simulators provide very accurate trajectory data of all the relevant vehicles involved in the passing process (subject, lead and opposing). Some studies analyzed the impact of age, gender and delay on passing decisions and maneuvers *(1, 17–20)*. Other studies focused on the effect of traffic conditions *(21)*. However, the absence of real risk during the experiment and the limited realism of the scenarios might be a disadvantage. Driving simulators have been validated in other fields of highway engineering research, such as the use of driving behavior questionnaires *(22)*, work zones *(23)* or headway choices *(24)*.

There is no previous comprehensive comparison between field observation of passing maneuvers and the use of driving simulators. Consequently, the validity and applicability of driving simulators cannot be ensured without such a comparison. This paper is motivated by the necessity of comparing both methodologies. The results can benefit and validate the use of driving simulator as a tool to obtain data of drivers' behavior on two-lane rural roads. Potential differences may suggest improvements on studies involving driving simulators.

OBJECTIVES AND HYPOTHESES

The main goal of this paper is to compare the observations of passing maneuvers from a field study with observations obtained from a driving simulator experiment. This may improve both methods and validate the use of simulation instead of observations. More specifically, the following objectives were determined:

- Characterize both studies in terms of the road and traffic characteristics and as well the participating drivers (field study and driving simulator experiment), in order to determine uniform conditions for the comparison.
- Compare drivers' performance in passing maneuvers (such as: passing time, distance travelled and speeds).
- Compare gap acceptance (accepted and rejected gaps in the opposing flow)

The underlying hypotheses is that driving simulator experiment would result in a lower critical gaps and more risky passing maneuvers, because of the absence of real risks. Besides, the limited screen resolution may make the detection of opposing vehicles more difficult contributing to a more risky behavior.

METHOD

The research methodology is based on the comparison of the most significant variables characterizing passing process, starting from the following process (such as: gap acceptance) to the completion of passing maneuvers (such as: passing time and distance, time-to-collision). Those variables were obtained from a field study in Spain, as well as from a driving simulator study in Israel. Firstly, each data collection methodology, scenarios and sites are described. Then, a comparison between passing maneuvers and between passing gap acceptance decisions is presented.

Field study

A field study obtained data from up to 781 maneuvers using two methodologies on 10 two-lane road segments. Both methods consisted of video recording of passing maneuvers without the intervention of observers *(10, 15)*. Following is a detailed explanation of each method.

Field study layout

The first methodology (named static) *(10)* consisted of recording videos from external fixed positioned cameras on 24 passing zones in 8 road segments. The mobile traffic laboratory of the Universitat Politècnica de València (Spain) was parked next to the two-lane highway. This equipment is composed of six digital video cameras installed on the top of an elevator platform of 11 meters height.

The second methodology (named dynamic) *(15)* used two instrumented vehicles (a passenger car and a truck). The objective was for other vehicles to pass the instrumented vehicles, collecting data of these maneuvers and the entire following process. The vehicle was driven along 6 road segments. In 4 of the segments, the static method was also applied, in order to compare passing maneuvers, to ensure that the dynamic method did not affect driver's behavior. The result of the comparison showed no differences between both the two methods with respect to passing times *(4)* FIGURE 1 summarizes the data collection.

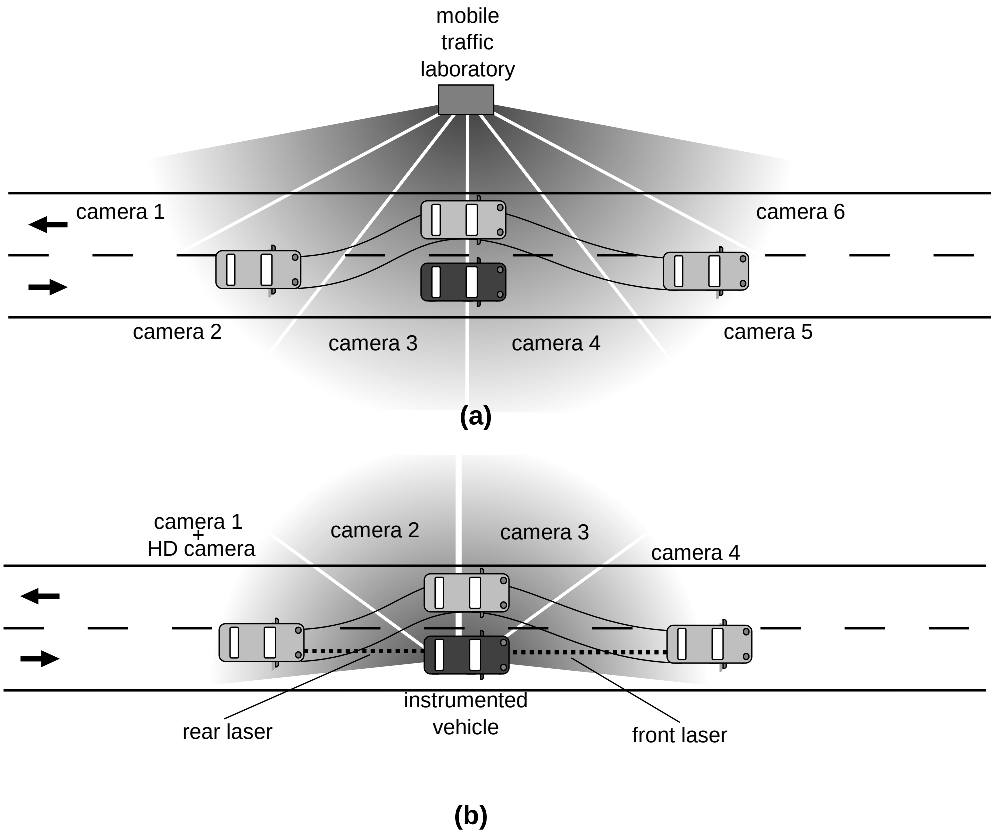

FIGURE 1 Field study layout: (a) static data collection; (b) dynamic data collection.

Site selection

The data was collected on 10 two-lane road segments (on 8 of them using the static method, and on 6 of them, the dynamic), in a variety of traffic and geometric design characteristics. Design speeds ranged between 70 and 120 km/h, and the roads were located on level and rolling terrain, being the longitudinal grade under 3%. Generally, lane width was equal to 3.5 m and shoulder width equal to 1.5 m. The Average Annual Daily Traffic (AADT) on the observed segments was between 4,517 and 15,342 veh/day.

A total of 20 passing zones with a length ranging between 99 and 1,855 meters were observed using the static method. The number of observed passing zones increased to 92 by using the instrumented vehicle.

Data collection and processing

During the static method data collection, a wireless network facilitated adjusting the zooming and focusing of the video cameras, in order to collect video images of the entire passing zone with uniform quality. This method provided data of passing times, passing and impeding vehicles' speeds and free flow speeds.

The instrumented vehicle (dynamic method) was equipped with four Video VBOX cameras, covering rear, left side and front of the vehicle. Two LTI S200 laser rangefinders measured distance gaps between the instrumented car and other vehicles behind and in front of it. Measuring systems are very small and are installed inside the car (cameras and recording units) or in front and rear bumpers (rangefinders). Following drivers did not perform unexpected maneuvers, like following without passing or with longer headways. A 10 Hz GPS tracker connected to the Video VBOX unit provided the position and speed of the instrumented vehicle. The speed of the instrumented vehicle was selected according to the observations of the static methodology, which had been previously carried out. The dynamic method provided very accurate information of the gap acceptance. A total of 848 gaps were registered, observing a sample of 282 drivers, characterized by their age and gender.

Combining data from the static and the dynamic methodologies resulted in a total of 781 completed passing maneuvers.

Driving simulator experiment

Experiment Design

Data of passing maneuvers were extracted from a driving simulator experiment conducted in a previous study *(1)*. In this study the STISIM driving simulator, which is a low-cost fixed-base, interactive driving simulator with a 60° horizontal and 40° vertical display was used. The driving scene was projected onto a wall 3.5 m ahead of the driver. The image was continually updated at a rate of 30 frames per second. The driving scenario consisted mainly of two-lane highway segment of a total length of 7.5 km, with no intersections, and designed on a level terrain. The traffic and geometric design of the road were varied in order to be able to assess their impact on drivers' passing decisions and behaviors. Good weather and daytime conditions (good visibility) were assumed.

In total 16 different scenarios were created following a design that included 4 main factors in two levels as detailed in TABLE 1. The selection of these factors was based on their significant impact on passing performance found in the literature. Further details on the experiment and the experimental design can be found in Farah and Toledo, 2010 *(1)*.

TABLE 1 Factors Included in the Experimental Design

Factor	Level	
	High	Low
Geometric design	Lane width: 3.75 m, Shoulder width: 2.25 m	
	Curve radius: 1500-2500 m	Curve radius: 300-400 m
Passing gaps in the opposite lane	Drawn from truncated negative exponential distributions	
	Mean: 10.3 s Min: 5.0 s, Max: 25.0 s	Mean: 18.0 s Min: 9.0 s., Max: 31.0 s
Speed of lead vehicles	Drawn from uniform distributions	
	67% between 80 and 120 km/h 33% between 40 and 80 km/h	33% between 80 and 120 km/h 67% between 40 and 80 km/h
Speed of opposing vehicles	Drawn from uniform distributions	
	67% between 80 and 120 km/h 33% between 40 and 80 km/h	33% between 80 and 120 km/h 67% between 40 and 80 km/h

In addition to these factors, the type of the front and opposing vehicles (truck or passenger cars) were considered. The type of the vehicles were randomly set in each scenario so that each participating driver encountered both types of vehicles.

Participants

An advertisement on the driving simulator experiment was published at the Technion campus university in Israel. Candidates who expressed their interest in participating had to fulfill the following two main criteria: First, interested drivers had to have a driving license for at least 5 years (i.e. already established their driving style); and secondly, drivers drive on a regular basis. The participation in the experiment was on a voluntary basis. The recruitment process resulted in 100 drivers (69 males, 31 females) with an age ranging between 22 and 70 years old.

Each driver completed 4 scenarios out of the total 16 created scenarios (2^4=16). The partial confounding method *(25)* was used to allocate 4 scenarios for each driver as described in Farah and Toledo *(1)*. Drivers were instructed to drive as they would normally do in real world and completed a familiarization scenario (~10 min) to get used to the simulator. No instructions were given regarding their driving speed, distance from other vehicles, or passing other vehicles.

Data Collection and Processing

The main goal of this study was to understand drivers' decisions to accept or reject passing gaps, under different conditions of traffic and road design. To answer these questions detailed trajectory data of the relevant vehicles and drivers' demographic characteristics were collected. The trajectory data included speeds, positions, and acceleration of the subject vehicle and all other vehicles at a resolution of 0.1 s. Using this raw data several other variables of interest, such as relative speeds and distances between vehicles, passing and following gaps were calculated.

Available passing gaps were defined as the time gaps between two consecutive vehicles in the opposing lane measured at the time the subject vehicle passes the lead vehicle in the opposing lane. A total of 6,654 gaps were observed, being 487 passing maneuvers completed.

Study variables

Both methods provided data on following, accepted and rejected gaps, and passing maneuvers. The analysis only focused on the following maneuvers that ended with a passing maneuver. This included as well all the rejected gaps from the moment the subject vehicle starts tracking the impeding vehicle and until the moment it accepts a gap and start performing the passing maneuver.

In general, the vehicles that are involved in a passing maneuver are:

- Following vehicle: in the field study is the vehicle following the instrumented vehicle, and in the driving simulator is the vehicle driven by the participant. In both cases, the driver of the following vehicle takes the passing gap acceptance decisions. If that decision is positive, the subject vehicle is also called the passing vehicle.
- Leader vehicle: is the vehicle located in front of the following vehicle, which was the instrumented vehicle when using the dynamic method in the field study. If a passing maneuver is performed, the leader vehicle is also called the impeding vehicle.
- Opposing vehicles: are vehicles travelling in the opposite direction on the left lane during the passing maneuver.

The analysis of the passing performance (successfully completed maneuvers): covered the characterization of the following variables summarized in TABLE 2, for both passenger cars and trucks as impeding vehicles.

TABLE 2 Variables Characterizing the Passing Performance

Variable	Symbol	Units
Type of impeding vehicle: passenger car or truck.	-	-
Passing time	$t13$	s
Passing distance	$d13$	m
Average speed of impeding vehicle during the passing time	Vi	km/h
Average speed of passing vehicle during passing time	Vp	km/h
Speed difference	$dV=Vp-Vi$	km/h
Clearance between impeding and passing vehicle before passing	$h1$	m
Clearance between impeding and passing vehicle after passing	$h3$	m
Speed difference at start	$dV1$	km/h
Time until crossing with next opposing vehicle, or safety margin	$t34$	s

The analysis of gap acceptance: focused on the characterization of the accepted and rejected passing gaps (passing opportunities). This analysis considered only passenger cars (for both the leader and the following vehicle). The following variables were considered:

- Passing gap (in seconds): time interval between crossing time with two consecutive opposing vehicles from the following (subject) vehicle point of view.

- Acceptance: accepted or rejected gap, respectively.
- Visibility of opposing vehicles: in the simulator, the opposing traffic is always visible, because there is unlimited sight distance and long gaps were discarded by the truncated negative exponential gap distribution. In the field data, there were both sight distance-limited cases (opposing vehicles were not seen) and opposing vehicle-limited cases (opposing vehicles were seen). The analysis was limited to only opposing-vehicle limited cases to make the two databases valid for comparison.
- Age (in years) and gender of the following driver: Using the dynamic method of the field study the co-driver estimated the age and gender of the following driver (using 5-years interval for the age). These data were included in the questionnaire in the case of the driving simulator.
- Waiting time since the following process started (in seconds): is the time spent following for each individual following vehicle and passing process.
- Leader vehicle speed (in km/h).

Results

This section presents first a summary of the data collected from the field and data collected in the driving simulator. This is followed by a comparison of the participating drivers in both studies in terms of their age and gender. Then a detailed analysis of the passing performance and gap-acceptance decisions is made while comparing the results from both data collection methods.

TABLE 3 summarizes all the collected data, from the field study and the driving simulator study. The number of observations could be different for each variable, because of the use of different methodologies (i.e., age and gender could be observed only with the instrumented vehicle and not from the static method).

TABLE 3 Summary of the Field Study and Driving Simulator Databases

Analysis	Sample	Impeding vehicle	Variable	n	mean/ mode	sd	min	max
Participants	Field data	Both types	Age (years)	282	41	11	20	70
			Gender (1=male)	282	na	na	na	na
	Simulator		Age (years)	100	33	10	21	70
			Gender (1=male)	100	na	na	na	na
Passing performance	Field data	Passenger car	Passing time *t13* (s)	538	7.2	2.1	2.4	16.5
			Safety margin *t34* (s)	291	9.4	7.8	0.5	40.0
			Impeding speed *Vi* (km/h)	349	66.7	9.7	44.4	112.0
			Speed difference *dV* (km/h)	347	20.6	8.9	na	74.3
			Passing distance *d13* (m)	346	171.5	49.9	79.1	459.0
			Clearance at start *h1* (m)	296	9.8	7.3	2.3	70.1
			Clearance at end *h3* (m)	296	23.7	9.5	na	71.9
			S. dif. at start *dV1* (km/h)	164	5.7	4.7	0.1	34.3
		Truck	Passing time *t13* (s)	243	9.4	2.8	3.6	20.3
			Safety margin *t34* (s)	131	7.6	5.6	-0.4	35.9
			Impeding speed *Vi* (km/h)	85	65.7	11.6	30.0	85.0
			Speed difference *dV* (km/h)	76	24.3	8.4	10.9	59.3
			Passing distance *d13* (m)	76	224.5	61.0	80.4	351.0
			Clearance at start *h1* (m)	40	9.8	3.6	3.6	18.7
			Clearance at end *h3* (m)	20	30.0	18.6	5.1	84.8
			S. dif. at start *dV1* (km/h)	na	na	na	na	na
	Simulator	Passenger car	Passing time *t13* (s)	403	6.7	2.0	2.1	14.3
			Safety margin *t34* (s)	403	3.4	3.7	0.0	20.7
			Impeding speed *Vi* (km/h)	403	61.4	16.1	42.8	103.0
			Speed difference *dV* (km/h)	403	33.3	16.6	7.9	118.8
			Passing distance *d13* (m)	403	172.8	54.5	69.0	388.4
			Clearance at start *h1* (m)	403	14.3	11.8	1.1	93.0
			Clearance at end *h3* (m)	403	36.5	21.9	2.0	138.0
			S. dif. at start *dV1* (km/h)	403	19.2	19.5	-2.1	116.0
		Truck	Passing time *t13* (s)	84	7.3	1.6	4.7	11.0
			Safety margin *t34* (s)	84	4.0	3.8	0.1	17.8
			Impeding speed *Vi* (km/h)	84	60.7	14.9	42.8	95.0
			Speed difference *dV* (km/h)	84	28.1	7.8	13.4	49.7
			Passing distance *d13* (m)	84	177.8	42.0	88.2	297.7
			Clearance at start *h1* (m)	84	13.6	8.4	4.3	50.0
			Clearance at end *h3* (m)	84	34.2	16.0	4.5	76.1
			S. dif. at start *dV1* (km/h)	84	12.7	8.8	0.1	48.2
Gap acceptance	Field data	Passenger car	Passing gap (s)	848	6.1	5.1	0.8	28.2
			Leader vehicle speed (km/h)	848	63.7	7.6	44.4	96
			Waiting time (s)	848	62.4	61.3	0	307.6
	Simulator	Passenger car	Passing gap (s)	6563	6.9	5.6	0.7	31.0
			Leader vehicle speed (km/h)	6563	71.7	19.9	26.9	146.0
			Waiting time (s)	6563	81.5	80.4	0.0	488.4

Participants

In both studies, drivers from different age groups and both genders participated. FIGURE 2 presents a comparison of the age and gender of the participants in the field study and the driving simulator study.

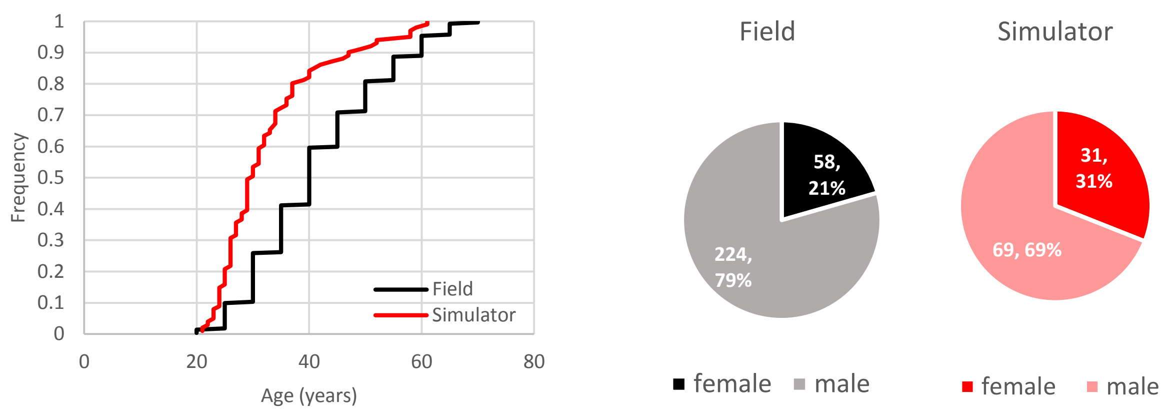

FIGURE 2 Age and gender distribution in the field study compared to the driving simulator study.

FIGURE 2 shows that the population of participants in the driving simulator study is significantly younger compared to the field study (K-S test: D=0.5040; P-value<0.0001). This is mainly because the driving simulator experiment took place in a university. Consequently, the age of the drivers was significantly lower (on average 33 years, against 41 in the field data). Still, the age range in both studies is similar. The gender distribution was also different, being 31% and 21% female in the driving simulator and in the field data, respectively. A Chi-square test showed that there is no significant differences in the distribution of gender between the field and the driving simulator studies ($\chi^2(1) = 2.60$, $p = 0.11$).

Passing performance

This sub-section of the results deals with the comparison of passing maneuver dynamics in both studies.

The cumulative frequency distributions resulting from the two databases are presented in FIGURE 3. To test whether the two samples are drawn from the same distribution, a two-sample Kolmogorov-Smirnov test was conducted. In Kolmogorov-Smirnov test the null hypothesis is of no difference between the empirical cumulative distribution functions of the two samples. This null hypothesis is rejected when the p-value is below 0.05 at the 95% confidence level.

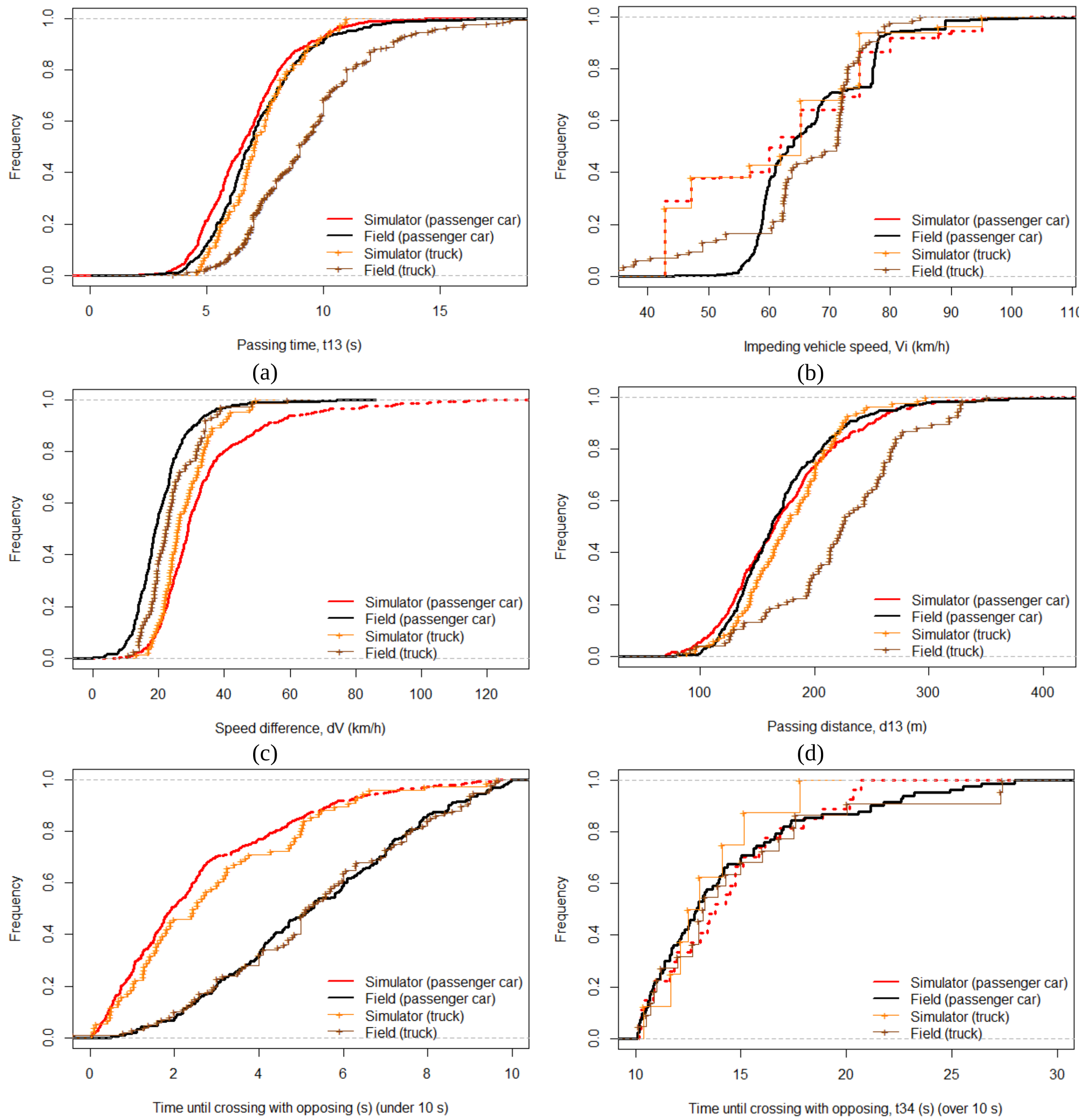

FIGURE 3 Comparison of passing performance related variables.

FIGURE 3(a) compares the passing time *t13* for both passenger car and truck impeding vehicle types. For passenger cars, the passing time was slightly but significantly higher in the case of field data (D=0.1405; p-value=0.0002). However, the difference in passing time was much stronger in the case of trucks (D=0.3943; p-value<0.0001).

FIGURE 3(b), shows that the speeds of the impeding vehicle *Vi* differ in both studies. In the driving simulator study there was significantly a higher proportion of impeding vehicles (cars and trucks) travelling at lower speeds compared to the field study. The K-S test results showed that this difference is significant for cars (D=0.3743; p-value<0.0001) as well as for trucks (D=0.2868; p-value=0.0019). The relatively high speeds of trucks in the driving simulator study stems from the fact that the type of the impeding vehicle (car or truck) was set randomly by the simulator software. As a result it was not possible to assign in advance systematically lower speeds for trucks in the simulator scenarios which resulted in a similar distribution as that for the passenger car as shown in FIGURE 3(b).

The average speed difference *dV* between the passing and impeding vehicles presented in FIGURE 3(c) shows significant differences in the distributions. This difference is significantly higher in the case of passenger cars (D=0.4784; p-value<0.0001) where the average speed difference in the driving simulator is higher compared to the field study. For the case of trucks, the difference is smaller but still significant (D=0.2807; p-value=0.0019).

The distance travelled on the opposing lane *d13* was very similar in both studies, when the impeding vehicle was a passenger car (D=0.0787; P-value=0.1992), but significantly different when the impeding vehicle was a truck (D=0.4424; P-value<0.0001), with longer passing distances in the field, as observed in FIGURE 3(d).

In general, both clearances *h1* and *h3*, were significantly higher (not plotted) in the case of driving simulator for passenger cars (*h1* was on average 4.5 m higher; D=0.2177; P-value<0.0001 and *h3* was on average 12.8 m higher; D=0.3572; P-value<0.0001). For trucks *h1* was higher too (D=0.3155; P-value=0.0091), but not for *h3* (D=0.2429; P-value=0.2518). Besides, in the case of passenger cars, drivers had significantly higher speed difference at the start of passing maneuvers (not plotted) in the field compared to the driving simulator (D=0.4969; P-value<0.0001).

Lastly, FIGURES 3(e) and 3(f) show the differences in the safety margin, or time until crossing with the next opposing vehicle *t34*. This variable has been divided into forced maneuvers (under 10 s, in FIGURE 3(e)) and not forced maneuvers (over 10 s, in FIGURE 3(f)). These figures show that there are significant differences for the forced maneuvers group (K-S test result in D=5161; p-value < 0.0001 and D=0.4311; p-value<0.0001, for passenger cars and trucks, respectively). On the contrary, there are no significant differences for the not forced maneuvers group (D=0.1709; p-value=0.5913 and D=0.1932, p-value=0.9809).

Gap acceptance

The second sub-section of the results compares the main variables related to gap acceptance. As gap acceptance involves several decisions during the following time, the field study data was obtained only by using the instrumented vehicle methodology.

FIGURE 4(a) plots the gaps distributions for the whole sample of both studies. The gaps were slightly but significantly lower in the case of field study (K-S test: D=0.1306; p-value<0.0001). For this comparison, only opposing vehicle limited decisions (in the field study) have been considered. It means that gaps higher than those limited by the available sight distance were not accounted in this paper, this is in order to establish uniform conditions for the comparison between the field study results with the driving simulator results, where an opposing vehicle always limited the gaps. Besides, gaps beyond the truncation values proposed in TABLE 1, for the driving simulator, have been discarded also in the field data, ensuring a uniform comparison.

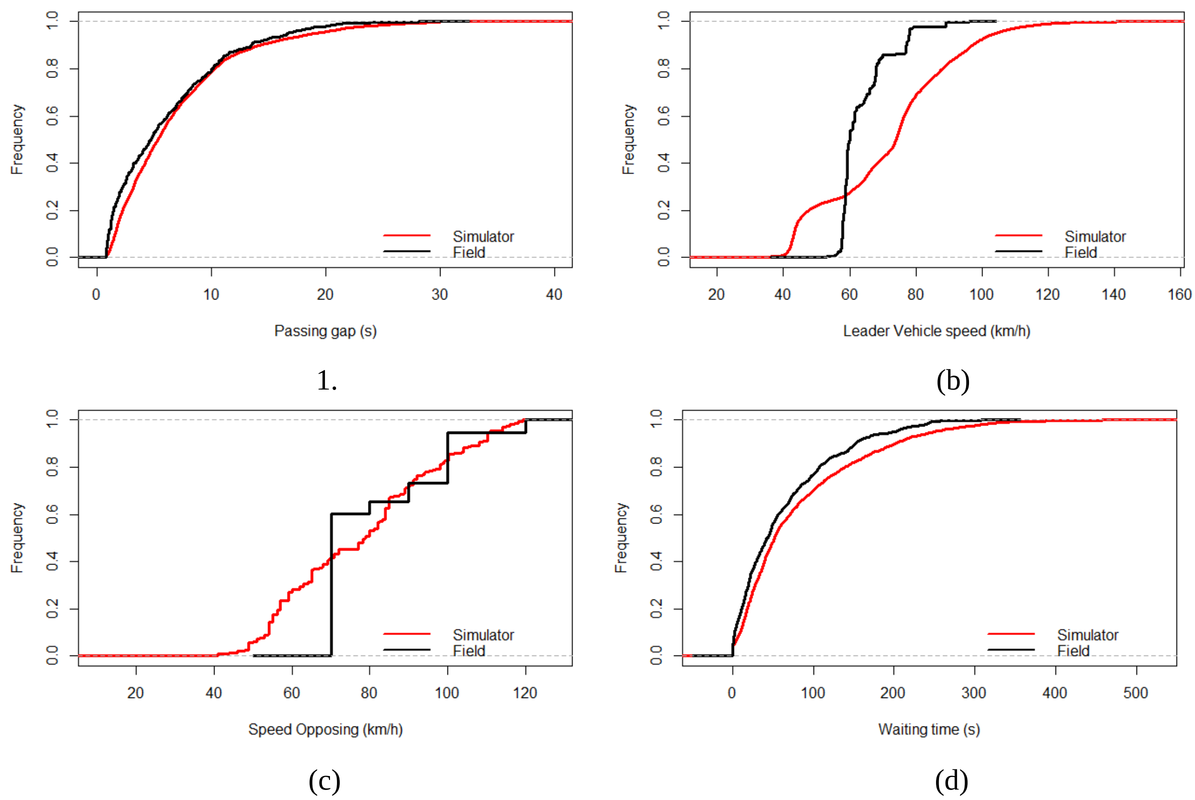

FIGURE 4 Gap distribution (expressed as TTC in s) (together accepted and rejected).

As seen in FIGURE 4(b), the range of leader vehicle speeds (for both accepted and rejected gaps) was significantly narrower and lower (D=0.4398; p-value<0.0001) in the field study because it was controlled by the researchers during the instrumented vehicle data collection, which represented the entire sample in the passing gap acceptance sub-section. The average values were 71 km/h and 63 km/h with standard deviations of 19.9 km/h and 7.6 km/h, in the driving simulator and field study, respectively.

The comparison in the speeds of the opposing vehicles, is shown in FIGURE 4(c). The K-S test results showed that the two distributions of the opposing speed from the field test and the driving simulator test significantly differ (D=0.4249; p-value<0.0001). In the case of the field study, this speed was assumed equal to the design speed values of the selected roads, because the actual speed could not be measured. In the case of the driving simulator the speed was randomly set from a truncated uniform distribution as shown in TABLE 1.

FIGURE 4(d) shows the distribution of waiting times. As can be seen, following processes were significantly (but slightly) longer during the simulator experiment (D=0.1045; p-value<0.0001).

Lastly, the distribution of the accepted and rejected passing gaps were plotted separately. As seen in FIGURE 5, the distributions of gaps are quite similar.

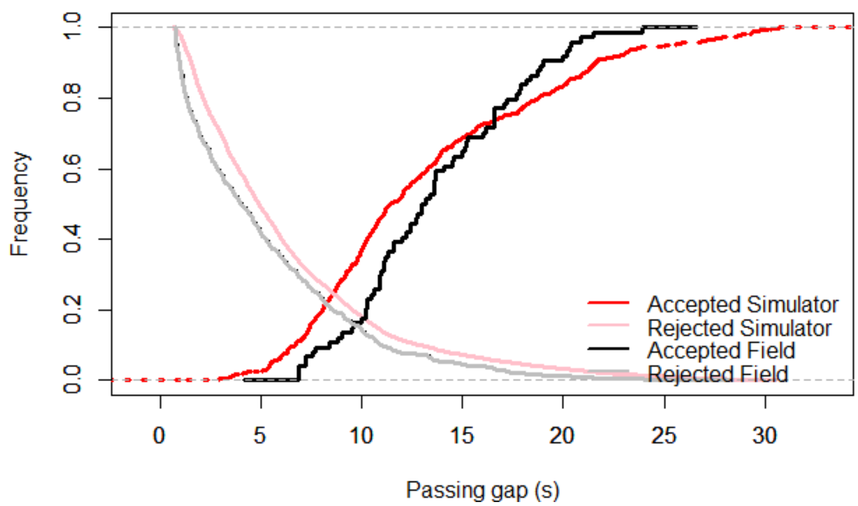

FIGURE 5 Accepted and rejected gap distributions.

Differences between accepted and rejected gaps were analyzed by using the K-S statistical test. The results showed significant statistical differences for the rejected gaps at the 95% confidence level (D=0.1637; p-value <0.0001). Accepted gaps distributions were not found to be significantly different (D=0.1584, p-value=0.0798), although lower accepted gaps were overrepresented in the case of the driving simulator. Consequently, the intersection of accepted and rejected gap distributions provided a lower critical gap for the driving simulator, which agreed with lower safety margin, as shown in FIGURE 3(e).

DISCUSSION & CONCLUSION

This paper has carried out a comprehensive comparison between two databases of passing maneuvers, the first one obtained from a field study and the second one, using a driving simulator. The aim of this comparison was to validate and contribute to improvement of the use of driving simulators for behavioral studies.

The data obtained from both these studies provided the same variables characterizing passing maneuvers and gap acceptance decisions. Definitions of the main factors and outputs were verified, ensuring the comparison between uniform variables.

With respect to the road characteristics of the simulated and observed scenarios, similar design speeds, traffic volumes and presence of curves were identified. However, one of the limitations of the driving simulator was the provision of unlimited sight distance. This did not match accurately the real conditions, where the visibility of opposing vehicles is not always possible, because of the presence of sight distance obstacles. The comparison was uniform though, after discarding the sight distance-limited maneuvers observed in the field study.

The analysis of the completed passing maneuvers focused on the opposing lane path. Both time and distance of opposing lane occupation were similar in the simulated and in the real conditions (for the case of passenger cars, mean times were 7.2 s and 6.7 s, and mean distances 171.5 m and 172.8 m in the field data and simulator studies, respectively). However, the values of the relative speeds and clearances between the passing and passed vehicles before and after the maneuver were quite different. This suggested that drivers passed faster (speed difference was on average 12.7 km/h higher) but kept higher clearances (on average 4.5 m higher at the beginning and 12.8 m higher at the end of the maneuver) in the driving simulator experiment.

The safety margin that drivers accepted in forced maneuvers (time until the opposing vehicle under 10 s) in the simulator was generally lower. In the driving simulator, drivers may not feel so forced to return to their own lane in case an opposing vehicle approaches because of the absence of real risk and real human behavior in the opposing vehicle *(26, 27)*. These differences in the safety margin were not observed for the not-forced maneuvers, because the interaction with opposing traffic is less significant.

The analysis of gap acceptance decisions was based on the measurements of gaps in the opposing traffic flow. The gap acceptance decisions were only compared within the ranges that existed in both experiments, truncating also the gaps from the field experiment at the same values indicated in TABLE 1 for the driving simulator experiment. Only some differences were found in the accepted gap distribution, where the presence of low, accepted gaps was more frequent in the simulator (confirming the hypothesis of riskier behavior in the simulator, by having a low critical gap and a low safety margin).

The results of the comparison of both studies, and the differences found, lead to the following recommendations and suggestions to improve the use of driving simulators in future studies on passing behavior:

- The selection of participants should replicate the real characteristics of drivers' population, as in the case of the presented study.
- The designed driving simulator scenarios to study passing maneuvers should include sight distance limitations along the road, since the effect of the visibility of opposing vehicles has been previously demonstrated *(28)*.
- The generation of gaps in the opposing flow, which included truncation of very small and very large gaps (since these are not of interest and the experiment time is limited), might have affected drivers' gap-acceptance decisions, and its analysis. For example, drivers might decrease their critical gaps when they are faced with very short gaps of vehicles driving in platoon.
- Similarly, to trigger drivers to pass in the driving simulator the speeds of the impeding vehicles were set to be relatively low. As a result, in the driving simulator there was higher frequency of speeds below 60 km/h, which in reality they are less frequent. In general, more realistic results would be achieved by using the real distributions of speeds.
- Driving speeds assigned to trucks in the driving simulator should represent the range of speeds in reality.
- Finally, to control for the higher risk taking levels in the driving simulator, a reward-penalty scheme can be used to encourage real-world driving. These strategies should be further investigated.

The field study was carried out in Spain, while the driving simulator experiment took place in Israel. Consequently, drivers' behavior may be different due to their cultural and social characteristics, and not only because of the different experiment settings. Additionally, the age and gender of participants were not distributed according to the same pattern in both experiments. The participants of the driving simulator experiment were younger, in comparison with the field data. The presence of more young drivers among the population could also be related with smaller critical gaps, or with higher passing speeds. However, the comparison is supported by similarities between the Spanish and Israeli road safety enforcement, speed limits, seat belt usage, and alcohol limits *(29)*. In addition, road safety figures affecting fatalities per inhabitant *(30)* and its reduction in recent years *(29)* are similar. Drivers' age distribution and its evolution *(31)*, as well as vulnerable road users' behavior *(32)* were as well found to be similar both countries.

To conclude, the driving simulator provided a reasonable representation of the real behavior of passing drivers, although it might be necessary to improve some aspects regarding road and traffic generation for the experiments. Future studies, should conduct such comparison within the same driving culture.

The importance of this validation relies on the potential applications of driving simulator, in comparison with the more traditional observation of passing maneuvers. The use of driving simulators may contribute to a deeper understanding of drivers' behavior, as their personal characteristics can be interviewed, in contrast with naturalistic field studies. Moreover, driving simulators allow the study of the response of drivers to changes in the infrastructure or traffic, such as the improvement of available sight distance, changes on marking or signing, or an increasing of traffic volume. This can easily be researched using simulation, without the necessity of collecting field data after the implementation of measures.

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