When Do Drivers Abort an Overtaking Maneuver on Two-Lane Rural Roads?

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ABSTRACT

Overtaking on two-lane roads is a complex driving maneuver. Drivers who desire to overtake a lead vehicle need to evaluate the available gaps in the opposite direction and accept a sufficient gap to successfully complete the overtaking maneuver. However, often drivers realize that the gap they accepted is shorter than what they actually need to complete the maneuver safely, and therefore decide to abort the overtaking maneuver. Previous research studies focused mainly on analyzing drivers' decisions to accept or reject available gaps in the opposite direction, and their overtaking performance. Very limited research investigated the conditions under which drivers decide to abort or complete an initiated overtaking maneuver. Increased frequency of aborted overtaking maneuvers has negative implications on safety and the operation of two-lane roads.

One hundred drivers from both gender and different age groups participated in a driving simulator experiment study. Driving scenarios with different geometric and traffic characteristics were developed. Detailed trajectory data of 670 overtaking maneuvers was collected, in which 554 were successfully completed and 116 were aborted. A logistic regression model was developed which predicts the probability that a driver aborts an overtaking maneuver. The results show that the probability to abort an overtaking maneuver is significantly affected by the size of the accepted gap in the opposite direction, the desired driving speed of the driver, the speed and type of the front lead vehicle, the cumulative waiting time to find an appropriate gap on the opposite direction, the road curvature, and drivers' age and gender.

KEY WORDS

Overtaking behavior, two-lane roads, driving simulator, aborted overtaking maneuver

INTRODUCTION

Two-lane roads represent a considerable proportion of the road network in many countries around the world. In the US, for example, according to the Federal Highway Administration [1] 97% of the total highway system is two-lane roads, and more than 65% of the total non-urban vehicular travel occur on this type of roads. In European countries, such as Spain, 91.7% of the roads are two-lane roads [2], and in Germany 90% of all rural roads have only two lanes [3].

Overtaking maneuvers have a substantial impact on the operation and safety of two-lane roads [4, 5]. Inappropriate overtaking behavior, resulting from driver's poor observational and judgment skills of other vehicles' speeds and locations and of overtaking distances [6, 7], is commonly seen as an important contributing factor to road crashes [6, 8, 9]. Several studies [10-12] have shown that until the angular velocity subtended by the vehicle in front was above a threshold value of about 0.003 - 0.006 radians/sec, drivers were unable to give reasonable estimates of the time to collision and cannot tell how fast a vehicle is moving, making the judgment of gap adequacy difficult.

Understanding drivers' overtaking decisions and performance on two-lane roads is complex, and requires the collection of detailed trajectory data. In the last two decades there have been several studies that focused on analysing overtaking maneuvers on two-lane roads using either data collected from a simulated environment, such as studies conducted in the US [13], Israel [14] and Italy [15], or field tests, such as studies conducted in Israel [5], Spain [16] and Uganda [17]. These studies adopted a behavioural approach to understand drivers' gap-acceptance decisions and the factors that influence these decisions [14, 15, 18, 19]. Other studies focused on: classification of overtaking maneuvers [13], evaluation of the overtaking sight distance [20, 21], evaluation of the risk associated with various overtaking sight distance lengths [22], estimation of overtaking duration and distance [16, 23, 24], overtaking intentions [25, 26], impact of drivers' age and gender [27, 28], evaluation of overtaking rates, operational effectiveness of overtaking zones, and capacities [17, 29, 30], and the design of overtaking assistance systems [9]. However, none of the previous studies have focused on understanding the conditions that lead drivers to abort overtaking maneuvers, and the characteristics of these aborted maneuvers. This topic has been largely overlooked [31]. Therefore, in depth empirical knowledge on aborted overtaking maneuvers is limited.

Few studies were found in the literature which addressed the topic of aborted overtaking maneuvers, and its frequency. Kaub [32] found that for a traffic flow range of 285-425 vehicles per hour, the percentage of aborted overtaking maneuvers was 0.8%, while for higher traffic flows, 400-590 vehicles per hour, the percentage increased to 7.0%. Similar results were reached in a recent study by Kinnear et al. [26]. In their study, aborted overtaking maneuvers accounted for less than 1% for a traffic flow range between 300–400 vehicles per hour, but increased to over 7.0% for traffic flow range between 400–500 vehicles per hour. In the study by Harwood et al. [20], only 7 aborted overtaking maneuvers were observed out of a total of 367 overtaking maneuvers' attempts (i.e. 1.9%). The authors found that drivers in those aborted overtaking maneuvers occupied the left lane for about 7.1 seconds on average, with a range between 4.1-9.5 seconds. Furthermore, drivers aborted the pass when they had completed 36% of the overtaking maneuver distance, i.e. before the abreast position which is normally reached after 40%-50% of the total overtaking maneuver distance [23, 33, 34]. In other words, drivers aborted overtaking maneuvers before reaching the critical position or the point of no return [35, 36]. The critical position or the point of no return is defined as the location where beyond it drivers are recommended to complete the overtaking maneuver rather than aborting it.

Saito [37] developed two analytical models for the aborted overtaking maneuvers. The models were developed under the assumption that the decision point of aborting the overtaking maneuver occurs when the overtaking vehicle is either trailing or at abreast position with the impeding vehicle, following the definition of Lieberman [38]. Saito also found that the deceleration rate of drivers when aborting an overtaking maneuver is 2.95 m/s^2, higher than the deceleration rate found by Glennon [39], which is equal to 2.4 m/s^2. Herman and Tenny [40] made an analogy between drivers' decisions to complete or abort overtaking maneuvers with the situation of approaching a signalized intersection exactly when the traffic light changes from green to amber phase. Based on that the authors developed a theoretical model that takes into account both the option of aborting or completing a pass during the overtaking maneuver. Ohene and Ardekani [31] defined the "passing dilemma zone" as the zone where it is not safe either to complete or to abort the overtaking maneuver. The authors indicated that the length of the dilemma zone should be equal to zero so that drivers have sufficient sight distance to be able to either complete or abort the maneuver. They developed a kinematic model and based on it derived recommended passing sight distance values so that the dilemma zone is zero.

Three main limitations can be identified in these previous studies: First, the small sample of aborted overtaking maneuvers' observations; Second, the fact that most models that were developed were mostly analytical models; and third, these studies are quite old by now. In light of the lack of empirical work addressing drivers' aborted overtaking maneuvers, this paper seeks to examine the factors and conditions that lead drivers to decide to abort an overtaking maneuver. The results of this paper is expected to contribute to: (1) understanding drivers' behavior when aborting overtaking maneuvers and the conditions that lead such decisions; and (2) development of overtaking controllers in autonomous vehicles which emulate real human behavior but at the same time maintain the safety margins [2].

The rest of the paper is organized as follows: the next section describes the methodology of the research study, including the experimental design, the recruitment of participants, the data collection and processing procedure, and the model formulation. This is followed by the results section, which first includes a preliminary analysis followed by the model estimation results. Finally, the discussion and conclusions are presented.

RESEARCH METHODOLOGY

The main objectives of this study are threefold: (1) to understand the characteristics of aborted overtaking maneuvers on two-lane roads; (2) to understand when do drivers decide to abort an overtaking maneuver; and (3) to develop a model that can predict the probability to abort an overtaking maneuver while taking into account the traffic, geometric and drivers' personal characteristics.

The following paragraphs describe the research methodology that has been adopted in this study.

Experiment Design

Data of completed and aborted overtaking maneuvers was extracted from a driving simulator experiment designed as part of a previous study [14] that focused mostly on investigating drivers' decisions to accept or reject an overtaking maneuver. Thus, the accepted but later aborted overtaking maneuvers have not been investigated, and of which is the focus of 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 scenarios consisted mainly of two-lane road segments, each of a total length of 7.5 km, with no intersections, and designed on a level terrain. The posted speed limit was set to 80 km/h. The traffic and geometric design of the road were varied in order to be able to assess their impact on drivers' overtaking decisions and behaviors. Good weather and day time 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 drivers' overtaking performance found in the literature.

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.
Overtaking 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 opposite 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 opposite vehicles (truck or passenger cars) were considered. The type of the front or opposite vehicles were randomly set in each scenario. In other words, 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 two main criteria: (1) a driving license for at least 5 years (i.e. already established their driving style); and (2) driving on a regular basis. The participation in the experiment was on a voluntary basis. The recruitment process resulted in 100 drivers (64 males, 36 females) with an age ranging between 22 and 70 years old.

Each driver completed 4 different scenarios out of the total 16 created scenarios (2^4=16), i.e. in total there were 400 scenario runs completed by the 100 drivers. The partial confounding method [41] was used to allocate 4 scenarios for each driver. This method is designed for experiments in which the number of scenarios that can be run in a block (in this case 4) is less than the total number of factor combinations (in this case 16), and so some effects have to be confounded. Using this method it is possible to maintain the identification of the main and lower level interaction (2^{nd} level interactions) effects of the various factors. In the design of this experiment third level interactions were confounded. Further details on the experiment and the experimental design can be found in [14].

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 driving simulator. No specific instructions were given regarding driving speeds, distances from other vehicles, or overtaking strategies.

Data Collection and Processing

To understand drivers' decisions to complete or abort initiated overtaking maneuvers in different road and traffic conditions, detailed trajectory data of all relevant vehicles during the overtaking process, as well as, information on the road geometric layout and drivers' personal characteristics are needed. Trajectory data was collected at a resolution of 0.1 second, and included speeds, positions, and accelerations of the subject vehicle and all other vehicles in the driving simulator scenario. Using this raw data several other variables of interest, such as relative speeds and distances between vehicles, overtaking and following gaps were calculated. The road curvature was as well calculated every 0.1 second based on the layout of the horizontal alignment of the road segments designed in the driving simulator. Finally, drivers' personal characteristics, and mainly drivers' age and gender, were collected using a questionnaire.

A completed overtaking maneuver is defined, in this study, as when the overtaking vehicle succeeds to overtake the front impeding vehicle and returns to its driving lane safely. An aborted overtaking maneuver is defined as when the driver is completely in the opposite lane but do not succeed to overtake the front impeding vehicle and decides to abort the maneuver and return to its driving lane. Aborted overtaking maneuvers that ended in a crash were excluded from the dataset. A driver is considered to have started the overtaking maneuver when the front left wheel crossed the centerline, and completed the overtaking maneuver when the rear left wheel crossed the road centerline.

Model Formulation

Logistic regression technique was applied to develop a model that predicts the probability of completing an overtaking maneuver. Generalized linear modeling $[GLM]$ in R Software is used for this purpose [42, 43]. The binary dependent variable (Y) is defined as follows:

$$Y = \begin{cases} 1, & \textit{Completed Overtaking Maneuver} \\ 0, & \textit{Aborted Overtaking Maneuver} \end{cases} \quad (1)$$

If $P\left(Y = 1 | X_i\right) = \pi$ and $P\left(Y = 0 | X_i\right) = (1 - \pi)$ denote the probabilities of individual maneuvers to be completed and aborted respectively, conditioned on a vector of independent variables X, then the logistic regression $(logit)$ function is defined as follows:

$$Logit\left(\frac{\pi}{1-\pi}\right) = \beta_o + \beta_i X_i \quad (2)$$

Where: β_0 is the intercept; β_i is the vector of coefficients of X_i – which is the vector of explanatory variables.

Parameters of the logit model in Eq. 2 were estimated for a vector of explanatory variables that maximizes the log-likelihood function in statistical software with GLM applications [43]. The expected probability of an individual overtaking maneuver to be completed conditioned on a vector of independent variables X is then computed as follows:

$$P(Y = 1 | X_i) = \pi = \frac{\exp(\beta_o + \beta_i X_i)}{1 + \exp(\beta_o + \beta_i X_i)} \quad (3)$$

Using Eq. 3 after calibration from observed data, it is possible to carry out sensitivity analysis of the model and to assess the effect of different explanatory variables on the probabilities of individual overtaking maneuvers to be completed or aborted.

RESULTS

The data base resulted in 670 overtaking maneuvers in which 116 were aborted (17.3%). This high percentage of aborted overtaking maneuvers supports the conclusion of Hanley and Forkenbrock [44] that drivers have a poor ability to initially judge acceptable conditions under which to begin an overtaking maneuver, and therefore, overtaking assistant systems might be useful in this regard [45].

Empirics of Aborted Overtaking Maneuvers

In order to get an evaluation of the time it takes drivers to abort an overtaking maneuver, FIGURE 1 was created which presents the cumulative distribution function of the duration (in seconds) of the aborted overtaking observations. The duration of an aborted overtaking maneuver is calculated in this study from the moment the driver initiated the overtaking maneuver, until he aborts the maneuver and complete the process of returning to his original driving lane.

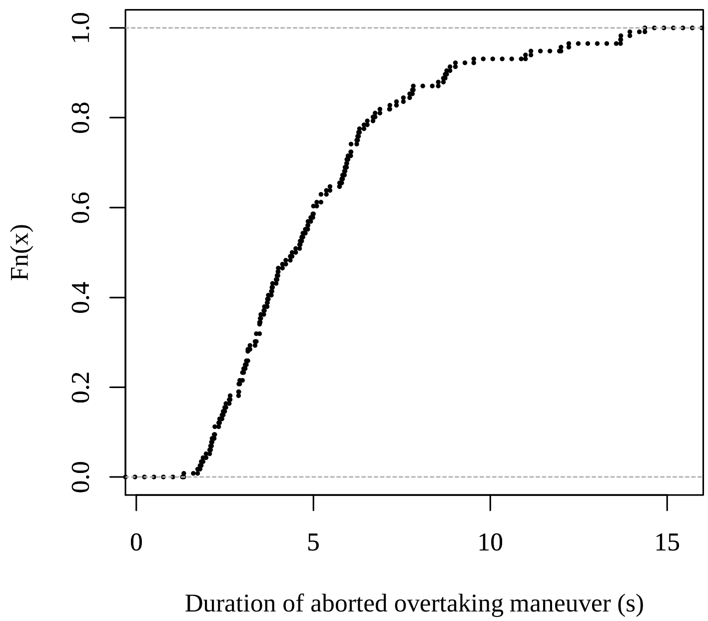

FIGURE 1 Cumulative distribution function of the duration of aborted overtaking maneuvers.

According to FIGURE 1 almost 85% of the aborted overtaking maneuvers were less or equal to a duration of 9 seconds, with an average of 5.11 seconds, and a standard deviation of 2.84 seconds. This average is lower than the average found in the study by Harwood et al. [20] which was 7.1 seconds. However, in this later study only 7 aborted overtaking maneuvers were included in the analysis. In a previous field study in Israel by Polus et al. [5] it was found that the minimum accepted overtaking gap was equal to 9 seconds, which supports the cumulative distribution function in FIGURE 1.

FIGURE 2 (left) presents the Kernel density of the relative distance from the front vehicle when aborting an overtaking maneuver, while FIGURE 2 (right) presents the Kernel density of the distance travelled until aborting. The Kernel Density Estimation (KDE) is a non-parametric way to estimate the probability density function of a random variable.

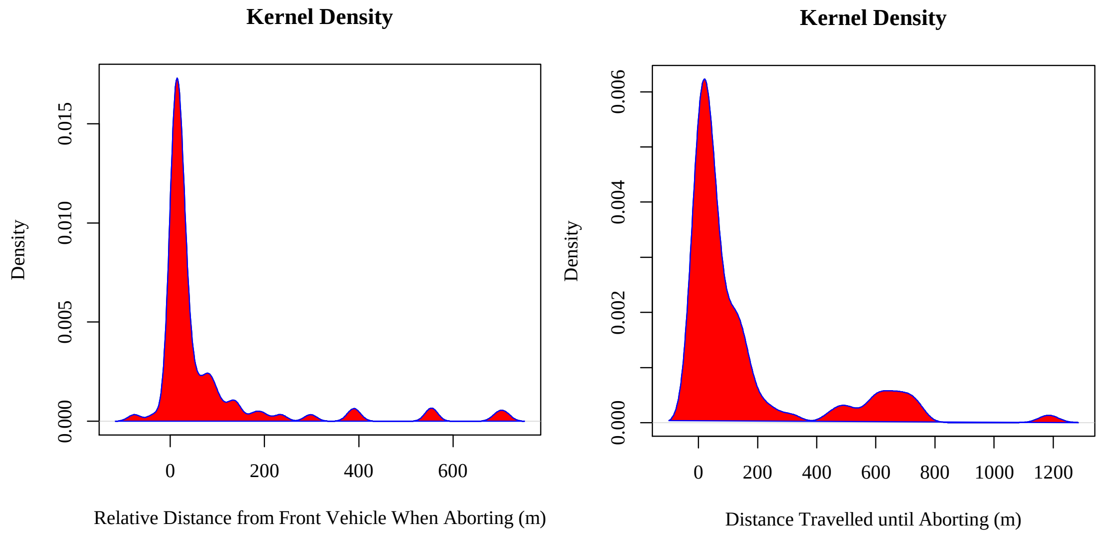

FIGURE 2 Kernel density of (Left) relative distances from front vehicles when aborting overtaking maneuvers, and (Right) distances travelled until aborting.

The Kernel densities in FIGURE 2 (left) show that most drivers abort overtaking maneuvers when they are at an abreast position with the front vehicle, and up to about 50 meters ahead of the front vehicle. The distances travelled on the opposite lane can reach values of 200 meters and more as shown in FIGURE 2 (right).

To assess the risk involved in aborting overtaking maneuvers two surrogate safety measures, that are widely used, were examined. The first is the time-to-collision, which is a surrogate for head-on collisions. The second is the following gap from the front vehicle, which is a surrogate for rear-end collisions. Both of these surrogate safety measures were calculated when overtaking vehicles returned to their original driving lane. FIGURE 3 (Left) presents the time-to-collision. It can be seen that in about more than 50% of the aborted overtaking maneuvers the time-to-collision was less than 3 seconds when overtaking vehicles just returned to their original driving lane. The rest of the aborted overtaking maneuvers had time-to-collisions greater than 3 seconds and up to 15 seconds. A reasonable hypothesis, for the large values of time-to-collision, is that these drivers started overtaking when there was no opposite vehicle in sight, and once they detected an approaching opposite vehicle they aborted the maneuver. However, future detailed analysis should be conducted to confirm this hypothesis.

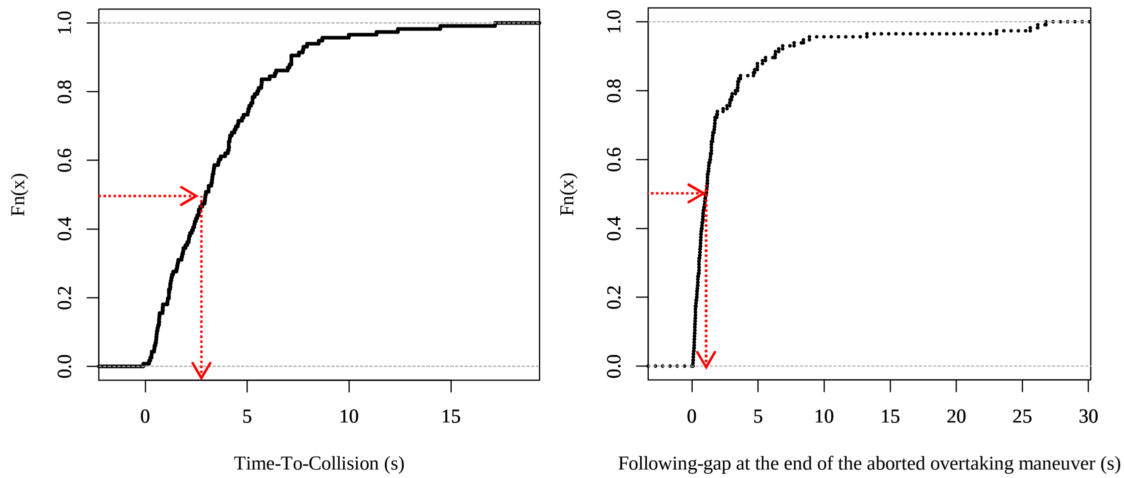

FIGURE 3 (Left) Time-to-collisions; (Right) following gaps from front vehicles, at the end of aborted overtaking maneuvers.

FIGURE 3 (Right) presents the following gap from the front vehicle. About half of the observations are less than 1 second. These short following gaps are considered to be risky and in some cases might lead to rear-end collisions or angle collisions, where the front of the overtaking vehicle collide with the side of the overtaken vehicle. It should be indicated that during the 400 scenario runs, 10 crashes occurred as a result of failed overtaking attempts.

Comparison between Completed and Aborted Overtaking Maneuvers

As a first step to compare the data of the completed and aborted overtaking maneuvers, a preliminary examination of the traffic and geometric related conditions at the moment of initiation of overtaking maneuvers, is presented in TABLE 2.

TABLE 2 Descriptive Statistics of Completed and Aborted Overtaking Maneuvers

	Completed				Aborted			
Variable	**mean**	**median**	**15th**	**85th**	**mean**	**median**	**15th**	**85th**
Overtaking gap (s)	**31.01**	27.32	22.11	34.68	**25.78**	22.25	16.71	32.66
Desired speed (m/s)	26.51	25.71	22.04	29.48	25.11	24.05	20.99	29.16
Overtaking speed (m/s)	19.81	19.70	13.63	23.67	21.16	21.19	13.48	25.57
Front speed (m/s)	16.86	17.28	11.90	20.80	18.52	19.97	11.90	20.80
Following gap (m)	**25.01**	15.79	10.14	27.20	**87.27**	26.77	12.99	68.47
Waiting time (s)	96.92	69.03	38.24	127.55	87.18	69.81	32.95	119.02
Cumulative waiting time (s)	143.82	127.61	85.78	192.06	125.69	102.51	63.42	179.47
Curvature (1/km)	-0.908	-0.700	-1.600	0.000	-0.484	-0.500	-1.300	0.400

The results in TABLE 2 highlight some differences between the aborted and completed overtaking related variables, mainly the overtaking gaps and the following gaps (bolded in the Table). To test these differences more precisely, FIGURE 4 presents the cumulative frequencies of the completed and aborted overtaking maneuvers' related variables.

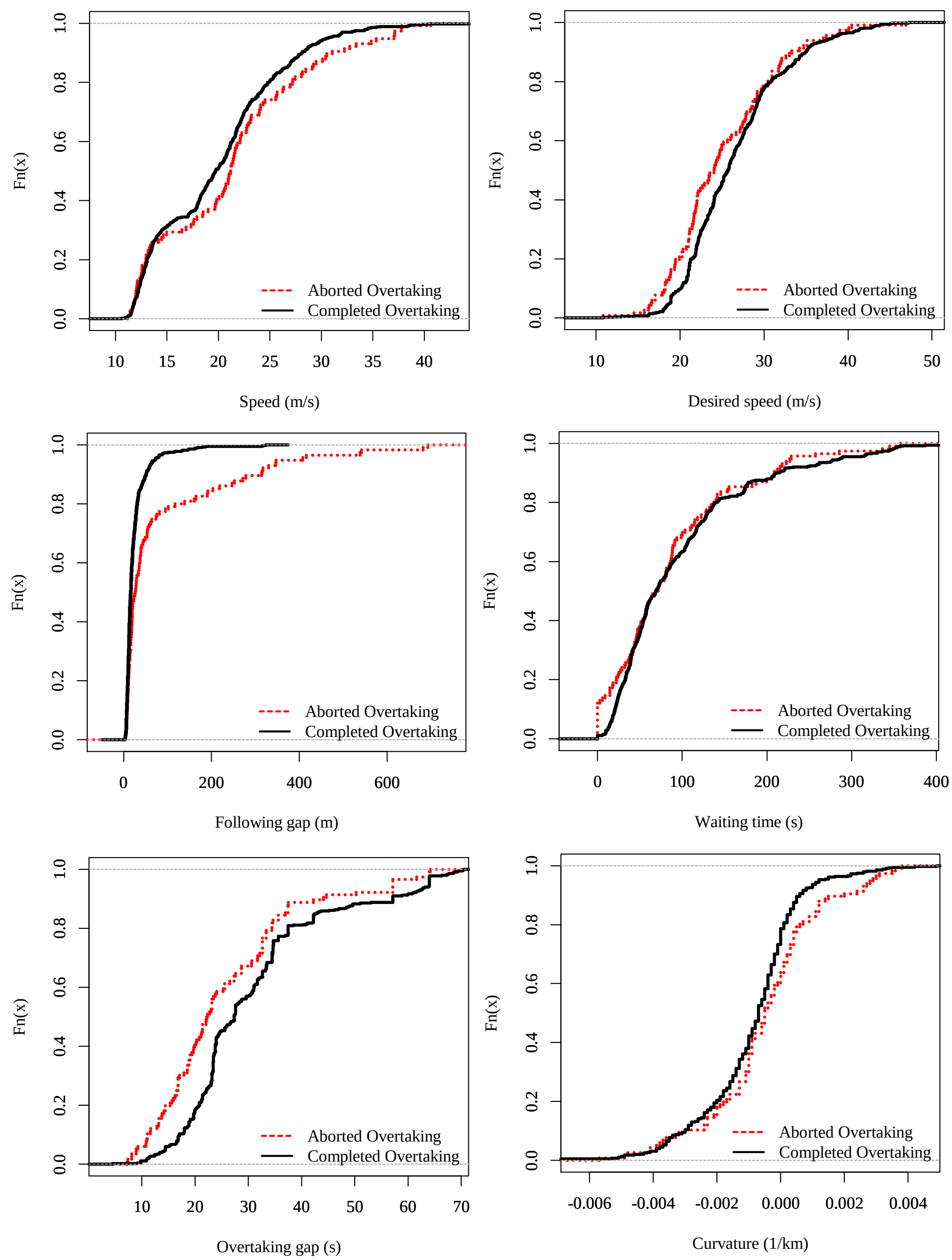

FIGURE 4 Cumulative frequencies of completed and aborted overtaking related variables.

As can be shown in FIGURE 4 drivers tend to complete overtaking maneuvers when their desired speeds are higher, following gaps from front vehicles at the moment of initiating overtaking maneuvers are shorter, accepted overtaking gaps are larger, and the road curvature is lower. These conditions facilitate the performance and completion of overtaking maneuvers and are according to a-priori expectations.

To test whether the two samples (in this case the completed and aborted related variables) are drawn from the same distribution, two-sample Kolmogorov-Smirnov tests were conducted. In a 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. Significant differences were found in the desired speeds (P-value=0.009), following gaps (P-value<0.001), overtaking gaps (P-value<0.001) and road curvature (P-value=0.028) of the completed and aborted cumulative distributions. No significant differences were found in the driving speeds of overtaking drivers (P-value=0.114), and the waiting times till drivers find acceptable overtaking gaps (P-value=0.070). In other words, there are initial conditions that increase the difficulty for drivers to complete their initiated overtaking maneuvers, and lead them to abort them, such as starting the overtaking maneuver from a larger following gap from the front vehicle.

A comparison, between the completed and aborted overtaking maneuvers, was also made in terms of the type of the overtaking, whether flying or accelerative overtaking. It was found that about 22% of the aborted overtaking maneuvers were flying, compared to only 13% of the completed overtaking maneuvers. However, since the samples differ in size (554 for completed and 116 for aborted), interpretation of this result should be carefully made.

Model Estimation

In this study, the parameters of the probability prediction model were estimated using the *GLM* applications package in R statistical software (v3.0.3), family binomial, and link function logit [46]. TABLE 3 presents the results of the model estimation.

TABLE 3 Estimation Results of the Probability Prediction Model To Complete an Overtaking Maneuver

Variable	Estimate	Std. Error	Z value	P-value
Intercept	-1.083	0.709	-1.526	0.127
Overtaking gap (s)	0.037	0.00978	3.819	<0.0001
Type of lead vehicle (1=truck)	0.566	0.297	1.904	0.0569
Speed of front vehicle (m/s)	-0.0970	0.023	-4.177	<0.0001
Cumulative waiting time (s)	0.00317	0.00149	2.116	0.034
Curvature (1/m)	-141.90	71.560	-1.983	0.047
Desired speed (m/s)	0.059	0.0198	3.007	0.0026
Gender (1=male)	0.628	0.240	2.611	0.009
Age 1 (21-25 years old)	0.069	0.045	1.524	0.127
Age 2 (25-45 years old)	0.078	0.039	2.009	0.044
Null Deviance	612.09 (on 663 degrees of freedom)			
Residual deviance:	547.41 (on 654 degrees of freedom)			
AIC	567.41			

The results in TABLE 3 indicate that the probability of a driver to complete an overtaking maneuver increases whenever the accepted overtaking gap is larger, the driver's desired driving speed is higher, and when the speed of the front impeding vehicle is lower. When the front vehicle is a truck (compared to a car), the probability to complete the overtaking maneuver is higher. Furthermore, drivers tend to complete the overtaking maneuvers (even if they need to take higher risks) whenever their cumulative waiting times are higher, which can indicate on higher levels of impatience. The road design as well affects drivers' decisions whether to complete or abort an overtaking maneuver. On roads with sharper curvatures, drivers tend more to abort overtaking maneuvers. Finally, male drivers have higher probabilities to complete overtaking maneuvers compared to female drivers. With respect to the age of drivers, no significant difference was found between the age group of 21-25 years old and drivers who are older than 45 years old. While the group of drivers between 25 and 45 years old tend more to complete overtaking maneuvers compared to the older group of drivers (>45 years old).

Sensitivity analysis was conducted while varying each time the variable of interest and fixing all other variables in the model. Unless varied, the figures below are based on the assumption that the overtaking gap is 30 seconds, the type of the front vehicle is a car and its speed is 17 m/s, the cumulative waiting time is 140 seconds (~2.33 min), the road is a straight road (no curvature), the subject driver desired speed is 26 m/s, the driver is a male driver in the age category of 25-45. The illustrations in FIGURE 5 confirm the above conclusions.

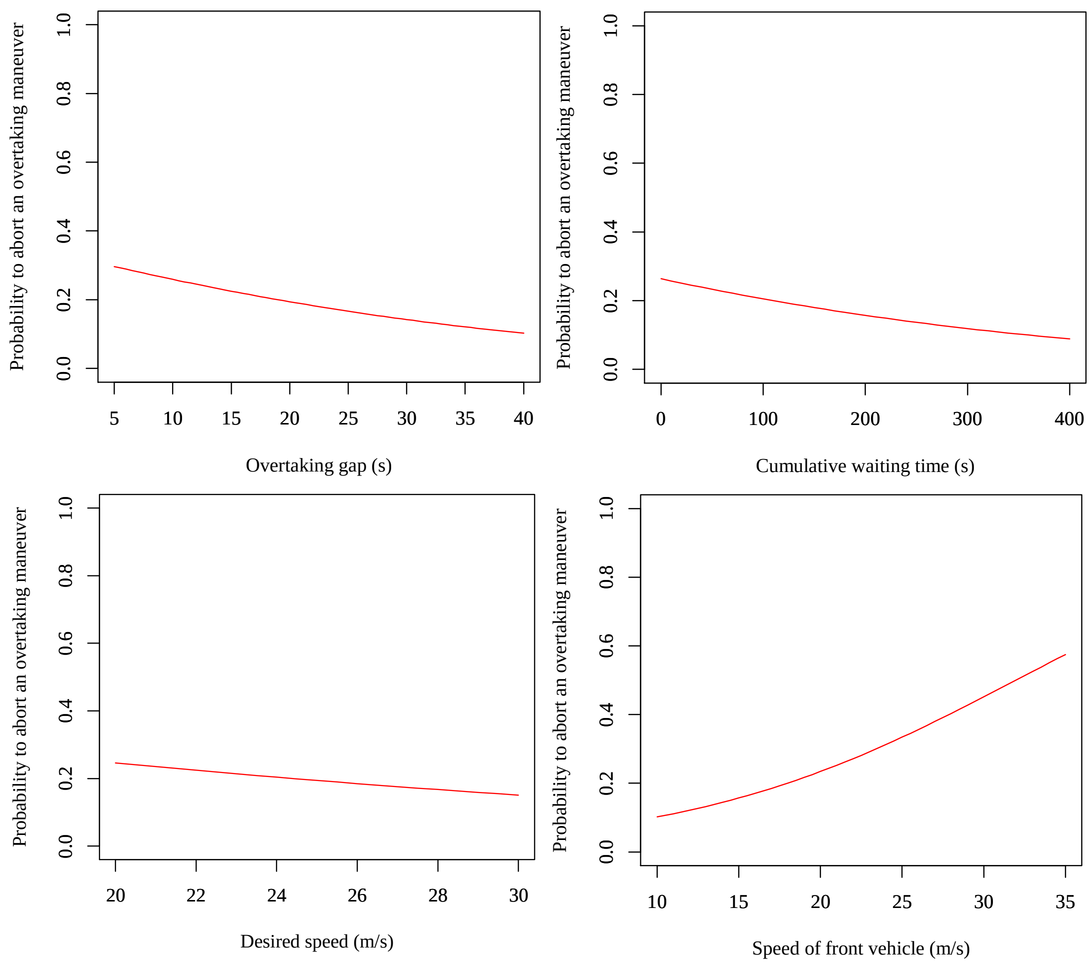

FIGURE 5 Sensitivity analysis of the probability prediction model to abort overtaking maneuvers.

DISCUSSION & CONCLUSIONS

Understanding drivers' decisions to abort overtaking maneuvers is of a high relevance to safety and operation of two-lane roads [4, 5]. The limited ability to successfully overtake slow moving vehicles, reduces the road capacity and its level of service [47]. It also affects the level of safety. Drivers who decide to abort overtaking maneuvers need to examine if the gap between the front passed vehicle and the vehicle behind it is sufficiently large to enable them to return to their driving lane. In cases where such gaps are not available, this can lead to forced merging maneuvers, run-off-the-road crashes, or head-on collisions. Despite this fact, there is limited studies in the literature to understand this behavior. Therefore, the main aim of this paper is to understand under what conditions drivers decide to abort initiated overtaking maneuvers. For this purpose, detailed trajectory data of 670 overtaking maneuvers was collected in a driving simulator experiment, in which 554 were successfully completed and 116 were aborted.

The preliminary results showed that the percentage of aborted overtaking maneuvers (17.3%) out of all overtaking attempts, is higher than the percentages found in previous field studies, which ranged between 0.8% - 7.0% [26, 32]. This difference might have resulted from several possible contributing factors. First, when defining the traffic flow in the driving simulator, very large gaps (above 31 s) and very low gaps (less than 5 s) were excluded so as to investigate drivers' decisions in the range of gaps that are of interest from the behavioral point of view. In field studies it is not possible to control the range of gaps available. In other words, drivers in the field encountered also the very short gaps (<5 s) which are not useful for overtaking maneuvers. Since decisions to abort overtaking maneuvers are conditioned on the fact that drivers first initiate overtaking, higher number of overtaking attempts increase the number of aborted overtaking maneuvers. Second, in virtual environment drivers take more risks, and might accept relatively short gaps that in reality they would reject [48]. Third, the characteristics of the population of the drivers differ which, as well, might lead to differences in driving behaviors and norms.

The empirical analysis of the aborted overtaking maneuvers revealed that the average time duration of initiating, aborting, and returning to the original driving lane (i.e. occupancy of the left lane) is 5.11 seconds with a standard deviation of 2.84 seconds. Only one study was found in the literature which measured the time duration only of 7 aborted overtaking maneuvers, and found that the average was 7.1 seconds [20]. This leads to the conclusion that future studies are needed. Most drivers who aborted the overtaking maneuvers did so before reaching the abreast position with the front vehicle, and up to around 50 meters ahead of the front vehicle. This result is in accordance with previous studies which found that drivers usually abort the pass before the abreast position; i.e. the critical point [23, 33, 34]. This information can be useful for the development of overtaking controllers in autonomous vehicles, where a cutoff point needs to be defined. This point according to Pérez Rastelli et al. [2] is used to determinate the time needed for overtaking and opposing vehicles to arrive to a safety point and, in function of that, abort or not the overtaking.

To assess the risk of aborting an overtaking maneuver, two surrogate safety measures were investigated, the time-to-collision with the opposite vehicle and the following gap from the front passed vehicle. Both measures were calculated at the end of the aborted overtaking maneuver. It was found that in 50% of the aborted overtaking maneuvers time-to-collisions were less than 3 seconds. According to AASHTO [34] and the Israeli design applications, a time-to-collision less than 3 seconds, is considered as a risky situation. Similarly, about 50% of the observations of the following gaps that drivers maintained from the front vehicle at the end of the aborted overtaking maneuvers were less than 1 second. Glennon [39] found that if the overtaking vehicle aborts its pass, it returns to its normal lane with a 1-s gap behind the overtaken vehicle. Therefore, the empirical data in this study show different results, and thus further research is needed to reach solid conclusions regarding drivers' behavior when aborting overtaking maneuvers. Furthermore, enhanced investigation of such observations by drivers' age, gender and driving experiences might be interesting for the development of overtaking controllers in autonomous vehicles. This would facilitate the development of overtaking controllers that are adapted to drivers' profiles and preferences using human driver experience as expert knowledge, but at the same time maintaining a safe behavior.

The comparison between the initial conditions of aborted and completed overtaking maneuvers showed that there are significant differences in drivers' desired speeds, following gaps from front vehicles, accepted overtaking gaps, the road curvature and the type of the overtaking maneuver (flying versus accelerative). To further understand how these factors affect the probability to complete or abort overtaking maneuvers, a logistic regression model was developed and estimated. The results show that the probabilities of drivers to complete overtaking maneuvers increase whenever the overtaking gaps are larger, their desired driving speeds are higher, and the speeds of the front vehicles are lower. The front vehicle types was also found to significantly affect the probability to complete overtaking maneuvers. Higher probabilities were found when the front vehicle is a truck. When drivers wait longer for appropriate gaps there is higher probability that they could complete the overtaking maneuver. On roads with sharper curvatures, drivers tend more to abort overtaking maneuvers. This is because on sharper curvatures it is harder for drivers to increase their driving speeds since there is a higher chance that they lose control over their vehicles. Finally, male drivers have higher probabilities to complete overtaking maneuvers compared to female drivers – which might stem from the fact that they are willing to accept higher risks [27, 49]. Similarly, drivers between 25 and 45 years old who are considered to be experienced drivers, but at the same time still relatively young (in comparison to drivers older than 45 years old), tend significantly less to abort overtaking maneuvers compared to the older group of drivers (>45 years old).

The results of this study shed light on the characteristics of drivers' aborted overtaking maneuvers and present a model to predict the probability of a driver to complete or abort an overtaking maneuver. Despite these promising results, this study has some limitations. One main limitation stems from the experimental apparatus and the fact that the data is extracted from a virtual environment. The validity of the results in this study depends on the realism degree of the driving simulator, which is determined by the resolution of the screens and the realism of the simulator mock-up. For example, the resolution of the screen can affect drivers' correct estimation of the oncoming vehicle approaching speed and distance, which in turn might affect their decisions to abort or complete overtaking maneuvers. Therefore, the lack of sufficient studies in the literature and the limitations of the current study emphasize the need for further future studies with the following research directions: (1) collect field observations of aborted overtaking maneuvers to validate the results of the driving simulator; (2) assess the impact of limited sight distances on drivers' decisions to abort overtaking maneuvers; (3) the results in this study showed that about 40% of the observed aborted overtaking maneuvers had time-to-collisions greater than 5 seconds and up till 15 seconds. In other words, drivers might have time to complete the overtaking maneuvers but chose to abort them. It would be interesting in future studies to investigate: (a) which drivers abort overtaking maneuvers under these conditions; (b) conduct an in-depth analysis of drivers' strategies in aborting overtaking maneuvers; (c) investigate the impact of human factors variables, such as mental workload and driving styles on drivers' aborting decisions; finally (4) compare the relative risk of an aborted overtaking maneuver with the potential risk that would have resulted if drivers had chosen to complete the overtaking maneuvers.

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